The Chronology Problem in the Outer Solar System: Constraining the "WHEN" of Major Dynamical and Geological Events

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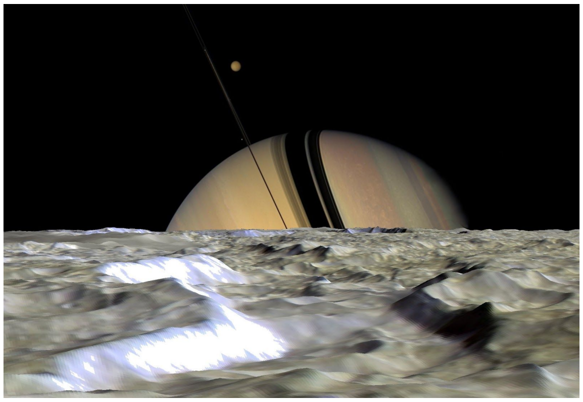

Perspective rendering from Cassini imaging and topography of pristine fractures on Rhea with Saturn and its glorious rings and moons in background. Are these features/events young or old?

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INTRODUCTION: Why We Need to Know "When" Events Occurred in the OSS

The prevalence of icy worlds with subsurface oceans and active venting in the Outer Solar System (OSS) has been one of the most important revelations of the Space Age. The Voyagers, Galileo, Cassini and New Horizons missions revealed families of incredibly diverse icy worlds. On some satellites, the observed activity is geologically recent or ongoing (i.e., resurfacing or venting on Enceladus, Triton, and possibly Europa and Pluto [1, 2, 3]), while in other cases it is likely extinct (e.g., (cryo)volcanism on Ganymede, Dione, Miranda, Ariel, Charon, and elsewhere [4, 5, 6]). These bodies also have complex geologic histories involving volcanism and tectonism that record the dynamical forces and geologic stresses (e.g., dynamically driven heating from tidal flexing) responsible for maintaining oceans and geologic activity. However, the sequence and timing of **WHEN and HOW LONG** geologic activity and related features occurred on these bodies, the geophysical and geochemical events and dynamical processes that formed them, and by extension, the dynamical evolution of the Solar System, is poorly constrained.

Until the ages and durations of geologic activity and oceans throughout the OSS can be better constrained, dynamical and geological processes, and especially those responsible for creating and maintaining subsurface oceans past *and* present, will be inadequately understood. *Thus, understanding OSS chronology is critical to understanding the history of dozens of worlds in this region of space, and provide key insights for astrobiology, for it could resolve the timing and duration of potentially habitable oceans.* In this white paper, we summarize the current state of surface age determination in the OSS and make recommendations and advocate for research into the Chronology of the OSS as a high priority for NASA over the next decade.

In Summary we make the following Recommendations (outlined in detail at the End):

1. **Improve completeness and interpretability of current and future crater counts**
2. **Improve knowledge of Kuiper Belt objects and related populations**
3. **Support development of novel methods to remotely determine absolute ages**
4. **Prepare NOW for remote age determinations on future landed platforms**

BACKGROUND: Current State of Knowledge of Surface Ages

Background: Impact Crater Populations Are the Only Method for Quantitative Chronology

In the absence of samples for analysis in Earth laboratories, and the absence of adequate *in situ* instrumentation on these bodies, the best available means of estimating *relative* surface ages of solid bodies is crater measurements using high-resolution surface imaging (Fig. 1), which has a long history (see reviews by [7, 8, 9] among others), and is supported by basic geologic principles of superposition (surfaces with a larger crater spatial density will be older). These efforts produce informative stratigraphic sequences for individual bodies and also allow a basis of comparison of ages *within* individual satellite systems.

This basic principle has been used for decades, but it is complicated by several unknowns related to crater-forming projectile populations: What is the role of asteroids versus other distinct dynamical populations like Centaurs, Trojans, Jupiter Family Comets (JFCs), or Kuiper

Belt Objects? What is the role of secondary craters [e.g., 11; formed from ejecta blocks launched during main crater formation]? What is the role of planetocentric impactors, that is, impactors that orbit within a satellite system; either sesquinary craters [formed from ejecta that becomes planet-orbiting] or other debris [e.g., 12]? How do craters and crater-related features (such as rays) on icy bodies degrade with time? All of these are poorly constrained in the OSS, and their study has been hindered by incomplete imaging coverage.

Imagery forms the basis for impact crater studies (Fig. 1). In comparison to the resolution and data rate challenged Voyager and Galileo missions, Cassini was an amazing success, providing near-global sub-km imaging for five of the six mid-sized satellites (only partial coverage for Iapetus). Very limited imaging at pixel scales better than 50 m/pix (and in rare cases < 10–20 m/pix) allows us to map craters <1 km across over targeted areas and substantially improving our understanding of the impact population.

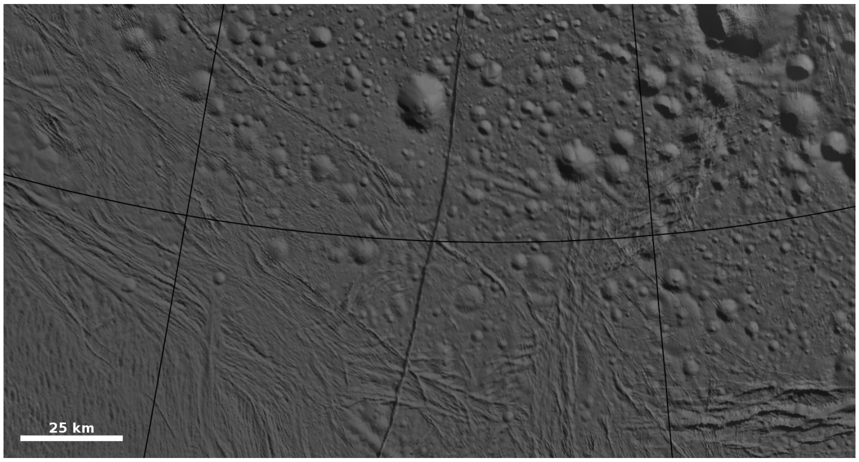

Figure 1. A typical region of the icy satellite Enceladus showing terrains of different ages [10]. Older terrains in the northeast are heavily cratered, while younger, tectonized terrains are lightly cratered and of varying crater spatial density. Despite constraints provided by the cratering record, the timing when tectonism occurred is uncertain by factors of 2 or more [10].

Meanwhile, the New Horizons provided substantial image coverage at resolutions as fine as 80 m/pix at Pluto, 130 m/pix at Charon and ~30 m/pix at (486958) Arrokoth, allowing for the study of impact craters again at the sub-km scale over at least some areas of these bodies [9]. **The legacy of all OSS mission data is still paying dividends, and NASA's healthy support of Galileo, Cassini, and New Horizons data analyses should be continued. Despite these successes, major gaps in the cratering record at Jupiter (where coverage is very limited) and at Uranus and Neptune remain and we encourage orbiter-style missions to constrain crater and impact population between 5 and 30 AU from the Sun, as well as missions deep into the Kuiper Belt.**

Background: Crater-Based Age Models Require Understanding the Dynamics of the OSS

In the absence of ground-truth calibration, any estimate of crater-based surface ages requires a dynamical model of the time-dependent impact flux in the OSS. The current state of knowledge of the impact flux in the OSS is relatively poor, and depends on several critical assumptions.

Our limited understanding of these assumptions, as well as ambiguities in the interpretation of the observed cratering record, result in uncertainties in absolute surface model ages that are on the order of at least a factor of 2, but likely significantly more [e.g., 13-16].

The most important assumption in interpreting crater counts is the nature and origin of the primary projectile population(s), their sources described briefly above. Phrased differently than above, there are three different potential dynamical groupings of impactors: (1) Impactors beyond Mars are identical to those that impacted the Moon, with some scaling factor applied [17, 18]. This model is dynamically unlikely [14]. (2) Bodies from Jupiter outward are impacted mostly by a common population of small bodies in the OSS, primarily Kuiper Belt Objects (KBOs) and their derived populations (e.g., Jupiter-family comets (JFCs) and Centaurs) [13, 19]. (3) Events within the gas and ice giant systems produce their own short-lived projectile populations of planetocentric debris [20] (for example, the Saturn ring-satellite system might be extraordinarily young [cf. 21]). Each hypothesis of the potential impactor population makes different assumptions regarding the current flux and its variation with time, and they can work together to significantly complicate things.

Unraveling these populations has proven to be very difficult, despite attempts over the past several decades. In some cases, such as the Saturn system, it is not known which population has been dominant [8], with serious implications (and therefore, current uncertainty) for derived model ages, despite Cassini's success. Modelers have explored how asteroids escape the main belt [e.g., 22], how Kuiper Belt Objects (KBOs) evolve into impacting populations for the gas giant and ice giant systems [e.g., 23], and how planetocentric populations may be produced and evolve [e.g., 24], but new simulations sometimes contradict others once additional physics or observational constraints are included.

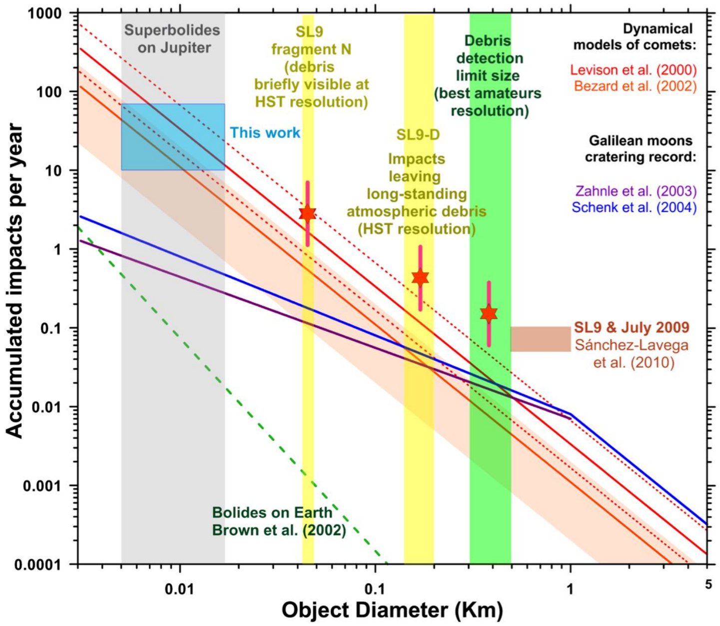

Figure 2. Current impact rate on Jupiter, from [25]. The figure shows the cumulative number of bodies larger than a given diameter expected to strike Jupiter and Earth per year compared. Data used include "superbolides" (impactors estimated to be ~10 m in diameter; SL9-scale

impacts (~100 m-1 km bodies), dynamical models of comets, and the cratering record of the Galilean moons. The observational estimates are higher than the model estimates.

Another important assumption is the rate at which these impactor populations produce craters. There have been attempts [13-16] at deriving this rate, especially over the past few Ga. Estimation of the current rate can come from observations of recent impacts, such as Shoemaker-Levy 9 and other impacts on Jupiter [13, 25], the dynamics of currently observed populations, and the record of changing crater spatial density over time on main belt asteroids and icy satellites. There have even been theoretical attempts to derive the rate during early epochs of heavy bombardment [26].

Uncertainty in the impact rates on the moons are dominated by the uncertainty in the rates on the primary planet. Hueso et al. [25] compiled estimates of the current impact rate on Jupiter (Fig. 2), based on flashes from "superbolides" entering Jupiter's atmosphere, the Shoemaker-Levy 9 (SL9) impacts, an SL9-scale impact in July 2009, dynamical models, and the cratering record of the Galilean satellites. Rates on Jupiter can be applied to the Galilean satellites by using scaling factors [13] but these also have large uncertainties. For instance, if the impact rate of >1 km bodies on Jupiter is 0.01/year, the corresponding rates on the moons are ~10^{-6}/year, i.e., a km-sized body is expected to strike each moon about once every million years. **Research into the dynamical evolution of projectile populations is urgently needed and should be supported in the coming decade.**

Background: Direct Observations of Impactors

Astronomical observations of KBOs have provided their size-frequency distribution (SFD) [e.g., 27, 28], but few objects smaller than 40 km in diameter have been observed. Thus, SFDs for smaller KBOs have to be extrapolated. Crater populations can be used to help resolve the size distribution of smaller KBOs, if one is able to disentangle the above-described different populations. Until New Horizons, it was unknown whether KBO-derived impactors had a shallow SFD slope (fewer small objects than large ones, compared to a standard SFD such as on the Moon) or a steep slope for bodies less than about 1 km across, due to the confused crater population and observational limits on impactors. Through crater SFDs measured on Pluto and Charon, New Horizons provided evidence that the KBO population has a shallow slope for bodies smaller than ~1 km [9]. The critical component that allows this for Pluto and Charon is that neither body shows secondary craters, and there are no known planetocentric impactors.

Additionally, major gaps remain in our observations of the KBO-derived populations at relevant size ranges to constrain how KBOs evolve into other OSS populations–like Centaurs–and if we might expect different SFDs. Surveys conducted by the LSST and ELT should be fully funded and supplemented where necessary to improve KBO knowledge. The Lucy mission, scheduled to launch in October 2021, is a good step toward a better understanding of Jupiter's Trojans, which models predict were captured from the same small body population as the KBOs, Centaurs, and JFCs. A mission to the Centaurs would be similarly helpful as would a complete Kuiper Belt survey. **Observational constraints on projectile (and crater) populations are urgently needed and should be supported in the coming decade.**

Background: Scaling Laws

Despite the crater results, one must still use scaling laws to derive the impactor population from the craters, adding some uncertainty. A final main assumption is how to convert observed crater diameters to projectile diameters through scaling laws [29]. Scaling laws and subsequent simple-to-complex modification parameters were initially derived for impacts into rocks and sand. Later works have derived some scaling relationships for ice-on-ice impacts, particularly impact melt and vaporization [e.g. 30]. However, further work is required to refine these laws and crater size relationships for ice, particularly with impurities. The various scaling laws currently give results that differ by at least ~1.5×, and compounded with other uncertainties described in the previous three background sub-sections, results in significant uncertainty in absolute model ages. **Additional laboratory work and numerical modeling efforts are required to scale and interpret observed impactor populations on icy moons to reduce uncertainties.**

Background: Novel Methods of Absolute Age Measurement

Classically, in the Inner Solar System (ISS; e.g., [31]), volcanic material abounds and straightforward methods of potassium-argon, rubidium-strontium, or other radioactive element measurements are made to determine absolute ages. These do not work in the OSS where there is no silicate-based volcanism (other than on Io), and novel age methods should be investigated as the next missions are developed. As an example of novel remote dating methods, water ice crystallinity on the surface can constrain the time of crystallization and thus the exposure age for icy satellites such as Rhea and Dione [32]. As another example, haze molecules created above the surface of some icy bodies could accumulate in sediments with a time constant related to their surface exposure. Novel methods could provide a non-sample basis to calibrate crater-derived surface ages. For other surfaces or where sample acquisition is unlikely in the foreseeable future, crater counts must be extrapolated from any anchoring point based on a much better understanding of the observed small-body populations, their dynamical and collisional evolution, scaling laws, and impact processes on icy surfaces, as described.

As an example of a novel *in situ* dating method, Dragonfly is scheduled to land on Titan in 2034 and will carry a mass spectrometer capable of measuring stable isotopes and cosmic-ray induced daughter products. If haze molecules contain a distinctive stable-isotope ratio, the accumulation might be measured; combining this with a modeled accumulation rate might provide a surface exposure age. However, it may be difficult to determine traditional cosmic-ray surface ages from Titan due to the thick atmosphere, and correlation to crater counts is complicated by severe surface erosion and atmospheric screening and ablation of incoming projectiles. Therefore, even if ages on Titan's surface can be measured, it will be extremely difficult to extrapolate them to other bodies in the OSS.

Both crystallization and exposure ages of materials on OSS bodies can potentially be useful. Ices are generally difficult to date radiometrically unless they have refractory inclusions that contain radiogenic elements such as potassium, but such materials are unlikely to represent the crystallization ages of the ices unless they also melted or were otherwise altered at the same time. Cosmic ray exposure ages, though difficult [33], could be useful for dating the formation of surface units, but they might be limited to the recent past and might be difficult to calibrate, given the radiation environments many icy satellites are bathed in. **Alternative and novel methods of absolute age dating in the OSS, including in situ sample analyses, should be investigated and supported in the next decade.**

RECOMMENDATIONS: AGE DETERMINATIONS IN THE OSS

The Problem: Poorly Constrained Age Determinations in the OSS

The ages, durations, and sequences of WHEN major dynamical and geologic events occurred throughout the OSS remain poorly constrained and remain uncertain to factors of at least 2. Overall, the keys to improving our understanding of ages in the OSS is in completing and better constraining the interpretation of observed crater counts and projective populations across the OSS and in calibrating the crater-based surface ages at one or more points in the stratigraphy, as has been (partially) done for the ISS. For the first point, chronology-related observational and theoretical research should be supported; for the latter point, we need to measure absolute ages of surface materials, either by sample return, development of methods of *in situ* dating, or exploitation of remotely measured time-variable surface processes.

Recommendations: We recommend that research supporting the following objectives within the general goal of constraining the ages of events in the OSS be *encouraged* and *supported*:

A. Improve completeness and interpretability of currently available and future crater counts

1. Obtain better and more complete imagery of cratered bodies in the outer solar system (especially in the Jupiter and Uranus/Neptune systems and new medium and large KBOs (see appropriate White Papers on missions to these targets). Additionally, support continued data analysis of NASA's back-catalog of images that can be used for this effort.
2. Improve understanding of the roles of secondary craters and sesquinary and planetocentric impactor populations on icy bodies of all sizes in the contamination of crater statistics.
3. Improve understanding of crater degradation processes and roles in crater erasure of relaxation, gardening, ray degradation, etc. in interpreting the cratering record.
4. Improve understanding of scaling of crater-to-projectile diameters through experimental and numerical modeling of ice rheology and mechanical properties and their role in crater formation.

B. Improve knowledge of Kuiper Belt objects and related populations

1. Improve knowledge of KBO populations as a function of solar distance.
2. Improve knowledge of the SFD of smaller KBOs (<100 km in diameter) through direct astronomical observations and planning for visits to medium-sized KBOs (>100 km).
3. Improve understanding of the fate of KBO populations during hypothesized past dynamical events that depleted and redistributed small bodies.
4. Improve understanding of the redistribution of KBOs into other populations including, but not limited to, Trojans, JFCs, Centaurs, and irregular satellites.

C. NASA should support research and development of novel methods to provide critical calibrations between impact crater age determinations and absolute ages

D. NASA should prepare NOW for remote age determinations on future landed platforms

1. Instrumentation development for *in situ* geochronology methods on icy bodies to anchor crater-derived stratigraphies should be supported.
2. Geologic context work should be supported to understand the best areas to sample terrain ages to best anchor chronology, for when methods exist to date those terrains.
3. Investments in sample acquisition, handling, and analysis chain hardware for icy surfaces (e.g. Europa lander work) should be continued.

Finally, due to the likely link between events in the ISS and OSS, improved constraints on the formation ages and durations of dynamical and geological events among the gas and ice giant systems (e.g., Grand Tack and Nice Model [34]) and the Kuiper Belt will open a new window on what happened and when, not only in the OSS, but throughout the Solar System.

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