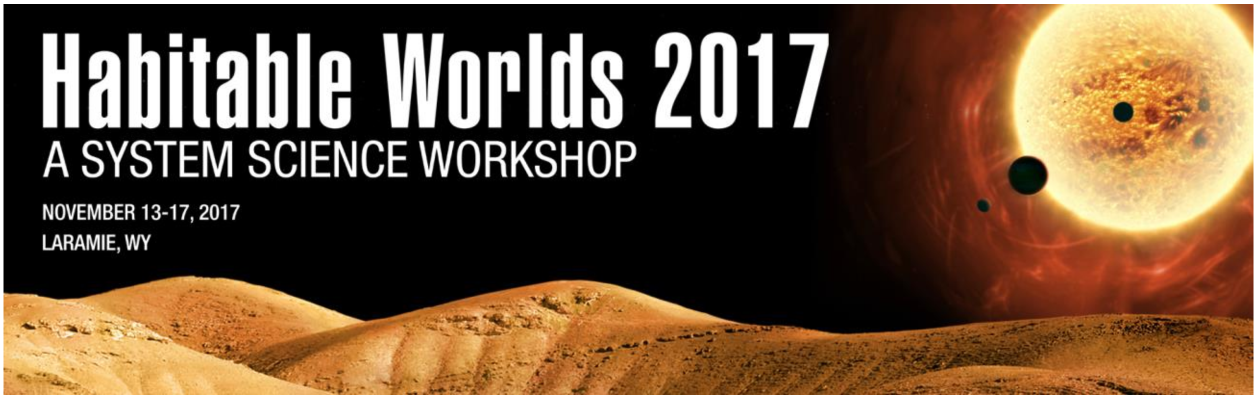

Program

LPI

USRA

Habitable Worlds 2017:
A System Science Workshop

November 13–17, 2017 • Laramie, Wyoming

Institutional Support

Lunar and Planetary Institute

Universities Space Research Association

Nexus for Exoplanet System Science (NExSS)

Convener

Hannah Jang-Condell
University of Wyoming

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Harvard University

Abstracts for this workshop are available via the workshop website at

https://www.hou.usra.edu/meetings/habitableworlds2017/

Abstracts can be cited as

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Guide to Sessions

Sunday, November 12, 2017

4:00–7:00 p.m.	UWCC Lobby	Early Registration
4:30–6:30 p.m.	UWCC Lobby	Welcome Reception

Monday, November 13, 2017

7:30 a.m.	MHRGC Lobby	Registration
8:15 a.m.	MHRGC Salons ABCD	What Does It Mean To Be Habitable?
12:30 p.m.	MHRGC Salons ABCD	Town Hall: What is NExSS Doing for the Community?
2:00–4:30 p.m.		Panel Session I MHRGC Salons AB — Habitable Zone Terrestrial Planets Around Low Mass Stars: The M-Dwarf Opportunity MHRGC Salons CD — Exoplanet Community Modeling and Analysis Tools Workshop
5:00–6:30 p.m.	UWCC Grand Ballroom	Poster Session I and Reception Biosignatures Definitions of Habitability Detection Methods Early Earth Exoplanet Characterization Origins of Life Planetary System Dynamics Planet Formation Miscellaneous

Tuesday, November 14, 2017

8:25 a.m.	MHRGC Salons ABCD	Planet Formation and Dynamics
2:00–4:30 p.m.		Panel Session II UWCC Salon E — Planetary Astrobiology: Identifying Solar System and Exoplanet Synergies MHRGC Salon D — How Do Star and Protoplanetary/ Debris Disk Composition Affect Planet Composition? UWCC Salons FG — A Statistical Approach to Characterizing Habitable Exoplanets
6:30 p.m.	MHRGC Salons ABC	Banquet

Wednesday, November 15, 2017

8:25 a.m.	MHRGC Salons ABCD	Biosignatures
11:00 a.m.	MHRGC Salons ABCD	Exoplanet Characterization I
Afternoon		Excursions

Thursday, November 16, 2017

8:25 a.m.	MHRGC Salons ABCD	Exoplanet Characterization II
9:10 a.m.	MHRGC Salons ABCD	Exoplanet Detection Methods and Missions
2:00–4:30 p.m.		Panel Session III MHRGC Salons AB — Will Evidence of Extant Life on an Exoplanet Be Detected by 2040? MHRGC Salons CD — NASA Exoplanet Missions
5:00–6:30 p.m.	UWCC Grand Ballroom	Poster Session II and Reception Biosignatures Definitions of Habitability Detection Methods Early Earth Exoplanet Characterization Origins of Life Planetary System Dynamics Planet Formation Miscellaneous

Friday, November 17, 2017

8:30–10:00 a.m.	MHRGC Salons ABCD	Wrap-Up

Program

Monday, November 13, 2017
WHAT DOES IT MEAN TO BE HABITABLE?
8:15 a.m. MHRGC Salons ABCD

8:15 a.m. Jang-Condell H. *
Welcome

Chair: Stephen Kane

8:30 a.m. Forget F. * Turbet M. Selsis F. Leconte J.
Definition and Characterization of the Habitable Zone **[#4057]**
We review the concept of habitable zone (HZ), why it is useful, and how to characterize it. The HZ could be nicknamed the "Hunting Zone" because its primary objective is now to help astronomers plan observations. This has interesting consequences.

9:00 a.m. Rushby A. J. Johnson M. Mills B. J. W. Watson A. J. Claire M. W.
Long Term Planetary Habitability and the Carbonate-Silicate Cycle **[#4026]**
We develop a coupled carbonate-silicate and stellar evolution model to investigate the effect of planet size on the operation of the long-term carbon cycle, and determine that larger planets are generally warmer for a given incident flux.

9:20 a.m. Dong C. F. * Huang Z. G. Jin M. Lingam M. Ma Y. J. Toth G. van der Holst B. Airapetian V. Cohen O. Gombosi T.
Are "Habitable" Exoplanets Really Habitable? A Perspective from Atmospheric Loss **[#4021]**
We will discuss the impact of exoplanetary space weather on the climate and habitability, which offers fresh insights concerning the habitability of exoplanets, especially those orbiting M-dwarfs, such as Proxima b and the TRAPPIST-1 system.

9:40 a.m. Fisher T. M. * Walker S. I. Desch S. J. Hartnett H. E. Glaser S.
Limitations of Primary Productivity on "Aqua Planets:" Implications for Detectability **[#4109]**
While ocean-covered planets have been considered a strong candidate for the search for life, the lack of surface weathering may lead to phosphorus scarcity and low primary productivity, making aqua planet biospheres difficult to detect.

10:00 a.m. Breakout Session Advertisement

10:10 a.m. BREAK

Chair: Natalie Hinkel

10:40 a.m. Desch S. J. * Hartnett H. E. Kane S. R. Walker S. I.
Detectability, Not Habitability **[#4070]**
Exoplanet characterization must move beyond questions of habitability, to detectability of life, comparing biotic and abiotic geochemical cycles. This shift in thinking guides the types of observations and modeling needed moving forward.

11:10 a.m. Wong M. L. * Friedson A. J. Willacy K. Shia R. L. Yung Y. L. Russell M. J.
A Methane-Rich Early Mars: Implications for Habitability and the Emergence of Life **[#4063]**
We use a coupled radiative transfer and photochemical model to investigate the climate of a CH_4-rich early Mars. Can high levels of CH_4 and SO_2 thaw Mars and make it suitable for the emergence of life? Applications to small terrestrial exoplanets.

11:30 a.m. Froning C. S. * France K. Loyd R. P. Youngblood A. Brown A. Pineda J. S. Schneider P. C. Roberge A.
Flexing our MUSCLES: The HST Mega-MUSCLES Treasury Survey **[#4052]**
The MUSCLES Survey is a large HST program to characterize the energetic emission from M stars. Here, we present the results from MUSCLES and introduce Mega-MUSCLES, a new program designed to provide key inputs to JWST observations of rocky planets.

11:50 a.m. Poster Pop-Ups

Monday, November 13, 2017
TOWN HALL:
NASA HEADQUARTERS AND NExSS FUTURE DIRECTIONS
12:30 p.m. MHRGC Salons ABCD

Come and hear from NASA Headquarters regarding future directions of the Astrophysics and Planetary Sciences divisions, as well as how NExSS and its activities are playing a role in shaping that future.

Monday, November 13, 2017
PANEL SESSION I

HABITABLE ZONE TERRESTRIAL PLANETS AROUND LOW MASS STARS: THE M-DWARF OPPORTUNITY

2:00–4:30 p.m.   MHRGC Salons AB

Kopparapu R.   Charbonneau D.

Some of the questions we want “answered” or discussed:

1. What observable features do recent climate/photochem/helio models predict for tidal-locked (synchronous and resonant rotating) planets?
2. How does variation in planetary and stellar characteristics (internal and atmospheric composition, age, stellar activity) affect the observables?
3. Discuss opportunities for atmospheric characterization with ELTs and JWST of known (and to be known) M-dwarf HZ planets.
4. How sure are we that there is a firm plan to search every one of the ~450 M-dwarfs within 15pc in the near future?

EXOPLANET COMMUNITY MODELING AND ANALYSIS TOOLS WORKSHOP

2:00–4:30 p.m.   MHRGC Salons CD

Arney G. N.   Mandell A. M.

A variety of modeling and analysis tools will be needed as new exoplanet observational capabilities come online, and observations of exoplanets span an increasingly wide swathe of parameter space. This will lead to a corresponding increase in the diversity of planetary processes that are observed. Each process would need to be modeled and/or examined in a variety of ways using a set of tools that can be effectively interfaced. Such studies would benefit from inter-tool comparisons, ensuring that our conclusions are not based on one set of assumptions or analytical methods. In addition, model- and tool-inter-comparison projects are valuable for modeling exoplanets or examining exoplanet observations in absence of extensive data on planetary properties: without data for comparison, the results of any given model are strengthened if independent models agree with each other. There is a growing acknowledgement of these needs in light of future telescopes that will discover and observe exoplanets.

The session is an opportunity for all members of the exoplanet community to share and discuss the wide range of software already developed or in development, and strategize how we can better collaborate and communicate. Individual researchers will present community modeling tools and provide short demos for running them. There will be ample time provided for interacting with the modeling tools presented and asking questions of the developers. We will also allow time for discussing inter-tool coupling/comparisons, how the community can work to advance the state of exoplanet and planetary modeling, and how to effectively share models across the community.

POSTER SESSIONS
Monday, November 13, 2017
and Thursday, November 16, 2017

5:00–6:30 p.m. UWCC Grand Ballroom

BIOSIGNATURES POSTERS

Airapetian V . S. Jackman C. H. Mlynczak M. Danch W. D. Hunt L.
Atmospheric Beacons of Life From Exoplanets Around G-M Dwarfs **[#4074]**
We propose to use the powerful emission from broad bands of nitric oxide, hydroxyl, and molecular oxygen as signatures of nitrogen, oxygen, and water rich atmospheres of terrestrial type exoplanets "highlighted" by stellar activity from G-M stars.

Hartnett H. E.
Signs of Life on Anoxic Worlds **[#4081]**
Anoxic metabolisms may be important for understanding exoplanet biosignatures because many systems may not have detectable oxygen. Early Earth was habitable, and inhabited, but would have had quite different biosignatures from today's Earth.

O'Malley-James J. T. Kaltenegger L.
UV Surface Environments of M Star Planets: Surface Habitability and Temporal Biosignatures **[#4128]**
Habitable planets around active M stars can be subjected to high levels of UV radiation. Here we model the UV surface regimes on such planets as a first step toward determining the habitability and novel biosignatures for such worlds.

POSTER SESSIONS
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5:00–6:30 p.m. UWCC Grand Ballroom

DEFINITIONS OF HABITABILITY POSTERS

Airapetian V. S. Glocer A. Khazanov G. Danchi W.
Space Weather Affected Habitable Zones **[#4076]**
Our global models show that atmospheres of terrestrial type exoplanets around M dwarfs are vulnerable to high XUV fluxes and magnetized winds causing atmospheric loss rate of O and N, which will make exoplanets uninhabitable within 10-100 Myr.

Chandler M. A. Sohl L. E. Jonas J. A. Carter D. O.
3-D Climate Modeling of the Cretaceous: Capacity and Conundrums That Reflect on the Promise of Simulating Habitable Exoplanets **[#4082]**
3-D GCM simulations of Paleo-Earth climates such as the mid-Cretaceous permit exploration of the dynamics impacting global or regional habitability of HZ planets, as well as a means to evaluate GCM performance and suggest lines of inquiry.

Checlair J. Abbot D. S.
A Test for the Habitable Zone Concept **[#4147]**
Traditional habitable zone theory assumes that the silicate-weathering feedback regulates the atmospheric CO_2 of planets within the habitable zone. We outline a test for this prediction by using a statistical approach on many planets with future observing facilities.

Del Genio A. D. Way M. J. Amundsen D. S. Aleinov I. Kelley M. Kiang N. Y.
Equilibrium Temperatures and Albedos for Habitable M Star Planets in a Coupled Atmosphere-Ocean General Circulation Model **[#4029]**
3-D exoplanet climate modeling shows that equilibrium temperature assessments of the habitable zone should account for the higher albedos of slowly rotating planets inside the tidal locking radius and the lower albedos of planets orbiting M stars.

Dong C. F. Lee Y. Ma Y. J. Bougher S. W. Luhmann J. G. Jakosky B. M. Curry S. M. Brain D. A. Toth G. Nagy A. F.
Modeling of Ion and Photochemical Losses to Space Over the Martian History: Implications for Exoplanetary Climate Evolution and Habitability **[#4023]**
This study informs our understanding of the long-term evolution of the Martian climate due to atmospheric losses to space, and has implications for analogous change on exoplanets. Thus, it offers fresh insights concerning the habitability of exoplanets.

Hall A. Acker-Moorehead M. Onyilagha J.
Origin of Life: Pathways of the 20 Standard Amino Acids of the Genetic Code **[#4157]**
How nature used four nucleotides to build its proteins and form genetic code is intriguing. Stereochemical, Coevolution, and Adaptive theories have been propounded. We updated biosynthesis pathways and give insight into ancient evolutionary events.

Hayworth B. P. Payne R. C. Kasting J. F.
The Effect of New Collision-Induced Absorption Coefficients on the Early Mars Limit Cycle Hypothesis **[#4125]**
Updating the Limit Cycling (LC) Model for early Mars with new absorption coefficients to test for changes to LC behavior and to potentially lower needed concentrations of greenhouse gases. Thought will be given to the effect of LC on habitability.

Hinkel N. R.
Avoiding 'The Boy Who Cried Wolf' In Exoplanet Habitability **[#4105]**
I will discuss the short-comings in the current definition of the habitable zone as well as how to move forward, taking into account both the physical and chemical relationships between a star and its planet.

Kane S. R.   Kopparapu R. K.   Domagal-Goldman S. D.
***A Catalog of Kepler Habitable Zone Exoplanet Candidates* [#4014]**
This presentation will describe the highlights of the HZ catalog and the plans for further validation of HZ candidates and follow-up studies.

Marounina N.   Rogers L. A.   Kempton E.
Constraining the Habitable Zone Boundaries for Water World Exoplanets **[#4135]**
We use coupled models of planet interiors, clathrate formation, liquid-gas equilibrium, and atmospheric radiative transfer to constrain the atmospheric abundance of CO_2 and corresponding habitable zone boundaries for water-rich exoplanets.

Mason P. A.
The Large-Scale Structure of Habitability in the Universe **[#4149]**
The emergence of life as we know it relies on several factors. Over time, galactic disks not only allowed for the concentration of elements, but the magnetized galactic wind of disk galaxies also provided protection.

Soto A.
How Ocean-Land Fraction and Distribution Affects Habitable Conditions on Earth-Like Planets **[#4027]**
We investigate how ocean-land fraction and distribution affects the creation of habitable conditions on the surface of Earth-like exoplanets by using a general circulation model to simulate a range of ocean-land fractions as well as distributions.

Tasker E. J.   Tan J.   Heng K.   Kane S.   Spiegel D.
We Need to Change How We Discuss Habitability **[#4042]**
Metrics are used to rank planets for follow-up studies. However, the results are frequently over-extended to suggest that we can quantitatively assess a planet’s capacity for supporting life. Such misrepresentation risks serious damage to the field.

Turbet M.   Forget F.   Leconte J.   Selsis F.   Bolmont E.
Habitability and Observability of Proxima Cen and TRAPPIST-1 Planetary Systems **[#4016]**
We use sophisticated 3-D numerical climate models to explore the habitability of two nearby planetary systems: Proxima Cen and TRAPPIST-1. Then we produce synthetic observables to prepare future observations with JWST and ELT-class telescopes.

Turbet M.   Forget F.   Leconte J.   Tobie G.   Charnay B.   Selsis F.   Bolmont E.
Glaciation Escape on Earth-Like Planets Limited by CO_2 Condensation **[#4017]**
We discuss the ability of Earth-like planets to escape from episodes of complete glaciation (i.e. snowball episodes) through volcanic CO_2 greenhouse warming. We show that CO_2 polar condensation prevents distant planets to escape glaciation.

Yang J.   Ding F.   Ramirez R. M.   Peltier W. R.   Hu Y.   Liu Y.
Abrupt Climate Transition of Icy Worlds from Snowball to Moist or Runaway Greenhouse **[#4007]**
Icy planetary bodies with low concentrations of greenhouse gases may transition directly to a moist or runaway greenhouse without passing through a habitable Earth-like state.

Young P. A.   Truitt A.
Constraining the Habitability Histories of Planets **[#4040]**
We present a method and example for calculating the probability that a planet at a given distance from its star has been habitable for a specified amount of time, even without a known age or composition for the host star.

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5:00–6:30 p.m. UWCC Grand Ballroom

DETECTION METHODS POSTERS

Chakrabarty A. Sengupta S.
Using Indian Telescopes for Transit Follow-Up: Prospects for Improved Longitudinal Coverage **[#4064]**
India seeks scopes to do transit searches and follow-ups with the new facilities (2m HCT, 3.6 m DOT) for other teams, by collaborating with them, to provide missing longitudinal coverage leveraging our newly demonstrated transit detection capability.

Elrod M. K.
The Search for Life: In-Situ, Remote Sensing, Modeling, and Archiving **[#4092]**
Instrumentation development and current technology.

Isaacson H. T. Siemion A. P. V.
Breakthrough Listen: Searching for Signatures of Technology **[#4144]**
Breakthrough Listen is searching for signals of extra-terrestrial technologies using radio and optical telescopes. Very nearby stars of all types. Stars across the HR diagram and galaxies are all of interest in the search for techno-signatures.

Lisse C. M. Sitko M. L. Marengo M. Kane S. R. Desch S.
The IRTF/SpeX Survey of Stellar Fluxes and Atomic Abundances in Kepler THZ Planet Systems **[#4061]**
We have used the results from our 100+ hours, 50+ systems NASA/IRTF SpeX spectral survey to understand the nature systems known to host planets and circumstellar disks. We present our latest stellar flux and abundance results for these systems.

Meyer M. R. Quanz S. P. Kasper M. Guyon O. Monnier J.
Blazing a Trail: Towards Imaging Super-Earths from the Ground and Space **[#4108]**
We will review recent progress in imaging super-earths around the very nearest stars, new opportunities for 10 microns imaging, contributions JWST will make to imaging ice giants, and complementary work to be done by WFIRST-AFTA.

Rizzo M. J. Roberge A. Lincowski A. P. Zimmerman N. T. Juanola-Parramon R. Pueyo L. Hu M. Harness A.
Realistic Simulations of Coronagraphic Observations with Future Space Telescopes **[#4097]**
We present a framework to simulate realistic observations of future space-based coronagraphic instruments. This gathers state-of-the-art scientific and instrumental expertise allowing robust characterization of future instrument concepts.

Rogers L. A. HabEx STDT
HabEx: Finding and Characterizing Habitable Exoplanets with a Potential Future Flagship Astrophysics Mission **[#4146]**
The Habitable Exoplanet Imager is one of four flagship missions that NASA is studying in advance of the 2020 Decadal Survey. The primary goal of HabEx is to directly image and characterize rocky planets in the habitable zones of sun-like stars.

Sorber R. L. Kar A. Hancock D. A. Leuquire J. D. Suhaimi A. Kasper D. H. Jang-Condell H.
The Search for Hot Jupiters Using Red Buttes Observatory **[#4112]**
The goal of this research is to perform operated observations of transiting exoplanet candidates, catalogued by the KELT (Kilodegree Extremely Little Telescope) Survey, transiting exoplanets around bright stars.

Tanner A. M.
Looking to the Future: What Will It Take to Confirm Life on an Exoplanet? **[#4141]**
I will present a continent neutral overview of ground and space-based observatories which will be devoted to searching for life outside of our solar system. I'll break it down to four phases: Discovery, Reconnaissance, Characterization, and LIFE!

Ellis T. Boyajian T. Bodman E. Wright J.
The Color Dependency of KIC 8462852's Dips **[#4159]**
KIC 8462852 earned its title of "The Most Mysterious Star in the Galaxy" when it was discovered to sporadically dip in luminosity upward of 20% by the Kepler mission. We present current photometry and colors of multiple modern dips.

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EARLY EARTH POSTERS

Ranjan S. Todd Z. Sutherland J. Sasselov D. D.
Planetary Sources for Reducing Sulfur Compounds for Cyanosulfidic Origins of Life Chemistry **[#4024]**
Sulfidic anions (e.g, HS^-, HSO_3^-) are invoked in prebiotic chemistries, but their abundance on early Earth is poorly constrained. We use simple equilibrium chemistry to estimate the abundance of sulfidic anions in surficial aquatic reservoirs.

Silverman S. N. Kopf S. Gordon R. Bebout B. Som S.
Measuring N_2 Pressure Using Cyanobacteria **[#4013]**
We have shown that cyanobacteria can record information about N_2 partial pressure both morphologically and isotopically, and thus may serve as useful geobarometers to help us better understand Earth's ancient atmosphere.

POSTER SESSIONS
Monday, November 13, 2017
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5:00–6:30 p.m. UWCC Grand Ballroom

EXOPLANET CHARACTERIZATION POSTERS

Apai D.
Exploring Habitable Worlds: Science Questions for Future Direct Imaging Exoplanet Missions **[#4049]**
We report on the SAG15 team's comprehensive effort to compile community input on key science questions for future exoplanet imaging missions, many of which are essential to recognizing habitable planets and for correcting interpreting biosignatures.

Batalha N. M. Bean J. Stevenson K. Sing D. Crossfield I. Knutson H. Line M. Parmentier V. Kreidberg L. Desert J.-M. Wakeford H. Crouzet N. Moses J. Benneke B. Kempton E. Berta-Thompson Z. Lopez-Morales M.
The Transiting Exoplanet Community Early Release Science Program for JWST **[#4151]**
We describe the program for JWST Early Release Science designed and executed by the transiting exoplanet community.

Bean J. L.
Comparative Exoplanetology in Era of the Great Observatories, JWST, and Beyond **[#4067]**
My presentation will focus on three topics: exoplanet atmosphere characterization with HST and Spitzer, expectations and plans for transit spectroscopy with JWST, and surprising chemical abundance results for solar twin stars.

Beatty T. G.
Gaussian-Process Techniques for Accurately Characterizing Exoplanet Atmospheres **[#4142]**
Gaussian-Process (GP) techniques create flexible systematic noise models for exoplanet observations. I will discuss real-life applications of GPs to observations of exoplanet atmospheres from the ground and space, and their applicability to JWST.

Bixel A. Apai D.
Probabilistic Assessment of Planet Habitability and Biosignatures **[#4066]**
We have computed probabilistic constraints on the bulk properties of Proxima Cen b informed by priors from Kepler and RV follow-up. We will extend this approach into a Bayesian framework to assess the habitability of directly imaged planets.

Bodman E. H. L. Desch S. J. Wright J. T.
Exoplanet Dust Tails as Windows to the Planetary Interior **[#4121]**
Disintegrating planets provide an opportunity to study the composition of the interiors of exoplanets. We model the dust tail and simulate observable signatures of composition for broadband photometry and IR spectra.

Bott K. Bailey J. Meadows V. Kedziora-Chudczer L. Cotton D. Crisp D.
Comparative Habitable Planet Signatures in Polarized Light **[#4077]**
VSTAR polarized light models of terrestrial worlds are compared for varying cloud, atmospheric, and surface conditions. Archetypal "Earth-like" planets are compared and the observability of their combined polarimetric effects assessed.

Chandler C. O. Kane S. R. Gelino D. M.
The Habitable Zone Gallery 2.0: The Online Exoplanet System Visualization Suite **[#4010]**
The Habitable Zone Gallery 2.0 provides new and improved visualization and data analysis tools to the exoplanet habitability community and beyond. Modules include interactive habitable zone plotting and downloadable 3D animations.

Fujii Y.   Del Genio A. D.   Amundsen D. S.
Water Vapor in the Upper Atmospheres of Synchronously Rotating Temperate Terrestrial Planets **[#4118]**
Using the GCM ROCKE-3D, we examine how the water vapor mixing ratio in the upper atmospheres of synchronously rotating temperate terrestrial planets responds to the various stellar irradiation.

Hanson J. R.   Desch S. J.
Nonstationary Mass Loss of Disintegrating Planets **[#4095]**
We present a nonstationary model of atmospheric mass loss of disintegrating planets. This model explains the observed variable transit depths and can be coupled to mineral condensation in order to predict planet composition based on JWST spectra.

Haqq-Misra J.   Wolf E. T.   Joshi M.   Kopparapu R. K.
Demarcating Circulation Regimes of Synchronously Rotating Habitable Planets **[#4048]**
We investigate the atmospheric dynamics of terrestrial planets in synchronous rotation around low-mass stars using aquaplanet simulations. We define three dynamical regimes in terms of the equatorial Rossby deformation radius and the Rhines length.

Hill M. L.   Kane S. R.   Duarte E. S.   Kopparapu R. K.   Gelino D. M.   Whittenmyer R. A.
Potential Habitable Zone Exomoon Candidates and Radial Velocity Estimates for Giant Kepler HZ Candidates **[#4003]**
We found 39 planet candidates greater than 3 Earth radii residing in the Optimistic Habitable Zone of their host star. While giant planets aren’t favored in the search for eta Earth, they indicate potential for moons residing in the habitable zone.

Jensen A. G.   Cauley P. W.   Redfield S.   Cochran W. D.   Endl M.
Possible H? and Sodium D Absorption in WASP-12b **[#4073]**
We report on the possibility of Hα and sodium D absorption in WASP-12b. An Hα detection would be only the second such exoplanetary detection after HD 189733b. We discuss this in the context of atmospheric loss/evolution and star-planet interactions.

Jontof-Hutter D.   Ford E. B.   Wolfgang A.   Lissauer J. J.   Fabrycky D. C.
Identifying Potentially Habitable Worlds with Transit Timing **[#4099]**
As planet characterization continue to progress to smaller planets orbiting further out than the earliest exoplanet detections, we evaluate the prospects of characterizing potentially habitable rocky planets around different hosts with TTVs.

Kasper D. H.   Cole J. L.   Cortez C. N.   Garver B. R.   Jarka K. L.   Kar A.   McGough A. M.   PeQueen D. J.   Rivera D. I.   Jang-Condell H.   Kobulnicky H. A.   Dale D. A.
Characterizing Giant Exoplanets Through Multiwavelength Transit Observations **[#4089]**
Giant exoplanets are important for system habitability. We have observed multiple transits of giant exoplanets using a 2.3 m observatory and Sloan filters. We present early constraints on the atmospheres of the exoplanets.

Lustig-Yaeger J.   Lincowski A. P.   Meadows V. S.
Extending Atmospheric Characterization to Earth-Sized Exoplanets with JWST: Transits, Eclipses, and the TRAPPIST-1 System **[#4098]**
We explore the potential to characterize the TRAPPIST-1 system of seven transiting planets. We devise a hierarchical observing scheme to maximize information content in observations of the atmospheres of TRAPPIST-1 planets while minimizing JWST time.

Lustig-Yaeger J.   Tovar G.   Schwieterman E. W.   Fujii Y.   Meadows V. S.
Detecting Oceans on Exoplanets Using Phase-Dependent Mapping with Next-Generation Coronagraph-Equipped Telescopes **[#4110]**
We describe a novel combination of observations to map Earth-like exoplanets using mulit-band lightcurves at multiple phases to identify the angle-dependent behavior of the reflecting surfaces, and thereby increase the robustness of ocean detection.

Mansfield M.   Bean J.   Line M. R.   Kreidberg L.
Constraining the Atmospheric Metallicity of HAT-P-11b **[#4012]**
The core accretion model of planet formation predicts decreasing atmospheric metallicity with increasing planet mass. We present new observations of the Neptune-sized planet HAT-P-11b to constrain its metallicity and test this mass-metallicity trend.

Merrelli A. J.   Turnbull M. C.   L'Ecuyer T. S.
Terran World Simulator **[#4087]**
The Terran World Simulator was developed to simulate direct detection of terrestrial exoplanets. It can be used to support preparatory studies for direct imaging missions such as NASA's WFIRST and other next generation observatories.

Tanner A. M.   Muna D.   Addison B.   Zohrabi F.   Geneser C.   Niffenegger R.
Starchive: The Open Access, Open Source Stellar Database **[#4086]**
It has become clear that we must understand the host stars as well as their exoplanets. The Starchive is an open source, open access stellar database and intuitive front-end to help astronomers find planets and determine habitability.

Wang J. J.   GPIES Collaboration
The Orbits and Atmospheres of Directly-Imaged Exoplanets from the Gemini Planet Imager Exoplanet Survey **[#4130]**
The Gemini Planet Imager Exoplanet Survey (GPIES) is a survey for young Jovian-mass exoplanets at solar system scales. I will show the orbits and near-infrared spectra of the exoplanets imaged by GPIES and discuss what we can learn from them.

Wolf E. T.   Gatlin D.   Kopparapu R. K.   Haqq-Misra J. H.   Villanueva G.
Observational Signals of TRAPPIST-1e Derived from a 3D Climate Model **[#4056]**
We conduct 3D climate simulations of TRAPPIST-1e with a variety of atmospheric compositions. Then we calculate theoretical observables from these worlds, such as thermal phase curves and transit spectra.

POSTER SESSIONS
Monday, November 13, 2017
and Thursday, November 16, 2017

5:00–6:30 p.m. UWCC Grand Ballroom

ORIGINS OF LIFE POSTERS

Bose M. Zega T. J. Haenecour P. Domanik K.
Correlated Isotopic Anomalies Associated with Organic Matter in Meteorites **[#4033]**
Rare domains with correlated isotopic anomalies, i.e., anomalous in H, C, and/or N have been identified in pristine carbonaceous meteorites.

Cruz-Castañeda J. Negrón-Mendoza A. Ramos-Bernal S. Colín-García M. Heredia A.
Radiolysis and Termolysis of Tetradecanoic Acid and Docosanoic Acid in Physicochemical Conditions Similar to Hydrothermal Vents **[#4101]**
Our results show the stability of carboxylic acids against different energy sources. Additionally, the reaction products may have importance in chemical evolution, since they could function as reagents towards synthesis of other important compounds.

Gordon R. Hanczyc M. M. Smoukov S. K.
Habitats for Shaped Droplets in the Origin of Life **[#4018]**
Cooled oil droplets are flat and polygonal, like some Archaea and bacteria. Shaped droplet protocells would constrain habitats for the origin of life to those where oil/water emulsions can form, remain, concentrate, and undergo temperature cycling.

Haenecour P. Zega T. J. Howe J. Y. Bose M. Wallace P.
Origins and Delivery of Volatile Elements in Terrestrial Planets: Insight from the Composition and Functional Chemistry of Organic Matter in Meteorites **[#4037]**
We report new EELS data on the elemental compositions and functional chemistries of primordial meteoritic organic matter to investigate the origin(s) of volatile elements in meteorites and their possible delivery to terrestrial planets.

Meléndez-López A. L. Negrón-Mendoza A. Ramos-Bernal S. Colín-García M. Heredia A.
Stability of Molecules of Biological Importance to Ionizing Radiation: Relevance in Astrobiology **[#4090]**
Our aim is to study the stability of amino acids in conditions that probably existed in the primitive environments. We study aspartic acid and glutamic acid, in solid state and aqueous solution, against high doses of gamma radiation at 298 and 77 K.

Rimmer P. B. Xu J. Thompson S. J. Gillen E. Sutherland J. D. Queloz D.
Prebiotic Chemistry on Exoplanets Within the Liquid Water Habitable Zone **[#4094]**
We explore whether life could originate on rocky planets by performing laboratory photochemical experiments and comparing the lamps we use to observe stellar spectra.

POSTER SESSIONS
Monday, November 13, 2017
and Thursday, November 16, 2017

5:00–6:30 p.m. UWCC Grand Ballroom

PLANETARY SYSTEM DYNAMICS POSTERS

Jackson J. M. Dawson R. I.
The Origin of Kepler-419B: A Path to Tidal Migration Through Secular Eccentricity Modulation **[#4038]**
The origin of the warm Jupiter Kepler-419B is examined using N-body simulations to rule out or allow for tidal migration of the planet.

Renaud J. P. Henning W. G.
Emergent Tidal Resilience for Exomoons and Extrasolar Planets via the Increased Tidal Dissipation of the Andrade and Sundberg-Cooper Rheological Models **[#4025]**
We find that an exomoon or exoplanet in an eccentric orbit will produce increased tidal dissipation compared to prior models, in certain temperature and frequency domains, when its interior is modeled with realistic rheologies.

Shan Y. Li G.
Obliquity Variations of Habitable Zone Planets Kepler-62f and Kepler-186f **[#4075]**
Obliquity variations play critical roles in a planet's climate and habitability. We study the spin axis dynamics of Kepler-62f and Kepler-186f in a large parameter space, finding the low-obliquity regimes to be stable assuming they are Earthlike.

Unterborn C. T. Hull S. D. Stixrude L. Teske J. K. Johnson J. A. Panero W. R.
Stellar Chemical Clues as to the Rarity of Exoplanetary Tectonics **[#4034]**
A host-star bulk composition affects the geology of terrestrial planets in that system. We present geochemical calculations quantifying how these changes affect the system's potential to produce tectonically active, and truly "Earth-like," planets.

Unterborn C. T.
Redefining "Earth-Like:" Habitable Planet Composition and the Case for Moving Beyond the Mass-Radius Diagram **[#4107]**
The composition of exoplanets affects its likelihood to be Earth-like and habitable. This talk will explore various geophysical consequences of varying exoplanet composition.

POSTER SESSIONS
Monday, November 13, 2017
and Thursday, November 16, 2017

5:00–6:30 p.m. UWCC Grand Ballroom

PLANET FORMATION POSTERS

Ballering N. P. Eisner J. A.
Protoplanetary Disk Masses in Taurus and the Orion Nebula Cluster **[#4133]**
We will discuss two studies of protoplanetary disk masses (a primary factor influencing planet formation): 1) radiative transfer modeling of Taurus disks to constrain dust temperature and opacity, and 2) ALMA observations of disks in the ONC.

Carrera D. Ford E. B. Wolfgang A.
Constraining the Composition of Super-Earths **[#4019]**
We use computer simulations to model planet formation, including migration, accretion, and atmosphere loss via giant impacts. For each model we predict the mass and density ratios of TTV planets, and compare them to super-Earths in the Kepler field.

Feng W. Desch S.
The Diversity of Rocky Bodies from White Dwarf Pollution **[#4102]**
Insight to the chemical diversity of extrasolar rocky bodies may be gained by observing heavy elements in white dwarf atmospheres. The disk accretion scenario is key to understanding the accreted rocky bodies.

Hori Y. Ogihara M.
Atmospheric Growth of the TRAPPIST-1 Planets **[#4123]**
We investigate the atmospheric growth and loss of a (non-)migrating planet around TRAPPIST-1 star and then we discuss whether the TRAPPIST-1 planets can have/retain their primordial atmospheres.

Jang-Condell H.
Constraints on Terrestrial Planet Formation in Close Binaries **[#4083]**
This poster presents a study on the feasibility of the formation of small, rocky planets in close binary systems based on the amount of material available in truncated disks.

Jennings J. Ercolano B. Rosotti G. Birnstiel T.
The Difficulty of Forming Earth Analogs **[#4136]**
In the protoplanetary disc, the streaming instability is a favored mechanism to form planetesimals. It may be induced by photoevaporation. I will discuss the conditions required for this process to produce Earth analogs and the difficulties involved.

Kalyaan A. Desch S. J.
Water Distribution and Icelines in Non-Uniform Alpha-Disks **[#4085]**
Icelines set where planets form in disks, and how much water they can carry. We perform simulations to understand the behavior of radial volatile transport processes that contribute to planet formation, as well as external factors they depend on.

Lopez E. D.
Kepler's Rocky Exoplanets: Born Rocky or Stripped Sub-Neptunes? **[#4129]**
I will review the current evidence for the role of photo-evaporation in shaping the known exoplanet population and the impact this may have on our current estimates of eta-Earth. I will then discuss observational paths forward.

Mai C. Desch S. J.
Exploring Proto-Atmosphere Accretion on Earth-Size Planets **[#4060]**
We perform a numerical study on how protoplanets can accrete extensive hydrogen/helium-rich atmospheres and how these atmospheres are subject to the nebula environment during terrestrial planet formation and their implication on habitability.

Millsaps C. S.   Domagal-Goldman S. D.
Building a Planet: Assessing the Habitability of K2-3 d **[#4041]**
We use ATMOS, a 1D coupled photochemical-climate model, to simulate a number of self-consistent atmospheres on the super-Earth K2-3 d over geologic time. We estimate the observational discriminants most likely to suggest habitable surface conditions.

Patience J.   Ward-Duong K.   Bulger J.   van der Plas G.   Menard F.   Pinte C.   Jackson A.   Bryden G.   Turner N.   Harvey P.   Hales A.   De Rosa R.
Disk Properties Across the Stellar/Substellar Boundary and Implications for Planet Formation and Detection of Planets Around M-Stars **[#4104]**
We report 885µm ALMA submm fluxes for 24 low mass Taurus members. The dust mass declines with object mass, and a number of targets have resolved disks. Based on standard gas:dust mass estimates, very few disks are amenable to giant planet formation.

Perez A. M.   Desch S. J.   Schrader D. L.   Till C. B.
Understanding the Conditions of Planet Formation Through Chondrules **[#4084]**
The heating mechanisms responsible for melting chondrules in the nebula are key to constraining astrophysical models of the disk and the energetic processes that were present during planet formation. We investigate this through furnace experiments.

Seligman D. Z.   Laughlin G.
A Vorticity-Preserving Hydrodynamical Scheme for Modeling Accretion Disk Flows **[#4120]**
We present a vorticity-preserving compressible scheme for simulating astrophysical disk flows that was developed in the context of modeling air flow past helicopter rotors.

Wagner K. R.   Daniel A.   Kasper M.
Status of the Scorpion Planet Survey: Establishing the Frequency of HR8799b-Like Planets **[#4028]**
Wide-orbit giant planets will likely affect plant formation and habitability of inner planets. In this presentation we will review the existing evidence on the occurrence rates of super-Jupiters and present the status of our VLT/SPHERE survey.

Zimmerman M. Z.   Jang-Condell H. J.
Modeling Debris Disk Spectra Using Varying Compositions **[#4062]**
We use Spitzer mid-IR spectra to help create a disk model, which allows the amount of different grain compositions within the disk to vary. We use an array of different compositions in order to learn more about the formation of habitable exoplanets.

POSTER SESSIONS
Monday, November 13, 2017
and Thursday, November 16, 2017

5:00–6:30 p.m. UWCC Grand Ballroom

MISCELLANEOUS POSTERS

Byrne J. F.
A Climate Classification Scheme for Habitable Worlds **[#4116]**
This presentation will include an exploration of the internal/external forcings and variability associated with climate using Earth as a reference model in addition to a classification scheme consisting of five categories.

Cardona M. C. Ramírez S. I.
Salinibater Ruber as a Model for the Habitability of Europa's Ocean **[#4039]**
The moon Europa has an ocean enriched with sulfate compounds. This work evaluates the adaptation strategies of Salinibacter ruber, a halophilic bacterium, when subjected to $MgSO_4$ and $NaSO_4$, two of the main salty components of Europa´s ocean.

Colose C. C. Del Genio A. Way M.
Climate Dynamics and Hysteresis at Low and High Obliquity **[#4113]**
We explore climate dynamics for an Earth-like planet, especially one near the outer edge of the habitable zone that is susceptible to global glaciations.

Echaurren J. C.
Korolev Crater, Mars: Estimating the Impact Conditions **[#4015]**
In this work, estimates are made for the main variables that give shape to an impact crater, taking as an example the Korolev impact crater that is on Mars.

Ko B. Shim S. Prakapenka V. Meng Y.
Mineralogy of the Silica-Rich Lower Mantle for Rocky Planets **[#4111]**
Our experiments show that Si-rich lower mantle of rocky planets may consist only of bridgmanite and calcium silicate perovskite, implying different physical properties of the lower mantle than the extrapolated model from the Earth.

Lorenzo A. M. Jr. Desch S. J. Unterborn C. Shim S. H. Byeongkwan K.
ExoPlex: A Code for Calculating the Mineralogy and Mass-Radius Relationships for Rocky Planets **[#4106]**
We present a code for finding the mineralogy and mass radius relationships for rocky exoplanets.

Staguhn J. Meixner M. Cooray A. Leisawitz D. Origins Space Telescope STDT
The Origins Space Telescope — A NASA Decadal Mission Study **[#4152]**
The Origins Space Telescope will discover or characterize exoplanets, the most distant galaxies, nearby galaxies and the Milky Way, and the outer reaches of our solar system. This talk will present the Origins Space Telescope Mission Concept 1.

Quintana E. V. Barclay T. Schlieder J. Boyd P. Thackeray-Lacko B.
Simultaneous, Multi-Wavelength Flare Observations of the M Dwarf Wolf 359 **[#4069]**
Wolf 359 is a nearby late-M dwarf that is known to produce frequent flares. We will present results from our observations in the optical, UV, X-ray, and radio wavelengths and discuss the potential impact on exoplanet habitability.

Roberge A. LUVOIR Mission Concept Team
Big Bang to Biosignatures: The LUVOIR Decadal Mission Concept **[#4065]**
The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a multi-wavelength space observatory with broad science goals. One of its major aims is to characterize habitable exoplanets around Sun-like stars and search them for signs of life.

Rubio D. G.   Ramírez S. I.
Bacterial Growth in the Salty Liquid Water Ocean of Europa **[#4050]**
We are interested in the adaptation strategies displayed by bacteria when exposed to laboratory-controlled conditions that represent the salinity, temperature, and available oxygen conditions of the salty liquid water ocean present on Europa.

Stern S. A.
An Answer to Fermi's Paradox in the Prevalence of Ocean Worlds? **[#4006]**
We suggest that the great majority of worlds with biology and civilizations are interior ocean worlds, cut off from communication by their nature inside of their host world, therefore not easily revealing themselves.

Tan S. P.
Liquid Phase Equilibria for Habitability **[#4138]**
The existence of liquid phase, which amplifies habitability, can be predicted using an equation of state from atmospheric composition, pressure, and temperature. If solid is also present, density inversion that keeps liquid from freezing is examined.

Tuesday, November 14, 2017
PLANET FORMATION AND DYNAMICS
8:25 a.m. MHRGC Salons ABCD

8:25 a.m. Jang-Condell H. *
Announcements

Chair: Aki Roberge

8:30 a.m. Apai D. *
The Formation of Habitable Worlds: Constraints, Challenges, and Pathways **[#4127]**
I will review the constraints, challenges, and pathways toward habitable planet formation.

9:00 a.m. Salyk C. *
Observing How Habitable Conditions Develop in Protoplanetary Disks **[#4126]**
An understanding of planet formation is necessary to infer the occurrence of habitable worlds beyond our solar neighborhood. I'll discuss how molecular spectroscopy is used to study the formation of potentially habitable planets.

9:20 a.m. Kim J. S. * Pascucci I. Allen L. Apai D. Bergin T. Ciesla F. Eisner J. Fang M. Krijt S. Najita J. Rieke G. Salyk C.
Earths in Other Solar Systems: Fundamental Protoplanetary Disk Properties and Their Evolution **[#4071]**
Earths in Other Solar Systems is a NASA interdisciplinary exoplanet research program aiming at understanding how and where habitable planets form. We present an overview of objective 2: How are volatiles and organics processed in protoplanetary disks?

9:40 a.m. Schneider A. C. * Shkolnik E. L.
HAZMAT III. The UV Evolution of Mid-Type M Dwarfs with GALEX **[#4093]**
Using photometry from the Galaxy Evolution Explorer (GALEX), we investigate the UV evolution early- and mid-type M dwarfs and discuss how that evolution could affect potentially habitable planets.

10:00 a.m. Breakout Session Advertisements

10:10 a.m. BREAK

Chair: Leslie Rogers

10:40 a.m. Mulders G. D. * Pascucci I. Apai D. Ciesla F. J. O'Brien D. P.
Constraining Planet Formation Models from the Kepler Exoplanet Population **[#4047]**
We use the Kepler exoplanet population to constrain the different planet formation models, with a focus on constraining exoplanet composition.

11:00 a.m. Ford E. B. * Carrera D. Jontof-Hutter D. Lissuer J. J. Rogers L. A. Wolfgang A.
Orbital Dynamics of Planetary Systems with Super-Earths and Mini-Neptunes **[#4080]**
Planet formation directly determines various properties of planets that impact their habitability. I propose to review the orbital dynamics of exoplanetary systems, emphasizing the implications for characteristics likely to impact habitability.

11:30 a.m. Brain D. * Chaffin M. Jakosky B. Luhmann J. Dong C. Yelle R. Egan H.
Would Mars be Habitable If It Orbited an M Dwarf? Lessons from the MAVEN Mission **[#4043]**
MAVEN measures atmospheric escape from Mars. The MAVEN data can be used to guide thinking about a Mars-type planet around an M Dwarf. Could it retain enough of an atmosphere to allow for a habitable surface?

11:50 a.m. Krijt S. * Bowling T. J. Lyons R. J. Ciesla F. J.
Fast Litho-Panspermia in Tightly-Packed Systems Around M Dwarfs **[#4051]**
We investigate the fate of impact ejecta in tightly-packed planetary architectures like the TRAPPIST-1 system, finding that material transfer in such configurations is many orders of magnitude faster compared to the inner solar system.

12:10 p.m. Poster Pop-Ups

12:30 p.m. LUNCH

Tuesday, November 14, 2017
PANEL SESSION II

PLANETARY ASTROBIOLOGY: IDENTIFYING SOLAR SYSTEM AND EXOPLANET SYNERGIES
2:00–4:30 p.m. UWCC Salon E

Meadows V. S.

In this panel session, we will bring together authors of a new book in the University of Arizona Space Science Series, *Planetary Astrobiology*. This book is motivated by the profound questions of how life originated and the search for habitable environments beyond Earth. To adequately address these questions requires an interdisciplinary approach at the intersection of astronomy, planetary science, biology, and other fields. In this session, chapter authors and editors of this book will discuss their plans and chapter outlines and solicit feedback from the rest of the community. Solar system and exoplanet researchers will be able to discuss current and future directions of this book, and we will find commonalities in how our communities view, plan for, and conduct in the search for life on planets both nearby and orbiting distant stars. By weaving together solar system and exoplanet science, this book aims to break down barriers traditionally separating exoplanets from solar system planets in the search for life elsewhere in the universe. All attendees are invited to attend and provide feedback.

HOW DO STAR AND PROTOPLANETARY/DEBRIS DISK COMPOSITION AFFECT PLANET COMPOSITION?
2:00–4:30 p.m. MHRGC Salon D

Teske J. K.

While results from Kepler indicate that small planets are common in the Galaxy, detecting them and distinguishing their characteristics is still challenging, especially those in the traditional "habitable zones" of their stars. And yet, the small sample of well-characterized planets varies widely in size, density, and orbital properties. Does this diversity originate in how planets form within circumstellar disks that themselves are diverse? We want to better understand how star and disk properties are related to planet properties to inform the assessment of habitability in detected planet systems, and to help prioritize the best targets more for intensive/expensive follow-up observations. Specifically in this breakout, we will focus on the following questions:

1. What is the most up-to-date picture of host star compositions and their relation to planet properties?
   Invited talk by Kamber Schwarz — Cataloguing the Chemical Inventory in Disks: Implications for Planets (25 minutes)
2. What is the most up-to-date picture of protoplanetary/debris disk compositions and their relation to planet properties?
   Invited talk by Gijs Mulders — The Relation Between Exoplanets and Stellar Composition (25 minutes)
3. How do various planet formation mechanisms impact planet composition?
4. What assumptions can we confidently make about the similarity of star-disk-planet compositions (for small, terrestrial planets)? Contributed talks (6 minutes each)
   Daniel Carerra — Origin of Super-Earth Atmospheres
   Nick Ballering — Measuring the Composition of Debris Disk Dust
   Cayman Unterborn — Gauging Terrestrial Exoplanet Diversity from Host Star Compositions
   Wanda Feng — The Diversity of Exoplanetary Composition from White Dwarf Pollution
   Leslie Rogers
5. What assumptions still need testing, and what star/disk simulations or observations would be most informative for future characterization of habitable systems?
   Discussion amongst the group (60 minutes)

A STATISTICAL APPROACH TO
CHARACTERIZING HABITABLE EXOPLANETS
2:00–4:30 p.m. UWCC Salons FG

Kempton E. M-R.

While we may never be able to characterize individual extrasolar planets to the degree that we can for solar system planets, exoplanets provide us with a rich sample of objects for performing statistical studies of comparative planetology. Such studies can be brought to bear on habitable-zone planets as a way of identifying and confirming broad trends related to habitability and the emergence of life. In this session, we will develop and discuss the statistical comparative planetology approach in the context of broader discussions about exoplanet habitability. Presentations will focus on tools and specific observations that could be used to find indicators of habitability among a large sample of planets. We will then move on to a group brainstorming activity and small-group discussions centered on developing a set of statistical experiments necessary to assess planetary habitability. Our goal is to identify what observational and theoretical resources will be necessary to execute meaningful statistical studies of habitable planets and to motivate impactful future work to this end.

Wednesday, November 15, 2017
BIOSIGNATURES
8:25 a.m. MHRGC Salons ABCD

What are the indicators of habitable conditions and their histories?

8:25 a.m. Jang-Condell H. *
Announcements

Chair: Robert Howell

8:30 a.m. Domagal-Goldman S. D. *
The History and Future of Exoplanet Biosignatures **[#4156]**
This is a review of exoplanet biosignature science, including proposed biosignatures, biosignature theory, biosignature frameworks, and future exoplanet biosignature observatories.

9:00 a.m. Harman C. E. Jr.* Felton R. C. Domagal-Goldman S. Kasting J. F.
Oxygen False Positives in Terrestrial Planetary Atmospheres: An Update from the Front Lines **[#4072]**
We revisit reported accumulations of abiotic O_2 in the atmospheres of terrestrial planets orbiting M dwarfs as part of an ongoing photochemical model intercomparison. Some of the reported cases rely on assumptions that may not be self-consistent.

9:20 a.m. Ranjan S. * Wordsworth R. D. Sasselov D. D.
The Surface UV Environment on Planets Orbiting M-Dwarfs: Implications for Origins-of-Life Chemistry and Need for Experimental Follow-Up **[#4008]**
Multiple lines of evidence suggest UV light may have played a key role in the origin of life on Earth. However, temperate M-dwarf planets are UV-poor environments. I discuss the implications for origin-of-life scenarios on M-dwarf planets.

9:40 a.m. Johnson B. W. * Goldblatt C.
A New Model of the Earth System Nitrogen Cycle: How Plates and Life Affect the Atmosphere **[#4054]**
We have developed an Earth system N cycle model, including biologic and geologic fluxes and key nutrients such as phosphorus. The atmosphere can change mass significantly over Earth history, and the solid Earth contains most of the planet's N.

10:00 a.m. Poster Pop-Ups

10:10 a.m. BREAK

Chair: Meredith Elrod

10:40 a.m. Sohl L. E. * Chandler M. A. Way M. J. Jonas J. A.
The Role of Topography in Modulating the Climates of Habitable Worlds **[#4103]**
Using topography (realistic, reconstructed, or idealized continental distributions) in coupled atmosphere-ocean GCM simulations of potentially habitable planets reveals diverse habitable states not apparent from aquaplanet simulations alone.

Wednesday, November 15, 2017
EXOPLANET CHARACTERIZATION I
11:00 a.m. MHRGC Salons ABCD

How can we observe indicators of habitability?

Chair: Meredith Elrod

11:00 a.m. Meadows V. S. * Lustig-Yaeger J. Lincowski A. Arney G. N. Robinson T. D. Schwieterman E. W. Deming L. D. Tovar G.
Characterizing Terrestrial Exoplanets **[#4114]**
We will provide an overview of the measurements, techniques, and upcoming missions required to characterize terrestrial planet environments and evolution, and search for signs of habitability and life.

11:30 a.m. Lincowski A. P. * Meadows V. S. Crisp D. Robinson T. D. Luger R. Arney G. N.
Habitability Imposters: Extreme Terrestrial Climates in the Habitable Zone of M Dwarf Stars **[#4091]**
We use coupled climate-photochemical modeling of TRAPPIST-1 planets to present a variety of evolved environmental states and their spectral discriminants, for use by upcoming M dwarf planet characterization observations.

11:50 a.m. Feng Y. K. * Robinson T. D. Fortney J. J.
Characterizing Earth Analogs in Reflected Light: Atmospheric Retrieval Studies for Future Space Telescopes **[#4068]**
We present the first systematic exploration of retrievals on the atmospheres of terrestrial exoplanets as observed in reflected light with future direct imaging space missions.

12:10 p.m. Poster Pop-Ups

12:30 p.m. LUNCH AND EXCURSIONS

Thursday, November 16, 2017
EXOPLANET CHARACTERIZATION II
8:25 a.m. MHRGC Salons ABCD

8:25 a.m. Jang-Condell H. *
Announcements

Chair: Dawn Gelino

8:30 a.m. Luger R. * Lustig-Yaeger J. Agol E.
Probing the Orbital and Atmospheric Properties of the TRAPPIST-1 Planets with JWST **[#4100]**
We investigate planet-planet occultations in the TRAPPIST-1 system. We show that these events are potentially detectable with JWST and can yield information about the eccentricities, masses, and day/night temperature contrast of the planets.

8:50 a.m. Kempton E. M.-R. * Rogers L. A. Marounina N. Le H. V.
Determining the Bulk Water Abundance of Low-Mass Exoplanets **[#4053]**
I describe efforts to build a self-consistent whole-planet modeling framework by coupling together calculations of a planet's interior structure and atmosphere to determine the observable signatures of a planet with a specified water content.

Thursday, November 16, 2017
EXOPLANET DETECTION METHODS AND MISSIONS
9:10 a.m. MHRGC Salons ABCD

Chair: Dawn Gelino

9:10 a.m. Batalha N. M. * Bryson S. T. Shabram M. Thompson S. E. Burke C. J. Coughlin J. L. Christiansen J. L.
Kepler Completes Its Prime Mission **[#4145]**
In 2017, Kepler formally completed its prime mission. The final planet catalog will be described, and some of the key new product deliveries will be highlighted. We will also report on a first look at planet occurrence rates using the DR25 products.

9:40 a.m. Charbonneau D. *
A Review of the Near-Future Opportunity Afforded by the Discovery of Temperate, Terrestrial Planets Orbiting Nearby M-Dwarfs **[#4132]**
Temperate, terrestrial planets orbiting nearby small stars offer the only opportunity to study the atmospheres of potentially habitable exoplanets in the next decade. I will review the M-dwarf opportunity with a focus on recent progress.

10:10 a.m. Breakout Session Advertisements

10:20 a.m. BREAK

Chair: Angelle Tanner

10:50 a.m. Turnbull M. C. * Macintosh B. Kasdin J. Seager S. Roberge A. Marley M. Mandell A. Lupu R. Hildebrandt S. Lewis N. Shaklan S. Stark C.
Direct Imaging of the Nearest Planetary Systems with NASA's WFIRST Mission **[#4155]**
Using the Coronagraph Instrument (CGI), WFIRST will enable our generation, for the first time in human history, to directly image and characterize planets similar to those in our solar system. We will review the purpose and status of the mission.

11:10 a.m. Rackham B. V. * Apai D. Giampapa M. S.
The Light Source Problem: The Effect of Heterogeneous Stellar Photospheres on Searches for Transiting Exoplanet Biosignatures **[#4032]**
TESS will soon enable the study of terrestrial exoplanet atmospheres. However, spots and faculae in stellar photospheres can complicate these measurements by mimicking or masking atmospheric features. We detail our work to constrain this effect.

11:30 a.m. Cable M. L. * Spilker L. J. Postberg F. Waite J. H. Kempf S. Clark K. Reh K. Sherwood B. Lunine J. I.
Enceladus Life Finder (ELF): A Proposed Mission to Assess the Habitability of a Plume-Bearing World **[#4124]**
Enceladus is a uniquely accessible ocean world due to its plume emanating from the south polar terrain. Here we discuss the Enceladus Life Finder mission concept and its implications for this and other ocean worlds.

11:50 a.m. Hinkel N. R. *
Using Stellar Abundances to Predict Exoplanet Host Stars **[#4059]**
Using the Hypatia Catalog, we have formulated a planet-predicting algorithm that uses an ensemble of stellar abundances to determine which stars in the solar neighborhood are likely (+90%) to host to-date undetected giant exoplanets.

12:10 p.m. Poster Pop-Ups

12:30 p.m. LUNCH

Thursday, November 16, 2017
PANEL SESSION III

DESIGNING THE FUTURE OF EXOPLANET EXPLORATION: NASA MISSION STUDIES FORUM

2:00–4:30 p.m. MHRGC Salons AB

Stapelfeldt K. R. Domagal-Goldman S. Stevenson K.

What are NASA and the community doing to design the future of Exoplanet Exploration ? This session will address this question by reviewing how NASA is organized to meet this challenge and what the community is doing to develop options for future exoplanet missions. Data archives, groundbased observations that support current and upcoming missions, and technology development are all going on today. The range of possible futures we'll discuss includes an Explorer mission dedicated to transit spectroscopy (FINESSE) and four large mission concepts to be considered by the 2020 Decadal Survey: 1) Habitable Exoplanet Imaging Mission (HabEx), 2) Large UV-Optical-InfraRed Surveyor (LUVOIR), 3) Lynx (a large general-purpose X-ray telescope), and 4) the Origins Space Telescope (OST).

Both HabEx and LUVOIR would image rocky exoplanets in habitable zones from ultraviolet to near-infrared wavelengths. OST will study circumstellar disks and obtain mid-infrared spectra of transiting habitable exoplanets, while Lynx would address the impact of stellar activity on habitability. We will discuss how individual scientists can become involved with these mission studies and the overall NASA Exoplanet Exploration Program (ExEP), and also invite your comments on what more NASA could or should be doing to advance the field toward the goal of discovering and characterizing habitable exoplanets in the solar neighborhood.

2:00 p.m. Introduction/Overview (Doug Hudgins, NASA Headquarters)
2:10 p.m. Origins Space Telescope Mission Concept (Johannes Staguhn, Johns Hopkins University)
2:25 p.m. Lynx Mission Concept (Jeremy Drake, Harvard Center for Astrophysics)
2:40 p.m. HabEx Mission Concept (Leslie Rodgers, University of Chicago)
2:55 p.m. LUVOIR Mission Concept (Aki Roberge, NASA Goddard Space Flight Center)
3:10 p.m. Break
3:20 p.m. FINESSE Explorer Mission Concept (Jacob Bean, University of Chicago)
3:35 p.m. Technology Development for Exoplanet Missions (Karl Stapelfeldt, JPL/Caltech)
3:50 p.m. Groundbased Mission Support (Dawn Gelino, NExScI TBC)
4:00 p.m. Community Discussion (ExoPAG EC members lead)

WILL EVIDENCE OF EXTANT LIFE ON AN EXOPLANET BE DETECTED BY 2040?

2:00–4:30 p.m. MHRGC Salons CD

Marounina N.

The search for evidence of life beyond the confines of Earth is a driving impetus in the field of exoplanets. Indeed, it is a primary motivation for the Habitable Worlds 2017 Workshop and it requires an interdisciplinary approach. This session will center around a debate of the proposition: **Will evidence of extant life on an exoplanet be detected by 2040?** This proposition is intentionally broad so that every attendee (including geologists, astronomers, planetary scientists, heliophysicists, and biologists) will have a perspective that they can add. The aim is for a lighthearted, friendly debate that will provide a fun way to synthesize the diverse topics covered throughout the workshop.

An initial case will be made by a pre-selected panel of 6 scientists from among the workshop registrants (3 for the “yes” side and 3 for the “no” side). Ample time will allow members of the audience to give arguments in support of either side and to ask questions to both teams. The goal is to foster high levels of active involvement from many different audience members. There will be a general vote on the debate question before and at the end of the debate. The winning side will be determined by the team that swayed the most voters.

Thursday, November 16, 2017
POSTER SESSION II

5:00–6:30 p.m. UWCC Grand Ballroom

Friday, November 17, 2017
WRAP-UP
8:30 a.m. MHRGC Salons ABCD

8:30 a.m.	Breakout Session Reports
9:30 a.m.	Discussion
10:00 a.m.	Adjourn

CONTENTS

Space Weather Affected Habitable Zones

Vladimir S. Airapetian[1], Alex Glocer[1], George V. Khazanov[1], William C. Danchi[1]
[1]*NASA/GSFC*

Abstract.

Atmospheres of exoplanets in the habitable zones around active young K-M stars are subject to extreme *X-ray* and EUV (*XEUV*) fluxes from their host stars that can initiate atmospheric erosion. Atmospheric loss affects exoplanetary habitability in terms of surface water inventory, atmospheric pressure, the efficiency of greenhouse warming and the dosage of the UV surface irradiation. Thermal escape models suggest that exoplanetary atmospheres around active K-M stars should undergo massive hydrogen escape (Lammer et al. 2008), while heavier species including oxygen will accumulate forming an oxidized atmosphere. Here we show that non-thermal oxygen ion escape could be as important as thermal, hydrodynamic H escape in removing the constituents of water from exoplanetary atmospheres under supersolar *XUVE* irradiation. Our models suggest that an exposure of atmospheres of a significant fraction of Earth-like exoplanets around M dwarfs and active K-G stars to high *XEUV* fluxes will incur a significant atmospheric loss rate of oxygen and nitrogen, which will make them uninhabitable within a few tens to hundreds of Myr, given a low replenishment rate from volcanism or cometary bombardment. Our non-thermal escape models have important implications for the habitability of the Proxima Centauri's and TRAPPIST-1 terrestrial exoplanets.

Atmospheric Beacons of Life from Exoplanets Around G and K Stars

Vladimir S. Airapetian[1], Charles H. Jackman[1], Martin Mlynczak[2], William Danchi[1], Linda Hunt[3] [1]NASA/GSFC, [2]NASA/LARC, [3]SSAI

Abstract

The current explosion in detection and characterization of thousands of extrasolar planets from the Kepler mission, the Hubble Space Telescope, and large ground-based telescopes opens a new era in searches for Earth-analog exoplanets with conditions suitable for sustaining life. As more Earth-sized exoplanets are detected in the near future, we will soon have an opportunity to identify habitable worlds. Which atmospheric biosignature gases from habitable planets can be detected with our current capabilities? The detection of the common biosignatures from nitrogen-oxygen rich terrestrial-type exoplanets including molecular oxygen (O_2), ozone (O_3), water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) requires days of integration time with largest space telescopes, and thus are very challenging for current instruments. In this paper we propose to use the powerful emission from rotational-vibrational bands of nitric oxide, hydroxyl and molecular oxygen as signatures of nitrogen, oxygen, and water rich atmospheres of terrestrial type exoplanets "highlighted" by the magnetic activity from young G K and M main-sequence stars. The signals from these fundamental chemical prerequisites of life we call atmospheric "beacons of life" create a unique opportunity to perform direct imaging observations of Earth-sized exoplanets with high signal-to-noise and low spectral resolution with the James Webb Space Telescope mid-infrared instrument MIRI, and potential future space observatories such as the Origins Space Telescope (OST) currently under study by NASA.

EXPLORING HABITABLE WORLDS: SCIENCE QUESTIONS FOR FUTURE DIRECT IMAGING MISSIONS.

D. Apai[1,2] and the EXOPAG SAG15 Team, [1]Steward Observatory and Lunar and Planetary Laboratory, University of Arizona (933 N. Cherry Avenue, Tucson, AZ 85721, apai@arizona.edu), [2]Earths in Other Systems Team, NASA Nexus for Exoplanet System Science.

Introduction: Although the pace of exoplanet discovery and characterization is accelerating, space missions that will be able to characterize habitable exoplanets require medium- to long-term planning. In considering the science requirements for next-generation space missions capable of characterizing habitable worlds, it is essential that the key science questions are identified early and that observational approaches to answering the science questions build on state-of-the art knowledge.

Exoplanets – whether gaseous, icy, or rocky – are complex systems and any future mission will only provide limited information on the individual planets. Therefore, it is essential that we identify the key science questions by building on a multi-disciplinary community.

The SAG15 Study: The SAG15 team conducted a comprehensive effort to solicit and compile community input on key science questions for future exoplanet imaging missions. The study benefitted from input from more than seventy researchers, building on both the NASA Exoplanet Program Analysis Group (EXOPAG) community and the NASA Nexus for Exoplanet System Science (NExSS) groups. The SAG15 study has been completed in July 2017 and resulted in a 100-page report providing an overview of exoplanet science questions that represent the current and next frontiers of our field that are well-suited to be studied via direct imaging missions. The report also includes brief reviews of the state-of-the-art for each topic, expected contributions from existing or near-future instruments/missions, as well as guidelines for the type and quality of data required to answer the science questions.

Science Questions: Our study grouped science questions in three categories. In category A, we included questions that aimed at understanding the statistical properties of exoplanetary systems. In category B, we included questions that focused on understanding the properties of individual exoplanets. In category C, we included questions that explored processes that shaped planetary interiors and atmospheres.

Understanding Habitable Exoplanets – A Prerequisite for Interpreting Biosignatures: It is almost certain that small exoplanets will display a great diversity in their formation and evolution pathways, resulting in a great compositional diversity and a broad range of processes that may continue to shape their atmospheres and climates. Correctly identifying habitable exoplanets will require answering several of the questions our SAG15 team has recognized. Even more importantly, correctly and robustly interpreting potential biosignatures will be impossible without a general understanding of the planet properties and the likely conditions on its surface – these again will be achieved through answering several of the questions identified by our team.

A study enabled by the NExSS/EXOPAG Community: Our study also represents one of the first large-scale studies that are *enabled* by the NExSS/EXOPAG interdisciplinary community. Multiple sections and aspects of science questions included in our report have been driven by earth and atmospheric scientists from the NExSS collaboration, who are otherwise often not engaged in the NASA Exoplanet Exploration Program. Their input, as well as input from the broader NExSS community collected via multiple avenues, represents a new approach for assessing the system-level questions future observations of habitable worlds will need to address.

SAG15 Report and Website: The website – including the final report, report development information and draft reports, and supporting documents – is available at http://eos-nexus.org/sag15/

THE FORMATION OF HABITABLE WORLDS: CONSTRAINTS, CHALLENGES & PATHWAYS. D. Apai[1,2], [1]Steward Observatory and Lunar and Planetary Laboratory, University of Arizona (933 N. Cherry Avenue, Tucson, AZ 85721, apai@arizona.edu), [2]Earths in Other Systems Team, NASA Nexus for Exoplanet System Science.

Introduction: The discovery and characterization of habitable worlds is at the forefront of exoplanet science, but identifying habitable worlds among habitable zone planets remains a major challenge. Many small, Earth-sized planets in the present-day habitable zones may be inhospitable to life due to their formation pathways or due to their subsequent evolution. Developing a robust understanding of habitable planet formation and of the key factors that determine whether a planet accretes the right inventory of volatiles and organics represents a major step toward our long-term goal of surveying habitable planets for biosignatures.

Constraints: I will review the key constraints on rocky planet formation from the young solar system (mainly cosmochemistry and orbital dynamics), from forming planetary systems (via studies of protoplanetary disks and forming planets), and from mature exoplanetary systems (mainly exoplanet population statistics). I will explore the time and amount of mass available for forming planetary systems and the constraints they pose on the planet formation process.

Challenges: The delivery of volatiles and organics in amounts that are compatible with allowing life to exist on rocky planets is a major a challenge to habitable planet formation. I will review the challenges disk evolution, stellar luminosity evolution, and the presence of giant planets pose on the availability and delivery of volatiles and organics to rocky planets that will end up in present-day habitable zones.

Pathways: Finally, I will review the different formation mechanisms that may lead to rocky planets and explore how the different pathways may influence the volatile and organics inventory of the forming (present-day) habitable zone small planets.

Throughout the talk I will highlight interdisciplinary connections and opportunities, as well as ongoing relevant research within the exoplanet and the NExSS communities. I will also connect the emerging knowledge on habitable planet formation to possible target selection strategies for next-generation NASA space telescopes aiming to explore habitable exoplanets.

PROTOPLANETARY DISK MASSES IN TAURUS AND THE ORION NUBULA CLUSTER. N. P. Ballering[1] and J. A. Eisner[1], [1]Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721

Introduction: The mass of solids in protoplanetary disks is a primary factor influencing the efficiency of planet formation and the properties of the resulting planetary systems. As members of the Earths in Other Solar Systems (EOS) team, we are studying the distribution of protoplanetary disk masses as a function of stellar mass, age, and environment. We will present the results from two projects in this area.

Radiative Transfer Models of Disks in Taurus: The dust mass of a protoplanetary disk is commonly calculated from its brightness in the (sub-)mm where thermal emission from the dust is assumed to be optically thin [1]. However, this procedure requires specific values for the dust temperature and opacity to be chosen. By examining the full spectral energy distribution (SED) of a disk, the dust temperature and opacity can also be constrained, providing a more accurate measure of the disk mass. The Taurus region hosts many protoplanetary disks with well-sampled SEDs. We used a Markov Chain Monte Carlo (MCMC) fitting technique (implemented with the *emcee* software [2]) to fit a large sample of Taurus class II disk SEDs with models generated using the radiative transfer software *Radmc-3d* [3]. In doing so, the dust temperature, opacity, optical depth, and total mass are computed in a self-consistent manner. Additionally, the uncertainty on the disk mass is robustly determined because we allowed many disk parameters to vary during the fitting, including: the disk size, inner edge location, scale height, flaring parameter, inclination, maximum grain size, and grain size distribution. In Figure 1 we show the results of our SED fitting procedure for two disks. We will discuss the implications of our calculated disk masses for the prospect of planet formation in these systems. We will also present the disk mass vs. stellar mass relation found from our analysis and compare it with previous investigations of this relation for Taurus [4] and other star-forming regions [5][6][7].

ALMA Observations of Disks in the Orion Nebula Cluster: While the Taurus region is relatively nearby and the disks there are amenable to detailed study, most stars and planets in the Galaxy form in rich cluster environments [8]. The Orion Nebula Cluster (ONC) provides one of the nearest examples of such an environment. We obtained an ALMA mosaic observation of the inner 1.5 × 1.5 arcminute region of the ONC in band 7 with ~ 0.08 arcsecond resolution. These observations provide the most sensitive and complete measurements of protoplanetary disks in the ONC to date. We will present the results of these observations, including the disk mass distribution and constraints on disk sizes, surface density profiles, and gas content. We will also discuss the properties of disks in this rich cluster environment in comparison with those of disks in lower-density star-forming regions.

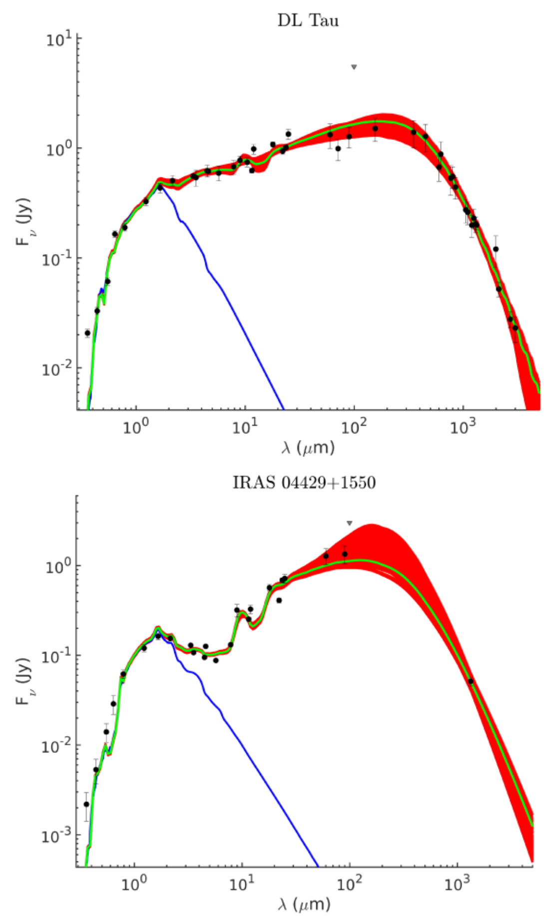

Figure 1. Fits of two Taurus disk SEDs. Data are plotted in black circles (detections) and gray triangles (3σ upper limits). The best-fitting model is shown in green and the best-fitting 10% of models from our MCMC posterior sample are shown in red. The stellar photosphere is shown in blue.

References: [1] Beckwith S. V. W. et al. (1990) *AJ, 99*, 924 [2] Foreman-Mackey D. et al. (2013) *PASP*, *125*, 306 [3] Dullemond C. P. and Dominik, C. (2004) *A&A*, *417*, 159 [4] Andrews S. M. et al. (2013) *ApJ*, *771*, 129 [5] Pascucci I. et al. (2016) *ApJ*, *831*, 125 [6] Ansdell M. et al. (2016) *ApJ*, *828*, 46 [7] Barenfeld S. A. et al. (2016) *ApJ*, *827*, 142 [8] Lada C. J. and Lada E. A. (2003) *ARA&A*, *41*, 57.

THE TRANSITING EXOPLANET COMMUNITY EARLY RELEASE SCIENCE PROGRAM FOR JWST.
N. M. Batalha[1], J. Bean[2], K. Stevenson[3], D. Sing[4], I. Crossfield[5], H. Knutson[6], M. Line[7], V. Parmentier[8], L. Kreidberg[9], J.-M. Desert[10], H. Wakeford[4], N. Crouzet[11], J. Moses[12], B. Benneke[13], E. Kempton[14], Z. Berta-Thompson[15], M. Lopez-Morales[16], [1]NASA Ames Research Center, [2]University of Chicago, [3]Space Telescope Science Institute, [4]University of Exeter, [5]Massachusettes Institute of Technology, [6]California Institute of Technology, [7]Arizona State University, [8]University of Arizona, [9]Harvard University, [10]University of Amsterdam, [11]Instituto de Astrofísica de Canarias, [12]Space Science Institute, [13]Université de Montreal, [14]Grinnel College, [15]Colorado University, [16]Smithsonian Astrophysical Observatory

A community working group was formed in October 2016 to consider early release science for JWST that broadly benefits the transiting exoplanet community. Over 100 exoplanet scientists worked collaboratively to identify targets that are a) observable within the first 5 months of science operations, b) yield high SNR over a single event (transit, eclipse, phase), c) have substantial scientific merit, and d) have known spectroscopic features identified by prior observations. The working group developed a program that yields representative datasets for primary transit, secondary eclipse, and phase curve observations and tests for the most promising instrument modes for high-precision spectroscopic timeseries (NIRISS-SOSS, NIRCam, NIRSPec, and MIRI-LRS). The centerpiece of the program is an open data challenge that promotes community engagement and leads to a deeper understanding of the JWST instruments as early as possible in the mission. The program will be executed in an open science environment in order to maximize the value of the early release science observations for the transiting exoplanet community.

KEPLER COMPLETES ITS PRIME MISSION. N. M. Batalha[1] and S. T. Bryson[1], M. Shabram[1], S. E. Thompson[1,2], C. J. Burke[1,2], J. L. Coughlin[1,2], J. L. Christiansen[3], [1]NASA Ames Research Center, [2]SETI Institute, [3]NASA Exoplanet Science Insitute, California Institute of Technology

In 2017, Kepler formally completed its prime mission – the analysis of data from the four-year observing campaign of the Cygnus-Lyra field. The project released its final planet candidate catalog (Data Release 25) together with the survey completeness and reliability measurements required to study exoplanet populations. Some of these products accompanied previous data releases while other are new to DR25. Collectively, they represent the most comprehensive and versatile suite of measurements produced by the mission. They are also the most complex. The final planet catalog will be described, and some of the key new product deliveries will be highlighted. We also report on a first look at planet occurrence rates using the DR25 products.

Comparative exoplanetology in era of the Great Observatories, JWST, and beyond. Jacob L. Bean[1], [1]University of Chicago

My presentation will focus on three topics in the area of comparative exoplanetology in the context of the push towards studying potentially Earth-like planets. In the first part of the talk I will present a summary of new results from large surveys of transiting exoplanet atmospheres using the Hubble and Spitzer Space Telescopes, with an emphasis on precise composition measurements, longitudinally-resolved temperature maps, and modeling innovations that maximize the return on investment of telescope time.

Building on these new results, and anticipating TESS and other transit detection experiments, in the second part of the talk I will look ahead at the likely exoplanet atmosphere science objectives in the JWST era. I will also summarize a community effort to quickly establish JWST's capabilities for transit spectroscopy measurements through the Early Release Science program.

Finally, I will present new results on stellar compositions from ultra-precise abundance measurements (2% level) of 17 elements for a large sample of solar twin stars. The surprising results from this project in terms of the abundance ratios C/O and Mg/Si have a bearing on the expected diversity (or lack thereof!) of the bulk and atmospheric compositions of planets ranging from giants to terrestrials.

Gaussian-Process Techniques for Accurately Characterizing Exoplanet Atmospheres Thomas G. Beatty[1], [1]Pennsylvania State University, Department of Astronomy, 525 Davey Lab, University Park, PA 16802, tbeatty@psu.edu

Over the next three years, Jupiter- and Neptune-sized planets will be the primary accessible targets for atmospheric characterization, until the launch of JWST allows us to begin pushing the characterization boundary down towards Earth-sized planets and potential biomarkers. As a part of this push towards measuring the subtle signatures of planetary habitability, we need to also ensure that we are accurately treating the sources of noise in these observations and incorporating this into our measurement uncertainties.

Gaussian-Process (GP) regression techniques offer one way to create flexible systematic noise models for exoplanet timeseries observations. Unlike traditional detrending techniques, a GP models the observed data points as random draws from a multivariate Gaussian distribution about some mean function. This is in contrast, for example, to a chi-squared fitting process, which models the data as random draws from a univariate Gaussian distribution. As a result, GPs are able to model the possible covariances between data points while remaining relatively agnostic about the precise functional form of the systematic noise model.

I will discuss the real-life application of GPs to observations of exoplanet atmospheres from the ground and space. Spectroscopic eclipse and phase-curve observations of transiting hot Jupiters using LBT, HST, and Spitzer all show how GPs can be used to model the systematic noise present in these observations, and that they do so in a way that captures the presence of this correlated noise in the final measurement uncertainties. This is in stark contrast to traditional polynomial detrends of the same data.

I will also discuss the applicability of GP methods to future NIRCam and NIRSpec spectroscopic characterization observations using JWST. GP noise models will allow us to construct accurate on-orbit noise models for these detectors, and should be able to capture the effect of pixel-sensitivity variations and interruptions in JWST's pointing.

Though computationally intensive, using GPs to model the systematic noise in exoplanet characterization observations will allow us to accurately report the results of future observations of habitable exoplanets.

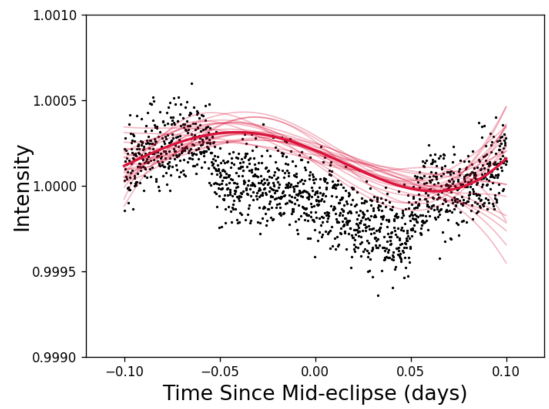

Figure 1: A simulated shallow eclipse lightcurve of a habitable exoplanet, with added systematic noise. Overplotted in red is the mean GP noise model (dark red) and a sample of possible draws from the underlying GP distribution (light red). The ability to provide multiple realizations of the underlying systematic noise illustrates the power and flexibility of GP modeling.

Probabilistic Assessment of Planet Habitability and Biosignatures A. Bixel[1] and D. Apai[1], [1]Steward Observatory/Department of Astronomy, The University of Arizona (abixel@email.arizona.edu)

Introduction: Future surveys to detect and characterize potentially habitable planets should frame their results in probabilistic terms which draw upon prior constraints from the literature. As an example, we present a case study of Proxima Cen b [1], in which we have placed posterior constraints on the mass, radius, and bulk composition of the planet based on previous results from *Kepler* and radial velocity mass measurements. We find that it is ~90% likely that Proxima Cen b is rocky, in which case we calculate expectation values and 95% confidence intervals of $\langle M \rangle = 1.63^{+1.66}_{-0.72}$ $M_\oplus$ for its mass and $\langle R \rangle = 1.07^{+0.38}_{-0.31}$ $R_\oplus$ for its radius. As precision RV surveys begin to detect more terrestrial-sized planets, we recommend a similar treatment be applied to better understand the statistics of potentially habitable planets and to prioritize follow-up observations with future direct imaging missions.

Recent studies have shed light on the tidal and radiative environments of exoplanet host stars and the implications for the habitability of planets within their habitable zones [2]. At the same time, an increasing array of potential biosignatures – and false positive signatures – has been accumulated in the literature [3]. These results suggest that the habitability and potential biosignatures of habitable planet candidates should be discussed in probabilistic terms, and considerable work has been done to further this discussion [4]. We discuss ongoing work to develop a quantitative Bayesian framework which, following the general scheme of our Proxima Cen b study, will use Monte Carlo simulations informed by prior knowledge of exoplanet statistics and theoretical results to compute the likelihood that a directly imaged planet (a) is habitable and (b) show signs of life. This framework will take into account various constraints on data quality and availability, as future detections of terrestrial planet candidates will be limited in this regard.

Although the data for such planets does not yet exist, the results of this project will be valuable in the near future. In particular, we plan to use our framework to evaluate the ability of future telescopes (such as HabEx and LUVOIR) to place reasonable constraints on the habitability of planets and the presence of life, both for individual targets and in a statistical sense. The framework will also enable us to determine the key prior constraints which should be developed by observers in the near future, and will be adaptable to incorporate new and updated results from the literature.

References:

[1] Anglada-Escudé, G. et al. (2016) *Nature*, 536, 437. [2] Lingam, M. & Loeb, A. (2017) *International Journal of Astrobiology*, 1-11. [3] Schwieterman et al. (2017) *Astrobiology*, submitted. [4] Catling, D. et al. (2017) *Astrobiology*, submitted.

Exoplanet Dust Tails as Windows to the Planetary Interior. E. H. L. Bodman[1,2], S. J. Desch[1], and J. T. Wright[3], [1]Arizona State University, Tempe, AZ 85287, [2]NASA Postdoctoral Program Fellow, NExSS, [3]Pennsylvania State University, University Park PA 16802.

Introduction: Disintegrating planets provide a unique opportunity to probe the interiors of exosolar planets and the possible range of planetary interior compositions. This class of sub-Mercury-sized planets transit near enough to their host star (an orbital period of a day or less) that material from the rocky surface evaporates, recondenses in the atmosphere, escapes in a wind, and forms into a comet-like dust tail. These planets display a characteristic asymmetric, triangular dip that is typically highly variable from transit to transit (KIC 1255 [1]; KOI 2700 [2]; K2-22 [3]). Since the dust is condensing from the components of planetary material, the mineralogy of the dust will be linked to the surface composition, which allows for direct examination of planetary interior composition. Detailed study of the dynamics of the dust tail constrains the composition of the dominant dust species [4,5] but these models assume only a single species and cannot constrain interior composition. Relative abundances of the common rock forming elements such as Mg, Si, Fe, O, and C are necessary to determine the dominant mineralogy of the planet's interior. The interior mineralogy has significant impact on the possible habitability of the planet as it constrains the plate tectonics and other mantle dynamics [6]. Determination of relative abundances requires a model with multiple dust species. Many dust species we expect, such as corundum, pyroxene, and olivine, have notable spectral features in the near- and mid-IR. Despite the transits being less than 1 percent deep, the transit is entirely due to the surrounding optically-thin dust cloud, making these planets strong targets for spectroscopic follow-up observations.

Methods: We model the observable effects of composition dependencies of the dust tail in two stages. First, using a particle simulation, we follow the path taken by a grain released near the planet determined by gravitational, radiation and magnetic forces and assume dust species that are probable condensates from evaporated Earth-like crust and mantle compositions. The temperature of the grain is also tracked for the inclusion of sublimation. The dust grains in the tails are near the sublimation temperature for the species of interest and have lifetimes comparable to or much less than the period of the host planet. We track the change in size of the grain since the radiation and magnetic forces are dependent on grain size; both increase with decreasing size. From the grain paths, we determine the size and density distribution of the dust tail and then simulate the transit light curve to compare with the averaged *Kepler* transit.

Using the dust size and density distributions from our simulations, we simulate the IR spectra of dust grains for each of the different dust species. We assume spherical dust grains and, with Mie theory, calculate extinction over the wavelength range covered by *JWST*. Currently, we are restricting ourselves to the simpler single dust species model.

Discussion: Stellar magnetic fields only significantly affect the paths of grains smaller than 0.05 microns and based on previous fits to forward scattering [7] and color information [3,8,9], the grains are 0.1-1.0 microns, so magnetic fields do not change the shape of the dust tail or the transit shape. However, the small, nanometer-sized grains become trapped in the magnetic field instead of being blown out by radiation pressure which increases the IR excess.

Comparing synthetic spectra, we examine where in the IR spectrum the dust species are most distinguishable for the NIRISS, NIRSPEC, and MIRI instruments on *JWST*. The most notable features of many silicates are in the 9-10 micron range but the SNR is also larger, making it more difficult to distinguish those features. We will present the results of our analysis and discuss the implications for the follow-up observations of these objects.

References: [1] Rappaport S. et al. (2012) *ApJ,* 752:1. [2] Rappaport S. et al. (2014) *ApJ.,* 784:40. [3] Sanchis-Ojeda R. et al. (2015) *ApJ,* 812:112. [4] van Lieshout R. et al. (2014) *A&A,* 572, A76. [5] van Lieshout R. et al. (2016) *A&A,* 596, A32. [6] Unterborn et al. (2014) *ApJ*, 793:124. [7] Brogi et al. (2012) *A&A*, 545, L5. [8] Bochinski et al. (2015) *ApJ,* 800:L21. [9] Croll et al. (2014) *ApJ,* 786:100.

CORRELATED ISOTOPIC ANOMALIES ASSOCIATED WITH ORGANIC MATTER IN METEORITES.
M. Bose[1], T. J. Zega[2], P. Haenecour[2], and K. Domanik[2], [1]School of Molecular Sciences, Arizona State University, Physical Sciences Building PSD-13, Tempe AZ 85287-1604 (mbose2@asu.edu), [2]Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd, Tucson, AZ 85721-0092.

Introduction: It is well established that carbon-rich macromolecules survived the early solar system processes and were accreted in primitive carbonaceous chondrite parent bodies [1−5]. These molecules can contain large isotopic enrichments in D, ^{15}N and ^{13}C [1−3], hypothesized to have formed via ion-molecule reactions mediated on grain surfaces of ices coating dust grains and initiated by UV irradiation [6, 7].

To investigate the isotopic and functional group chemistry, and origins of domains carrying correlated isotopic anomalies in H, C and/or N, we carried out isotopic imaging of a serie of meteorites with different solar system histories. This information, in addition to the knowledge of the conditions in protoplanetary disks, can allow us to trace the origins of numerous chemical species, and provide insights into delivery of organics to the disk and/or terrestrial planets in our solar system or other habitable worlds in exoplanetary systems.

Samples and Methodology: Several carbonaceous chondrites: four CMs (Murray, Murchison, Cold Bokkeveld, and QUE 97990), three ungrouped chondrites (Bells, NWA 1152 and NWA 5958), and one CV (Allende) were investigated. All investigated samples were characterized with a Cameca SX-100 electron microprobe. Isotopic measurements with the NanoSIMS 50L (secondary ion mass spectrometry) was performed to measure H, C, and N on the exact same areas. Subsequently two isotopically anomalous domains were extracted by FIB (focused ion beam) and studied using X-ray absorption near edge spectroscopy (XANES) for their functional group chemistry.

Results: The abundance of D anomalies far exceed those containing ^{15}N-rich anomalies. Carbon isotopic anomalies, although present, are rare. The $^{14}N/^{15}N$ ratios range from 77 to 1070 (terrestrial ratio ~ 272) while the $^{12}C/^{13}C$ (terrestrial ratio ~89) isotope ratios are between 80 and 98. The D/H ratios show anomalies of larger magnitude than N, and range from 1.24×10^{-4} to 1.41×10^{-3} (terrestrial ratio ~1.56×10^{-4}). All domains are carbon-rich (C/Si ratios up to 5000). In all but few occurences, the H, C and N anomalies are spatially uncorrelated. In comparison, six domains have anomalies in N and C that are spatially correlated. Two separate regions have D excesses as well as ^{15}N excesses, while one area is D-rich, ^{13}C rich and ^{15}N-poor. A few observations were made from these data: Domains that have correlated N and C isotopic anomalies exhibit a narrow range in $^{14}N/^{15}N$ ratios between 207 and 218. The degree of enrichments in D observed in these domains are high (D/H = 6.95×10^{-4} and 8.71×10^{-4}) but ^{15}N ($^{14}N/^{15}N$ = 197−211) enrichments are not large. Domains with multiple anomalies are highly scarce. One of the C and N anomalous domain shows XANES K-edge peaks that can be ascribed to aromatic or olefinic, carboxyl and carbonate groups. Another ^{15}N rich domain shows these, in addition to the nitrile functional group.

Discussion: The reaction pathways that can lead to isotopic anomalies in simplest molecules can be investigated via this study, and can allow us to pin down their origins. The correlated N and H anomalies are possibly produced by the same process on N- and H-bearing precursor materials including ion molecule reactions in the gas phase, ion-grain reactions on grain mantles in cold environments and/or UV mediated photolysis reactions on ice mantles [6, 7, 8]. In comparison, carbon anomalies are produced by two opposing processes, namely ^{12}C excesses by gas phase ion-molecule reactions vs ^{13}C excesses by the UV mediated self shielding process, which could erase any correlated effects in other elements. In addition, the large ^{15}N excesses in most areas could be an interstellar product, while the small ^{15}N excesses observed in the correlated isotopic anomalies could reflect the average composition of the gas in the outer solar nebula, before the collapse of the protosolar nebula. Finally, we show that smaller C- and N-bearing species form the first chemical species under cold conditions. Nitrile feature present in the ^{15}N-rich domain but absent in a correlated N and C anomaly show that different set of reactions can occur on different substrates. To our knowledge, this is the first observation of a difference in the carrier phase chemistry of materials that carry an isotopic anomaly in N versus ones that have correlated ^{15}N and ^{13}C excesses.

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Comparative habitable planet signatures in polarized light K. Bott[1,2] , J. Bailey[1,3,4], V. Meadows[1,2], L. Kedziora-Chudczer[3,4], D. V. Cotton[3,4], and D. Crisp[1,5], [1]Virtual Planetary Laboratory (NASA Astrobiology Institute Virtual Planetary Laboratory, University of Washington, Seattle, Washington; email: kimbott@uw.edu), [2]Astronomy Department (University of Washington, Seattle, Washington), [3]Department of Astrophysics (University of New South Wales, Sydney, NSW, Australia; email: j.bailey@unsw.edu.au), [4]Australian Centre for Astrobiology (University of New South Wales, Sydney, NSW, Australia), [5]NASA Jet Propulsion Laboratory (California Institute of Technology, Pasadena, California)

Context: The ability to distinguish between truly habitable Earth-like worlds and "imposters" such as a Venus-like world are a crucial first step in habitability studies. Polarimetry provides unique information about planetary atmospheres and surface properties complementing more conventional observations. However, polarimetry is currently an under-utilized technique for planet characterization, especially for smaller planets, where its utility is poorly understood. Models of polarised light from terrestrial planets can allow for the detection of biosignatures and habitability markers. Comparisons of the signatures of worlds akin to Earth or Venus may provide an important means of quick comparison.

Methods: Combining the abilities of the Virtual Planetary Laboratory's "Earth" model planetary system code and the University of New South Wales' VSTAR radiative transfer code with surface and atmospheric polarimetric capabilities we explore the detectability of ocean glint, atmospheric compositions, varying surface conditions and cloud cover for a selection of nominally Earth-like planets in polarised light. This is compared to theory (e.g. [2] [3] [4]) and assessed in observational contexts. When applied to the robust problem of actual system observations using Virtual Planetary Laboratory's "Earth Model", this provides a means to map planets with spatially varying contributions from land/sea and atmospheric inputs including clouds throughout an orbit, consider noise sources, and begin the problem of disentangling signatures in multiple-planet systems. The Rayleigh and glint dominated "true Earth" is compared to the effects of backscatter from Venusian clouds in combination with Rayleigh scattering, and for inflated water-rich cores and worlds with ice-cover contributions.

Results and Significance: A first pass test for assessing the likelihood of an Earth-sized planet having an Earth-like atmosphere is developed. The time-varying signatures of a habitable Earth-like world is compared to signatures from Venus-like worlds which may prove otherwise difficult to distinguish from modern Earth, early Earth, and the volatile depleted cores of ice giants. We explore the capabilities of polarimetry in the context of state-of-the-art Earth-based imaging and aperture polarimeters (e.g. SPHERE [6] or HiPPI [7]) and next era space telescopes (e.g. HabEx or LUVOIR). Contributions of a spatially varying surface and cloud cover are addressed. This research is relevant to upcoming large ground-based and future NASA exoplanet characterization missions, such as the proposed HabEx and LUVOIR telescope concepts, particularly in the context of coronagraphy.

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WOULD MARS BE HABITBLE IF IT ORBITED AN M DWARF?: LESSONS FROM THE MAVEN MISSION. D. Brain[1], M. Chaffin[1], S. Curry[2], B. Jakosky[1], J. Luhmann[2], C. Dong[3], R. Yelle[4], and H. Egan[1], [1]LASP / University of Colorado (david.brain@colorado.edu), [2]SSL / University of California Berkeley, [3]PPPL / Princeton University, [4]LPL / University of Arizona, [2]SSL / University of California Berkeley.

Introduction: The planet Mars provides an intriguing laboratory for investigations of habitability on exoplanets. Though conditions at the Martian surface today are not well-suited for life, the Martian surface and atmosphere hold many clues that suggest that the necessary conditions for life were present billions of years ago. Habitable surface conditions long ago are thought to require a substantially different atmosphere, implying that much of the Martian atmosphere escaped to space over time. Mars may have been particularly susceptible to escape (compared to Earth) because of its small size and/or its lack of global magnetic field to shield the atmosphere. Each of these differences has implications for the loss rates of both neutral and charged particles over time.

The MAVEN mission to Mars has provided a wealth of data over the past three years that teach us about atmospheric escape processes and rates both today and over Martian history. These data can be applied (with caution) to situations at other planets both in our solar system and beyond; in a sense Mars is a nearby laboratory for examining issues of atmospheric retention and habitability terrestrial exoplanets.

Mars as an Exoplanet: If Mars is a laboratory for exoplanets, one could consider what might happen if a 'Mars' were discovered orbiting a nearby star. Since M Dwarf stars are both particularly numerous and host exoplanets, we choose to consider how Mars might fare if it orbited an M Dwarf.

MAVEN's measurements have enabled estimates of the thermal loss of hydrogen from the Mars extended exosphere, the photochemical loss of oxygen from the thermosphere, and the loss of oxygen ions accelerated by electric fields near Mars. In addition, MAVEN's data have been used to validate models for the loss of atmosphere from the planet. We consider how each of these 'pathways' for atmospheric loss would be changed if: the stellar photon and particle flux were consistent with a typical (such as it is) M Dwarf star, stellar disturbed (i.e. storm) periods were more frequent and more intense, and the planet orbited at a closer distance from the star. We discuss the conditions for which Mars-sized terrestrial planets could retain an atmosphere capable of supporting liquid surface water at some point in their history, and disucss how these inferences can help guide our search for rocky habitable worlds.

A Climate Classification Scheme for Habitable Worlds

Jonathan Forest Byrne, RSC

Climate Overview

The boundary conditions for evolution of habitable planets within a CHZ are the product of stochastic processes as a function of time. In the case of terrestrial planets habitability and specifically a biosphere is an emergent phenomenon resulting from the interrelationship between internal and external variability including geologic, hydrospheric and atmospheric forcings. The most significant outcome of these interrelationships is climate which, in turn, can be defined by two states 1) a vector state - a set of changing conditions with space and time 2) a scalar state which emerges from the vector state and is defined as a mean set of values within a fixed point in space and time. In the case of Earth the vector state includes climatic oscillations from warm, ice free periods through cold, glacial periods as the emergent scalar value on a global scale is the current mean temperature of 15c, and atmospheric pressure of 1013 hPa. However, such values decompose on local scales i.e. geographic location. Habitability, is a product of local climatic conditions which in turn determines biotic environments hence the substructure of ecosystems ranging from lower entropic levels e.g. terrestrial and marine extremophile environments to higher entropic levels of e.g. rain forests and coral reefs.

Earth as a Working Model

Using the Earth's history as a working model, this investigation will commence by expounding upon the relationship between climate and habitability i.e. the emergence of a biosphere within fluctuating and changing boundary conditions on both local and global scales. For example, Earth's biotic evolution is determined by orbital variability e.g. changes in earth-sun geometry, solar output, and suborbital variability e.g. atmospheric and oceanic composition and circulation .plate tectonics e.g. continental drift and the redistribution / configuration of continental plates. The spatial / temporal framework for this investigation will include the six eras of terrestrial evolution (developed by R. Hazen), the Koppen climate classification scheme, and chaos theory (originated by R. Poincare and further pioneered by E. Lorenz).

Habitable Worlds: A New Climate Classification Scheme

The investigation will culminate in a new climate classification scheme for terrestrial planets in which their respective stable climate states represent a range of potential habitability from lower entropic extremophile environments to higher entropic ecosystems. The respective classifications can be summarized as follows: **Type 1: Water World** - $\triangle$T values within the range for liquid state water with significant surface water mass present. Examples: Earth = 71%; Exoplanets Kepler 22b and GJ 1214 b. **Type 2: Frozen Water World-** $\triangle$T within the range for liquid water subterranean to a solid state surface. Examples: Europa and Enceladus. **Type 3: Pseudo-Water World.** $\triangle$T << 0c resulting in liquid hydrocarbons e.g. ethanol / methane and surface liquid state mass (oceans) and atmospheric dynamics that mimic the hydrologic cycle. Example: Titan.**Type 4:** Desert World: $\triangle$T within range for liquid water, mostly subterranean but surface liquid water mass absent. Type 5: Hothouse - $\triangle$T >> 100c

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ENCELADUS LIFE FINDER (ELF): A PROPOSED MISSION TO ASSESS THE HABITABILITY OF A PLUME-BEARING WORLD. M. L. Cable[1], L. J. Spilker[1], F. Postberg[2], J. H. Waite[3], S. Kempf[4], K. Clark[1], K. Reh[1], B. Sherwood[1] and J. I. Lunine[5], [1]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (Morgan.L.Cable@jpl.nasa.gov), [2]Heidelberg University, Heidelberg, Germany, [3]Southwest Research Institute, San Antonio, Texas, [4]University of Colorado, Boulder, CO, USA, [5]Cornell University, Ithaca, NY, USA (jlunine@astro.cornell.edu).

Enceladus, one of the moons of Saturn, has become popular recently due to the plethora of discoveries by the Cassini Mission. Not only does this moon have a stable, sustained plume emanating from its south polar terrain, but this plume also contains signatures that strongly suggest Enceladus has the ability to harbor life in its global, subsurface ocean.

We are in a unique position to assess the habitability of this ocean world. First, the ocean is accessible directly via the plume. By sampling the gas and grains of the plume, we can draw conclusions about the composition of the subsurface ocean, something that cannot be so easily achieved (so far) with other ocean worlds in the solar system. Second, the data from Cassini can be leveraged to design a targeted payload for a follow-on mission. Thanks to Cassini, we have bounds on parameters such as ocean pH and salinity, which are critical for selecting the best instruments to assess habitability and search for life. Additionally, the Cosmic Dust Analyzer (CDA) and Ion and Neutral Mass Spectrometer (INMS) instruments aboard Cassini mapped plume gas density and grain distribution, respectively. These measurements have provided for the generation of detailed plume gas and grain models, enabling careful mission planning to optimize parameters such as flyby altitude, trajectory and speed.

The Enceladus Life Finder (ELF) is a mission concept proposed to the recent New Frontiers call. By tasting the compounds in the gas and grains of the plume, ELF would address key questions of habitability and search for biosignatures. We will discuss the ELF concept and how the ELF payload uniquely addresses the habitability question. We will also discuss the implications of this type of habitability-focused mission for other ocean worlds such as Europa.

Salinibater ruber as a model for the habitability of Europa's ocean.

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Introduction: Life on Earth can be found in environments that are considered extreme in comparison with the conditions to which mesophiles, or regular forms of life, develop [1]. The organisms that proliferate in the extreme environments are called extremophiles, and particular examples can be found in the three domains of life [2, 3]. Some extreme environments possess at least one physical or geochemical condition like those described for the planetary bodies of astrobiological importance in the Solar System [4]. This is the case for Europa, one of the satellites of Jupiter, whose most relevant characteristic is the presence of a liquid water ocean under its icy surface, enriched with sulfate compounds like $MgSO_4$ and Na_2SO_4 [5, 6]. This extraterrestrial saline environment gives us the opportunity to study the strategies used by halophilic bacteria in terms of compounds different to NaCl.

Salinibacter ruber is an extreme halophilic bacterium whose growth and adaptation to different concentrations of NaCl and $MgSO_4$ have been previously studied in our group [7]. The aim of this work is to evaluate the adaptation strategies of *S. ruber* when is subjected, at once, to $MgSO_4$ and $NaSO_4$, two of the main salty components of the ocean of Europa.

Materials and Methods: Growth kinetics were used to determine the optimal growth conditions at different concentrations of Na_2SO_4, and Na_2SO_4+$MgSO_4$. Growth rate and duplication time were used to evaluate the results. The presence of compatible solutes was evaluated by quantitative NMR, and the expression of proteins in different saline stress conditions was identified by electrophoresis and shotgun proteomics.

Results and discussion: Growth curves show a most favorable fit of *S. ruber* in Na_2SO_4 compared whit the growth in $MgSO_4$. These results may be correlated with the Hofmeister series, as the cation Na^+ is more cosmotropic than Mg^{2+}. This is also the case for the anion SO_4^{2-} when compared with Cl^- [8]. The optimal growth in Na_2SO_4 occurred at smaller concentrations than in $MgSO_4$ as Na_2SO_4 provides a higher ionic charge than $MgSO_4$. The best growth was observed at osmolarities of around 6.5 osm/L in both salts, regardless of the concentration.

The analysis of the protein expression at different NaCl, $MgSO_4$ and Na_2SO_4 concentrations shows particularities on the type and on the quantity of the proteins involved in the adaptation strategies of *S. ruber*. It has been found that *S. ruber* accumulates betaine as compatible solute when is subjected to saline stress on NaCl [7], so we will verify if other compatible solutes are also present when *S. ruber* is exposed to other salty conditions.

The present results show the capability of terrestrial organisms to subsist and adapt to salty environments different from NaCl. This faculty can be used to search with more detail, if they are also able to adapt to the salty conditions of the liquid water ocean of Europa, rich in sulfates. The study of the mechanisms of adaptation *of S. ruber* to sulfate salts allows the evaluation of the physical and chemical limits of some of the life forms we know, and eventually the study of the metabolic mechanisms that help them to survive, will give us clues on the possibility to find a living being in a scenario of astrobiological importance.

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CONSTRAINING THE COMPOSITIONS OF SUPER-EARTHS. D. Carrera[1], E. B. Ford[1], and Angie Wolfgang[1], [1]Center for Exoplanets and Habitable Worlds, Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802.

Introduction: In this work we seek to use present day observations along with planet formation models to constrain the compositions of potentially habitable super-Earths. We have two main goals:

- *Estimate the role of gas accretion vs outgassing.* An accreted atmosphere would be hydrogen-rich, and affect the biomarkers, detectability, and location of the habitable-zone relative to a planet with an outgassed atmosphere [1].

- *Estimate the planet's water budget*. If super-Earths form primarily beyond the snow line, then the vast amount of water could form a high-pressure ice that shuts down the carbon-silicate cycle responsible for the stability of Earth's climate [2].

Observational constraints: We use a sample of Kepler exoplanets with masses measured by transit timing variations (TTVs;Daniel Jontof-Hutter, private comm.). A key insight is that the *ratios* of TTV masses are often much better constrained than the planet masses themselves [3]. Likewise, for transiting planets the primary source of uncertainty in planetary radii is the uncertainty in the stellar radius. Therefore, the *ratios* of the planet radii and densities are more precise and robust than the radii or densities of individual planets. In this work we use the mass and density ratios of neighboring planets measured by TTVs as our primary observational constraint.

Planet formation: We are conducting computer simulations of planet formation. Our runs begin with a series of isolation-mass protoplanets [5] embedded in an evolving protoplanetary disk model [6] where the planet experiences disk migration, accretion, and atmosphere loss resulting from giant impacts [4] both during and after the disk phase. The result of each simulation is a planetary system where we track each planet's core mass, atmosphere mass, and water abundance. In a post-processing step, we compute the atmosphere scale height [7] to obtain the planet radii.

Preliminary results: Figure 1 shows the mass and density ratios for our sample of TTV planet pairs. We conducted 5,000 bootstrap re-samplings to obtain a distribution of best-fit lines, $y = m\ x + b$, where $x = log(M_{out}/M_{in})$ and $y = log(\rho_{out}/\rho_{in})$. Figure 2 shows the 68% and 95% confidence intervals for (m,b), and the (m,b) values from two example simulations. The take-away is that we can use mass and density ratios to discard some models at high confidence. We are now conducting new simulations with more sophisticated models, and we will present those results at the Habitable Worlds workshop.

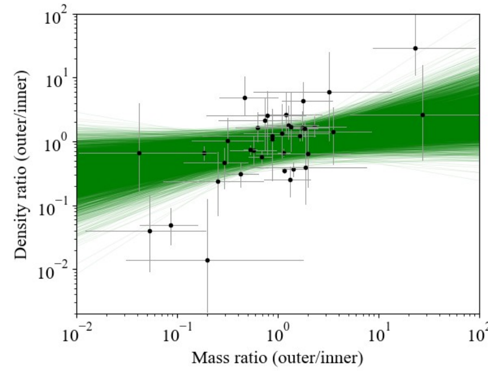

Figure 1: Mass and density ratios of neighboring planets with TTV masses, along with best-fit linear models for 5,000 re-samplings.

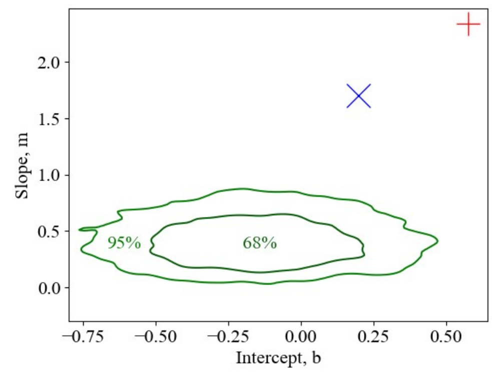

Figure 2: Confidence intervals for the best-fit lines in Fig 1 (green contours). The red and blue crosses are the best-fit lines for two planet formation models.

The difference between the models in Fig 2 is that one (blue) starts with lower-mass protoplanets. The fact that we can discern between these models is important because it links to the water budget: Lower-mass seeds imply lower isolation masses. The isolation mass is determined by the disk surface density, which is tied to the location of the water snowline. For example, at a time when the isolation mass at 1 AU is 0.2 $M_\oplus$, the snowline is at ~6.3 AU, and when the isolation mass drops to 0.03 $M_\oplus$, the snowline is at ~4.1 AU. In our newest runs we make the explicit connection between initial masses, stage of disk evolution, and location of the snowline.

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USING INDIAN TELESCOPES FOR TRANSIT FOLLOW-UP: PROSPECTS FOR IMPROVED LONGITUDINAL COVERAGE. A. Chakrabarty[1] and S. Sengupta[2]. [1]Indian Institute of Astrophysics, 100 Feet Road, Koramangala, Bangalore 560034, Karnataka; aritra@iiap.res.in, [2]Indian Institute of Astrophysics, 100 Feet Road, Koramangala, Bangalore 560034, Karnataka; sujan@iiap.res.in.

Introduction: Transit photometry is a key tool for the detection and characterization of exoplanets [1,2]. A challenge with observations of transient events like transit is longitudinal coverage: it is important to ensure 360° longitudinal coverage around the globe, to make sure that events can be observed regardless of when they occur. This is especially important for potentially habitable planets whose temperate conditions require wide orbits with infrequent transits [3].

We describe here new transit observation capacity in India, which fills in crucial missing longitudinal coverage from. To our knowledge, there is a 54° gap in the coverage of ≥2m class telescopes from 48°35´E (2m telescope, Shamakhi Astrophysical Observatory, Azerbaijan) to 102°47´E (2.4m telescope, Yunnan Astronomical Observatory, China). With telescopes such as 2m Himalayan Chandra Telescope (HCT), 78°57´E, 3.6m Devasthal Optical Telescope (DOT), 79°41´E and 1.3m Jagadish Chandra Bhattacharya Telescope (JCBT), 78°50´E India is well-positioned to provide the missing longitudinal coverage.

The transit capacity of Indian observatories was most recently demonstrated with observation of the transit of TRAPPIST-1b using the 2m HCT. We discuss this observation as a case study, and seek partnership for further observation programs.

Observed Transit Event and Results: TRAPPIST-1 b was observed using HCT as part of a coordinated campaign lead by [4]. We secured the raw data obtained by [4], reduced and analyzed them using the DAOPHOT package and retrieved the transit light curve. We modeled the transit (Fig. 1) using an MCMC algorithm in conjunction with the analytic transit model from [2]. The planet/star radius ratio, orbital distance, impact factor and mid-transit time we derived were consistent with the values derived by [4].

Future Observations: Based on the demonstrated capacity of HCT to detect small planets transiting M-dwarfs, we have begun a program to search nearby M-dwarfs for transits. We are also planning for observation of G and K dwarfs using JCBT. The observations are aimed at finding new close-in short-period planets around selected targets not known to host planets. With collaboration with other teams we can do coordinated observations of targets, especially of K or M spectral type, continuously for ~3-4 days.

In 2013 [5] searched for planets orbiting brown dwarfs using HCT. However, their SNR was insufficient for detection of habitable planets with $P_{HZ\ out} \leq 8$ hr (corresponding to the outer edge of the liquid water “habitable zone”). Building on the insight of [5] that J-band observations with a ≥3.5m class telescope could detect such planets with $P_{HZ\ out} \leq 8$ hr, we have initiated a program on the 3.6m DOT to do so. We are open to collaborating with other teams to coordinate searches for close-in habitable planets around brown dwarfs and other stars using transit photometry [5,6]. India can contribute to this search by coordinating follow-up transit observations with other teams for the sake of planet confirmation and parameter refinement, leveraging its newly demonstrated transit detection capability and unique longitudinal coverage.

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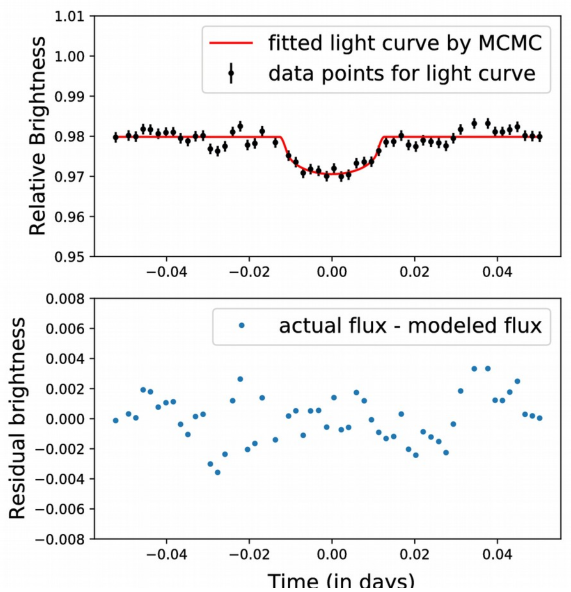

Fig. 1: The transit light curve of TRAPPIST-1b observed by [4] using HCT and reduced and analyzed by us. The upper panel shows the light curve model fitted to the data, and the lower panel shows the residuals of the fit.

THE HABITABLE ZONE GALLERY 2.0: THE ONLINE EXOPLANET SYSTEM VISUALIZATION SUITE

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ABSTRACT

We present the Habitable Zone Gallery 2.0 (HZG2), an online service that provides visualizations of known exoplanet systems. We pull all exoplanet data available from the NASA Exoplanet Archive and utilize the the latest climate models to compute and render planetary orbits, stellar parameters, and the Habitable Zone boundaries that indicate where liquid water could exist on the surface of a rocky planet. The HZG2 delivers new perspectives via interactive plotting and data analysis tools. We have crafted algorithms that intelligently discern the most appropriate view of an exoplanetary system, along with publication-ready vector-based plots that are available on-demand. Users can easily copy and modify any figure we host using tools that we provide. Anyone may download the plots in myriad file formats, or directly access the data in table form. The HZG2 supplies animated 3D visualizations of exoplanet systems with an aim to demonstrate orbital characteristics. Each exoplanet system has a dedicated webpage that, in addition to the plots, contains an integrated Aladin Lite module that summons actual imagery in an interactive view of the area of sky the exoplanet host system occupies. The HZG 2.0 upgrade promises to facilitate insights into the nature of exoplanetary systems while providing invaluable visualization tools and publication assets to the astronomical community.

Keywords: astrobiology – exoplanet habitability – data visualization

3-D CLIMATE MODELING OF THE CRETACEOUS: CAPACITY AND CONUNDRUMS THAT REFLECT ON THE PROMISE OF SIMULATING HABITABLE EXOPLANETS.
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Introduction: 3-D global climate model (GCM) simulations of potentially habitable worlds have shown that the definition of the habitable zone inner edge can be dramatically impacted by features such as stabilizing cloud feedbacks [1] and dynamic responses to changes in land/ocean distribution [2]. Coupled atmosphere-ocean GCMs also provide the capability to explore the climate dynamics that can lead to either enhanced global habitability or limited regional habitability. Paleo-Earth simulations for time slices within the last 1 Gyr of Earth history offer a means to evaluating GCM performance against proxy data, and suggest both lines of inquiry and benchmarks for improving model performance.

Approach: The Mid-Cretaceous Period (ca 100 Mya) is the archetypal warm, equable planetary greenhouse environment and was likely the warmest, most extensively inhabited time on Earth since continents became emergent. The oceans teamed with life, continental floral and faunal coverage was maximal, and both ocean ice and land ice coverage was minimal. Proxy evidence indicates that the warm temperatures were a result of higher atmospheric carbon dioxide levels, with from 4X to 20X preindustrial atmospheric levels [3]. Carbon dioxide was elevated in part due to increased volcanic activity and higher spreading rates at the Earth's mid-ocean ridge plate boundaries [4]. The higher geothermal heat flow expanded the ocean floor, displacing water onto continents and, combined with the lack of ice sheets on land, caused Cretaceous sea level to reach the maximum height for any time period since terrestrial life evolved. Abundant proxy data reveals that tropical to temperate climates extended to the poles, with evidence showing angiosperms (flowering plants), having originated in the Early Cretaceous, dominated by the Mid-Cretaceous [5]. These included tall broadleaf tree canopies with a strong leaf red edge combined with a high area of foliage per ground area, which would provide the most demonstrable red edge signal, presenting a clear contrast with other Phanerozoic and Proterozoic time periods being simulated.

Since the earliest days of 3-D global climate modeling many GCM development programs have tested their models by attempting to simulate the Cretaceous climate [6, 7]. Cretaceous simulations represent some of the first efforts to simulate, using complex 3-D computer models, planets with non-modern geographies and atmospheres that at the time would have seemed extreme compared to that used in modern Earth GCMs. Once the challenge (and it is a difficult challenge) of successfully creating realistic boundary conditons for the paleoEarth is met, the elevated CO_2 levels and lower continental albedos make it rather simple for GCMs to simulate a Cretaceous climate having global surface air temperatures that are much warmer than the present, with a severely reduced cryosphere, and a strongly enhanced hydrologic cycle. However, throughout nearly four decades of model development, a persistent problem in simulating the Cretaceous climate has been a limited ability to simulate the meridional temperature gradients that most paleoclimatologists believe existed based on fossil and sedimentological proxy evidence. Attempts to simulate polar temperatures that match proxy data always require greenhouse gas forcings that then yield tropical temperatures which exceed the levels consistent with Cretaceous tropical life.

A search for ways to alleviate the meridional temperature gradient model/data disconnect has borne some results through the generations of model improvements and re-evaluations of Cretaceous paleoclimate data. However, we know that the polar amplification problem remains a conundrum for simulating an array of warm paleoclimates in Earth's past. Using the latest versions of NASA's coupled ocean atmosphere Earth System Model [8] and NASA's newest planetary GCM [9], we explore the problem in more depth with an eye to understanding how warm, equable and super-habitable exoplanets would be simulated using GCMs, and how their dynamic atmospheres, oceans and land surfaces operate.

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A REVIEW OF THE NEAR-FUTURE OPPORTUNITY AFFORDED BY THE DISCOVERY OF TEMPERATE, TERRESTRIAL PLANETS ORBITING NEARBY M-DWARFS. D. Charbonneau[1], [1]Harvard-Smithsonian Center for Astrophysics, 60 Garden St. MS-16, Cambridge, MA 02138; dcharbonneau@cfa.harvard.edu.

Temperate, terrestrial planets orbiting nearby small stars offer the only opportunity to study the atmospheres of potentially habitable exoplanets in the next decade. The purpose of this talk is to review the M-dwarf opportunity and recent progress for the benefit of the relatively broad community of scientists assembled at this meeting.

The closest star, Proxima, hosts a temperate world (although it likely does not transit), and two nearby stars, TRAPPIST-1 and LJS1140, were recently found to host small and temperate planets that do transit. Even closer and hence more spectroscopically accessible temperate worlds transiting nearby M-dwarfs likely remain to be discovered. For their atmospheres to be accessible to upcoming telescopes, such planets likely need to be within a distance of 15 parsecs, yielding a list of approximately 450 potentially targets. Numerous surveys will search subsets of this list, including the dedicated ground-based transits surveys such as MEarth and SPECULOOS, the NASA TESS Mission (scheduled for launch in Spring 2018), and a plethora of dedicated radial velocity surveys including CARMENES, SPIROU, HPF, IRD, and NIRPS. I will first summarize these efforts and answer whether these efforts will in fact conduct a complete and definitive survey of these 450 stars.

The launch of the James Webb Space Telescope in October 2018 may afford the opportunity to search for atmospheric gases such as water, carbon dioxide, and methane, while the subsequent deployment of extremely large ground-based telescopes such as the GMT, TMT, and the ELT may permit the search for molecular oxygen. Thus, working in concert, JWST and the ELTs may present the chance to detect potential atmospheric biosignature gases, as well as the other atmospheric gases that will required to consider whether such potential biosignature gases are indeed biogenic. I will present representative signal-to-noise calculations for both JWST and the ELTs and discuss the opportunities for atmospheric characterization.

Finally, the interpretation of the provenance of any molecular detections will demand a number of characterization studies of the host stars. We must gather spectra of the UV and high-energy emission while we have functioning space facilities, and we need to conduct a comprehensive survey of the stellar properties, including rotation, activity, binarity, and metallicity of all M-dwarfs within 15 parsecs.

The work to understand the closest small stars and their potentially habitable planets is an interdisciplinary effort, and I will attempt to summarize the vigorous research by the broad community that is making rapid progress on this challenge.

A TEST FOR THE HABITABLE ZONE CONCEPT. J. Checlair[1] and D. S. Abbot[1], [1]University of Chicago, Department of the Geophysical Sciences, 5734 S, Ellis Ave., Chicago, IL 60637 (email: jadecheclair@uchicago.edu)

Abstract: Traditional habitable zone theory assumes that the silicate-weathering feedback regulates the atmospheric CO2 of planets within the habitable zone to maintain surface temperatures that allow for liquid water. There is some non-definitive evidence that this feedback has worked in Earth history, but it is untested in an exoplanet context. A critical prediction of the silicate-weathering feedback is that, on average, within the habitable zone planets that receive a higher stellar flux should have a lower CO2 in order to maintain liquid water at their surface (Figure 1). We can test this prediction directly by using a statistical approach involving low-precision CO2 measurements on many planets with future observing facilities such as JWST, LUVOIR, or HabEx. The purpose of this work is to carefully outline the requirements for such a test. First, we use a radiative-transfer model to compute the amount of CO2 necessary to maintain surface liquid water on planets for different values of insolation and planetary parameters. We run a large ensemble of Earth-like planets with different masses, atmospheric masses, inert atmospheric composition, cloud composition and level, and other greenhouse gases. Second, we post-process this data to determine the precision with which future observing facilities such as JWST, LUVOIR, and HabEx could measure the CO2. We then combine the variation due to planetary parameters and observational error to determine the number of planet measurements that would need to effectively marginalize over uncertainties and resolve the predicted trend in CO2 vs. stellar flux. The results of this work may influence the usage of JWST and will enhance mission planning LUVOIR and HabEx.

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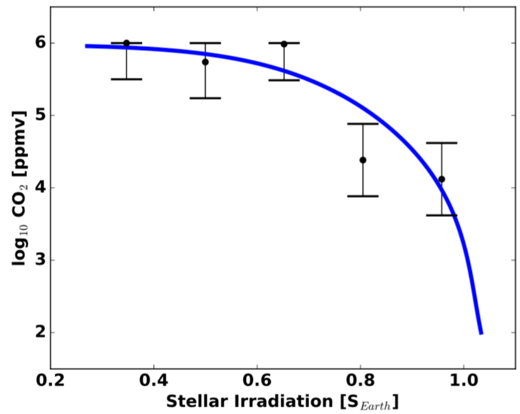

Figure 1. A decrease in atmospheric CO_2 as stellar irradiation increases is expected within the habitable zone, assuming a functioning silicate-weathering feedback. This could provide a viable test for the concept of the habitable zone. The blue curve shows the predicted CO_2 needed to maintain a surface temperature of 290 K. The black points are binned data for hypothetical planets that assume the theoretical irradiation-CO_2 curve but are scrambled away from it based on the plotted 1-error bars, assuming four planets per bin. Points and error bars have a physical limit on CO_2 values of 10^6 ppmv or less. Using the error estimations shown here the trend predicted by the theory could be inferred from the data. Taken from [1].

CHASING SMALL EXOPLANETS WITH GROUND-BASED NEAR-INFRARED TRANSIT PHOTOMETRY. K. D. Colón[1], G. Barentsen[2,3], Z. Vinícius[2,3], A. Vanderburg[4], J. Coughlin[5], S. Thompson[6], F. Mullally[5], T. Barclay[1], and E. Quintana[1], [1]NASA Goddard Space Flight Center (Exoplanets and Stellar Astrophysics Laboratory, Code 667, Greenbelt, MD 20771), [2]NASA Ames Research Center (M/S 244-30, Moffett Field, CA 94035), [3]Bay Area Environmental Research Institute (625 2nd St. Ste 209 Petaluma, CA 94952), [4]Harvard-Smithsonian Center for Astrophysics (60 Garden St, Cambridge, MA 02138), [5]SETI Institute (189 Bernardo Ave, Suite 200, Mountain View, CA 94043), [6]Space Telescope Science Institute (3700 San Martin Dr, Baltimore, MD 21218).

Introduction: NASA's K2 mission has discovered a plethora of transiting exoplanets along the ecliptic plane, and NASA's TESS mission will surpass these discoveries in its all-sky search for transiting exoplanets. The discoveries from both K2 and TESS are important for identifying key exoplanet targets that should be characterized in detail with NASA's James Webb Space Telescope (JWST) and other advanced facilities. Here, I present the latest results from an ongoing program to use the 3.5-meter WIYN telescope at Kitt Peak National Observatory for near-infrared transit photometry of K2 exoplanets and candidates. Our program of high-precision, high-cadence, high-spatial-resolution near-infrared transit photometry is providing improved measurements of the orbital and physical properties of K2 exoplanets and candidates as well as identifying false positives within the K2 candidate list. To date, 25 unique K2 targets have been observed with WIYN. I also describe additional observations that will take place in January 2018 as part of a campaign to observe exoplanet transits in the near-infrared simultaneously with the Kepler spacecraft during K2 Campaign 16. Our WIYN program greatly complements an ongoing Spitzer program to observe transits of K2 exoplanets [e.g. 1, 2] and also demonstrates WIYN's capabilities for observations of exoplanets to be discovered by TESS. This program will ultimately contribute to the identification of prime super-Earth-size and Neptune-size planets for detailed atmospheric characterization with JWST.

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We explore the large-scale climate dynamics at low and high obliquity for an Earth-like planet using the recently developed NASA GISS ROCKE-3D general circulation model. We describe the role of ocean heat storage and transport in determining the seasonal cycle at high obliquity, and discuss the dynamics of the large-scale circulation and resulting regional climate patterns that develop for exotic tilt configurations. We also discuss the hysteresis structure for a high obliquity planet near the outer edge of the habitable zone to varying CO2 concentrations, and discuss prospects for habitability for a high obliquity planet susceptible to global glaciation.

RADIOLYSIS AND TERMOLYSIS OF TETRADECANOIC ACID AND DOCOSANOIC ACID IN PHYSICOCHEMICAL CONDITIONS SIMILAR TO HYDROTHERMAL VENTS.

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Introduction: Carboxyl acids are important compounds in biological systems, and their stability to diverse physicochemical conditions present in various environments probable in the primitive Earth is of paramount importance [1]. A proposed geological environment in which it could carry out significant reactions for the synthesis of compounds of pre-biological importance are the hydrothermal vents [2].

This research focuses on the study of the stability of tetradecanoic acid and docosanoic acid, as examples of high molecular weight fatty acids. These compounds were exposed to high temperatures, in addition to the presence of a gamma radiation field. It is probably that both energy sources may have been present near hydrothermal vents. To this end, the molecules were irradiated with gamma rays in oxygen-free aqueous solutions, and the thermal decomposition was studied in a static system at temperatures up to 90°C, simulating a white hydro-thermal vent. The analysis of these systems was performed by ATR-FTIR spectroscopy and gas chromatography (GC) and GC-coupled to a mass spectroscopy.

Our results show the relative stability of these carboxylic acids under different energy sources. Additionally, the reaction products may have importance in the chemical evolution, since they could function as reagents towards the synthesis of other compounds of pre-biological importance [3].

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EQUILIBRIUM TEMPERATURES AND ALBEDOS FOR HABITABLE M STAR PLANETS IN A COUPLED ATMOSPHERE-OCEAN GENERAL CIRCULATION MODEL.

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Introduction: The potential habitability of detected exoplanets is typically assessed using the concept of equilibrium temperature (T_e) based on cloud-free 1-D models with assumed albedo equal to Earth's (0.3) to determine whether a planet lies in the habitable zone [1]. Incident stellar flux appears to be a better metric for stars unlike the Sun [2]. These estimates, however, ignore the effect of clouds on planetary albedo and the fact that the climates of synchronously rotating planets are not well predicted by 1-D models [3]. Given that most planet candidates that will be detected in the next few years will be tidally locked and orbiting M stars, how might the habitable zone be tailored to better inform characterization with scarce observing resources?

Methods: We use the ROCKE-3D general circulation model (GCM) [4] to simulate two very different types of potentially habitable planets. We use available information about Proxima Centauri b [1] to represent cool, weakly-irradiated M-star planets. Our experiments include Earth-like and elevated greenhouse gas atmospheres, synchronously rotating and 3:2 spin-orbit resonance planets, aquaplanets and planets with land and ocean, and oceans ranging from fresh to hypersaline [5]. For warm, highly-irradiated planets, we simulate a hypothetical ancient Venus orbiting a young Sun [6] and a planet orbiting an M star modeled loosely after Kepler-1649b [7] but with weaker instellation (1.4 x Earth-Sun) and artificially slower rotation (50 d period) than the actual detected planet to keep its temperatures moderate. Simulations use a dynamic ocean to achieve more realistic day-night differences than do slab ocean models [5]. All simulations produce stable surface liquid water over some fraction of the planet.

Results: For 10 Proxima Centauri b simulations (e.g., Fig. 1, left), actual T_e values based on emitted longwave radiation range from 234-242 K (vs. 255 K for Earth), but the habitable fractions of the planets range from 20-87%. None of the simulated planetary albedos (range .16-.26) are as high as Earth's 0.3 albedo used to define the nominal habitable zone. This is primarily due to the greater absorption of starlight by the atmosphere for cool stars whose instellation is mostly in the near-IR, where H_2O and CO_2 absorb strongly. This was noted by [2], but their albedos are much lower because they ignore clouds.

For ancient Venus with a land-ocean configuration based on observed D/H and topography [6], we simulate T_e = 254 and 263 K for cases with 1.5 and 2.4 x Earth's solar irradiance, respectively. These correspond to surface temperatures of 11°C and 42°C, and albedos of 0.52 and 0.67. The higher albedos result from thick dayside clouds that consistently arise in GCM simulations of slowly rotating planets [6, 8, 9, 10, 11]. For the modified Kepler-1649b (Fig. 1, right), with an aquaplanet surface and instellation 1.4 x Earth's but for an M star, the equilibrium temperature is 265 K, very similar to the warmer Venus case, but with an albedo much lower (0.42) and a surface temperature much higher (59°C). In all cases the albedo is much higher than the 0.3 value for Earth.

Our results and others [6, 8, 9, 10] suggest that the nominal habitable zone boundaries should be modified to account for (a) albedos higher than Earth's for planets inside the tidal locking radius, and (b) albedos lower than Earth's for planets orbiting cool stars, so that promising candidates for characterization by future observations are not needlessly excluded from consideration. The expanding record of exoplanet GCM simulations can provide useful guidance for this.

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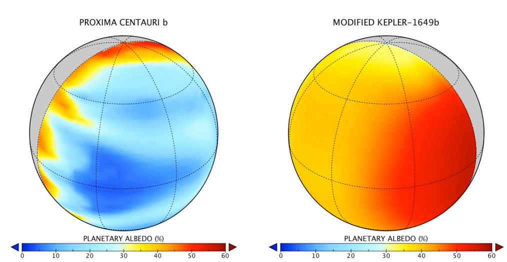

Fig. 1. Planetary albedo maps for (left) Proxima Centauri b and (right) modified Kepler-1649b simulations.

DETECTABILITY, NOT HABITABILITY. S. J. Desch[1], H. E. Hartnett[1,2], S R. Kane[3], and S. I. Walker[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe, AZ 85287-1404 (steve.desch@asu.edu), [3]School of Molecular Sciences, Arizona State University, PO Box 871406, Tempe AZ, 85287. [2]Dept. Physics and Astronomy, San Francisco State Univ., 1600 Holloway Ave., San Francisco CA 94132.

The grand challenges of astrobiology are to understand how life begins on this planet and others, and to search for life elsewhere in the Universe. Toward that end, the 2015 NASA Astrobiology Strategy document lists identifying, exploring and characterizing environments for habitability and biosignatures, and constructing habitable worlds, as major topics of research. The community, and this workshop, have focused on habitability and formation of habitable worlds: obviously one must be certain life could exist on a planet before searching for life on it. But we argue that habitability is not precisely what the community should be assessing, and we argue instead for assessing *detectability* of life.

Others [1] have critically examined the current usefulness of habitability as a concept, noting habitability is just equated with liquid water on the surface, and limited observational data is used to judge even that factor. The Habitable Zone Index for Transiting Exoplanets [2] and the Earth Scalability Index [3] are metrics of habitability that use only planetary mass and radius, stellar flux, and orbital information to assess whether the planets have liquid water or are similar to Earth, which is not the same as habitability. To state the obvious, Mars, Enceladus and Europa might all be habitable without liquid water on their surfaces.

We make the separate point that habitability is not precisely what we want to assess anyway. The observational strategy in the near term is to find promising planets in their stars' habitable zones, then characterize their atmospheres using transmission spectroscopy enabled by *JWST* or other future missions. Identification of putative biosignature gases like O_2 and CH_4 in their atmospheres would constitute the evidence in support of life. The problem is that habitable worlds are quickly becoming dime-a-dozen. *Kepler* and other surveys have discovered hundreds of rocky exoplanets $< 1.6\ R_E$ (exoplanets.eu), with a large number in their stars' habitable zones. Yet *JWST* will only be able to characterize the atmospheres of a handful of these. To prioritize future observations, something more precise than habitability is needed.

What is needed is an assessment of how easily life can be conclusively detected on an exoplanet. This means predicting an exoplanet's observable quantities (e.g., atmospheric gas concentrations) in two cases: 1) the case with the highest plausible amount of life; and 2) the abiotic case. If an observable is different between the two, then life is detectable. Otherwise, the question of habitability is moot: whether or not life exists, it cannot be conclusively identified, and such an exoplanet should be deprioritized for observations.

The case of "aqua planets"---planets like Earth in all respects except covered in oceans, without land, illustrates the difference between detectability and habitability. By all measures, such a planet is habitable, and might easily support life merrily engaging in oxygenic photosynthesis. However, biological productivity in Earth's central ocean gyres is $10\text{-}10^2$ times than it is near continental sources of bioessential elements, and $\sim 10^3$ times lower than in highly-productive terrestrial environments [4]. Production of O_2 on a planet without land and continental runoff would be lower than on Earth, perhaps comparable to abiotic rates of O_2 production like photolysis of water. If models robustly predicted that on an aqua planet the most favorable biological rates were only comparable to abiotic rates, then no observation of O_2 in its atmosphere would be taken as conclusive evidence for life. Aqua planets might be an example of planets that are habitable, but where life is not especially detectable.

Detectability provides a guide for future exoplanet system characterization. The need to assess abiotic geochemical cycles and biogeochemical cycles means determination of a host star's composition is a necessary starting point. Other constraints on planet formation and solar system architecture are also desirable, and extensive modeling is essential. It cannot be emphasized enough that detectability demands thinking about exoplanets as planets, and incorporating tools and insights from the geophysical and geochemical communities. Assessing detectability may be best conceptualized within a Bayesian framework [5].

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THE HISTORY AND FUTURE OF EXOPLANET BIOSIGNATURES. S. D. Domagal-Goldman[1], [1]NASA Goddard Space Flight Center (shawn.goldman@nasa.gov)

This review talk will cover exoplanet biosignatures, based on the reports from the workshop organized by the Nexus for Exoplanet Systems Science (NExSS), the NASA Astrobiology Insitute (NAI), and the Exoplanet Analysis Group (ExoPAG). These reports discuss previously proposed biosignatures [1], the lessons we have learned about biosignature theory from the careful consideration of O2 as a biosignature [2], quantification of that theory using Bayes's Theorem [3], frameworks for biosignatures and a guide to their future development [4], and the future observatories that will unveil exoplanet biosignatures [5]. In this review talk, we will cover this material, which will also present a history of and future pathways for biosignature theory. In this presentation, an attempt will be made to introduce biosignature work presented by other authors (including poster presentations) at this meeting.

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Are "Habitable" Exoplanets Really Habitable? −A perspective from atmospheric loss.
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Introduction: In the last two decades, the field of exoplanets has witnessed a tremendous creative surge. Research in exoplanets now encompasses a wide range of fields ranging from astrophysics to heliophysics and atmospheric science. One of the primary objectives of studying exoplanets is to determine the criteria for habitability, and whether certain exoplanets meet these requirements. The classical definition of the Habitable Zone (HZ) is the region around a star where liquid water can exist on the planetary surface given sufficient atmospheric pressure, but this definition largely ignores the impact of the stellar wind and stellar magnetic activity on the erosion of an exoplanet's atmosphere. Amongst the many factors that determine habitability, understanding the atmospheric loss is of paramount importance [1,2]. Most of the recent attention has been centered around the study of exoplanets orbiting M-dwarfs since the latter are highly numerous in our Galaxy (and in the Universe). The study of these exoplanets has also received a major boost from the discovery of Proxima Centauri b (PCb) [3] and seven Earth-sized planets in the TRAPPIST-1 system [4].

Method: In our Solar system, the most sophisticated codes tend to use magnetohydrodynamic (MHD) models for modeling the interactions of the solar wind with magnetized (such as Earth) and unmagnetized (such as Mars and Venus) planets, and the interactions of planetary magnetospheric flow with its moons (such as Titan). We use the BATS-R-US MHD model [5] developed at the University of Michigan that has been well validated and applied to different solar system objects. For the stellar wind parameters (such as the stellar wind velocity, density and interplanetary magnetic field), we adopt the AWSoM model [6] to simulate those parameters based on the observed magnetograms of M-dwarf stars. The BATS-R-US MHD model is then adapted to exoplanet research by modifying the stellar wind inputs and exoplanetary atmospheric profiles, compositions, and photochemistry.

Results: Fig. 1 presents the contour plots of the O^+ ion density, the magnetic field strength **B** and the magnetic field lines for unmagnetized and magnetized PCb. The total ion escape rate varies from ~ 10^{26} s^{-1} (magnetized) to ~10^{27} s^{-1} (unmagnetized) over one PCb's orbital period, about 1-2 orders of magnitude higher than those of terrestrial planets in our Solar system. As the escape losses for PCb in the unmagnetized case are about two orders of magnitude higher than our Earth (~ 10^{25} s^{-1}), all of the atmosphere could be depleted much faster--possibly in a span of O(10^8) years. In turn, this has very important ramifications for surface-based life as we know it, given the importance of elements like oxygen.

If gases such as oxygen are depleted on these short timescales, sufficient time may not exist for complex life to evolve. Our simulations indicate that the escape rates for PCb in the magnetized case are higher than that of the Earth, implying that some of the above conclusions for the unmagnetized case are also valid here. However, it is equally important to recognize that the magnetized case is quite sensitive to the values of the stellar wind parameters [7]. The atmosphere depletion could occur over O(10^8) and O(10^9) years for the magnetized case with minimum and maximum stellar wind dynamic pressure P_{dyn} over one PCb, respectively.

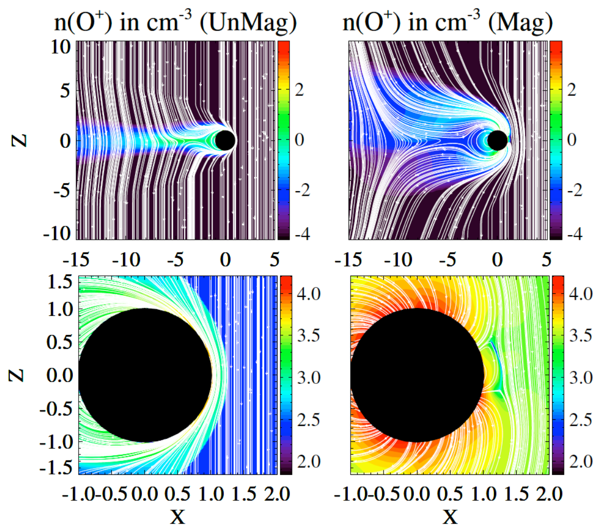

Figure 1 The logarithmic scale contour plots of the O^+ ion (outflow) density (first row) and magnetic field strength (second row) with magnetic field lines (in white) in the meridional plane for the unmagnetized (UnMag) and magnetized (Mag) PCb [7].

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Modeling of Ion and Photochemical Losses to Space over the Martian History: Implications for Exoplanetary Climate Evolution and Habitability. C. F. Dong[1], Y. Lee[2], Y. J. Ma[3], S. W. Bougher[4], J. G. Luhmann[5], B. M. Jakosky[6], S. M. Curry[5], D. A. Brain[6], G. Toth[4], and A. F. Nagy[4], [1]Princeton University (dcfy@princeton.edu), [2]NASA GSFC, [3]IGPP, UCLA, [4]CLaSP, University of Michigan, [5]SSL, UCBerkeley, [6]LASP, CU-Boulder

Introduction: Mars may have had a thicker atmosphere and liquid water on its surface between 3.5 and 4 billion years ago. However, today's Red Planet has dry and cold surface environments and a small surface pressure (~6 mbar) mainly resulting from the thin and cold atmosphere. So one of the most important questions is: where did all of the atmosphere and liquid water go? One of the MAVEN's primary objectives is to quantify the atmospheric escape to space over time [e.g., 1,2]. In order to understand the effect of atmospheric losses to space on the long-term evolution of the Martian atmosphere (e.g., loss of water) and its climate change over its history, the well-validated 3-D state-of-the-art numerical tools are essential to study both the ion and photochemical escape back to 4 billion years ago.

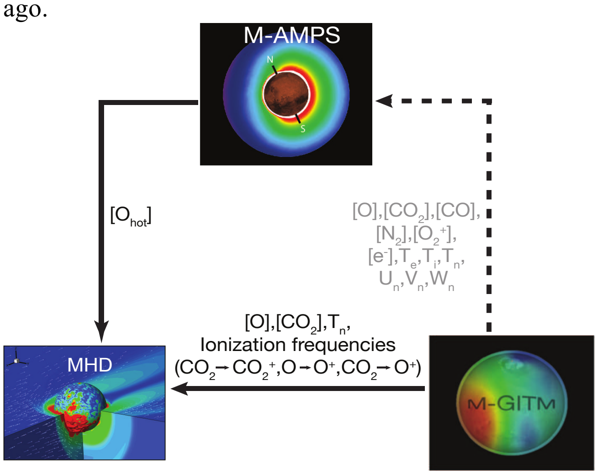

Figure 1: A sketch of a one-way coupling approach between M-GITM, M-AMPS, and MHD [4]. The notation T_n denotes neutral atmosphere temperatures, and [O], [CO_2], and [O_{hot}] are the neutral O, CO_2, and hot atomic oxygen number densities, respectively.

Method: In this study, we adopted the one-way coupled framework (Fig. 1) which has been employed to study the ion and photochemical losses at the current epoch [3,4]. We adopted the 3-D Mars thermosphere (i.e., neutral temperatures T_n, neutral densities [O], [CO_2], and photoionization frequencies I_O, I_{CO2}) from the Mars Global Ionosphere Thermosphere Model (M-GITM) [5] and the hot atomic oxygen density, [O_{hot}], from the Mars exosphere Monte Carlo model Adaptive Mesh Particle Simulator (M-AMPS) [3]. These neutral profiles are one-way coupled with the 3-D BATS-R-US Mars multi-fluid MHD model [6]. The M-AMPS hot oxygen corona and the associated photochemical loss rate were calculated based on the thermospheric/ ionospheric background from M-GITM. The historical solar radiation and solar wind parameters were adopted from Ref. [7]. We started the simulation at the current epoch based on the autumnal equinox solar cycle moderate conditions.

Results: Fig. 2 presents the calculated ion (solid lines) and photochemical (dashed line) escape rates by using this one-way coupled framework (Fig. 1) over the Martian history. In Fig. 2, the O^+ ion loss dominates over heavy ion species (O_2^+ and CO_2^+) at early Mars and the corresponding O^+ ion escape rate is much higher than the current value. Although the photochemical escape is the dominant loss mechanism at current Mars, the total ion escape rate is much higher than the photochemical escape rate at early Mars.

In summary, this study informs our understanding of the long-term evolution of the Martian climate due to atmospheric losses to space, and has implications for analogous change on exoplanets. Thus, it offers fresh insights concerning the habitability of the increasing number of exoplanets discovered yearly.

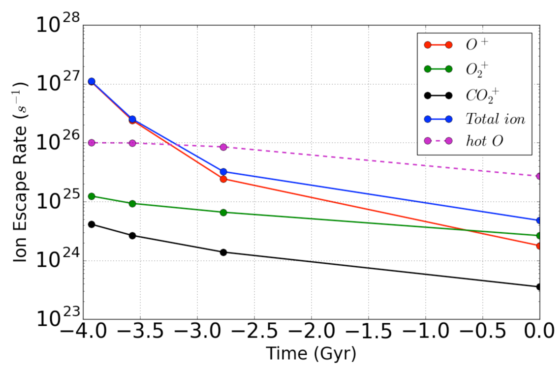

Figure 2: Calculated ion and photochemical escape rates over the Martian history.

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KOROLEV CRATER, MARS: ESTIMATION THE IMPACT CONDITIONS. J. C. Echaurren[1], [1]Codelco Chile, Chuquicamata Division, jecha001@codelco.cl

Introduction: Within the aspects that affect the habitability of the planets, the impact with asteroids becomes one of the most destructive phenomena that an evolving planet must tolerate. In this work, estimates are made for the main variables that give shape to an impact crater, taking as an example the Korolev impact crater, that is on Mars. Then, Korolev Crater (73 N 195.5 W) [1] is an 84-km-wide crater located in the Mare Boreum quadrangle of Mars. Thermal studies of Korolev undertaken in 2005 indicated that the crater contained, at minimum, several meters thick of ice or ice rich regolith. Recent investigations using radar sounding have shown that the water ice contained in Korolev may approach 2-km thick. The models used here are based on some equations postulated by Holsapple (crater depth) [2]; scaling; polynomial analysis; and an adaptation of quantum formalism for the mathematical representation of the energy pulse generated in the impact point, in where besides, is used one solution (soliton type) of the Korteweg-De Vries's equation [3].

Results obtained with the models: The development of this crater is realized in 4 stages [4], in which are specified the variables of impact more common, as follows: a). <u>Contact/Compression Stage:</u> In this stage the diameter of the impactor is estimated in ~ 5.82 km, the velocity of impact is ~ 7.09 km/s, the impact angle is ~ 80.57°, the density of impactor is ~ 2.03 g/cm^3, the crater depth is estimated in ~ 4.29 km [2], the melt volume is ~ 699.65 km^3, the total energy of impact is estimated in ~ 4.41×10^{29} Erg (~ 1.05×10^{7} megatons), pressure to 1 km of the impact point is ~ 3,275.06 Gpa, and the seismic shock-wave magnitude is >10.0 according the Richter Scale. b). <u>Modification/Excavation Stage:</u> In this stage the diameter of transient crater is ~ 55.55 km, the number of ejected fragments is ~ 3.32×10^{9}, the average size of the fragments is ~ 22.08 m, the average density of fragments is ~ 1.47 g/cm^3, the minimal distance of ejection of the fragments is ~ 159.11 km, the velocity of ejection is ~ 1,155.32 m/s, the minimal angle of ejection is ~ 13.12°, and the minimum height of ejection is ~ 9.27 km. c). <u>Collapse/Modification Stage:</u> In this stage the pressure toward the final crater rim decrease to ~ 1.86 Gpa. d). <u>Final Crater Stage:</u> The relation between the transient crater and the final crater is ~ 0.66, value that is in accordance with the specification realized by Bevan French [4], the time of creation for the final crater can be estimated in ~ 1.17 minutes according to Schmidt and Housen [2], the hydrothermal zone could spread from ~ 4.13 km to ~ 27.77 km from the nucleus of impact, i.e., a hydrothermal band of ~ 23.64 km, the lifetimes estimated for this hydrothermal band are of ~ 0.88 Ma to ~ 1.4 Ma with uncertainties of ~ (+/-) 1.06 % to ~ (+/-) 2.92 %, i.e., from ~ (+/-) 0.01 Ma to ~ (+/-) 0.04 Ma, hydrothermal temperatures from 0.25 years to 1,400 years, after of the impact, are estimated in ~ 90.69 °C to ~ 35.57 °C.

Discussion: In this model the total energy, is the sum between the energy of radiated friction (in the atmosphere of Mars), and the energy released in the point of impact on the surface of Mars. This total energy, differs conceptually from the kinetic energy of the impactor. The kinetic energy of the impactor, is latent energy, and the total impact energy, is energy released. This energy behaves like a pulse consisting of a fundamental transient, followed by a train of permanent soliton waves, which move radially from the point of impact towards the edge of the crater. A more detailed analysis of how this energy pulse behaves, will be addressed in future work.

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The color dependency of KIC 8462852's dips Tyler G Ellis[1], Tabetha Boyajian[1], Eva Bodman[2], and Jason Wright[3] and Collaboration [1] Louisiana State University, Department of Physics & Astronomy, 202 Nicholson Hall, Baton Rouge, LA 70803 *telli17@lsu.edu*, [2] ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, [3] Department of Astronomy & Astrophysics, Eberly College of Science, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802

Introduction: KIC 8462852 earned its title of "The Most Mysterious Star in the Galaxy" when it was discovered to sporadically dip in luminosity upward of 20% by the Kepler mission. Additional further analyses reveal a longterm dimming trend throughout the original mission that continues to the present day. As the star appears by every measure a typical F3 main sequence source lacking any infrared excess, both the dimming and dips are extraordinary. No hypothesis has been shown to provide a satisfactory explanation of all of the star's behavior.

Since 2016, we have continually monitored this star's flux to detect changes and trigger rapid response spectral observations. We observed a dipping event in late 2017 May, which was corroborated and followed up by other ground based observatories. Three further dipping events have been observed since the first.

We present our photometric and analytic techniques as well as the color dependencies of these dips. Analysis indicates the presence of a large volume of dust, potentially circumstellar. Future observations will continue to monitor the star so that the composition, size, and location of the dust may be further refined.

The Search For Life: In-Situ, Remote Sensing, Modeling And Archiving. M.K.Elrod, [1]NASA Goddard Space Flight Center (8800 Greenbelt rd, Greenbelt, MD, meredith.k.elrod@nasa.gov).

Introduction: In seeking out habitable worlds it is necessary to use quitea variety of tools including tried and true instrumentation to cutting edge technology. New and revised models are regularly employed and improved to find the best candidates for habitiablity. Finally, all data is currently archived into the PDS for current and future use. While this is still in the development stage, it is part of the PDS4 madnate to also archive and maintain models used by scientific teams in verification of instrumental data and scientific software. This implies that eventually the PDS will house the strong atmospheric models like the GTIM group, DCMP, and the more established planetary formation models. Current limitations in data gathering techniques, both in-situ and remote sensing drive instrument development. In order to begin seeking out habitability beyond our near system, it is necessary to build and exapand upon our existing infrastructure. It is with this goal in mind that by examing current technology the community will be able to develop new technology plans.

THE DIVERSITY OF ROCKY BODIES FROM WHITE DWARF POLLUTION. W. Feng[1] and S. Desch[2], [1]School of Earth and Space Exploration, Arizona State University, P.O. Box 871404, Tempe, AZ 85287-1404 (wanda.feng@asu.edu; steve.desch@asu.edu)

Introduction: As white dwarfs (WDs) cool below approximately 30,000 K, heavy elements are no longer radiatively accelerated in their atmospheres, and must therefore gravitationally settle [1]. However, approximately 30% of cool WDs are observed with metallic absorption lines such as O, Si, Mg, Fe, and Ca [2]. The prevailing hypothesis for this heavy element "pollution" invokes the accretion of rocky bodies that are tidally disrupted to form circumstellar disks [3]. Insight to the chemical diversity of extrasolar rocky bodies may be gained by observing heavy elements in WD atmospheres.

The disk accretion scenario is key to understanding the accreted rocky bodies. A disk of solid particles forms when a rocky body falls within the WD Roche radius and particles are subsequently transported inward by Poynting-Robertson drag [4-5]. At high temperatures close to the WD, solid particles sublimate to gas that accretes onto the WD and viscously spreads outward. Current models can explain the accretion rates derived from observations if the gas viscously spreads at rates consistent with partially suppressed magnetorotational instability (MRI) [5]. However, disk chemistry and dust-to-gas mixing for various sources of ionization are not considered in this assumption. We present ionization fractions for thermal and non-thermal processes to assess the extent of MRI in WD disks.

Disk Conditions: The presence of water in WD disks has been inferred from observed oxygen excess after converting elemental abundances to their oxide forms [6]. By assessing disk chemical compositions inferred from spectra [6-7], we assume that WD disks are comprised of 10 wt% water. Considering the sublimation temperature of water ice, 130 K [8], with the blackbody definition of disk temperature, it is evident that pure water ice would sublimate before the rocky body falls within the Roche radius. If water instead takes the form of phyllosilicates like serpentine, which dehydrates at 900 K [9], then water vapor may be present in WD disks.

Disk Ionization State: For MRI to operate, WD disks must be at least partially ionized to dynamically couple the gas to magnetic fields. Critical ionization is the electron fraction below which Ohmic dissipation will suppress MRI and the disk viscosity parameter, $\alpha = 0$.

WDs emit strongly in the UV, which can ionize water molecules. The ionization fraction due to UV can be derived by balancing the number of absorptions and recombinations per volume per time. We calculate the column densities at which the UV ionization fraction becomes critical. For context, one of the most heavily polluted WDs has a total column density 10^22 cm^−2[10]. By taking a mass-weighted average where the top ionized layer may have up to $\alpha = 0.1$ (typical of compact disks) and everything below has $\alpha = 0$, we estimate α if UV were the dominant ionization source in WD disks.

X-rays have been shown to ionize protoplanetary disks [11]. WD X-ray luminosities are significantly lower than young stellar objects, however we calculate the ionization fraction due to X-rays and show that this effect is non-negligible. As with UV ionization, we calculate the column densities at which the X-ray ionization fraction becomes critical and estimate the disk α.

The inner edges of protoplanetary disks are thought to sustain thermal ionizations where the temperature is high enough to ionize gas-phase alkali metals like potassium [12-13]. [14] show that high-temperature ionization depends on the work function of solid grains rather than the ionization potential of alkali atoms. We calculate the temperature at which the electron density by high-temperature ionization becomes critical.

Results and Conclusions: The disk viscosity parameter α for UV, X-ray, and high-temperature ionization of WD disks are 10^−9 , 10^−2 , and 0.1 at temperatures greater than 700 K. These results differ dramatically if considering flared disk geometries.

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CHARACTERIZING EARTH ANALOGS IN REFLECTED LIGHT: ATMOSPHERIC RETRIEVAL STUDIES FOR FUTURE SPACE TELESCOPES. Y. K. Feng[1], T. D. Robinson[1], and J. J. Fortney[1], [1]Department of Astronomy and Astrophysics, University of California, Santa Cruz, 1156 High St., Santa Cruz, CA, 95064, USA; kat.feng@ucsc.edu

Introduction: Characterizing exoplanets is key to unlocking questions surrounding planet formation and evolution, and understanding whether processes taking place on Solar System worlds are common. Current methods rely on transits and moderate contrast direct imaging, well-suited for short-period planets and young, self-luminous giant planets, respectively. In spite of technological challenges, the characterization of habitable Earth-like planets may soon be within reach. Results from NASA's *Kepler* mission suggest that one in ten Sun-like stars hosts a terrestrial planet in a one-year orbit [1]. However, given the geometric requirements for a transit to occur, direct imaging is the preferred method to study Earth-like exoplanets.

The coming decades hold enormous potential for the direct imaging of exoplanets, fueled by NASA's upcoming *Wide-Field InfraRed Survey Telescope* (*WFIRST*) mission and the Habitable Exoplanet Imaging (HabEx) and the Large UltraViolet-Optical-InfraRed (LUVOIR) mission concepts. The latter, especially, aim to achieve the high contrasts ($\sim 10^{-10}$) needed to observe Earth-like planets.

Here, we perform the first systematic exploration of the information content in reflected light data from terrestrial planets around Sun-like stars. We use a Bayesian retrieval framework [2,3] to examine the feasibility of detecting key atmospheric species when observing an Earth-like planet with a future high-contrast instrument (e.g., *WFIRST* with a starshade).

A retrieval, or inverse technique, is a powerful data driven way to fully characterize uncertainty distributions for quantities used in a parameterized forward model. In our forward model, we utilize a well-tested albedo code [4–7] to simulate the reflected light spectrum of an Earth-sized planet around a Sun-like star. The species of interest in our model atmosphere include water vapor, ozone, and oxygen. We incorporate Rayleigh scattering due to molecular nitrogen, a wavelength-independent surface albedo, and pressure-dependent molecular opacities. We include one parameterized water cloud layer and fractional cloudiness. We also retrieve for planet radius and surface gravity.

We simulate data for wavelength resolutions (R) of 70 and 140. For each resolution, we examine the retrieval performance at signal-to-noise ratios (SNR) of 5, 10, 15, and 20, using a published high contrast noise model [8]. We also examine the results for data sets similar to *WFIRST* observations, which utilize photometry in the Rayleigh-scattering regime. We discuss future work and improvements, including extensions to super-Earths.

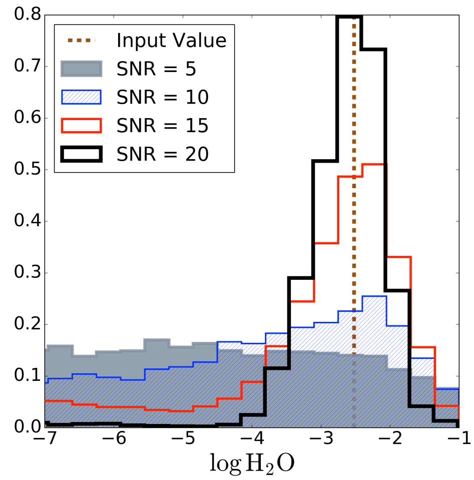

Figure: The posterior distributions of water as retrieved from simulated data sets with wavelength resolution of 70 with increasing SNR.

Results: Having multiple sets of data allows us to consider the trade-offs between R and SNR combinations. The figure above demonstrates the improvement in constraint of the water vapor abundance for a given R as SNR increases. We find that at R = 70, a SNR of 15 is necessary for water vapor, ozone, and oxygen to be measured simultaneously, while at R = 140, a SNR of 10 is needed.

Conclusions: We have created the first retrieval framework to interpret reflected light data from Earth-like planets to prepare for the era of space-based high contrast imaging. This tool demonstrates the capability to constrain molecular abundances for water and ozone in a terrestrial atmosphere and could be utilized to understand the science return of a mission concept given a proposed architecture, thus aiding the planning of upcoming missions in a concrete statistical manner.

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LIMITATIONS OF PRIMARY PRODUCTIVITY ON "AQUA PLANETS": IMPLICATIONS FOR DETECTABILITY

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The habitability of "aqua planets"- planets that are largely or entirely covered by a global ocean- have been a topic of interest in the astrobiology community [1]. Due to the emphasis on the necessity of water for life as we know it [2], such ocean worlds would seem to be strong candidate for harboring detectable biospheres.

However, this characterization may not be accurate. On Earth, the primary source of phosphorus in the oceans is river run-off from surface weathering [3]. In the absence of continental weathering, the predominant source of phosphorus is the submarine weathering of felsic rock [3], and therefore the rate of this weathering is the ultimate control on phosphorus input. Phosphorus is removed from the ocean via sedimentation, water-rock interactions in hydrothermal systems [4], and biological uptake, though for the purposes of our modeling, we focused was primarily on the former two.

To investigate the rate and quantity of phosphorus input to an ocean-covered world, we generated a box model of an Earth with five times as much liquid surface water, and the same amount of continental (felsic) rock. Using the mineral dissolution rate

$$\log R = \log k_{H+} - n_{H+}\mathrm{Ph}\ [5]$$

where R is the log dissolution rate, k_{H+} is the intrinsic rate constant in mol m^{-2} s^{-1} and n_{H+} is the reaction order with respect to H^+. Assuming a pH of 6.7 (based on a higher CO_2 abundance in the absence of carbon drawdown from surface chemical weathering), a log k_{H+} of -4.50, and an n_{H+} of 0.90 (both based on the combined average values for whitlockite, merrillite, chlorapatite, and fluorapatite), the dissolution rate of a prototypical phosphate-bearing mineral is approximately $2.95*10^{-11}$mol P m^{-2} s^{-1}. Based on the surface area of Earth's continental rock, this sets an upper limit of $1.37*10^5$ mol P per year – orders of magnitude lower the 10^{10} mol P per year lost via water-rock interactions in hydrothermal systems[4]. Consequently, in the absence of surface run-off (which accounts for an input flux of phosphorus of $2.2*10^{10}$ mol per year on Earth) [4], the ocean would quickly become phosphorus depleted.

As phosphorus is one of the primary limiting nutrients for primary productivity [3] this could result in a highly oligotrophic biosphere that produces relatively little in the way of relevant biosignature compounds (such as O_2 or methane). While further modeling is needed, these preliminary results suggest it might be difficult or impossible to detect an aqua planet biosphere from Earth at our current level of technology.

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Orbital Dynamics of Planetary Systems with Super-Earths and Mini-Neptunes. E. B. Ford[1,2,3], D. Carrera[1], D. Jontof-Hutter[4], J. J. Lissauer[5], L. A. Rogers[6], and A. Wolfgang[1,2,], [1]Center for Exoplanets & Habitable Worlds, Department of Astronomy & Astrophysics, 525 Davey Laboratory, Pennsylvania State University, University Park, PA, USA, ebf11@psu.edu, [2]Center for Astrostatistics, [3]Institute of CyberScience, [4]Department of Physics, University of the Pacific, 3601 Pacific Avenue, Stockton, CA 95211, USA, djontofhutter@pacific.edu, [5]Space Science and Astrobiology Division, MS 245-3, NASA Ames Research Center, Moffett Field, CA 94035, USA, jack.j.lissauer@nasa.gov, [6]Department of Astronomy and Astrophysics, University of Cicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA, larogers@uchicago.edu.

Introduction: The planet formation process directly determines various properties of planets that impact their habitability. Some of these properties (e.g., size, mass, orbital distance) can be measured with existing techniques. Other properties (e.g., abundance of water, CO_2 and other volatiles, ratio of C and Si, minerology, oxidation state, a liquid core, a strong magnetic field) are extremely difficult to constrain observationally. Therefore, it will typically not be practical to perform a complete assessment of the potential habitability of a planet soley based on observations of that planet alone. Instead, it will be important to incorporate insights gathered from the architecture of the host planetary system, the history of planet formation in that planetary system at hand, and information gathered from exoplanet populations [1,2].

I propose to review the current state of knowledge regarding the orbital dynamics of exoplanetary systems [3], emphasizing the implications for characteristics likely to impact habitability. I will focus on systems with multiple transiting planets discovered by NASA's *Kepler* mission [4], since these include systems with sizes and masses suggesting a rocky composition. For many systems with multiple transiting planets that undergo significant mutual gravitational perturbations, *Kepler* measured transiting timing variations [5] that provide a powerful probe of planet masses, current orbital parameters, dynamical state, and planet formation history [6-11]. I will describe how the present architectures and dynamical states of these systems constrain their formation histories. Next, I will compare these systems with super-Earth and sub-Neptune-size planets to the multiple planet systems identified by radial velocity surveys [12-19] and radial velocity follow-up of stars hosting a transiting planet [20]. There are significant differences in the architectures typical of these sets of planetary systems. Therefore, I describe the current state of knowledge regarding whether the multiple planet systems identified by Kepler are likely to be representative of planetary systems with multiple rocky planets in general.

Finally, I will discuss how the principles of hierarchical Bayesian analysis can be applied to characterize planetary populations [21,22]. I anticipate presenting new results on the mass-radius relationship of small planets and the implications for their bulk compositions. While interesting in their own right, these results will also serve to demonstrate the challenges and potential for a Bayesian framework to guide future inferences about habitability.

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DEFINITION AND CHARACTERIZATION OF THE HABITABLE ZONE. F. Forget[1] , Martin Turbet[1], Franck Selsis[2], Jeremy Leconte[2], [1]Laboratoire de Météorologie Dynamique/IPSL, CNRS, UPMC BP99, Paris, France (forget@lmd.jussieu.fr), [2]Laboratoire d'Astrophysique de Bordeaux, CNRS, Univ. Bordeaux, Pessac, France.

Introduction. While we develop the observation tools that will, someday, characterize planets possibly suitable for life, the concepts of habitability and habitable zone remain challenged. We will review the concept of habitable zone, why it is useful, and how we can agree to define it and characterize it.

Habitable = liquid water available. It is not easy to define life and to specify what is needed for its emergence and evolution. We usually postulate that "habitable=liquid water available" because liquid water seems required for life as we know it, as we can imagine it, and above all, as we think we can recognize it.

Different classes of habitability. Worlds with liquid water can be seen as more or less habitable, depending on 1) the available molecules and energy sources (notably light), 2) the time available for life to emerge and evolve. The exploration of the solar system combined with theoretical studies have revealed that the ice-rich worlds formed beyond the "snow line" should, in a majority of cases, harbor subsurface oceans within their icy mantles. As suggested by Lammer et al. (*AAR*, 2009) and Forget (*IJB*, 2013), 4 classes of habitability can be defined, ranging, from worlds with liquid water enclosed between thick ice layers in the deep interior, to Earth-like cases with liquid water on the surface, enabling possible photosynthesis.

Looking for life on exoplanets using the concept of "habitable zone". The consensus is now to define the "Habitable zone" as the range of orbits on which a planet can sustain liquid water on its surface. That does not mean that worlds in the habitable zone are habitable (the Moon is not), and that planet outside the Habitable zone are not (they can have subsurface liquid water). Originally the habitable zone was naturally defined to represent the conditions that Earth enjoy, at a time when the concept of subsurface oceans was not obvious. Nowadays, focusing on planets with surface liquid water is justified by the idea that astronomers are looking for worlds where photosynthetic life could have affected the environment enough to be detectable remotely. In other words the Habitable zone ("HZ") could be nicknamed the "Hunting Zone" because its primary objective is to help astronomers prepare future observations. This has interesting consequences.

Only one habitable zone per star? Within that context, we could agree to define the "Habitable zone" as the region outside which it is impossible for a rocky planet to maintain liquid water on its surface. One should refrain to use the concept for a specific body (i.e. stating that the Moon is not in the habitable zone because it has no atmosphere). Nevertheless, around a given star, we may use different criterions to define the edges of the habitable zone for different categories of planets (e.g. for CO_2-H_2O atmosphere, for H_2 atmosphere, for tidally-locked planet, etc.). Interestingly, we can show that the inner edge of the HZ is not very sensitive to the composition of the atmosphere (but to planetary rotation and cloud modeling), while the outer edge does not very strongly vary with the assumed cocktail of greenhouse gases (the uncertainties related to cloud are almost higher) except for the particular cases of Hydrogen -rich atmospheres.

The reference work of Kasting et al. (1993) rightly put forward the concept of planetary thermostat (e.g. due to the carbonate-silicate cycle) in the theory of surface habitability, showing that it would be necessary for the Earth to remain habitable if it was moved away from the Sun. This is crucial, but it should not be involved in the definition of the habitable zone. If the Earth had kept its atmosphere of ~3 to 4 Ga (with sufficient greenhouse gases to compensate the faint young Sun), it would have remained habitable throughout its history. Any planet with a thick greenhouse atmosphere (e.g. with a few bars of CO_2) would maintain surface conditions suitable for liquid water over a wide range of orbits throughout the habitable zone. Based on what we know about other stellar systems and their diversity, it is likely that many terrestrial planets orbiting in the habitable zone of their star may be volatile-rich. The concept of habitable zone must be generalized to volatile-rich planet and ocean planets.

Characterizing the habitable zone with realistic 3D climate models. Around a given star, and assuming a specific type of atmosphere and volatile/water inventory, the possible climates can now be explored using 3D global climate models analogous to the ones designed to simulate the Earth as well as the other terrestrial atmospheres in the solar system. Our experience with Earth, Mars, Titan and Venus suggests that realistic climate simulators can be used, allowing to simulate clouds, 3D transport, cold traps, and ultimately all the key processes controlling planetary climates. Within that context, the key questions are: what atmospheres can we expect? Which processes control their evolution? Our solar system experience is too limited. Observations are needed. Much can be learned by characterizing atmospheres, even outside the habitable zones.

References: So many good recent and not so recent studies should be listed in this 1 page abstract! They will be reviewed and detailed at the conference.

Flexing our MUSCLES: the HST Mega-MUSCLES Treasury Survey. C. S. Froning[1], K. France,[2] R. P. Loyd[2], A. Youngblood[2], A. Brown[2], J. S. Pindea[2], P. C. Schneider[3], and A. Roberge[4]. [1]McDonald Observatory, University of Texas at Austin, Austin, TX, cfroning@astro.as.utexas.edu; [2]University of Colorado at Boulder; Boulder, Co; 3Hamburgder Sternwarte, University of Hamburg, Germany; [4]Goddard Space Flight Center, Greenbelt, MD

Introduction: Understanding what happens to rocky planets and their atmospheres in the habitable zones (HZs) of low mass stars is currently one of the greatest astronomical challenges. The nearest Earth mass planets in the HZ orbit M dwarfs, and these are prime targets for spectroscopic biomarker searches in the next decade. The ultraviolet (UV) stellar spectrum drives atmospheric heating and chemistry on Earth-like planets. At present, we do not have sufficient observations and panchromatic stellar models to accurately predict the UV spectrum of a particular M dwarf. Without the stellar UV spectrum or the means to infer it, we will not be able to interpret observations of the atmospheres of potentially habitable planets in these systems.

MUSCLES: To address this shortfall, we initiated the MUSCLES (Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems) Treasury Survey with HST, Chandra, XMM, and ground-based observatories. With MUSCLES, we measured the spectrally and temporally resolved UV radiation fields of seven M and four K dwarf exoplanet host stars [1,2,3,4,5,6] and obtained new panchromatic observations of these nearby exoplanet hosts to provide a comprehensive picture of their energetic radiation environments. The 5 Å – 5.5μm broadband SEDs were compiled and provided to the astronomical community for observational and modeling inputs. The MUSCLES data products have become key inputs for studies of stellar and exoplanet evolution, habitability, and the production of biomarkers [7,8,9,10].

Looking Ahead: the Mega-MUSCLES Treasury Survey: Building on the success of the MUSCLES survey, we have initiated the Mega-MUSCLES program, an approved HST Cycle 25 large Treasury program. With Mega-MUSCLES, we will expand the sample of panchromatic stellar spectra to include: (a) new M dwarf exoplanet hosts with varying properties; (b) reference M dwarfs below 0.3 solar masses that may be used as proxies for M dwarf planet hosts discovered after HST's lifetime; and (c) more rapidly rotating stars to probe XUV evolution over gigayear timescales. We will gather the first panchromatic SEDs of rocky planet hosts GJ1132 and Trappist-1. The sample is particulary selected to provide the information necessary to interpret observations of rocky planets around M stars that are the likely focus of upcoming TESS and JWST observations. To do so, we must understand the high-energy SED of their host stars: X-ray/EUV irradiation can erode a planet's gaseous envelope and FUV/NUV-driven photochemistry shapes an atmosphere's molecular abundances, including potential biomarkers like O2, O3, and CH4.

In this presentation, we will give an overview of the results of the MUSCLES survey, including: a) determinations of the energetic radiation environment around M star exoplanet hosts; b) measurements of flare activity, energetics, and particle fluxes; c) calculations of habitable zone exoplanet irradiance and atmophotospheric dissociation rates; and d) results of modeling exoplanet atmospheres with these data to trace evolution and habitability effects and predict biomarker signatures. Finally, we will give initial results from the Mega-MUSCLES program and show how the upcoming survey will inform future observations of Earth-like exoplanets around low mass stars.

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WATER VAPOR IN THE UPPER ATMOSPHERES OF SYNCHRONOUSLY ROTATING TEMPERATE TERRESTRIAL EXOPLANETS.

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Background and Aims: H_2O is a key molecule in characterizing atmospheres of temperate terrestrial planets, both as a tracer of habitable conditions and as a clue to the birthplaces and evolutional pathways of the planets. Its spectral signatures may be targeted in the near future transmission spectroscopy using JWST or next-generation ground-based telescopes. Several studies modeling transmission spectra of the Earth (e.g., [1]) found modest signatures of water vapor. Such modest features of water vapor are related to the efficient "cold trap"; water vapor evaporated from the surface is transported upward, but condenses as air rises and cools, and most of it precipitates, leaving the stratosphere—where transmission spectroscopy typically probes—fairly dry. However, the effciency of the cold trap depends on various conditions.

The abundance of water vapor in the upper atmosphere is also closely related to the rate of planetary water loss, which impacts planetary habitability. This motivated the earlier works to study the reponse of upper humidity to the varying irradiation and atmospheric properties (e.g., [2][3]). Most of these investigations were, however, limited to 1D models.

Here we study the effect of irradiation on realistic 3D water vapor structures, using a general circulation model (GCM). We are particularly interested in synchronously rotating planets due to their relevance to transmission spectroscopy, as its primary targets are planets around low-mass stars, which are likely to be synchronously rotating. Indeed, the permanent dayside and nightside of synchronously rotating planets question the validity of 1D models, calling for 3D studies.

Method: We use the ROCKE-3D GCM [4] to obtain 3D atmospheric structures of temperate terrestrial planets with surface water. ROCKE-3D GCM is a generalization of the ModelE2 GCM [5], which has been developed for the Earth at NASA's Goddard Institute for Space Studies. We consider synchronously rotating Earth-size planets wholly covered with ocean, and assume a 1 bar atmosphere composed mainly of N_2, analogous to the Earth. We change the total incident flux with 4 representative stellar spectra ranging from M-type to G-type, and see how the atmospheric structures respond to it. We also simulate transmission spectra based on our GCM outputs.

Results: We observe a more gentle increase of the water vapor mixing ratio in the upper atmosphere in response to increased incident flux than 1D models suggest. This is in qualitative agreement with the climate-stabilizing effect of dayside clouds previously observed in GCMs applied to synchronously rotating planets (e.g., [8]). However, the water vapor mixing ratio in the upper atmosphere starts to increase while the surface temperature is still moderate. This is explained by the large-scale circulation in the upper atmosphere, which is seen in the runs with high incident flux, causing efficient vertical transport of water vapor. This circulation is driven by the radiative heating due to absorption by water vapor and cloud particles in the upper atmosphere. Consistently, the water vapor mixing ratio in the upper atmosphere is found to be well correlated with the near-infrared portion of the incident flux, regardless of the stellar spectral type [6] (Fig. 1).

We also show that for the highly irradiated planets the H_2O signatures may be strengthened by a factor of a few or larger, compared with the standard model assuming an Earth-like atmospheric profile [6]. The larger features would considerably loosen the observational demands for a H_2O detection.

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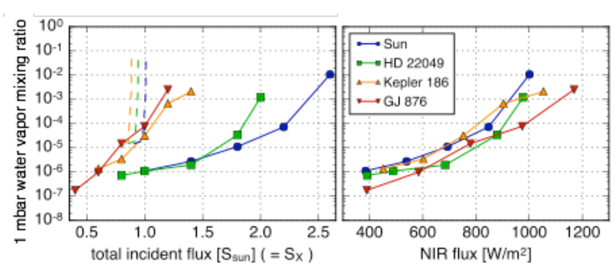
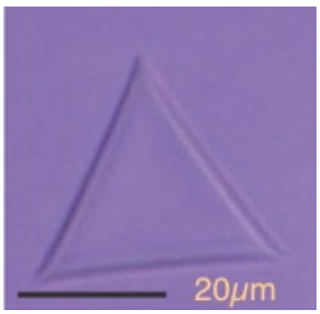


Fig 1.—Water vapor mixing ratio at 1.39 mbar as a function of total incident flux (left) and the near-infrared portion of the incident flux integrated between 0.9 and 3.0 μm (right) [6]. Dashed lines are adapted from the 1D model of [8] for varying stellar effective temperatures: 5800 K (navy), 4800 K (green), and 3800 K (orange).

HABITATS FOR SHAPED DROPLETS IN THE ORIGIN OF LIFE. R. Gordon[1], M.M. Hanczyc[2], S.K. Smoukov[3], [1]Embryogenesis Center, Gulf Specimen Aquarium & Marine Laboratory, 222 Clark Drive Panacea, FL 32346 USA and C.S. Mott Center for Human Growth & Development, Department of Obstetrics & Gynecology. Wayne State University, 275 E. Hancock Detroit MI 48201 USA, DickGordonCan@gmail.com, [2]Laboratory for Artificial Biology, Centre for Integrative Biology (CIBIO), University of Trento, Via Sommarive, 9 I-38123 Povo (TN) Italy and Chemical and Biological Engineering, University of New Mexico, USA, martin.hanczyc@unitn.it, [3]Active and Intelligent Materials Laboratory, Department of Materials Science & Metallurgy, University of Cambridge Cambridge CB3 0FS, UK, sks46@cam.ac.uk.



Introduction: If an alkane oil droplet suspended in water is cooled slowly in the presence of a surfactant it takes on a flat, polygonal shape, such as the triangle shown here ([1], with permission of Nature Publishing Group). We have hypothesized that these hoop compression tensegrity structures are the original protocells [2] rather than water containing membrane bound vesicles [3, 4]. Selectable traits or processes could have transformed shaped droplets into a replicating system. For example, the sharp plastic phase edges may provide sites for polymer localization and polymerization, and a short day/night cycle [5] might lock in structural gains, producing precursors of cytoskeleton, RNA and DNA. Confined linear cytoskeletal polymers kink producing planar polygons [6], and we can imagine a positive feedback with shaped droplet protocells. Water-oil-water emulsions [7] may have led to membrane-enclosed cells and eventually flat polygonal Archaea and Bacteria [2, 8, 9].

The Shaped Droplet Lipid World: The presence of hydrophobic organic molecules suggests a "lipid world" origin of life [10], supported by the proteomics extrapolation of "a highly hydrophobic (oily) last common ancestor" [11] and the life-like behavior of oil droplets [12]. The interstellar medium contains organics including aliphatic hydrocarbons, cyanide derivatives of paraffin, and fullerenes [13]. UV irradiation of interstellar ice analogs produced not only various organic molecules [14, 15], but also structures resembling oil droplets and vesicles [16]. Certain carbonaceous chondrite meteorites contain an organic crust with oily substances including aliphatic and aromatic hydrocarbons that form oil droplets in water [17, 18]. Lightning in the atmosphere of early Earth or exoplanets could have been a source for organic molecules [19, 20], yielding tar and oil phases [21, 22]. The ocean floor, via serpentinization and Fischer-Tropsch type synthesis, can produce short and medium chain alkanes [23, 24], which could form oil droplets, though their buoyancy [25] might bring them to surface waters. Hydrocarbons, especially alkanes, could thus become available on planets and form oil droplets in water. The addition of polar moieties in the synthesis of such organics could have produced a variety of surfactants [26]. A mixture of oily organic compounds and liquid water can produce shaped oil droplets [27]. We extend this argument to extraterrestrial habitats and note that for oil droplets to form, the simplest conditions would be the presence of liquid water and organics including surfactants. Past or present liquid water is indicated on Mars, Venus, Europa, Enceladus, Ganymede and Ceres, and perhaps soon exoplanets.

Conclusion: Shaped droplet protocells constrain habitats for the origin of life to those where oil/water emulsions can form, remain, concentrate and undergo temperature cycling.

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ORIGINS AND DELIVERY OF VOLATILE ELEMENTS IN TERRESTRIAL PLANETS: INSIGHT FROM THE COMPOSITION AND FUNCTIONAL CHEMISTRY OF ORGANIC MATTER IN METEORITES. P. Haenecour[1], T. J. Zega[1,2], J. Y. Howe[3], M. Bose[4] and P. Wallace[1]. [1]Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ, USA. [2]Dept. of Materials Science and Engineering The University of Arizona, Tucson, AZ, USA. [3]Hitachi High-Technologies America Inc., Clarksburg, USA. [4]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA. (pierre@lpl.arizona.edu).

Introduction: It is believed that chondrites were a major sources of volatiles for terrestrial planets, including the Earth. The volatile component consist of water and organics. Chondrites can contain up to 6 wt% C, much of which occurs in the insoluble organic matter (IOM) fraction [1]. Meteoritic IOM often exhibits isotopic anomalies in N and/or H. However, the elemental composition and functional chemistry of the organic carriers of these isotopic anomalies is still poorly constrained. Here, we report electron energy-loss spectrometry (EELS) analyses of D-rich carbon nanoglobules identified in the meteorite CM2.6 Queen Alexandra Range (QUE) 97990 meteorite.

Experimental Methods: D-rich hotspots were identified by NanoSIMS 50L raster ion imaging of ^{1}H, ^{2}H, ^{12}C and ^{16}O isotopes in multicollection mode of matrix areas in a thin-section of QUE 97990. We then selected several hotspots for further characterization with transmission electron microscopy (TEM). We extracted three hotspots located in two NanoSIMS images (3Aa1 and 3Aa11) using the Helios Focused-Ion Beam SEM at the University of Arizona (UA). Subsequently, the FIB section was analyzed using the newly installed 60-200 keV Hitachi HF5000 TEM/STEM at UA. All our STEM/TEM data were acquired at 60 kV to avoid sample damage.

Results and Discussion: QUE 97990 is one of the least altered CM chondrites [2] and it is more D-rich than most CMs (bulk δD of IOM residue = 1218 ± 5 ‰) [3]. We identified numerous D-rich hotspots (D/H ratio up to 6.25×10^{-4}) in fine-grained matrix areas of QUE 97990. The three hotspots extracted for TEM study have D/H ratios between 4.04 – 6.25×10^{-4}. TEM images of the cross-section of these hotspots show that one is filled with an aggregate of nanoglobule-like objects, possibly hollow, that are surrounded and intimely associated with fine-grained fibrous silicates. The two other hotspots do not show any C-rich material but show the presence of phyllosilicates, suggesting that these phyllosilicates are the carriers of these D enrichments. We obtained detailed EELS spectal imaging of two carbon nanogubles adjacent to a hotspot and their energy-loss near-edge structure (ELNES) for C, K are consistent with the presence of aromatic functional groups (sharp rise from edge onset to a peak at 285 eV, the π* peak). Our observation of aqueous alteration in the area of the hotspot associated with the D-rich isotopic and aromatic C compositions of the IOM is inconsistent with a previous observation of a decrease in the fraction of aromatic nanoglobules with increasing degree of aqueous alteration [4]. The spectrum also indicates the presence of S, N, and O in these nanoglobules but they are heterogeneously distributed (Fig.1); e.g., area #1 does not contain detectable amount of S and has significantly less N. The N/C and O/C elemental ratios of these two hotspots are similar to nanoglobules in other CM chondrites [5], but significantly higher than the N/C ratios of bulk IOM residues (typically lower than 0.05 [1]). EELS analysis of additional hotspots within QUE 97990 and other CM and CR chondrites, which we plan to do prior to the meeting, will better constrain the carriers and distribution of volatiles in meteoritic organics; thus allowing us to better understand the delivery of volatile elements to terrestrial planets.

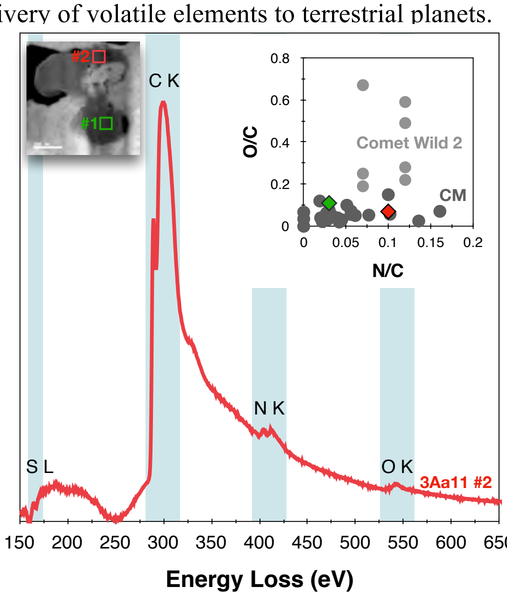

Fig. 1. EELS spectrum of an small area in the C nanoglobule adjacent to hotspot 3Aa11. Comparison (inset) with other nanoglubes in CM chondrites [5] and organics from Comet Wild 2 samples [6].

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Origin of Life: Pathways of the 20 Standard Amino Acids of the Genetic Code**

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There was no life in the prebiotic world, but only nine out of the 20 standard amino acids, which make up the genetic code existed during the period. However, evolutionary events resulted in a lifeless world giving rise to a world of abundant living organisms. How nature used only four nucleotides to build its proteins and forming the genetic code are intriguing. Three theories have been propounded about the origin of the genetic code, a) the stereochemical theory, which deals with codon assignments as determined by physico-chemical affinity between amino acids and the anticodons, b) the Coevolution theory, which hypothesizes that the code structure coevolved with amino acid biosynthesis pathways, and c) the Adaptive theory, also known as error minimization theory, which is based on natural selection to lessen the detrimental effects of point mutations and translation errors. Our research has two goals, a) to update the biosynthesis pathways of the 20 standard amino acids, and b) to ascertain whether metabolic pathways found in living organisms can serve as accurate guides to ancient evolutionary events. We utilized comparative computer platforms such as BLAST and Protein Databank among others in our efforts to uncover relationships of enzymes involved in the biosynthesis pathway. Our results are consistent with previous reports that show some distinctions between the "early" and "late" amino acids of the genetic code. For example, biosynthetic steps in many of the late amino acids are longer than those in the early ones, and longer steps suggest the involvement of many more enzymes. Again, synthesis of some late amino acids is not a "one-way traffic" from early members because some late amino acids can give rise to some early amino acids through well-defined pathways. This finding complicates some of the key assertions of the Co-Evolutionary theory. Example, there is no precursor-product relationship that connects Glycine (Gly), early amino acid and Threonine (Thr), late amino acid. In other words, Thr cannot be synthesized from Gly and *vice-versa*. Nevertheless, our results show new pathways that facilitate the biosynthesis of Thr from Gly and/or *vice-versa*. Several other such examples exist in our new updated pathways with respect to early versus late amino acids.

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NONSTATIONARY MASS LOSS OF DISINTEGRATING EXOPLANETS

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Introduction: Recent observations of several short period exoplanets found highly variable transit depths and asymmetric transit profiles indicative of large, comet-like tails trailing behind transiting exoplanets [1,2,3,4]. Theoretical constraints imply these disintegrating planets are small, somewhere between lunar and earth mass, yet are losing mass at rates of roughly an earth mass per gigayear [5]. The large clouds of gas and dust that are ejected from these planets provide a unique opportunity to observe planetary material in vapor form, which is pivotal to our understanding of the formation and composition of low mass, potentially habitable, planets.

The use of broadband spectroscopy has yet to reveal any measurable difference in transit depth, which implies the particles leaving these planets are roughly micron sized grains of unknown composition [3,6,7]. With JWST, infrared mineral spectroscopy of these systems can be carried out that will constrain the mineralogy of these grains, but to link the mineralogy to a given surface composition requires a model that couples atmospheric dynamics with mineral condensation of gas into dust.

To this end, we propose a non-stationary atmospheric mass loss model based on supersaturation and subsequent formation of "rock clouds". We show exactly why stationary hydrothermal escape is not to be expected for these low mass planets and necessitates a non-stationary model. The result is an atmospheric escape model that explains the chaotic dynamics of disintegrating planets (shown in Figure 1) and can readily be coupled to mineral condensation codes.

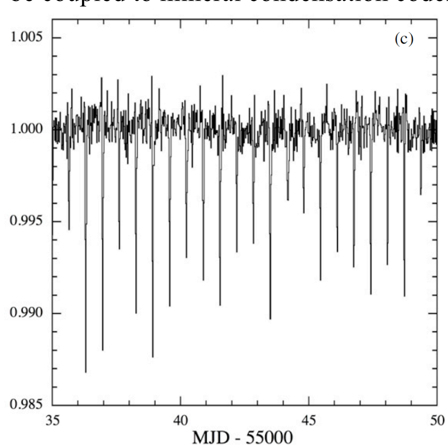

Figure 1 – Transit photometry of disintegrating planetary system KIC-1255 demonstrating the variable nature of atmospheric mass loss. Figure adopted from [1].

Background: Disintegrating planets are found on periods of roughly one day, which implies effective temperatures hot enough to vaporize rock. Due to their low mass, a high thermal pressure gradient dominates over gravity and drives bulk hydrothermal escape of the planet's atmosphere. If this process is stationary, it is known as a Parker Wind, named after Eugene Parker's 1958 model of the solar wind [8]. Since the original Parker Wind model, many non-stationary models have been put forth to describe hydrothermal expansion in stellar atmospheres [9] but few non-stationary models exist to describe hydrothermal expansion in planetary atmospheres. While in some cases non-stationary sophistications are not necessary (e.g. [10]), the highly variable transit depth of disintegrating planets implies such sophistications are absolutely essential to a working theory. In addition, the observed micron sized grains provide evidence that condensation is an important non-stationary process yet to be considered.

Theory: The parameter regime over which the Parker Wind solution is valid encompasses almost all stars due to their high temperature and low mean molecular weight atmospheres. When applied to disintegrating planets, however, the rock vapor atmosphere is much heavier and much cooler than stars, and a Parker Wind solution is extremely fine tuned (such that a given temperature corresponds to a single mean molecular weight and vise versa).

Our non-stationary model is based on a feedback process between the production of solids in a planet's atmosphere and the optical depth of the atmosphere. As the surface vaporizes, the pressure of the constituent elements increases faster than the timescale for dynamic escape causing condensation, superstation, and the semi-stochastic formation of rock clouds. These clouds, in turn, slow the rate of surface vaporization and absorb stellar energy resulting in their ejection.

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DEMARCATING CIRCULATION REGIMES OF SYNCHRONOUSLY ROTATING HABITABLE PLANETS.
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Summary: M-dwarf stars provide an abundance of environments for potentially hosting habitable planets. The discoveries of Proxima Centauri b around our closest stellar neighbor [1] and the seven planets of the TRAPPIST-1 system [2] indicate that M-dwarfs can harbor terrestrial plants within their liquid water habitable zones [3, 4, 5, 6, 7, 8], which makes them likely targets for upcoming surveys with JWST and TESS. Due to the small size of their host stars, and their short period orbits, habitable planets around M-dwarf stars are the easiest to detect and to characterize their atmospheres.

Speculation that planets in orbit around low-mass stars would be prone to synchronous rotation—so that one side experiences permanent day, while the other experiences permanent night—initially led toward concern that such planets would be prone to freeze out their atmospheres and thus might not be habitable at all [9]. But subsequent investigation with simplified climate models [10] and general circulation models (GCM's) [7, 8, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25] have demonstrated that energy transport from the day to night hemisphere is sufficient to avoid atmospheric collapse across a wide range of atmospheric compositions and rotation rates.

Here we use the Community Atmosphere Model (CAM) to investigate the atmospheric dynamics of terrestrial planets in synchronous rotation around low-mass stars. We show that the temperature contrast between the day and night hemispheres decreases with an increase in incident stellar flux, with little dependence upon stellar spectral type and no dependence upon rotation rate. This trend is opposite that seen on gas giants, where the same forcing shows a *decrease* in the day-night temperature contrast instead.

We define three dynamical regimes in terms of the equatorial Rossby deformation radius and the Rhines length [26]. The slow rotation regime is characterized by the deformation radius exceeding planetary radius, which should occur for planets around stars with effective temperatures of 3700 K to 4500 K. The rapid rotation regime is defined by a deformation radius being less than planetary radius, which occurs for planets orbiting stars with effective temperatures of less than 3000 K. In between these two limits is the Rhines rotation regime with planetary-scale turbulent flow, which occurs for planets around stars with effective temperatures of 3000 K to 3300 K. The dynamical state can be inferred from astronomical observations of orbital period, spectral type of the host star, and the day-night temperature contrast. These dynamical regimes all respond differently to increases in stellar forcing, which also suggests different responses of these atmospheres to the main sequence brightening of their host star.

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Oxygen False Positives in Terrestrial Planetary Atmospheres: An Update from the Front Lines.
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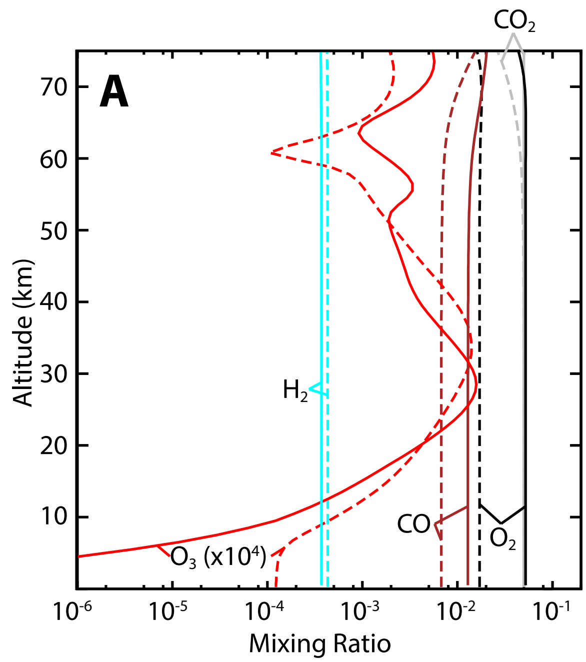
Introduction: Life has substantially and irrevocably altered the chemical composition of Earth's atmosphere and surface. Chief among these changes has been the rise of oxygen (O_2) and ozone (O_3), byproducts of oxygenic photosynthesis coupled with organic carbon burial. O_2 (and by extension, O_3) are often regarded as one part of the gold standard for life detection (O_2/O_3 + H_2O + CO_2) [1]. However, work within the last five years has highlighted a number of scenarios in which photochemically-derived O_2 can accumulate to detectable concentrations in a planet's atmosphere. This includes planets with oxidizing atmospheres [2], planets orbiting an M star during its main sequence lifetime [3] and in its pre-main sequence lifetime [4], and planets with low non-condensable inventories [5]. Some of these scenarios have been the subject of follow-up work [6,7,8], as well as an ongoing model intercomparison. Here, we present some of the preliminary work between the Harman et al. [7] model and the `Atmos` model [9] for terrestrial planets orbiting M dwarf host stars.

Results: As seen in the included figure, with identical bulk composition and boundary conditions, the two models reproduce the same qualitative behavior. Differences in the chemical network and secondary model features drive the bulk of the discrepancies. The amount of free O_2 present in both model atmospheres constitutes a false positive [7]. As before, the assumptions buried in the selection of boundary conditions and the remaining questions regarding the ultimate fate of dissolved CO and O_2 in seawater [7] constitute the largest stumbling blocks in resolving this type of false positive, beyond distinguishing it from a biological signal [8]. However, as we will describe, there are other aspects of what constitutes a 'terrestrial' planet that call into question how robust this false positive is.

Figure caption: Comparison of major atmospheric constituents between the Harman et al. [7] model (solid curves) and `Atmos` (dashed). This case is for a terrestrial planet with a 5% CO_2 atmosphere orbiting at 1.3 AU equivalent around GJ 876 with 'worst case' scenario boundary conditions, following Fig. 5 of Harman et al. [7].



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What are the Signs of Life on Anoxic Worlds? H. E. Hartnett[1]. [1]School of Earth and Space Exploration and School of Molecular Sciences, Arizona State University, Box 876004, Tempe AZ 85287-6004. Email: h.hartnett@asu.edu

Although Earth today has an O_2-rich atmosphere, we know that was not always the case. For nearly 2 billion years of its history, life on Earth inhabited a very different world – an anoxic world – with chemistry and ecosystems very different from those with which we are familiar today. The early Earth was probably not unique. Anoxic worlds are common in our own Solar System and are likely to be common for exoplanets as well. The goal of this presentation is to consider what we need to know in order to recognize and detect the signs of life on **anoxic worlds** that are dominated by **anoxygenic photosynthesis**.

To search for life beyond Earth it is critical that we determine diagnostic biosignatures for anoxic metabolisms and devise strategies to search for them in diverse settings. In particular, understanding photosynthetic life on anoxic worlds is key for exploring exoplanets because ecosystems that can use light-energy from their stars are the most likely to generate high biomass or high metabolic rates. The evolution of oxygenic photosynthesis permanently changed Earth's atmosphere but O_2 did not dominate the biosphere until about 2.4 Ga [1]. The earliest photosynthetic life on Earth was anoxygenic; it did not evolve O_2 or use H_2O as an electron donor [2]. Modern anoxygenic photoautotrophs use H_2S as an electron donor (and potentially also H_2, NO_2^-, and Fe^{2+}) and generate elemental sulfur as byproduct, but we have not yet established clear, well-developed, biosignatures for this metabolism.

There are potentially many habitable anoxic worlds beyond Earth. In our Solar System, Mars's surface may have been habitable for <1 Ga [3-4]. In that short window, life could have had time to evolve anoxygenic photosynthesis, but probably not oxygenic photosynthesis. If the ocean worlds of Europa and Enceladus are inhabited, life will likely be dominated by chemoautotrophs using energy from reduced inorganic compounds instead of light. Although, there is the intriguing possibility of anoxygenic photosynthesis based on thermal IR, which has been observed at a deep-sea hydrothermal vent on Earth [5]. Finally, life on exoplanets is most likely to be detected if it is photosynthetic, because such biospheres are near the surface and have the potential to be large. However, if Earth's history is typical, we will encounter many inhabited exoplanets dominated by anoxygenic photosynthesis, as well as many on which the rate of O_2 production is insufficient to overwhelm geologic sinks for O_2.

In each case, we need to develop a knowledgebase that allows us to recognize the signs of life on anoxic worlds. In what ways are such worlds fundamentally different from the world we inhabit today? How long do habitable planets remain anoxic? How can we optimize our search for biosignatures to reflect the biology, biogeochemistry, and sedimentology of anoxic worlds? And importantly, how are such biosignatures degraded and preserved under anoxic conditions.

Achieving the astrobiology goals of understanding the *co-evolution of life and the physical environment*, and *identifying, exploring and characterizing environments for habitability and biosignatures* thus requires a better understanding of anoxic systems. Interdisciplinary investigation Earth's anoxic ecosystems (e.g., stratified lakes, deep sediments, high-temperatures systems) can reveal information about how these environments shape the evolution and complexity of anoxic life and record that story in the geologic and biomolecular materials that anoxygenic life produces.

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THE EFFECT OF NEW COLLISION-INDUCED ABSORPTION COEFFICIENTS ON THE EARLY MARS LIMIT CYCLE HYPOTHESIS.

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Introduction: The warming early Mars problem has been a subject of debate for decades. A consensus has yet to be reached regarding the warming mechanisms that allowed for fluvial feature formation to occur. One school of thought suggests early Mars was warmed by a thick greenhouse atmosphere, while others suggest that early Mars was cold but warmed occasionally by impacts or by episodes of enhanced volcanism. However, these latter hypotheses struggle to produce the amount of rainfall needed to form the martian valleys.

Recently, a new warming mechanism has been proposed for early Mars to levels that could sustain liquid water long enough to produce fluvial features. Using an energy balance climate model (EBM), it has been shown that Mars should oscillate between globally glaciated states and shorter periods of warmth [1]. The existence of these limit cycles forgo the necessity for Mars to exist in a warm steady-state in order to produce the observed fluvial features.

Limit Cycling and the Habitable Zone: The role of the carbon-silicate cycle on long term habitability is a concept that has been studied and extensively modeled. Put simply, as planetary temperatures decrease, so does silicate weathering. This causes a negative-feedback, allowing the atmosphere to accumulate CO_2 which rewarms the planet. This in turn increases silicate weathering, again cooling the planet. The feedback-mechanism suggests that planets with relatively low solar flux and/or volcanic outgassing rates cycle between prolonged periods of glaciation, and shorter warm climatic periods [1]. The model used explored these cycling conditions near the outer edge of the conventional liquid-water habitable zone and found that warm periods on the order of 10 Myr could have existed on early Mars, which could perhaps have allowed sufficient time for fluvial feature formation [1,2].

Collision-Induced Absorption:

In previous model runs using the EBM it was found that CO_2 by itself is not able to completely deglaciate early Mars, so substantial amounts of H_2 and/or CH_4 outgassed into the atmosphere were used to increase the greenhouse effect [3]. However, the concentrations required of CO_2, H_2, and CH_4 to produce an effective greenhouse effect to undergo limit cycling are higher than many workers think are reasonable for an early martian atmosphere.

Calculations for collision-induced absorption spectra for CO_2-H_2 have shown that the greenhouse effect is further amplified by this interaction, allowing for lower greenhouse gas concentrations to be used. Recently, updated absorption coefficients for CO_2-H_2 have been calculated, suggesting an even stronger greenhouse effect [4]. Testing these new coefficients with the EBM and 1-D climate model may yield sufficient conditions for limit cycling to occur, but with lower concentrations of CO_2 and H_2. Furthermore, new calculations for collision-induced absorption coefficients between CO_2-CH_4 suggest even more greenhouse warming, reducing the concentrations necessary even further [4].

Limit cycling offers a plausible solution to the warming early Mars paradox. It allows for liquid water to persist for long enough periods of time to create fluvial features. By improving the limit cycling model with the new collision-induced absorption coefficients, the greenhouse concentrations can be lowered to more plausible levels.

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POTENTIAL HABITABLE ZONE EXOMOON CANDIDATES AND RADIAL VELOCITY ESTIMATES FOR GIANT KEPLER HZ CANDIDATES.

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Abstract: The NASA Kepler mission has discovered thousands of new planetary candidates, many of which have been confirmed through follow-up observations. A primary goal of the mission is to determine the occurrence rate of terrestrial-size planets within the Habitable Zone (HZ) of their host stars.

A major product of the HZWG is a list of HZ exoplanet candidates from the Kepler Data Release 24 Q1- Q17 data vetting process [1]. We used a variety of criteria regarding HZ boundaries and planetary sizes to produce complete lists of HZ candidates, including a catalog of 104 candidates within the optimistic HZ. We cross-matched our HZ candidates with the Data Release 25 stellar properties and confirmed planet properties to provide robust stellar parameters and candidate dispositions. We also performed dynamical analysis simulations for multi-planet systems that contain candidates with radii less than two Earth radii as a step toward validation of those systems.

From this list we found 39 planet candidates greater than 3 earth radii residing in the Optimistic Habitable Zone of their host star. While giant planets are not favored in the search for eta Earth, they do indicate a potential for large, potentially rocky moons residing in the habitable zone. These giant planets can also provide a potential for a wider range of "habitable" incident flux due to additional energy sources from tidal energy, etc. Thus we analyzed each giant planet, estimating their mass and then calculating the estimated Radial Velocity Semi Amplitudes of each planet for use in follow up observations. We then calculated the planets Hill radius and determined the maximum angular separation of potential moons.

This presentation will describe the highlights of the HZ catalog giant planets and the plans for further validation of HZ candidates and follow-up studies.

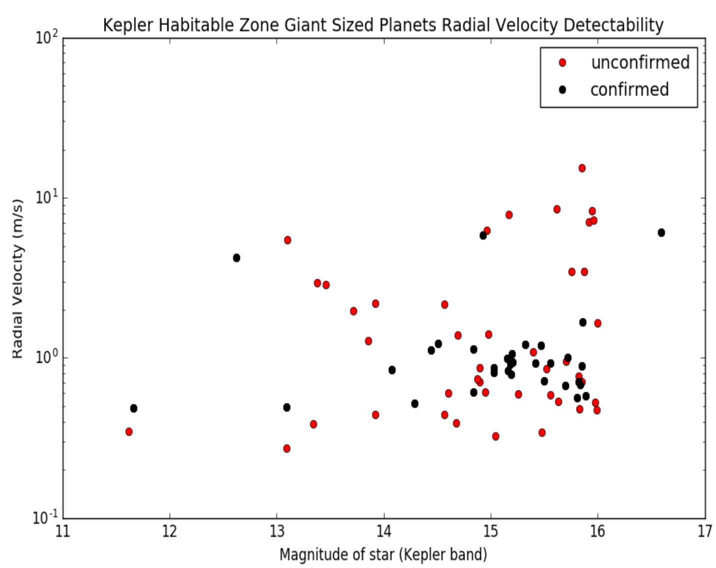

Fig. 1 – Plots both the unconfirmed and confirmed Giant (>3⊕R) Kepler candidates expected Radial Velocity signatures vs the Kepler Magnitude of their host star.

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AVOIDING 'THE BOY WHO CRIED WOLF' IN EXOPLANET HABITABILITY. N. R. Hinkel[1], [1]Department of Physics & Astronomy, Vanderbilt University, Nashville, TN 37235 (natalie.hinkel@gmail.com)

Introduction: The canonical habitable zone is defined as the distance at which a planet must be from the host star such that the surface of an Earth-like planet can support liquid water [1]. To calculate the habitable zone, the only information that is required is the star's effective temperature or luminosity. In other words, while it is required that temperatures be suitable for liquid water, there is no determination, calculation, or measurement as to whether the planet or its suface even has water.

The breakdown of current exoplanet limitations, especially as it relates to language, was well examined in [2]. They argued that the idea of habitability, by definition, restricts all calculations and observations to be with respect to the planet's surface. As a result, 1) equilibrium temperature must act as a (poor) proxy for surface temperature; 2) atmospheric models must be either inferred from whatever parameters (pressure, temperature profile, and gas composition) are available or assumed to be Earth-like; and 3) the planet's surface must be deduced from not-well-constrained mass and radius measurements with respect to know Solar System planets, of which there are no "super-Earths" [3]. None of these restrictions touch on the presence of magnetic fields, impact history, tidal locking, or stellar activity [4] – which is an important condition too often ignored in the quest to find the copious number of exoplanets orbiting cool M-dwarf stars [5].

Stellar Abundances and Planets: In the last few years, it has become a common occurrence to hear that "if you know the star, you know the planet." Obviously, given the above discussion, this is an overly simplified statement. Yet it still remains that criticial stellar properties, namely the elemental abundances, are not being well utilized when characterizing exoplanets and their possible interiors.

Just as important as the other properties, the planet's composition needs to be taken into account when determining habitability. It is only through the presence of certain raw, elemental materials that a planet can be geophysically and geochemically active. Namely, the interior structure and composition must be one that can allow for plate tectonics, mantle convection, the generation of magmas, volcanism, and a variety of other processes that are vital to life as we know it on Earth. Without stellar abundances, the physical properties of a planet are merely columns in a table and our understanding of that planetary system is only half complete.

Conclusion: In this review talk, I will discuss not only the current state of exoplanet "habitability" and the ways in which it falls short, but I will also offer possible solutions or directions to clarify research on planetary systems. Additionally, I will go over the current state of the stellar abundance community, which also requires a overhaul in order to achieve confidence in stellar abundance measurements [6]. However, it is imperative that the chemical relationship between stars and their planets, as informed by planetary formation and disk models, be utilized to model the structure and minerology of planets [7].

It is possible to build a comprehensive view of potential planetary habitability and detectability of life through consideration of both the physical and chemical stellar properties as well as planetary orbital parameters, interior structure, and geology. However, it first requires an open discussion on the limitations and shortcomings within the various sub-fields. Only then will we be able to truly quantify the diversity of exoplanets by combining geology, astronomy, data science, and exoplanetary science in an inclusive and interdisciplinary nature that bridges jargon, "standard methodology," and misconceptions.

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USING STELLAR ABUNDANCES TO PREDICT EXOPLANET HOST STARS. N. R. Hinkel[1], [1]Department of Physics & Astronomy, Vanderbilt University, Nashville, TN 37235 (natalie.hinkel@gmail.com)

Introduction: Since the initial discovery of the "planet-metallicity" relationship for giant planets, as popularized by Fischer & Valenti [1] the iron content within a star, or the [Fe/H] ratio, has been used as a proxy for the overall metallicity of the star. While it has been assumed that the abundances of other important bio-essential elements, such as C, O, Si, and Mg, have been consistent with the Fe-trends in giant planet hosting stars, these results have not been seen despite a variety of studies over the last ~10 years. Additionally, there has not been any detected correlation between stellar abundances and smaller, terrestrial planets.

Despite the huge number of exoplanetary detections from the Kepler mission, the traditional radial velocity and transiting detection techniques only utilize the physical properties of the stellar system. Here we take advantage of the *host's stellar abundances* in order to statistically examine any possible dependence of the occurrence of exoplanets to the chemistry of the star. We used the Hypatia Catalog [2, 3] as a large sample of non-Fe abundances for stars that do and do not have detected exoplanets. We produced a target list of possible planet-hosting stars that have a high probability of hosting a detectable exoplanet.

Hypatia Catalog: The Hypatia Catalog is a database of stellar abundances which includes +65 elements and species within >6000 FGK-stars that are less than 150 pc from the Sun. Hypatia was compiled from over 200 literature sources such that the data were homogenized to the same solar scale. The median value was used during those instances where multiple literature values existed for the same element in the same star. Hypatia currently contains stellar abundances for +300 exoplanet host stars.

Supervised Machine Learning: When comparing non-Fe element ratios in stars with and without planets, the standard method has looked at individual elements between the two groups. However, by employing the award-winning supervised machine learning algorithm *XGBoost* [4], we are able to analyze the elements as an *ensemble* in a way that is very similar to the Netflix movie recommendation algorithm. For example, after watching a number of movies, Netflix is able to assess that you enjoy a particular genre of movies. It then applies this information to the back catalog of movies that you haven't watched and makes recommendations, with listed probabilitoes, that you will like the movie.

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Similarly, our algorithm collects a random subsample of detected exoplanet hosts, based on the NASA Exoplanet Archive[1]. A classifier is then trained on the sample of data where the prediction (whether or not the star has a planet) is known. The classifier is then applied to stars in the Hypatia Catalog not currently known to host exoplents. This process is done for thousands of iterations, calculating the mean probabilities, until our model scores no longer change per iteration. In this way, we were able to produce a metric that determines the probability of an existing exoplanet while averaging out noise inherent to the data.

Conclusion: Our model had a very striking "positive rate," or when it was able to correctly predict the existence of an exoplanet. This means that a high predictive score is an excellent indicator that a star hosts a planet. However, a bad score doesn't necessarily mean that no planet exists, but it isn't as likely. In addition, while we have confirmed that Fe is important to predicting exoplanet hosts, a surprising result has been that C, O, and Na are also statistically influential. Ultimately, we produce a list of stars that have a +90% chance of hosting an exoplanet based on the stellar abundances alone. The success that we have achieved with our model is likely due to the large range in non-Fe element abundances, analyzed within a multitude of different element ensembles.

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[1] exoplanetarchive.ipac.caltech.edu

Atmospheric Growth of the TRAPPIST-1 Planets

Yasunori Hori[1,2], Masahiro Ogihara[3]

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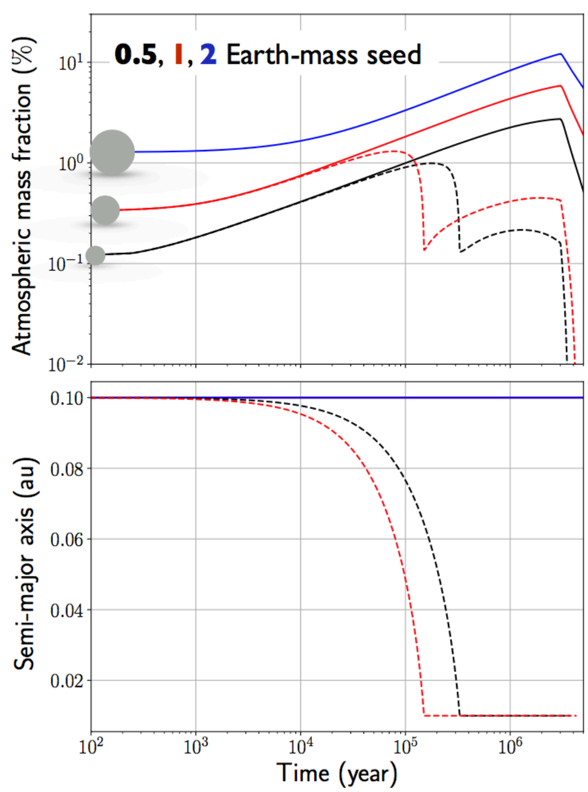
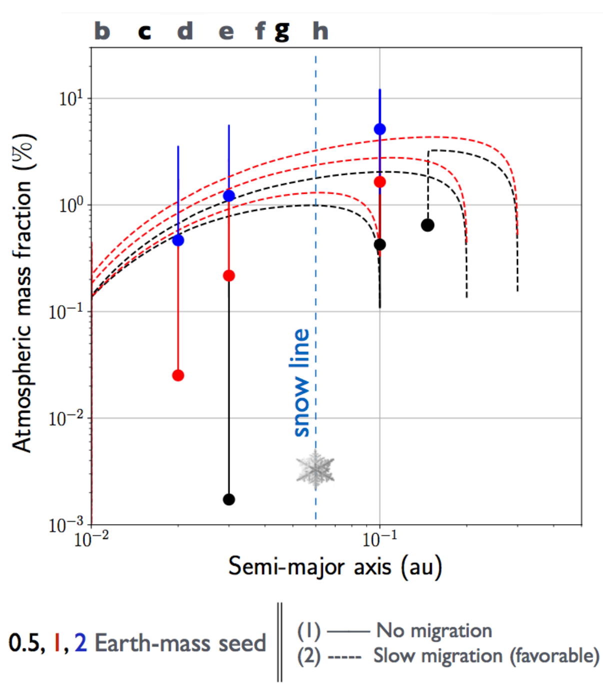
Close-in super-Earths are common among over 3,600 exoplanets. Most of them have low mean-densities, which means the existence of an atmosphere onto a core; if some of them possess hydrogen-rich, namely, primordial atmospheres, their atmospheres likely originated from a disk gas. Two ideas for the origin of short-period low-mass planets with atmospheres have been proposed so far: in-situ formation, including giant impacts, and Type I migration. We simulate gas accretion onto a non-migrating/migrating planet embedded in a dissipating protoplanetary disk around TRAPPIST-1 star and investigate its atmospheric growth. Based on a theoretical relationship between planetary mass and the final atmospheric mass fraction obtained in our study, we discuss whether the TRAPPIST-1 planets can have/retain the primordial atmospheres.





(Left) Time evolution of a planetary seed which was initially located at 0.1au. (Right) The final atmospheric mass fraction v.s semi-major axis

Breakthrough Listen: Searching for Signatures of Technology. H. T. Isaacson[1] and A. P. V. Siemion[2], [1]Univeristy of California, Berkeley. Campbell Hall 50 94720-3411, USA. hisaacson@berkeley.edu (include full mailing address and e-mail address if desired) for first author, [2] University of California, Berkeley. Campbell Hall 50 94720-3411, USA. siemion@berkeley.edu.

Introduction: The Breakthrough Listen Initiative is collecting observations across the electromagnetic spectrum in the search for signals from intelligent civilizations beyond the Earth. Current observations are taking place at the Green Bank Observatory, the Parkes Telescope in Australia and the Automated Planet Finder at Lick Observatory. The primary target list consists of three samples, a 5pc volume complete sample, a sample of stars across the main sequence, and a small set of nearby galaxies. The primary target list will be observed in both the radio in the optical. The volume complete 5pc sample is of special interest because the many M-dwarfs that comprise the sample will be valuable targets in the search for bio-signatures around potentially habitable planets. Determining the probability of habitability for these stellar systems, using space based photometry, and ground based resources will guide the search for signals from extra-terrestrial intelligence. Space based observations of these stars could provide information about the stellar activity cycles, including spot cycles. By including space based X-ray surveys, we can begin to paint a picture of the chances of habitability around our nearest neighbors, and focus our search for extra-terrestrial intelligence. Future observations will include a radio survey of the 1,000,000 nearest stars, as well as survey of the Galactic Plane and the Galactic Bulge. The next few years hold the promise all-sky optical and All-sky radio surveys.

The Origin of Kepler-419B: A Path to Tidal Migration Through Secular Eccentricity Modulation.
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Abstract: While hot Jupiters (periods less than 10 days) are some of the most well-studied exoplanets, warm Jupiters (periods between 10 and 200 days) have often been overlooked. Formation and migration theories postulated so far are unable to reproduce the observed semi-major axis and eccentricity distributions of warm Jupiters. One possible way to remedy this disconnect is for a secularly perturbing companion to excite the eccentricity of the planet high enough to induce tidal migration. Many warm Jupiters are found in multi-planet systems, so if this mechanism is common among these systems, it could be a prolific warm Jupiter creator. While no known systems have yet been shown to undergo this mechanism, Kepler-419, a system with one warm Jupiter and one eccentric outer companion, is an interesting study case. In its current configuration, the outer perturber cannot excite the eccentricity of the warm Jupiter high enough to undergo tidal circularization; however, if there exists a third giant planet in the system, it could periodically boost the secular eccentricity oscillations of the inner planet enough for migration to occur. We explore the parameter space of this potential third giant planet using a suite of 3040 N-body simulations with a range of initial conditions. Preliminary results rule out this mechanism for much of the parameter space of initial conditions. If and when we are able to determine the area of parameter space most likely to boost the eccentricity without destabilizing the system, we will convert the results to a radial velocity signal. This will either rule out the presence of a third body capable of explaining the warm Jupiter's formation or inform future observations of the system, providing a constrained parameter space in which to search for an additional planet.

Constraints on Terrestrial Planet Formation in Close Binaries

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Circumstellar disks in close binary systems ($a < 100$ au) will be truncated by interactions with the stellar companion. Given the small amount of disk material remaining in these systems, planet formation should be inhibited. Despite this challenge, planets have been discovered in close binaries, showing that planet formation is a robust process. In this poster, I present a study on the feasability of the formation of small, rocky planets in close binary systems based on the amount of material available in truncated disks. As more planets are discovered in close binaries, this will set limits on their occurence rates and inform us about the robustness of planet formation overall.

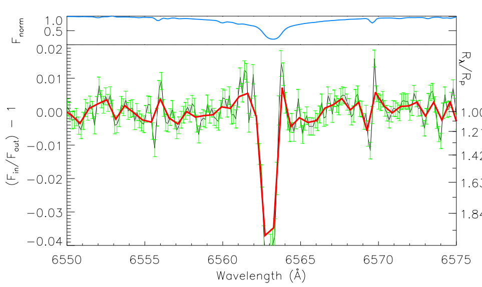
The difficulty of forming Earth analogs J. Jennings[1], B. Ercolano[1,2], G. Rosotti[3], and T. Birnstiel[1] [1]University Observatory, Faculty of Physics, Ludwig-Maximilians-Universitaet Munchen, Scheinerstr. 1, 81679 Munich, Germany, [2]Excellence Cluster Origin and Structure of the Universe, Boltzmannstr. 2, 85748 Garching bei Munchen, Germany, [3]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, UK.

Within the protoplanetary disc, the growth of dust grains to build planetesimals, km-size bodies that may subsequently coalesce into terrestrial planets (and giant planet cores), is known to be theoretically problematic. Throughout this process dust particles encounter a number of barriers that suggest growth is largely inefficient, yet the ubiquity of planets implies these obstacles are commonly overcome. One route to quickly cross multiple hurdles may be the trapping of dust particles in gas pressure maxima within the disc to trigger the streaming instability, which is able to catalyze the aggregation of dust on kyr timescales, bypassing the fragmentation and drift barriers to form planetesimals. However there remains a lack of consensus on the physical mechanism(s) predominantly responsible for initiating this instability. I will discuss one potential method, photoevaporative disc dispersal, wherein the preferential removal of relatively dust-free gas can increase the disc metallicity. Late in the gas disc lifetime, photoevaporation may dominate the disc's evolution and create a steep gradient in the depleted gas surface density where photoevaporative mass loss is concentrated; this induces a local pressure maximum that collects drifting dust particles, which may then be susceptible to the streaming instability. I will summarize our results using a one-dimensional viscous evolution model of a disc subject to internal X-ray and EUV photoevaporation to determine the efficacy of this process in building an Earth mass of planetestimals between 1 – 10 AU. Over a range of parameters for the dust and gas disc evolution and the photoevaporative intensity, we have found that only under quite liberal circumstances can the photoevaporation-induced streaming instability yield sufficient planetesimal concentrations to seed an Earth analog. Our results typically form much less than an Earth mass near 1 AU, and I will thus conclude by summarizing the physical scenarios required to realize planetesimal formation under our models and produce the seeds of terrestrial planets in the habitable zone of a low mass star.

POSSIBLE Hα AND SODIUM D ABSORPTION IN WASP-12B. A. G. Jensen[1], P. W. Cauley[2], S. Redfield[2], W. D. Cochran[3], and M. Endl[3], and, [1] University of Nebraska at Kearney, Department of Physics & Astronomy, 2401 11th Ave, Kearney, NE 68849; JensenAG@unk.edu, [2]Van Vleck Observatory, Astronomy Department, Wesleyan University, 96 Foss Hill Drive, Middletown, CT 06459; pwcauley@wesleyan.edu, sredfield@wesleyan.edu, [3]University of Texas, Department of Astronomy, Austin, TX 78712; wdc@astro.as.utexas.edu, mike@astro.as.utexas.edu.

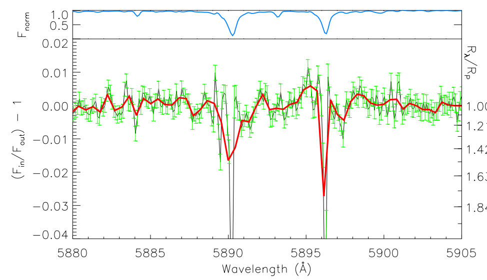
Introduction: Transmission spectroscopy of exoplanetary atmospheres is an extremely useful tool that can be used for understanding exoplanetary composition as well as potentially revealing star-planet interactions from radiation, magnetic fields, and more. The hot Jupiter planet WASP-12b is interesting in that it is very close to its star (0.02 AU) [1], has a large calculated scale height, has had water and metals detected in its atmosphere [2], and has had varying observational and theoretical constraints placed on its C/O ratio [3]. Here we present a preliminary analysis of the optical transmission spectrum of WASP-12b taken with the Hobby-Eberly Telescope (HET). Our data covers the optical wavelength range from approximately 4800 to 6850 Angstroms. Most notably this includes two Balmer lines of hydrogen (Hα at 6563 Å and Hβ 4861 Å) and the sodium D doublet (at 5890 and 5896 Å). Due to the relative faintness of the system's central star and different instrumental settings, the analysis involves several challenges that are not present in previous transmission spectroscopy observations with the HET.

Results: At Hα the transmission spectrum shows a strong feature. Our investigation concludes that this transit-correlated feature cannot be due to a lack of sky or telluric subtraction, or the presence of faint companions to WASP-12 at the edge of the fiber. A Monte Carlo-style analysis indicates that the significance of this result is between 2.5σ and 4σ, depending on our choice of error estimation. The Hα transmission spectrum is shown below.



We also find a marginal detection of sodium D that is consistent with a tentative detection by [4]. The sodium D transmission spectrum is shown below.

The possible presence of Hα absorption is worth additional study, as our previous HET detection of Hα in HD 189733b [5] was confirmed and strengthened by follow-up Keck observations [6, 7]. The presence of significant hydrogen in the n=2 state in hot Jupiters is not well-understood. The only known detections, HD 189733b and WASP-12b, provide an interesting comparison as WASP-12b is closer to its star but WASP-12 is a less active star than HD 189733.



Studying Hα allows us to potentially access hydrogen envelopes in the visible, something that will be necessary when the Hubble Space Telescope's UV capabilities will no longer be available. Furthermore, even though hot Jupiters are not good targets for habitability studies, they are the most likely planets to show exospheric signals that may be relevant to understanding atmospheric loss and evolution, including by star-planet interactions, for other potentially habitable planets such as super-Earths close to M dwarfs.

Acknowledgements: This work was completed with supported by NASA Exoplanet Research Program grant 14-XRP14_2-0090 to the University of Nebraska-Kearney (PI: A.G.J.) and by the National Science Foundation through Astronomy and Astrophysics Research Grant AST-1313268 (PI: S.R.). The Hobby-Eberly Telescope is a joint project at the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universitat Munchen, and Georg-August-Universitat Gottingen and is named in honor of its primary benefactors, William P. Hobby and Robert E. Eberly.

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A new model of the Earth system nitrogen cycle: how plates and life affect the atmosphere

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Introduction: Nitrogen is the main component of Earth's atmosphere. Nitrogen plays a key role in the evolution of the biosphere and surface of Earth [1]. There are contrasting views, however, on how N has evolved on the surface of the Earth over time. Some modeling efforts [e.g., 2] indicate a steady-state level of N in the atmosphere over geologic time, while geochemical [e.g., 3], other proxies [e.g., 4], and more recent models [5] indicate the mass of N in the atmosphere can change dramatically over Earth history. This conundrum, and potential solutions to it, present distinct interpretations of the history of Earth, and teleconnections between the surface and interior of the planet have applications to other terrestrial bodies as well.

To help investigate this conundrum, we have constructed an Earth-system N cycle box model. To our knowledge, this is the most capable model for addressing evolution of the N reservoirs of Earth through time. The model combines biologic and geologic processes, driven by a mantle cooling history, to more fully describe the N cycle through geologic history. In addition to a full biologic N cycle (fixing, nitrification, denitrification), we also dynamically solve for PO4 through time and we have a prescribed O2 history.

Initial model results indicate that the atmosphere of Earth could have experienced major changes in mass over geologic time. High initial atmospheric mass, suggested as a solution to the Faint Young Sun Paradox [1], is drawn down over time, supports work that indicates the mantle has significantly more N than the atmosphere does today [6]. Importantly, the amount of N in the atmosphere today is directly dependent on the total N mass in the silicate Earth. Thus, given some assumptions, the atmosphere itself may be a proxy for total planetary N.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Goldblatt et al. (2009) *Nat. Geosci., 2,* 891-896. [2] Berner, R. (2006) *Geology., 34,* 413-415. [3] Barry, P.H. and Hilton (2016) *Geochem. Persp. Letters, 2,* 148-159. [4] Som, S.M. et al. (2016) *Nat. Geosci., 9,* 448-451. [5] Stueken et al. (2016) *Astrobiology, 16,* in press. [6] Johnson et al. (2015) *Earth Science Reviews, 148,*150-173.

Identifying Potentially Habitable Worlds with Transit Timing.

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Introduction: With current techniques, the most accessible clues to habitability for exoplanets require precise measurements of size, mass and incident flux. These allow simple estimates of bulk density, composition, equilibrium temperature and most crudely, the atmospheric scale height.

Only a small fraction of known exoplanets are small enough to likely be rocky and cool enough to have liquid water [1,2,3] since their transits are shallow and transit likelihood declines with orbital distance. And only a tiny subset of known exoplanets small enough to likely be predominantly rocky and cool enough for liquid water have measurable masses since their gravitational effect on their host stars is too small to cause a detectable radial velocity (RV) signal and most of the hosts are faint or otherwise not good targets for high-precision RV observations.

The few potentially rocky planets that are cool enough for liquid water and have measurable masses are in multi-transiting systems with transit timing variations (TTVs) where planetary orbits deviate slightly but measurably from constant periods due to mutual gravitational perturbations [4,5]. TTVs scale with orbital period [6,7,8] and have enabled mass measurements of rocky planets with orbital periods of days to months [9,10,11], including in the habitable zone of cool stars [12,13].

With TTVs, fully characterizable planets require favorable orbital periods and transiting neighbors in close proximity and/or with favorable orbital period ratios. We will summarize the progress and limitations of using TTVs to characterize potentially habitable exoplanets among known systems using follow-up photometry including from ground-based observatories.

We will further discuss the prospects of using TTVs to detect potentially habitable worlds detected around nearby stars by the upcoming TESS mission [14]. We will highlight in which cases TTV analyses will benefit from additional constraints from RV, particularly for potentially habitable planets around cool, low-mass stars, and where TTV characterizations will complement the RV survey at longer periods around hotter host stars.

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WATER DISTRIBUTION AND ICELINES IN NON-UNIFORM α-DISKS A. Kalyaan[1] and S. J. Desch[2], [1,2]
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Introduction: Icelines, where temperature and pressure conditions in the nebula suit the phase change of water vapor to ice, set the location of planet formation in the disk. Higher sticking coefficients of ice-bearing rocky solids contribute towards higher rates of coagulation and growth of particles beyond the iceline leading to giant planet formation via pebble accretion [1][2]. Also within the iceline, smaller terrestrial planets may be formed similarly after growth of dehydrated solids that drift across the iceline into the warmer inner nebula [3]. Morever, icelines dictate bulk volatile abundances, and therefore set reservoirs of bioessential elements in planets depending on where they formed in the protoplanetary disk.

In order to understand the planet forming potential around icelines, it is important to examine the behavior of radial transport processes that determine the distribution of volatiles across this region. There are chiefly two processes: the inward radial drift of icy particles from the outer nebula, and the outward diffusion of vapor from the inner nebula. Once the ice-laden solids reach the iceline, ice in them sublimates to vapor, which can then diffuse outward. This establishes a cyclical flow of volatiles across the iceline [4][5]. The distribution of water is dependent on the timescales of these various processes as well as other factors such as local disk viscosity that can regulate diffusion, presence of photoevaporation that may remove water vapor from the inner disk, or an accreting proto-planet beyond the iceline that will hinder the inward flow of icy particles [6][7]. This work will focus on the effect of disk turbulent viscosity on the distribution of water in the solar nebula.

Methods: Two types of disk evolution models (described in [8]) are used to examine the effect of turbulence on water distribution across the disk: i) a simple α-disk model, where α is assumed to be uniform at all radii, and ii) a non-uniform α-disk model, where α varies with radius and time, and α(r,t) is derived from magnetorotational instabilities. To these models, we include particle transport based on [9], by adding two slowly drifting populations of solids: small chondrule sized solids that transport water ice, and asteroidal bodies that grow from chondrules in timescales of ~1Myr. Radial drift of chondrules is implemented using the treatment of Takeuchi & Lin (2002)[10] in the Epstein drag regime. (We neglect the presence of fast migrators and migration of asteroids). We also include volatile advection and diffusion using the treatment from Desch et al. (2017)[11]. We track water by assuming five 'fluids': vapor, icy chondrules (composed entirely of water ice), silicate chondrules, 'icy' asteroids (that grow from icy chondrules) and silicate asteroids (that grow from silicate chondrules). Location of condensation-evaporation of water ice is determined from the saturation pressure of water ice at each radius r, estimated from [12] and [13]. Accretional heating is also included, where the uppermost layers of the disk are considered to be active.

Results: We vary the α value across a range of values (0.0003, 0.001, 0.03) with the uniform α model and find that higher α leads to higher ice-gas ratios beyond the iceline, as well as more depletion of water vapor in the inner disk. In the non-uniform α disk (Fig.1), we find that water is concentrated at 0.5-1AU and 10 AU regions in the disk. Disk regions with higher ice/gas ratios likely lead to quicker planet formation and lead to higher water content in planets.

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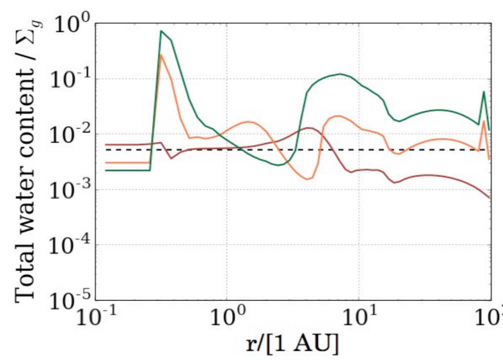
Fig.1: Profiles shows total water content in ice in chondrules and asteroids as well as vapor, to gas, across the disk at times 0, 0.1, 1, 2 Myr (dashed, red, orange, green) [i.e., vapor/gas within the iceline (0.5 AU); ice/gas outside of the iceline.]



A Catalog of Kepler Habitable Zone Exoplanet Candidates.

S. R. Kane, M. L. Hill, J. F. Kasting, R. K. Kopparapu, E. V. Quintana, T. Barclay, N. M. Batalha, W. J. Borucki, D. R. Ciardi, N. Haghighipour, N. R. Hinkel, L. Kaltenegger, F. Selsis, G. Torres

Abstract: The field of exoplanetary science has seen a dramatic improvement in sensitivity to terrestrial planets over recent years. Such discoveries have been a key feature of results from the Kepler mission which utilizes the transit method to determine the size of the planet. These discoveries have resulted in a corresponding interest in the topic of the Habitable Zone (HZ) and the search for potential Earth analogs.

The Habitable Zone Working Group (HZWG) was created to form a core group of Habitable Zone experts to properly vet and characterize the increasing number of Kepler exoplanet candidates whose orbital location and physical size make them prime candidates for habitability. A major product of the HZWG is a list of HZ exoplanet candidates from the Kepler Data Release 24 Q1-Q17 data vetting process. We used a variety of criteria regarding HZ boundaries and planetary sizes to produce complete lists of HZ candidates, including a catalog of 104 candidates within the optimistic HZ and 20 candidates with radii less than two Earth radii within the conservative HZ. We cross-match our HZ candidates with the Data Release 25 stellar properties and confirmed planet properties to provide robust stellar parameters and candidate dispositions. We also performed dynamical analysis simulations for multi-planet systems that contain candidates with radii less than two Earth radii as a step toward validation of those systems. The four different categories of candidates allow the community to adopt the criteria that are most useful for a particular follow-up program.

Our analysis of the radii distributions for candidates in the HZ compared with the general candidate population shows that the two are very similar within the constraints of selection effects and systematic noise that impacts longer-period terrestrial planets (see Figure 1). The implication is that the distribution of planets outside of the HZ is representative of the distribution of planets that exist within the HZ. This presentation will describe the highlights of the HZ catalog and the plans for further validation of HZ candidates and follow-up studies

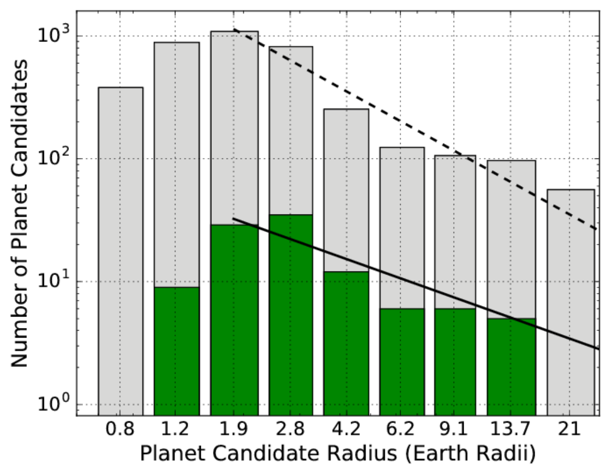


Fig. 1 - Histogram of all Kepler candidate radii (gray) relative to those candidates that are in the optimistic HZ of their host star (green). The solid lines are power law fits to the HZ candidates and the dashed lines are power law fits to the entire Kepler distribution. Statistical analysis of the distributions shows that there is little evidence of a significant difference in the populations.

References:

[1] Kane, S. R., et al. (2016) *ApJ, 830,* 1.

Characterizing Giant Exoplanets through Multiwavelength Transit Observations D. H. Kasper[1], J. L. Cole[1,2], C. N. Cortez[1,3], B. R. Garver[1,4], K. L. Jarka[1,5], A. Kar[1], A. M. McGough[1], D. J. PeQueen[1,6], D. I. Rivera[1,7], H. Jang-Condell[1], H. A. Kobulnicky[1], D. A. Dale[1], [1]University of Wyoming, Department of Physics and Astronomy, 1000 E. University, Dept. 3905, Laramie, WY 82071, dkasper@uwyo.edu, [2]Middle Tennessee State University, Department of Physics and Astronomy, 1301 East Main Street, Murfreesboro, TN 37132, [3]California State University San Bernardino, 5500 University Parkway San Bernardino, CA 92407, [4]Seattle Pacific University, Physics Department, 3307 3rd Ave, Ste. 307, Seattle, WA 98119 [5]Colorado College, Physics Department, 14 East Cache La Poudre Street, Colorado Springs, CO 80903, [6] Embry-Riddle Aeronautical University, Department of Physical Sciences, 600 S. Clyde Morris Blvd, Daytona Beach, FL 32114, [7] San Diego State University, Department of Astronomy, 5500 Campanile Drive. P131, San Diego, CA 92182

The one confirmed habitable world exists in a stellar system with giant planets. Given the significant influence of giant planets in our Solar System's habitability, giant exoplanets are important for stellar system habitability through gravitational effects (e.g. shaping proto-planetary environment, asteroid deflection, hosting habitable moons). Observing the characteristics of giant exoplanets is possible with ground-based telescopes and modern observational methods. We are performing characterizations of multiple giant exoplanets based on 66 continuous nights of transit observations with the 2.3 m Wyoming Infrared Observatory using Sloan filters. In particular, constraints can be made on the atmospheres of our targets from the wavelength (in)dependence in the depth of the transit observations. We present early multiwavelength photometric results on 12 exoplanet targets. The presented targets span a range in previous publication histories from the frequently observed HD 189733 b to the recently discovered KELT-9 b. Results from this ensemble of exoplanets will influence interpretation of potentially habitable exoplanets in the WFIRST, JWST, and TESS missions.

DETERMINING THE BULK WATER ABUNDANCE OF LOW-MASS EXOPLANETS

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Introduction: Measuring the bulk water abundance of exoplanets through remote sensing is a key step on the road toward identifying and characterizing habitable planets. While the terrestrial planets in our Solar System are all relatively dry, 'water-worlds' — planets with bulk water content in the tens of percent — are robustly predicted as an outcome of planet formation (e.g. [1], [2]). Yet tying the water abundance derived from atmospheric observations to a planet's bulk water abundance is not straightforward. Models must be used to relate the water content of the planet's interior to that of its atmosphere. In these models, the partitioning of water into disparate layers of the planet must be carefully accounted for. In this talk, I will describe efforts to build a self-consistent whole-planet modeling framework by coupling together calculations of a planet's interior structure and atmosphere to determine the observable signatures of a planet with a specified water content. We focus here on planets composted of iron, rock, water, and H/He, with atmospheres composed of mixtures of H_2O, H_2, and He. The aim of this work is to have a modeling toolkit at the ready to capitalize on atmospheric observations of water-rich exoplanets and provide the first unambiguous detections of water-worlds with *JWST*, ultimately paving the way toward the characterization of smaller habitable exoplanets.

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EARTHS IN OTHER SOLAR SYSTEMS: FUNDAMENTAL PROTOPLANETARY DISK PROPERTIES AND THEIR EVOLUTION.
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Introduction: Earths in Other Solar Systems (EOS) is a NASA-funded five-year interdisciplinary exoplanet research program aiming at understanding how and where habitable planets form (PI, D. Apai). EOS is also part of the NASA Nexus for Exoplanet System Science. EOS has four main objectives that focus on tracing the evolution of volatiles and organics from star-forming regions into protoplanetary disks, planets, and Solar System bodies like meteorites and comets.

In this contribution, we will give an overview of our EOS Objective 2: *How are volatiles and organics processed in protoplanetary disks?* We will discuss results from our surveys of protoplanetary disks that aim at establishing how fundamental properties such as disk masses, disk lifetimes, and stellar accretion rates change as a function of age, stellar mass, and environments. We will present initial results on the distribution of the main molecular carriers of C, H, and N in disks, and also visit role of photoevaporation on disks. Finally, we will present state-of-the art chemical and physical models of disks that trace the evolution of gas and dust.

Methods: We targeted protoplanetary disks in star-forming regions, from low-mass to rich clusters, of different median ages at optical, infrared, and millimeter wavelengths. Optical spectroscopy was used to homogeneously re-classify stars and measure mass accretion rates while millimeter interferometry yielded disk masses. High-resolution (R~10 km/s) optical and infrared spectroscopy was carried out on a sub-sample of disks to identify bound vs. non-bound material and determine the radial extent of volatiles and organics. Disk models couple the dynamical and chemical evolution of protoplanetary disks with focus on the planet-forming region.

Results: Our optical and millimeter surveys of protoplanetary disks demonstrate that the dust disk mass-stellar mass scaling relation is steeper than linear and further steepens with age (see Figure 1, [1]). Similarly, steep relationships are found between mass accretion rates and stellar masses [2,3]. We are in the process of expanding our Orion submillimeter survey [4,5] to measure dust disk masses at even younger ages for a rich stellar environment. Optical high-resolution spectroscopy identified a new and more direct diagnostic of MHD-driven disk winds and demonstrates that such winds are common in Myr-old disks [6]. We also have tentative evidence for an evolution in disk winds with the possible disappearance of the MHD-driven component as the inner disk clears out. Our high-resolution mid-infrared spectroscopy of a few disks finds that water and other organics trace gas at terrestrial planet forming radii [7]. These observations are critical to properly interpret lower resolution but more sensitive infrared spectroscopy that can be carried out with JWST. Our disk models demonstrate the importance of dynamical effects in setting the location of the water snowline [8]. We will conclude by providing a revised view on habitable planet formation guided by these findings and will discuss how these new observational constraints inform other objectives within EOS.

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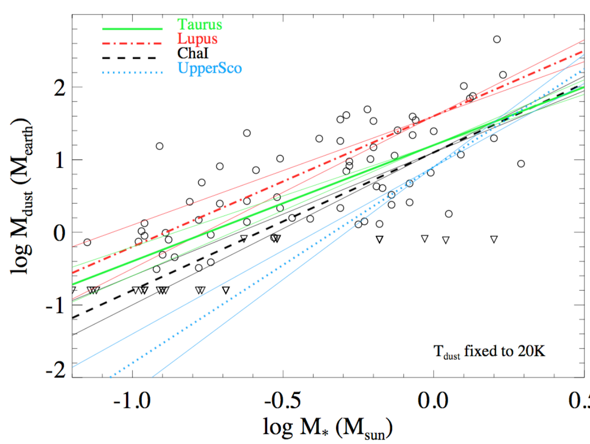

Figure 1: Dust disk mass-stellar mass relation in four different regions, from [1]. Note that the ~10 Myr-old Upper Sco association has a stepper relation than the other three younger star-forming regions.

MINERALOGY OF SILICA-RICH LOWER MANTLE IN ROCKY PLANETS. B. Ko[1], S. Shim[1], V. Prakapenka[2] Y. Meng[2]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ (byeongkw@asu.edu), [2]Advanced Photon Source, lemont, IL.

Introduction: Mantle mineralogy is a key factor for understanding chemical evolution of the mantle for Earth-like rocky planets. Physical and thermal properties of the mantle depend highly on its constituent phases. One common way to describe the mantle mineralogy is to use the ratio of divalent cations (Mg+Fe+Ca) to Si. Depending on the ratio, the lower mantle mineralogy can be explained by a combination of the four major phases: $(Mg,Fe)SiO_3$ bridgmanite (Bm); (Mg,Fe)O ferropericlase (Fp); $CaSiO_3$ calcium silicate perovskite (CaPv); and SiO_2 stishovite (St). For example, in the lower mantle conditions, for (Mg+Fe+Ca) > Si, Fp should form in addition to Bm and CaPv, whereas St would form instead of Fp for (Mg+Fe+Ca) < Si. If (Mg+Fe+Ca) = Si, neither Fp or St would form, but only Bm and CaPv will be stable. In the case of the Earth, pyrollitic composition is known to form Bm+Fp+CaPv in the lower mantle conditions due to the ratio of Mg+Fe+Ca to Si (1.49). However, the mineralogy for various possible mantle compositions for rocky exoplanets has not well explored although the ratio of Mg+Fe+Ca to Si for exoplanets may widely range from <0.9 to >2.0 [1,2]. In this study, we conducted high pressure and temperature experiments at the lower-mantle related conditions to investigate the mineralogy of the silica-rich compositions. Our results of compositions with Mg+Fe+Ca to Si close to 1.0 show that nearly pure Bm was formed without either Fp, St, or CaPv at 65 to 100 GPa and at 2200 to 2450 K, inconsistent with the previous prediction for the deep mantle.

Experimental method: Two compositions of starting material were synthesized as glass by the laser levitation method [3]. The compositions of sample 1 and sample 2 were chosen to have ratios of (Mg+Fe+Ca)/Si = 1.15 and (Mg+Fe+Ca)/Si = 0.94, respectively [4]. The sample was mixed with a gold powder (10 wt%) that served as a pressure standard [5]. The mixture was compressed to be a thin foil (~10 μm thick) which was loaded into a sample chamber in pre-indented Re gasket. Ne or Ar was loaded as a pressure medium and a thermal insulator. Laser-heated diamond anvil cell combined with X-ray diffraction was used at 35, 50, 65, and 100 GPa and 2000 to 2450 K in Advanced Photon Source, in order to synthesize sample and identify stable phases. Equation of state of Bm was measured during decompressing from the synthesis pressure to 1 bar at 300K. The composition of the recovered samples was analyzed by using the aberration-corrected electron microscope (ACEM) combined with energy-dispersive X-ray spectroscopy (EDS) at ASU.

Results and discussion: We have found that in compositions with (Mg+Fe+Ca)/Si ~1 Bm incorporates Ca at 65 and 100 GPa and 2300-2450 K, whereas CaPv exists as a separate phase together with Bm at 35 and 50 GPa and 2000-2300 K. At 35 and 50 GPa at 2000-2300 K, sample 1 formed 81 mol% of Bm and 19 mol% of CaPv, while sample 2 formed 75 mol% Bm, 20 mol% CaPv, and 5 mol% St. At higher pressures of 65 and 100 GPa at 2300-2450 K, both sample 1 and 2 showed nearly pure Bm >95 mol%. The chemical analysis of the pure Bm samples revealed that significant amount of Ca was incorporated in Bm. The composition of Bm for sample was determined to be $Ca_{0.18}Mg_{0.61}Fe_{0.22}Al_{0.15}Si_{0.85}O_3$ which is nearly the same with the composition of the starting material. Na was not measured due to the loss during preparation for ACEM. These results of mineralogy are not consistent with previous experiments of pyrolitic composition with (Mg+Fe+Ca)/Si = 1.49 that showed CaPv as a separate phase at 27-100 GPa and 2000-2350 K [6,7]. We also found that Ca may increase the unit-cell volume of Bm possibly due to the greater ionic size of Ca than Mg. If Ca expands the crystal lattice of Bm and CaPv doesn't exist in the sytem, Bm may be a potential storage for some large-sized trace elements, such as U^{4+} and Th^{4+}. Also, Ca-bearing Bm may have different bulk modulus that determines the compressibility of the lower mantle of a rocky planet. On the other hand, the absence of Fp in Si-rich lower mantle may result in an increase in viscosity of the lower mantle compared to the Earth because of the greater strength of Bm to the mantle convection [8].

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FAST LITHO-PANSPERMIA IN TIGHTLY-PACKED SYSTEMS AROUND M DWARFS S. Krijt[1], T. J. Bowling[1], R. J. Lyons[1], and F. J. Ciesla[1], [1]Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA (email: skrijt@uchicago.edu)

Introduction: When a comet or asteroid impacts a planet's surface, debris ejected above the planet's escape velocity has the potential of reaching other, nearby celestial bodies. In the inner Solar System, travel times for debris between the terrestrial planets are typically $10^{6\text{-}7}$ years [1,2], while these timescales can be much shorter in more compact systems [3]. Litho-panspermia refers to the idea that if such debris contained life-bearing material capable of surviving the initial impact, the ensuing journey through space, and the accretion onto another planet, then that target planet could be seeded with life [4].

The recently-discovered planetary system orbiting M dwarf TRAPPIST-1 is a particularly interesting environment to think about litho-panspermia because the system is very compact and potentially houses 3 Earth-size planets inside the Habitable Zone [5,6,7].

Results: We present numerical simulations using the `SyMBA` routine of the `swifter` software package [8,9,10] investigating the fate of impact ejecta in the TRAPPIST-1 system. We assume an orbital architecture and planetary masses based on [6]. Test particles are ejected from the 3 planets most likely to be in the Habitable Zone (e, f, and g) at different velocities and angles, and is followed until it is (re)accreted onto a different body or ejected from the system. Figure 1 shows the fates of test particles released at 3 different velocities [11]. While a major fraction of the ejected material re-accreted onto the planet of origin (especially for low ejection velocities), significant fractions end up on other planets. Moreover, the material transfer was found to be extremely fast: for ejection just above escape velocity, very little material was still in orbit after 10^4 years, while ~10% of ejecta reached another Habitable Zone planet within 100 years [11].

Discussion: Our simulations indicate that if there is a non-negligible flux of impactors present in planetary systems like the one around TRAPPIST-1, material transfer between planets should be relatively common and many orders of magnitude faster than in the inner Solar System, providing greater opportunities for life to find environments in which it can thrive.

With M dwarfs being the most common stars in the solar neighborhood and the planet formation process favoring tightly-packed configurations of Earth-size planets around these low-mass stars [12], such material exchange could play a significant role in the evolution of the majority of Earth-like worlds in our Galaxy.

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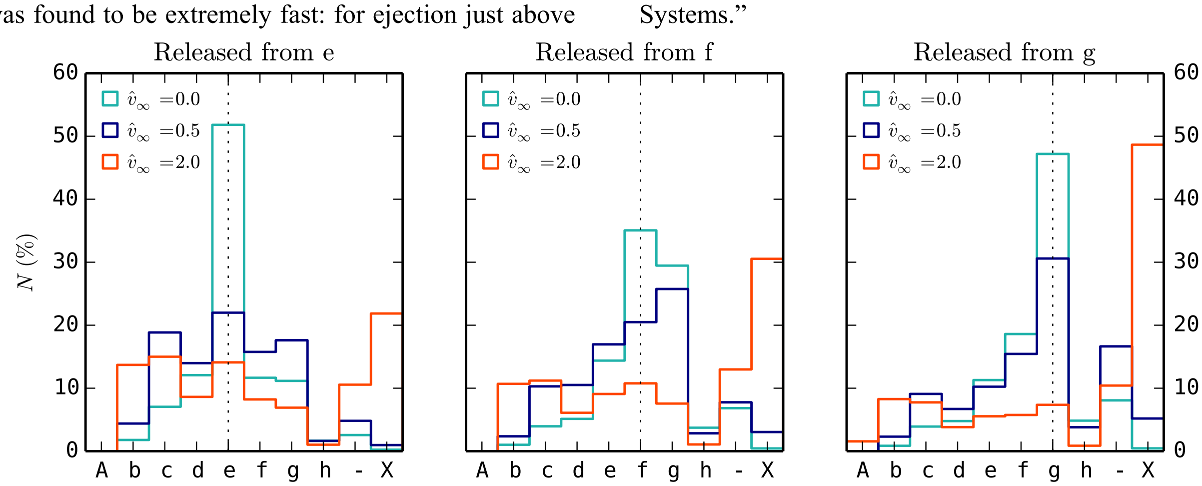

Fig. 1: Fate of ejecta after 10^4 years of being released from planets e, f, and g, at different normalized ejection velocities. Different bins correspond to: accretion onto the primary (A) or planets (b-h), ejection from the system (X), and still in orbit (-). The ejection velocity is given in units of excess velocity at infinity, normalized to the escape velocity from the planet's surface.

Transits in the Solar System and the Composition of the Exoplanet Atmospheres

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Our knowledge about exoplanets depends on very limited measurements and resolution. Atmospheric compositions are limited only to hot Jupiters and Neptunes. Detection of possible biosignatures on Earth-sized planets is not possible today. However, upcoming space missions, like e.g. TESS, JWST, CHEOPS, and PLATO will give us unprecedented access to exoplanet light curves. Before the new results arrive, it could be useful to collect the only known living planet's and other well-known other planet's light curves for the future comparison and habitability modelling. For this, we need to seek possibilities to measure Earth's and other terrestrial planet's transits, occultations, and reflections from different locations in the Solar System. I will present some past events and experiments, potential locations and events, probes, and their instruments that could be used, as well some limitations and challenges.

WHITE DWARFS AND ICY WORLDS - EVOLVING HABITABILITY P. E. Laine[1], [1]Departments of Physics and Computer Science and Information Systems, P.O. Box 35, FI-40014 University of Jyväskylä, Finland, pauli.e.laine@jyu.fi.

White dwarfs are the final state of stellar evolution of the most stars in the Milky Way. These stars (like our Sun) have long hydrogen-fusing steady period during terrestrial planets could be in habitable zone at few AU distance. At the end of the steady period, they undergo expansion to red giant phase, when inner planets are engulfed by the star, thus ending their habitability. However, during this period potential icy moons of the gas giant planets (exo-Jupiters) in outer orbits could still remain habitable (also, if these gas giants remain entire). After a red giant phase, the star will shed its outer layer and leave behind the core, the white dwarf. Could the icy worlds in outer system remain habitable during the whole lifespan of the star, from main sequence star to red giant, outer layer escape to slowly cooling white dwarf? If so, these icy worlds could then have at least tens of billions of years for life to emerge and evolve. This paper will evaluate the evolving habitability of these icy worlds.

Exo-Kuiper belts and water deliverable to planets. Jean-François Lestrade[1], [1]LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, F-75014, Paris, France, jean-francois.lestrade@obspm.fr.

Introduction:

Far-IR observatories Herschel and Spitzer have discovered a few hundreds exo-kuiper belts around main sequence stars in the solar neighborhood and the total masses of their icy planetesimals have been estimated. A few belts have been angularly resolved and their radii direcly measured. In addition, a few exo-asteroidal belts are known. The ice and hydrated minerals of their planetesimals provide a reservoir of water deliverable to their inner planetary system. We study how stellar encounters, in the early evolution phase of these systems when they are still embedded in the open cluster of their birth, can trigger comet showers and deliver water to the planets.

HABITABILITY IMPOSTERS: EXTREME TERRESTRIAL CLIMATES IN THE HABITABLE ZONE OF M DWARF STARS. A. P. Lincowski[1,2], V. S. Meadows[1,2], D. Crisp[2,3], T. D. Robinson[2,4], R. Luger[1,2], and G. N. Arney[2,5], [1]Department of Astronomy and Astrobiology Program, University of Washington, Box 351580, Seattle, WA 98185, USA (alinc@uw.edu), [2]NAI Virtual Planetary Laboratory, Seattle, WA, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, M/S 183-501, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, [4]Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ 86011, USA, [5]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

Introduction: Next year, the launch of the *James Webb Space Telescope* (JWST) will provide an unprecedented opportunity to assess small, nearby planets around M dwarfs for signs of habitability and life. Although small M dwarf habitable zone (HZ) planets are likely common, they may be desiccated from experiencing a super-luminous pre-main-sequence phase, which can result in hundreds of millions of years of runaway greenhouse [1,2]. To inform characterization attempts with upcoming instruments, we couple our new 1D VPL Climate model with a photochemical model, to determine possible climates for evolved O_2 and CO_2-dominated atmospheres in the seven-planet TRAPPIST-1 system [3–5]. We generate transmission and direct imaging spectra of these planetary environments to predict observational discriminants. These discriminants may be used to distinguish evolutionary histories and determine current habitable conditions planets in or near the habitable zones of M dwarfs.

Methods: To model the evolved atmospheres of M dwarf HZ planets, we used the VPL Climate model for O_2- and CO_2-dominated atmospheres. VPL Climate is a generalized, terrestrial-based 1D radiative-convective-equilibrium climate model using SMART [7], a rigorous line-by-line radiative transfer code. The VPL Climate model employs linear flux Jacobians to efficiently timestep the radiative fluxes, and mixing length theory for convective heat transport [8]. The VPL Climate code is now coupled to *Atmos*, a terrestrial photochemical model that has been applied to a variety of worlds [2,9,10].

We apply this coupled model to the potential climates of the TRAPPIST-1 planets, which span both ends of the habitable zone [3–5]. We posit O_2-, and CO_2-dominated climates, including moist, Venus-like, and severely desiccated scenarios, which may result from outgassing during the super-luminous pre-main-sequence phase.

From the variety of possible climatic states, we generate high-resolution synthetic transmission and direct imaging spectra using SMART [6,11]. We compare these spectra to identify observational differences between the planets driven largely by their distance from the parent star. We also identify observational discriminants for each planet's different potential environmental states. These spectra and discriminants can be used in instrument simulators to determine detectability and thereby inform observation programs [12].

Results: We find that completely desiccated O_2-dominated atmospheres, despite strong absorption of stellar radiation from O_2-O_2 collisional induced absorption and ozone, provide poor surface warming, and result in globally-averaged temperatures well below freezing within the habitable zone. However, even a small amount of outgassed water and SO_2 combined with thick oxygen atmospheres can significantly heat these planets, potentially raising the surface temperature above freezing. Alternatively, CO_2-rich atmospheres formed early on via strong stellar and atmospheric evolution, and maintained by the lack of a surface ocean, can provide sufficient warming to elevate surface temperatures in the HZ above 500K.

These atmospheres can be discriminated based on their water content, O_2, O_3, O_2-O_2, CO_2, and CO bands. For TRAPPIST-1 habitable zone planets, transmission features for CO_2 may exceed 100 ppm, while O_3 can exceed 50 ppm. These features may be observable with JWST [12].

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The IRTF/SpeX Survey of Stellar Fluxes and Atomic Abundances in Kepler THZ Planet Systems

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Abstract: Stellar abundances are thought to reflect the feedstocks available for making a star's planets. A simple argument contends that systems of high metallicity have relatively more of the material needed to make rocky terrestrial planets and planetary cores. I.e., systems with high Si/H and Fe/H and Mg/H ratios have relatively more of the material required to make silicate dominated planetesimals, like the asteroids and terrestrial planets found in our system. Extremely high Fe/H systems may lead to large core, thin mantle worlds. Systems with unusually high C/O ratios may tend to make "carbon planets" based on SiC geochemistry instead. And systems with very high O/H ratios are thought to lead to water-rich worlds.

As part of the ASU NExSS project (PI Steve Desch), we have used the results from our 100+ hours, 50+ systems NASA/IRTF 3m Near InfraRed Disk Survey (NIRDS; [1]), a spectral survey utilizing the R~1000, 0.8 - 5.0 µm spectra provided by the SpeX spectrometer [2] to understand the nature of 50+ star systems. AFGK systems were selected for observation if they have been reported to host planets and/or circumstellar debris disks.

In conjunction with the stellar spectra in the SpeX cool star library [3], we find that we can measure a star's photospheric emission from 0.8-5.0 um to 1% relative precision. This spectral range contains absorption features of Ca, Na, Mg, Al, Fe, Si, C, and H we have used to measure their abundances in the host star, while at the same time classifying the star & characterizing much of the astrobiologically active flux (especially for the later K and M stars), filling in an important gap in knowledge of a system (most groups simply rely on inaccurate coarse photometry for this purpose). We have also searched for emission above the primary's photosphere due to belts of comets, asteroids, and KBOs, for material that could supply astrobiological material to any *in situ* planets, while also providing clues to the evolutionary state of the system.

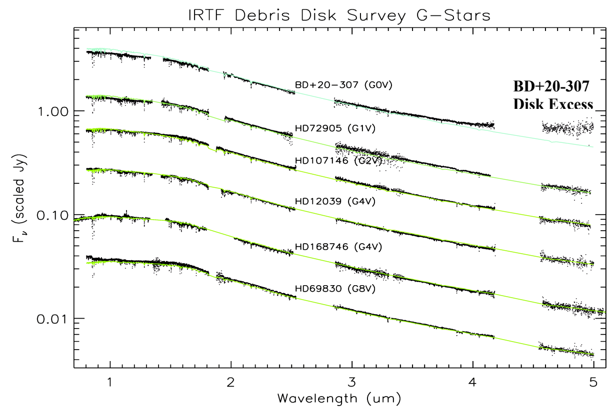

Fig. 1 - NIRDS G-star observations through 2016, showing the range of SpeX broad spectral behaviors found by NIRDS. SpeX data are in black, stellar photospheric models in green.

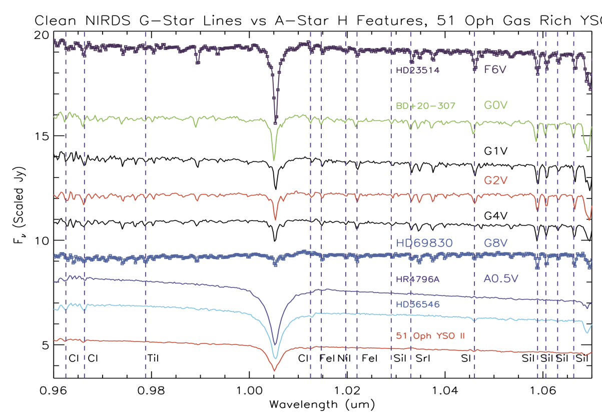

Fig. 2 - Detail of some of the important SpeX 0.96 - 1.07 µm G-star absorption lines used for abundance determination.

Our 2017 observations focused on the 12 most promising Kepler THZ planetary candidate systems. In this paper we present our new stellar flux and abundance results for the Kepler systems, and discuss any unusual findings versus the mean aggregate behavior of our program systems.

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KEPLER'S ROCKY EXOPLANETS: BORN ROCKY OR STRIPPED SUB-NEPTUNES?

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Introduction: The current population of known rocky exoplanets is dominated by planets either on highly irradiated orbits or around late type stars. Over their lifetimes such planets are bombarded by vast amounts of ionizing radiation that can drive vigorous photo-evaporative atmospheric escape, which over time can completely strip away a planet's gaseous envelope. As a result, most currently known rocky exoplanets may not have formed rocky but may instead be the stripped cores of sub-Neptunes. I will review the current evidence for the role of photo-evaporation in shaping the known exoplanet population and the impact this may have on our current estimates of eta-Earth. I will then discuss observational paths forward for distinguishing between rocky planet populations that formed through photo-evaporative stripping vs those that were born rocky like the Earth.

EXOPLEX: A CODE FOR CALCULATING THE MINERALOGY AND MASS-RADIUS RELATIONSHIPS FOR ROCKY PLANETS A. M. Lorenzo[1], S.J. Desch[1], C. Unterborn[1], S.H. Shim[1], K. Byeongkwan[1], [1]Arizona State University School of Earth and Space Exploration, email: Alejandro.Lorenzo@asu.edu.

Introduction: The field of exoplanets has moved from one of discovery to one of characterization. In the aftermath of surveys by Kepler and CoRoT, thousands of exoplanets of various mass, radius, and orbital parameters have been discovered, many are rocky and Earth-like in size and mass. The search for life in the universe will begin with observations of these planets. Characterization of Earth-like planets is the next phase of exoplanet studies, but it is still in its infancy. In many cases, we don't know much more about a planet than its mass, radius, and insolation. In the lack of further information, and in the absence of a clear definition of the community, "Earth-like" has become synonymous with a 1 Earth-mass, 1 Earth-radius planet. But the search for life will demand more than this. Detectability of life is possible if a planet's abiotic geochemical cycles are observably different from its biogeochemical cycles with life. Assessing detectability requires characterization of not just mass and radius, but a planet's internal composition, and the manifestation of this geochemistry on its surface.

As is well understood, mass and radius alone allow too many degenerate solutions to constrain planetary composition beyond "rock", "ice", "metal", and "atmosphere". It is vital to supplement these studies with stellar elemental compositions. In parallel with observational efforts, better modeling tools are needed. To that end, we have developed the ExoPlex code, which is a planetary mass-radius and mineralogy code. For a given bulk planetary composition, we calculate the mineralogy as a function of depth in the planet and derive M-R relations. The mineralogy as a function of depth allows assessments of mantle rheology, vigor of mantle convection, and other factors important to geoscience.

Methods: Our model is for rocky bodies differentiated into a core, mantle and water layer. Inputs of relative elemental abundances of Mg-Si-Fe-S-O-Al-Ca are used to set the core mass fraction. We use techniques similar to [1,2,3] where we assume planets to be spherically symmetric, so our model varies only along the radial direction.

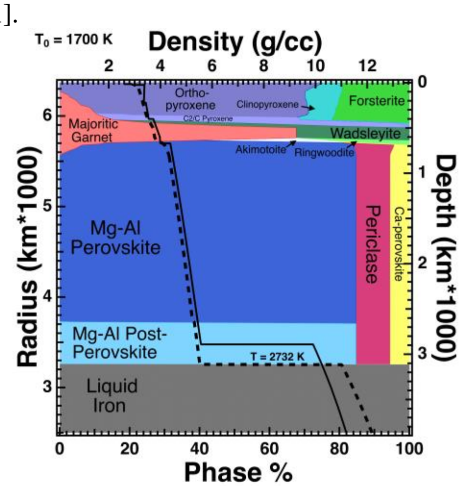
From the surface, we integrate the equation of hydrostatic equilibrium and calculate along a compositionally self-consistent adiabatic temperature gradient. Temperature and pressure fields are then used to find density using the appropriate equation of state for each region. Temperature and pressure profiles are then updated iteratively until the fractional change in density of every layer is < 10^{-6}.

Mantle mineralogy is found using the Gibbs free energy minimization code, PerpleX [4]. Thermoelastic parameters for the resultant phase assemblages are calculated from the formulation of [5,6].

Alloys of Fe with S, Si, and O are considered for model cores in addition to pure Fe. In core conditions, light elements effectively reduce the molar weight of Fe for the equation of state with no significant impact on compressibility [7].

Our water layer consists of liquid water and ices Ih, VI, and VII. We use melting curves from [9] to find the state within the water phase diagram.

Results: A figure from ExoPlex illustrating the mantle phase diagram of a planet with solar composition appears below [10]. The solid line is the density calculations from ExoPlex and the dotted is from the PREM [11].



Discussion: ExoPlex is available now at: https://github.com/CaymanUnterborn/ExoPlex. Initial studies looking at the effects of stellar bulk composition on planetary structure are forthcoming and scheduled for release Fall 2017.

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PROBING THE ORBITAL DYNAMICS AND ATMOSPHERIC PROPERTIES OF THE TRAPPIST-1 PLANETS WITH JWST. R. Luger[1,2,3], J. Lustig-Yaeger[1,2,3] and E. Agol[1,2,3], [1]Astronomy Department, University of Washington, Box 951580, Seattle, WA 98195, USA, [2]Astrobiology Program, University of Washington, Box 351580, Seattle, WA 98195, USA, [3]NASA Astrobiology Institute – Virtual Planetary Laboratory Lead Team, USA.

Introduction: The TRAPPIST-1 system hosts seven transiting terrestrial-size planets in orbits with periods under 20 days [1, 2]. At a distance of only 12 pc, these planets are ideal candidates for transmission and secondary eclipse spectroscopy follow-up with the James Webb Space Telescope (JWST), particularly because three of the planets lie within the star's habitable zone. While these observations will yield valuable information about these planets' atmospheres, the proximity of the system and the compactness of its planetary orbits opens a door to a novel characterization technique that has not previously been possible for exoplanetary systems: the detection of planet-planet occultations (PPOs). During a PPO, a planet is occulted by another planet in the same system, resulting in a slight dimming of the total flux received at Earth [3]. Although analogous to a transit, the signal from a PPO is typically orders of magnitude weaker because of the large star/planet contrast. However, in extremely coplanar systems such as TRAPPIST-1, PPO depths are comparable to secondary eclipse depths and should therefore be observable.

Methods: We develop a general photodynamical model for predicting and computing PPOs and apply it to the TRAPPIST-1 system. We first estimate the probability of PPOs in this system based on estimates of the system parameters, including the coplanarity of the planets, which we show are aligned to $< 0.3°$ at 90% confidence. We predict the probability of events as a function of the phases, durations, and impact parameters for pairs of planets. We further develop a fast integration scheme to compute PPO light curves under different assumptions about the planets' atmospheres.

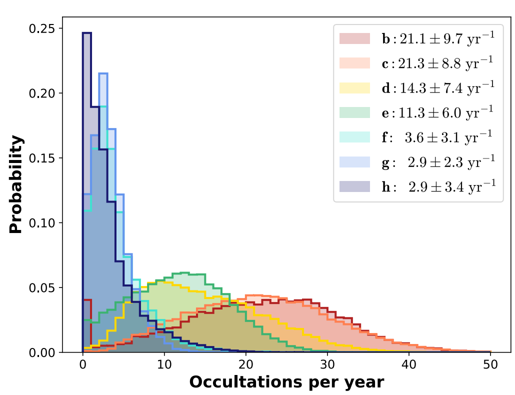

Figure 1 Number of potentially observable planet-planet occultations for each of the TRAPPIST-1 planets in one year. Planets b and c undergo ~20 significant occultations per (Earth) year.

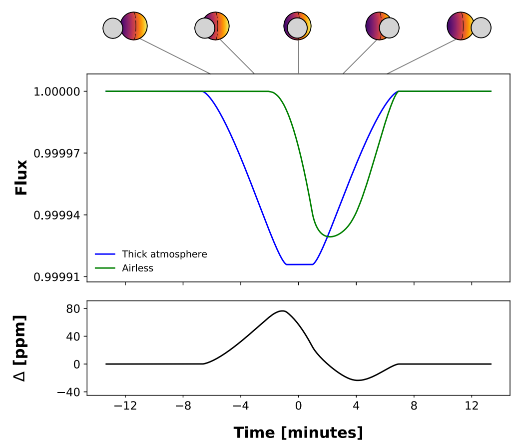

Figure 2 Occultation of c by d, assuming an atmosphere with strong recirculation (blue) and one with negligible recirculation to the nightside (green). The asymmetry in the latter case is a powerful diagnostic of the day/night temperature contrast of the inner TRAPPIST-1 planets.

Results: Marginalizing over all current uncertainties on the orbital parameters of the TRAPPIST-1 planets, we find that of order one PPO should occur per (Earth) day, while 80 PPOs should occur per year with the potential for detection (Figure 1). We find that dynamical analysis of the timing of these PPOs can be used to strongly constrain the planet eccentricities and masses and to break TTV degeneracies. We also show how PPOs can be used to constrain a planet's day-night temperature contrast (Figure 2) and construct crude surface maps. Finally, we investigate the prospects for detection of PPOs in TRAPPIST-1 with JWST, which looks promising if several events can be be observed and stacked at 12-15 µm. The proposed Origins Space Telescope shows even better promise at longer wavelengths.

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EXTENDING ATMOSPHERIC CHARACTERIZATION TO EARTH-SIZED EXOPLANETS WITH JWST: TRANSITS, ECLIPSES, AND THE TRAPPIST-1 SYSTEM. J. Lustig-Yaeger[1,2,3,†], A. P. Lincowski[1,2,3], V. S. Meadows[1,2,3], [1]Univ. of Washington, Department of Astronomy, [2]NAI Virtual Planetary Laboratory, [3]Univ. of Washington, Astrobiology Program, [†]jlustigy@uw.edu

Introduction: The discovery of Earth-sized planets in temperate orbits around nearby, low-mass stars ushers in a new era of *Earth-sized* exoplanet atmospheric characterization [e.g. 1, 2, 3]. Transmission and emission (secondary eclipse) spectroscopy of these small transiting worlds with the upcoming James Webb Space Telescope (JWST) may offer a first glimpse into the lower atmospheres of extrasolar planets and a first opportunity to search for signs of habitability and biosignatures beyond the Solar System. However, extending transmission and emission spectroscopy down to Earth-sized exoplanets will push the limits of JWST, and identifying optimal systems, measurements, and instruments to characterize potenatially habitable Earth-sized planets will enhance the overall science return from the mission.

The TRAPPIST-1 System hosts seven tightly packed Earth-sized planets that transit an M8 star with a radius of about 12% that of the Sun [2, 3, 4]. The large transit and eclipse depths (for Earth-sized planets) makes the planets particularly observable and likely to be one of JWST's first exoplanet targets when it launches in 2018. A detailed atmospheric characterization of all seven TRAPPIST-1 planets would tell a rich story of the formation, migration, and evolution of a set of planets spanning the habitable zone of their late M dwarf host.

Defining key planetary characteristics and the best methods to detect them requires predictions for the most likely environmental state given our current knowledge of atmospheric climate and photochemistry. M dwarf planets may be highly evolved [5] and exhibit O_2- or CO_2- dominated atmospheres very different to the Earth's [6]. Or they may be airless bodies, stripped of their primordial atmospheres [7]. To aid the search for indicators of M dwarf evolutionary processes we have used theoretical and instrument models to determine the observational characteristics of these environments [8], and explored the optimum observing strategies for studying these worlds using the JWST instrument simulator PandExo [9] and a custom MIRI imaging tool. With this suite, we considered transmission/emission spectroscopy using all the available instruments aboard JWST.

Transmission vs. Emission: We find that JWST's visible through MIR wavelength coverage in concert with the small radius and faint luminosity of the TRAPPIST-1 star makes secondary eclipse particularly viable beyond 5 μm for the innermost planets. Molecular absorption signals observed in secondary eclipse increase towards longer wavelengths as the planet-to-star flux ratio increases. However, thermal and background noise also increase with wavelength, making the optimal choice of wavelength/instrument nontrivial and target dependent. For instance, planets with more extreme greenhouses are easier to characterize in secondary eclipse over transit observations. But windows into the atmosphere, if predicted and targeted, can be used to take advantage of strong greenhouse emission.

The case for secondary eclipse of the Earth-sized TRAPPIST-1 planets will be strengthened if they have secondary, outgassed atmospheres with high mean molecular weights. Additionally, the temperate habitable zone atmospheres may exhibit small scale heights that are particularly challenging to observe in transmission, even without condensates which would further obscure the atmospheric composition. However, under most circumstances, for wavelengths < 5 μm, transmission remains optimal for detecting atomic and molecular transitions.

JWST Observing Modes: We devise a hierarchical observing scheme to maximize information content in observations of the atmospheres of TRAPPIST-1 planets while minimizing JWST time. MIRI secondary eclipse photometry in the 12.8 μm and 15 μm filters can be used to measure the dayside temperatue of the innermost planets, inferring the presense of an atmosphere, and searching for atmospheric CO_2, in a relatively small number of eclipses. These initial results could be used to update hypotheses on the atmospheric composition to decide if and how best to proceed with JWST observations of the TRAPPIST-1 planets, including emission spectroscopy with MIRI/LRS and/or transmission spectroscopy with NIRISS and NIRSpec.

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DETECTING OCEANS ON EXOPLANETS USING PHASE-DEPENDENT MAPPING WITH NEXT-GENERATION CORONAGRAPH-EQUIPPED TELESCOPES.

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Introduction: A single exposure of a directly imaged habitable exoplanet will contain no spatial information, despite potentially containing reflected light from continents, oceans, and clouds. However, as it rotates on its axis we may observe subtle modulations in the time-series photometry as different surface features rotate in and out of view. Fitting these lightcurves allows one to infer the exoplanet's longitudinal surface map. In this presentation, we discuss the prospects and limitations of using rotational variability to map terrestrial exoplanets using NASA's next-generation telescope concepts, and the insights into exoplanet habitability that can be gained from such observations. In particular, habitability may be assessed via detection of specular reflection from a liquid ocean, which is enhanced when the planet is near crescent phase [1]. However, scattering from aerosols and clouds may display similar phase-dependent properties. Here we describe a novel combination of observations that use time-resolved, multi-band photometry as a function of phase to identify the phase-dependent behavior of the dominant reflecting surfaces, and thereby increase the robustness of ocean detection.

Methods: We model time-series, multi-band photometry of a realistic Earth-analog exoplanet [1,2,3] under various observational assumptions, and then invert the problem to solve for the surface covering fractions and geometric albedo spectra of dominant surface types. The models used are introduced below.

VPL Earth Model. Earth is our only example of a habitable world and is a critical reference point for potentially habitable exoplanets. Although disk-averaged views of Earth that mimic exoplanet data can be obtained by interplanetary spacecraft, these datasets are often restricted in wavelength range, and are limited to Earth phase angles and viewing geometries that the spacecraft can feasibly access. We can overcome these observational limitations using a sophisticated UV-MIR spectral model of Earth that has been validated against spacecraft observations in wavelength-dependent brightness and phase [2,3]. This model is used to create multi-wavelength, time-dependent, disk-averaged observations of Earth.

Coronagraph Noise Model. Stars significantly outshine planets, often by a factor of $\sim10^{10}$, and directly imaging Earth-like exoplanets requires suppressing the star's light to overcome this contrast. Star-light suppression could be obtained by using a coronagraph or starshade to block the star's light and reveal the underlying exoplanetary system. We use a coronagraph noise model [4] – which accounts for telescope, instrument, and astrophysical noise – to simulate multi-band lightcurves of an Earth-like planet, and assess the mapping capabilities of and technical requirements for next-generation coronagraphic telescopes, such as the Large UV/Optical/IR (LUVOIR) Surveyor and Habitable Exoplanet Imaging Mission (HabEx).

Mapping. Building on previous terrestrial mapping studies [5,6,7], we use Principle Component Analysis (PCA) to identify the number of unique surfaces contained in our synthetic directly-imaged exoplanet lightcurves. We then employ a new rotation unmixing model to simultaneously extract the longitudinal covering fraction and geometric albedo spectrum for each surface. Despite this solution containing fundamental degeneracies, important inferences into relative surface colors and their longitudinal distributions can still be determined [8].

Results: Using our Earth, telescope, and mapping models we extract the longitudinal albedo maps for the dominant surfaces on Earth as if it were an exoplanet, observed at quadrature and crescent phases. At quadrature, the dominant surface is dark blue, whereas at crescent, the same longitudinal map (to within measurement uncertainties), shows that the derived surface albedo is now ~4x more reflective. Using the extracted map as the key, we demonstrate that the same surface that appears dark blue at quadrature phase is a non-Lambertian, specular reflecting surface at crescent. This is a strong suggestion that liquid surface water is present on the exoplanet of interest.

Conclusion: Phase-dependent longitudinal mapping could be used with next generation direct-imaging telescopes to infer the surface composition of Earth-sized exoplanets, including the detection of liquid surface water.

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EXPLORING PROTO-ATMOSPHERE ACCRETION ON EARTH-SIZE PLANETS. C. Mai[1] and S. J. Desch[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe AZ 85287-1404 (chuhong.mai@asu.edu).

Introduction: Protoplanets are believed to form before gas dissipates in the stellar nebula and thus they are likely to capture proto-atmospheres from the nebula gas [1,2]. Such atmospheres should have similar composition as the stellar nebula and therefore be rich in hydrogen and helium. The detection and characterization of low density planets that are believed to have extensive H_2-rich atmospheres in exoplanetary systems (e.g. super Earths and mini Neptunes, [3]) have driven the community to investigate the role of proto-atmospheres in terrestrial planet formation. Modeling the accretion and evolution of proto-atmospheres is fundamental to science topics both inside and outside of the solar system, including the nebula origin of terrestrial water and other volatiles (H_2, CO/CO_2, N_2, etc.) in Earth-like planets, the supply of Earth's noble gases [4] and the role of proto-atmospheres in chondrule-forming planetary bow shocks [5], [6]. Understanding how the proto-atmospheres could influence or even create the current terrestrial planetary environments in the solar system also has general significance to the study of exoplanet geochemistry and habitability.

Recent research efforts on simulating the capture and loss of the planetary hydrogen envelopes using hydrodynamic codes [7-9] indicate an Earth-size planet is able to accrete thousands of bars of H_2/He. However, much of the relevant parameter space is still unexplored.In most simulations, the protoplanet is stationary and planetesimal accretion rate is constant; these assumptions must be relaxed to better represent the nebula environment and corresponding behaviors of terrestrial proto-atmospheres. Especially, migration of planets has been revealed to be common in our solar system and exoplanetary systems [10], [11]. Due to dynamical resonances or encounters, these planets can be scattered onto very eccentric orbits, on which the the relative velocity of planets to nebula gas might or might not exceed sound speed. In either case, the accretion scenario of proto-atmospheres is fundamentally changed. Yet no models have considered the influence from eccentric orbits.

Methodology: We have been using the hydrodynamics code FLASH to simulate the gravitational accretion of gas onto a protoplanet and its subsequent evolution. FLASH is a modular, adaptive-mesh, parallel and Fortran-based simulation code capable of handling problems of compressible flows like gas and atmospheres [12]. We first establish a one-dimensional stationary model assuming spherical symmertry and constant accretion luminosity (due to planetesimal impacts) to benchmark the results with [7] which used a different numerical approach. We assume a two-part analytical atmosphere structure – an optically thin outer part approximated as isothermal and an optically thick inner part combining the convective and the lower radiative regions. The nebular density, as an upper boundary of the atmospheres, is varying from 10^{-10} to 10^{-25} g cm^{-3} to simulate the dissipation of nebula gas. We are investigating planets with 0.1 to 5 M_E masses, covering the range of sub-Earth to super Earth exoplanets. The modeling efforts will be extended from 1-D spherical to 2-D cylindrical treatments.

Discussion: The preseantation will focus on the series of work in progress and in plan to model the proto-atmosphere accretion in a more physically realistic sense, including implementing sophisticated treatments of planetesimal accretion rate, planet mass and atmosphere opacities, and exploring the influence from the planet traveling on an eccentric orbit. Prelimnary results by the time of the workshop will be presented as well.

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CONSTRAINING THE ATMOSPHERIC METALLICITY OF HAT-P-11b. M. Mansfield[1], J. Bean[2], M. R. Line[3], and L. Kreidberg[4]; [1]University of Chicago Department of Geophysical Sciences, 5734 S. Ellis Ave., Chicago, IL 60637, meganmansfield@uchicago.edu; [2]University of Chicago Department of Astronomy & Astrophysics; [3]Arizona State University School of Earth and Space Exploration; [4]Harvard-Smithsonian Center for Astrophysics.

The composition of an exoplanet's atmosphere provides a record of its formation, including the environment in which it formed, its formation mechanism, and its migration (e.g. [1-8]). In particular, the core accretion model of planet formation predicts decreasing atmospheric metallicity with increasing planet mass. This trend has been confirmed for a few gas giant planets such as WASP-43b [9] and the Neptune-sized exoplanet HAT-P-26b [10], but remains largely uncertain for lower-mass planets. Water has been detected in the atmosphere of the Neptune-sized planet HAT-P-11b [11], but this detection provided only weak constraints on its metallicity. We present new HST WFC3 observation of HAT-P-11b in the G102 grism to further constrain its metallicity.

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CONSTRAINING THE HABITABLE ZONE BOUNDARIES FOR WATER WORLD EXOPLANETS

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Planets with global water oceans have been the subject of intrigue both in Hollywood and in the exoplanet community. Kuchner (2003) [1] and Leger et al. (2004) [2] first proposed the possibility of water worlds - water-rich (>1% water by mass) super-Ganymede exoplanets that formed from volatile ice-rich material beyond the snow line but that never attained masses sufficient to accrete or retain large amounts of H_2/He nebular gas. This pathway for producing low-mass water-rich planets has played out as a robust prediction of planet formation simulations, leading to planets that could have a comet-like composition, with up to 50% of their mass constituted of astrophysical ices. If located at an appropriate orbital separation from their host star, water worlds may host a global surface water ocean. Habitable (liquid ocean-bearing) water worlds are especially timely because 1) water worlds formed from remnant cores of evaporated mini-Neptunes could be one of the dominant formation mechanisms for volatile-rich habitable zone planets around M dwarf stars [3], and 2) their larger sizes relative to terrestrial planets make them more amenable to observations with current and upcoming telescopes such as Hubble Space Telescope (HST) [4] and James Webb Space Telescope (JWST) [5].

The classical habitable zone does not apply to water worlds with global oceans. Currently, most calculations of the habitable zone consider Earth-like planets, for which the amount of CO_2 in the atmosphere is stabilized by the carbonate-silicate cycle. Water worlds lack exposed landmass for continental silicate weathering feedback. Due the important oceanic mass, the hydrostatic pressure at the oceanic floor may reach the stability field of high pressure polymorphs of water ice (ice phases VI and VII), hindering chemical interactions between the liquid water and the silicates. In the absence of a carbonate-silicate cycle, the solubility of CO_2 in the ocean [6] and the formation of CO_2-rich clathrates [7] determine the concentration of CO_2 in the water world's atmosphere. We use coupled models of planet interiors, clathrate formation, liquid-vapor equilibrium, and atmospheric radiative transfer to constrain the atmospheric abundance of CO_2 and corresponding habitable zone boundaries of water world exoplanets. We focus in particular on planets orbiting M dwarf stars, since these will be prime targets for characterization with JWST.

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THE LARGE-SCALE STRUCTURE OF HABITABILITY IN THE UNIVERSE. P. A. Mason[1], [1]New Mexico State University, Las Cruces, NM 88003, pmason@nmsu.edu

Introduction: Life was impossible in the early Universe. The emergence of life as we know it relies on several factors. First, the elements essential to life must be fused in stars. Galaxies formed soon after the formation of the first stars. Over time, galactic disks not only allowed for the concentration of life's essential elements, but the magnetized galactic wind of disk galaxies also provided protection of habitable planets.

Supernovae, especially those that explode into their previously ejected winds, play a critical role. The supernova rate reasonably tracks the star formation rate within galaxies. Habitability became more probable once the star formation rate, supermassive black hole activity, and gamma-ray burst rate decreased; see Figure 1. Biospheres are further protected from high-energy charged particles by an astrosphere driven by stellar winds and a planetary magnetic field if present. A planet's atmosphere can be especially protective to life on its surface.

Timeline of cosmobiology: A timeline for habitability in the Universe is developed based on astrophysical constraints on complex life as we know it and for extremophiles. The emergence of life does not occur simultaneously everywhere in the Universe. Some regions may accumulate sufficient elemental abundances to support life, however, they may be located too close to accreting black holes, supernovae, and gamma-ray bursts, that occasionally produce dangerous radiation and particle fluxes. Mergers of galaxies are especially harmful to complex life. Some galaxies, especially those with no or low-mass supermassive black holes, promote complex life as they have sufficient star formation without excessive sterilizing threats. Finally we consider the future for life in the Milky Way and elsewhere in the local Universe.

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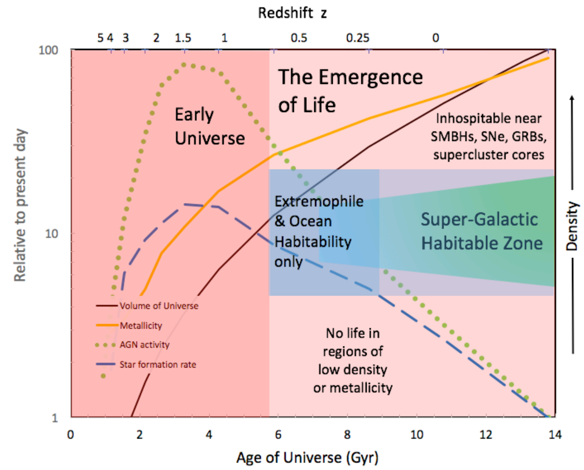

Figure 1: Time evolution of habitability in the Universe. The elements of life build up slowly, while habitability threats decrease. On the right side is a schematic view of the development of a Super-Galactic Habitable Zone (SGHZ). Life is impossible near the center of rich superclusters and merging galaxies. The blue shaded region around 8 Gyr and extending to later times corresponds to extremophile habitability without complex life on land as we know it. Figure from Mason & Biermann (2017).

CHARACTERIZING TERRESTRIAL EXOPLANETS V. S. Meadows[1,2,3], J. Lustig-Yaeger[1,2], A. Lincowski[1,2], G. N. Arney[2,4], T. D. Robinson[2,5], E. W. Schwieterman[2,6], L. D. Deming[2,7], G. Tovar[1,2] [1]Univ. of Washington, [2]NASA Astrobiology Institute – Virtual Planetary Laboratory, [3]Astrobiology Center – Univ. of Tokyo, [4]NASA Goddard Space Flight Center, [5]Northern Arizona Univ., [6]Univ. of California - Riverside, [7]Univ. of Maryland.

Observations of terrestrial exoplanet environments remain an important frontier in comparative planetary science. Studies of habitable zone (HZ) terrestrial planets will set our own Earth in a broader context, and help reveal the diversity of processes that shape worlds like our own. Complementing these observations, studies of high insolation terrestrial exoplanets such as GJ1132b [1] and the inner TRAPPIST-1 planets [2,3,4] can provide insights into extremes of terrestrial planet evolution—and may reveal planetary processes that could mimic signs of life. In the next 5 years, observations of Earth-sized planets orbiting M dwarfs will be attempted with HST, Spitzer, JWST and ground-based telescopes. Thermal phase curves with JWST could be used to search for the presence of an atmosphere, and molecules such as CO_2 and O_3 [5,6]. While transmission spectroscopy of terrestrial planet atmospheres with JWST will be extremely challenging, it provides our first chance to characterize these atmospheres with sufficient precision to search for life. However, atmospheric refraction, clouds and hazes may limit JWST's ability to sample the deep atmosphere of habitable zone terrestrial planets [7,8], reducing the detectability of water vapor in the lower atmosphere, and confining biosignature searches to gases that are abundant in the upper atmosphere—such as evenly-mixed O_2, or photochemical byproducts of biogenic gases [9,10].

Ground-based telescopes will use starlight suppression and/or high-resolution spectroscopy to search for O_2 and other gases in M dwarf planetary atmospheres. Transmission spectroscopy may be used for transiting planets [11], and a combination of starlight suppression and high-resolution reflected-light spectroscopy could probe the atmospheres of nearby non-transiting planets like Proxima Centauri b [12,13]. In the next 10 years Extremely Large Telescopes (ELTs) on the ground will increase the power of high-resolution spectroscopy for M dwarf planets, and at least one planned first generation instrument may acquire 10μm direct-imaging observations of planets orbiting Sun-like stars [14]. The NASA WFIRST mission, if flown with a starshade [15], may observe a few HZ terrestrials.

For the decade beyond that, NASA is currently considering three telescope concepts that could observe terrestrial exoplanets. Two of these, HabEx [16] and LUVOIR [17], would use direct imaging to study terrestrial HZ planets, potentially probing the entire atmospheric column and planetary surface of HZ planets orbiting more Sun-like stars. These observations would complement the transmission and ground-based spectroscopy of M dwarf planets, and telescope sizes under consideration would enable detection of as many as 160 HZ terrestrials[18]. These telescopes will monitor time- and phase-dependent photometry to generate spatially-resolved maps of the planets [19], search for signs of ocean glint [20] and surface inhomogeneity, and use direct imaging spectroscopy in the visible-NIR to determine atmospheric and surface composition [6].

In this review we will discuss the desired measurements to characterize terrestrial planets for signs of habitability and life. This work is supported by theoretical modeling of a diversity of terrestrial exoplanet environments for habitable Earth-like, early Earth and highly-evolved M dwarf HZ and hot terrestrial planets - with photochemistry and climates that are driven by host stars of different spectral types. We will present simulated observations of these planets for transmission (JWST), ground-based (ELTs) and direct imaging (HabEx/LUVOIR-class) observations. We will identify the most observable features of these planetary environments, and the strengths and limitations of each class of observation, and identify suites of complementary observations that can provide the most robust characterization of habitability and biosignatures.

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THE ORIGINS SPACE TELESCOPE – a NASA Decadal Mission Study

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Introduction: The *Origins Space Telescope* is an evolving concept for the *Far-Infrared Surveyor* mission, and the subject of one of the four science and technology definition studies supported by NASA Headquarters to prepare for the *2020 Astronomy and Astrophysics Decadal Survey*. The *Origins Space Telescope* will discover or characterize exoplanets, the most distant galaxies, nearby galaxies and the Milky Way, and the outer reaches of our solar system. This talk will present the Origins Space Telescope Mission Concept 1 (Fig. 1).

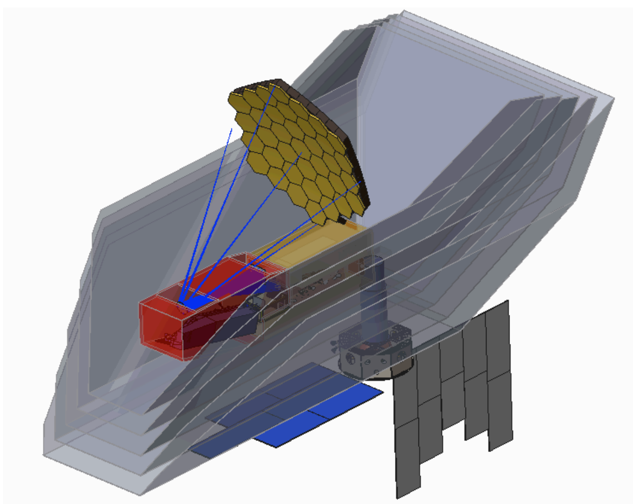

Figure 1: *Origins Space Telescope* mission Concept 1 (4 K baffle omitted to enable unobstructed viewing of the telescope and Instrument Accommodation Module).

The telescope is a ~9 m off-axis, segmented telescope that is cryogenically cooled to ~4 K. A baffle (not shown) and cryocoolers ensure the telescope environment is maintained at ~4 K. The primary is deployed and the secondary is fixed inside the instrument accommodation module. Five instruments covering 5 to 660 µm enable the broad range of scientific activity: Medium Resolution Scanning Spectrometer, R~500 and R~40,000 for 30-660 µm; Far-Infrared Imaging Polarimeter, 40, 80, 120 and 240 µm simultaneous imaging; High Resolution Spectrometer, R~10^5 and R~10^6 for 25-200 µm; Heterodyne Instrument, R~10^6-10^7 for 63 µm and 111 to 566 µm; and Mid-Infrared Imager, Spectrometer and Coronagraph, 5 to 38 µm, R~300, 1000 and 20,000 with special transit spectrometer channel. The telescope, instrument accommodation module, sunshield and space craft would be launched in an 8 m sized fairing. The scope of the Mission Concept 2 will also be discussed.

STABILITY OF MOLECULES OF BIOLOGICAL IMPORTANCE TO IONIZING RADIATION: RELEVANCE IN ASTROBIOLOGY.

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Introduction: Research related to the synthesis of organic matter of biological importance is relevant for astrobiology. Likewise, the study of the stability of organic compounds should have the same concern in the face of the extreme conditions that probably existed in the primitive environments [1]. These environments may have been exposed to large doses of ionizing radiation [2], which could have as a consequence the degradation of the organic matter present in them; but not only that, the interaction of radiation-matter could also promote the synthesis of simpler or more complex molecules that are important in the metabolisms of current organisms [3]. The aim of this work is to demonstrate the stability of two non-essential amino acids (aspartic acid and glutamic acid) in different conditions such as in solid state and in aqueous solution, high doses of gamma radiation (up to 200 kGy) and two temperatures (298 and 77 K). The results show the high stability (~100%) of the amino acids in solid state and in counterpart, the low stability of the amino acids in aqueous solution, processes in which the products of water radiolysis play a major role. The products of the radiolysis of the amino acids in aqueous solution are important molecules in current metabolisms, for example, the Kelvin cycle. The analytical techniques used to quantify the amino acids and the products of the radiolysis were spectrophotometric (UV and IR spectrophotometry), chromatographic (HPLC-UV and HPLC-ESI-MS), and electron spin resonance (ESR).

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[3] Negrón M. A. and Ramos B. S. (2000) Astrobiology: Origins from the Big-Bang to Civilization, Kluwer Academic Publishers, 71-84.

Terran World Simulator

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Margaret Turnbull, SETI Institute
Tristan L'Ecuyer, Dept. of Atmospheric and Oceanic Sciences, U. Wisconsin–Madison

The Terran World Simulator was designed to be a flexible framework for modeling directly detected terrestrial exoplanets. Among the wide range of potential exoplanets, we consider the term terrestrial to mean that both the atmosphere and surface are significant contributors to the total disk-integrated signature of the exoplanet. This implies a moderately thick atmosphere, like Earth's: the atmosphere has a significant impact at all wavelengths (e.g., clouds and gas absorption bands), while allowing for atmospheric "windows" that allow for emission and reflection directly from the planet surface. For the direct detection scenario, these planets are distinctly different than rocky planets with no atmospheres, or gas giants where the atmosphere completely obscures the surface. Therefore, any accurate modeling framework must take a 3D approach that correctly accounts for the spatial distribution of the atmosphere and surface and how the observation geometry varies over the spherical surface.

Our modeling framework uses a modular approach, separating the geometric calculations from the radiative transfer. This approach has been used by multiple published studies (Robinson 2011, Fujii 2011, Tinetti 2006). The geometric calculations allow for arbitrary orbital parameters, which can then be applied to pre-computed radiative transfer databases. These radiative transfer databases could be computed for any plausible terrestrial environment, as long as the number of different cloud and surface types is limited to a small number. Thus, our framework is intended to simulate easily other configurations of exoplanets, to widen the range of simulations from “Earth-twins” to arbitrary terrestrial worlds. The division of geometric and radiative transfer calculations also allows for efficient re-use of high spectral resolution radiative transfer model runs. This efficiency reduces the simulation complexity for time series observations, such as phase curves, or planets through seasonal variations.

This framework was developed with support from the WFIRST Preparatory Science team. The original focus was to simulate terrestrial exoplanets in reflected visible and near infrared spectral bands, such as those in the proposed WFIRST coronagraph. The flexible design of the framework imposes no restrictions on the spectral range. Thus, the Terran World Simulator could be used to support preparatory science activities for other planned or proposed exoplanet direct imaging missions.

BLAZING A TRAIL: TOWARDS IMAGING SUPER-EARTH FROM THE GROUND AND SPACE

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The discovery and characterization of extrasolar planets has been data-driven: clearly there are more things in heaven, than are dreamt of in our philosophies. As the demographics of the myriad diverse systems becomes known, we begin to piece together the larger story of their formation and evolution. Ultimately, we seek to understand the prospects for life elsewhere in the Universe. In addition to this scientific quest, 'exploration' also plays a role. In particular, the nearest star systems provide an opportunity to explore in detail strange new worlds. The recent announcement of a planet < 10 Mearth in the liquid-water zone of Proxima Centari sent shock waves through the community. What is the nature of this planetary system found in our own galactic backyard? Could it be habitable? How will we know and when?. Here we attempt to review recent progress in imaging super-earths and terrestrial planets around the very nearest stars, contributions JWST will make to imaging sub-Saturns (perhaps with habitable moons) at larger orbital radii, and complementary work to be done by WFIRST-AFTA in reflected light, which could enable us to detect the impact of greenhouse gases in an exoplanet system perhaps by the end of the next decade.

Recent work exploits the current generation of ground-based adaptive optics systems equipped with state-of-the art 3-5 micron imaging systems on 6-10 meter telescopes in an attempt to image planets around the very nearest stars. While JWST will be superior in sensitivity in the thermal IR compared to anything extant or planned in the next decades, it will probably not be competitive in the contrast limit within 10 lambda/D around the very nearest bright stars where advanced natural guide star AO has key advantages. Neptune- and Uranus-sized with temperatures > 300 K (typically < 1 AU at a few lambda/D), expected to be in thermal equilibrium with the insolation of their host star are just barely accessible with 6-10 meter telescopes around the very nearest stars (Alpha Centari A and B). We can also search for gas giant planets in the process of cooling around these nearby stars (at larger orbital separations), as well as Sirius A, Altair, Procyon A, and Proxima Cen. We will review recent progress and near-term plans for 3-5 micron imaging with current adaptive optics on 6-10 meter telescopes.

There are many challenges to overcome: a) predicting what we should see and when we should look; b) developing new algorithms and reducing the data; and c) predicting how we can extend this work with the next generation ELTs in the thermal IR, as well as from the ground and in space with reflected light. We can predict accessible super-earth populations around the very nearest stars, based on Kepler statistics. Next steps will include taking into account host star mass as well as system multiplicity. Predicting how many epochs, and at what temporal spacing, are need to fully sample the orbital phase space of a system given planet orbital separation, inclination, and eccentricity is non-trivial: one observation of each system is likely not enough! We will also present results on 3 and 5 micron data recently obtained L-band data for Proxima Centari in an attempt to combine with extant astrometry to contrain outer gas giants (possibly needed to delivery water-rich planetesimals to Proxima b).

There is the potential to extend AO assisted observations from 3-5 microns on 6-10 meter telescopes to 10 microns. Taking advantage of new detector technologies, it may be possible to image an Earth-sized planet in the habitable zone around the very nearest star within the next few years.

We will also review the capacity of JWST to image ice giants at large orbital radii (in the background, rather than contrast limit) around nearby stars. This is a discovery space uniquely available to JWST. If Uranus and Neptune mass planets are common beyond 10 AU around nearby (preferentially young) stars, JWST will see them. Whether such planets could support habitable environments is another question entirely.

Finally, we will outline the prospects to extend achievements on 6-10 meter class telescopes, making predictions concerning future work on the next generation ground- and space-based facilities. Preliminary analysis of what we think a 3-15 micron camera on a 25-40 meter class ELT can achieve compares well to expectations for future scattered light capabilities. For example, there are expected to be a handful of object which can be detected both in thermal emission AND scattered light with WFIRST-AFTA, resolving the albedo/radius ambiguity for these systems. This is an important synergy to explore as it would enable unprecedented characterization of those objects (perhaps even the search for a greenhouse effect).

IDENTIFYING THE LINKAGES BETWEEN MICROBIAL ACTIVITY AND GAS FLUX OF SUBAERIAL VOLCANIC ENVIRONMENTS: A GUIDE TO EXPLORING MAGMATIC PLANETS AND MOONS.

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Introduction: Volcanic activity and hydrothermal fluid flow are likely to have persisted, or still exist in subsurface environments of several planets in our solar system, and beyond. Ongoing NASA orbiter and rover missions are collecting physical and geochemical data to characterize planetary environments and their natural satellites, with the aim of locating habitable worlds. Even though some of the earliest experiments looking for evidence of life were based upon the premise that biological processes throughout the universe mimic those on Earth, promising contemporary analogs for habitable environments elsewhere are fumaroles associated with active arc volcanism.

Arc volcanoes, unlike the picturesque hot spot volcanoes of Yellowstone National Park, are characteristically explosive, being formed and fueled by a subducting oceanic crust. This process, driven by high temperatures and pressures at depth, encourages the release of volatiles trapped in the older lithosphere, including water vapor, CO_2, H_2S, among others. As a result, associated terrestrial environments are mineral-rich, acidic, and vent enormous quantities of reduced gases that can be assimilated or mineralized by microbial communities.

Considering all the data collected thus far from Mars [1,2,3], several environments here on Earth have been identified as "Mars analogues", leveraged as models for experimental scientists to investigate conditions promoting life [4]. Recognizing the composition of volatiles trapped in martian mudstone, including high concentrations of H_2O, CO_2, SO_2, H_2, H_2S, HCl, and other trace gases [2], it is conceivable that present-day microbes sustained by volatile outgassing associated with subduction-zone volcanism may offer a prime opportunity to conduct "analogous-microcosm" studies using soils collected from such environments here on Earth.

Leveraging coupled fumarole soil and gas samples collected from several Aleutian Island volcanoes in 2015 (Gareloi, Kanaga, Kiska, Little Sitkin) and 2016 (Okmok), and Costa Rica (2017), both of which are subduction zone systems, this research is seeking to identify the linkages between subaerial volcanic gas flux and the accompanying bacterial and archaeal activity. DNA has been extracted from the soil and is being used to describe microbial community composition, and subsequently correlated with the outgassing measurements. Preliminary data suggests a relationship between the abundance of specific groups of prokaryotes known to metabolize reduced gases, such as sulfur-reducers, carbon monoxide oxidizers, and methylotrophs, and the abundances of the degassing volatiles, including hydrogen sulfide, carbon dioxide, and methane. Ongoing studies aimed at investigating the relationship between the genomic composition of the fumarolic microbial community and the physical and chemical properties of the soil (i.e. mineralogy, bulk geochemistry, nutrient concentration, gas flux, and environmental measurements) are underway. These data will be used to evaluate the potential for microbial communities to remove volcanic carbon and store it as biomass, or to modify the volatile carbon flux through metabolic activities. With these correlations, it is expected that further refinement to the definition of "habitability" on other planets will be discerned.

References: References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] J. P. Grotzinger *et al.* (2014) *Science, 343*
[2] D. W. Ming *et al.* (2014) *Science, 343*
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BUILDING A PLANET: ASSESSING THE HABITABILITY OF K2-3 d. Camerian Millsaps[1] and Shawn Domagal-Goldman[2,3], [1]Department of Atmospheric, Oceanic, and Earth Sciences, George Mason University, 4400 University Drive, Fairfax, VA 22030; cmillsap@gmu.edu, [2]NASA Astrobiology Institute's Virtual Planetary Laboratory, Box 351580, U.W. Seattle, WA 98195 [3]Planetary Environments Laboratory, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771.

Introduction: 1-D atmospheric modeling provides an efficient method of exploring habitability constraints within specific potential follow-up target systems. We use ATMOS, a 1-D coupled photochemical-climate model, to simulate a number of self-consistent atmospheres on the super-Earth K2-3 d over geologic time. K2-3 d's mass has been measured, but is poorly constrained; we incorporate these uncertainties by exploring a range of plausible masses. We also parameterize potential atmospheric compositions. We adapt the model to accommodate both rapidly-rotating and tidally-locked scenarios. Within these scenarios, we examine a range of surface, cloud, and haze-driven albedo impacts over varying latitudes, in effect converting the model to a 1.25-D model. In doing this, we estimate the range of observational discriminants most likely to suggest habitable surface conditions.

HABITABLE PLANETS WITH DYNAMIC SYSTEM OF GLOBAL AIR-WATER-SOLID PLANET AND LIFE.

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Introduction: Habitable zone of water planet (Earth) and life (Earth) is mainly discussed by moderate temperature to keep water and life previously [1-4]. Present new model for water and life are based on two dynamic system of macro-planet and micro-life separately in micro-system of water planet. The present paper is discussed by duplicated dynamic systems in micro-planet system globally as the main purpose [1-7].

Dynamic systems of Earth and life: Planet Earth is composed of three materials states of air-liquid-solid states macroscopically as follows:

F(Earth) = *f* (air) + *f*(liquid) + *f*(solid) ....(1)

Liquid is mixed fluids to be formed by compressed between solid and air states only in increased temperature and pressure condition of planetary shock wave process through collision impact, quake or volcanic events generally. Life on our Earth is also composed of three materials states of air-liquid-solid states microscopically as follows:

F(life) = *f* (air) + *f*(liquid) + *f*(solid) ....(2)

Liquid of life is involved by organic materials of tube between solid (bone) and air (gas) states only duplicated dynamic systems of macroscopic Earth planet. In this model, temperature factor is one of required condition of two dynamic systems for their formation and development, where global liquid fluids are the most significant factor for two systems to develop three material states by evaporation and cooling change process within macro-planetary system.

Life system on inorganic water-planet: Life system is formed by inorganic and organic molecules under liquid-condition of macro-Earth system. Therefore organic life was completely ended after its activity by replacement to inorganic materials of inorganic planet called as solidified "**fossil rocks**" only survived as confined "**stopped and reserved condition**" within active Earth system for long geological history. In this model, detection of life on ex-planets is difficult for inorganic **water** and **gas** molecules because of organic life are largely discarded. **Secondary evidences** of **fossil stones** and ocean floor sediment of **carbonates** (with carbon-bearing grains) are considered to be new evidences for dynamic material changes related with water-planet and life-activity.

Remote-detection of water and life remnants: The remote-detection with telescopic instruments can be applied for detection signals of water and carbon to carbonates which are used at the FT-IR detection method in water-planet Earth widely [5-7]

Summary: The results are summarized as follows.
1) Two dynamic systems of water-Earth and life are expressed by equations (1) and (2).of air-liquid-solid factors.
2) Cyclic systems of life and Earth are not stably obtained because of continuous changes within macro-inorganic system.
3) Quasi-life of fossil (solidified stone) can be remained by life relicts, but usually replaced to bio-minerals (carbon, silica, apatite and calcite carbonates) in active Earth system.
4) Habitable zone in this study is dynamic process zone with three phase states (air-liquid-solid) of large to smaller ranges for active material exchange globally, which will be obtained in multiple circulated systems of water-planets with effective reaction for volatile (water, carbon)-bearing exchanges.
5) Water and carbon-bearing grains at older stones of samples from the Moon, Mars and Asteroids suggest that there are no global ocean water system on these worlds because of stopped states for longer times relatively (with less dynamic and circulated system).

References: [1] Miura Y. and Kato T. (1993): *American Institute of Physics Conf. Proc.*, 283, 488-492. [2] Miura Y. (1994) *Astronomical Society of the Pacific Conference Series*, 63, 259-264..[3] Miura Y. and Fukuyama S.(1999), *J. Materials Proc. Tech.* (Elsevier), 85, 192-193.[4] Miura Y. (2010) *LPI Contribution (AbSciCon)*, abstract #5037.#5398. [5] Miura Y. (2015). *LPS XXXXVI*, #181 [6] Miura Y. *et al.* (2017): *Planetary Science Vision 2050 Workshop 2017* (LPI Publication No. 1989), #8101. [7] Miura Y. (2017): *SPS-2017* (Sendai, Japan), No. 22. pp.4.

THERMAL EFFECTS OF BOMBARDMENTS IN THE EARLY SOLAR SYSTEM.

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Introduction: The most heavily cratered landscapes in the inner solar system are preserved in the ancient highlands of the Moon, Mars and Mercury. Intense early cratering affected all inner solar system bodies by melting and fracturing crusts, draping large areas in impact ejectae, generating regional-scale hydrothermal systems (i.e. on Earth, Mars' cryosphere, very early Venus), and increasing atmospheric pressure (and thereby, temperature) to modulate climate.

Bombardment scenarios: Post primary-accretionary bombardment scenarios that shaped the worlds of the inner solar system can be imagined in several ways (**Figure 1**): either as a simple exponential decay with an approximately 100 Myr half-life, or as a "sawtooth" timeline characterized by both faster-than-exponential decay from primary accretion and relatively lower total delivered mass, followed by a second, short and intense bombardment epoch. Indications are that the "late" bombardment spike was superposed on an otherwise broadly monotonic decline subsequent to primary accretion, of which two sub-types will be investigated: a classical (albeit, an idea that is now out of favor) "cataclysm" peak of impactors centered at ca. 3900 Ma that lasted 100 Myr, and a protracted bombardment typified by a sudden increase in impactor flux at ca. 4100-4300 Ma with a correspondingly longer decay time (~400 Myr).

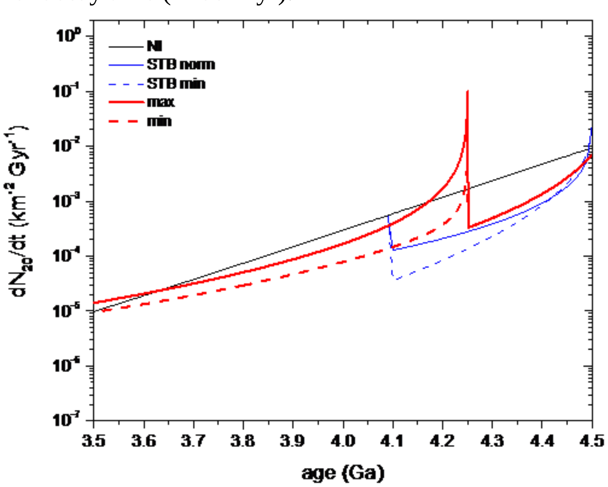

Figure 1. *Differential number of lunar craters > 20 km (N20) as a function of time and per unit surface for scenarios considered herein. These are used to compute the terrestrial impactor flux. The different scenarios range from a* ***monotonic decay*** *of the flux (no LHB; black curve of [ref.1]), a* ***sawtooth bombardment*** *(STB) with a moderate increase of the flux during the LHB arbitrarily set at 4.15 Gy ago (blue curve from [ref. 2]), and a red curve with a rapid rise in impacts at 4.25 Ga.*

We report new 3-D analytical thermal models for each of the scenarios cited above to (i) explore how silicate crusts (and in the case of Mercury, its mantle) thermally responded to bombardment with abundant liquid water (Earth, very early Venus, early Mars), or in a cryosphere (Mars), or under completely dry conditions (Mercury, late Venus, Moon); and (ii) provide detailed dynamical models [e.g. ref. 3,4] of solar system evolution to explain these bombardments.

Results: Our preliminary work has shown that depending on the chosen scenario, other physical effects of impacts were at least as important as impact melt generation. For example, between 10 and 100% of the Hadean Earth and Noachian Mars surface was covered by impact craters and blanketed in resultant (hot) ejecta [5,6,7]. In the case of the habitability of early Mars – a generally arid and cold planet that was always at the edge of the solar system's habitable zone [8] – heating from impacts punctuated an otherwise cold, arid surface state by intermittently destabilizing the near-subsurface cryosphere to generate regional-scale hydrothermal systems.

We assess using new dynamical studies of solar system evolution whether impacts were deleterious to the proclivity of the inner solar system to host emergent biospheres (at least on Earth). Specifically, we show how impacts affect the volume and duration of the surface/subsurface geophysical habitable zones, including an evaluation of the habitable potential of Venus in the first hundred million years.

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CONSTRAINING PLANET FORMATION MODELS FROM THE KEPLER EXOPLANET POPULATION.
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Introduction: The Kepler Spacecraft has discovered a population of exoplanets ranging in size from Mars to Neptune and in orbital period from a day to a year. This population of exoplanets orbits the majority of stars in the galaxy, and has changed our idea of what typical planetary systems look like, how they may form, and what composition they may acquire. The composition of rocky planets in terms of water and other bio-critical ingredients may not be directly observable right now, but statistical constraints can be gained from understanding how these planets form and where they accrete their material from [1,2]. With a well-understood detection efficiency and survey bias, the Kepler exoplanet population provides the most stringent constraints to date on exoplanet formation models.

Exoplanet Populations: Kepler has monitored stars with a wide range of masses and metallicities for transiting planets. These stellar properties trace the conditions in the protoplanetary disk at the time of planet formation, and leave an imprint on the exoplanet population. We derive planet occurrence rates as a function of stellar mass [3] and metallicity [4]. We find that lower mass stars contain more planets overall, but fewer giant planets. The heavy-element mass of planetary systems anti-correlates with stellar mass, in stark contrast with observed protoplanetary disk dust masses which show a positive correlation, see Figure 1. The increased efficiency at which low-mass stars form planetary systems close to their host stars shows that inward migration of planetary building blocks plays a crucial role in the planet formation process [5].

Exoplanet Composition: Inward migration of forming planets significantly impacts the amount of water and other volatiles that can be accreted from outside the snow line(s). As part of the Earths in Other Solar Systems team (EOS, PI:D. Apai) we are currently running creating a large database of high-resolution planet formation simulations including a detailed accretion history for individual planets. By comparing the planetary systems formed in these simulations with the observed exoplanet population we can put statistical constraints on exoplanet composition.

Constraining Planet Formation Models: In this talk I will showcase the Exoplanet Population Observation Simulator (EPOS). EPOS is a tool to compare the outcome of planet formation and planet population synthesis models with observed exoplanet populations that accounts for survey completeness and planet multiplicity. I will show how current planet population synthesis models compare to the Kepler data: different planet formation mechanisms, in particular in situ formation and planet migration, reproduce different regions of exoplanet parameter space. I will highlight areas where these models need to be augmented, in particular in damping the inlinations of multi-planet systems formed in situ and in reproducing the orbital-period distribution of super-earths that migrated to their current locations.

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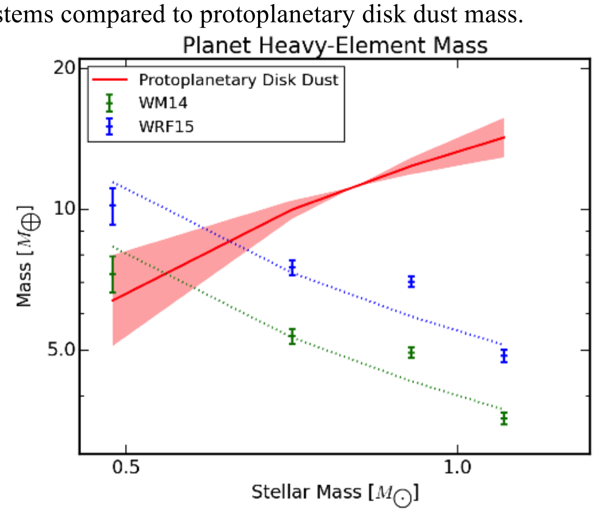
Figure 1: Heavy-element mass of exoplanetary systems compared to protoplanetary disk dust mass.



UV SURFACE ENVIRONMENTS OF M STAR PLANETS: SURFACE HABITABILITY & TEMPORAL BIOSIGNATURES. J. T. O'Malley-James[1] and L. Kaltenegger[1], [1]Carl Sagan Institute, Cornell University, Ithaca, NY 14853, USA.

Introduction: The nearest known habitable planets orbit red dwarf (M) stars in the solar neighborhood, such as Proxima Centauri[1], TRAPPIST-1[2] and LHS-1140[3]. More nearby habitable worlds around similar stars will be uncovered in the near future. Therefore, the first cohort of habitable worlds we are likely to characterize will be orbiting nearby M stars. However, M stars present a challenge for habitability in the form of strong, frequent flares. These flares can cause surface ultraviolet (UV) radiation fluxes on habitable zone (HZ) planets to increase by up to two orders of magnitude[4], which would be harmful for any surface life. Even more intense UV surface regimes would exist on planets without protective ozone layers, or planets with thin atmospheres.

Biosignatures exhibited by life on Earth may not be present on these highly UV-irradiated worlds. Any surface life would need to employ UV defense strategies, while atmospheric biosignature gases could be reduced or erased. Therefore, we need to begin assessing the UV environments of these planets to determine the types of life that could both survive and produce observable biosignatures. These biosignatures could be very different from the traditional suite of signatures associated with Earth's biosphere.

Here we begin this process by presenting models of the UV surface environments of the TRAPPIST-1[5] and Proxima Centauri[6] systems, for both oxygen-containing and anoxic atmospheres over a range of possible atmospheric densities. We compare these environments to the known tolerances of terrestrial life and determine the forms of life best suited to forming stable biospheres on these worlds.

Methods: The high-energy X-Ray and EUV fluxes from stars like these can erode planetary atmospheres. Therefore, our model atmospheres range from dense 1 bar atmospheres to low-density 0.1 bar atmospheres. To simulate UV surface radiation environments we use a coupled 1D radiative-convective atmosphere code developed for rocky exoplanets (EXO-Prime)[7] with stellar input spectra based on observations or models of the active M star hosts.

Results: If a dense Earth-like atmosphere with a protective ozone layer could be maintained on these planets, UV surface environments would be similar to the present-day Earth, even for highly active stars. However, eroded or anoxic atmospheres allow high shortwave UV fluxes to reach planetary surfaces, making surface environments hostile even to highly UV-tolerant terrestrial extremophiles (*Fig. 1*). If future observations detect ozone in the atmospheres of any of the HZ planets around active stars, these would be interesting targets for the search for surface life. However, some UV defense strategies, such as biofluorescence could produce an observable temporal biosignature for more highly UV-irradiated planets during flares[8][9].

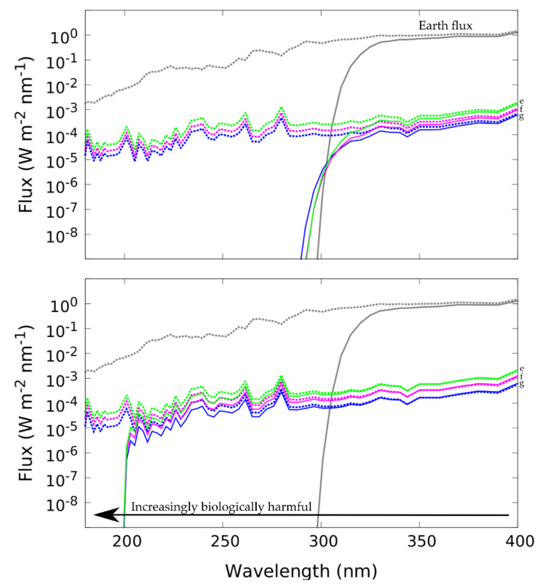


Figure 1*. Model UV top-of-atmosphere (dashed) and surface fluxes (solid) for the TRAPPIST-1 system (planets e, f, g)[5]. (Top) Earth-like atmosphere. (Bottom) Anoxic atmosphere. Earth fluxes are shown for comparison in gray. Surface UV fluxes increase to extremely biologically damaging levels for anoxic and low-density atmospheres, making planets uninhabitable for exposed surface life.*

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DISK PROPERTIES ACROSS THE STELLAR/SUBSTELLAR BOUNDARY AND IMPLICATIONS FOR PLANET FORMATION AND DETECTION OF PLANETS AROUND M-STARS.
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Introduction: With a combination of submm/mm observations, we are investigating the properties of disks around low mass M-stars and brown dwarfs in the Taurus star-forming region. Disk masses, sizes and multi-wavelength spectral slopes are important properties to assess the viability of planet formation in the disks and scenarios for grain growth in disks and formation of brown dwarfs. M-stars have a central role in current, planned, and possible future exoplanet search and characterization programs and understanding their environments informs detection experiments. Highlighting the importance of characterizing M-star environments are the large population of M-stars (e.g. ~75% of the field; Henry et al. 2006) and recent discoveries of intriguing systems of low mass planets orbiting M-stars such as Proxima Centauri (Anglada-Escude et al. 2016), LHS 1140 (Dittmann et al. 2017) and TRAPPIST-1 with seven planets around this M8 star near the brown dwarf limit (Gillon et al. 2017).

Sample and Observations: A sample of 24 Class II Taurus members with spectral types from M4-M7.75 were observed with ALMA at 885μm (Ward-Duong et al. 2017) and a subset of these targets were observed at ~3mm with PdBI or ALMA. The 24 targets represent half of the Class II members in this spectral type range with *Herschel*detections and span the full range of PACS 70μm fluxes rather than a subset of the brightest members. This pilot study includes 7 transition disks and 1 truncated disk, and the non-detections are both transition disks. The 885μm ALMA maps have a typical 1-sigma sensitivity level of ~0.13mJy/beam and a beam size of approximately 0.3arcseconds.

Results: All 24 targets are detected in either continuum or CO, with 20 detected in both. In continuum, 22 systems are detected at levels ranging from 1.0 mJy to 55.6 mJy (Ward-Duong et al. 2017). The two continuum non-detections are transition disks, though other transition disks in the sample are detected. Converting the ALMA continuum measurements to masses using standard scaling laws and radiative transfer modeling yields dust mass estimates ranging from ~0.3M⊕ to ~ 20M⊕ . The dust mass shows a declining trend with the mass of the central object when combined with results from submillimeter surveys of more massive Taurus members. The substellar disks appear as part of a continuous sequence and not a distinct population. Compared to older Upper Sco members with similar masses across the substellar limit, the Taurus disks are brighter and more massive. The disks around the early M-type stars in Taurus typically contain more mass in small solid particles than the average for heavy elements in the planetary systems found with *Kepler* on short-period orbits around M-dwarf stars (Mulders et al. 2015). Assuming a gas:dust ratio of 100:1, only a small number of the low-mass stars and brown dwarfs have a total disk mass amenable to giant planet formation, consistent with the low frequency of giant planets orbiting M-dwarfs. Several dust disks are spatially resolved, though more compact than disks around more massive stars. Compared to the dust disks, the gas disks are typically larger, with many spatially resolved and showing Keplerian velocity maps.

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UNDERSTANDING THE CONDITIONS OF PLANET FORMATION THROUGH CHONDRULES . A. M. Perez[1], S. J. Desch[1], D. L. Schrader[1], and C. B. Till[1], [1]School of Earth and Space Exploration, Arizona State University, P.O. Box 871404, Tempe, AZ 85287-1404, alexandra.m.perez@asu.edu

Introduction: A major constituent of chondrites are mm-sized igneous inclusions called chondrules, which are known to have formed during the protoplanetary disk phase during the initial stages of the Solar System [1]. The heating mechanisms that initially melted chondrules in the nebula are key to constraining astrophysical models of the disk and the energetic processes that were present during planet formation, but their formation mechanism(s) remains a mystery.

Chondrules display a variety of different textures controlled by parameters such as grain size, peak temperature, heating duration, and cooling rate, but the most dominant texture are porphyritic, making approximately 82 to 99% of all chondrules [2]. These textures can be described as having euhedral to subhedral phenocrysts of olivine and/or pyroxene set within a fine grain matrix.

Large-scale (spiral density wave) shocks and bow shocks around planetary embryos (radius >1000 km) are currently the most favored astrophysical models for chondrule formation. These models meet all the constraints required for an ideal chondrule formation mechanism, which include ambient temperature, peak temperature, and heating duration [3]. We are investigating the planetary embryo bow shock model (PEBSM) [4,5], a relatively new and attractive model that suggests chondrules were byproducts of planet formation instead of the building blocks, but this model predicts cooling rates in excess of 3000 K/hr. Despite a plethora of experiments to understand chondrule formation, it is not clear whether or not porphyritic chondrules can be formed at cooling rates consistent with the PEBSM. So far, these textures have only been reproduced by cooling rates up to 2500-3000 K/hr [6].

Approach: To experimentally investigate the PEBSM, we created chondrule analogs by mixing the minerals olivine, diopside, and albite [7]. The analogs are suspended from a thermocouple inside a 1 atmosphere vertical gas mixing furnace located at the Experimental Petrology and Igneous process Center (EPIC) at ASU, and undergo various parameter combinations, including varying grain sizes, peak temperatures, heating durations, cooling rates, and further investigating nucleation sites through the addition of spinel into the starting bulk compositions. The resultant blebs are subsequently mounted in epoxy, polished, and carbon coated for electron probe microanalysis.

Results: Results show a continuum of textures at cooling rates around 5000 K/hr (Figure 1). These textures include spinifex-like, a quench crystal texture, skeletal grains, relic grains, and a combination of both spinifex and relic grains. Currently, we have not been able to reproduce porphyritic textures at cooling rates in excess of 3000 K/hr. However, the PEBSM shows a similar cooling rate of 2000 K/hr through the crystallization range if the evaporation of dust is present [8].

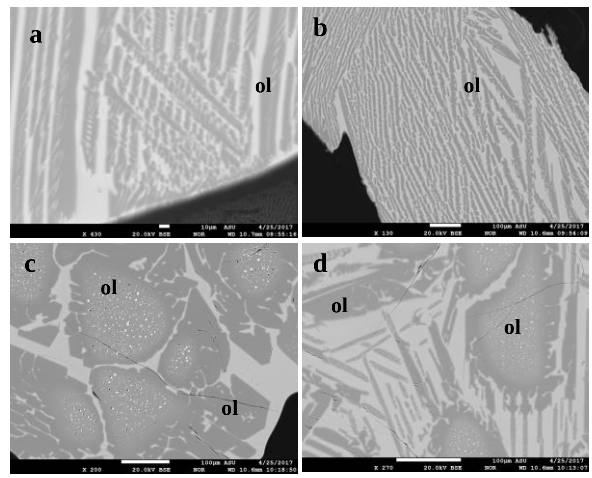

Figure 1. Experimental results with cooling rates at approximately 5000 K/hr. The analogs were heating for 10 minutes at the liquidus prior to being cooled. Runs (c) and (d) show possible Fe cores in olivine phenocrysts that could be a result due to lack of using oxygen fugacity.

If we are able to find the right parameter combination(s) consistent with the PEBSM to successfully reproduce porphyritic textures, this model would be found to be consistent with all the known chondrule properties to make a chondrule formation model successful, increasing our understanding of the energetic events that were present during the early stages of the Solar System responsible for planet formation.

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Simultaneous, Multi-Wavelength Flare Observations of the M dwarf Wolf 359. E. V. Quintana[1], T. Barclay[2], J. Schlieder[2], P. Boyd[2], and B. Thackeray-Lacko[2]. [1]Goddard Space Flight Center, Exoplanets and Stellar Astrophysics Laboratory, 8800 Greenbelt Road, Greenbelt, MD, 20771, [2]University of Maryland, College Park, Department of Astronomy, College Park, MD, 20742.

Introduction: Wolf 359, aka CN Leo, is a nearby late-M dwarf that is known to produce frequent flares with a duration of minutes to hours. M dwarfs are smaller, cooler and less luminous than the Sun, and therefore difficult to observe in detail. At just 2.4 parsecs away, Wolf 359 is bright, making it an ideal target for the study of stellar activity in low mass stars. We have begun a pilot study to obtain simultaneous, multi-wavelength observations of Wolf 359 to form a comprehensive picture of its stellar activity. We will present results from our observations in the optical, UV, X-ray, and radio wavelengths using K2, Swift, and ground based observatories. We will discuss the potential impact on exoplanet habitability and describe the prospects of future multi-wavelength flare observations in the era of TESS.

Stellar Activity: Most of what is known about stellar activity comes from studies of our Sun. The Sun's magnetic activity is sustained through a complex combination of convection and radiation, while smaller stars rely proportionally less on radiation, with the smallest being completely convective. The intrinsic magnetic activity of convective low-mass stars like Wolf 359 is manifested in part by stochastic, short-term brightenings; flares. The magnetic activity driving flares is critical to planetary atmospheres and habitability. High-energy radiation and energetic particle emission associated with activity drive photochemistry, can erode atmospheres, and impact habitability.

Observations: K2, the repurposed Kepler mission, observed Wolf 359 for over 80 days in May-August 2017. These high-precision, 1-minute cadence photometric observations will allow us to measure the epochs, frequencies and energies of flares. Simultaneous X-Ray and Ultra-Violet observations were taken using the space-based SWIFT observatory. These higher energy wavelengths reveal the amount of energy being released during flare events. We obtained simultaneous radio observations with a wide range of frequencies which will allow us to look for correlations between radio bursts, coronal mass ejections, and optical flaring events. Our full analysis will begin when the K2 data is downlinked in September 2017.

Planets?: Low-mass stars are the most common stars in the Galaxy and have been targeted in the tens-of-thousands by K2. The Kepler and K2 missions have taught us that M dwarfs typically host multiple small planets, many of which reside within the habitable zone. Observations from the Hubble Space Telescope and ground-based telescopes have ruled out the presence of giant planets like Neptune orbiting Wolf 359. The existence of smaller Earth-sized planets, however, remains uncertain. If Wolf 359 does harbor small planets, and they transit the star as viewed from Earth, K2 could reveal their presence. Regardless, the information gained by studying Wolf 359 will help us understand the stellar-planetary environment of similar stars that harbor planets.

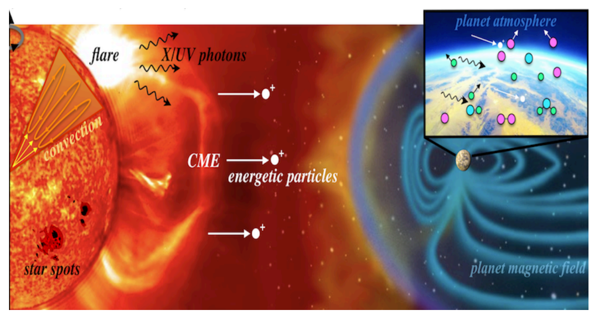

Figure 1: Intense stellar activity, such as flares and coronal mass ejections, can project energetic particles towards a planet which interact with the atmosphere.

Implications: M Dwarfs will be prime targets in the search for habitable worlds by the upcoming James Webb Space Telescope. There are predictions that a combination of flares and energetic particles from an M Dwarf could strip a planet's atmosphere. However, these predictions rely on extrapolating observations of the Sun's radiation environment by orders of magnitude to model events on M dwarfs. This multi-wavelength campaign to observe the M dwarf Wolf 359 will pave the way towards a larger study with TESS, the Transiting Exoplanet Survey Satellite - set to launch in mid-2018. TESS is expected to find a large number of planets orbiting nearby M dwarfs that are amenable to follow-up observations. Our long-term goal is to study flares in a population of both young and old M dwarfs, and in a wide range of M dwarf masses (from TRAPPIST1-like stars that are about 8% the mass of our Sun, to Kepler-186-like stars that are about 50% the mass of our Sun) and metallicities. These observations will help us understand if we can apply our knowledge of the Sun's activity to low mass stars, or if new models will need to be established. M dwarfs constitute more than 70% of all stars in the Solar neighborhood, thus understanding their stellar activity and effects on planets will have big implications on the abundance of potentially habitable planets in our galaxy.

THE LIGHT SOURCE PROBLEM: THE EFFECT OF HETEROGENEOUS STELLAR PHOTOSPHERES ON SEARCHES FOR TRANSITING EXOPLANET BIOSIGNATURES. B. V. Rackham[1], D. Apai[2]. M. S. Giampapa[3]. [1]Dept. of Astronomy, University of Arizona, 933 North Cherry Ave., Tucson, AZ 85721, USA (brackham@as.arizona.edu); [2]University of Arizona, Tucson, AZ. [3]National Solar Observatory, Tucson, AZ.

Introduction: Transmission spectroscopy offers the exciting possibility of studying terrestrial exoplanet atmospheres in the near-term future. Ground- and space-based facilities in the coming decade may identify biologically produced molecules from opportune targets with this technique [1, 2, 3], which can constrain the chemical composition of the upper atmosphere of a transiting exoplanet. The Transiting Exoplanet Survey Satellite (TESS), scheduled for launch next year, is expected to discover thousands of transiting exoplanets around bright host stars, including an estimated 48 habitable zone exoplanets with radii less than two Earth radii [4]. The brightness of the TESS host stars, combined with refined observational strategies and near-future facilities, will enable searches for atmospheric signatures from smaller and cooler exoplanets.

These observations, however, will be increasingly subject to noise introduced by heterogeneities in the host star photospheres, such as star spots and faculae. In short, the transmission spectroscopy method relies on the assumption that the spectrum of the transit chord does not differ from that of the integrated stellar disk or, if it does, the contribution of photospheric heterogeneities to the transmission spectrum can be constrained by variability monitoring. However, any axisymmetric populations of spots and faculae will strongly affect transmission spectra, and their presence cannot be deduced from monitoring efforts. Given this, a clear need exists for a more robust understanding of stellar contamination on transmission spectra.

In a recent study on the transiting sub-Neptune GJ 1214b, for example, we found its optical transmission spectrum is strongly influenced by unocculted stellar faculae in the photosphere of the host star [5]. Follow-up work utilizing our same modeling framework for assessing the stellar and exoplanetary contributions to transmission spectra shows that a large subset of published spectra are likewise affected by heterogeneous stellar photospheres, leading to misinterpretations of spectral feautres purportedly originating in the exoplanets' atmospheres [6]. In order to successfully identify and interpret biosignatures, the community will need to develop metrics for understanding when heterogeneous stellar photospheres will be important and methods for handling their effects.

This Work: Here we summarize our work [7] on the impact of heterogeneous stellar photospheres on transmission spectra and detail implications for atmospheric characterization efforts. We focus on M dwarf exoplanet host stars, which offer the best opportunities for atmospheric characterization of small, rocky exoplanets in the near-term future.

By modeling spot and faculae distributions in stellar photospheres, we find that spot-covering fractions extrapolated from observed variability amplitudes are significantly underestimated. Likewise, corrections to transmission spectra based on variability monitoring likely fall short of the actual stellar spectral contamination. We provide contamination spectra across a range of spectral types for typical levels of stellar activity, including contributions from spots and faculae. For M dwarfs, molecular absorption features in spots can imprint apparent features in transmission spectra on the scale of atmospheric features from small exoplanets, while contamination from unocculted faculae can mask real exoplanetary features. Additionally, we explore the specific case of the TRAPPIST-1 system, determining realistic ranges of spot- and faculae-covering fractions consistant with the observed variability amplitude and providing the associated stellar contamination spectra.

Our results suggest that constraining stellar contamination will likely be a limiting factor for detecting atmospheric features in transmission spectra of low-mass exoplanets around late-type stars from TESS, including potential biosignatures from habitable zone exoplanets.

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HABITABLE ZONES: EXTENSIONS IN SPACE AND TIME R.M. Ramirez[1] and L. Kaltenegger[2], [1] Earth-Life Science Institute, email: ramsesny@gmail.com, [2]Carl Sagan Institute and Cornell University, email: lkaltenegger@astro.cornell.edu

Introduction: The habitable zone (HZ) is the circular region around a star in which liquid water could exist on the surface of a rocky planet [1]. Previously established definitions of the habitable zone have assumed that the main-sequence (MS) phase of stellar evolution, and the most common greenhouse gases on our planet – CO_2 and H_2O vapor – can be used to standardize habitability throughout the cosmos.

However, some habitable worlds could exist orbiting stars undergoing their pre-MS and post-MS evolutionary phases. Also, other greenhouse gases, such as H_2 and CH_4, can significantly extend the width of the traditional CO_2-H_2O habitable zone. We also discuss the potential habitability of Proxima Centauri b and the TRAPPIST-1 planets under our expanded HZ definitions.

Methods: As in previous HZ studies [2 – 4], we used a 1-D radiative-convective climate model to compute habitable zone boundaries for stars of stellar effective temperatures (T_{eff}) ranging from 2,600K to 10,000K

Results: We compute the HZ boundaries for the pre- to post-MS HZ and also show how the addition of 1 – 50% H_2 and 1 – 10% CH_4 can change the boundaries of the traditional CO_2-H_2O HZ (Figures 1 – 4) [3 - 5].

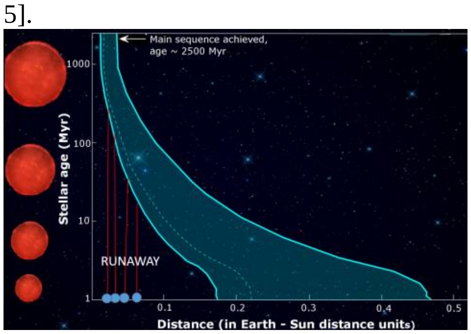

Figure 1: Pre-MS HZ boundaries for TRAPPIST-1 (~ M8) star and the planets e,f,g, and h (in distance (Earth-sun distance units or AU) and stellar age (Myr). All four planets are well past the pre-MS inner edge and suffer a runaway greenhouse.

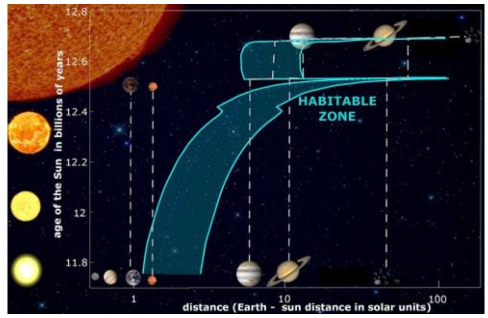

Figure 2: Solar system Post-MS HZ boundaries. Stellar winds completely erode atmospheres of Earth-sized planets located as far as Jupiter's orbit.

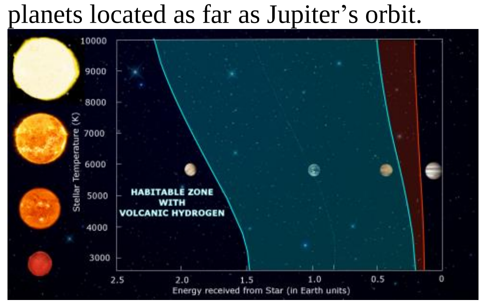

Figure 3: Orbital distance for the classical (blue) and volcanic hydrogen (red) habitable zone.

Discussion:. The HZ is wide during the pre-MS and can last over 2 billion years for late M stars, making such systems prime targets for next-generation telescopes [3]. However, many planets (e.g. TRAPPIST-1 planets and Proxima Centauri b) around such stars could have undergone a runaway greenhouse during the pre-MS and may not be habitable today (Figure 1). In contrast, the HZ moves outward as the star expands during the post-MS phase, potentially providing a "second wind" of habitability (Figure 2) [4].

Adding volcanic hydrogen also widens the classical HZ. At 50% H_2, the outer edge of our solar system moves outward from 1.67 to ~2.4 AU (Fig 3) [5]

Also, CO_2-CH_4 absorption has been shown to significantly warm early Mars [6,7]. We apply that idea to the CO_2-H_2O HZ and discuss how it may extend or shrink it.

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[7] Ramirez, R.M. , (2017), Icarus, 297, 71-82.

Planetary Sources for Reducing Sulfur Compounds for Cyanosulfidic Origins of Life Chemistry. S. Ranjan[1,5], Z. Todd[2], J. Sutherland[3], and D. D. Sasselov[4]. [1]Harvard-Smithsonian CfA, 60 Garden Street, Cambridge, MA 02138; sranjan@cfa.harvard.edu, [2]Harvard-Smithsonian CfA, 60 Garden Street, Cambridge, MA 02138; zoe.todd@cfa.harvard.edu, [3]MRC Laboratory of Molecular Biology, Francis Crick Avenue, Cambridge Biomedical Campus, Cambridge CB2 0QH, UK.; johns@mrc-lmb.cam.ac.uk, [4]Harvard-Smithsonian CfA, 60 Garden Street, Cambridge, MA 02138; dsasselov@cfa.harvard.edu, [5]MIT EAPS, 77 Massachusetts Ave., Cambridge, MA 02139

Introduction: A key challenge in origin-of-life studies is understanding the chemistry that lead to the origin of the key biomolecules of life, such as the components of nucleic acids, lipids, and proteins. Prebiotic reaction networks based upon reductive homologation of nitriles (e.g., [1,2], and sources therein), are building a tantalizing picture of sustained abiotic synthesis of activated ribonucleotides, amino acids, sugars, and lipid precursors under environmental conditions thought to have been available on early Earth. Sulfidic anions in aqueous solution (e.g., HS^-, HSO_3^-) under near-UV irradiation play important roles in these chemical pathways. However, the sources and availability of these anions on early Earth have not yet been quantitatively constrained. Here, we evaluate the potential for the atmosphere to serve as a source of sulfidic anions, via dissolution of volcanically-outgassed SO_2 and H_2S into water reservoirs.

Methods: We combine photochemical modeling from the literature [3] with equilibrium chemistry calculations to place constraints on the partial pressures of SO_2 and H_2S required to reach the elevated concentrations of sulfidic anions (≥1 μM) thought to be necessary for prebiotic chemistry.

Results: We find that micromolar levels of SO_2-derived anions (HSO_3^-, SO_3^{2-}) are possible through simple exposure of aqueous reservoirs like shallow lakes to the atmosphere, assuming total sulfur emission flux comparable to today. Millimolar levels of these compounds are available during the epochs of elevated volcanism, due to elevated sulfur emission flux. Radiative transfer modeling suggests the atmospheric sulfur will not block the near-UV radiation also required for the cyanosulfidic chemistry. However, H_2S-derived anions (e.g., HS^-) reach only sub-micromolar levels from atmospheric sources, meaning that prebiotic chemistry invoking such molecules must invoke specialized, local sources. Prebiotic chemistry invoking SO_2-derived anions may be considered more robust than chemistry invoking H_2S-derived anions. In general, epochs of moderately high volcanism may have been especially conducive to cyanosulfidic prebiotic chemistry

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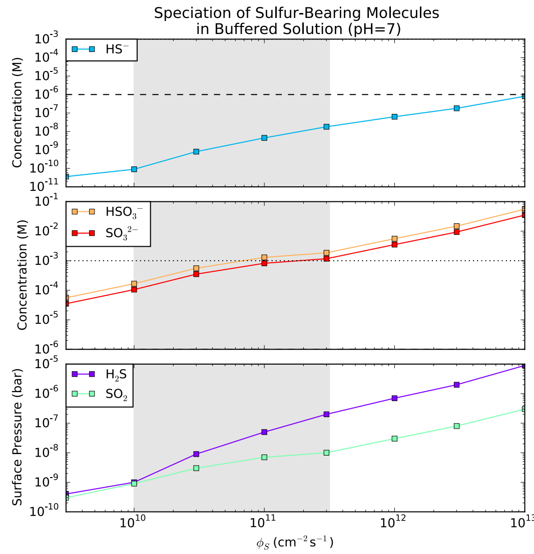
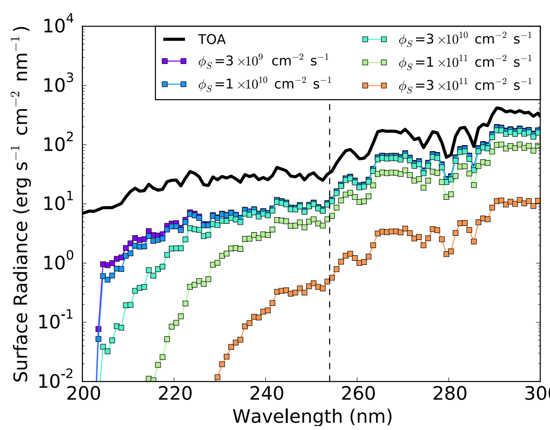


Speciation of sulfur-bearing molecules in an aqueous reservoir buffered to pH=7 as a function of total sulfur emission flux φ_S. The range of φ_S for emplacement of basaltic plains on Earth is shaded in grey. The horizontal dashed and dotted lines demarcate micromolar and millimolar concentrations, respectively.



UV surface radiance for the early Earth as a function of φ_S, using the models of [3]. The black solid line indicates the irradiation incident at the top of the atmosphere from the young Sun. The vertical dashed line demarcates 254 nm, the emission wavelength of the low-pressure mercury lamps commonly used in prebiotic chemistry studies.

The Surface UV Environment on Planets Orbiting M-dwarfs: Implications for Origins-Of-Life Chemistry & Need for Experimental Follow-Up.

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Introduction: Potentially-habitable planets orbiting M-dwarfs are of intense astrobiological interest because they are the only rocky worlds accessible to atmospheric characterization and biosignature search over the next 10+ years due to a confluence of observational effects [1,2,3]. Simultaneously, recent experimental and theoretical work suggest that UV light may have played a key role in the origin of life on Earth, and especially the origin of RNA [4,5,6]. Characterizing the UV environment on M-dwarfs planets is important to understanding whether life as we know it could emerge on them.

Methods: We couple radiative transfer models to observed M-dwarf spectra to determine the UV environment on prebiotic Earth-analog planets orbiting M-dwarfs. We combine these surface UV spectra with simple physical chemistry models to quantify the impact of different host stars on prebiotically-important photoprocesses by calculating relative reaction rates.

Results: We find that M-dwarf planets have access to 100-1000 times less bioactive UV fluence than early Earth. It is unclear whether UV-sensitive prebiotic chemistry that may have been important to abiogenesis, such as the only known prebiotically plausible pathways for pyrimidine ribonucleotide synthesis, could function on M-dwarf planets. This uncertainty affects objects like the recently-discovered habitable-zone planets orbiting Proxima Centauri, TRAPPIST-1, and LHS 1140. Laboratory studies of the sensitivity of putative prebiotic pathways to irradiation level are required to resolve this uncertainty, and we describe the specific studies required [7].

We evaluate whether thinner atmospheres or elevated M-dwarf UV output during the pre-main sequence phase can compensate for this lack of UV, and find they cannot. However, transient elevated UV irradiation due to flares may suffice; laboratory studies can constrain this possibility as well. If laboratory studies bear out this possibility, then planets orbiting active flare stars may be more compelling candidates for biosignature search than previously considered, especially if their atmospheres are stable to escape [7].

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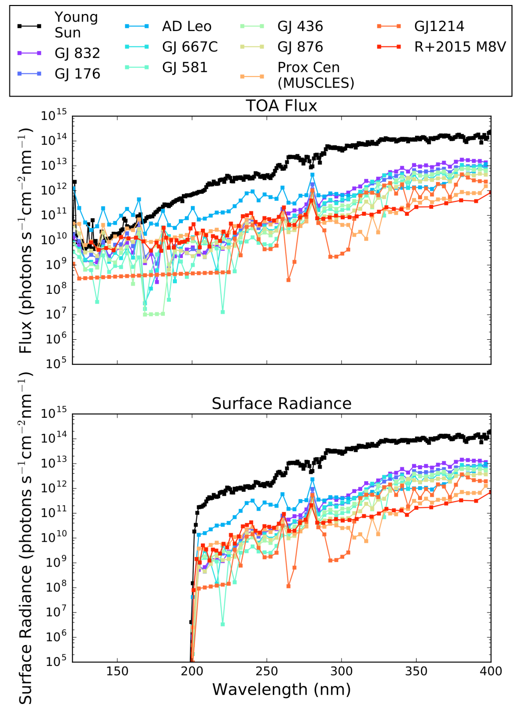
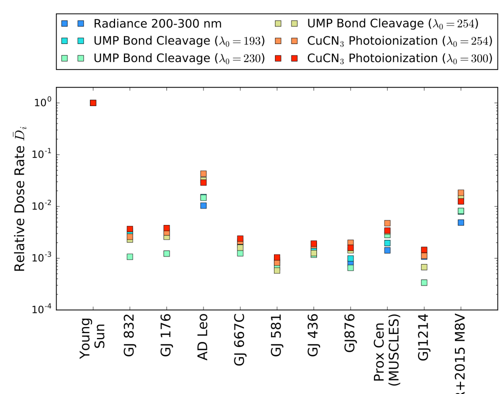


Top-of-atmosphere and surface UV radiation environment for early-Earth analog planets orbiting M-dwarfs. M-dwarf planet surfaces are UV-poor environments.



Relative dose rates for prebiotically relevant photoprocesses for M-dwarf planets. M-dwarf reaction rates are suppressed by 2-4 orders of magnitude relative to Sunlike stars, and it is uncertain if prebiotic photochemistry can function on them. Experiments can resolve this uncertainty.

Emergent Tidal Resilience for Exomoons and Extrasolar Planets via the Increased Tidal Dissipation of the Andrade and Sundberg-Cooper Rheological Models

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Abstract: The habitability of extrasolar moons can be expected to follow a pattern similar to our own outer Solar System, whereby tidal heating plays a major role in maintaining the warmth required for the presence of liquids even in very low insolation environments [1]. We show that a satellite in an eccentric orbit will produce increased tidal dissipation compared to prior models, in certain temperature and frequency domains, when its interior is modeled with realistic rheologies. The microphysics of common terrestrial rock samples have been well-documented in laboratory settings by the geological community, but such data have been somewhat underutilized for planetary tidal applications. By examining low-to-moderate temperature mantles (1400—1600 K), we find realistic rheological models such as the Andrade rheology [2] produce at least 10x the dissipative heating compared to the traditional Maxwell model. Further heating is generated from more recent extensions beyond the Andrade rheology, such as the composite model of Sundberg and Cooper [3], which capture an even greater range of grain-scale phenomena.

This creates a new spectrum of tidal-convective equilibrium points [4] that a cooling or warming planetary object can fall into, thereby driving the system to unique long-term states. This has implications for the thermal-orbital history of common tidally active systems, such as relaxed limits on the timing of tidal activation during mean motion resonance assembly. In particular, the enhanced heat production at such lower mantle temperatures can significantly improve the ability for tides in silicate exomoons to recover from low-eccentricity excursions, and thus to return to highly active tidal states; a condition we term 'tidal resilience.' Together the properties of tidal resilience, and fewer restrictions on resonance capture, can mean a greater number of tidally active worlds among all extrasolar systems, with commensurate improvements in opportunities for altering habitability.

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PREBIOTIC CHEMISTRY ON EXOPLANETS WITHIN THE LIQUID WATER HABITABLE ZONE.

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How universal is life? It has been determined in the laboratory that many of the key building blocks of life can be formed photochemically [1,2]. At the same time, the part of almost every exoplanet system that we understand best is the star. Going beyond whether life can survive on a particular rocky planet, we explore whether life could originate on a rocky planet within the liquid water habitable zone by comparing the laboratory photochemistry ('light chemistry'), which is performed under the light of a mercury lamp, to the ultraviolet (UV) spectra of various stars [3]. The laboratory chemistry begins with hydrogen cyanide, water, and an anionic source of solvated electrons [1]. We then measure the rate of bimolecular reactions of the hydrogen cyanide and the anions in the absence of the UV light ('dark chemistry'), which lead to inert adducts and not to prebiotic species. The competition between the light and dark chemistry is dependent on the UV spectrum of the star. We find that quiescent emission from main sequence stars hotter than K5 (4400 K) provide enough UV flux for the light chemistry to win out over the dark chemistry. Life cannot originate photochemically on planets around quiet stars cooler than 4400 K. We also find that very active stars may be able to drive the formation of prebiotic species with their flares. So it may turn out that, especially for ultracool stars, exoplanets around active stars would be better targets for the search for life than planets around quiet stars.

References: [1] Patel B. H. et al. (2015) *Nature Chemistry,* 7(4), 301. [2] Sutherland, J. D. (2017) *Nature Reviews Chemistry*, 1, 0012. [3] France, K. et al. (2016) *ApJ*, 820(2), 89.

REALISTIC SIMULATIONS OF CORONAGRAPHIC OBSERVATIONS WITH FUTURE SPACE TELESCOPES.
M. J. Rizzo[1], A. Roberge[1], A. Lincowski[2], N. T. Zimmerman[1], R. Juanola-Parramon[1], L. Pueyo[3], M. Hu[4], A. Harness[4], [1]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt MD 20771, maxime.j.rizzo@nasa.gov; [2]Dept of Astronomy, University of Washington, Box 351580, Seattle, WA 98195; [3]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; [4]Dept of Aerospace Engineering, Princeton University, Princeton, NJ 08544

We present a general framework to simulate realistic observations of future space-based coronagraphic instruments. This framework gathers state-of-the-art scientific and instrumental expertise and provides an end-to-end tool to simulate full observing scenarios, allowing robust characterization of future instrument concepts.

First, a spatially and spectrally resolved astrophysical scene is constructed with a star, a planetary architecture, and dynamically-consistent exozodiacal dust structure. It is superimposed to a background scene with stars and galaxies with realistic colors, which is based on the Hubble Ultra Deep Field galaxies. Several pre-computed scenes exist for different types of coronagraphs, and will be made publicly available. Scenes without exozodiacal dust can be constructed within the software.

The input science cube is processed with a coronagraph model, using pre-computed libraries of on- and off-axis point-spread funtions. Several instrument models can be chosen, including the WFIRST coronagraph, a starshade, and the LUVOIR coronagraph. These instrument simulations take into account time-varying wavefront errors that can degrade the contrast and decrease the performance of post-processing algorithms.

Various detector models are proposed to read out the focal plane, including the photon-counting EMCCDs baselined for WFIRST and LUVOIR. This generates realistic data products that can be used for post-processing.

Elementary post-processing methods, such as reference differential imaging (RDI), are also included as a set of basic post-processing routines. In the case of RDI, the user needs to run the code by also simulating the observation of a reference star, in addition to a target star.

We can also simulate using an integral field spectrograph as a backend instrument to the coronagraph. This allows to recover a full spatio-spectral datacube representing the input scene. The model for this instrument is the WFIRST integral field spectrograph, but it is simple to modify parameters in order to adapt them to other architectures.

This versatile simulation framework is written in Python and made publicly available to the community. It is aimed at helping the design of future coronagraph instruments by developing accurate sensitivity models, constructing realistic data products, and producing visually-appealing images to showcase the performance of these instruments (e.g. see Figure 1 for a WFIRST simulation).

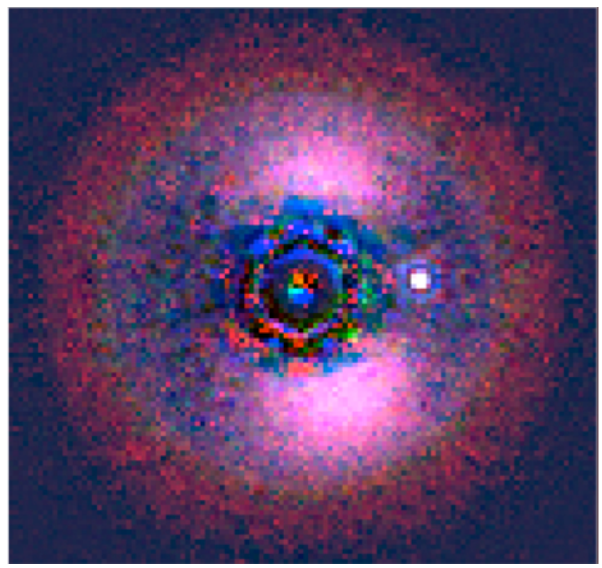

Figure 1: RGB composite of a simulated scene through the WFIRST Shaped Pupil coronagraph (Disk Mode). The scene represents a Jupiter-size planet at 2AU, seen in a system at 3pc. Two resonant dust structures can be seen at the Lagrange points of the system. The speckle noise floor is representative of a 10 picometer wavefront error. The composite image is from three filter bands, at 660nm, 720nm and 880nm, and simulates a total integrated exposure time of 24h across the three bands.

Big Bang to Biosignatures; The LUVOIR Decadal Mission Concept. Aki Roberge[1] and the LUVOIR Mission Concept Team, [1]NASA Goddard Space Flight Center, Code 667, Greenbelt MD, 20771

Introduction: The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multi-wavelength observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the epoch of reionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing habitable exoplanets around Sun-like stars and searching them for signs of life.

LUVOIR is one of four Decadal Survey Mission Studies initiated in Jan 2016. The final report will be submitted to NASA and then the US National Academies in 2019. Here I will summarize LUVOIR's broad and revolutionary science goals. Then I'll explain our current vision for the instrument suite and aperture sizes to be studied. Figure 1 shows a visualization of LUVOIR Architecture A. Finally, I'll discuss the study process and what will happen over the next years in preparation for the 2020 Decadal Survey.

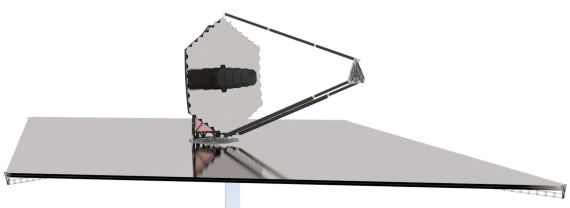

Figure 1: A preliminary rendering of the LUVOIR Architecture A, a space telescope facility with a 15-m diameter primary telescope aperture and four instruments.

HabEx: Finding and Characterizing Habitable Exoplanets with a Potential Future Flagship Astrophysics Mission

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HabEx – the Habitable Exoplanet Imager - is one of four flagship missions that NASA is studying in advance of the 2020 Astrophysics Decadal Survey. The primary goal of HabEx is to directly image and characterize rocky planets in the habitable zones of sun-like stars. Specifically, HabEx aims to search for signs of liquid water oceans and biological activity on such worlds. In addition to the search for life on Earth-like exoplanets, HabEx will enable a wide range of general astrophysics, from studying the earliest epochs of the history of the Universe, to investigating Solar System objects.

The technical drivers for HabEx are determined by the significant challenges associated with the direct imaging and characterization of potentially habitable exoplanets. This requires a sufficiently large collecting area to collect light from these very dim targets, and the ability to block light from the dramatically brighter host star the planet orbits. There are multiple approaches to these challenges, and the goal of the HabEx study is to demonstrate that at least one can be executed with technologies that can be matured in time for launch in the 2030s.

In this presentation, we will discuss the top-level exoplanet science goals of HabEx, and outline how those goals lead to basic and preliminary architectural properties such as aperture size, starlight suppression technique, and wavelength range. We will then discuss how these architectural properties allow for the astronomical study of other targets in and beyond the Solar System.

Bacterial growth in the salty liquid water ocean of Europa. D. G. Rubio, and S. I. Ramírez, Centro de Investigaciones Químicas, Universidad Autónoma del Estado de Morelos. Av. Universidad No. 1001 Col. Chamilpa, Cuernavaca, Morelos, México, C. P. 62209. Tel. 52 777 329 7997. daira.grubio@uaem.edu.mx, ramirez_sandra@uaem.mx

Introduction: Astrobiology seeks to scientifically understand the origin and distribution of life in the Universe. Consequently, it is concerned with information that helps to determine if terrestrial life can adapt to the conditions of a planet or satellite of the Solar System [1]. One of the research strategies used to explore the validity of this approach deals with the understanding of the extremophiles.

We are interested in the adaptation strategies displayed by the halophilic bacterium *C. marina* [2], the psychrophilic bacterium *P. cryohalolentis* [3], and *Bacillus pumilus*, a non-halophilic bacterium [4], when exposed to laboratory-controlled conditions that represents as closely as possible, the salinity, temperature, and available oxygen conditions of the salty liquid water ocean present on Europa [5].

Material and methods: Growth kinetics were performed in each bacterial nominal and modified media. *C. marina* nominal medium was modified with 1.37 M NaCl and 0.41 M $MgSO_4$. *B. pumilus* nominal medium was modified with 0.43 M NaCl and 0.27 M $MgSO_4$. Experiments without and with 2.0 and 5.0 mM of betaine were also done. The growth of *P. cryohalolentis* was evaluated in the absence of salts and up to 3.3 M NaCl and 2.1 M $MgSO_4$. The water activity (a_w) of each medium was measured with a dew point hygrometer (Aqualab 3TE). Bacterial growth was evaluated at 30, 20 and 10 °C (IRO80 Lumistell), and was monitored by changes in the optical density at 630 nm using a UV-Vis spectrophotometer (Cary 8454, Agilent Tech.). From a linear adjustment by the least squares method of the exponential phase region of each growth kinetic, the specific growth rate (μ) and the duplication time (t_D) were calculated.

Results and discussion: The growth of *C. marina*, in modified media decreases as the temperature drops in the range of 30 to 10 °C. In the nominal medium there were minimal changes between 30 and 20 °C, but the values were smaller at 10 °C. The value of μ at 30 °C increases as the value of a_w changes from 0.992 to 0.951, however at 20 °C the value of μ increases from 0.992 to 0.976, and an abrupt decrement was observed from 0.976 to 0.951. At 10° C, μ goes down as a_w decreases. In the growth curves of *C. marina* no changes were observed in μ when betaine was added Probably the salt concentrations did not induce a strong osmotic stress to the bacterium and the use of betaine to combat osmotic stress and thus maintain their cellular activity, is not necessary [6].

B. pumilus can growth in media modified with NaCl as well as with $MgSO_4$, so it can be considered as a halotolerant bacterium. The value of μ in the modified media showed minimal changes when the temperature decreased from 30 to 20 °C and decreased in the range of 20 to 10 °C, contrary to the situation in the nominal medium, where a continuous decrement is observed throughout all the temperature range studied. The value of μ at 30 °C decreases when a_w diminishes from 0.999 to 0.993, however at 20 °C and 10 °C, μ has a little increment between 0.999 and 0.994, but begins to lower up to 0.993. When *B. pumilus* was exposed to lower temperatures and low a_w values the compatible solute betaine did not make any difference in the growing, contrary to the situation reported for *Bacillus subtilis* strain 168, where betaine had a positive action in the growing particularly at low temperatures [7].

P. cryohalolentis growth was done in the absence and up to 2.0 M NaCl. In the media modified with $MgSO_4$, growing was observed up to 1.35 M.

In Europa's ocean the concentration of $MgSO_4$ varies from 0.1 to 282 g/L [8], our experiments covered the salinity values of 49.3 g/L up to 162.5 g/L $MgSO_4$ and the three bacteria exposed, showed a significant growing. This allows us to propose that, in terms of salinity, microbial terrestrial life could be able to thrive in the salty liquid ocean of Europe. According to the model proposed in [8], the temperature of the salty ocean would range from 210 to 270 K (-63 °C to -3 °C) without considering the thermal energy generated by cryovolcanism or hydrothermal vents, which can change the estimated temperature in the ocean floor. All the above information can be used to evaluate the habitability potential of Europa's ocean.

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Long Term Planetary Habitability and the Carbonate-Silicate Cycle.
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Introduction: The potential habitability of exoplanets is traditionally assessed by determining whether or not its orbit falls within the circumstellar 'habitable zone' of its star [1]. However, this metric does not readily account readily for changes in the abundance of greenhouse gases and their associated radiative forcing as a result of the action of the carbonate-silicate cycle.

Methods: We develop a model of the carbon cycle on Earth, coupled with a a 1-D radiative-convective climate model with an Earth-like atmospheric water vapour profile [1], to explore the potential changes in the CO2 greenhouse under conditions of varying planet size (0.5 – 2 R⊕) and stellar flux (0.75 to 1.25 S⊕).

Results: We find that likely changes in global topography, tectonic outgassing and uplift, and the hydrological cycle on larger planets results in proportionally greater surface temperatures and pCO$_2$ for a given incident flux. For planets between 0.5 and 2 R⊕ the effect of these changes results in average global surface temperature deviations of up to 15 K, which suggests that these relationships be considered in future studies of planetary habitability.

Furthermore, by coupling this model with the stellar evolution scheme presented in [2] and setting an upper temperature limit of 343 K, the habitable period of the Earth-sized world around the Sun can be quantified. For a 1 R⊕ planet, this limit is approximately 6.35 Gyr after planet formation, or 1.81 Gyr from present day.

Additionally, atmospheric CO_2 falls below the limit at which C3 and C4 plants can effectively photosynthesize after ~5.38 Gyr and ~6.1 Gyr respectively, which may initiate a significant reorganization of the biosphere of the planet well before average surface temperatures render it uninhabitable.

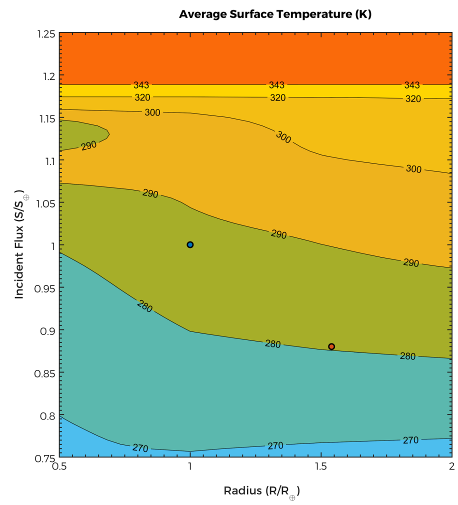

Fig. 1: Surface temperature as a function of planet radius and incident flux, both normalized to present Earth values. Also shown are the present day Earth (blue-filled marker) and GJ 667 Cc (red-filled marker).

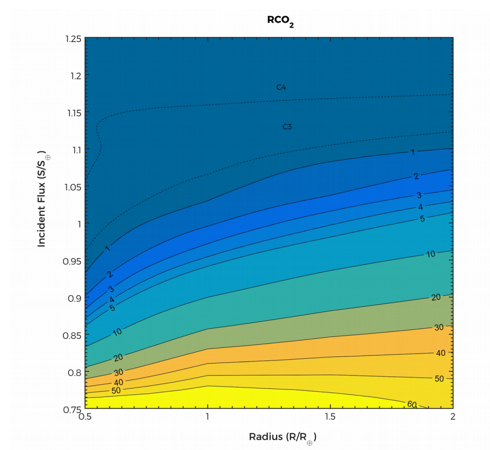

Fig. 2: pCO2 as a function of planet radius and incident flux, both normalized to pre-industrial levels (280 ppm). Also shown are contours showing the photosynthesis limit for C3 and C4 plants.

References: [1] Kopparapu *et al.*, 2013 *The Astrophysical Journal* 765(2) [2] Rushby *et al.*, (2013) *Astrobiology*, 13(9), 833-849.

NEW PHOTOMETRIC OBSERVATIONS OF THREE TRANSITING HOT JUPITERS NAMED TrES-3b, WASP-2b and HATP-30b.

M. I. Saeed[1], S. N. Goderya[2], F. M. Khan[1] and F. A. Chishtie[3]
[1]Institute of Space Technology, Islamabad, Pakistan.
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[3]Asian Disaster Preparedness Center, Bangkok, Thailand.

Introduction: We present the analysis and parameters estimation of three transiting extrasolar planets (TEP) TrES-3b, WASP-2b and HAT-P-30b. This work involves detailed photometric study of three hot Jupiters using a university acquired small 0.8 m Telescope at Tarleton State University and carried out mathematical modeling on the observed transit light curves. Transit Analysis Package (TAP) is used for light-curve fitting and analysis yield estimates of planetary radii and orbital periods. TrES-3b, WASP-2b and HAT-P-30b have orbital periods of 1.3, 2.15 and 2.811 days respectively. TrES-3b, WASP-2b and HAT-P-30b have radii of 1.305, 1.035 and 1.36 RJup respectively. Similarly, a/R* calculated for these planetary systems are 6, 7.27 and 7.38 with orbit inclination angles of 82, 85 and 84 degrees. This suggests that hot Jupiters can be observed using small educational telescopes as well.

OBSERVING HOW HABITABLE CONDITIONS DEVELOP IN PROTOPLANETARY DISKS. C. Salyk[1], [1]Vassar College (124 Raymond Ave, Poughkeepsie, NY 12604; cosalyk@vassar.edu)

Abstract: Observations of protoplanetary disks can be used to study the large-scale physical and chemical processes that lead to habitable planets. While habitable planets may eventually be discovered in the solar neighborhood, an understanding of planet formation processes is necessary to infer the occurrence of habitable conditions throughout the galaxy and beyond. I'll provide a brief overview of the current status of disk observations, including summarizing key observational techniques, and what we do and don't know about disk properties. Then I'll focus, in particular, on how molecular spectroscopy is being used to study the processes that lead to some of the key properties of planets that determine their habitability, including planetary size and type (terrestrial vs. gas giant), location and chemistry. I'll provide updates on ongoing ground-based observing campaigns to study disk molecules, and highlight what will soon become possible with the launch of the James Webb Space Telescope.

Habitability and the Multiverse M. E. Sandora[1], [1]Tufts University (McCullen.Sandora@tufts.edu).

Introduction: The concept of the multiverse states that the laws of physics may be different elsewhere. This framework is likely impossible to test directly, leading one to rely on indirect tests based on the premise that we inhabit a universe especially capable of supporting life. The crux of this argument, however, relies crucially on the requirements for habitability, which to date are incompletely known. While using rather generic criteria, such as the existence of stars and stability of atoms, has had some success, advancing this line of reasoning requires exploring life's requirements in more detail. For this purpose, advances in the science of habitability will allow us to make progress in the field of fundamental physics, and vice-versa. Investigating the dependence on fundamental physics of characteristics of our universe such as plate tectonics, core and mantle composition [1], biological homochirality [2], photosynthesis, and the size distribution of planets [3], among others, can allow us to make predictions for which locales are expected to provide the conditions to host complex life. Conversely, discovering where complex life is capable of existing will allow us to infer which physical parameters must be environmentally selected, and indeed whether the multiverse hypothesis is correct. The interplay between fundamental physics and the emerging science of habitability promises to lead to fruitful advances on both fronts.

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HAZMAT III. The UV Evolution of Mid-type M Dwarfs with GALEX. A. C. Schneider[1] and E. L. Shkolnik[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 871404 (aschneid10@gmail.com)

Introduction: Low-mass stars, or M dwarfs (0.1-0.6 M_{Sun}), make up the vast majority of stellar constituents of the Solar neighborhood. Recent results have shown that the majority of M dwarfs host planets, with ~25% hosting an Earth-size or super-Earth-size planet within their habitable zone[1]. Furthermore, planet occurrence rates have been shown to increase with decreasing stellar mass [2], and the planets found around low-mass stars are typically smaller than those around higher-mass stars [3]. Considering that the stellar mass function peaks around spectral type M4 [4] and the numerous observational advantages that low-mass stars provide, mid-type M dwarfs may supply the most opportunities and advantageous conditions for detailed characterizations of habitable zone planets. However, because M dwarfs have active chromospheres and coronae that produce high-energy radiation that may be harmful for life, determining the habitability of planets orbiting M dwarfs is not straightforward. The Habitable Zones and M dwarf Activity across Time (HAZMAT) program was initiated specifically to determine the time-dependent habitability around such perpetually UV-active stars. Using UV photometry from the Galaxy Evolution Explorer (GALEX), we are investigating hundreds of young M dwarfs in the Solar neighborhood to measure the change in stellar activity over planet formation and evolution timescales.

Methods: The HAZMAT I study [5] investigated the UV evolution of early M dwarfs (M0-M3) using targets from several nearby moving groups and clusters with well-determined ages. Recent efforts have significantly increased the number of confirmed low-mass members of these groups, allowing us to extend the original HAZMAT study to later spectral types (M3-M6.5). We are combining the results of these surveys for low-mass members with UV photometry from GALEX to map out the high-energy environment, and thus potential habitability of planets, revolving and evolving around mid-M dwarfs.

Results: In the HAZMAT I study of the evolution of early type (<M3) M dwarfs [5], it was shown that the median of GALEX near- and far-UV fluxes drops by a factor of 12 and 31, respectively, from 10 Myr to a few Gyr. We are extending this work to lower mass M dwarfs (M3-M6.5), which are especially valuable since they have closer-in habitable zones and remain active for even longer with greater flare variability. We find clear evidence that mid-M dwarfs to not follow the same evolutionary trend as early-Ms. Mid-Ms retain high levels of UV activity up to field ages, with only a factor of ~3 decrease in GALEX FUV and NUV flux between young and old stars. We also investigate the the evolution of the FUV/NUV ratio, which can affect the photochemistry of important biosignatures, and again find significant differences between early- and mid-Ms. While the FUV/NUV ratio is both spectral type and age-dependent for early-Ms, it remains constant for mid-Ms throughout their lifetimes.

E. S. and A. S. appreciate support from NASA/Habitable Worlds Grant NNX16AB62G.

References:

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Abstract

Habitable Worlds 2017

Darryl Seligman

Vortices, turbulence, and unsteady non-laminar flows are likely both prominent and dynamically important features of astrophysical disks. Such strongly nonlinear phenomena are often difficult, however, to simulate accurately, and are generally amenable to analytic treatment only in idealized form. We explore the evolution of compressible two-dimensional flows using an implicit dual-time hydrodynamical scheme that strictly conserves vorticity (if applied to simulate inviscid flows for which Kelvin's Circulation Theorem is applicable). The algorithm is based on the work of Lerat, Falissard & Sidé (2007), who proposed it in the context of terrestrial applications such as the blade-vortex interactions generated by helicopter rotors. We present several tests of Lerat et al.'s vorticity-preserving approach, which we have implemented to second-order accuracy, providing side-by-side comparisons with other algorithms that are frequently used in protostellar disk simulations. The comparison codes include one based on explicit, second-order van-Leer advection and another that implements a higher-order Godunov solver. Our results suggest that Lerat et al's algorithm may be useful for simulations of astrophysical environments in which vortices play a dynamical role, and where strong shocks are not expected.

Obliquity Variations of Habitable Zone Planets Kepler-62f and Kepler-186f. Y. Shan[1] and G. Li[1], [1]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA, yshan@cfa.harvard.edu

Introduction: Obliquity variations play important roles in the climate and habitability of a planet, as they determine the latitude distribution of stellar radiation [e.g, 1]. Orbital modulations caused by planetary companions and planetary spin axis precession due to the torque from a host star may lead to resonant interactions and cause large amplitude obliquity variations [e.g., 2, 3]. Here, we select Kepler-62f and Kepler-186f from the list of habitable zone planets in multi-planet systems [4], and we characterize the parameter space where their obliquity angles are stable, which could represent a condition more favorable to habitability.

Methods: We use a numerical approach to calculate the obliquity evolution of planet Kepler-62f and Kepler-186f. An example of the obliquity variation of Kepler-186f is shown below.

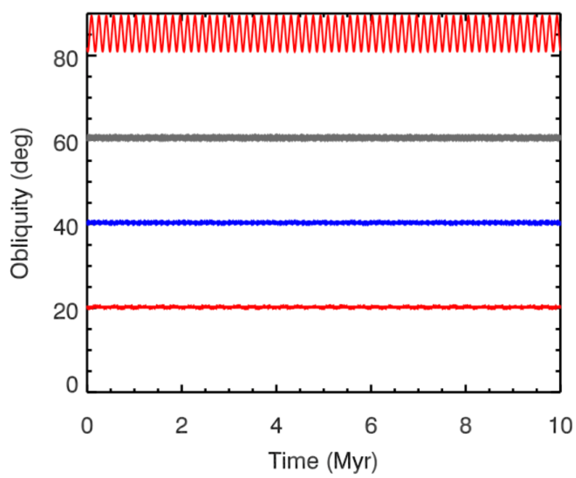

Figure 1. Obliquity of Kepler-186f as a function of time, assuming Kepler-186f has an Earth-like interior structure and a rotation period of 1 day.

Next, we adopt an analytical approach to interpret the numerical results and to characterize the regions in parameter space that allow high amplitude obliquity variations. In particular, we consider different planetary architectural configurations and planetary rotation periods, based on the observational results, and we estimate the orbital modulation frequencies and the planetary spin-axis precession frequencies to determine the locations of resonant regions, which correspond to regimes that allow large obliquity variations. The uncertainties in the mass and the orbital parameters of all the planets in the Kepler-62 and Kepler-186 systems are also considered in this approach.

Results: We find that the obliquity of both Kepler-62f and Kepler-186f have small variations in the low obliquity regime, assuming the planets are Earth analogues. This supports regular seasonal variations. However, the high obliquity regions allow moderate variabilities. In addition, farther planetary companions and/or the existence of a satellite may render the low obliquity region unstable. Better constraints on the existence of additional planetary companions and large satellites can further predict the variability of the obliquity angle.

References:

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MEASURING N_2 PRESSURE USING CYANOBACTERIA. S. N. Silverman[1,2,3], S. Kopf[1], R. Gordon[4], B. Bebout[3] and S. Som[2,3], [1]Department of Geological Sciences (University of Colorado at Boulder, USA), [2]Blue Marble Space Institute of Science (Seattle, Washington, USA), [3]Exobiology Branch, NASA Ames Research Center (Moffett Field, California, USA), [4]Gulf Specimen Aquarium & Marine Laboratory (USA & Wayne State University, USA)

Introduction: Assessment of whether extrasolar planets are deemed habitable or inhabited will be based on their atmospheric composition. Added insight regarding habitability will be obtained by comparing these exo-atmospheres to that of habitable Earth. Earth's atmosphere has remained habitable despite varying in redox state and total mass over geological time. As such, "snapshots" of Earth's atmosphere through the planet's evolution can provide a catalogue of different habitable atmospheres. At any timepoint in Earth's history, an upper limit can be placed on the number of possible air constituents by knowledge of atmospheric pressure at that time. Experimentally, this can be broken down by focusing on trends of specific gases over history.

Dinitrogen (N_2) is thought to have been a major, though not necessarily constant, constituent of Earth's atmosphere throughout the planet's history. Despite its physical importance as a key component of the atmosphere and its role as the largest reservoir of nitrogen at the Earth's surface, only a few constraints exist for the partial pressure of N_2 [1], [2], [3], [4]. In this study we evaluate two new potential proxies for atmospheric N_2: the physical spacing between heterocysts and the isotopic signature of nitrogen fixation in filamentous cyanobacteria.

Experimental background: Heterocyst-forming filamentous cyanobacteria are some of the oldest photosynthetic microorganisms on Earth, and debated fossilized specimens have been found in sedimentary rocks as old as 2 Ga [5]. These organisms overcome nitrogen limitation in their aqueous environment through cellular differentiation along their filaments. The specialized cells that develop, known as heterocysts, fix the nitrogen and laterally distribute it to neighboring cells along the filaments.

Because the concentration of the dissolved N_2 available to the filaments correlates directly with the atmospheric partial pressure (Henry's law constant for N_2 gas in water is 6.1 x 10^{-4} mol L^{-1} atm^{-1} [6]), any preservable physiological response of the organism to the changed N_2 availability constitutes a potential proxy for atmospheric N_2.

Experimental approach: In the laboratory, we have examined how pN_2 is reflected in the heterocyst spacing pattern and in the isotopic signature of nitrogen fixation by subjecting the representative species *Anabaena cylindrica* and *Anabaena variabilis* to different N_2 partial pressures during growth at constant temperature and lighting (in media free of combined nitrogen).

Results: We show experimentally that the distance between heterocysts and the nitrogen isotope fractionation measured in bulk biomass reflect the nitrogen partial pressure experienced by *Anabaena cylindrica* organisms. As such, this renders them an ideal target to potentially record atmospheric nitrogen concentrations on ancient Earth. Current work is investigating these responses in *Anabaena variabilis*. When heterocystous cyanobacteria fossilize, these morphological and isotopic signatures should preserve information about the atmospheric N_2 partial pressure at that time. Application of this relationship to the rock record may provide a paleoproxy to complement the two existing geobarometers [1], [2].

References: [1] Som S. M. et al. (2016) *Nat. Geosci., 9,* 448–451. [2] Som S. M. et al. (2012) *Nature, 484*, 359–362. [3] Marty B. et al. (2013) *Science, 342,* 101–104. [4] Berner R. A. (2006) *Geochim. Cosmochim. AC, 65,* 685–694. [5] Licari G. R. and Cloud P. E. (1968) *PNAS*, *59*, 1053–1060. [6] Sander R. (2015) *Atmos. Chem. Phys., 15,* 4399–4981.

PLANETESIMAL FORMATION: EVIDENCE FOR A UNIVERSAL INITIAL SIZE DISTRIBUTION. J. B. Simon[1,2], P. J. Armitage[1,3], A. N. Youdin[4], R. Li[4], [1]JILA, University of Colorado and NIST, 440 UCB, Boulder, CO 80309-0440, [2]Department of Space Studies, Southwest Research Institute, Boulder, CO 80302, [3]Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, [4]Department of Astronomy and Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721

Introduction: Planetesimals are the precursors to planets, and understanding their formation is an essential step towards developing a complete theory of planet formation, whether it be that of our own solar system or of the many extrasolar planetary systems discovered in recent years. Furthermore, a detailed understanding of planetesimal formation is necessary for explaining the observed properties of asteroids and Kuiper Belt objects.

Traditional theories attempt to explain planetesimal formation from a "bottom-up" approach; small particles (e.g., dust grains) continually grow upward in mass and scale, finally reaching gravitationally bound objects. For these small solid particles to coagulate into planetesimals, however, requires that these particles grow beyond centimeter sizes; with traditional coagulation physics, this is very difficult [1,2]. The streaming instability [3,5], however, generates sufficiently dense clumps of these smaller constituents that the mutual gravity between the particles eventually causes their collapse towards planetesimal mass and size scales.

Results: Here, we present a series of high resolution, first principles numerical simulations of protoplanetary disk gas and dust to examine in detail, the formation of planetesimals and their resulting size frequency distribution. We find that their differential size distribution can be well-modeled as a power law with power law index -2.8. This equates to a top-heavy distribution, with most of the mass in the largest objects (see Figure 1). This power law index is robust to resolution, initial particle size and concentration, relative strength of gravity to tidal shear, and conditions prior to collapse. We present tentative evidence that this universality can be tied to the power spectrum of particle mass density prior to collapse.

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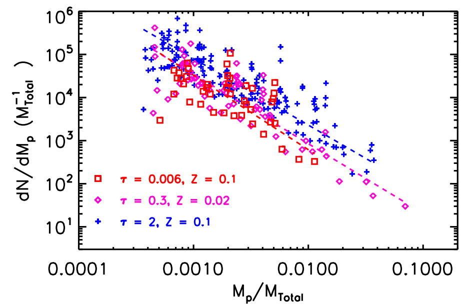

Figure 1 - The initial differential planetesimal mass function derived from simulations with different particle Stokes numbers, τ, and concentrations, Z. The simulation with the smallest particles (τ = 0.006, red) forms a significantly smaller total mass of planetesimals during the duration of the run, but no significant differences in the slope of the derived mass function are observed. The best fit power law is overplotted as dashed lines. (This figure is a modified version of Fig. 2 in [4]).

THE ROLE OF TOPOGRAPHY IN MODULATING CLIMATES OF HABITABLE WORLDS. L. E. Sohl[1,2], M. A. Chandler[1,2], M. J. Way[2], J. A. Jonas[1,2], [1]Center for Climate Systems Research, Columbia University, 2880 Broadway, New York, NY 10025, linda.sohl@columbia.edu, [2]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025.

Introduction: The surface features of distant potentially habitable worlds are currently unknown, and it may be some time before a technique such as spin-orbit tomography permits us to retrieve even basic 2-D information [1]. Within the Solar System, the original surfaces of Paleo-Earth (>2 Gyr) and paleo-Venus have long since been altered by tectonics and/or eruption events [2, 3]. As a consequence, 3-D general circulation model (GCM) simulations of the climates of these worlds typically utilize an aquaplanet configuration (no emergent land) [e.g. 4], which has the benefit of simplifying assumptions but may limit the assessment of planetary habitability. We highlight here the differences in simulated climates that are produced when using realistic, reconstructed, or idealized continental distributions.

Approach: We employed the latest versions of NASA's coupled ocean atmosphere Earth System Model [5] and NASA's newest planetary GCM, ROCKE-3D [6] for the simulations discussed. Paleo-Earth simulations, which did not require special radiative transfer capabilities but did benefit from running at higher resolution (2˚x2.5˚x40L atmosphere, 1˚x1.25˚x32L ocean) for purposes of checking against proxy data from the geologic record, were run with the regular Earth System Model. Paleo-Venus, Early Earth and various exoplanet simulations were run with ROCKE-3D to take advantage of expanded radiative transfer and stellar spectral capabilities in conjunction with slightly coarser resolution (4˚x5˚x20L or 40L atmosphere, 4˚x5˚x13L ocean) for improved computational speed.

Habitable world scenarios:

Paleo-Earth: A range of habitable states exists throughout the last two billion years of Earth history, including periods that are representative of both inner and outer edge environments, i.e., Snowball Earth and the Cretaceous Greenhouse [7]. There is high confidence in continental reconstructions with emergent land back to ~300 Myr, with moderate confidence reconstructions dating to at least 1 Gyr. Using reconstructed land/ocean distributions with the GCM permits us to test hypotheses based on conceptual models (does a supercontinent at tropical latitudes encourage global cooling via albedo feedbacks?) as well as explore far-field climate teleconnections that may explain enhanced habitability (does the closing of an equatorial seaway drive increased heating in polar regions?). These runs have the added benefit of being evaluatable against known climate states of the past.

Paleo-Venus: Using current Venus topography as a proxy for paleo-Venus landscapes, and a slow rotation rate, we have shown that having a large land fraction in the tropics combined with modest amounts of water actually limits the amount of planetary warming to habitable levels, moreso than aquaplanets – or even a modern Earth topography – given the equivalent solar flux [8]. This result suggests that more surface water is not necessary "better" for habitability under certain circumstances, and also shows that the inner edge of the HZ is more transitional than previously described.

Early Earth/Exoplanets: A series of idealized continents simulations, varying the total global land fraction from 75% to 6.25%, and varying the location of continents from polar-centered positions to scattered rectangular continents produces as much as a 20˚C difference in global mean annual temperature for otherwise identical simulations (same solar/GHG forcings).

A synchronously rotating exoplanet such as Proxima Centauri b, modeled both as an aquaplanet and with modern Earth topography [9], shows how land barriers to zonal water/heat transports result in a global mean annual surface temperature that is ~10˚C colder than the equivalent aquaplanet scenario. Ice and snow cover increases by roughly a factor of two when land is beneath the substellar point, rather than ocean – an outcome with ramifications for the area of habitable space available.

Future research and challenges: We recognize that introducing topography adds complexity and time to the creation and running of GCM simulations, and that the parameter space to explore is potentially quite broad. However, we feel that there are clear benefits to including some emergent land fraction experiments along with aquaplanets, in terms of the diversity of habitable planetary environments that can be identified.

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Abstract:

The Search for Hot Jupiters using Red Buttes Observatory

The goal of this research is to perform remotely operated observations of transiting exoplanet candidates catalogued by the KELT (Kilodegree Extremely Little Telescope) Survey. The KELT survey is a photometric search for transiting exoplanets around bright main sequence stars. The KELT Follow-up Network (KELT-FUN), a collaboration of small-aperture telescope users located all over the world, confirms new exoplanet candidates. As part of KELT-FUN, students use the University of Wyoming's Red Buttes Observatory to monitor candidates identified by the KELT team. Using the 0.6 meter telescope at Red Buttes Observatory we are able to detect transits around stars that are 8-12 magnitude in brightness, with a transit duration of ~4 hours and relative change in brightness ~3%. Using AstroImageJ, we process the data and we look for any indication of a transit occurrence in the processed lightcurve which might confirm the presence of the exoplanet in question. We are also able to compare our data with previous observations by other members of the collaboration and help expand the search for exoplanets. This project gives undergraduates an authentic scientific research experience, learning how to operate a telescope, performing data processing, and participating in a scientific collaboration.

HOW OCEAN-LAND FRACTION AND DISTRIBUTION AFFECTS HABITABLE CONDITIONS ON EARTH-LIKE PLANETS. Alejandro Soto[1], [1]Southwest Research Institute, Boulder, CO, USA; asoto@boulder.swri.edu.

Introduction: At the global and regional scale, the habitability of a terrestrial planet is dependent upon the ability of the climate system to sustain a vigorous hydrological cycle and to maintain relatively active precipitation over land [1, 2, 3]. Most previous investigations have focused on the planetary and stellar parameters required to create climate conditions that would meet these criteria for habitability; research has particularly focused on the parameters required to achieve global mean temperatures above the triple point of water, i.e., 273 K. However, the mere existence of surface liquid water on a terrestrial planet does not guarantee the global distribution of this water. For a given ocean-land fraction, there should be an associated 'habitable' fraction of the planet, but this relation between ocean-land fraction and habitable fraction remains under-explored. A planet with a small ocean-land fraction may be mostly dry. But is this true for all distributions of the oceans? At what ocean-land fraction does a planet transition to being mostly wet? As we continue to observe exoplanets, the answers to these questions will be critical to determining the extent of habitability. Our investigation works to address these questions.

Simulations: We use the Earth version of the Planet Weather Research and Forecasting (PlanetWRF) model, which was built to numerically simulate a wide range of terrestrial atmospheres. PlanetWRF is a modified version of the National Center for Atmospheric Research (NCAR) Weather Research and Forecasting (WRF) model, capable of mesoscale to global scale modeling of the atmospheric circulation [4]. PlanetWRF provides us with an array of robust surface physics schemes with which to simulate the hydrological environment.

Figure 1 shows the effect of the ocean-land fraction and distribution. This simulation has a 25% ocean-land fraction with a circular north polar ocean. We gave the north polar ocean a ragged coastline similar to the coastline of the putative paleo-ocean on Mar, but there is no topography in this simulation. As seen in Figure 1, the annual mean cloud activity is concentrated over the oceans, which is consistent with ocean surface heating by the sun leading to convection and cloud formation over the ocean. The bulk of the clouds remain confined in the polar region, apparently unable to mix equator-ward. In this type of configuration, any habitable environment dependent on regular access to liquid water will be constrained to the northern portion of the planet. It is possible that the bulk of this planet would remain a desert, both hydrologically and biologically. This simple test highlights the possible climate states due to the ocean-land fraction and distribution.

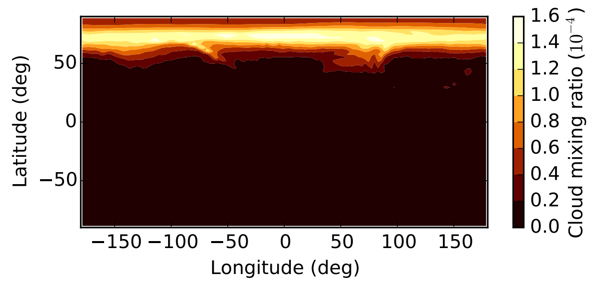

Figure 1: **A map of the annual mean cloud mass mixing ratio at ~700 mbar for a 25% ocean-land fraction simulation. The ocean is centered on the north pole. The simulation is an Earth-like planet in an Earth-like orbit around a G-type main sequence star like the Sun. The contours are for the mixing ratio of liquid water.**

Conclusion: We are investigating how ocean-land fraction and distribution affects the creation of habitable conditions on the surface of Earth-like exoplanets. Our simulations explore a range of ocean-land fractions as well as distributions, providing new insight into the extent of habitable conditions on Earth-like exoplanets.

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An Answer to Fermi's Paradox In the Prevalence of Ocean Worlds? S. A. Stern[1], [1]Southwest Research Institute, Space Science and Engineering Divisdion, 1050 Walnut Street, Suite 300, Boulder, CO 80503, astern@swri.edu

Introduction: The Fermi Paradox asks the question about extraterrestrial civilizations, "Where are they?" Given speculations based on numerical evaluations of the Drake Equation that would seem to indicate that the likelihood of precisely N=1 communicating extraterrestrial civilizations in the Universe is small (i.e., that we are unique), the Fermi Paradox has not been resolved. Many explanations have been proffered [1]. We suggest another, that the great majority of worlds with biology and civilizations are interior ocean worlds, cut off from communication because they are inside of their host world, therefore not easily revealing themselves.

The Fermi Paradox: The Fermi Paradox (hereafter, FP) is the apparent contradiction between the lack of evidence for detected extraterrestrial civilization in an old universe and the oftentimes-large number estimates (e.g., those given by the Drake Equation) for the number of extant extraterrestrial civilizations. As summarized in [1] a range of potential explanations for the Fermi Paradox have been proffered; we offer a new potential explanation, namely that most life, and most intelligent life in the universe inhabits interior water ocean worlds (WOWs) where their presence is cloaked by massive overlying burdens of rock or ice between their abode and the universe.

Interior Ocean Worlds Are Likely More Conducive to Life: Whereas it was once thought that among the worlds of our solar system only Earth sports a water ocean, that conclusion turned out to be an observational selection effect. Earth, it turns out, is an uncommon type of water ocean world—at least in our solar system, because it wears its oceans on its exterior. Beginning in the early 1980s and extending to the present, an increasing number of worlds in our solar system have been shown to through gravitational, magnetic, or geological/geophysical evidence to indicate that they are likely to possess water oceans [2]. As a result, water ocean worlds are now thought to be common in our solar system [3]. There are three types of these worlds known, which we classify as follows: (Type I) solid bodies with external oceans (currently only Earth, but apparently also Venus or Mars or both in the distant past), (Type II) icy satellites and small planets with interior oceans (e.g., Europa, Enceladus, and Pluto), and (Type III) giant planets like Uranus and Neptune with high-pressure interior oceans. The predominant Type of ocean world in our present day solar system is of Type II, though late in the Sun's evolution when it becomes a red giant, Type (i) WOWs are likely to dominate as numerous icy worlds and small planets in the Kuiper Belt develop exterior liquid oceans on their surface [4]. Water ocean worlds of Type II appear to be particularly conducive to the development of life owing to several key advantages, including: (1) *Environmental Independence to Stellar Type, Multiplicity, and Distance*. Owing to the several to hundreds of kilometers depth of typical Type II liquid water oceans, and the overlying thermal insulation provided by the planetary lid atop these oceans, the energy balance, temperature, pressure, and toxicity in Type II ocean worlds is only weakly coupled to their host star's stellar type, stellar multiplicity, stellar distance, and stellar evolutionary stage (i.e., from protostars with winds and high activity through the main sequence to stellar remnants). And (2) *Environmental Stability*. Again owing to the depth of typical Type II oceans and the overlaying thermal insulation provided by the planetary lid atop these oceans, these environments are protected from numerous kinds of external risks to life, such as impacts, radiation, surface climate and obliquity cycles, poisonous atmospheres, and nearby deleterious astrophysical events such as novae and supernovae, hazards stellar flares, and even phenomena like the Faint Early Sun. As a result of these factors, WOWs of Type II require much less of their parent planet and star to remain oceans viable for life than do ocean worlds of Type I. In contrast, the latter can only remain oceans in a comparatively limited range of insolation conditions, thereby in turn eliminating most combinations of planet-star distance, stellar multiplicity, orbital eccentricity, and planetary spin states from creating a habitable zone for such ocean worlds. Similarly, Type II WOWs do not require planetary magnetospheres for protection, nor do they suffer from external threats due to asteroid/comet impacts, supernovae and novae induced insolation and charged particle radiation, obliquity extremes, and they are also immune to the passage of their host star through giant molecular clouds of high opacity. Indeed, Type II WOWs can even remain liquid and therefore candidate abodes to life on unbound planets that orbit no star. This makes Type II WOWs attractive sites for the potential development of biologies.

A New Solution to Fermi's Paradox: Ocean Worlds Isolation May Naturally Sequester Intelligent Civilizations: Because ecosystems inside Type II WOWs are, by definition, isolated from their surface environments by thick shells of ice or rocks or both, these potential abodes cannot communicate directly to space using most electromagnetic means. Indeed, it is not even clear that intelligent species living in Type II WOWs know of the external surface of their worlds, and if they do it is unclear why they would explore much less inhabit such an alien (and likely lethal) environment. Even if they do, such civilizations would be at a disadvantage to persist there or to travel off their home worlds into space, compared to residents of Type I (external) WOWs, since they are likely to be constrained by the need to carry copious and therefore heavy water supplies to live in on their world's surface or in space. Taking this logic a step further, it is not even clear that civilizations in Type II WOWs that explore their world's surface would even recognize or take up astronomy to learn that the sky above their world is filled with other worlds across space. And even if they did they might naturally be biased to only consider life and extraterrestrial civilizations as residing inside other far away worlds, thereby obviating most rationales and methods for extraterrestrial communications, particularly with worlds like ours. "Where are they?" The answer may simply be, "At home in their type II WOWs where they either cannot communicate or are simply not aware that other worlds exist or would have communicable civilizations."

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LIQUID PHASE EQUILIBRIA FOR HABITABILITY. Sugata P. Tan, Planetary Science Institute, Tucson, AZ (mailing address: 1043 Boswell Dr., Laramie, WY 82070; e-mail address: stan@psi.edu).

Introduction: Unlike gas and solid phases, which are ubiquitous in the Universe, liquid phase only exists in very narrow ranges of temperature and pressure (see Fig. 1). Therefore, it is not surprising that liquid phase is rarely found even in the Solar System. Only Earth and Titan, which is the largest moon of Saturn, have liquids on their surfaces. Other bodies that have liquids must keep them under surface, even if the body supposedly lies within the habitable zone (e.g. Mars).

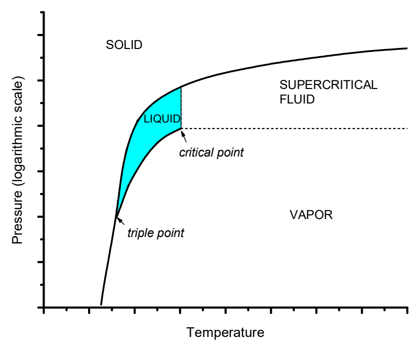

Fig. 1. Typical phase diagram of pure substance: liquid phase occupies small ranges of temperature and pressure (blue region). Mixtures have similar behavior.

It has been widely recognized in the scientific community that water is not an absolute condition for the existence of life, though it is the case on Earth for life as we know it. However, it is hard to believe a life form without liquids, because the other phases (gas and solids) do not have properties to support the operation of most biochemical processes and metabolism of life beings. Unless the beings do not have physical bodies, they need liquids in their flesh, even though not necessarily water. Therefore, it is also common to assume that life first emerged in liquids before evolving to more advanced form on land.

It is an observable fact that planetary bodies, in the Solar System and beyond, revolve around their parent stars. This motion introduces climate patterns to most of the bodies, in which the temperature and pressure change accordingly and affect the atmospheres and their interaction with the surfaces. On Earth, these changes lead to phase changes of the existing liquid, i.e., water; becoming vapor in hot days and solid ice in winter. The solid must not jeopardize any beings that live in liquids. The only phase behavior that can protect life from complete solidification is the density inversion where the density of solid is less than that of its liquid; on Earth water ice floats in water. The solid that sits on the liquid surface is the heat insulator that keeps the liquid from freezing due to the coldness of winter.

In this presentation, Titan's fluid will be used as an example for analyses, whether or not the liquid phase can persist in extremely cold weather and whether it undergoes density inversion in the case of solid formation. Study of the fluid in the example is complementary to our knowledge of water on Earth.

Method: The analysis tool is a thermodynamic equation of state (EOS) known as CRYOCHEM [1,2] that has been successfully applied to describe Titan's surface liquids in the seas [3] and solid solutions in the tropopause [4]. In near future, when the atmospheric chemical composition and temperature/pressure profile of extraterrestrial bodies, including exoplanets, are reliably measured, these data are all the input that the EOS needs to analyze the phase behavior of the atmospheres and any liquids that may exist on the surface. The existence of liquid phase predicted by the EOS, even if it is non-water liquid, would amplify the habitability of the body, perhaps by an exotic physical life form unknown to us as of today. The EOS offers a useful tool in the search of habitable worlds in many years to come before interstellar travel is possible.

Titan's liquid. It was shown that Titan's liquid is in thermodynamic equilibrium with the atmosphere [1,3]. The whole atmosphere is subject to condensation into liquid or solid phases as it consists of mainly nitrogen and methane and has extremely low surface temperature of about 90 K in the northern polar region that hosts most of Titan's lakes/seas. The liquid is dominated by methane, ethane, and nitrogen [3,5]. It will be discussed in the presentation that Titan's fluid may be sufficiently modeled as a mixture of these three components.

Extremely cold liquids. It can be shown that it is possible to encounter liquid phase in nitrogen/methane/ethane atmospheres at an extreme condition, e.g. 62 K and low pressure of 0.1 bars. This is counterintutitive as the condition generally allows only vapor and solid phases. It would give wider range of conditions where liquid phase can exist, the implication of which for the limiting conditions of habitability in distant worlds may be subsequently inferred.

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LOOKING TO THE FUTURE: WHAT WILL IT TAKE TO CONFIRM LIFE ON AN EXOPLANET? A. M. Tanner[1], [1]Mississippi State University (Dept. of Physics & Astronomy, Hilbun Hall, 355 Lee Blvd, MSU, MS 39762)

Introduction: With thousands of confirmed exoplanets exhibiting an impressive range of physical properties, we now have a tantalizing sample of terrestrial mass worlds which could be harboring some form of extraterrestrial life. The key to confirming life-signs on any exoplanet lies in designing, launching and operating space missions supported by an army of precursor ground-based observations. Right now, we are in the discovery stage – the critical era in which we survey the skies both near and far one star at a time and by the thousands to identify the best targets for future scrutiny. Before we know it we will have a rich list of the nearest exoplanetary systems like Trappist[1], Proxima[2] and Tau Ceti[3] to focus all of our attention on to study their atmospheres and search for biomarkers. For this review talk, I will present a continent neutral overview of ground and space-based observatories which will be devoted to searching for life outside of our solar system. I'll break it down to four phases: Discovery, Reconnaissance, Characterization and LIFE!

Discovery: Because we are deep in discovery mode with Kepler, K2, high-contrast direct imaging, and ground-based RV and transit programs (to name a few) I will review the census of known exoplanets as it relates to habitability. I will emphasize those systems best suited for follow-up and outline what parts of parameter space future planet search programs like Gaia, TESS, Plato, CHEOPS and the next generation of <1 m/s RV instruments will explore.

Reconnaissance: To be able to confidently explore the atmospheres of habitable planets we will need to know whether these systems have additional planets or a debris disk as well as the properties of the host star itself. This is one area where ground-based telescopes will make a significant contribution. For instance, before and after the discovery phase, we will need to know the distance, metallicity, spectral type and radius of the star to high precision to place sufficient constraints on the mass, density and habitability of an exo-life candidate. We will need to thoroughly sample the intrinsic variability of the photosphere of the star to be sensitive to Earth-mass planets via RV measurements and even more so for those transiting planets for which we will be devoting a large amount of telescope time for the intense reflected light transit spectroscopy needed to conclusively identify biomarkers. I will review the state of observing programs involved in these types of measurements.

Characterization: In the not so distant future, there will be a suite of missions and ground-based telescopes which will be able to characterize the atmospheres of directly-imaged or transiting Earth-mass, habitable planets. On the ground, we will have to look toward the 20 to 40 meter telescopes which are developing science programs to study the atmospheres of habitable planets around nearby M dwarfs with, for instance, infrared Doppler transit spectroscopy [4]. The TMT, GMT and ELT telescopes are designing sophisticated instruments with terrestrial planet atmospheric characterization in mind. In space, we all look forward to the successful launch of JWST which has a near- and mid-infrared spectrographs (NIRSpec & MIRI) with the sensitivity to study the atmospheres of transiting M dwarf planets, however, it's uncertain as to whether there will be enough devoted mission time to reach the SNR needed to identify multiple biomarkers. Other more specialized telescopes like the newly selected FINESSE[5] mission might achieve sufficient sensitivity via transmission spectroscopy to probe the atmospheres of select habitable M dwarf planets. We might have to focus our attention on direct imaging missions such as the New Worlds Telescope which will be a direct imaging mission that uses a separate starshade to block the light from the host star. I will discuss the telescope & instrument combinations with the best hope of providing us the spectra necessary to search for all of the molecular biomarkers needed to confidently confirm life on an exoplanet.

LIFE! Will we find life? Your guess is as good as mine. It will take the combined efforts of an armada of facilities, hundreds of hours of observing time, many PhD's worth of analysis and some clever and out of the box thinking to guarantee that we will forever change our place in the Universe in our lifetime. I plan on providing this meeting a fresh review of the substantial engineering and observational efforts to accomplish the quintessential scientific discovery – aliens.

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Starchive: The Open Access, Open Source Stellar Database

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Introduction: The past two decades have witnessed the golden age for exoplanet discoveries. In addition to discovering new exoplanets, astronomers are also carrying out follow-up observations of them to understand their physical properties and orbits, formation and migration histories, bulk and atmospheric compositions, and potential habitability. With these endeavors it has also become clear that we must know as much as possible about the host star(s) in order to calculate some of the planets physical properties, determine habitability and even the best methods for finding the planets in the first place.

However, both the initial target sample development and follow-up science is challenging due to limited time on large telescopes. Therefore, it is crucial to identify the most fruitful host stars for both the discovery and follow-up phases of exoplanet exploration. Archives such as SIMBAD, VizieR, the Washington Double Star Catalog, and various exoplanet databases used by the astronomical community currently lack comprehensive lists of stellar properties for candidate host stars to be properly vetted. This is especially true given the wide variety of exoplanet detection and characterization methods from direct imaging to transit timing variations to microlensing. This is where the Starchive database will fill in the void and be a major asset to the community.

The Starchive: The Starchive (under construction at starchive.org) is an open source, open access stellar database. It will host observable, physical, and derived properties of stars and planets as well as observational data such as direct imaging (AO and seeing limited), spectra, light curves, and other time series data sets.

Initially, Starchive will consist of stars from four populations: (1) stars within 30pc, (2) young nearby stars, (3) brown dwarfs, and (4) debris disk hosts. Once we have completed the database for these stellar populations, we plan on expanding its content with the help from the community. The database will host a pallet of plotting tools to help the community investigate and present these complex datasets.

While we are gathering a large collection of metadata to be present in the Starchive upon its release, it will be designed so that the community will be able to put data into the database themselves. To make sure that the integrity of the quality of the data is upheld, we will utilize a committee of volunteer astronomers to curate the content as its added to the database. To encourage the community to contribute to the database, we will send out a monthly newsletter highlighting the papers which are associated with new datasets and include relevant plots made with those datasets. We intend for the Starchive to be the go to site for assembling all future exoplanet search target lists as well as a new model for big data assembly, sifting, vetting, distribution and visualization. It will also be a significant resource for determining habitability as users will be able to easily assemble all known observational and physical parameters of the host star for each new exoplanet discovery.

During my presentation, I will highlight the current state of Starchive, its content, usability and the many different ways it will benefit the exoplanet community.

WE NEED TO CHANGE HOW WE DISCUSS HABITABILITY. Elizabeth Tasker[1], Joshua Tan[2], Kevin Heng[3], Stephen Kane[4] and David Spiegel[5], [1]Institute of Space and Astronomical Science, Japan Aerospace Exploration Agency, Yoshinodai 3-1-1, Sagamihara, Kanagawa, Japan, mail:elizabeth.tasker@jaxa.jp, [2]Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile, [3]University of Bern, Center for Space and Habitability, Sidlerstrasse 5, CH-3012, Bern, Switzerland, [4]Department of Physics & Astronomy, San Francisco State University, 1600 Holloway Avenue, San Francisco, California 94132, [5]Analytics & Algorithms, Stitch Fix, San Francisco, California 94103.

The discovery of extrasolar planets with similar radii and mass to the Earth has opened the door to scientific debate about the likelihood that such worlds could be habitable. This has recently resulted in the formulation of metrics to rank planets most likely to have conditions suitable for life. Such quantitative assessment has been proposed for target selection, to ensure the best use of the limited resources available for further observations. However, the results from these metrics are frequently over-extended, both by the popular media and even in scientific literature.

Discussions regarding the `most habitable' planet or `Earth's twin' in combination with the result from such a metric, have made repeated headlines in the last few years. However, the reality is that we have no way to quantitatively assess a planet's ability to support life. The conditions relevant to detectable biological activity are those on the planet's surface. Unfortunately, observing the surface is beyond even the most ambitious future missions, and may even be perpetually blocked from view by the planet's atmosphere. Instead, we must estimate surface conditions based on the properties we can observe at this one point in time. For the majority of exoplanet discoveries, this consists of only two independent measurements: the incident flux from the star and either the planet's radius or minimum mass. Our own Solar System is a warning against such simplicity: Earth and Venus differ in size by only 5% and the incident radiation from the Sun is within a factor of two. Extrapolation from the Earth would suggest a Venusian surface temperature of around 315 K, rather than the reality of a lead-melting 462 K. The available information is therefore both sparse and not linearly related to habitability.

Claims that metrics can measure the comparative habitability of planets are potentially extremely harmful to the field. By implying that we are able to measure the degree to which a planet is able to support life, we undermine future projects to explore factors such as atmospheric conditions. Public apathy in such areas could result in funding for these missions being ever harder to achieve and research efforts getting steadily less recognition. The way discussions of habitability are presented both in scientific journals and articles for a general audience is therefore deserving of serious consideration by the scientific community.

Moreover, the scientific purpose for such metrics is to focus resources on the targets most likely to return a high yield in data. Planets should therefore be selected based on the detectability of a signature --biological, geological or otherwise-- that would provide the most insight into planet formation. If such a signature is undetectable, the metric should always yield zero regardless of planet properties.

This poster highlights the information we currently have available on individual exoplanets, points out how this cannot be used to quantitively assess habitability and suggests both a change in language and focus of the metrics themselves, turning towards detectability, not habitability [1].

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HABITABILITY AND OBSERVABILITY OF PROXIMA CEN AND TRAPPIST-1 PLANETARY SYSTEMS. **M. Turbet**[1], F. Forget[1], J. Leconte[2], F. Selsis[2] and E. Bolmont[3]. [1]Laboratoire de Météorologie Dynamique, Sorbonne Universités, UPMC Univ Paris 06, CNRS, 4 place Jussieu, 75005 Paris, France (martin.turbet@lmd.jussieu.fr), [2]Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France; [3]Laboratoire AIM Paris-Saclay, CEA/DRF - CNRS - Université Paris Diderot, IRFU/SAp Centre de Saclay, 91191, Gif-sur-Yvette.

Introduction: The years 2016-2017 have been incredibly fruitful in discoveries of nearby temperate Earth-size exoplanets, with the detection of Proxima b [1] - the closest exoplanet from us - and the seven planets of the TRAPPIST-1 system [2-4]. These are our best potentially habitable candidates for future atmospheric characterization by either transit spectroscopy, direct imaging, or thermal phase curve with the forthcoming astronomical ground (e.g. E-ELT) or space-based (e.g. JWST) observatories [5,6].

Habitability: Despite a hotter past and an active host star, the planets could have retained enough volatiles to sustain surface habitability [7,8]. We use here the 3-D LMD Generic Global Climate Model (GCM) to explore the possible climate regimes of Proxima b and TRAPPIST-1e, depending on the surface + atmosphere content of water and greenhouse gases (see Figure 1). We find that a broad range of atmospheric compositions allow surface liquid water on these two planets [6]. Remarkably, we find that if Proxima Cen b / TRAPPIST-1e are 1) in synchronous rotation and possess 2) a sufficient H_2O reservoir covering the whole surface (i.e. that cannot be fully trapped on the nightside), then the planets should always have a patch of liquid water at least at their substellar point, whatever their atmosphere (as thick or thin as wanted) [6,9].

Observability: For each of the climate regimes obtained in our analysis, we produce synthetic observables that could be used to prepare future observations of the planets by either JWST or ELT-class telescopes. In the case of Proxima Cen b, we produced reflection and emission spectra, and phase curves for the simulated climates. We find that atmospheric characterization of the planet will be possible via direct imaging with forthcoming large telescopes. The angular separation of $7\lambda/D$ at 1 μm (with the E-ELT) and a contrast of $\sim 10^{-7}$ will enable high-resolution spectroscopy and the search for molecular signatures, including H_2O, O_2, CO_2 [6] ... The observation of thermal phase curves can be attempted with JWST, thanks to a contrast of 2×10^{-5} at 10 μm [6].

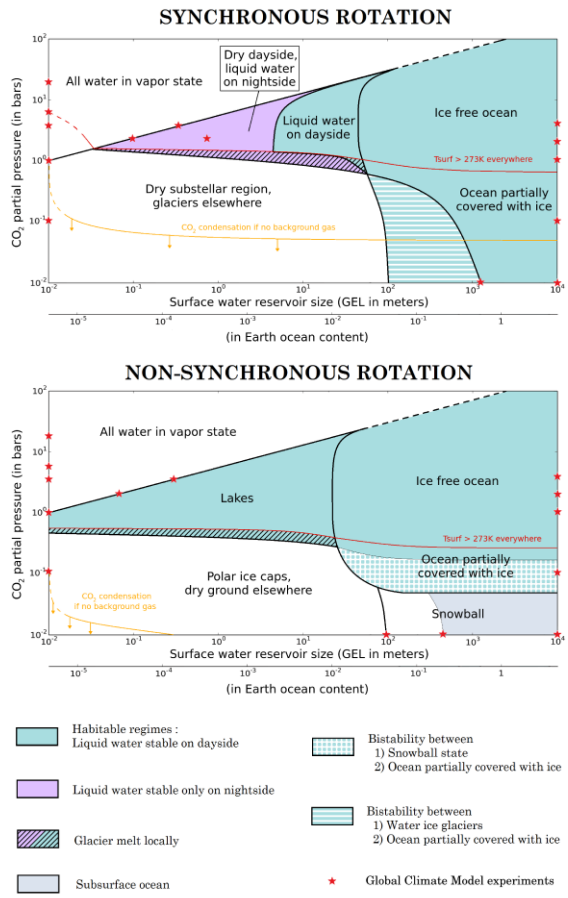

Figure 1: Schematic diagrams of the possible climate regimes reached by Proxima Cen b (and TRAPPIST-1e, by extension) as function of the available CO_2 and H_2O contents. More details can be found in [6].

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GLACIATION ESCAPE ON EARTH-LIKE PLANETS LIMITED BY CO_2 CONDENSATION.

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Introduction: It is widely considered that the carbonate-silicate cycle [1] is the main agent - through volcanism - to trigger deglaciations by CO_2 greenhouse warming on Earth and by extension on Earth-like planets, when they get in frozen state. We use the LMD-G 3D Global Climate Model (with both CO_2 and H_2O cycles) to simulate the ability of planets initially completely frozen to escape from glaciation episodes by accumulating enough gaseous CO_2 [2,3].

Around a Sun-like star: We find that planets that are initially completely frozen and which accumulate CO_2 through volcanism can evolve in different climate regimes depending on their insolation and obliquity. Initially the greenhouse effect of CO_2 is too weak to trigger a deglaciation. The planet stays in a snowball state but keeps accumulating CO_2 in the atmosphere. Then, if CO_2 continues to accumulate, two outcomes are possible 1) The greenhouse effect of CO_2 is sufficient to raise the surface temperatures in equatorial regions above the melting temperature of water ice and the planet escapes from glaciation. 2) The greenhouse effect of CO_2 is too weak to raise the surface temperatures of the poles above the condensation temperature of CO_2 and CO_2 collapses there. The planet is locked in a global glaciated state, with two permanent CO_2 polar ice caps. Quantitatively, we find (see Fig. 1) that planets with Earth-like characteristics orbiting a Sun-like star may never be able to escape from glaciation if their orbital distance is greater than 1.27 AU (62% of the Solar constant), because CO_2 would condense at the poles (the cold traps) forming permanent CO_2 ice caps [2].

Furthermore, for planets with a significant water ice cover, we find that CO_2 ice deposits (1.6x denser than H_2O) should be gravitationally unstable [2,3]. They get buried beneath the water ice cover in geologically short timescale ~10^4 yr, mainly controlled by the viscosity of water ice. CO_2 could then be permanently sequestered underneath the water ice cover, in the form of CO_2 liquids, CO_2 clathrate hydrates and/or dissolved in subglacial water reservoirs. This would considerably increase the amount of CO_2 trapped and further reduce the probability of deglaciation.

Around a M-dwarf: The water ice bolometric albedo is considerably reduced around cool stars [4], making the scenario of CO_2 polar condensation less efficient. However, planets orbiting M-dwarfs are subject to tidal locking. The temperature on the nightside of a synchronous planet can be extremely low, favoring CO_2 condensation. This possibility, already explored in [3], will be presented at the Habitable Worlds 2017 conference.

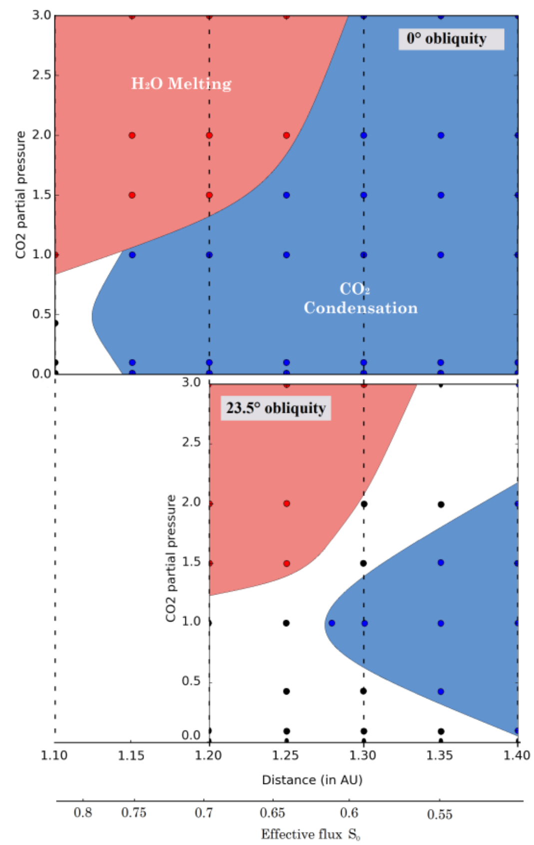

Figure 1: Climate regimes reached as function of the distance from a Sun-like star and the CO_2 partial pressure, assuming a cold start [2]. Figures correspond to Earth-like planets with 0/23.5° obliquity (for upper/lower panels, respectively). The red color depicts the region where deglaciation is observed. The blue region represents glaciated states where CO_2 collapses permanently. The white region describes cases where none of this two previous conditions were reached.

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Direct Imaging of the Nearest Planetary Systems with NASA's WFIRST Mission. M. C. Turnbull[1], B. Macintosh[2], N. J. Kasdin[3], S. Seager[4], A. Roberge[5], M. Marley[6], A. Mandell[5], R. Lupu[7], S. Hildebrandt[8], N. Lewis[9], S. Shaklan[8], C. Stark[9], the WFIRST Science Investigation Teams, and the Starshade Probe Study Team [1]SETI Institute (turnbull.maggie@gmail.com), [2]Stanford University (bmacint@stanford.edu), [3]Princeton University (jkasdin@princeton.edu), [4]Massachusetts Institute of Technology (seager@mit.edu) [5]NASA Goddard Space Flight Center (roberge@nasa.gov), [6]NASA Ames Research Center (mmarley@ames.nasa.gov), [7]Bay Area Environmental research Institute (roxana.e.lupu@nasa.gov), [8]Jet Propulsion Laboratory (srh.jpl.caltech@gmail.com; stuart.b.shaklan@jpl.nasa.gov), [9]Space Telescope Science Institute (nlewis@stsci.edu; cstark@stsci.edu)

Introduction: Using the Coronagraph Instrument (CGI), WFIRST will enable our generation, for the first time in human history, to directly image and characterize planets similar to those in our Solar System. The CGI will also perform detailed studies of the properties of debris disks around nearby stars, giving us insight into the formation of planetary systems. Finally, the mission is baselined to include accommodations for operating with a starshade, should a separate starshade probe rendezvous mission be approved.

We will provide a status update for the mission as a whole (currently nearing the end of Phase A), including results from the currently ongoing independent cost and technology review. To address WFIRST's pathfinding role in achieving the ultimate goal of directly detecting a "pale blue dot" around a sunlike star and search for signatures of habitability, we will describe the specific advances in both (1) the technological capability and (2) the scientific methodology that will contribute to future 4- to 12-m class exoplanet mission concepts such as LUVOIR and Hab-Ex.

Imaging and Photometry with WFIRST Coronagraph: The primary science targets of the WFIRST CGI are giant planets that are already known to exist through radial velocity measurements. However, this imaging survey will also be sensitive to currently unknown planets orbiting the nearest stars. With the constraints of limited mission time and scheduling, such a survey would likely target 20-60 nearby stars, selected to optimize planet detectability [1][2]. Simulations show that such a survey would discover a mean of 4 planets (+-2) with radii as small as ~2 Earth radii. The smaller planets would be too faint for spectroscopic characterization, but photometry could determine whether the planets have methane/hydrogen-dominated atmospheres, and the systems thus discovered would be prime targets for follow-up with future missions.

The survey would also identify circumstellar dust down to 10-20 times the solar zodiacal level. These measurements, combined with observations in the infrared by LBTI, represent direct precursur science for missions like Hab-Ex and LUVOIR.

Spectroscopy with the WFIRST IFS: Lupu et al. [3] and other groups have found that a range of exoplanet atmospheric chemical processes can be reliably probed with the current WFIRST CGI+IFS design for a small, but meaningful, sample of known exoplanets if the spectral resolution (>50) and SNR of the spectrum (>15) are adequate. The current sensitivity predictions show that 3-4 known RV planets will be spectroscopically characterizable at high SNR, and ~18 planets will be accessible to photometry, in addition to potential new-planet discoveries. This presentation will describe how the complete process of acquiring images, selecting targets for spectroscopic followup, and conducting retrieval studies to constrain planetary properties is crucial to refining the scientific methodology and setting requirements for the larger HabEx/LUVOIR missions.

WFIRST Starshade Readiness and Probe Study: Finally, the WFIRST Project has been directed to determine the minimum required impact to the observatory in order to make it "starshade ready." No starshade is planned as part of the WFIRST mission itself, but should a future probe mission be approved to rendezvous with WFIRST, certain decisions must be made now in order to insure compatibility.

A WFIRST starshade mission would enable the detection and spectral characterization of smaller planets (down to flux ratios of ~1e-10 or fainter) orbiting at smaller angular separations (down to ~75 mas) from their stars, potentially including binaries (if used in tandem with the CGI). At the same time, the lack of an *outer* working angle will reveal the distribution of exozodiacal dust present in these systems, which may be indicative of the presence of unseen far-out planets and/or asteroid belts. This "deep dive, big picture" capability would represent a significant step forward in constructing complete family portraits of our nearest neighbors, allowing a first look at the relationships between planetary system architectures and planetary properties.

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THE IMPORTANCE OF SELF-TUNED WAVE GUIDES IN FLUID HABITATS FOR LIFE. Robert H. Tyler[1,2], (1) Geodesy and Geophysics Laboratory, Code 61A NASA Goddard Space Flight Center; Greenbelt, MD 20771; Email: robert.h.tyler@nasa.gov; Tel: 301-614-6472; (2) Department of Astronomy, University of Maryland at College Park.

Resonant excitation of fluid wave guides will arrive in predictable situations where there is a match in form and frequency between available forces and the fluid's eigenmodes of oscillation. The resonant response is typically orders of magnitude more energetic than in non-resonant configurations involving only slight differences in parameters, and the behavior can be quite different because different oscillation modes are favored in each. This study shows that self-tuned wave guides can form in fluids, with an important consequence of greatly raising the efficiency in which a system's spin/orbit energy is tidally transferred to the fluid. The study also suggests that such resonantly forced, energetic scenarios may be more common than exotic because these scenarios appear as stable "attractors" in the space of potential scenarios.

The resonances are easily identified in solutions by the associated peaks in the power. But because these peaks may be both very many and relatively narrow, calculation of millions of solutions can be required to complete the description of the solution's dependence over the range of parameter values. (Construction of these large solution spaces is performed using a fast, semi-analytical method that solves the forced, dissipative, Laplace Tidal Equations subject to the constraint of dynamical consistency (through a separation constant) with solutions describing the vertical structure.)

Filling in the solution space in this way is used not only to locate the parameter coordinates of resonant scenarios but also to study allowed migration paths through this space. It is suggested that resonant scenarios do not arrive through happenstance but rather because secular variations in parameters make the configuration migrate into one of many resonant scenarios, with associated feedbacks either accelerating or halting the configuration migration. Where the effect of increased energy due to approaching resonance acts as a negative feedback on the migration parameters, the scenario is stabilized in a state near resonance.

Most directly, these resonant scenarios describe elevated work raising the wave energy of the system. But the low-entropy wave energy is ultimately transferred to high-entropy heat and other dissipative energy forms. This provides then a collection of energy considerations important to habitats of life.

REDEFINING "EARTH-LIKE": HABITABLE PLANET COMPOSITION AND THE CASE FOR MOVING BEYOND THE MASS-RADIUS DIAGRAM C.T. Unterborn[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe, AZ 85287

The Earth is more than a one Earth-mass, one Earth-radius, one Earth-density planet. It is the only known terrestrial planet to undergo plate tectonics, have continental crust and a strong geodynamo. Whether aiding in regulating surface climate or shielding the planet from stellar winds, each of these unique aspects of the Earth are, in part, geophysical consequences of its geochemical composition. By mole, 95% of the Earth's composition is comprised of only four elements: Mg, Si, Fe, and O [1]. These elements are the major terrestrial-planet-building elements, the relative proportions of which govern a planet's dominant mantle mineralogy, determine the relative core size, and primarily control on a planet's mass and radius for those without large volatile envelopes [2, 3, 4]. The remaining minor elements (e.g. Ca, Al, and Na) control crustal composition and weathering, melting and degassing relations, and may even play a role in tectonics [5, 6].

Mass-radius models, however, are extremely insensitive to the abundances of the important minor elements. As we search for habitable worlds, mass-radius models will provide only a coarse picture of a terrestrial planet's surface geology and dynamic state. This means we must move beyond a description of planets as "Earth-like" based on bulk density alone and instead quantify a planet's likelihood to be of a composition which allows it to truly be like the Earth: dynamic over geologic timescales.

In this review talk, I will provide a broad overview of how terrestrial planet composition affects a planet's dynamic state, which in turn, aids in creating a habitable surface. Topics will include core formation and the minimum criteria needed for a geodynamo, the creation and weathering of continents, the rate and chemistry of degassing, interior storage and transport of volatiles, mantle convection and heat budget, and compositional constraints on the likelihood of plate tectonics. The details of many of these topics, even for the Earth, are still not well understood and heavily debated in the Earth and planetary science communities. Thus, rather than attempt to answer the complex question of whether specific currently known exoplanets are Earth-like, dynamic and habitable, this review talk will explore the broader potential compositional diversity of terrestrial exoplanets as informed by the wide range of stellar compositions observed in the Galaxy [7].

Given the breadth of this compositional parameter space, we may only be able to determine compositions which are "Not Earth-like." However, the detection of life is binary, and thus maximizing our limited resources to study those planets *more likely* to be behaviorly similar to the Earth is of paramount importance moving forward as a community.

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STELLAR CHEMICAL CLUES AS TO THE RARITY OF EXOPLANETARY TECTONICS

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Abstract: Earth's tectonic processes regulate the formation of continental crust, control its unique deep water and carbon cycles, and are vital to its surface habitability. A major driver of steady-state plate tectonics on Earth is the sinking of the cold subducting plate into the underlying mantle. This sinking is the result of the combined effects of the thermal contraction of the lithosphere and of metamorphic transitions within the basaltic oceanic crust and lithospheric mantle. The latter of these effects is dependent on the bulk composition of the planet, e.g., the major, terrestrial planet-building elements Mg, Si, Fe, Ca, Al, and Na, which vary in abundance across the Galaxy. As refractory elements, the relative ratios of these abundances are a first order control on a terrestrial exoplanet's bulk composition, and thus the mineralogy of its depleted mantle and melt-extracted crust. Here, we present thermodynamic phase-equilibria calculations of planetary differentiation to calculate both melt composition and mantle mineralogy. We show that a planet's refractory and moderately-volatile elemental abundances control a terrestrial planet's likelihood to produce mantle-derived, melt-extracted crusts that sink. Those planets forming with a higher concentration of Si and Na abundances are less likely to undergo sustained tectonics compared to the Earth. We find only 1/3 of the range of stellar compositions observed in the Galaxy is likely to host planets able to sustain density-driven tectonics compared to the Sun/Earth. Systems outside of this compositional range are less likely to produce planets able to tectonically regulate their climate and may be inhospitable to life as we know it. Furthermore, this work provides a broad framework for future studies to explore the role of both physical and chemical disk processes on the final bulk composition and potential tectonic state of a terrestrial exoplanet. Finally, these results show the benefit in including heretofore underutilized measurements of a host star's planet-building elemental abundances in determining the potential *geology* of a terrestrial exoplanet. Only by including these concepts in the discussion of whether an exoplanet is "Earth-like" and habitable will we as a community expand beyond the current scope of planetary classification as one of bulk density alone.

Kevin Wagner - Habitable Worlds Abstract Submission - Laramie, WY - 2017

Status of The Scorpion Planet Survey: Establishing the Frequency of HR8799-b like planets.

The Scorpion Planet Survey aims at establishing the frequency of wide-orbit super-Jovian planets around young A-type stars through direct imaging with VLT/SPHERE. The motivation for the survey is to place constraints on the population of HR 8799-b-like worlds: those that orbit at ~80-100 au from their host stars. At such wide separations, these worlds present challenges and constraints for planet formation and migration models. If super-Jupiters are common in the outer planetary systems it is likely that they will also significantly affect the habitability of rocky planets in the inner planetary systems by both influencing the planet formation process and by impacting the dynamics of the emerging planetary systems. In this presentation we will review the existing evidence on the occurrence rates of super-Jupiters and present the status of our on-going survey.

The Orbits and Atmospheres of Directly-Imaged Exoplanets from the Gemini Planet Imager Exoplanet Survey. J. J. Wang,[1] and the Gemini Planet Imager Exoplanet Survey Collaboration, [1] Department of Astronomy, University of California, Berkeley, CA 94720, USA (j-wang@berkeley.edu)

Introduction: While thousands of exoplanets have been discovered to date, only a limited number of them are amenable to detailed characterization. Direct imaging allows us to measure the orbits of exoplanets as well as measure light from their atmospheres. Additionally, direct imaging allows us to characterize Jupiter-like exoplanets on long period orbits, which are challenging for the transit and radial velocity detection methods. However, systems with giant planets in wide orbits will be attractive targets for future terrestrial planet searches, since giant planets may be crucial to shielding the terrestrial planet zone from bombardment [1].

Gemini Planet Imager Exoplanet Survey (GPIES): The Gemini Planet Imager (GPI) is an infrared instrument dedicated to imaging exoplanets by combining a high-order adaptive optics system to correct for atmospheric turbulence, a coronagraph to suppress the glare of the star, and an integral field spectrograph to take simultaneous images and spectra of exoplanets [2]. GPIES is a 600-star survey for young, Jovian-mass exoplanets at Solar System scales. GPIES combines the advanced instrumentation of GPI with sophisticated data analysis algorithms [3,4] to image faint exoplanets that would otherwise be swamped by the glare of their host stars.

Exoplanet Characterization with GPIES: To date, GPIES has imaged six exoplanets [2,5,6,7,8] and three brown dwarfs [9,10,11]. GPIES also has developed open-source data reduction tools necessary to characterize these companions [3,4]. I will show the orbits of the companions and discuss what inferences we can make from their dynamics. I will also present their 1 to 2.4 micron near-infrared spectra and the insights into their atmospheres. GPIES also has made use of an automated data processing infrastructure that allows for consistent data products and extremely quick follow-ups on the most promising planet candidates. I will discuss how the tools and lessons learned from GPIES will allow us to characterize potentially habitable Earth-like planets from future direct-imaging missions, especially as turnaround times need to be quick in order to follow up and constrain the orbits of Earth-like planets in the habitable zone.

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Remnant Planetary Systems at White Dwarfs. David J Wilson[1] and Boris T Gänsicke[1],
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Observations of remnant planetary systems at white dwarfs provide important contributions to exoplanet science in general and habitability in particular. Foremost among these is the only method to directly measure the bulk chemical composition of solid extrasolar material. The high density of Earth radii, but ~ Solar mass white dwarfs implies that metals heavier than hydrogen or helium sink out of their atmospheres on short timescales. The metal absorption lines seen in ~30 percent of white dwarfs must all therefore have an external origin. Observations of transiting material and dusty debris discs from tidally disrupted planetesimals, scattered into the white dwarf by planets that survived the main sequence evolution, confirm this scenario. High resolution spectroscopy of an increasing number of white dwarfs has revealed a plethora of atomic species, allowing detailed conclusions about planetesimal compositions to be drawn. As the progenitor stars of white dwarfs are, on average, 2-3 Solar masses, these observations also explore a parameter space of host stars that is hard to be studied in systems with host stars still on the main sequence.

In this talk, I will first review the historical observations that have led to our current understanding of remnant planetary systems at white dwarfs, as well as the state of the field today. I will present Hubble Space Telescope and Very Large Telescope data of metal polluted white dwarfs where multiple metals have been detected, including objects with high levels of core (Fe, Ni) material that may have undergone mantle stripping during the post main sequence, as well as objects with carbon and oxygen measurements that can be used to place limits on the existence of the hypothetical carbon planets. Finally, I will describe how white dwarfs can be used to search for water in extrasolar systems via detection of excess oxygen and hydrogen.

Observational Signals of TRAPPIST-1e Derived From a 3D Climate Model. E.T. Wolf[1], D. Gatlin[1], R.K. Kopparapu[3], J.H. Haqq-Misra[4], G. Villanueva[2,5] [1]University of Colorado, Laboratory for Atmospheric and Space Physics (eric.wolf@colorado.edu) [2]NASA Goddard Space Flight Center [3]Univeristy of Maryland [4]Blue Marble Space Institute of Science [5]Catholic University of America

Summary: In recent years, a wide variety modeling studies have focused on determining potential climate states for generically Earth-like extrasolar planets. These studies have estimated the limits to the habitable zone around main sequence stars, and have identified important atmospheric processes that may occur on these worlds. However, it is critical that we connect the dots between our climate models and observations to be returned by the next generation of exoplanet observing telescopes. What results from our 3D simulations are directly useful for interpreting observations of terrestrial extrasolar planets?

Recently seven terrestrial planets were discovered transiting the ultracool star TRAPPIST-1 [1]. The TRAPPIST-1 system provides a tremendous opportunity for studying potentially habitable worlds, and is a primary target for follow-up observations. Early modeling studies indicate that planets b, c, and d lie too close to the host star and are probably desiccated today. Planets f, g, and h are probably increasingly cold and icy [2, 3], requiring thick atmospheres to deglaciate if at all. Planet e, located in the center of the system, provides the best opportunity for a habitable world [2, 3].

TRAPPIST-1e orbits on a 6.1 Earth-day period, and is believed to be tidally locked to its host star. Planet e has a radius of 0.918 R_{Earth}. While there is significant uncertainty regarding the planet's bulk density, the best estimate places its density at ~0.89 ρ_{Earth}. Planet e receives about 66% of the modern solar insolation, although the incident stellar spectrum is significantly redder than the Sun.

Here, we conduct 3D climate simulations of TRAPPIST-1e considering a variety of atmospheric constituents, including N_2, CO_2, CH_4, and H_2O. We then analyze our simulations with an eye towards notable observable characteristics. In particular, we calculate spectrally resolved thermal emission phase curves [4], which may be used to characterize the atmosphere (Fig. 1). We also show results from the Planetary Spectrum Generator [5], which allows us to simulate transit measurements yielded by real telescopes and instruments, using our 3D modeled atmospheres as simulated target objects. Our primary goal is to determine signals that may differentiate habitable from uninhabitable climate states for TRAPPIST-1e.

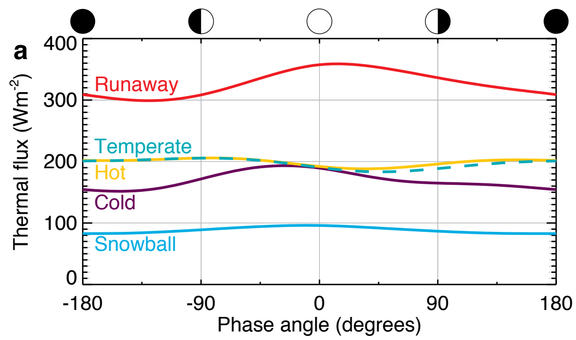

Fig 1. Thermal emission phase curves from simulations of different possible climatic outcomes for planets in the TRAPPIST-1 system.

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A METHANE-RICH EARLY MARS: IMPLICATIONS FOR HABITABILITY AND THE EMERGENCE OF LIFE

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Introduction: We investigate the radiation and chemistry of a ~4.0 Ga, CH_4-rich martian atmosphere in an effort to assess whether or not Mars was once habitable and suitable for the emergence of life. While the primary goal of this work is to elucidate mysteries in martian history, our results can help us understand the nature of the numerous small terrestrial exoplanets that we are only beginning to discover and characterize. High atmospheric CH_4 may be consistent with a mantle that does not reach the requisite pressure (24 GPa) and temperature (1900 K) for the silicate spinel-to-perovskite transition (Dale et al., 2012; McCammon, 1997; Wadhwa, 2001; Wood et al., 2006). Impact degassing from chondritic material can also contribute substantial amounts of CH_4 to the atmosphere (Schaefer and Fegley, 2007).

CH_4 plays an important role in atmospheric radiation. Atmospheric models have demonstrated that a purely CO_2 atmosphere, even one as massive as 7 bars, is incapable of heating Mars above an annual-mean surface temperature of 273 K (Forget et al., 2013), although recent studies show that recurring wet states could have been induced in an H_2-rich atmosphere (Batalha et al., 2015, 2016). We show that CH_4 alone is insufficient to warm early Mars above freezing—in fact it produces an anti-greenhouse effect—but it substantially raises middle atmospheric temperatures. We determine whether or not such high temperatures could prolong the photochemical lifetime of SO_2, another potent greenhouse gas.

We use RC1D, a non-gray 1-D radiative-convective equilibrium model, to calculate the atmospheric thermal structure consistent with the radiative heating and cooling associated with the composition computed at each chemical model time step. KINETICS, the Caltech/JPL chemistry transport model (e.g. Nair et al., 1994), determines the chemical makeup of the atmosphere, evaluating steady-state chemical profiles and the synthesis of astrobiologically relevant molecules. H_2O is in vapor pressure equilibrium at the surface. We consider conditions forced by the faint-young Sun's spectrum and luminosity.

By coupling RC1D and KINETICS, we are able to paint a more realistic picture of Mars's early climate, calculating the surface temperature under a CH_4-rich atmosphere, and assessing the production of key electron acceptors, such as sulfate and nitrate.

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Abrupt Climate Transition of Icy Worlds from Snowball to Moist or Runaway Greenhouse. Jun Yang[1], Feng Ding[2], Ramses M. Ramirez[3], W. R. Peltier[4], Yongyun Hu[1], and Yonggang Liu[1], [1]Department of Atmospheric and Oceanic Sciences, Peking University (junyang@pku.edu.cn; yyhu@pku.edu.cn), [2]Department of the Geophysical Sciences, University of Chicago, [3]Department of Astronomy, Cornell University, and [4]Department of Physics, University of Toronto.

Abstract: Ongoing and future space missions aim to identify potentially habitable planets in our Solar System and beyond. Planetary habitability is determined not only by a planet's current stellar insolation and atmospheric properties, but also by the evolutionary history of its climate. It has been suggested that icy planets and moons become habitable after their initial ice shield melts as their host stars brighten. Here we show from global climate model simulations that a habitable state is not achieved in the climatic evolution of those icy planets and moons that possess an inactive carbonate-silicate cycle and low concentrations of greenhouse gases. Examples for such planetary bodies are the icy moons Europa and Enceladus, and certain icy exoplanets orbiting G and F stars. We find that the stellar fluxes that are required to overcome a planet's initial snowball state are so large that they lead to significant water loss and preclude a habitable planet. Specifically, they exceed the moist greenhouse limit, at which water vapour accumulates at high altitudes where it can readily escape, or the runaway greenhouse limit, at which the strength of the greenhouse increases until the oceans boil away. We suggest that some icy planetary bodies may transition directly to a moist or runaway greenhouse without passing through a habitable Earth-like state (Fig. 1).

Background and Conclusion: Icy worlds are common in the solar system (such as Europa, Enceladus, Ganymede, and early Earth) and plausibly also in extra-solar systems. A fundamental question is that: Would such icy planets and moons become habitable once their ice cover melts? There are two ways for the icy worlds to escape the globally ice-covered snowball states. One is that continuous atmospheric accumulation of CO_2 from volcanic outgassing during the snowball phase triggers the melting [1]; this is plausible for planets having an active carbon cycle (e.g., Earth), and they become habitable for life after the ice melts. The other is that the stars brighten with time and the ice melts once the stellar flux exceeds a critical value; this is the case for planets and moons lacking an active carbon-silicate cycle and having low concentrations of greenhouse gases (e.g., Europa). Here, we investigate the second case using a series of three-dimensional (3D) climate model experiments.

Using 0D and 1D energy balance climate models and a 3D gray-gas atmospheric general circulation model (GCM), previous studies had examined the climate evolution of a snowball planet having low concentrations of greenhouse gases [2-4]. However, their models were unable to account for the effects of clouds, lapse rate, spatial snow and ice distributions, realistic atmospheric radiative transfer, and/or meridional atmospheric heat transport, which have been identified to be critical for simulating the snowball climate. Moreover, the simple climate models cannot simulate vertical water vapor transports or the onset of a moist greenhouse state. These studies showed that a post-snowball climate should be hot, but whether it is habitable for life or not remains unclear. In contrast to previous studies [5-7] that suggest the existence of a habitable world after the snowball deglaciation, here we show that the increased stellar insolation will force the planet into an uninhabitable moist or even runaway greenhouse state. Note that our conclusion applies to planets that have an inactive carbonate-silicate cycle and low concentrations of greenhouse gases in G-star and F-star systems, but not to Earth-like planets with active carbonate-silicate cycle and massive CO_2 accumulation in a snowball state.

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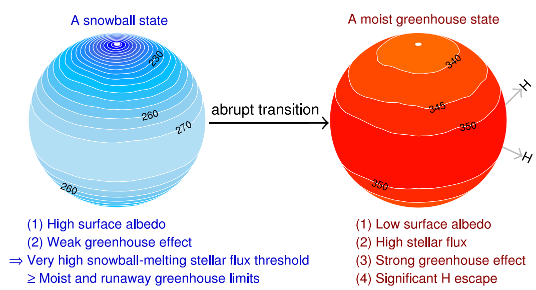

Fig. 1. Schematic illustration of the climate transition under stellar brightening and the underlying physical mechanisms. The contour lines are surface temperatures right before snowball melting (left) and after the melting (right), with a contour interval of 5 K.

For more details, please see our paper: Abrupt Climate Transition of Icy Worlds from Snowball to Moist or Runaway Greenhouse, *Nature Geoscience*, in press.

CONSTRAINING THE HABITABILITY HISTORIES OF PLANETS.

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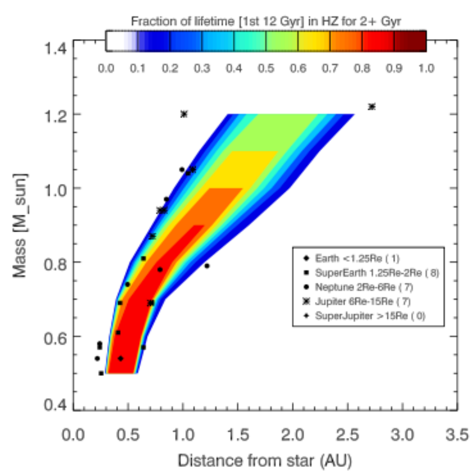
Introduction: For any given set of assumptions about the location of a habitable zone (HZ) around a star, the instantaneous "habitability" of a detected planet can be determined by (relatively) straightforward measurement of stellar properties. If we are interested in the actual surface conditions of a planet or the likelihood of detectable life on it, it is necessary to have some knowledge of its history. For a star of known mass, age, and composition, the evolution of the stellar habitable zone can be predicted to the limits of a model's accuracy. Codes and libraries of models for various HZ descriptions and stars of a wide range of masses and detailed abundances are readily available.

In practice, it is often difficult to determine the age of field dwarfs to better than a gigayear. While the situation is rapidly improving, many stars do not have high quality chemical abundance information. We present a method for probabilistic determination of HZ evolution in the absence of constraints on stellar age and composition of an individual system to contribute to prioritizing targets for biosignature detection observations.

Methods: Developing predictions for HZ evolution requires three components. We use the library of stellar models presented in [1] and [2]. The database includes time-dependent HZs derived from the stellar models and HZ parameterizations from [3]. In this work we use the conservative moist greenhouse and maximum greenhouse cases. Second, we must choose a constraint on the HZ evolution that is informative for target selection. For this example we choose a 2 Gy continuous HZ (CHZ_2). This choice is based on the interpretations of Paleozoic sediments that propose life modified Earth's atmosphere at a level that might be detectable from a nearby stellar system with about two billion years. Finally, we choose priors describing the stellar population. In this test case we assume a uniform distribution of stellar ages and a metallicity distribution identical to that in the *Hypatia* stellar abundance database [4]. Different priors can, of course, be chosen, such as more complicated age distributions motivated by star formation history models. Combining these, we can assign a probability that a planet orbiting at a given distance from a star of (approximately) known mass has been in the HZ for at least 2Gy, even if we do not know the age or composition of the star. In principle, this schema can be adjusted to an arbitrary number of degrees of freedom, with greater or lesser predictive power.

To compute the 2 Gyr HZ statistical probabilities, we create radius and step through each star's evolution in the Tycho. At each stellar age, we measure whether the radius falls within the calculated HZ limits, and if it remains for at least 2 Gyr, then we add the current time-step to that bin. For each model, we end up with the amount of time that each orbital radius is in the HZ for at least 2 Gyr, and we also know the total lifetime of each model. To combine the various models, we sum the total time in all models spent in each radius bin, and divide the results by the total time of all models. Finally, we incorporated the *Hypatia* Fe distribution into a combined plot by taking the fraction of the *Hypatia* stars in each of our metallicity bins, normalized to 1. While combining the metallicity models we multiplied the radial 2 Gyr HZ fractions by the corresponding normalized *Hypatia* bin value, again dividing by total time of all the models. This results in a 2 Gyr HZ probability curve, weighted by the Hypatia metallicity distribution.

Results: Figure 1 shows the probability that a given orbital distance has been in the HZ for at least 2Gy, for a star of unknown age and metallicity. Probabilities are for a uniform age distribution with a cutoff of 12 Gy and the *Hypatia* metallicity distribution. Planets from the NASA exoplanet archive are overplotted for comparison.



References:

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LIMITS TO CREATION OF OXYGEN-RICH ATMOSPHERES ON PLANETS IN THE OUTER REACHES OF THE CONVENTIONAL HABITABLE ZONE.
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Introduction: Why Earth has an oxygen-rich atmosphere is not a solved problem, although the crucial importance of O2 to life on Earth, and its generation by life on Earth, are unquestioned. The factors that promote or frustrate the generation of free oxygen are central to what we mean by habitability, because it is O2 that makes a world fit for creatures like us. The astronomical mission to identify and characterize an inhabited planet remains focused on the quest to detect O2 (or its byproduct O3) because, apart from artificial molecules such as CF4, oxygen remains the leading indicator of habitation as we know it. We can expect that eventually, perhaps within 100 years, we will have accumulated a database of such exoplanets and we will begin to be able to evaluate basic hypotheses regarding the origin of oxygen (if not the origin of life).

To the best of our knowledge, a general discussion of which habitable planets are conducive to oxygen has not taken place. Theories for the rise of oxygen fall into 4 categories: (i) It is governed by the intrinsic rate of biological innovation, independent of environmental factors. (ii) It is caused by mantle evolution, probably consequent to secular cooling. (iii) It is caused by hydrogen escape, which irreversibly oxidizes the Earth. (iv) O2 is a Gaian response to the brightening Sun, suppressed until reduced greenhouse gases were no longer needed to maintain a clement climate. All but the first of these make implicit astronomical predictions that can be quantified and made explicit.

Here we will focus on the third hypothesis as the best posed, most readily quantified, and most testable. In this hypothesis hydrogen escape is like an hourglass: the oxygen left behind by the tiny but steady trickle of hydrogen into space inexorably oxidizes all the relevant reduced mineral buffers (they are titrated, as it were) before free abundant O2 first becomes possible.

Of course there is no guarantee that planetary oxidation causes the emergence of oxygenic photosynthesis, nor for that matter is there any guarantee that life is even present on the planet. It is easy to imagine planets where the table is set for O2 yet oxygenic photosynthesis fails to arise (e.g., Mars). But the hydrogen hourglass does make the clear prediction that O2 will not be present if hydrogen escape has been insufficient. We will therefore focus on this aspect of the hypothesis in this talk.

The fourth hypothesis—the Gaian response—makes two kinds of predictions. One is trivial almost to the point of tautology: if Gaian mechanisms are the norm, we should expect the temperatures of habitable planets to be under thermostatic control. Under Gaian governance, a habitable planet that receives less sunlight will compensate by emitting a more potent mix of greenhouse gases, and/or presenting an anomalously low albedo, and it will maintain liquid water at the surface despite the faintness of its sun. Some of the greenhouse gases will be best explained as biogenic. The second kind of prediction is implicit: the rate of biological evolution should be set by the rate of stellar luminosity evolution, because it is evolving Gaia's ingenuity that keeps pace with the star. To first approximation, this has been the case for Earth for most of its history. This prediction would imply that the emergence of O2-rich atmospheres is a function of spectral type.

That the second hypothesis can make predictions is clear—to first approximation, the rate that planets cool must depend on the surface-to-volume ratio—but otherwise it is difficult to make much progress at present because, despite decades of work on the “mantle-first” hypothesis, there is no agreed-upon mechanism that directly links the thermal state of the mantle to the redox state of the surface and atmosphere.

Most studies of hydrogen escape from planets focus on determining how fast the hydrogen escapes. In general this requires solving hydrodynamic equations. But for planets from which hydrogen escape is modest or insignificant, the atmosphere can be approximated as hydrostatic, which is much simpler, and for which a relatively full-featured treatment of radiative cooling by embedded molecules, atoms, and ions such as CO2 and H3+ is straightforward. Previous work has overlooked the fact that the H2 molecule is extremely efficient at exciting non-LTE CO2 15 micron emission, and thus that radiative cooling can be markedly more efficient when H2 is abundant. We map out the region of phase space in which terrestrial planets keep hydrogen-rich atmospheres, which is what we actually want to know for habitability. Finally, we might briefly address the implications of diffusion-limited escape to the empirical observation that rocky planets with thin or negligible atmospheres are rarely or never bigger than ~1.6 Earth radii.

Modeling Debris Disk Spectra Using Varying Compositions

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Debris disks reveal much about habitable exoplanets; their formation, compositions, and structure can be inferred from the nature of the surrounding material in the circumstellar disk. The accretion of disk material causes exoplanets and planetesimals to form, and the composition of this dust can tell us about the potential habitability of such objects. We use with mid- IR spectra from Spitzer for a selection of debris disks in order to understand the properties of their dust grains. We use these spectra to help create the disk model, which we plan to apply to near and mid IR spectra and photometry of known debris disks. After calculating the dust absorption and emission within debris disks with Mie Theory, we use a varying mixture of grain compositions and sizes to generate MCMC fits for the spectral data. By identifying the main compositional components of debris disks, we hope to learn more about the formation and nature of exoplanets.