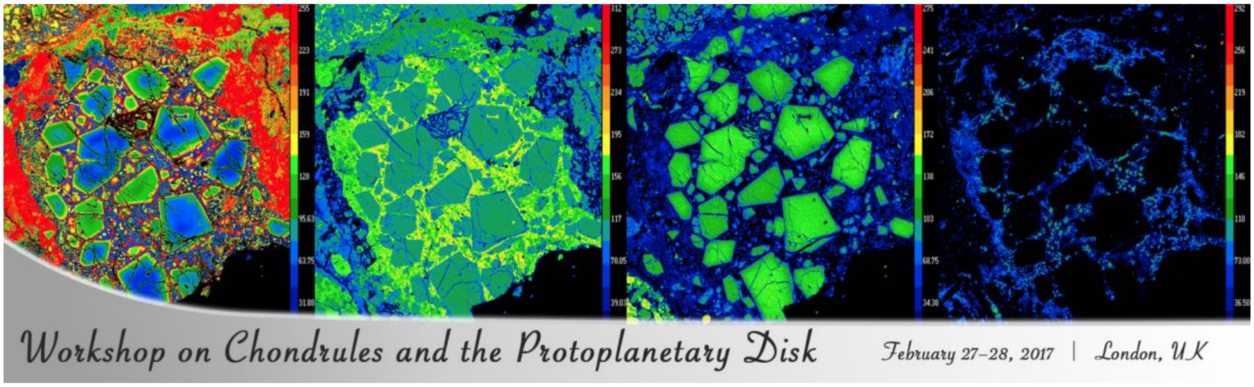

Program

LUNAR AND PLANETARY INSTITUTE

USRA

Workshop on Chondrules and the Protoplanetary Disk

February 27–28, 2017 • London, United Kingdom

Organizer

Lunar and Planetary Institute

Conveners

Sara Russell
Natural History Museum, London, United Kingdom

Harold C. Connolly, Jr.
Rowan University, Glassboro, New Jersey, U.S.A.

Alexander (Sasha) Krot

University of Hawai'i at Mānoa, Honolulu, Hawai'i, U.S.A.

Invited Speakers

Conel Alexander, *Carnegie Institution*
Martin Bizzarro, *Natural History Museum, Copenhagen*
Phil Bland, *Curtin University*
Jim Connelly, *Natural History Museum, Copenhagen*
Denton Ebel, *American Museum of Natural History*
Roger Fu, *Massachusetts Institute of Technology*
Dominik Hezel, *University of Cologne*
Alex Hubbard, *American Museum of Natural History*
Munir Humayun, *Florida State University*
Anders Johansen, *Lund University*
Brandon Johnson, *Brown University*
Rhian Jones, *University of Manchester*
Thorsten Kleine, *University of Muenster*
Emmanuel Jacquet, *Muséum National d'Histoire Naturelle*
Melissa Morris, *SUNY Cortland*
Kazuhide Nagashima, *University of Hawaii*
Ian Sanders, *Trinity College Dublin*
Travis Tenner, *Los Alamos National Laboratory*
Brigitte Zanda, *Muséum National d'HistoireNaturelle*

Lunar and Planetary Institute 3600 Bay Area Boulevard Houston TX 77058-1113

Abstracts for this workshop are available via the workshop website at

www.hou.usra.edu/meetings/chondrules2017/

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Guide to Sessions

Monday, February 27, 2017

8:00 a.m.	Flett Atrium	Registration
8:45 a.m.	Flett Theatre	Chondrule Precursors: Relationship Between Chondrules, Matrix, and Refractory Inclusions
2:00 p.m.	Flett Theatre	Chronology of Chondrule Formation
5:00–7:00 p.m.	Flett Atrium	Poster Session

Tuesday, February 28, 2017

8:30 a.m.	Flett Atrium	Registration
9:00 a.m.	Flett Theatre	Thermal History of Chondrule Melts and Environment in the Chondrule-Forming Regions
2:00 p.m.	Flett Theatre	Mechanisms of Chondrule Formation

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Program

Monday, February 27, 2017
CHONDRULE PRECURSORS:
RELATIONSHIP BETWEEN CHONDRULES, MATRIX, AND REFRACTORY INCLUSIONS
8:45 a.m. Flett Theatre

This session discusses the precursor material to chondrules and the relationship between chondrules and matrix.

Chairs: **Guy Libourel**
Rhian Jones

8:45 a.m. Russell S. S. *
Welcome and Introductions

9:00 a.m. Krot A. N. * Nagashima K. Libourel G. Miller K. E.
Multiple Mechanisms of Transient Heating Events in the Protoplanetary Disk: Evidence from Precursors of Chondrules and Igneous Ca,Al-Rich Inclusions **[#2009]**
Here we review the mineralogy, petrography, O-isotope compositions, and trace element abundances of precursors of chondrules and igneous CAIs which provide important constraints on the mechanisms of transient heating events in the protoplanetary disk.

9:30 a.m. Jacquet E. * Piani L. Weisberg M. K.
Chondrules in Enstatite Chondrites **[#2001]**
We review the properties of enstatite chondrite chondrules, including metal-sulfide nodules, and their (astro-)physical-chemical significance.

10:00 a.m. Bland P. .A. * Hezel D. C. Palme H. Bigolski J. N.
Characteristics of Primitive Chondrite Matrices and Connection to Chondrule Formation **[#2013]**
Were chondrules transported large distances to mix with matrix, or did both form in the same region? We discuss the degree to which chondrules and matrix may have sampled a common source, and how this informs models of disk formation and evolution.

10:30 a.m. BREAK

11:00 a.m. Zanda B. * Zanetta P.-M. Leroux H. Le Guillou C. Lewin É. Pont S. Deldicque D. Hewins R. H.
The Chondritic Assemblage **[#2035]**
Complementarity between chondrules and embedding matrix would have important implications for our understanding of the protoplanetary disk. We review the existing data and suggest new accurate analyses of primitive matrices are necessary.

11:30 a.m. Hezel D. C. * Palme H. Bland P. A. Jacquet E.
The Chondrule-Matrix Complementarity **[#2007]**
Chondrules and matrix in the chondrite have different elemental compositions and ratios. Yet for some ratios, the bulk chondrite is solar. This is called complementarity. In consequence chondrules and matrix formed from the same parental reservoir.

12:00 p.m. Schönbächler M. * Bauer K. K. Fehr M. A. Chaumard N. Zanda B.
Nucleosynthetic and Mass-Dependent Titanium Isotope Variations in Individual Chondrules of Ordinary Chondrites **[#2031]**
We present evidence for nucleosynthetic Ti isotope heterogeneity between individual chondrules of ordinary chondrites difficult to reconcile with chondrule formation from molten planetesimals. Metamorphism resulted in stable Ti isotope fractionation.

12:15 p.m. Defouilloy C. * Sanborn M. E. Yamakawa A. Kita N. T. Ebel D. S. Yin Q.-Z.
Cr and O Isotope Systematics in CV/CK Chondrite Chondrules **[#2016]**
Combined *in-situ* high-precision measurements of Cr and O isotopic ratios reveal heterogeneities of compositions and the diversity of reservoirs of origin of silicate grains in CV/CK chondrite chondrules.

12:30 p.m. *Discussion on Chondrule Precursors*

1:00 p.m. LUNCH

Monday, February 27, 2017
CHRONOLOGY OF CHONDRULE FORMATION
2:00 p.m. Flett Theatre

This session discusses the timescales of chondrule formation.

Chairs: **Maria Schönbächler**
Richard Ash

2:00 p.m. Connelly J. N. * Bollard J. Bizzarro M.
U-Pb Chronology of Chondrules **[#2025]**
We present a summary and implications of our U-Pb chronometry of chondrules. We find that chondrules began forming contemporaneously with calcium aluminum inclusions and formed for 3.6 Myr.

2:30 p.m. Nagashima K. * Kita N. T. Luu T.-H.
^{26}Al-^{26}Mg Systematics of Chondrules: Progresses and Issues from the Last Five Years **[#2040]**
We summarize the recent progresses and issues made in ^{26}Al-^{26}Mg systematics of chondrules in the last five years.

3:00 p.m. Kleine T. * Budde G. Hellmann J. L. Kruijer T. S. Burkhardt C.
Tungsten Isotopes and the Age and Origin of Chondrules **[#2032]**
The Hf-W chronology of chondrule formation and chondrite accretion, as well as the W isotope complementarity between chondrules and matrix, will be reviewed.

3:30 p.m. BREAK

4:00 p.m. Bizzarro M. * Connelly J. N.
Chondrules — Ubiquitous Chondritic Solids Tracking the Evolution of the Solar Protoplanetary Disk **[#2024]**
The only record of our solar system's formation comes from mm- to cm-sized calcium-aluminium-rich inclusions and chondrules. We review the chronology and stable isotopic compositions of chondrules and discuss the evolution of the protoplanetary disk.

4:30 p.m. *Discussion on Chronology*

Monday, February 27, 2017
POSTER SESSION
5:00–7:00 p.m. Flett Atrium

Arakawa S. Nakamoto T.
Co-Aggregation of Chondrules and Nanometer-Sized Matrix Grains in the Solar Nebula: A New Scenario for Rocky Planetesimal Formation **[#2010]**
We propose a scenario in which rocky planetesimals are formed via co-aggregation of chondrules and nm-sized matrix grains. The critical velocity for collisional growth exceeds the maximum collision velocity when matrix grains are smaller than 10 nm.

Kadlag Y. Becker H.
Combined Study of Highly Siderophile Elements and Cr Isotopes in the Chondrules of Unequilibrated Chondrites **[#2027]**
We are presenting the highly siderophile element abundances and Re-Os isotope systematics and Cr isotope composition of bulk chondrule fractions from unequilibrated chondrites to understand the chondrule formation processes.

Bridges J. C. Hicks L. J.
Chondrules from the Outer Solar System: Results from Stardust **[#2039]**
Stardust samples of Comet Wild2 contain fragments similar to Type II FeMg and Al-rich chondrules from carbonaceous chondrites. They may be the result of radial drift from the inner solar system or, alternatively, formation in the outer solar system.

Ash R. D.
Recycling in the Early Solar System: Evidence from Oxygen and Magnesium Isotopes and Trace Element Abundances in CAIs and Chondrules **[#2044]**
Isotope ratios and trace element abundances indicate major recycling of CAI material into Allende chondrules, something not observed in those from OC and EC meteorites.

Quintana A. Segura A. Ostrooumov M.
The Carbon Participation in the Crystal-Chemistry Formation of the Porphyritic Chondrules **[#2047]**
In our experimental work we made a fusion with olivine Mg-rich or forsterite, anorthite, and graphite with a high degree of purity. The silicate minerals and graphite were subjected at ambient pressure (0 atm), using a CO_2 laser.

Rubin A. E.
Multiple Indicators for Multiple Melting of Chondrules **[#2006]**
Many workers maintain that most chondrules crystallized after a single melting event. However, petrographic features and experimental constraints show that most chondrules were melted multiple times.

Hellmann J. L. Kruijer T. S. Kleine T.
Tungsten Isotopic Evidence for Coeval Metal-Silicate Fractionation and Chondrule Formation in Ordinary Chondrites **[#2028]**
Hf-W systematics of ordinary H, L, and LL chondrites indicate a nebular metal-silicate fractionation at ~2–3 Ma after CAIs, implying chondrule formation and chondrite parent body accretion at that point in time.

Pape J. Mezger K. Bouvier A.-S. Baumgartner L. P.
In-Situ ^{26}Al-^{26}Mg Mineral Isochron Dating of Chondrules by SIMS: Samples, Measurement Procedure, and Data Correction **[#2014]**
Here we present and discuss the analytical set up, correction methods, and first results of *in-situ* Mg isotope measurements in chondrules for ^{26}Al-^{26}Mg mineral isochron dating.

Budde G.   Kruijer T. S.   Kleine T.
Hf-W Chronology of CR Chondrites **[#2023]**
Hf-W systematics of CR chondrites define an age of ~3.7 Ma after CAIs for CR chondrule formation. CR metal and silicates have complementary nucleosynthetic W and Mo isotope anomalies due to the uneven distribution of a presolar s-process carrier.

Barosch J.   Hezel D. C.
Mineralogical Chondrule Zonation in Ordinary Chondrites **[#2017]**
The majority of chondrules in carbonaceous chondrites are mineralogically zoned. We examine the appearance, abundance, and distribution of mineralogical zonation in chondrules of several ordinary and enstatite chondrites.

Hernández-Reséndiz P.   Cervantes-de la Cruz K.   Segura A.   U'Ren A.   Cruz-Ramírez H.
Thermal Histories of Barred Chondrules from Melts Generated Experimentally **[#2020]**
We simulate the formation of chondrules by melting olivine grains with 50W CO_2 laser. We measure the temperature during and after the formation of the artificial chondrules. We will compare the melts characteristics with the natural chondrules.

Stockdale S. C.   Franchi I. A.   Anand M.   Grady M. M.
Constraining the Cooling Rates of Chondrules **[#2037]**
The cooling rates of chondrules are an important constraint on chondrule formation. By measuring and modelling diffusion profiles between relict grain and overgrowth formed during cooling, we will calculate the cooling rate of the host chondrule.

Greenwood J. P.   Herbst W.
Experimental Simulation of Chondrule Textures Using Symmetrical Heating and Cooling Rates: Testing the Radiative Model for Chondrule Formation **[#2038]**
As a test of the radiative model for chondrule formation, we report on experimental simulation of chondrule textures using symmetrical heating and cooling curves. We also report on how chondrule simulation experiments can help refine this model.

Kuzina D. M.   Nurgaliev D. K.   Gareev B. I.   Batalin G. A.   Silantev V. V.   Statsenko E. O.
Preliminary Results on Studying of Meteorites from Geological Museum of Kazan University by X-Ray Fluorescence and Computed X-Ray Tomography **[#2019]**
Micro X-ray fluorescence and X-ray computed tomography used for studying meteorites (particularly chondrules and iron-nickel alloys) from Geological Museum (Kazan), their elemental composition, and distribution of these objects in the body of meteorite.

Berzin S. V.   Stepanov S. Yu.   Yakovlev G. A.   Muftakhetdinova R. F.   Grokhovsky V. I.
Unusual Xenoliths in Chelyabinsk LL5 Meteorite **[#2034]**
Description of some xenoliths, which were found in Chelyabinsk meteorite.

Montoya-Perez M. A.   Cervantes-de la Cruz K. E.   Ruvalcaba-Sil J. L.
Nondestructive Method for Bulk Chemical Characterization of Barred Olivine Chondrules **[#2048]**
This work develops a bulk chemical characterization of barred olivine chondrules based on the XRF analysis using a portable equipment at the National Research and Conservation Science Laboratory of Cultural Heritage (LANCIC-IF) in Mexico City.

Chan Q. H. S.   Zolensky M. E.   Bodnar R. J.   Farley C.   Cheung J. C. H.
The Distribution of Major Carbonaceous Components in Chondritic Materials **[#2015]**
With the use of Raman spectroscopy we present a study of the structure of the organic matter in the matrix and carbonate phases in five CM chondrites: Jbilet Winselwan, Murchison, Nogoya, Santa Cruz, and Wisconsin Range 91600.

Davison T. M.   Collins G. S.   Bland P. A.
Mesoscale Numerical Modelling of Impact Processing of Chondrule/Matrix Mixtures **[#2026]**
We present mesoscale simulations of the heterogeneous shock compaction of chondrite precursor materials. Our results provide an important link between meteoritic evidence and the thermal and compaction histories of meteorite parent bodies.

Gyollai I.   Polgári M.   Bérczi Sz.   Veres M.   Gucsik A.   Pál-Molnár E.
Signs of Bioweathering in Ordinary Chondrites **[#2005]**
Our OM, FTIR, and micro-Raman data showed invasive terrestrial microbially mediated texture in L chondrites (obscured chondrules, contamination in microtexture, micromineralogy, embedded organic compounds). We offer new bioweathering interpretation.

Micca Longo G.   Longo S.
Atmospheric Entry of Carbonate Micrometeoroids **[#2003]**
Micrometeoroids have similarities in chemistry and mineralogy to the CI, CM, and CR chondrites. A first study of carbonate micrometeoroids atmospheric entry is performed. A thermal decomposition model of initially pure magnesium carbonate is proposed.

Tuesday, February 28, 2017
THERMAL HISTORY OF CHONDRULE MELTS AND ENVIRONMENT IN THE CHONDRULE-FORMING REGIONS
9:00 a.m. Flett Theatre

This session discusses the thermal histories of chondrules during their formation.

Chairs: **Brigitte Zanda**
Dominik Hezel

9:00 a.m. Jones R. H. * Villeneuve J. Libourel G.
Thermal Histories of Chondrules: Petrologic Observations and Experimental Constraints **[#2029]**
We summarize petrologic properties of chondrules, and results of chondrule analogue experiments, that together place constraints on chondrule thermal histories.

9:30 a.m. Alexander C. M. O'D. * Ebel D. S. Libourel G.
Vapor-Melt Exchange - Constraints on Formation Conditions and Processes **[#2045]**
Here we review the evidence for vapor-chondrule interactions, the constraints that they place on formation conditions, and highlight some unanswered questions.

10:00 a.m. Libourel G. * Portail M.
Overlooked Chondrules: A High Resolution Cathodoluminscence Survey **[#2008]**
CL panchromatic images and hyperspectral analyses on different types of chondrules of various chondrites reveal overlooked olivine internal structures at a hitherto unprecedented detail. Implications of this finding on chondrule formation will be discussed.

10:15 a.m. Deng Z. * Chaussidon M. Moureau J. Moynier F.
Mg Isotope Constraints on the Origin of Mg-Rich Olivines and Mesostasis Phases from Allende Chondrules **[#2046]**
An *in-situ* Mg isotopic study has been conducted by LA-MC-ICP-MS to constrain the origin of Mg-rich olivines and mesostasis phases in Allende chondrules.

10:30 a.m. BREAK

11:00 a.m. Tenner T. J. * Ushikubo T. Nakashima D. Schrader D. L. Weisberg M. K. Kimura M. Kita N. T.
O-Isotope Features of Chondrules from Recent SIMS Studies **[#2030]**
We highlight results of recent chondrule O-isotope studies by SIMS: (1) primary and secondary features based on the level of isotope homogeneity, (2) comparing ranges of host and relict data among chondrites, (3) O-isotope vs. major element links.

11:30 a.m. Marrocchi Y. *
Redox Conditions During CV Chondrule Formation **[#2004]**
The presence in CV chondrules of fayalitc halos and previously unrecognized magnetites of magmatic origin implies the formation of these chondrules under impact-generated oxidizing conditions.

11:45 a.m. Metzler K. * Pack A. Hezel D. C.
Ordinary Chondrite Chondrules: Oxygen Isotope Variations **[#2042]**
Chondrules in some H and LL chondrites show positive/negative correlations between size and oxygen isotopic composition. This indicates that they exchanged oxygen with different oxygen reservoirs and cannot stem from a common chondrule population.

12:00 p.m. Fu R. R. * Weiss B. P. Kehayias P. Schrader D. L. Walsworth R. L.
Records of Magnetic Fields in the Chondrule Formation Environment **[#2043]**
Paleomagnetic measurements can potentially constrain the formation mechanism and location of chondrules. We will present results on LL and CR chondrites, which appear to have experienced strong and weak magnetic fields, respectively.

12:30 p.m. *Discussion on Thermal History*

1:00 p.m. LUNCH

Tuesday, February 28, 2017
MECHANISMS OF CHONDRULE FORMATION
2:00 p.m. Flett Theatre

This session discusses the various mechanisms proposed for chondrule formation.

Chairs: Melissa Morris
Brandon Johnson

2:00 p.m. Morris M. A. * Boley A. C.
Formation of Chondrules by Shock Waves **[#2022]**
We describe and assess current shock models for chondrule formation, particularly those driven by gravitational disk instabilities and bow shocks. We discuss predictions made by shock models and further work needed.

2:30 p.m. Hubbard A. I. * Ebel D. S.
Combining Dynamical and Cosmochemical Constraints on the Processes of Chondrule Formation: Layered Disks **[#2036]**
Dynamics and cosmochemistry imply that the chondrule formation region was close to, but separate from, the parent body formation region. That points to a layered disk scenario with chondrules forming at the surface and settling to a cool midplane.

3:00 p.m. Johansen A. * Okuzumi S.
Harvesting the Decay Energy of 26-Al to Drive Lightning Discharge and Chondrule Formation **[#2012]**
We demonstrate that positrons released in the decay of 26-Al cause large-scale charging of dense pebble regions. The charge separation is neutralized by lightning discharge and this can lead to the formation of chondrules.

3:30 p.m. BREAK

4:00 p.m. Johnson B. C. * Ciesla F. J. Dullemond C. P. Melosh H. J.
Formation of Chondrules by Planetesimal Collision **[#2018]**
We explore the hypothesis that chondrules were formed by impacts between growing planetesimals.

4:30 p.m. Sanders I. S. *
Making Chondrules from Molten Planetesimals **[#2021]**
Making chondrules by splashing molten planetesimals remains a viable model, but nucleosynthetic complementarity in CVs invites exploration of plume dynamics.

5:00 p.m. Lichtenberg T. * Golabek G. J. Dullemond C. P. Schönbächler M. Gerya T. V. Meyer M. R.
A Thermo-Mechanical 'Goldilocks' Regime for Impact Splash Chondrule Formation **[#2041]**
We present a new chondrule formation scenario where chondrules originate from the collision aftermath of small, partially molten planetesimals, which poses strong constraints on the formation conditions of the first planetesimal families.

5:15 p.m. Herbst W. * Greenwood J. P.
The Radiative Heating Model for Chondrule and Chondrite Formation **[#2011]**
We show that chondrules can form when pre-existing aggregates of solids of m-size, or smaller, are sintered by exposure to hot lava at the surfaces of molten planetesimals during close fly-bys. Chondrite lithification may accompany these events.

5:30 p.m. *Discussion on Chondrule Formation Models*

5:50 p.m. Connolly H. C. * Krot A. N. Russell S. S.
Summary of the Meeting

PRINT ONLY

Herd R. K.
Mineralogy and Texture Descriptions to Help Understand Chondrule Origins **[#2033]**
Alpha-numeric codes for (intra)chondrule textures, from a single chondrite or from many, allow for their detailed description, and enable observers to ponder the processes that may have affected chondrule formation.

Szurgot M.
Mean Atomic Weight of Chondrules and Matrices in Semarkona, Allende and Sharps Meteorites **[#2002]**
Mean atomic weight Amean of chondrules and matrices of Semarkona, Allende and Sharps meteorites was determined using chemical composition and Amean(Fe/Si) dependence. Amean values of matrices are higher than chondrules and meteorites.

CONTENTS

VAPOR-MELT EXCHANGE – CONSTRAINTS ON FORMATION CONDITIONS AND PROCESSES.

C.M.O'D. Alexander[1], D. S. Ebel[2,3], and G. Libourel[4]. [1]DTM, Carnegie Institution of Washington, 5241 Broad Branch Road, Washington DC 20015, [2]American Museum of Natural History, New York, New York 10024, USA, [3]Dept. of Earth & Environmental Sci., Columbia University, New York [4]Université de la Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, F-06304 Nice Cedex 4, France.

Introduction: There has been a longstanding debate about the extent to which chondrules and H_2-rich nebular gas interacted during and after chondrule formation. Experimental simulations of chondrule textures suggest that they were rapidly heated to near liquidus temperatures of 1500-1700°C for relatively brief periods and then cooled to solidus temperatures (1000-1200°C) at 10-1000°C/hr [1]. This implies formation timescales of hours to days. On these timescales, interactions between chondrules and gas would have been inevitable. Here we review the evidence for such interactions, the constraints that they place on formation conditions and highlight some unanswered questions.

Discussion: For typical nebula pressures, chondrule liquidus temperatures, chondrule formation timescales, experiments and models predict that evaporation from melt would have been inevitable. In environments with low chondrule+dust (solids) densities, there would have been extensive evaporation with relatively little back reaction of the gas. Chondrules forming under these conditions should have the characteristic isotopic and elemental fractionations associated with Rayleigh distillation. However, while chondrules do show elemental fractionations that seem to be related to volatility, they do not show the predicted systematic isotopic fractionations in S, K, Fe, Mg, Si or O [1]. Their absence implies that chondrules were stable melts in equilibrium with the surrounding gas.

Equilibrium and kinetic models indicate that to produce stable chondrule-like melts at inferred chondrule temperatures and formation timescales solids must be enriched by ≥1000 relative to solar at a total pressure of $P^{tot}=10^{-3}$ bars. Higher enrichments are required for lower P^{tot}.

However, other evidence suggests that enrichments in solids may have been much higher during chondrule formation. Even at 1000 times dust enrichments and $P^{tot}=10^{-3}$ bars, at near liquidus temperatures Na and K will be entirely in the gas, and only recondense into the melt after most olivine and pyroxene has already crystalized. Measurements of Na in olivine phenocrysts from OCs show that Na was present in some chondrule melts throughout their crystallization, requiring orders of magnitude higher enrichment in solids [2,3]. Exactly how high depends on several factors, principally how much Na evaporated at peak temperatures – estimates have ranged from ~10% to ~50%. Nevertheless, the solids enrichments or absolute densitites that the Na requires during OC chondrule formation are much higher than current nebula models can explain.

Similar studies of Na in phenocrysts have not been conducted on CC chondrules. This is primarily because CC chondrules typically have much lower abundances of Na, making the measurements of Na in the phenocrysts much more difficult. Iron is the next most volatile major element. Metallic iron is a common component of chondrules, particularly FeO-poor ones (type I). Iron metal also seems to have been stable during chondrule formation again requiring high solid densities, although not placing as strong constraints on conditions as Na. On the other hand, there are some indications that S was present in chondrule metal melts. While the presence of S in chondrule metal has received less attention than Na, it may require even higher solid densities.

Given this evidence that chondrule melts were stable and that only a fraction of even the most volatile elements were in the gas, it is surprising that there are such small isotopic fractionations amongst chondrules and that there are petrologic features of type I chondrules in OCs and CCs that have been interpreted as the result of SiO_2 metasomatism towards the end of crystallization. Experiments show that condensation of $SiO_{(gas)}$ into the chondrules is able to explain the observed textures [4].

The small isotopic fractionations could simply be due to incomplete re-equilibration of chondrules with a range of precursor compositions. The evidence for SiO_2 metasomatism is more problematic as perhaps ~3-15 % of the SiO_2 in these chondrules was introduced by this metasomatism [5]. If this much SiO_2 was in the gas phase, then much more of the more volatile Na and Fe should have been in the gas. At present, there is no evidence that this was the case. Resolution of this apparent inconsistency is vital since the geochemical and petrologic evidence provide the most important constraints on chondrule formation models.

References: [1] Chondrites and the Protoplanetary Disk (eds. A.N. Krot, E.R.D. Scott & B. Reipurth). [2] C.M.O'D. Alexander et al. (2008) *Science, 320,* 1617–1619. [3] R. H. Hewins et al. (2012) *Geochim. Cosmochim. Acta, 78,* 1-17. [4] L. Tissandier et al. (2002) *Meoritics &Planet. Sci.,* 37, 1377-1389. [5] P. Friend et al. (2016) *Geochim. Cosmochim. Acta, 173,* 198-209.

CO-AGGREGATION OF CHONDRULES AND NANOMETER-SIZED MATRIX GRAINS IN THE SOLAR NEBULA: A NEW SCENARIO FOR ROCKY PLANETESIMAL FORMATION. S. Arakawa[1] and T. Nakamoto[1], [1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan; arakawa.s.ac@m.titech.ac.jp

Introduction: Chondrules are millimeter-sized rock particles and they are the principal components of the most common meteorites, chondrites. This fact means that the majority of rocky planetesimals might be formed via accretion of chondrules. However, it is not yet understood how millimeter-sized chondrules grow into kilometer-sized planetesimals. This is because there are several difficulties for rocky planetesimal formation, e.g., the bouncing barrier, the fragmentation barrier, and the radial drift barrier.

Okuzumi et al. [1] revealed that icy planetesimals could be formed by direct aggregation of submicron-sized ice particles. This is because icy aggregates consisting of submicron-sized monomers are strong enough to avoid catastrophic disruption, and the internal densities of these aggregates formed from cluster-cluster aggregation process are low enough to avoid serious radial drift to the Sun. In addition, these aggregates can stay porous even if we consider the effect of the static compression by the ram pressure of the nebular gas or the self-gravity [2].

If the building blocks are only millimeter-sized chondrules, then bouncing and fragmentation of chondrules might be severe problems. However, chondrites consist of not only chondrules but also matrix grains. In addition, matrix grains are not millimeter-sized but micron-sized [3] or even nanometer-sized [4]. Arakawa and Nakamoto [5] argued that the size distributions of matrix grains indicate that these fine grains are formed by evaporation and recondensation events in the solar nebula [6], and they initially condensed as nanometer-sized grains. The existence of fine matrix grains is important because the critical collision velocity for collisional growth depends on the size of monomer components [7], and the critical velocity exceeds the maximum collision velocity when matrix grains are smaller than ~ 10 nm.

Model: We propose a scenario in which rocky planetesimals are formed via co-aggregation of chondrules and nanometer-sized matrix grains. We verify whether the growth of aggregates is rapid enough to overcome the radial drift barrier by comparing the timescales of growth and radial drift.

We assume the minimum mass solar nebula [8]. The structure of dust aggregates is obtained from the formula given by Kataoka et al. [9]. The radius of nanometer-sized matrix grains is 2.5 nm and the radius of chondrules is 0.25 mm in this study.

Results: Our calculations reveal that aggregates of chondrules and matrix grains can overcome the radial drift barrier. Figure 1 shows the growth pathway of aggregates at 1 au from the Sun. We assume the alpha parameter associated with the strength of turbulence is 10^{-4} in this study. We also plot the temporal change of the growth timescale in Figure 2, and the result suggests that what we can observe in protoplanetary disks are not monomer matrix grains but centimeter-sized fluffy aggregates of chondrules and matrix grains.

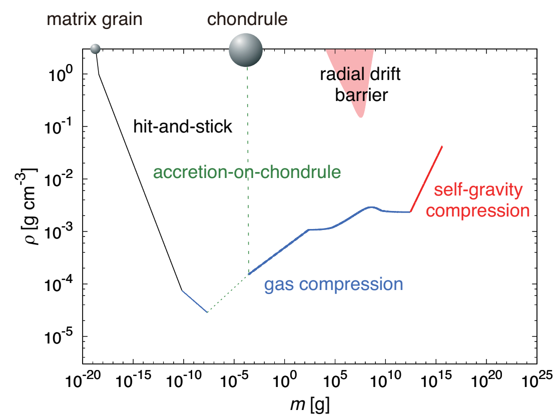

Figure 1: The pathway of planetesimal formation.

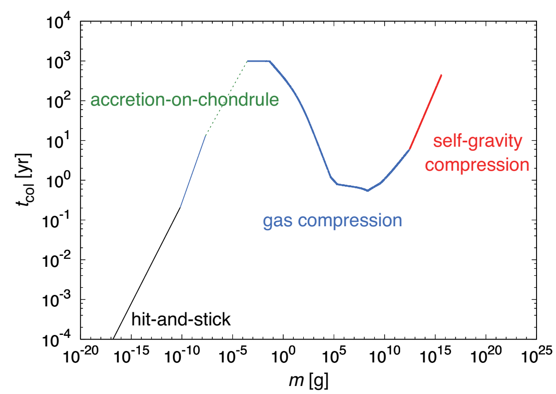

Figure 2: The temporal change of the growth timescale.

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RECYCLING IN THE EARLY SOLAR SYSTEM; EVIDENCE FROM OXYGEN AND MAGNESIUM ISOTOPES AND TRACE ELEMENT ABUNDANCES IN CAI AND CHONDRULES.

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Introduction: The relationships, if any, between chondrules, calcium-aluminum-rich inclusions (CAI) and matrix is complex. The chronometric information relating to formation times is in a state of flux, with measurements made to extraordinarily high precision, but with some debate as to their accuracy. Hence the chronological relationship between CAI and chondrule formation is much tested but remains muddied [1-5].

Calcium Aluminium-rich Inclusions (CAI) are usually considered the oldest solid materials formed in the solar system, with high resolution (20,000 – 50,000 years) Pb-Pb and Al-Mg measurements demonstrating a time difference between CAI and chondrule formation of 1-3Myr. However recent measurements have suggested that these apparent time differences may be a result of nucleosynthetic and chemical effects causing variations in initial isotopic abundances.

Major, minor and trace elements in CAI are diagnostic of their high temperature formation and can be used as a characteristic tracer of their origins and fate. Similarly oxygen and magnesium stable isotopes in CAI are not endogenous in other chondritic components, hence may be used as tracers in conjunction with elemental abundances to track CAI.

Methods: We have taken a suite of chondrules from carbonaceous, ordinary and enstatite chondrites carried out petrographic and mineralogical characterization and determined their trace element abundances, in particular their rare earth element patterns and Nb/Ta which are characteristic of particular types of CAI. In some cases we have measured Mg isotope abundances as well as oxygen isotopes.

Results: Results show that the Allende chondrules show a far greater range of trace element behavior than either the ordinary or the enstatite chondrite chondrules. Half (8) of the chondrules exhibit non-chondritic REE patterns and these samples also show Nb/Ta lower than the chondritic value of 19.9 [6], reaching as low as 3.8 for the most Nb depleted chondrule (CAI ratios may reach unity). The REE patterns are strongly reminiscent of CAI REE patterns see figure 1.[7]. Where we have oxygen isotopic compositions for these chondrules they exhibit non-mass dependent characteristics, lying along the Allende CCAM line. Furthermore where determined these chondrules also show evidence for fractionated MG isotopes and an excess of ^{26}Mg [8]. None of the OC chondrules exhibit fractionated REE abundances or any variation from the chondritic value for Nb/Ta. There is some variation in the EC chondrules, but none that are reminiscent of CAIs, but may be the result of chalcophile behavior and fractionation.

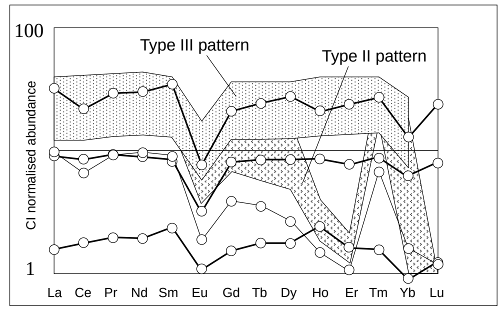

Figure 1. CI normalised REE abundances in fractionated Allende chondrules (circles) and CAIs [7]

At present we have neither oxygen nor magnesium isotopic data for the ordinary or enstatite chondrite chondrules.

Discussion: The presence of a significant population of chondrules in Allende that exhibit correlated CAI-like chemical and isotopic behavior indicates that there is recycling of CAI material in the chondrule forming region sampled by the CV chondrite parent body that was available in neither the enstatite nor the ordinary chondrite sampling regions.

This implies that the CAI are exogenous to the chondrule forming region and were incorporated primarily into the meteorites where they are observed today, and many have been mixed with local material and processed into chondules.

There are potential implications for Al-Mg ages if there is mixing of other Al reservoirs, followed by remelting, in the chondrule forming region.

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MINERALOGICAL CHONDRULE ZONATION IN ORDINARY CHONDRITES. J. Barosch[1] and D. C. Hezel[2], [1] University of Cologne, Institute of Geology and Mineralogy, 50674 Köln, Germany, jbarosch@uni-koeln.de, [2]dominik.hezel@uni-koeln.de.

Introduction: The majority of chondrules in carbonaceous and Rumuruti chondrites is mineralogically zoned [1]. These chondrules consist of an olivine core, which is surrounded by a low-Ca pyroxene rim. In this study we examine the appearance, abundance and distribution of mineralogical zonation in chondrules of several ordinary (H, L, LL) and enstatite chondrites. The results will provide insights to the origin of chondrule textures, bulk compositional variations, conditions of chondrule formation and the origin of chondrule matrix complementarity.

Methods: Chondrule zonation and mineral compositions were investigated with an electron microprobe by spot analyses and element mapping. Phase maps were created from the elemental distribution of Mg and Si with the Mathematica application PHAPS [2]. These are false color images that show each mineral phase in a different color. They can be used to identify olivine, pyroxene and mesostasis, as well as structural properties e.g. thickness, abundance and distribution of rims.

Results: So far, we studied 91 chondrules in 2 different L-chondrites of low petrological types. Preliminary results show that, in a conservative count, ~60% of the studied chondrules are zoned. They feature weak to strong poikilitic, low-Ca pyroxene rims that surround or enclose the olivine (Fig. 1). The rim thickness strongly varies and ranges from extremely thin rims of a few µm up to thick rims with over 100 µm.

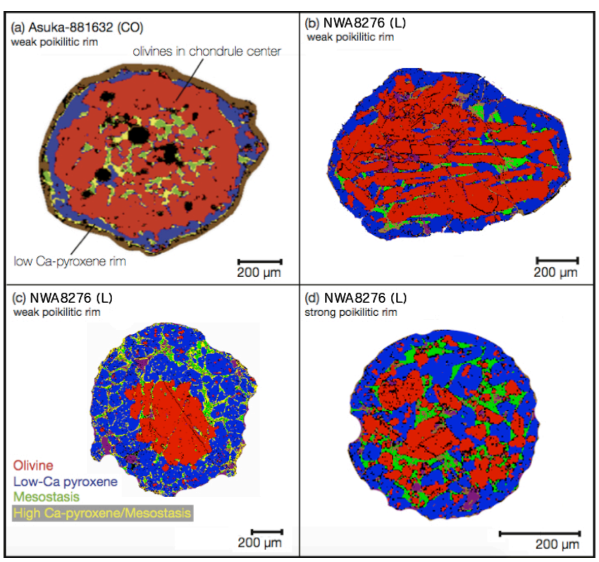

Fig. 1: Examples for mineralogically zoned chondrules in (a) CO [1] and (b, c, d) L-chondrites with weak to strong poikilitic, low-Ca pyroxene rims.

Discussion: The observed percentage of zoned chondrules in L-chondrites concurs with the results for carbonaceous and Rumuruti chondrites (~75%, [1]). Zoned chondrules are, therefore, the dominant and typical chondrule type in both chondrite classes. Several chondrules do not show any zonation. However, some of them might be rim-sections, which then would further increase the amount of zoned chondrules. Most porphyritic chondrules may in fact be PO chondrules with low-Ca pyroxene rims. The classification of PO, POP and PP chondrules might, therefore, simply represent different sections through zoned chondrules.

Mineralogical zonation introduces fundamental constraints on chondrule formation conditions. To form the zonation, chondrules interacted substantially with the surrounding gas and exchanged material in an open system [1]. The low-Ca pyroxene rims most probably formed from the reaction of SiO rich gas with chondrule olivine. The remaining gas could then have condensed into the matrix. Parent body processes can be excluded since they do not allow the required material transport and do not provide the necessary reaction temperatures.

The open system scenario is in agreement with previous studies on chondrule formation, as well as chondrule matrix complementarity, and suggests a common chemical reservoir of chondrules and matrix.

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UNUSUAL XENOLITHS IN CHELYABINSK LL5 METEORITE. S. V. Berzin[1], S. Yu. Stepanov[1], G. A. Yakovlev[2] , R. F. Muftakhetdinova[2] and V. I. Grokhovsky[2], [1]The Zavaritsky Institute of Geology and Geochemistry, Russian Federation, Ekaterinburg, 620016, Vonsovskiy street, 15, sbersin@yandex.ru, [2]Institute of Physics and Technology, Ural Federal University, Russian Federation, Ekaterinburg, 620002, Mira street, 21, grokh47@mail.ru.

Introduction: Based on mineral compositions, oxygen isotopic composition and texture, the Chelyabinsk meteorite is a typical impact breccia LL5 ordinary chondrite with shock stage S4 and weathering grade W0 [1-4]. This meteorite consist of three main lithologies [5, 6]. Also, a few xenoliths have been found during examination of Chelyabinsk meteorite samples recently. All of them are situated in light lithology

Methods: Thin section of first sample and microsection of second sample have been prepared. Both of them were studied using optical microscope Carl Zeiss Axiovert 40 MAT, scanning electron microscopes Carl Zeiss Sigma VP and JSM-6390LV from JEOL with EDX spectrometers X-max 80 from Oxford Instruments.

Results and discussions: Usually chondrules in Chelyabinsk meteorite are recrystallized, they are deformed or broken and in size up to 1.0 mm, but in our case xenoliths achieve 10 mm in size. Xenolith (6x10 mm) in first sample contain only barred olivine chondrules with worm-like texture. Metal and sulfides grains are rare. External part of barred olivine chondrules consist of olivine monocrystals forming hollow skeletal box crystals. Chondrules internal parts contain acidic plagioclase glass with microcrystals of olivine, clinopyroxene and, very rare, orthopyroxene. Recrystallized matrix is absent in this xenolith. Structure of space between chondrules and chondrules structure are very similar. Their chemical composition according to microprobe data is also very similar. The difference in chemical composition of matrix and chondrules in non-xenolith part of meteorite is more evident. Xenolith have continuous orthopyroxene rim 100-200 µm width (fig.1). It's worth to note that compound chondrule have been found in matrix of the Chelyabinsk meteorite. The origin of this chondrule probably resemble scheme, discussed in [7].

Composition and structure of xenolith in other fragment is different. Chondrules have not been found in this round inclusion 10 mm in diameter. Xenolith contains net of veins. These veins are formed by mineral which chemical composition reminds plagioclase. Spaces between veins are filled with olivine. Tiny chromite inclusions were noticed, sulfides have not been found.

Variations in composition and texture of examined objects due to different chondrule precursors are discussed.

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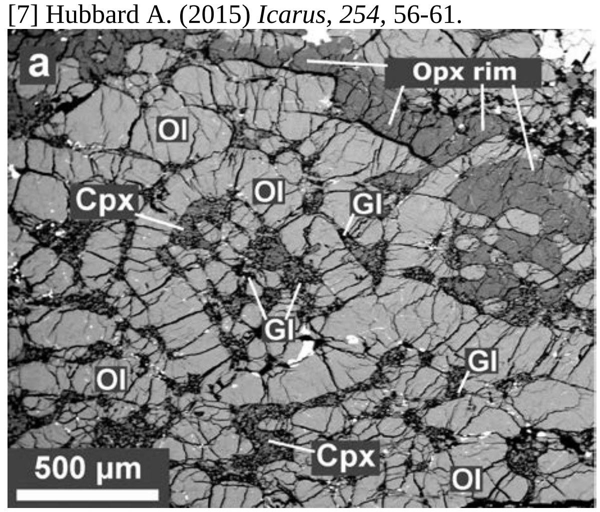

Figure 1. Structure of xenolith in first sample of Chelyabinsk meteorite. Orthopyroxene rim around xenolith and agglomerated barred olivine chondrules. Ol – Olivine, Cpx – Clinopyroxene, Opx – Orthopyroxene, Gl – acidic plagioclase glass.

CHONDRULES – UBIQUITOUS DISK SOLIDS TRACKING THE EVOLUTION OF THE SOLAR PROTOPLANETARY DISK. M. Bizzarro[1] and J. N. Connelly[1], [1]Centre for Star and Planet Formation, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark.

In the Solar System, a record of the earliest evolutionary stages of the protoplanetary disk is preserved in chondrite meteorites, which are fragments of asteroids that avoided melting and differentiation. Most chondrites consist of chondrules, refractory inclusions [Ca,Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs)], and fine-grained matrix. CAIs represent the oldest Solar System dated solids and, thus, define it's age at 4,567.3±0.16 Myr [1]. It is commonly accepted that CAIs formed in a hot (~1300 K) disk region near the proto-Sun characterised by approximately solar oxygen isotopic composition near the proto-Sun by evaporation, condensation and aggregation processes during a brief time interval that corresponded to high stellar mass accretion rates (~$10^{-5} M_{\odot}$ y^{-1}) [2]. Some CAIs were subsequently melted, most in the same disk region. Most chondrules formed by melting (typically incomplete) of solid precursor material during transient heating events (peak temperature of ~2000 K) of unknown nature in different, relatively cold dust-rich regions throughout the protoplanetary disk during its entire lifetime [1]. Therefore, CAIs and chondrules provide time-sequenced samples allowing us to probe the composition of the disk material that accreted to form planetesimals and planets.

The majority of chondrules formed as melt droplets in high-density regions of the protoplanetary disk and accumulated in the disk mid-plane together with other chondritic components. Chondrules are mainly composed of olivine and pyroxene minerals, which crystallised within minutes to days between ~1800 and ~1300 K [3]. Several heat sources have been proposed for the thermal processing of chondrule precursors, including shock waves [4], current sheets [5], x-winds [6], magnetised disk wind [7], and colliding planetesimals [8]. A long standing paradigm used to constrain chondrule-formation models is the so-called chemical complementarity that apparently exists between chondrules and matrix in individual chondrite groups [9]. In this model, it is proposed that chondrules and matrix are genetically related and formed in highly-localised regions of the protoplanetary disk. The chronology of chondrule formation is typically based on the short-lived ^{26}Al to ^{26}Mg decay system (^{26}Al decays to ^{26}Mg with a half-life of 0.705 Myr). Assuming that ^{26}Al was uniformly distributed in the protoplanetary disk with the canonical ^{26}Al/^{27}Al ratio of 5×10^{-5} commonly observed in CAIs, the ^{26}Al-^{26}Mg systematics of chondrules suggest that these objects formed >1 Myr after CAIs and rapidly accreted into chondrite parent bodies together with matrix in discrete events during the lifetime of the disk [2]. In this view, chondrule formation is restricted to the inner regions of the solar protoplanetary disk.

However, a number of recent studies investigating the absolute chronology of chondrule formation as well as the isotopic systematics of individual chondrules from various chondritic meteorites requires a reassessment of current thinking with respect to the formation history of chondrules as well as the parent asteroids of chondrite meteorites. For example, the absolute isotopic dates of individual chondrules suggest that the formation of these objects started contemporaneously with the condensation and melting of CAIs and lasted ~3.5 Myr [10], which indicate the existence of multiple generations of chondrules within individual chondrites. Moreover, variability in the titanium and chromium stable isotope compositions of chondrules from individual chondrites suggest that these objects or their precursor were formed in distinct regions of the protoplanetary disk and subsequently transported to the accretion regions of their respective parent bodies [11, 12, 13]. These new data are at odds with the traditional view of a short formation history for chondrule population from individual chondrites, the basic concept of chondrule-matrix complementarity as well as the timescales and style of chondrite parent body accretion. In this contribution, we review the current state-of-the-art data with respect to the chronology and stable isotopic compositions of individual chondrules from various chondrite groups and discuss how these data can be used to provide novel insights into the thermal and chemical evolution of the solar protoplanetary disk, including mass transport processes.

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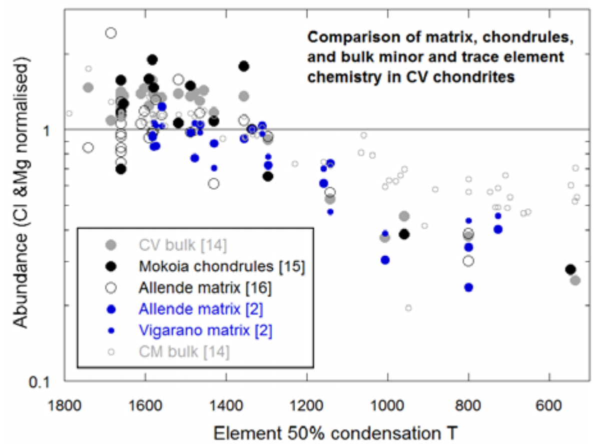
CHARACTERISTICS OF PRIMITIVE CHONDRITE MATRICES AND CONNECTION TO CHONDRULE FORMATION. P. A. Bland[1], D. C. Hezel[2], H. Palme[3] and J. N. Bigolski[4], [1]Department of Applied Geology, Curtin University, GPO Box U1987, Perth, WA 6845, Australia, p.a.bland@curtin.edu.au; [2]Institut für Geologie und Mineralogie, Universität zu Köln, Zülpicherstrasse 49b, D-50674 Köln, Germany, dominik.hezel@uni-koeln.de; [3]Senckenberg Forschungsinstitut und Naturmuseum, 60325 Frankfurt am Main, Germany; [4]Department of Earth and Environmental Sciences, CUNY Graduate Center, New York, NY, USA.

The degree to which the components of chondritic meteorites (chondrules and matrix) sampled a common source informs models of protoplanetary disk formation and evolution. Were chondrules transported large distances to mix with matrix, or did both form in the same region, affected by common processes?

Several authors have noted a chemical [1-8] and isotopic [9,10] complementarity between chondrules and matrix within a chondrite group, discussed in detail in a companion paper [11]. For it to have significance as a constraint on chondrule formation (and disk models), it must be a product of chondrule formation (and not, for instance, a result of redistribution during hydrothermal alteration). The details of the chemical relationship (e.g. elements related to open system behavious in chondrule melts, rather than soluble elements), and the observation of complementary nucleosynthetic Mo isotope [9] and ^{183}W anomalies [8,10], would tend to argue for the former. Others have suggested carbonaceous chondrites are mixtures of two components, volatile free chondrules enriched in refractory elements and volatile rich matrix (CI-like material). Both components could have formed independently at different heliocentric distances [e.g. 12], a model originally proposed by Anders [13]. In this scenario complementarity would simply be a function of exchange during aqueous alteration in the parent body [e.g. 12].

Is there additional chemical evidence linking chondrules and matrix? Most chondrites show a monotonic depletion in volatile and moderately volatile elements. The degree of depletion varies amongst chondrite groups. If chondrules formed from a matrix-like precursor, one would expect to see the bulk depletion signature translate to these components. There is evidence that it does. In the case of CVs, matrix, chondrules and bulk follow a similar trend (see figure) that is clearly distinct from other chondrite groups (e. g. CM).

Other components can offer insights. Microchondrules (≤ 40 µm) [17], potentially establish a generational gap between chondrules and matrix. Coarse-grained rims are found to be more similar to the mean chondrule composition than to that of the specific chondrule with which they are associated [18]. Matrix compositions were also found to be similar to coarse grained rims, suggesting that all three components were related. The relation between type I and II chondrules and enclosing rim types is also informative [19].



In summary, multiple lines of evidence indicate that CV chondrules and matrix formed in the same, chemically distinct nebula region, and exchanged elements during chondrule formation. Together with geochronological evidence for multiple generations of chondrules within a chondrite group which can be separated by 1-2 Myr (e.g. based on U-Pb chronology) [20,21]), this presents interesting constraints on disk models. We discuss the situation with respect to other chondrite groups, and mechanisms that would allow a feeding zone to remain (at least partially) chemical isolated in the disk for extended periods, at the conference.

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CHONDRULES FROM THE OUTER SOLAR SYSTEM: RESULTS FROM STARDUST. J. C. Bridges and L. J. Hicks, Space Research Centre, Leicester Institute for Space and Earth Observation, University of Leicester LE1 7RH, UK. j.bridges@le.ac.uk

Introduction: The *Stardust* mission sampled a Jupiter Family Comet 81PWild2 and brought back samples for analysis in 2006 [1]. The subsequent work has revealed mineralogical and isotopic affinities with carbonaceous chondrites. For instance, one of the major findings of *Stardust* has been the identification of chondrule and CAI fragments. As these are objects associated with localised melting in the inner Solar System, their presence in an object which originated within the Kuiper Belt was not expected. Here we describe the occurrence of chondrule fragments in Wild2 and their significance for models of the Early Solar System.

Chondrule Fragments in Wild2 Samples: Collection from the comet's coma at 6 kms^{-1} means that the samples are necessarily fragmented. However, ~10s μm-sized terminal grains in aerogel keystones have preserved pristine mineral assemblages with limited effects from capture. Burchell et al. [2] showed that Type A tracks in aerogel contain strong materials, typically consolidated into a single, volatile-poor grain e.g. either olivine, pyroxene, or chondrule fragments. Transmission Electron Microscopy studies of Type A track terminal grains have revealed that a large proportion of the coarse grains (>2 μm) may be fragments of chondrules that bear some chemical and isotopic similarities to those found in chondrites e.g. [3,4].

Similarities to Meteoritic Chondrules: There are differences in the chemistry and mineralogy between Wild2 chondrule fragments and meteoritic chondrules. The most common type of meteoritic chondrules are rounded FeO- and volatile-poor chondrules (Type I), but no chondrule fragments with such chemistry have yet been identified in Wild2 [5]. In contrast, several examples of FeO-rich, volatile-rich chondrule fragments have been identified in Wild 2 (so-called Type II), but are relatively less common in meteorite samples [3]. Two chondrule-like particles named Iris and Callie, Track #74, are examples of the similarities to Type II chondrules [6]. The Iris particle, from Track #74, is similar to chondrules in CR chondrites. Plagioclase in the FeMg Wild2 particle, Pyxie (Track #81), was analysed for Mg isotopes. The inferred initial $^{26}Al/^{27}Al$ ratio of plagioclase in Pyxie is <5×10. The $^{26}Al/^{27}Al$ ratio and $\Delta^{17}O$ resemble those of CR3 chondrules with Mg# <98 [6]. In addition, the presence of Al-rich chondrule fragments with Al-rich diopside and ^{16}O-rich compositions are very similar to those typical of carbonaceous chondrites [7].

Implications for the Early Solar System: In the presence of chondrules it is clear that Wild2 has preserved signs of high temperature processing. This complements the presence of CAIs [1] and magnetite formed by water-rock reaction on a parent body [8]. There is an absence of direct evidence in the chondrule fragments for extinct ^{26}Al [6, 9]. Assuming homogenous distribution of ^{26}Al in the solar nebula, one FeMg chondrule fragment crystallized at least 3 Myr after the earliest Solar System objects [9]. Thus there is no obvious evidence that the heat source associated with these chondrules was ^{26}Al, though more sample analyses may change this conclusion.

The presence of abundant chondrule fragments has changed our understanding of the formation of comets and icy planetesimals. It has been interpreted as evidence for large scale movement of common asteroidal-type materials from the inner Solar System by radial drift [10]. However, radial drift models have yet to resolve whether the drift material could escape the gravitational well of the gas and ice giants, or whether the residence time of chondritic fragments in the outer Solar System would be sufficient to allow incorporation into cometary parent bodies [7]. Thus an alternative posisbility is that chondrule formation also occurred within parts of the outer Solar System.

The *Stardust* samples have provided a unique opportunity to constrain models of the early Solar System, using the mineralogical analyses of chondrule fragments to inform new theoretical models.

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Hf-W CHRONOLOGY OF CR CHONDRITES. G. Budde, T. S. Kruijer, and T. Kleine, Institut für Planetologie, University of Münster, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany (gerrit.budde@uni-muenster.de).

Introduction: Understanding the origin of chondrules is key for constraining the processes affecting solid material in the solar nebula, ultimately leading to the formation of planetesimals. Addressing these issues requires information on the timescale of chondrule formation, and on genetic links between the individual components of chondrites. Previous studies have shown that most chondrules formed at ~2 Ma after formation of Ca-Al-rich inclusions (CAIs), although some chondrules may have formed as early as CAIs, while others may have formed ~4 Ma later (see [1] for an overview). In particular, chondrules from CR chondrites appear to be significantly younger than other chondrules [2,3]. However, the relatively young ages obtained for CR chondrules do not necessarily require a late formation, but might, at least in part, reflect disturbance or resetting during alteration on the CR parent body.

Compared to the Al-Mg and Pb-Pb systems, which are most commonly used to assess the chronology of chondrule formation, the ^{182}Hf-^{182}W system ($t_{1/2}$ = 8.9 Ma) is far more robust against resetting by parent body processes. This makes the Hf-W system ideally suited to assess whether or not CR chondrules formed later than other chondrules. Moreover, CR chondrites can be well dated using the Hf-W system, because they contain abundant Fe-Ni metal. As chondrule formation was associated with metal-silicate separation [*e.g.*, 1], chondrule formation can be dated via metal-silicate Hf-W isochrons for CR chondrites.

We present precise Hf-W ages for four different CR chondrites. In addition, we also determined high-precision (non-radiogenic) W and Mo isotope compositions for individual components of CR chondrites. These data provide important insights into the genetic links between these components, which in turn allows us to assess the chondrule-forming mechanism [1,4].

Methods: We obtained Hf-W and Mo isotope data for bulk samples, magnetic separates, and individual components (metal, chondrules) from four CR2 chondrites (Acfer 097, GRA 06100, NWA 1180, NWA 801). The analytical methods followed our established procedures [1,4], and all isotope measurements were made using the Neptune *Plus* MC-ICP-MS at Münster. The Mo and W isotope data are internally normalized to ^{98}Mo/^{96}Mo and either ^{186}W/^{183}W or ^{186}W/^{184}W, and are reported as ε-unit deviations (i.e., 0.01%) relative to the bracketing solution standards. Repeated analyses of terrestrial rock and metal standards (BHVO-2, NIST 129c) define an external reproducibility (2 s.d.) for the W and Mo isotope ratios of ~0.1 and 0.2–0.4 ε-units, respectively.

Nucleosynthetic isotope anomalies in CR components: The analyzed samples show variable anomalies in ε^{183}W (~0.1–0.7), where the metal fractions have the lowest and the silicate-dominated fractions the highest excesses in ε^{183}W. The ε^{183}W variations are correlated with measured Mo isotope variations (ε^{92}Mo: ~2–10), and are attributable to the uneven distribution of a presolar carrier enriched in *s*-process nuclides. Of note, metal and silicates show complementary nucleosynthetic isotope anomalies, indicating that relative to the bulk meteorite, metals are enriched in an *s*-process carrier, whereas silicates are depleted in this carrier. This finding is consistent with the isotopic complementarity observed for Allende chondrules and matrix [1,4] and provides further evidence that the major components of (carbonaceous) chondrites are genetically linked and formed together from one common reservoir of solar nebula dust.

Timescale of chondrule formation: After correction of the measured ε^{182}W for nucleosynthetic anomalies after [1], all analyzed samples plot on well-defined isochrons. Note that the correction for nucleosynthetic isotope anomalies is <0.05ε for most samples and thus smaller than the analytical uncertainty. All investigated CR chondrites have indistinguishable Hf-W ages and combined define an age of 3.7±0.6 Ma after CAI formation. This age is in excellent agreement with the mean Al-Mg age for CR chondrules of 3.7±0.3 Ma [3], as well as a Pb-Pb age of 3.7±0.6 Ma (corrected to ^{238}U/^{235}U = 137.786) obtained for six chondrules from the CR2 chondrite Acfer 059 [2]. Thus, three different chronometers provide consistent ages for the formation of CR chondrules, demonstrating that they formed ~1–2 Ma later than chondrules from ordinary chondrites. Collectively, these data suggest that the CR chondrite parent body accreted later than several other chondrite parent bodies, perhaps because the CR chondrites derive from a greater heliocentric distance. This is consistent with the ^{15}N signatures of the CR chondrites, and with the idea that carbonaceous chondrites initially accreted in the outer solar system, beyond the orbit of Jupiter [4,5].

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THE DISTRIBUTION OF MAJOR CARBONACEOUS COMPONENTS IN CHONDRITIC MATERIALS.

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Introduction: Carbonate materials comprise the second most abundant class (~3 vol%) of carbon-bearing phases in CM chondrites after organic matter, followed by other C-bearing phases such as diamond, silicon carbide, and graphite [1, 2]. Understanding the abundances of carbonates and the associated organic matter provides critical insight into the genesis of major carbonaceous components in chondritic materials, which were likely also the feedstock for chondrules.

With the use of Raman spectroscopy we present a study of the structure of the organic matter (OM) in the matrix and carbonate phases in five CM chondrites: Jbilet Winselwan, Murchison, Nogoya, Santa Cruz, and Wisconsin Range (WIS) 91600. We determined the degree of maturation of the OM in these meteorites and the formation conditions of the carbonates.

Methods: We identified carbonates in each sample with an optical microscope. The samples were then analyzed using a Jobin-Yvon Horiba LabRam HR Raman microprobe with a 40× objective. The excitation source was a 514.53 nm laser provided by a Modu-Laser Stellar Pro-L, 100 Mw solid-state laser. The peak position and full width half-maximum of each Raman band were determined by peak fitting to Lorentzian profiles and linear baseline correction.

Results and Discussion: Our observations indicate that the five CM2 samples have all experienced typical levels of aqueous processing, as evidenced by the presence of considerable amounts of Ca carbonates. A detailed description of the carbonate peak assignments is provided in [3, 4].

The organic compositions of the analyzed carbonates in the CM2 samples show notable variations. All the analyzed calcite grains observed in Murchison samples lacked typical Raman OM features. Calcite grains in Nogoya were also barren of organics, but the dolomite grain contains OM showing a degree of maturation that is distinctive from the organics observed in Nogoya matrix. Jbilet and Santa Cruz are hosts to a mixture of carbonate grains, with and without organics. Calcite in WIS 91600 also contains organics. Our Raman observations suggest that carbonates in the CM2s were produced under diverse chemical conditions, perhaps with an evolving fluid composition, or different sources of fluid. This is supported by the view that different carbonates might not have formed under equilibrium conditions from the same fluid [5].

Differences in the nature of carbonate phases in different CMs were also noted in previous studies based on isotopic and petrologic observations [6-8]. Carbonates that show typical Raman OM features are comparable to the type 2 carbonate described in literature of which the $\delta^{18}O$ value ≈ 19‰. This type of carboante was reported to occur as pseudomorphs replacing chondrule silicates in some CM2s [9], and was identified in all CM chondrites investigated in this study except for Murchison. Carbonate grains which lack typical Raman OM features might be comparable to type 1 carbonate ($\delta^{18}O$ value ≈ 34‰).

The matrix OM of the CM meteorite samples in this study has a lower structural order than the carbonate organics, which indicates variation in their organic components. Since different types of organic precursors should mature in a distinctive manner and thus should lead to discontinuities in the graphitization process [10], the maturity trend observed for the organics in matrix and carbonate suggests that they are likely derived from a similar source of precursors and/or exhibit a generic relationship.

Summary: The carbonate OM shows an apparently higher degree of maturation compared to meteorite matrix OM, indicating that the carbonate OM contains different organic components than the matrix OM. We propose that the initial aqueous activity that formed the first generation of carbonate could have involved highly oxidized fluids that led to the oxidation of OM and thus the production of the OM-barren carbonate. The aqueous activity ceased upon the termination of the heating event. A later short-term heating event recreated a favorable condition for the second generation of carbonate to precipitate, and at places they replaced chondrule silicates. The associated aqueous event could also have synthesized other organic materials observed in carbonaceous chondrites [11, 12]. Therefore carbonate and more evolved OM could coexist.

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U-PB CHRONOLOGY OF CHONDRULES. J. N. Connelly[1], J. Bollard, and M. Bizzarro[1], [1]Centre for Star and Planet Formation, Natural History Museum of Denmark, University of Copenhagen, 1350 Copenhagen K, Denmark.

Chondrules form from primitive dust that has been heated above its melting temperature and rapidly cooled in hours to days, one or more times [1]. "Nebular chondrules" are taken here as chondrules that formed within the protoplanetary disk before the dust and gas cleared. A second group of chondrules apparently formed by planetary collisions [2].

The high temperatures and melting associated with chondrule formation effectively increases their U/Pb ratios making them amenable to dating by this decay system. Chondrule melting raises the $^{238}U/^{204}Pb$ ratio (μ value) from starting Solar values of approximately 0.2 to upwards to values of 20 to 100's [3,4]. Using the stepwise dissolution method of [5], there is now 22 individual chondrules dated by the Pb-Pb method [3,4] with 6 chondrules of the 22 dated having measured $^{238}U/^{235}U$ ratios that overlap the Solar value of 137.786 [3]. In this chronometric framework, nebular chondrules started forming at the same time that calcium aluminum inclusions (CAIs) were formed (4567.30±0.16 Ma, [3]) and continued to form for ca. 3.6 Myr. This age range defines the minimum lifespan of the Solar System's protoplanetary disk, with the age of chondrules formed by planetary collision defining the maximum lifespan of the protoplanetary disk at 4.8 Myr [6]. As importantly, approximately half the chondrules dated by this method were formed within the first million years of the Solar System's formation.

The extrapoloation to the y-axis in an inverse Pb-Pb diagram ($^{204}Pb/^{206}Pb$ vs $^{207}Pb/^{206}Pb$) provides chronometric information, whereas a projection in the opposite direction to higher $^{204}Pb/^{206}Pb$ ratios provides information about the Pb isotopic composition at the time of chondrule formation. The projected compositions of the oldest chondrules are consistent with them having acquired an isotopic composition that had not radiogenically evolved significantly from the Solar System initial composition. Conversely, the younger chondrules inherited Pb isotopic compositions with evolved compositions relative to the Solar System intial values. This trend indicates that the younger chondrules acquired an elevated μ value earlier in their history, an observation most consistent with them having first experienced heating and melting (i.e. chondrule formation) early in the protoplanetary disk and later reworked. Collectively, our data set of ages and estimates of the intial Pb isotopic composition suggests that there are two distinct phases of nebular chondrules formation: 1) a primary chondrule formation episode within the first million years of the Solar System and 2) a more prolonged period lasting up to 3.6 Myr in which the primary chondrules continued to be reworked.

Our results are in direct contrast to the age range of chondrule formation inferred from the ^{26}Al-^{26}Mg decay system [7 for review] and recent estimates based on the ^{182}Hf-^{182}W decay system [8,9]. In the case of the ^{26}Al-^{26}Mg ages, we conclude that an offset to younger ages relative to the Pb-Pb age range and the so-called "chondrule gap" reflects heterogeneous distribution of the $^{26}Al/^{27}Al$ ratio in the protoplanetary disk. In contrast, the younger age range for chondrule formation based on $^{182}Hf/^{182}W$ ages most likely reflects an average age for chondrules formation derived by bulk analyses of large numbers of chondrules. The $^{182}Hf/^{182}W$ age estimates for chondrules are also compromised if the author's assumption that bulk chondrules and their host matix were in isotopic equilibrium at the time of chondrules formation is incorrect.

Recent models of planetesimal formation by streaming instabilities leading to efficient chondrule accretion predict that planetesimals will only effectively begin forming contemporaneously with the first appearance of chondrules [10]. As such, the earliest chondrules forming contemporaneously with CAIs is consistent with the existence of a crust on the angrite parent body already by 4564.39±0.24 Ma [11]. The reduced abundance of ^{26}Al in the protoplanetary disk defined by recent models [12] also predicts the onset of planetesimal accretion to have started within a few 100 kyr after CAI formation else there will be insufficient thermal energy to drive differentiation.

Finally, the assembly of chondrules with diverse ages and isotopic signatures [13,14] in a single chondrite requires that chondrules formed in different regions of the protoplanetary disk before they were transported to their respective accretion regions. This precludes a genetic link between the chondrules or between chondrules and matrix as predicted by models of chemical complimentarity in chondrites [15].

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MESOSCALE NUMERICAL MODELLING OF IMPACT PROCESSING OF CHONDRULE/MATRIX MIXTURES

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Introduction: Previous numerical studies of impact processing (e.g., compaction, heating) of primordial solids [e.g. 1, 2] have estimated 'bulk' pressure-temperature conditions over large (planetesimal) scales. However, primordial solar system solids accumulated as bimodal mixtures of mm-scale zero-porosity inclusions (chondrules) surrounded by highly porous, sub-μm dust particles (matrix). To model these bimodal mixtures explicitly, and resolve heterogeneity in shock response at the scale of individual chondrules, requires "mesoscale" modelling [e.g. 3]. Our results [4, 5] provide an important link between meteoritic evidence and the bulk thermal and compaction histories of meteorite parent bodies.

Modelling: Mesoscale planar impact simulations [5] were performed using the iSALE shock physics code [6–8], in which shock waves were propagated through a bimodal mixture of explicitly resolved non-porous disks (the chondrules) surrounded by a highly porous matrix. Chondrules were placed with random sizes (0.3–1 mm) and spacing within the computational mesh until the desired matrix-to-chondrule volume ratio was reached. The ANEOS equation of state for forsterite [9] was used to describe the thermodynamic response of chondrules. The solid component of the matrix was described by either forsterite or the ANEOS table for serpentine [10].

Compaction of porosity and material strength were modeled using the methods described in [7, 8, 11]. The chondrules had a high cohesive strength (1 GPa), whereas the porous matrix was assumed to be very weak, (a few kPa). Simulations spanned a range in impact velocity (0.75–3 km/s), initial matrix volume fraction (30–80%) and initial matrix porosity (60–80%), with an initial temperature of 300 K. Lagrangian tracer particles recorded the peak- and post-shock state of the matrix and chondrule material, from which the bulk state was determined.

Results: The bulk (volume averaged) shock pressure, temperature and porosity of the mixture simulated using our new mesoscale models are consistent with previous macroscale models (using the bulk values as the initial conditions [e.g. 2]) and Hugoniot curves created with the $\varepsilon - \alpha$ porous compaction model. Resolving at the finer mesoscale, our simulations reveal a complex, heterogeneous response to shock within the mixture. While peak pressures are similar in the chondrules and the matrix, for $v_i > 1.5$ km/s they are ~ 2 times higher than the average bulk pressure recorded; this is a consequence of the mesoscale structure, which creates resonant oscillations about the steady wave amplitude, the peaks of which are recorded in the chondrules and matrix.

Temperature dichotomy: Moreover, there is a large dichotomy between the temperatures recorded in the matrix and the chondrules: The massive difference in compressibility between the porous matrix and the nonporous chondrules results in much greater energy deposition in the matrix. Consequently, while the chondrules record only a modest temperature change, well below the bulk temperature increase, the post-shock temperature increase in the matrix is much larger (hundreds of K) than in the bulk and highly variable. The juxtaposition of hot matrix and cold chondrules imply that the temperature difference is short-lived: the chondrules act as a heat sink, equilibrating the mixture to the bulk post-shock temperature in seconds.

Strain: Strain maps were constructed from tracer particle positions using the method described in [12]. There is good qualitative agreement of the strain from the models with that derived from EBSD maps of Allende [13]. Strain in the chondrules is low for low velocities (< 1.5 km s^{-1}), and localised near chondrule margins. For higher velocity (2 km s^{-1}), strain is more evenly distributed throughout chondrules. Strain in the matrix is higher than in the chondrules, although this includes both the strain in the matrix grains and that associated with the collapse of pore space. Mean strain increases with increasing impact velocity.

Conclusions: Simulations with a range of initial conditions produce final materials with porosities and matrix abundances similar to meteoritic material. Using this method to model specific scenarios allows a full quantitative analysis of the shock evolution of primitive materials; shock direction can be inferred from strain and porosity distributions. This enables a firm link between numerical modelling and measurements of meteoritic samples.

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Cr AND O ISOTOPE SYSTEMATICS IN CV/CK CHONDRITE CHONDRULES. C. DEFOUILLOY[1*], M. E. SANBORN[2], A. YAMAKAWA[2], N. T. KITA[1], D. S. EBEL[3], Q.-Z. YIN[2], [1]WiscSIMS, Dept. of Geoscience, Univ. of Wisconsin-Madison, USA. (defouilloy@wisc.edu). [2]Department of Earth & Planetary Sciences, University of California, Davis, USA. [3]American Museum of Natural History, New York, USA.

Introduction: The combination of bulk Δ^{17}O (= δ^{17}O–0.52× δ^{18}O) and ε^{54}Cr isotopic analyses of meteorites has shown two trends: (1) carbonaceous chondrites (CCs) and (2) the other meteorite groups (Fig.1), suggesting a disk-scale isotope heterogeneity in the early Solar System [e.g., 1]. Previous studies have shown that individual chondrules in a single CC group show a significant variabilities in Δ^{17}O and δ^{54}Cr compared to those of bulk CCs [2,3]. Here we report coordinated Δ^{17}O and δ^{54}Cr measurements of individual chondrules from carbonaceous chondrites (CC) along with their petrographic descriptions. These data are used to explore the origin of the distinct isotope reservoirs in the protoplanetary disk.

Analytical procedures: 10 chondrules from Allende (1.5-3 mm) and 9 chondrules (1-1.5 mm) from Karoonda were hand-picked for ultra-high precision Cr isotope analyses, electron microscopy and SIMS O isotope analyses.

Results: All chondrules but one are internally homogeneous in their O-isotope ratios. The range of data are similar to those previously obtained for CV chondrite chondrules [3], in which δ^{18}O and δ^{17}O values follow the PCM line [4], domain of CC chondrules. FeO-rich BO chondrules in Allende are off the PCM line, which plot on the TF line and near the ordinary chondrites (OC) domain. The Δ^{17}O values of Allende chondrules systematically increase with decreasing Mg#, similar to those in other CCs [5]. The Δ^{17}O values of Allende chondrules in this study distribute widely from –5‰ to 0‰, in contrast to previous data from CV chondrules [5] as well as to those of Karoonda in this study that cluster at –5‰. This systematic difference could be linked to the larger than average size of the Allende chondrules analyzed in this study.

Cr isotope ratios (ε^{54}Cr) are more variable for Allende chondrules (–0.5ε to 0.8ε) than for Karoonda (–0.3ε to 0.6ε). The majority of chondrules show ε^{54}Cr values lower than the bulk CV and CK chondrite data.

Discussions: Fig. 1 shows the obtained ε^{54}Cr and Δ^{17}O data. Most Karoonda chondrules cluster in a small region at Δ^{17}O ~ –5‰ and ε^{54}Cr ~ 0ε, which appears to be an extension of the bulk CC trend. Two chondrules shift towards the non-CC meteorite region with higher Δ^{17}O and lower ε^{54}Cr. In contrast, Allende chondrule data distribute into four distinct regions: (1) POP chondrules with Δ^{17}O ~ –3‰ and ε^{54}Cr ~ +0.8ε, in the vicinity of bulk CV3 [1]. (2) BOs with Δ^{17}O ~ 0‰ and ε^{54}Cr ~ –0.5ε, close to the OC and achondrite area [1]. (3) PO chondrules with negative ε^{54}Cr and negative Δ^{17}O, intermediary between the non-CC cluster and the Karoonda cluster (Δ^{17}O ~ –5‰ and ε^{54}Cr ~ 0ε), possibly belonging to the same mixing line between two reservoirs as the intermediary Karoonda chondrules. (4) Finally, one Al-rich chondrule is internally heterogeneous in O-isotopes with Δ^{17}O of from –10‰ to –20‰, but with an intermediate ε^{54}Cr~ 0ε.

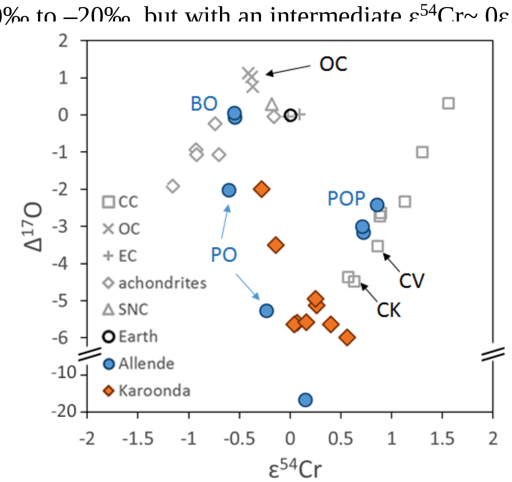

Fig. 1: ε^{54}Cr- Δ^{17}O in Allende and Karoonda chondrules. Literature data from [1].

Conclusion: Combined analyses of Cr and O isotopic ratios at the chondrule level reveal mixing trends that are not observed in bulk meteorite data. Precursors of chondrules in CV/CK chondrites might come from multiple Cr-O isotope reservoirs, including OC-like and CC-like isotope reservoirs. This is consistent with [6] who found chondrules with similar OC-like O isotopic composition in ungr. CC Yamato 82094, and with [3] who reported a large variability of ε^{54}Cr in CV chondrites, indicating that precursor material for CV chondrites may have originated from various regions of the inner nebular disk.

The heterogeneous chondrule also shows a mixing between grains falling on the non-CC domain and a CAI-like refractory precursor (Δ^{17}O ~ –25‰ and ε^{54}Cr ~ –6ε[7]), which indicates a complex history of mixing between different reservoirs over time and space.

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Mg isotope constraints on the origin of Mg-rich olivines and mesostasis phases from Allende chondrules.

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Introduction: Reduced type I chondrules, that represent up to 95% of all chondrules from carbonaceous chondrites, are made of Mg-rich olivines (for the type IA), metal, variable fractions of glassy mesostasis, low-Ca pyroxene and other minor phases. These components are high-temperature phases but their origins remain unclear. A large fraction of Mg-rich olivines can be demonstrated on the basis of their chemical and oxygen isotopic compositions to be relict phases that partially re-equilibrated with the mesostasis during the last melting event underwent by the chondrules[1-3]. Previous bulk Mg isotopic studies showed that individual chondrules in carbonaceous chondrites exhibited mass-dependent isotopic variations larger than 1000 ppm per amu[4-6]. Despite these variations can be expected to result from evaporation and/or condensation during chondrule formation, the systematics that these processes have imprinted, at micron scale, on the Mg contents, the Mg mass-dependent and non mass-dependent isotopic variations, have never been explored. Here we present an in-situ Mg isotopic study of 20 Allende chondrules analyzed by LA-MC-ICP-MS, aiming at better constraining the origin of Allende chondrules.

Methods: A laser ablation system was coupled with a Thermo Fisher Neptune MC-ICP-MS to analyze in-situ Mg isotopic composition at a spatial resolution of 40-50 μm. This approach was preferred to MC-SIMS to better control matrix effects on Mg instrumental isotopic fractionation[7]. The use of a HelEx sample cell improves the delivery efficiency of ablated aerosols. On MC-ICP-MS, four faraday cups are aligned to simultaneously measure intensities of $^{24}Mg^+$, $^{25}Mg^+$, $^{26}Mg^+$ and $^{27}Al^+$. Peak jumping from central mass 25 to 23 was conducted to monitor $^{44}Ca^{2+}/^{24}Mg^+$ each four cycles. A set of synthetic olivines and basalt glasses that have been chemically and isotopically characterized were used to correct matrix effects on the measured Mg isotopic ratios, to calibrate $^{27}Al/^{24}Mg$ measurements and to determine the instrumental $^{44}Ca^{2+}/^{48}Ca^{2+}$ ratio used for the correction of the $^{48}Ca^{2+}$ interference on $^{24}Mg^+$. The chemical compositions of the sections of Allende studied were mapped by SEM before laser ablation. This approach enabled us to measure $^{27}Al/^{24}Mg$ ratios together with mass-dependent ($\delta^{25}Mg$) and non mass-dependent (^{26}Mg excesses noted $\delta^{26}Mg^*$) Mg isotopic variations in chondrules. We have precisions of ±0.15‰ for $\delta^{25}Mg$ and ±0.03‰ for $\delta^{26}Mg^*$ on San Carlos olivines.

Results: The Mg-rich olivines in Allende chondrules tend to have slightly negative $\delta^{25}Mg$ values, while the ferrous olivines and mesostasis phases have positive values. This is also observed in some cases within individual Mg-rich chondrules in CM2 chondrites[5]. Mg-rich olivines show weak but detectable ^{26}Mg deficits (up to a few tens of ppm) relative to bulk Allende, while ^{26}Mg excesses are present in the mesostasis phases. Correlations of these excesses with $^{27}Al/^{24}Mg$ ratios define ^{26}Al-^{26}Mg isochrones. Assuming an homogeneous initial $^{26}Al/^{27}Al$ ratio of 5.23×10^{-5} at the time of formation of Ca, Al-rich inclusions (CAIs) from Allende[8], the mesostasis in one Allende Type I chondrules formed at $1.64^{-0.19/+0.23}$ Ma after CAIs, while those of two Type II chondrules quenched at $2.23^{-0.19/+0.23}$ Ma and $2.69^{-0.27/+0.37}$ Ma, respectively.

Discussion: The $\delta^{25}Mg$ difference between Mg-rich olivines and mesostasis phases within individual chondrules suggests that the Mg-rich olivines did not crystallize from the parental melts of the mesostasis[1-3]. The enrichment of light Mg isotopes in the Mg-rich olivines can point to fractionations due to non-equilibrium condensation[9], or to a fractionated parental reservoir. The detectable ^{26}Mg deficits suggest that these olivines have been isolated early from the solar nebula. The heavier Mg isotopic composition of the mesostasis together with the higher Al/Mg ratios could imply fractionations due to partial Mg evaporation during chondrule formation. The timing of these chemical fractionations is constrained by the $^{26}Al/^{27}Al$ ratios of up to 1.0×10^{-5}. Modeling of evaporation is able to explain the variations in Mg contents together with $\delta^{25}Mg$ and $\delta^{26}Mg^*$ variations. These variations present within individual chondrules are new constraints on the origin of chondrules and are consistent with previous Mg data for bulk chondrules[4-6].

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RECORDS OF MAGNETIC FIELDS IN THE CHONDRULE FORMATION ENVIRONMENT. Roger R. Fu[1], Benjamin P. Weiss[2], Pauli Kehayias[3], Devin L. Schrader[4], Ronald L. Walsworth[3]. [1]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA (rf2006@ldeo.columbia.edu). [2]Dept. of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, MA, USA. [3]Dept. of Physics, Harvard University, Cambridge, MA, USA. [4]Center for Meteorite Studies, ASU, AZ, USA.

Introduction: Chondrules contain minor amounts of ferromagnetic minerals, which typically consist of the FeNi alloys kamacite and taenite. If the cooling of chondrules to ambient conditions took place in the presence of a magnetic field, the chondrules would have acquired a thermoremanent magnetization that can be measured in the laboratory and used to estimate the strength of the primordial ambient magnetic field.

In the absence of post-formation remagnetization processes, a pristine record of nebular magnetic fields can place several important constraints on the mechanisms and setting of chondrule formation. Hypothesized formation processes predict different magnetic field intensities. The x-wind model predicts strong solar fields of ~1000 μT (i.e., ~20 times Earth strength; [2]). In contrast, nebular shocks and planetesimal collisions are likely to result in magnetic fields substantially lower than 100 μT [3], assuming background magnetic fields of order 10 μT [4].

Paleomagnetic records of primordial field intensity may also constrain the location of chondrule formation. Assuming a constant accretion mechanism and rate [5], magnetic field strength is expected to decline rapidly within increasing orbital radius, falling by a factor of ~20 between 1 and 10 AU [6]. As such, systematic paleointensity variations among chondrite groups may reflect their formation radii. In particular, lower paleointensities recovered from chondrules of carbonaceous chondrites would support the Grand Tack hypothesis of planetary migration and the in-situ formation of chondrules at large orbital radii [7].

Chondrule paleomagnetism: Despite these motivations for the recovery of paleofield intensities from chondrules, the acquisition of robust measurements has proven challenging. Aqueous alteration, metamorphism, and shock on parent bodies are effective mechanisms for removing primordial remanent magnetization, implying that only a very small subset of chondrites are suitable for paleomagnetic analyses. Another challenge is that most FeNi metal in chondrules occurs in >>1 μm blebs, which are too large to retain a high fidelity record of ancient fields [8].

We will review recent results from the Semarkona LL3 ordinary chondrite [9], which meets the above criteria for the lack of parent body remagnetization processes. To avoid the poor magnetic field recording properties inherent to most chondrule metals, we extracted and measured only dusty olivine-bearing chondrules. Mean paleointensities computed from five dusty olivine-bearing chondrules suggest a magnetic field during chondrule formation of 54±21 μT, most consistent with a low magnetic field mechanism such as nebular shocks or planetesimal impacts.

To test the uniformity of chondrule formation mechanisms and setting across different chondrite classes, we then obtained paleomagnetic data from seven sub-samples of three chondrules from the CR carbonaceous chondrite LAP02342, which has experienced a lower degree of metamorphism than Semarkona and mild aqueous alteration compared to other CR chondrites [10]. Unlike Semarkona chondrules, the measured chondrules from LAP 02342 carry no internally coherent components of magnetization. By imparting the chondrules laboratory magnetizations in the presence of ever weaker magnetic fields, we determined that the magnetic field strength in the CR chondrule formation environment was likely <15 μT to produce the observed lack of coherent magnetization.

If this result is confirmed, chondrules from CR chondrites formed in a weaker magnetic field than those from LL chondrites, implying that the former were produced at greater orbital radii, at a later time in nebular evolution, or in a distinct formation mechanism. However, because our chondrules from LAP 02342 contain >1 μm grains of FeNi metal, the accuracy of the inferred paleointensity is lower than that for Semarkona chondrules, while the location of these FeNi blebs in silicate grain boundaries raises the possibility that they were affected by aqueous alteration. To address these uncertainties, we will present ongoing paleomagnetic measurements on three dusty olivine-bearing chondrules in the CR chondrite GRA95229. The <1 μm grain size typical of the dusty olivine metals and their location within enclosed olivine grains are expected to permit the accurate recovery of remanent magnetization unaffected by aqueous alteration.

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EXPERIMENTAL SIMULATION OF CHONDRULE TEXTURES USING SYMMETRICAL HEATING AND COOLING RATES: TESTING THE RADIATIVE MODEL FOR CHONDRULE FORMATION.

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Introduction: We have recently proposed a model for chondrule formation involving the passage of dust aggregates during close fly-bys of planetesimals with exposed magma at the surface [1]. This model predicts symmetrical heating and cooling of chondrule precursor materials to make chondrules and possibly the chondrites themselves [1,2] (Fig. 1). A reasonable first test of this model is to simulate chondrule textural types under predicted thermal histories, which involve heating chondrule precursor materials to <2000 K for hours or less on symmetrical heating and cooling paths (Figs. 1,2).

Experimental Methods: We began this program of chondrule simulation experiments following the initial experimental protocols of Radomsky and Hewins [3], wherein they used sieved size fractions of minerals to match Type I and Type II chondrule compositions [4]. Specific experimental configuration: Deltech VT-31 furnace w/ Eurotherm 2404 16-step programmable temperature controller; CO_2/CO to keep fO_2 near IW; Temperature monitored with calibrated Pt-Pt13%Rh thermocouple next to the experimental charge, w/ high purity Fe next. Initial experiments were done in open Pt capsules. Chondrule analog compositions are made with a mixture of olivine, pyroxene, plagioclase, and diopside, following [3,4]. Specifically, Type I: 70% San Carlos olivine, 10% bronzite porphyry, 10% diopside, and 10% oligoclase; Type II: 70% Fayalite-rich slag (containing cm-sized Fa100 bars), 10% bronzite porphyry, 10% diopside, and 10% oligoclase. Purity of these phases will be improved.

Initial Results: Using the heating and cooling curve shown in Fig. 2, we have produced textures similar to those seen in chondrules for both FeO-rich (Barred Olivine) and FeO-poor compositions (Porphyritic Olivine). The FeO-rich Type II analog developed a texture of long fayalite-rich olivine bars and glass, for two grain-size fractions (45-63 µm; 63-125 µm). The FeO-poor, Type I composition developed a porphyritic texture, with relict grains, that was similar to chondrule textures for several size fractions (32-63 µm; 63-125 µm).

Future Work: We will continue to experiment with different size fractions of two analog compositions (Type I and II) and a range of heating and cooling paths to determine which produce chondrules, as well as which thermal paths fail to produce chondrule textures, to further refine our model. We will also try different chondrule precursor assemblages, such as granular olivine aggregates [5,6], finer grain sizes than have previously been employed, and increased level of purity of precursor minerals. We also hope to explore 'dirty snowball' precursors as well.

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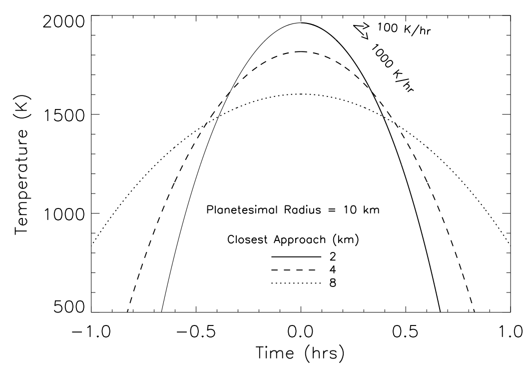

Figure 1. Calculated heating and cooling curves of dust aggregates on a model fly-by of a 10 km planetesimal with exposed magma at its surface.

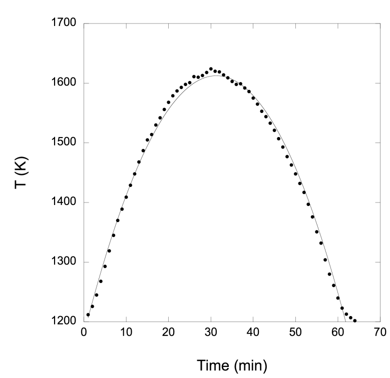

Figure 2. Heating and cooling curve of experiment S2. Solid curve is a 2nd order polynomial fit; points are temperature measurements of thermocouple next to experiment in hot zone of furnace.

SIGNS OF BIOWEATHERING IN ORDINARY CHONDRITES. I. Gyollai[1,2], M. Polgári[2], Sz. Bérczi[1], M. Veres[3], A. Gucsik[4], E. Pál-Molnár[5], [1]Eötvös University, Dept. of Materials Physics, Cosmic Materials Space Res. Group, H-1117 Budapest, Pázmány P. str. 1/a, Hungary, e-mail: gyildi@gmail.com; [2]Research Center for Astronomy and Geosciences, IGG, HAS, 1112 Budapest, Budaörsi str. 45, Hungary, e-mail: rodokrozit@gmail.com; [3]Wigner Research Centre for Physics, HAS, H-1121 Budapest, Konkoly-Thege M. str. 29-33, Hungary, e-mail: veres.miklos@wigner.mta.hu; [4]University of Johannesburg, Dept. of Geology, 2600 Auckland Park, Johannesburg, South Africa; [5]Szeged University, Dept. of Mineralogy, Geochemistry and Petrology, 6722 Szeged, Egyetem str. 2, Hungary, e-mail: palm@geo.u-szeged.hu

Introduction: Chondrite constituents are considered as solar cloud condensates and surviving primordial dust grains accumulated in chondrules and minerals. The chondrites are fragments of asteroidal sized parent bodies where several transformation processes occurred: thermal metamorphosis, impact induced shock transformations and aqueous alteration. The aim was a high resolution textural and mineralogical characterization of the transformation products of UOC.

Samples: We investigated Mező-Madaras, Knyahinya, Mócs and Nyírábrány meteorites. The Mező-Madaras chondrite is brecciated and xenolithic. In Knyahinya, Nyírábrány and Mócs the boundaries of the chondrules are obscured, while the matrix is partly recrystallized, with gradually grown mineral grains in the matrix.

Methods: High resolution petrographic structural-textural studies were undertaken on four thin sections using a petrographic microscope (OM). We used FTIR and micro-Raman spectroscopy for the determination and distribution of micro-mineralogy and organic compounds.

Microtexture: Mineralized microbially produced texture (MMPT) in the form of pearl necklace-like, vermiform inner signatures, embedded in the stone meteorites has been observed for the first time. Our observations (OM) focused on the iron-containing opaque grains, glass, olivines and pyroxenes, which were well populated by micrometer-sized microbial filamentous elements and clusters in their boundary region within the matrix and inside the minerals. In the chondritic textures we observed that microbial "invasion" started in the fine-grained matrix and extended into the chondrules mainly through the Fe-containing minerals. The MMPT is very extensive, reaches 70-80 % of the sections, and is intimately woven in the full cross-section of the thin sections of the whole stone meteorite. All thin sections showed signs of Fe mobilization and oxidation (brown haloes around mineral grains, brown filaments).

Mineralogy: *ATR-FTIR* The iron-oxidizing microbial structures have a mixed composition containing iron oxides (ferrihydrite. goethite) [1], olivine [2], and montmorillonite [3]. Hydrocarbon compounds were also detected (long chain hydrocarbon, diene; [4,5], and C-H stretching of aliphatic hydrocarbons [4]. The presence of olivine and montmorillonite spectra proves the weathering of olivine, while the appearance of ferrihydrite corresponds to bacterial originated remobilization of iron from olivine and troilite. IR vibrations of isoprenoids were also detected [5,6,7].

Raman spectroscopy Besides olivine and pyroxene, hydrogenated amorphous carbons and carbonyl and also peaks, related to organic materials of recent iron bacteria were detected (isoprenoid) [3]. The kandite group of minerals (kaolinite, dickite, halloysite) correspond to weathering of Fe-Mg-silicates [8]. The smectite group was also detected (montmorillonite, nontronite). The spectra also contain iron oxide phases (ferrihydrite, lepidocrocite, magnetite).

Results: Our data confirm dense and invasive terrestrial microbially mediated contamination in the chodrites, supported by microtexture, micromineralogy and embedded organic compounds, which effected most of the mass of the samples. As the transformation processes are supposed to happen on the parent bodies, it raises contradictions as it seems that these products manifest in microbially mediated texture. In our study we offer basically different interpretation to solve these contradictions.

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TUNGSTEN ISOTOPIC EVIDENCE FOR COEVAL METAL-SILICATE FRACTIONATION AND CHONDRULE FORMATION IN ORDINARY CHONDRITES. J. L. Hellmann[1], T. S. Kruijer[1] and T. Kleine[1], [1]University of Münster, Institut für Planetologie, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (Contact: jan.hellmann@uni-muenster.de).

Introduction: Assessing the timescale for chondrule formation is key for understanding the origin of chondrules and the accretion history of chondrite parent bodies. However, the timing and duration of chondrule formation is still hotly debated, and reported ages for chondrules range from ~0 to ~3–4 million years (Ma) after formation of Ca-Al-rich inclusions (CAI) [1-3]. As chondrules probably accreted into chondrites shortly after their formation [1, 4], independent constraints on the timing of chondrule formation can be obtained by dating the accretion of chondrite parent bodies. Here we show that the timing of chondrite parent body accretion can be determined by dating the metal-silicate fractionation among ordinary chondrites.

Ordinary chondrites contain abundant metal and exhibit variable metal-to-silicate ratios, defining the three subgroups (H, L and LL), which each represent a distinct parent body. As the distinct metal abundances in the ordinary chondrites led to different bulk Hf/W ratios [5], the timing of metal-silicate fractionation among ordinary chondrites can be examined using the short-lived ^{182}Hf-^{182}W decay system. We conducted a Hf-W isochron study on metal and silicate separates of equilibrated H, L and LL chondrites of petrologic types 4 to 6, and here report data for three L chondrites (Tennasilm, L4; Saratov, L4; Kunashak, L6), four LL chondrites (NWA 7545, LL4; NWA 6935, LL5; Tuxtuac, LL5; NWA 5755, LL6), and three H chondrites (Ste. Marguerite, H4; ALH 84069, H5; Estacado, H6).

Methods: The chondrites were gently crushed to grain sizes between 40 and 250 µm. The grain size separates were then subdivided into different fractions using a hand magnet, resulting in several silicate-rich fractions and metal separates. The methods for separation of Hf and W, the measurement of Hf and W concentrations by isotope dilution, and the W isotope measurements followed our established procedures [1]. All measurements were conducted using the Neptune *Plus* MC-ICPMS at Münster, and results are reported in ε^{182}W as the parts-per-10^4 deviation from the ^{182}W/^{184}W of terrestrial bracketing standards.

Results: All metal separates have deficits in ε^{182}W, consistent with their very low Hf/W ratios. In contrast, the silicate fractions show more radiogenic and variable ε^{182}W values coupled with higher Hf/W ratios. For each sample, ε^{182}W is linearly correlated with Hf/W, defining precise isochrons. The isochron intercepts are essentially defined by the metal data points, which provide precise estimates of the initial ε^{182}W for each sample.

Discussion: Our results show that type 6 ordinary chondrites have younger Hf-W ages than type 4 samples, consistent with the slower cooling expected for chondrites of higher petrologic types. These systematic variations are consistent with a concentrically layered 'onion-shell' structure of chondrite parent bodies after they had undergone thermal metamorphism [6, 7]. In a diagram of initial ε^{182}W *vs.* time, all type 4 chondrites (including H, L and LL samples) cluster around a common initial ε^{182}W and Hf-W age corresponding to ~3-4 Ma after CAIs. In contrast, for type 6 chondrites the initial ε^{182}W vary and decrease from LL6 to L6 to H6, yet they all have similar Hf-W ages of ~9–11 Ma after CAIs. These data show that the different groups of ordinary chondrites evolved with distinct Hf/W ratios, where LL chondrites are characterized by the highest and H chondrites by the lowest Hf/W. The distinct Hf/W ratios are correlated with the variable silicate-to-metal ratios of ordinary chondrites, which also decrease in the order LL>L>H. Thus, the distinct Hf/W ratios of the ordinary chondrites were most likely established by a nebular metal-silicate fractionation just prior to accretion of ordinary chondrite parent bodies.

The Hf-W isotope evolution lines for each ordinary chondrite group intersect at ~2–3 Ma after CAIs. This observation suggests that the primitive ordinary chondrite reservoirs first evolved with a uniform Hf/W ratio up to that point in time and that the distinct bulk Hf/W of the H, L, and LL groups were only established later, at ~2–3 Ma after CAI formation. Thus, the metal-silicate fractionation among ordinary chondrites leading to their different bulk Hf/W occurred significantly later than CAI formation, but coincided with the formation of chondrules from ordinary chondrites at ~2 Ma after CAI formation. Collectively, these data indicate that chondrule formation, metal-silicate fractionation and chondrite accretion were coeval at about ~2 Ma after CAI formation.

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The Radiative Heating Model for Chondrule and Chondrite Formation. W. Herbst[1] and J. P. Greenwood[2], [1]Astronomy Dept., Wesleyan University, Middletown, CT 06457, wherbst@wesleyan.edu. [2]Earth & Environmental Sciences Dept, Wesleyan University, Middletown, CT 06457, jgreenwood@wesleyan.edu.

Introduction: Chondrules form at higher densities and with a wider range of oxygen fugacity than is plausible for the solar nebula [1,2]. Their porphyritic textures and other properties, however, do not support direct condensation from hot ejecta that may arise from planetesimal collisions [3]. We have recently proposed that radiative heating of pre-existing dust aggregates could be the primary or only mechanism for chondrule formation [4; hereinafter Paper I]. Here we develop and explore that idea in more detail.

Heating Model: Two potential sources of the required radiant energy that could be present within the asteroid belt at the time of chondrule formation (1-4 Myr) are: 1) giant planets, powered by gravitational collapse, and 2) planetesimals with radii ≥ ~10 km, powered by the decay of ^{26}Al. Models of young planetesimals show that one can expect them to be fully molten at that time [5]. Collisions and/or crustal foundering will lead to the emergence of substantial amounts of lava at their surface from time to time. Aggregated solids of mm- to m-size flying by at the right time will be heated to the temperatures necessary for chondrule formation.

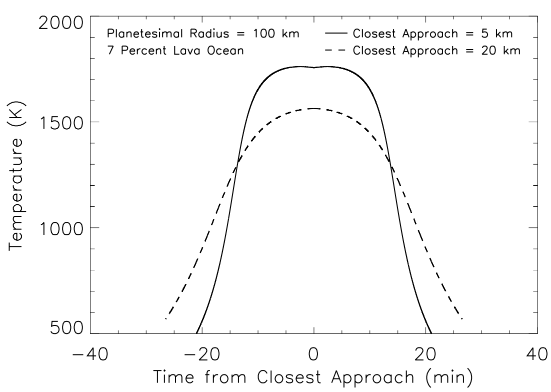

Fig. 1. Representative heating/cooling curves predicted by our chondrule formation model.

In Fig. 1 we show the predicted heating and cooling curve for a model fly-by of a 100 km radius planetesimal with a lava ocean covering 7% of its surface. This serves as an example of what can be expected in such an event. Details will vary with the height at closest approach and the extent and temperature of the lava ocean. Generally speaking, however, one will achieve sub-liquidus temperatures and heating/cooling rates within the constraints known to result in chondrule textures in laboratory settings [6].

Chondrite Lithification: All of the chondrules presently in our possession have arrived embedded in chondritic meteorites. The general problem of chondrite lithification is poorly understood. Pressures and temperatures on plausible parent bodies appear insufficient to account for the observed porosity of carbonaceous or ordinary chondrites [7]. It is possible that chondrites arrived on their parent bodies in already-lithified form. Here we advance the hypothesis that the same heating event that formed the chondrules may also have been involved in lithifying the chondrites, through sintering.

Discussion: We know from the ages of iron meteorites and from modeling [5] that molten planetesimals appeared within the first ~1 Myr and persisted for a few Myr, providing a plausible source for the radiative energy needed for chondrule formation by this mechanism. We also know that virtually all solids in the asteroid belt are swept into large bodies rapidly. Monte Carlo simulations indicate that a 100 km planetesimal in the asteroid belt will suffer ~10^{14} collisions during its lifetime, mostly with 0.1-1 m sized objects [7]. Therefore, a similar number of these dust-laden aggregates must experience close (~40 km or less) fly-bys. On some occasions they will be heated by exposed lava in a manner consistent with chondrule formation and, perhaps, chondrite lithification.

Our proposed mechanism for chondrule formation is consistent with all known constraints on the environment within the asteroid belt at 1-4 Myr. It accounts or potentially accounts for the age and epoch of chondrule formation, the constraint from their textures on heating and cooling rates, the co-mingling of Type I and Type II chondrules, the phenomenon of complementarity, the possibility of re-heating of some chondrules, the bimodal size distribution (chondrules and matrix) of chondrite components, melted rims on some CAI's, and other features. It is a model with firm, testable predictions, that has significant implications for the evolution of solids in the solar nebula.

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Mineralogy and Texture Descriptions to Help Understand Chondrule Origins

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Introduction: Attempts to understand chondrule origins almost always involve chemical and isotopic approaches before, or in place of, other observations. Chondrules are tiny rocks, produced by cosmic processes and containing, therefore, some evidence within themselves of their origin, preserved in their mineralogy and textures. Simple, mnemonic and alpha-numeric codes to describe these fundamental features have been developed and are now being refined [1,2,3,4,5].

Methodology: The codes allow an at-a-glance means of recording mineralogy and textures dominated by bi- or multi-modal crystal-size populations of olivine (O) and pyroxene (P) of variable habit. Chondrule images, (e. g. BSE grey-scale) may be annotated with letters that compile into number sequences that convey essential detailed and comparative classification information. They resemble ISBNs, Bar Codes, or Credit/Debit Card numbers, a familiar format in this digital age.

Potential: Alpha-numeric codes or tags allow researchers: to document and label intra-chondrule textures in each chondrule, from relatively coarse- to fine-grained; to map out the distribution of similar or dissimilar chondrules in any chondrite; to compare the kinds of chondrules present in different chondrites; and to teach observers to ponder the processes that may have affected chondrule formation. The discipline of having to assign an alpha-numeric label to each chondrule leads to detailed textural observations that might not otherwise have been made, e.g. of melting, annealing, and reaction textures at different scales. Robust, evidence-based constraints and ideas on chondrule origins should result, that need to be considered along with others from e.g. cosmochemical approaches.

Description schemes: The most robust textural-mineralogical scheme used by meteoriticists [6] to describe (intra)chondrule textures has been in successful use for 35 years and is firmly entrenched. It tends to lump, rather than split and for detailed studies is not ideal. Recognizing that the size distribution of minerals and crystals in chondrules can be subdivided into four size ranges for each and every chondrule -- megacrystic (M), macrocrystic (m), microcrystic(µ), and mesostasis (*ms*) -- with tags for equant (q), elongate (l), angular (a), and rounded (r), an alphabetic scheme that splits rather than lumps yields many details [1,2,3]. For example, two chondrules from the ordinary chondrite Saratov (L4) labelled S2 and S4, respectively, are classified as follows under the alphabetic system:

S2:	POP	mµ*ms*	mOla, Plr, Pqr / µPla / meso
S4:	POP	mµ*ms*	mOqa/ µPla, Pqa / meso

Both chondrules are POP [6]. Neither contain megacrysts. S2 contains macrocrysts of angular elongate olivine, elongate rounded pyroxene, and equant rounded pyroxene; and microcrysts of elongate angular pyroxene. S4 contains macrocrysts of equant angular olivine; and microcrysts of elongate angular pyroxene, and equant angular pyroxene. Both show (unresolvable) mesostasis. They therefore have different detailed mineralogy and textures, but this is still not readily grasped at-a-glance.

The new system: The most up-to-date and improved version of the new system substitutes numbers for the letters, arranged in 4 sequential fields with 5 slots each:1=Ola, 3=Olr, 5=Oqa, 7=Oqr, 2=Pla, 4=Plr, 6=Pqa, 8=Pqr , 9=unresolvable, 0=not present. *spaces are for notes on the immediately preceding size ranges.

S2 becomes:	0000*1048*0020*9999*	(cf. mOla, Plr, Pqr / µPla / meso)
S4 becomes:	0000*5000*0026*9999*	(cf. mOqa/ µPla, Pqa / meso)

The first five digit spaces are for M. At each scale the left 2 spaces are assigned to O, the right 2 spaces to P. As above, odd numbers describe olivine, even numbers pyroxene, except for 9 and 0. The next five digit spaces are for m, the next for µ, and the last for *ms.*

Results: The chondrules are clearly different at-a-glance in the numeric system.

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THERMAL HISTORIES OF BARRED CHONDRULES FROM MELTS GENERATED EXPERIMENTALLY.

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Introduction: Meteorites are samples of early processes in the protoplanetary disk where the Solar System was formed, in particular chondrites preserve the oldest components of the Solar System. Chondrules are the main component of chondrites and they are among the most primitive materials in the Solar System: 4567-4565 Myr [1], their formation coincide with the planets accretion. They are compoused of olivine $(Mg,Fe)_2SiO_4$ and poor Ca pyroxene $(Mg,Fe)SiO_3$. They were formed at temperatures in the range of 1300-1800 °C in the course of seconds and at most several minutes [2,3]. The important unknowns in the formation of chondrules are:

- The starting composition of the precursors.
- The physical conditions of their formation (pressure, temperature and time).
- The mechanisms that produce them.

The main aspects of chondrules are:

1. The retention of volatile materials such as S, Na and K, wich had not survived heating and/or cooling for long periods of time.
2. The existence of grains and edges indicating different heating pulses, instead of monotonic cooling after a single heating.

Barred chondrules represent the 10% of all chondrules in ordinary chondrites [4]. They determine an upper limit in temperature for chondrule formation conditions because their characteristic texture is only formed at higest temperatures (with respect to other textures). It is not known what is the precise mechanism of heating of chondrule precursors. The most accepted model is "flash heating", originated by shockwave fronts propagating through the interior of the solar nebula [5].

The thermal histories provide the most important information in the chondrule formation, therefore the constrains on thermal histories are keys to find the processes that originated chondrules [6]. The formation models of chondrules propose thermal histories of chondrules which do not agree sufficiently well with those found experimentally.

Objectives: There are two main objectives:

- To determine what kind of heating conditions reproduce the features observed in chondrules located in chondrites.
- To associate the experimental thermal histories with those proposed by chondrule formation models, in order to constrain the conditions of the disk that gave rise to the Solar System.

Methodology: We simulate the formation of barred olivine chondrules by melting olivine crystals using a 50 W CO_2 laser emitting in the infrarred at a wavelength of 10.6 μm. We measure the temperature during and after the melting, therefore each melt has one thermal history recorded. Subsequently, we perform petrological, chemical, crystallographic and textural analysis of the melts. These set of analysis will be compared with the natural chondrules. The thermal histories of those experimental melts that reproduce the characteristics of natural chondrules will be used to constrain the scenarios of chondrule formation and the physical conditions of the solar nebula.

Preliminary results: During the experimental formation, the maximum temperature range was 800 to 1800 ºC. The cristallization time was in a few cents of second. The bars width range is 9-16 μm; compared with natural chondrules, the bars width is similar to measurements in barred chondrules of some ordinary chondrites [7]. The diameter of experimental melts is similar to the natural chondrules [8], the range was 500-1000 μm (see figure 1).

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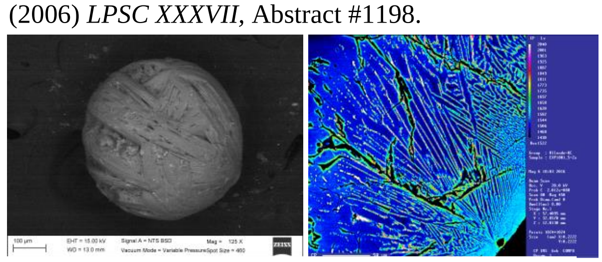


Figure 1. Sample EX18_1-5, one of the melts obtained.

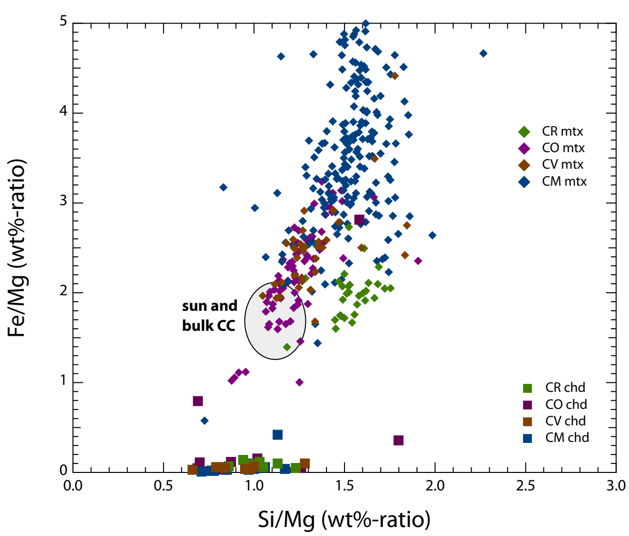
THE CHONDRULE-MATRIX COMPLEMENTARITY. D. C. Hezel[1,2], H. Palme[3], P. A. Bland[4] and E. Jacquet[5], [1]University of Cologne, Department of Geology and Mineralogy, Zülpicher Str. 49b, 50674 Köln, Germany, [2]Department of Mineralogy, Natural History Museum, Cromwell Road, London, SW7 5BD, UK, [3]Forschungsinstitut und Naturmuseum Senckenberg, Senckenberganlage 25, D-60325 Frankfurt am Main, Germany, [4]Department of Applied Geology, Curtin University, Perth, WA 6845, Australia, [5]Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, Muséum National d'Histoire Naturelle, CP52, 57 rue Buffon, 75005 Paris, France.

Chondrules are found throughout the solar system, in chondritic meteorites, but also in comets [1]. Chondrules mark a significant step in protoplanetary disk evolution, when interstellar dust grows to planetesimals and finally to planets. The mechanism of chondrule formation is, hence, not only vital for planet formation, but also an integral part of protoplanetary disk evolution. Chondrule formation is therefore a prerequisite of building planets, but also important for understanding protoplanetary disk formation in general.

Unfortunately, and despite many decades of efforts, the search for the mechanism of chondrule formation remains inconclusive, and still a significant number of hypotheses of how chondrules formed compete [e.g. 2].

Chondrules and matrix together account for typically >95 vol.% of a chondrite. Despite the large structural variations, bulk chondritic meteorites are chemically similar. Understanding the relationship of chondrules and matrix, and a potential genetic link between these two components, will provide conclusive and unequivocal constraints that any suggested mechanism of chondrule formation has to meet.

The majority of chondrules and matrix in a single meteorite formed either in the same region or in spatially separate regions. A significant number of hypotheses on how chondrules formed require that chondrules and matrix formed in spatially separated regions. Therefore, the answer to the question whether chondrules and matrix of a single meteorite formed in the same or in separate regions will allow to either support or discard a potentially large number of suggestions regarding chondrule-forming mechanisms.



Chondrules and matrix have different element compositions. For example, chondrules in carbonaceous chondrites typically have higher Mg/Si ratios than matrix (figure). Together, chondrules and matrix represent the bulk chondrite Mg and Si content, hence, the bulk chondrite Mg/Si ratio is the combination of chondrules and matrix. It is then a critical observation that the bulk chondrite Mg/Si ratio is not just any such combination, but exactly the ratio of CI chondrites. The fact that chondrules and matrix have different element ratios while the bulk has an CI chondritc element ratio is called chondrule-matrix complementarity. Such complementarity has now been reported for a number of element pairs (e.g. Mg/Si, Al/Ca, Al/Ti, Fe/Mg), and isotope systems (e.g. W, Mo) in different carbonaceous chondrites [3-10].

It is difficult to achieve such complementarity by mixing chondrules and matrix of different compositions from different regions of the solar nebula, resulting in a CI chondritic bulk composition. Hence, any model requiring mixing that cannot explain complementarity must be excluded. Still, some recent theoretical calculations invoking radial [11] or vertical [12] transport may reconcile complementarity with a plurality of sources in the limit of tight coupling of chondrules and dust with the gas.

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COMBINING DYNAMICAL AND COSMOCHEMICAL CONSTRAINTS ON THE PROCESSES OF CHONDRULE FORMATION: LAYERED DISKS. A. Hubbard[1] and D. S. Ebel[2], [1]Department of Astrophysics, American Museum of Natural History (ahubbard@amnh.org), [2]Department of Earth and Planetary Sciences, American Museum of Natural History (debel@amnh.org)

Introduction: The field of astrophysics has been making large strides in the understanding of the processes of collisional dust growth, dust transport, concentration and aerodynamical sorting, and planetesimal formation in protoplanetary disks [1,2,3]. Similarly, cosmochemists have been developing an exciting relatively new constraint on the correlation between chondrules and matrix in chondrites known as complementarity [4,5,6]. Combined, these advances make striking predictions about the physical partitioning of protoplanetary disk regions associated with chondrule formation that match well with a standard global picture of protoplanetary disks as accreting through magnetically active surface layers while the midplanes are quiescent [6].

Complementarity: Across a wide range of elements and isotopes, the composition of matrix and chondrules within a given chondrite differ significantly. Further, the ratio of chondrules to matrix varies strongly between chondrites. Nonetheless, the bulk elemental and isotopic abundances of chondritic meteorities are flat across chondrite classes [4,5,6]. This implies that chondrules and matrix within a given chondrite were co-genetic, forming from a single reservoir of near-solar composition. It also implies that parent body assemblage had to have occurred shortly after and spatially near chondrule formation [8].

Spatial sorting: One mystery associated with complementarity is how the chondrules and matrix can have different compositions in the first place. This challenge was made particularly pressing by the recent W/Hf isotope measurements of Budde et al [6]. Separating matrix from their co-genetic chondrule precursor grains would have required strong aerodyanmical sorting [8]. While radial pressure perturbations can concentrate large dust grains and act as a sorting mechanism [2], chondrules are too small to have been easily concentrated in such a fashion.

Planetesimal formation and chondrule size: It has become clear that naked chondrules (on order of 500 micron diameter and smaller) could not have directly proceeded to planetesimal formation, and must have stuck together to form large agglomerations [10]. However, outside of a few rare examples [11], meteorites do not record the thermal processing of such agglomerations. Thus, in tension with complementarity, chondrule formation regions must have been separate (either in space or in time) from the parent body assemblage regions.

Layered disk structure: These challenges and constraints point to a layered disk scenario, where chondrule formation events were restricted to the upper layers, well above a cool midplane. In that case, strong vertical stratification and settling would have allowed the spatial sorting of chondrule precursors and matrix grains. Once the newly formed chondrules settled to the midplane, they could agglomerate without those agglomerations being thermally processed. Further, the low aspect ratio of protoplanetary disks means that this scenario would have required only relatively small vertical distances with concomitantly short transport times. Thus, this scenario would have allowed the matrix and chondrules in a narrow radial annulus to remain co-genetic through the aerodynamical sorting, chondrule formation and parent body formations stages.

This picture is particularly attractive because it meshes well with the conventional astrophysical picture of magnetically accreting layered protoplanetary disks: quiescent, low ionization midplanes and non-thermally ionized, magnetically active surface layers [7]. However, it also places a constraint on chondrule formation models: the mchanism should preferentially occur in the upper reaches of disks. While the dissipation of magnetic turbulence would be consistent with that constraint [12], the strong vertical gradients invoked to allow spatial sorting might have allowed other mechanisms such as lightning [13]: spatial sorting is a mechanism to drive charge separation over large length scales.

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CHONDRULES IN ENSTATITE CHONDRITES. E. Jacquet[1], L. Piani[2], M. K. Weisberg[3] [1]Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, CRNS & MNHN, UMR 7590, 57 rue Cuvier, 75005 Paris, France (emmanuel.jacquet@mnhn.fr), [2]Department of Natural History Sciences, Hokkaido University, Sapporo 060-0810 Japan. [3]Department of Physical Sciences, Kingsborough College, CUNY, Brooklyn, NY 11235, USA; Earth and Environmental Sciences, Graduate Center, CUNY, NY, NY 10024, USA; Department of Earth and Planetary Sciences, AMNH, NY, NY 10024, USA.

Introduction: Beside the classical porphyritic ferromagnesian chondrules in ordinary and carbonaceous chondrites, there is a whole world of unusual chondrules which, *to the extent* they can be traced to a common origin, may provide new powerful constraints on the chondrule-forming process(es). Among those, chondrules in enstatite chondrites (EC, divided in two chemical groups EH and EL; [1]) present especial interest. On the one hand, they may be compared in terms of size [2] and major silicate parageneses to type I chondrules in other chondrite clans, and their O isotope composition link them to inner solar system material [3]. On the other hand, their mineralogies, in particular opaque phases, testify to *extremely* reduced conditions—more so than any other known early solar system sample—which are as yet not understood astrophysically. With considerable progress accomplished in the last decade, it is timely to review the properties and origins of enstatite chondrite chondrules.

Petrography, chemistry, O isotopes: EC chondrules generally contain nearly FeO-free enstatite, subordinate silica, a volatile-rich mesostasis [2,4], Si-bearing kamacite and a wide array of sulfides such as troilite, niningerite (EH), alabandite (EL) etc. Olivine-rich chondrules and ferroan pyroxene fragments or spherules also occur in EC. All these phases show O isotopic compositions close to bulk EC [1], although some olivine grains scatter along the “primitive chondrule mineral” line of [5]. Bulk chondrules are depleted in siderophile and chalcophile elements [6] and show negative Eu and Yb anomalies not reflected in most of their ferromagnesian silicates [7-9].

Besides silicate chondrules, EC contain metal-sulfide nodules (MSN; [10-13]) which may be genetically related to them and in fact have sometimes been called “metal-sulfide chondrules” [13]; we thus included them in the scope of the review. They contain kamacite, sulfides, sometimes concentrically layered as in EH chondrites. Oldhamite in EH MSNs is enriched by 1-2 orders of magnitude in REE over chondritic values with frequent positive Eu and Yb anomalies [14-15]. MSN may contain silicates, such as the frequent enstatite ± sinoite laths in EL’s [16-17].

Condensation vs. melting: Were the peculiarities of EC chondrules inherited from their putative precursors, presumably themselves the result of some condensation sequence, or were they acquired during their melting? Most of the past literature has envisioned the first option, with reducing conditions being achieved by supersolar C/O ratios (see [18] and introduction to [19] and references therein). For C/O ~ 1, oldhamite, as an early condensate, would be predicted to concentrate REE but with Eu, Yb anomalies of the wrong sign; other condensate phases such as carbides would also be expected which are not observed.

The existence of relatively oxidized isotopically local phases in EC as well as the tetravalent state of a significant portion of the Ti in EC chondrules [20] suggest that the precursors of EC chondrules were actually quite “normal” and were melted in a O-poor and S-rich environment, leading to the sulfidation of silicate phases ([19], [4]). MSN in EH might have been expelled from chondrules [9] while those of EL may have an impact origin [16-17].

Whatever the stage where the reducing conditions applied, their astrophysical context remains to be determined. An origin inside the snow line would allow to decouple solids from water, but whether the S (and other volatile) enhancements can be reproduced in a nebular setting is still open to question.

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Harvesting the decay energy of 26-Al to drive lightning discharge and chondrule formation. A. Johansen[1] and S. Okuzumi[2], [1]Lund Observatory, Lund University, anders@astro.lu.se, [2]Department of Earth and Planetary Sciences, Tokyo Institute of Technology.

Introduction: Chondrules in primitive meteorites likely formed by recrystallisation of dust aggregates that were flash-heated to nearly complete melting. Chondrules may represent the building blocks of rocky planetesimals and protoplanets in the inner regions of protoplanetary discs, but the source of ubiquitous thermal processing of their dust aggregate precursors remains elusive. Here we demonstrate that escape of positrons released in the decay of the short-lived radionuclide 26-Al leads to a large-scale charging of dense pebble structures, resulting in neutralisation by lightning discharge and flash-heating of dust and pebbles. This charging mechanism is similar to a nuclear battery where a radioactive source charges a capacitor. We show that the nuclear battery effect operates in circumplanetesimal pebble discs. The extremely high pebble densities in such discs are consistent with conditions during chondrule heating inferred from the lack of volatile gradients within chondrules. The sedimented mid-plane layer of the protoplanetary disc is also prone to charging by the emission of positrons. Heating by lightning discharge in this relatively low-density environment would result in complete sublimation of solids and recondensation of the vapour as metal grains and small silicate grains similar to the matrix present between chondrules in meteorites. Our results imply that the decay energy of 26-Al can be harvested to drive intense lightning activity in protoplanetary discs. The total energy stored in positron emission is comparable to the energy needed to melt all solids in the protoplanetary disc. The efficiency of transferring the positron energy to the electric field nevertheless depends on the relatively unknown distribution and scale-dependence of pebble density gradients in circumplanetesimal pebble discs and in the protoplanetary disc mid-plane layer.

FORMATION OF CHONDRULES BY PLANETESIMAL COLLISION. B. C. Johnson[1], F. J. Ciesla[2], C. P. Dullemond[3], and H. J. Melosh[4], [1]Department of Earth, Environmental and Planetary Sciences, Brown University (Brandon_Johnson@Brown.edu).[2]Department of the Geophysical Sciences, The University of Chicago.[3]Heidelberg University, Center for Astronomy, Institute of Theoretical Astrophysics. [4]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University.

Introduction: Chondrules are the mm scale previously molten droplets found in chondritic meteorites. These pervasive yet enigmatic particles hint at energetic processes at work in the nascent Solar System. Chondrules and chondrites are well studied and many of the details about their compositions, ages, and thermal histories are well known. Without the proper context of a formation mechanism, however, we can only imagine what chondrules may reveal about the processes at work in the early Solar System. Here, we explore the hypothesis that chondrules were formed by impacts between growing planetesimals. Specifically, we focus on shock heating associated with accretionary impacts as a means for melting chondrule precursor material. We explore the predictions of this model and its implications for our understanding of early solar system history and meteoritics. We also discuss potential issues and uncertainties while identifying avenues for further development and testing of the impact origin hypothesis.

Jetting model and comparison to constraints: Here we focus on the often overlooked process of impact jetting, which has recently been suggested as way to reconcile an impact origin for chondrules with observational constraints [1]. Jetting is an extreme process that occurs very early in an impact when the projectile is still coming into contact with the target. A small amount of material is shocked to high pressures and temperatures as it is squirted out from the region where the projectile is coming into contact with the target. This process can now be directly resolved in numerical models. This material is typically ejected at velocities exceeding the impact velocity (Fig. 1).

We compare this model's prediction to the observed sizes of chondrules [2], the overall abundance of chondrules in the meteorite record [3], cooling rates inferred from chondrule textures [4], constraints on dust enrichment and total pressure inferred from chondrule volatile content [5], lack of isotopic fractionation [6], the overall composition of chondrites and observations suggesting while chondrules are depleted in volatiles the surrounding matrix material is enriched [7] and a similar trend for tungsten isotopes [8]. Although there are still large uncertainties, which may be resolved by more detailed modeling, we find the jetting model is currently consistent with all of these constraints.

Conclusions: Our understanding of planet formation suggests that planets are built through a series of mergers and impacts. Accretion models imply that the impact velocities necessary to jet partially melted material are an expected outcome of the accretion process [1]. Other models indicate this jetted material would be efficiently accreted onto smaller bodies (<1000 km in diameter) [9]. Thus, in contrast to some other models for chondrule formation, the potentially chondrule forming impact jetting process was very likely occurring at the time of chondrule formation and chondrule formation during planetesimal collisions is the natural consequence of planet formation. Impact jetting is an unavoidable consequence of hypervelocity impacts. If no signs of this process are seen in the meteoritic record, then this implies that Moon-sized bodies never formed in the main belt region.

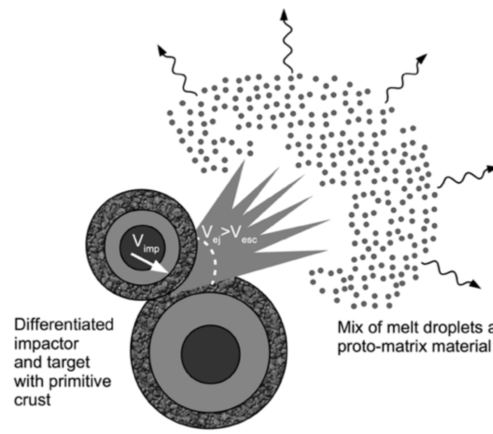

Fig 1: Schematic representation of the formation of chondrules and proto-matrix by impact jetting. Early in the impact primitive crustal material is ejected above the escape velocity of the target body. Some of this material is partially melted and breaks up becoming melt droplets. The rest of the material is only lightly shocked and become proto-matrix material. As the jetted material moves outward it radiatively cools. The vast majority of impact ejecta are bound to the target body.

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THERMAL HISTORIES OF CHONDRULES: PETROLOGIC OBSERVATIONS AND EXPERIMENTAL CONSTRAINTS. R. H. Jones[1], J. Villeneuve[2] and G. Libourel[3], [1]School of Earth and Environmental Sciences, The University of Manchester, Rhian.jones-2@manchester.ac.uk., [2]Centre de Recherches Pétrographiques et Géochimiques, Vandoeuvre-lès-Nancy, johanv@crpg.cnrs-nancy.fr, [3]Observatoire de la Côte d'Azur, Nice, libou@oca.eu.

Introduction: Petrology is fundamental to understanding chondrules. Knowing what minerals are present, their chemical compositions, and how those minerals are arranged, allows us to interpret important chemical and physical characteristics of the chondrule formation process. Chondrules show diverse compositions and textures that indicate variation in chondrule precursors, heating and cooling rates, interactions with local gas, chondrule density in the formation region, relationships with refractory inclusions, and many other parameters. In addition, experimental studies of chondrule analogues provide important insights into the conditions controlling chondrule melting and crystallization. Here we focus on the observations and experiments that specifically place constraints on chondrule thermal histories, which are fundamental to discriminating between chondrule formation models.

Observations of natural chondrules: Petrologic properties of chondrules are the most direct way of determining their thermal histories. Chondrule textures are described as either porphyritic or non-porphyritic, with the dominant silicate mineralogy consisting of crystalline olivine and pyroxene, and an interstitial feldspathic mesostasis [1]. Different textures represent differing degrees of nucleation as the chondrule cools: incomplete melting results in a high density of nucleation sites, which leads to a porphyritic texture, whereas complete melting results in destruction of nucleation sites and a non-porphyritic texture [2,3].

Several other petrologic indicators can also constrain cooling rates. Both olivine and pyroxene show growth zoning, especially in more FeO-rich chondrules: diffusion modeling of this zoning can put quantitative constraints on cooling rates [4]. The presence of relict grains that persisted through the melting event puts limits on thermal histories, from considerations of dissolution rates and from chemical and isotopic diffusion modeling of relict / overgrowth zoning profiles [1,3]. The presence of clinoenstatite, and glass with quench microcrystallites, both indicate rapid cooling. Pyroxene and metal microstructures give information about lower-temperature thermal histories at sub-liquidus temperatures [5,6].

Chondrule analogue experiments: Dynamic crystallization experiments on chondrule analogue compositions have provided the most important quantitative constraints on chondrule thermal histories [2,3,9]. In general, chondrules were heated to peak temperatures in the range 1500 to 2000 °C and cooled at rates of 10 to 1000 °C/hr, with ambient temperature <400 °C.

More recent work adds further insights. For example, [10] showed that in order for plagioclase to nucleate and grow in type I chondrule analogues, very slow cooling rates are necessary in the temperature range close to the solidus. [11] showed that it is possible to produce type II chondrules from type I chondrules by oxidation, although this requires thermal histories that are not typically considered. [12] has shown that olivine dissolution in chondrule-like melts is fast, with rates of about ten $\mu m.min^{-1}$, suggesting that cooling rates as high as 1000–8000 °C/hr are required to preserve relict olivines in type IA chondrules.

Discussion: We know a lot about the petrology of chondrules, and we have a good general understanding of thermal constraints. These observations and experiments provide essential parameters for thermal histories in chondrule formation models. However, there are still some important questions to answer such as: 1) What is the thermal history prior to the (last recorded) rapid heating event, and also close to and below the solidus? 2) Relationships between composition and texture should be investigated further. Specifically, kinetic effects in open system experiments should be explored. 3) More modelling of chemical and isotopic zoning would be useful to determine thermal histories specific to individual chondrules. 4) The role of metals has not been fully investigated. Does the thermal history recorded by metal in chondrules match the silicate one? How do metals segregate from molten chondrules, and does this place time and / or physical constraints on melting?

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Combined study of highly siderophile elements and Cr isotopes in the chondrules of unequilibrated chondrites. Y. Kadlag[1] and H. Becker[1], [1]Freie Universität Berlin, Institut für Geologische Wissenschaften, Malteserstr. 74-100, 12249 Berlin, Germany (Contact: yogita@zedat.fu-berlin.de).

Introduction: Chondrules are the main component of all but CI chondrites. The formation mechanisms of these spherical silicate rich objects are still debated [1]. In this study, we have analysed highly siderophile elements (HSE: Re, Os, Ir, Ru, Pt, Rh, Pd and Au), ^{187}Re-^{187}Os and Cr isotope systematics of bulk chondrule fractions of unequilibrated chondrites Allende (CV3.6), Murchison (CM2) and QUE 97008 (L3.05) to understand chemical and isotopic equilibration during chondrule formation and the preservation of isotopic heterogeneity inherited from precursor dust.

Chondrule fractions (2.2 to 29 mg weight) were separated from the meteorites and dissolved in aqua-regia in an Anton Paar™ High Pressure Asher System (HPA-S) at 320°C. The sample solutions were splitted into six different aliquots to determine, I) HSE abundances, II) major and minor elements, III) chalcogen element concentrations (S, Se and Te), IV) the ^{55}Mn/^{52}Cr ratio, V) Os isotopic compositions and VI) Cr isotopic compositions. Concentrations of all elements were determined using Element XR™ ICP-MS. Osmium and Cr isotope compositions were measured on a Triton TIMS. Details of the chemical procedures are published elsewhere [2, 3]. In this report we will only discuss the siderophile element abundances, Re-Os and Cr isotope systematics.

Abundances of HSE: CI-normalized abundances of HSE + Fe, Mn and Cr of chondrules are shown in the Fig. 1. Chondrules of the Allende meteorite show nearly CI chondritic ratios and abundances of all HSE except Pd. Higher abundances of HSE compared to Fe indicate the presence of HSE metal alloys in silicates of chondrule fractions which were not completely equilibrated with Fe-Ni metal or troilite of the matrix (Fig.1).

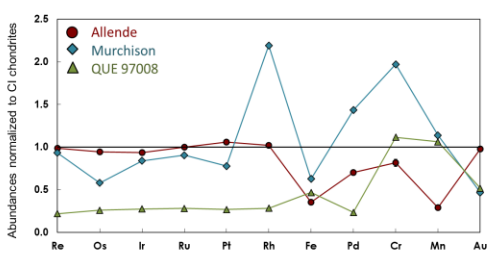

Fig. 1. CI normalized abundances of siderophile elements (Element order indicates the increase in volatility from left to right)

Murchison chondrules show fractionated HSE ratios relative to CI chondrites, with higher CI normalized abundances of Rh and Pd (and the less siderophile Cr) compared to other HSE. Chondrules from QUE 97008 show lower CI normalized abundances of refractory HSE (Re, Os, Ir, Ru, Pt, Rh and Pd) compared to Au. Fractional condensation and/or evaporation (in case of Allende and QUE 97008) along with alteration processes (Murchison chondrules) on the parent bodies may explain these fractionated abundance patterns.

^{187}Re-^{187}Os systematics: All chondrule fractions scatter off a 4.567 Ga isochron [2, 3], showing deviation towards the low-Re/Os side of the isochron (higher ^{187}Os/^{188}Os for given ^{187}Re/^{188}Os values). The preferred explanation of these deviations is recent open system redistribution of Re and/or Os at low temperatures on parent bodies or during terrestrial weathering.

^{53}Mn-^{53}Cr systematics: The ^{53}Mn-^{53}Cr systematics of chondrule fractions (Fig.2) yields a value for ^{53}Mn/^{55}Mn = 4.5 ± 1.0 x 10^{-6}), which may be interpreted such that the chondrules formed about 2.0 ± 1.3 Ma after the time of formation of the solar system (assuming the solar system age is 4567.3 ± 1.9 Ma defined by the bulk chondrite ^{53}Mn-^{53}Cr isochron, [4]).

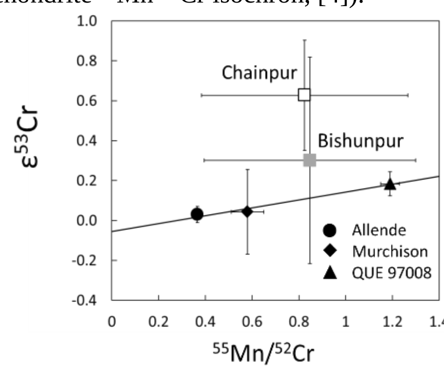

Fig. 2. ^{53}Mn-^{53}Cr isochron diagram of bulk chondrule fractions and the average of literature data forChainpur and Bishunpur chondrules[5].

This result also indicates that despite substantial disturbance in the ^{187}Re-^{187}Os systematics, the Mn-Cr systematics of chondrules was not disturbed by alteration processes. The correlation defined by chondrule fractions from different chondrites in the isochron diagram is consistent with the view that ^{53}Mn was homogeneously distributed in the chondrule precursors.

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TUNGSTEN ISOTOPES AND THE AGE AND ORIGIN OF CHONDRULES. T. Kleine, G. Budde, J. L. Hellmann, T. S. Kruijer, and C. Burkhardt, Institut für Planetologie, University of Münster, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany (thorsten.kleine@wwu.de).

Introduction: The short-lived ^{182}Hf-^{182}W system ($t_{1/2}$ ~8.9 Ma) is a versatile tool to study the timescales and processes of chondrule formation and chondrite accretion. Dating chondrites is possible because chondrule formation typically was associated with metal-silicate separation. As W is siderophile, whereas Hf is lithophile, metal-silicate separation leads to Hf/W fractionation, making it possible to determine Hf-W isochrons [1]. Tungsten isotopes also provide information on genetic links between chondrules and other components of primitive chondrites. This is because chondrules, matrix, and metal in at least carbonaceous chondrites exhibit nucleosynthetic W isotope anomalies that arise through the uneven distribution of presolar components among chondrite components [2].

Isotopic complementarity of chondrules and matrix: Chondrules and matrix from the CV3 chondrite Allende exhibit complementary ^{183}W anomalies: chondrules have ^{183}W excesses, the matrix has ^{183}W deficits [2]. The same samples also show complementary isotope anomalies for Mo, but not for Ba [3]. These data are best explained by the preferential incorporation of a presolar metal carrier enriched in *s*-process nuclides into the matrix, and the complementary depletion of this carrier in the chondrules. This uneven distribution of a presolar metal probably results from metal-silicate fractionation during chondrule formation [3].

Bulk meteorites, including Allende, show only small if any ^{183}W anomalies. This observation, and the presence of large ^{183}W variations in chondrules and matrix, indicates that these two components derive from a single reservoir of nebular dust; otherwise they would not show complementary isotope anomalies resulting from the uneven distribution of a single presolar carrier [2]. As such, the ^{183}W data are inconsistent with an impact origin of chondrules, but instead require that chondrules formed in the solar nebula. Moreover, after their formation, neither appreciable chondrules nor matrix could have been lost, because otherwise bulk Allende would show a significant ^{183}W anomaly. This implies that after their formation chondrules and matrix accreted rapidly to their parent body and that chondrules from a given chondrite group formed within a narrow time interval [2].

Hf-W chronology of chondrule formation: Allende chondrules and matrix define a precise Hf-W isochron, corresponding to an age of 2.2±0.8 Ma after CAI formation [2]. Metal and silicate separates from four CR chondrites define an isochron corresponding to an age of 3.7±0.6 Ma after CAI formation [8]. Thus, chondrules from CR chondrites formed 1.5±0.7 Ma later than those from CV chondrites. The CR chondrules also formed later than chondrules from ordinary chondrites, which based on Al-Mg systematics formed at ~2 Ma after CAI formation [4]. To date, no isochrons for type 3 ordinary chondrites have been obtained, and so the formation of ordinary chondrite chondrules has not been dated directly using the Hf-W system. However, Hf-W ages for equilibrated ordinary chondrites of petrologic types 4 to 6 indicate that the different bulk Hf/W of H, L and LL chondrites were established at ~2–3 Ma after CAI formation, most likely as a result of nebular metal-silicate separation that was coeval with chondrule formation [9]. Combined, these data indicate that most chondrules formed at ~2–3 Ma, and that chondrule formation extended until at least ~4 Ma, post CAI formation.

Implications for the distribution of ^{26}Al in the solar nebula: The Hf-W ages for CV and CR chondrites not only constrain the chronology of chondrule formation, but they also provide insights into the distribution of ^{26}Al within the solar nebula. There are now four different types of samples, spanning an age range of ~5 Ma, that have been dated with both the Hf-W and Al-Mg systems: bulk CAI, CV chondrules, CR chondrules and the angrites D'Orbigny and Sahara 99555. For all four samples the Hf-W and Al-Mg ages are in excellent agreement, and so provide no evidence for ^{26}Al heterogeneity. Using the scatter around the correlation line of ages from both systems shows that any potential ^{26}Al heterogeneity was <10–20%, i.e., much smaller than proposed based on the comparison of Al-Mg and Pb-Pb ages [5].

Conclusions: Tungsten isotope measurements on chondrites have led to the following constraints: (1) chondrules formed in the solar nebula; (2) chondrules from a given chondrite group formed in a narrow time interval; (3) most chondrules formed at ~2–3 Ma after CAIs, but CR chondrules formed ~1.5 Ma later; (4) ^{26}Al was homogeneously distributed in the nebula.

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MULTIPLE MECHANISMS OF TRANSIENT HEATING EVENTS IN THE PROTOPLANETARY DISK: EVIDENCE FROM PRECURSORS OF CHONDRULES AND IGNEOUS CA,AL-RICH INCLUSIONS. Alexander N. Krot[1*], Kazuhide Nagashima[1], Guy Libourel[1,2], and Kelly E Miller[3]. [1]University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA. *sasha@higp.hawaii.edu. [2]Université Côte d’Azur, CNRS, 06304 Nice Cedex 4, France. [3]University of Arizona, Tucson, AZ 85721, USA.

Porphyritic chondrules are the dominant textural type of chondrules in most chondrite groups. The mineralogy, petrography, and oxygen-isotope compositions of porphyritic chondrules suggest their formation by melting (often incomplete) of isotopically diverse solid precursors during localized transient heating events in different dust-rich regions of the accretionary disk characterized by ^{16}O-poor average compositions of dust (Δ^{17}O ~ –5‰ to +3‰). The chondrule precursors included Ca,Al-rich inclusions (CAIs), amoeboid olivine aggregates (AOAs), chondrules of earlier generations, fine-grained matrix-like material, and, may be, fragments of pre-existing thermally processed planetesimals. Reprocessing of refractory inclusions during formation of porphyritic chondrules resulted in their melting to various degrees, destruction of Wark-Lovering rims, gas-melt interaction, replacement of melilite by Na-bearing plagioclase, oxygen-isotope exchange, and transformation into Type C-like igneous CAIs and anorthite-rich chondrules [1]. Whether chondrule precursors were completely anhydrous or partially hydrated is not known [2]. These observations preclude formation of porphyritic chondrules by splashing of differentiated asteroids. Instead, they are consistent with melting of dust-balls during localized nebular transient heating events in the protoplanetary disk (PPD), such as bow-shocks [3] short circuits [4], and collisions between chondritic planetesimals [5].

Like porphyritic chondrules, coarse-grained igneous CAIs formed by melting, often incomplete, of isotopically diverse solid precursors during localized transient heating events [6, 7]. In contrast to porphyritic chondrules, the precursors of igneous CAIs consisted exclusively of refractory inclusions of earlier generations ± ^{16}O-rich forsterite-rich dust, and the melting occurred predominantly in an ^{16}O-rich gas (Δ^{17}O ~ –24‰) of approximately solar composition, most likely near the protoSun [8]. The U-corrected Pb-Pb absolute and ^{26}Al-^{26}Mg relative chronologies of igneous CAIs [9–11] indicate that the CAI melting events started at the very beginning of the PPD evolution and appear to have lasted up to 0.3 Ma after condensation of CAI precursors, providing clear evidence for very early transient heating events capable of melting refractory dust-balls in the innermost part of the PPD. Melting of CAIs may have resulted from their ejection from the inner solar accretion disk via the centrifugal interaction between the solar magnetosphere and the inner disk rim [12]. There is no evidence that chondrules were among the precursors of igneous CAIs, consistent with an age gap between CAIs and chondrules [11].

In contrast to typical chondrites, the CB chondrites contain exclusively magnesian non-porphyritic chondrules with skeletal olivine (SO) and cryptocrystalline (CC) textures. These chondrules formed in an impact generated gas-melt plume about 5 Myr after CV CAIs, either in the late-stage accretionary disk or the debris disk [13, 14]. Bulk chemical compositions of CB chondrules and equilibrium thermodynamic calculations suggest that the collision involved differentiated bodies [15, 16]. However, the ^{15}N-rich bulk compositions of CB chondrites and the presence of CAIs in CB chondrites suggest that some amount of chondritic material must have been reprocessed in the plume as well. The uniformly ^{16}O-depleted igneous CB CAIs most likely formed by complete melting of pre-existing CAIs accompanied by gas-melt interaction in the plume [17]. Therefore, the uniformly ^{16}O-depleted igneous CB CAIs are chondrules formed by melting of precursors composed entirely of the CAI-like material.

CH chondrites represent a mixture of the CB-like material (magnesian SO and CC chondrules and uniformly ^{16}O-depleted igneous CAIs) and the typical chondritic material (magnesian, ferroan, and Al-rich porphyritic chondrules, uniformly ^{16}O-rich CAIs, and chondritic lithic clasts). We infer that CH chondrites contain multiple generations of chondrules formed by different mechanisms [1, 17].

Some relict CAIs inside CH porphyritic chondrules are texturally (igneous, spinel-rich) and isotopically (uniformly ^{16}O-depleted) similar to the CB-like CAIs, which are interpreted as a result of complete melting and oxygen-isotope exchange in the CB impact plume [1]. If this is the case, the CH porphyritic chondrules with the CB-like relict CAIs must have postdated the impact plume event. Formation of these chondrules by asteroidal impacts seems most likely. This mechanism may also be responsible for the formation of at least some chromite-rich chondrules in equilibrated ordinary chondrites [18], and sulfur-rich chondrules in unequilibrated Rumuruti chondrites [19].

We conclude that there are multiple mechanisms of transient heating events that operated during the accretionary and debris stages of the PPD evolution and resulted in formation of chondrules and igneous CAIs.

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PRELIMINARY RESULTS ON STUDYING OF METEORITES FROM GEOLOGICAL MUSEUM OF KAZAN UNIVERSITY BY X-RAY FLUORESCENCE AND COMPUTED X-RAY TOMOGRAPHY. D. M. Kuzina[1], D. K. Nurgaliev[1], B. I. Gareev[1], G. A. Batalin[1], V. V. Silantev[1], E. O. Statsenko. [1]Kazan (Volga Region) Federal University, Institute of Geology and Petroleum Technologies, Russia, Kazan, Kremlyevskaya street, 4. E-mail: di.kuzina@gmail.com

In this work we want to perform investigations of meteorites from geological museum of Kazan Federal University. Collection of museum includes different types of meteorites: chondrites, achondrites, stony-iron, iron etc.

Using non-destructive methods was performed for investigations almost all samples from museum collection. Particular attention was on studying of chondrules and iron-nickel alloys. The aim was to study elemental composition and distribution of this objects in the body of meteorite, their geometry, sizes and studying secondary alterations such as melting, diffusion etc.

For such investigations we used Micro X-ray Fluorescence method and X-ray computed tomography. For determining elemental composition was used polycapillary Micro X-ray Fluorescence spectrometer M4 Tornado (Bruker). Elemental mapping of the surface made almost for all meteorites from collection (which is valid size and have polish surface). Analysis conditions were chosen individually, depending on a sample. Maximum possible current is 600mkA, voltage – up to 50 kV, minimum size of X-ray point from 25 micron. Result of the measurements is elements distribution on the surface. Computed X-ray tomography was performed on Phoenix v|tome|x s (General Electrics). It is versatile high-resolution system for 3D computed tomography (CT) (micro ct and nano ct) . To allow high flexibility, the v|tome|x s is equipped with a 180 kV/15 W high-power nanofocus X-ray tube and a 240 kV/320 W microfocus tube.. Due to this unique combination, the CT system is a very effective and reliable tool for the studying inclusions in meteorites and looking into our samples. Best resolution that we can get for our samples is ~ 1 μm.

OVERLOOKED CHONDRULES: A HIGH RESOLUTION CATHODOLUMINESCENCE SURVEY. G. Libourel[1,3] and M. Portail[2], [1]Université Côte d'Azur, Observatoire de la Côte d'Azur, Lagrange, Nice, libou@oca.eu. Cedex 4, France, [2]Centre de Recherches sur l'Hétéro-Epitaxie et ses Applications, CRHEA-CNRS, Sophia Antipolis, [3]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu.

Chondrules, millimeter-sized igneous spherules making chondritic meteorites, formed during the Solar System's first few million years. They may provide powerful constraints on conditions in the solar protoplanetary disk only if the processes that led to their heating, melting and crystallization can be understood [1]. This problem remains unresolved yet, and the central question of whether the heating mechanism was an nebular or a planetary process is still debated. Tough heating by shock waves in the protoplanetary disk [2, 3] is currently one of the most favored mechanisms, chondrules generated by protoplanetary impacts is recently gaining interest [4].

Given the great diversity of chondrules, laboratory experiments are invaluable in i) yielding information on chondrule thermal history, and ii) judging a chondrule formation model viable or nonviable by their ability to meet these constraints. Experiments aimed at producing chondrule-like objects have moved from simply producing melt droplets, and then crystallizing them, to more complex scenarii by exploring melt-solid and melt-gas interaction [5, 6]. Owing to this approach, chondrule texture and chemistry, volatile element behavior (e.g., alkalis), oxygen isotope variations as well as chemical zoning profiles of olivine single crystals have provided some of the most crucial constraints on the thermal histories of chondrules, i.e., peak temperature, cooling rates, redox conditions and environment opacity, etc, that were then employed either as input or targeted parameters in astrophysical models of solar protoplanetary disk evolution [1-4].

Determining the main textural characteristic of chondrules together with the intimate structures of their constituting phases : olivine, pyroxene, metal, sulfide and glass, is therefore key to decipher the chondrule formation processes ; any mistinterpretations in these observations leading unavoidably to erroneous thermal histories and unreliable processes/scenarii for chondrule formation.

Cathodolumiscence theory, i.e., emission of photons after injection of high voltage electrons promotes valence electrons to conduction band, predicts that intrisic CL of minerals will be enhanced by defects and structural imperfections in the lattice and/or by substitutional or interstitial elements which distort the lattice. Few elements can perform the opposite role modifying the energy level arrangement so that the CL process does not operate or is diminished. These are "quenchers", with Fe^{2+} being the most common. As long as CL quenchers are low in concentrations, high resolution CL could be able to resolve very subtle changes of CL activators, which in turn should allow to resolve internal structures not seen by other techniques (including electron microscopy and both EDS or WDS X-ray imaging). In the more favorable cases, only a few ppm or tenth of ppb of an activator are enough for CL emission. The ferromagnesian silicates in Type I chondrules of unequilibrated chondrites exhibiting magnesian-rich compositions (mg# = Mg/(Mg + Fe >> 0.95) provide motivation for this high-resolution CL survey of chondrules. Both porphyritic and barred chondrules belonging to several representative carbonaceous and ordinary chondrite samples (CV, CR, CO and OC) have been surveyed for this study, using CL hyperspectral imaging acquired with high resolution CL facility mounted on FEG-SEM.

Comparison between back scattered electron (BSE) with our high resolution CL images of the same chondrules reveals unambiguously the quantum difference between these two observations. Our results show that CL panchromatic images and hyperspectral analyses on different types of chondrules of various chondrites reveal overlooked olivine internal structures at a hitherto unprecedented detail by resolving faint changes of CL activator concentrations of iron-poor olivines (e.g., Al^{3+}, Cr^{3+}, Mn^{2+}). These stunning features observed in all the studied magnesian chondrules so far tell a complex, but similar, record of dissolution and epitaxial growth episodes of olivines during chondrule formation events, at odds with classical and quiescent cooling history models inferred for chondrules. Implications of this finding on chondrule formation will be discussed.

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A THERMO-MECHANICAL 'GOLDILOCKS' REGIME FOR IMPACT SPLASH CHONDRULE FORMATION. T. Lichtenberg[1,2], G. J. Golabek[3], C. P. Dullemond[4], M. Schönbächler[5], T. V. Gerya[1], M. R. Meyer[2,6], [1]Institute of Geophysics, ETH Zürich, Sonneggstrasse 5, 8092 Zürich, Switzerland, [2]Institute for Astronomy, ETH Zürich, Wolfgang-Pauli-Strasse 27, 8093 Zürich, Switzerland, [3]Bayerisches Geoinstitut, University of Bayreuth, Universitätsstrasse 30, 95440 Bayreuth, Germany, [4]Institute for Theoretical Astrophysics, Heidelberg University, Albert-Ueberle-Strasse 2, 69120 Heidelberg, Germany, [5]Institute of Geochemistry and Petrology, ETH Zürich, Clausiusstrasse 25, 8092 Zürich, Switzerland, [6]Department of Astronomy, University of Michigan, 1085 S. University Avenue, Ann Arbor, MI 48109, USA.

Introduction: Still, a conclusive and astrophysically consistent chondrule formation scenario remains elusive. Major constraints include chemical, isotopic and textural features of chondrules, in particular retained metal abundances, bulk Fe/Mg ratios, porphyritic textures and the intra-chondrite chemical diversity. Here, we suggest a new coupled evolution-collision scenario where chondrules originate from the collision aftermath of low-mass planetesimals, which are only partially molten from aluminum-26 decay. The model is consistent with the vast majority of thermal and chemical constraints and invokes a diversity of pre-chondrule material compositions. The thermo-mechanical 'Goldilocks' regime favored in our scenario constrains the timing and formation conditions of the earliest planetesimal families and thus the onset of terrestrial planet formation.

Metal-silicate segregation constrains impact splash models: Asphaug and co-workers [1] revived collision models by suggesting that chondrules may originate from low-velocity impacts among fully molten planetesimals. In *Figure 1* we show, however, that the ubiquity of Fe-Ni metal rings/blebs [2] in the direct vicinity of chondrules and their chemical heterogeneity rule out excessively molten (and thus differentiated) planetesimals as chondrule precursors.

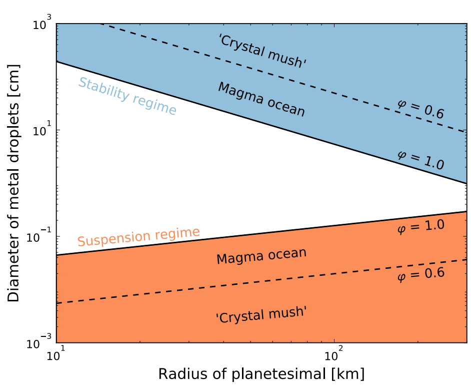

Figure 1: Metal droplets cannot be suspended in planetesimals with vigorously convecting magma oceans. The likely metal droplet sizes for various planetesimal radii and silicate melt fractions φ ['stability', 3] in a magma ocean is shown versus the droplet sizes which can be suspended in liquid magma by convection ('suspension').

Mutual collisions between radiogenically preheated, but undifferentiated, planetesimals: Planetesimals of preferentially low-mass, however, were significantly pre-heated but did not differentiate extensively (*Figure 2*). They allow chondrule formation from subsonic (~1 km/s) impacts, which are chemically, isotopically and texturally consistent with observations, and fit well to recent dynamical models of planet formation [5, 6].

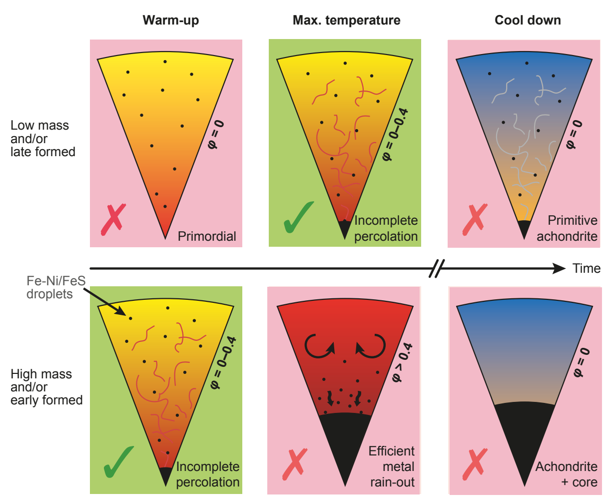

Figure 2: Suggested 'Goldilocks' regime for chondrule precursor planetesimals (green). Red scenarios are either chemically, texturally or isotopically inconsistent with laboratory measurements [2, 7] or dynamical models [1, 2, 5].

Repeated collisional recycling in separate annuli: If different parent bodies accreted from isolated feeding zones without mutual mixing, chondrule-matrix complementarity [2] and distinct nucleosynthetic anomalies in individual chondrules can be retained.

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REDOX CONDITIONS DURING CV CHONDRULE FORMATION. Yves Marrocchi[1], [1]CRPG-CNRS, 15 rue Notre Dame des Pauvres, 54500 Vandoeuvre-lès-Nancy, yvesm@crpg.cnrs-nancy.fr.

Introduction: Chondrules are submillimeter silicate spherules that constitute up to 80% by volume of primitive meteorites. Although the mineralogy, petrography, bulk chemical and isotopic compositions of chondrules are well-documented, the nature of the chondrule-forming events remain enigmatic. One of the main open questions is the redox conditions at which chondrules formed, because the reduced conditions (i.e., oxygen-poor) estimated for the accretion disk are difficult to reconcile with the chemical observations in chondrules. Especially, CV chondrules are characterized by the presence of spindle-shaped fayalitic halos occuring in forsterites. Such halos likely result of the oxidation of olivine-enclosed Fe-Ni metal beads prior to their incorporation in their parent body(ies) [1]. I will present new results suggesting that fayalitic halos and Fe^{3+}-bearing minerals (e.g.., magnetite) are contemporaneous of the chondrule-forming event.

Results: I report a petrographic and isotopic survey of FeS- and magnetite-bearing chondrules in the CV3 chondrites Kaba and Vigarano. FeS are mainly located within the low-Ca pyroxene outer zone and their amount increases with the abundance of low-Ca pyroxene within chondrules [2]. The magmatic FeS commonly occurs in close association with Cr-poor magnetite within Fe-Ni metal-free structures that present liquid-shaped textures. These characteristics suggest that magnetite are high-temperature products resulting from the crystallization of FeSO melts [3].

Discussion: FeS associated to magnetite present homogeneous S- isotopic compositions ($\delta^{34}S = \delta^{33}S \approx 0‰$). Magnetites show O-isotopic compositions that define a linear array with a slope of 0.94 with no hint for mass fractionation, contrary to what could be expected in case of aqueous alteration processes. Hence, isotopic compositions of FeS-Fe_3O_4 assemblages are in line with magnetite being high temperature magmatic minerals. According to phase diagrams, forming FeSO melts in chondrules can only be achieved under oxidizing conditions (IW+1/IW+2), suggesting that chondrules interacted with an oxidizing gas likely generated by impact between planetesimals. Such oxidizing conditions would also produce the fayalitic halos commonly observed in CV chondrules.

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ORDINARY CHONDRITE CHONDRULES: OXYGEN ISOTOPE VARIATIONS.

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Introduction: Chondrules from ordinary chondrites (OCs) plot above the terrestrial fractionation line in the oxygen 3-isotope diagram, falling along a correlation line [e.g. 1-3]. This line with a slope between 0.63 and 0.77 for unequilibrated OCs [2-4] can be interpreted as a mixing line between ^{16}O-rich chondrule material and a ^{16}O-poor component, e.g. nebular gas [e.g. 5]. It is argued by [7-8] that exchange reactions with ^{16}O-poor fluids on the parent body can also explain the above correlation. It was shown by [6,8] that LL3 chondrule mesostasis is usually enriched in heavy oxygen compared to co-crystallized olivine and pyroxene. This indicates that chondrule mesostasis was altered to some extent on the parent body, leading to an increase of ^{17,18}O. Although this alteration may have somewhat modified the original mixing line, it cannot be the general reason for its slope and extension. Most reported mesostasis δ^{18}O values are between 3 and 10‰, i.e. just in the range of bulk LL3 chondrule values (4-9‰ [3]) and hence cannot have shifted original bulk chondrule values considerably. Although some mesostasis δ^{18}O values are as high as 17‰ [6], mass balance considerations reveal that the influence of such enhanced δ^{18}O values on bulk chondrule values should be small, since the modal amount of mesostasis rarely exceeds 15 vol%.

A systematic dependence of oxygen isotopic composition on chondrule size was described by several authors. A <u>negative</u> size vs. δ^{18}O correlation was observed in the LL3.4 chondrite Chainpur by [7] and in a cluster chondrite clast from NWA 5205 (LL3.7) [3], but not in Parnallee (LL3.6) [9] or Bo Xian (LL3.9) [10]. The variation in Chainpur might reflect a more extensive exchange of smaller chondrules with surrounding ^{17,18}O-rich material due to their larger surface/volume ratio [7]. If this interpretation is right, this exchange should have occurred when chondrules where molten, since parent body processes probably influenced the oxygen isotopy of bulk chondrules only marginally (see above). On the contrary, a <u>positive</u> size vs. δ^{18}O correlation was observed in the H chondrites Dhajala (H3.8) and Weston (H4) [5]. No correlation at all between size and δ^{18}O was found by [11] in a set of size-sorted chondrules from Tieschitz (H/L3.6).

Samples and analytical methods: To further investigate this unexpected relationships between size and O-isotopic composition, we separated 49 chondrules from 4 different OCs (H, L, L/LL, LL) [12]. The investigated samples are (number/size range of chondrules): NWA 2465 H4 (13/0.5-2.9 mm); Saratov L4 (12/0.4-2.3 mm); Bjurböle L/LL4 (11/0.4-2.4 mm); NWA 7545 LL4 (13/0.4-2.9 mm). All chondrules were documented by micro-computed tomography (µ-CT). Their bulk oxygen isotopic compositions were measured by IR laser fluorination. Oxygen isotope values for their host meteorites were obtained by the same method.

Results: As expected, chondrules from the investigated OCs plot along mixing lines in the oxygen 3-isotope diagram with variable positive slopes. Although our bulk oxygen isotope data for Bjurböle and Saratov are indistinguishable within errors from literature values [5], the investigated chondrules from all 4 samples show higher δ^{18}O values than their bulk meteorites. A similar observation for H chondrites was already described in [5]. Either the majority of the small (< 500 µm) non-analyzed chondrules and/or interchondrule matrix should represent the complementary component to yield the comparatively low δ^{18}O values of the bulk meteorites.

In case of the investigated L4, L/LL4, and LL4 samples we could not observe any distinct correlation between chondrule size and oxygen isotopic composition. However, the H4 chondrite shows a well-defined positive correlation, confirming similar observations on other H chondrites [5].

Conclusions: If the OC chondrules mixing line in the oxygen 3-isotope diagram formed by the interaction of chondrule melts and their nebular surroundings, and if the observed size vs. δ^{18}O correlations reflect more severe reactions of small chondrules during this process, then chondrules from LL chondrites [e.g. 3] and H chondrites exchanged with very different oxygen isotope reservoirs. In this case the H-reservoir was distinctly more ^{16}O-rich compared to that of LL chondrites [12]. The difference in δ^{18}O values between large (~2mm) chondrules from the LL chondrite NWA 5205 [3] and the H4 chondrite NWA 2465 is large (~4‰; δ^{18}O: ~6‰ vs. ~10‰). This indicates that chondrules from the various OC chemical groups cannot stem from a common chondrule reservoir.

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ATMOSPHERIC ENTRY OF CARBONATE MICROMETEOROIDS G. Micca Longo[1] and S. Longo[2], [1]Dipartimento di Chimica, Università degli studi di Bari Aldo Moro, Via Orabona 4, I-70126 Bari (Italy) (gaia.miccalongo@uniba.it), [2]Dipartimento di Chimica, Università degli studi di Bari Aldo Moro, Via Orabona 4, I-70126 Bari (Italy) & CNR-Nanotec Bari Section, Via Amendola 122/D, I-70126 Bari (Italy) (savino.longo@nanotec.cnr.it).

Introduction: Micrometeoroids have similarities in chemistry and mineralogy to the CI, CM and CR chondrites [1], suggesting that they are very primitive materials in the Solar System. But most micrometeoroids experience atmospheric entry heating that changes primary mineralogy. Actually, [2] reported the discovery of eight micrometeorites containing chondritic igneous objects, which indicates that at least a portion of coarse-grained crystalline micrometeorites represent chondrule fragments. This suggests that the parent bodies of micrometeorites resemble the parent asteroids of chondrulebearing carbonaceous chondrites. Relative volatile components present in these samples are specially interesting in the discussion of origin and diffusion of life and complex organic chemistry in the Solar systems. Among these, inorganic carbonates play a very important role when meteor matter is considered in an astrochemical context [3–7]: the knowledge of their physical and compositional properties and of their survival during atmospheric entry may provide information about the presence of organic matter in their parent bodies (comets, asteroids, interplanetary dust). Indeed, carbonates are often associated with the presence of organic matter [8–10], so, in this perspective, they could be one of the keys to understand the complex chemistry of the Solar System [11]. $(Mg,Fe)CO_3$ (the carbonate analogue of the Forsterite-Fayalite series) is common among phyllosilicate-rich micrometeorites and CI chondrites and has been reported as well in micrometeorites [12]. Carbonates of II group elements (in particular aragonite and calcite) have been detected spectroscopically in cometary grain in close association to complex organic molecules [13]. In [14], the facile decomposition of magnesium carbonate has been advocated as a possible cooling mechanism during delivery scenarios of organic matter to primordial Earth.

In spite of this state of the art, there has been little attention to the thermal properties of carbonate minerals in the context of meteoritic studies, in particular to assess their behavior when grains rich in carbonates enter Earth's atmosphere. It is true that the thermal decomposition of carbonates is poorly characterized from a kinetic point of view [15-17]. While this difficulty is hardly overemphasized, times are mature to start a rigorous theoretical study of the behavior of pure and mixed carbonates in atmospheric entry scenarios, in order to gather the essential information on which future evaluations will be grounded.

A preliminary work for a specific material (pure magnesite), based on a rigorous dynamic and thermal model of the grain entry, is presented and a first-attempt model of the decomposition kinetics is proposed. Pure magnesite ($MgCO_3$) is proposed as a mineral model. A dynamic-kinetic model has been developed, very close to that reported on [18] although improved in some minor details, and used as a standard description of the entry process in order to evaluate the effects to carbonate evaporation kinetics.

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NON DESTRUCTIVE METHOD FOR BULK CHEMICAL CHARACTERIZATION OF BARRED OLIVINE CHONDRULES . M. A. Montoya[1], K. E. Cervantes-de la Cruz[2] and J. L. Ruvalcaba-Sil[3] [1]Facultad de Ciencias, Universidad Nacional Autonoma de Mexico, UNAM (karina-cervantes@ciencias.unam.mx), [2]Instituto de Ciencias Nucleares, UNAM, [3]Instituto de Fisica, UNAM.

Introduction: Ever since asteroids were discovered, they've been seen as remains of planetary formation [1], because they registered the processes that occurred in the origin of the Solar System in the same way that Earth's history is studied from geological registry. Chondrites represent unique study objects because the materials conserved in them were formed during the early stages of the Solar System [2]. The purpose of this work is to develop a bulk chemical characterization of 11 barred olivine chondrules in four Allende chondrite thin sections based on the X-ray fluorescence (XRF) analysis using the SANDRA portable equipment [3] at the National Research and Conservation Science Laboratory of Cultural Heritage (LANCIC-IF) in Mexico City.

Procedure: The SANDRA portable equipment was run at a voltage of 35 kV and a current of 0.3 mA. No vacuum was used. Each chondrule in the thin sections was scanned three times using a 500 μm diameter X-ray beam for 120 seconds.

The raw spectra were then transferred to the AXIL software. Using AXIL, the area under the peak was calculated. We calculated the average of the areas to find one value per element per sample.

To build a standard. We selected one of the chondrules with a matrix/olivine proportion that was average to the chondrule's sample. Punctual analysis with Electron Micro Probe Analyzer (EMPA) in matrix and olivine of the selected chondrule used to create a standard.

We calculate the elemental composition of all chondrules comparing the X-ray spectrum of the standard with spectrum of each one of them.

We distinguish the total iron in kamacite (FeNi) from the iron in troilite (FeS) and ferrous oxide (FeO) using the percent in weight to Ni and S. We calculated the magnesian oxide (MgO) percent wight in the same way.

Results: We estimated magnesium number (#Mg) for each chondrule with their MgO and FeO concentrations (Table 1). These values range from 80.2 to 94.8, very close to values of 93.0 [4] and 94.8 [5] previously reported. These values represent a poorly evolved olivine.

Final Thoughts:

Basic analysis with SANDRA portable equipment allowed to measure magnesium values very close to the ones reported before. Deeper future analysis may solve the variations showed in some calculations in this work.

Table 1. Magnesium number of each chondrule.

Sample	FeO (%Wt)	MgO (%Wt)	#Mg
Standard	3.984	36.219	90.09
C.BO.A*			93.0
C.BO.A**			94.8
Chondrule 1	3.308	61.336	94.88
Chondrule 2	4.039	38.403	90.48
Chondrule 3	4.622	62.064	93.07
Chondrule 4	3.475	97.919	96.57
Chondrule 5	4.409	29.849	87.13
Chondrule 6	3.625	68.252	94.96
Chondrule 7	5.864	23.843	80.26
Chondrule 8	3.984	36.219	90.09
Chondrule 9	4.068	60.608	93.71
Chondrule 10	4.524	75.532	94.35
Chondrule 11	4.032	70.436	94.58

#Mg = 100 x (MgO / MgO + FeO).

C.BO.A* : #Mg values calculated for Allende's barred olivine chondrules by Simon and Haggerty [4].

C.BO.A**: #Mg values calculated for Allende's barred olivine chondrules by Rubin and Wasson [5].

Even though this technique cannot yet substitute more advanced ones, it will be a quick and simple non invasive way to analyze the chemical bulk composition. Therefore, this technique represents an excellent opportunity to the study and conservation of very important materials in the meteorite field and planetary sciences.

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FORMATION OF CHONDRULES BY SHOCK WAVES. M. A. Morris[1,2] and A. C. Boley[3], [1]SUNY Cortland, P.O. Box 2000, Cortland, NY 13045-0900, melissa.morris@cortland.edu, [2]School of Earth and Space Exploration, Arizona State University, P.O. Box 871404, Tempe, AZ 85287-1404, melissa.a.morris@asu.edu, [3]University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, acboley@phas.ubc.ca.

Introduction: Understanding the "chondrule-formation mechanism" has been an elusive task for over a century [1]. Proposed formation mechanisms include lightning, interactions with the young sun, planetesimal impacts, and nebular shocks [2-5]. Among these, the heating of chondrule precursors in nebular shocks is one of the most fully developed and rigorous models for chondrule formation and is the most consistent with the meteoritic record [6], although some questions certainly remain.

Shock mechanisms: There are several possible mechanisms for driving shocks in the solar nebula, including gravitational disk instabilities, X-ray flares or accretion shocks, and bow shocks around planetesimals or protoplanets on eccentric orbits [7-10]. X-ray flares and accretion shocks have largely been eliminated as a possibile driver for chondrule-forming shocks, because these would take place at the surface of the disk, whereas chondrule precursors are expected to have settled to the midplane.

Gravitational Instabilities (GIs). Spiral asymmetries arising from disk instabilities can spontaneously form in massive protoplanetary disks when the magnitude of the disk's self-gravity is comparable to or greater than the vertical gravity (measured at the disk scale height) due to the central star [11]. These types of instabilities almost certainly occurred in the early solar nebula [12], driving strong shocks where high-density gas in the asymmetries collided with lower density gas. Such structure has recently been observed by ALMA in the disk around the young star Elias 2-27 [13].

Bow Shocks. Planetesimals/protoplanets on eccentric orbits while gas is present in the disk will induce bow shocks. At 2.5 AU, within the presumed chondrule-forming region, gas orbits the Sun at the Keplerian velocity of $v_K \sim 20$ km/s. A planetary body with eccentricity e will have phases of speeds relative to the gas of $\sim e\, v_K$. Planetesimals in resonance with a proto-Jupiter will have had eccentricities as high as $e \sim 0.3$-0.5 [9], driving strong bow shocks (~ 8 km/s).

Both GI-driven shocks and bow shocks have been shown to be consistent with the inferred range of thermal histories of porphyritic chondrules, with cooling rates at the low and high end respectively [5-6, 14].

Meteoritic Constraints: We discuss the wealth of meteoritic observations that constrain chondrule formation in general, and compare these to the results found through modeling of chondrule formation in nebular shocks. We discuss in particular the inferred thermal histories of chondrules [15] and their retention of volatiles [16], including recent studies that question the long-accepted thermal histories [17-18].

Discussion: We assess current shock models for chondrule formation and discuss what further work is needed. Models of large scale shocks, such as those driven by GIs, are most consistent with the cooling rates of chondrules, but have yet to be modeled with the high densities of solids thought to be necessary for volatile retention, and have not accounted for vertical energy losses. Bow shocks occur in an environment conducive to volatile retention, but cooling rates are at the very upper end of (or above) the range of the inferred thermal histories of chondrules. Finally, as both GI-driven shocks and bow shocks could have occurred in the solar nebula, we discuss predictions made by shock models and challenge the meteoritical community to examine available samples to test these predictions.

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^{26}Al-^{26}Mg systematics of chondrules: Progresses and issues from the last 5 years. K. Nagashima[1], N. T. Kita[2], and T.-H. Luu[3], [1]Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA (kazu@higp.hawaii.edu), [2]Department of Geoscience, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA, [3]School of Earth Sciences, University of Bristol, BS8 1RJ, UK.

Introduction: The short-lived radionuclide decay system ^{26}Al-^{26}Mg (half-life ~0.7 Myr) has been considered to be a high precision chronometer to date processes in the protoplanetary disk. Since the first report of excesses of ^{26}Mg due to *in situ* decay of ^{26}Al in a chondrule [1], ^{26}Al-^{26}Mg chronometer have been applied to chondrules from several chondrite groups. If their initial ^{26}Al/^{27}Al ratios ((^{26}Al/^{27}Al)$_0$) represent the timing of their formation, ^{26}Al ages of chondrules provide important cosmochemical constraints such as lifetime of the protoplanetary disk, chondrule-forming processes, and chondrite accretion processes. The ^{26}Al-^{26}Mg systematics of chondrules and implications to the evolution of protoplanetary disk have been summarized based on the data obtained before 2012 [2]. This abstract serves as a summary for the recent progresses and issues on ^{26}Al-^{26}Mg systematics of chondrules from the last 5 years.

^{26}Al abundances in chondrules inferred from internal isochrons: The (^{26}Al/^{27}Al)$_0$ in chondrules from three ordinary and carbonaceous chondrite groups (LL3.0, CO3.0, and Acfer 094 ungrouped C3) are ~6-7×10^{-6} [2]. Since then, reliable (^{26}Al/^{27}Al)$_0$ have been obtained for chondrules from CR2-3 [3-5], CH3 [6], and CV3.1 [7]. The (^{26}Al/^{27}Al)$_0$ from CR2-3 and CH3 chondrules are distinctly different from those in LL3.0 and CO3.0. While a few chondrules have (^{26}Al/^{27}Al)$_0$ of ~6×10^{-6}, most of them are systematically lower than 3×10^{-6}. The (^{26}Al/^{27}Al)$_0$ of chondrules in Kaba (CV3.1) have (4.8±1.1)×10^{-6}, similar to/slightly lower than those of LL3.0 and CO3.0. The (^{26}Al/^{27}Al)$_0$ of the chondrules from the chondrite groups decrease in the order of LL ~ CO ~ Acfer 094 ≥ CV ≥ CR ~ CH. In addition, each chondrite group may have multiple populations of chondrules [4].

^{26}Al abundances for chondrule precursors inferred from bulk chondrules: The model (^{26}Al/^{27}Al) ratios of chondrule “precursors” have been estimated from bulk chondrules ^{26}Al-^{26}Mg isotope analyses that range from ~5×10^{-5} to ~1×10^{-5} [8,9]. Luu et al. [9] suggested the minimum value (1.2×10^{-5}) corresponds to the time that formation of the precursors stopped or were separated from a nebular reservoir. The difference of (^{26}Al/^{27}Al)$_0$ between the bulk and *in situ* data may correspond to a time difference between the precursor formation and the last melting of chondrules.

Homogeneous/heterogeneous distribution of ^{26}Al in the disk: To convert (^{26}Al/^{27}Al)$_0$ values to relative ^{26}Al ages, we have to assume that ^{26}Al/^{27}Al was homogeneously distributed throughout the disk. This assumption has been challenged and is highly controversial. Recent studies on multiple chronometers (^{26}Al-^{26}Mg, ^{182}Hf-^{182}W, ^{206}Pb-^{207}Pb) of CAIs, chondrules and achondrites suggest consistent relative ages that support the homogeneous distribution of ^{26}Al throughout the disk and its chronological significance. For example, the Allende CV3 chondrule ages determined from ^{182}Hf-^{182}W systematics (2.2±0.8 Myr after CV CAIs [10]) and U-corrected Pb-Pb age (1.8±0.9 Myr after CV CAIs [11]) are in good agreement with 2.5 (-0.4/+0.7) Myr obtained from the (^{26}Al/^{27}Al)$_0$ of Kaba CV3 chondrules [7]. In contrast these are largely inconsistent with the old Pb-Pb ages of Allende chondrules [12], that might be due to the Pb-Pb ages compromised by the common Pb [13].

On the other hand, the Al-Mg and U-corrected Pb-Pb ages of volcanic angrites determined by Schiller et al. (2015) indicate ^{26}Al-^{26}Mg and ^{207}Pb-^{206}Pb ages compared to CV CAIs are inconsistent by ~1.5 Myr. The U-corrected Pb-Pb ages of individual chondrules range from 0 to ~3-4 Myr after CAIs, and their (^{26}Al/^{27}Al)$_0$ are much lower than those expected from their Pb-Pb ages, supporting the reduced abundance of ^{26}Al in the disk regions where chondrules originated [12,14].

Because of this controversy, it is not clear what the differences in (^{26}Al/^{27}Al)$_0$ among and within chondrite groups represent: spatial heterogeneity of ^{26}Al abundances in chondrule-forming region(s) and/or reflect multiple generations of chondrules formed at different times.

Implication for thermal history of parent asteroids: Despite the possibility of heterogeneous distribution of ^{26}Al in the disk, the (^{26}Al/^{27}Al)$_0$ recorded in chondrules potentially provide an upper limit on ^{26}Al abundances available as a heat source of their parent asteroids due to decay of ^{26}Al. The inferred (^{26}Al/^{27}Al)$_0$ of chondrules are similar to/slightly higher than those indicared from thermal modeling of their parent asteroids [15], suggesting rapid accretion of chondrules into their parent bodies after their formation. The (^{26}Al/^{27}Al)$_0$ in the Kaba chondrules is too low to melt a CV parent asteroid [7] and contradicts the existence of a molten core (e.g., [16]).

We will present more details at the workshop and in a chapter of the forthcoming book.

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IN-SITU ^{26}Al-^{26}Mg MINERAL ISOCHRON DATING OF CHONDRULES BY SIMS: SAMPLES, MEASUREMENT PROCEDURE AND DATA CORRECTION.
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Introduction: In-situ Mg isotope measurements of mineral and mesostasis phases in unequilibrated chondrules provide important information on chondrule formation and potentially allow to determine the crystallization ages of individual chondrules using the decay of the short-lived ^{26}Al ($t_{1/2}$ = 0.717 My) to ^{26}Mg. Previously published data point to chondrule formation from c. 0.5 to 3.5 My after CAIs [e.g. 1, 2]. The comparison of datasets derived from different laboratories within the last decates, however, is not straightforward due to varying analytical setups and individual approaches of data correction to account for instrumental and natural mass fractionation. Here we present our set up which aims to extend the already existing data set of chondrule ages by internally consistent high-precision Mg isotope measurements for a comprehensive suite of chondrules from carbonaceous and ordinary chondrites. Key questions of chondrule formation that will be addresses are: Are all chondrules in one meteorite class identical or do they show a spread in ages? Are there systematic age differences among different chondrule types?

Samples: The set of samples selected for this study comprises some of the least metamorphosed carbonaceous as well as ordinary chondrites (NWA 779 (CV3), NWA 8276 (L3.00)) some of which were requested from and kindly provided by NASA from their collection of Antarctic Meteorites for this project (MET 00452 (L(LL)3.05), MET 96503 (L3.10), QUE 97008 (L3.05), MET 00526 (L(LL)3.05), DOM 08006 (CO3)).

Methods: Samples are measured using the Cameca IMS 1280-HR large radius secondary ion microprobe at the SwissSIMS laboratory, University of Lausanne. Primary minerals yielding high Al/Mg ratios (e.g. feldspar) are relatively rare and tiny in chondrules whereas suitably sized glassy mesostasis is more commonly found but tend to have lower Al/Mg ratios. To derive age information from a high number of chondrules applying the identical analytical procedure and thus minimizing methodological bias on the results, we decided to set up a routine for Mg isotope measurements in mesostasis following in parts previously published analytical protocols [3, 4]. To achieve high precision on the isotopic ratios even for the mesostasis the samples are sputtered with a high primary beam intensity (13 kV, O^-) of about 28 nA, resulting in $>10^9$ cps for ^{24}Mg in olivine (Mg#90) with a typical beam size <40 µm. Internal errors on δ^{25}Mg due to counting statistic are between 0.02 and 0.06‰ (2 s.e.).

To derive accurate and precise isochrons, especially from low Al/Mg material, precise correction for instrumental mass fractionation (IMF) of Mg isotopes during SIMS analysis becomes critical. Here we report the procedure we apply to correct for IMF using instrumental mass fractionation laws determined during each session measuring a set of terrestrial reference materials, and discuss the aspect of natural mass fractionation correction.

First Results: After correction for mass fractionation 40 measurements on 6 different terrestrial standards (olivine and pyroxene of different composition, synthetic and natural glass standards) measured during one session show no excess or deficit ^{26}Mg with an average $\delta^{26}Mg^*$ (i.e. radiogenic ^{26}Mg/^{24}Mg) of -0.002 (±0.009, (2 s.e.))‰, consistent with their terrestrial origin. First measurements in chondrules reveal resolvable radiogenic ^{26}Mg for most samples and well defined isochrons resulting in $(^{26}Al/^{27}Al)_0$ ranging from 7.38 (±0.35) $*\ 10^{-6}$ to 1.93 (±0.76) $*\ 10^{-5}$.

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THE CARBON PARTICIPATION IN THE CRYSTAL-CHEMISTRY FORMATION OF THE PORPHYRITIC CHONDRULES.

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Introduction: The properties of chondritic compounds offers knowledge about 1) local density of solid matter at the time of formation of the chondrules, 2) the average number of events experienced by rapid heating chondrules and 3) physic-chemical conditions existing during the early stage of pre-chondritic matter formation and chondrules. On the other hand, Carbon is one of most fundamental and abundant elements in the solar nebula and main constituents of carbonaceous Chondrites and is the form of disordered graphite in the interstitial spaces between chondrules [1]. In this work, it will be emphasized in the porphyrytic chondrules of olivine (Forsterite, Mg_2SiO_4), because such silicate mineral phase is the first to condense from the cooling gas in the solar nebula [2].

Physical and Chemical Properties of Precursors. As precursor material we used olivine Mg-rich with grain measurements of 212, 250 and 300 µm, anorthite (An. No. 100), and graphite with a high degree of purity. We applied theses silicates in three combinations 1) Olivine-Graphite, 2) Olivine-anorthite, 3) Olivine-graphite-anorthite and 4) Olivine standard. In amounts of 1.3-1.8 mg for olivine, graphite and 1.7-2 mg 0.01-0.05 mg of anorthite.

Conditions of the fusion environment: The silicate minerals and graphite were subjected at ambient pressure (0 atm), using a CO_2 laser with an emissivity of 85 and 90% power and 85%. While times were alternated between 8/7 they 9/8 and where the total times of the melting plateau were 8 and 7 minutes.

Samples and Techniques: Were applied to the obtained fused masses, Scanning Electron Microscope, Raman Spectroscopy and Infrared Spectroscopy. The set of results obtained allow to observe and determine the crystallography and chemistry of carbon participation in the petrogenetic composition porphyritic chondrules of MgO-rich.

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MULTIPLE INDICATORS FOR MULTIPLE MELTING OF CHONDRULES. Alan E. Rubin[1,2], [1]Department of Earth, Planetary, and Space Sciences, [2]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA. (aerubin@ucla.edu)

Introduction: Many workers maintain that most chondrules crystallized after a single melting event. However, petrographic and experimental constraints show that most chondrules were melted multiple times.

1. Relict grains: These include "dusty" ferroan olivines in Type-I chondrules [1] and low-FeO olivines in ferroan olivine grains in Type-II chondrules [2,3]; many low-FeO grains are ^{16}O rich [4-6], resembling grains in Type-I chondrules [4,5]. Relicts occur in ≥15% of OC & >90% of CO Type-II chondrules [3,7].

2. Olivine shards: Many Type-II CO3 chondrules have small olivine shards with acute internal angles; these appear to be fragments of prior chondrules [3].

3. Small FeO-rich olivines: Some Type-II CO3 chondrules have ~10-µm olivines with central Fa values much higher than those in the centers of large olivine grains (e.g., Fa_{47} vs. Fa_{26}) [3]. Both sets of grains are normally zoned with similarly ferroan edges; they could not have crystallized at the same time.

4. Dynamic crystallization experiments: Normal porphyritic textures were produced only in those experiments with precursor nuclei ≥40 µm [8], suggesting that relatively coarse relicts (and more than one heating event) are required for forming porphyritic textures.

5. Overgrowths on relict olivines: A Type-II chondrule in Semarkona contains relict olivines with many small blebs of low-Ni metal formed by reduction of FeO; these grains are flanked by 3-5-µm-thick low-FeO overgrowths formed after remelting [9]. Numerous Type-II CO3 chondrules have small relict low-FeO olivines with 2-12-µm-thick high-FeO overgrowths [3].

6. Pyroxene overgrowths: In some Type-II LL3 chondrules, low-Ca pyx grains show multiple overgrowth layers apparently produced by secondary melting [10]. After initial melting produced the original spheroidal chondrule, minor reheating events melted only mesostasis. The first low-Ca pyx overgrowth that forms after reheating has low Ca and Fe; these cations gradually increase in concentration until cooling halts diffusion. The next melting event remelts and mixes local mesostasis; a normal igneously zoned layer subsequently forms. This process is repeated several times.

7. Trapped chromite within olivine: A coarse ferroan olivine grain in a Type-II CO3 chondrule contains small chromites (similar to those in the mesostasis) located ~5 µm from the olivine grain edge. This suggests that, after the final reheating event, a 5-µm-thick olivine overgrowth layer trapped the chromites [3].

8. Overgrowths in FeO-rich olivines: P X-ray maps reveal that many Type-II LL3 and CO3 chondrules have multiple sets of thin P-poor/P-rich olivine layers that appear to be overgrowths formed during secondary heating [11]. These layers are generally not evident in Fe, Cr, Ca or Al X-ray maps because rapid diffusion of these cations during reheating smoothed out the overgrowths, mimicking normal zoning.

9. Very large phenocrysts: About 20% of PO CO3 chondrules contain large phenocrysts that constitute 40-90 vol.% of their chondrules [12]. These are likely relicts that acquired small amounts of dust and debris that melted during later chondrule heating.

10. Microchondrules in chondrule rims: Numerous microchondrules occurring within fine-grained rims around Type-I chondrules formed by partly melting pyroxene grains at the chondrule edge [13].

11. Igneous rims: These rims surround ~10% of OC and ~50% of CV chondrules. They have igneous textures and formed by melting finer-grained rims around pre-existing primary chondrules.

12. Enveloping compound chondrules: These commonly consist of a primary chondrule surrounded by a secondary chondrule spherical shell. The shell formed by a later melting event.

13. Nested BO chondrules: A Semarkona chondrule consists of a primary BO chondrule surrounded by three nested BO layers, each containing olivine bars, mesostasis and small metal blebs [14].

14. Non-spherical chondrules: Most Type-I CO3 chondrules are multi-lobate or irregular objects with rounded margins. If they had been totally molten, they would have collapsed into spheres far faster than their ~20-µm-size olivines could have grown. They are likely chondrule fragments rounded during remelting [15].

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ON MAKING CHONDRULES FROM MOLTEN PLANETESIMALS I. S. Sanders, Dept. of Geology, Trinity College, Dublin 2, Ireland (isanders@tcd.ie)

Introduction: This contribution is an update of the review by [1] of the splashing model for chondrule formation proposed by Zook [2]. The model contends that at least some, perhaps most, chondrules are frozen droplets of spray from impact plumes launched when thin-shelled planetesimals with fully molten interiors collided and merged at low speed. This idea is appealing because it seems to concur with much of what is known of the young protoplanetary disk. For example, it is probably no coincidence that during the first 2-3 Myr, while chondrules were being made, the disk was populated with molten planetesimals, probably melted by the decay of ^{26}Al, ready to burst open and spill their incandescent contents into space. The model provides ample energy for melting, and it circumvents the need for a special 'nebular' heat source because it does not invoke dust-clump precursors. It accounts for the retention of Na and FeO in crystallizing chondrule liquids because the droplets would have been very closely spaced in the early stages of plume expansion. Also other examples of frozen droplets in nature are interpreted as spray from large melt volumes, and never as melted dust clumps. However, the splashing model has its detractors and since 2012 the following arguments have been leveled against it.

Chronology: Pb-Pb dating by Connelly et al. [3] showed that some chondrules formed contemporaneously with CAIs. On the face of it this rules out splashing because planetesimals need time to melt. However, within the limits of quoted errors there would have been time for total internal melting to occur.

Melt composition: Johnson et al. [4] proposed that chondrules were formed by high-speed impact melting and jetting of primitive near-surface materials on colliding bodies. They claimed that low-speed disruption of molten bodies would have yielded fractionated chondrule compositions. The claim is unfounded because the splashing model invokes totally or near-totally molten planetesimal interiors which would have meant primitive magma chemistry.

Relict grains: Nagashima et al. [5] noted that the ubiquitous presence in Kakangari of relict ^{16}O-rich grains in chondrules suggests that they formed from precursor materials that had diverse O-isotope compositions. They felt this was inconsistent with formation of chondrules by splashing. However, the impact plume in the splashing model could plausibly have been contaminated with abundant ^{16}O-rich dust grains from the cool carapace of one or both colliding bodies. These dust grains could have become engulfed by the molten droplets they encountered, making them xenocrysts rather than 'relict grains'.

Complementarity: Palme et al. [6] noted that in CV chondrites the matrix typically has much higher Fe/Mg and Si/Mg than the bulk rock, which is solar, and chondrules have ratios lower than solar. They felt that this chemical 'complementarity' was inconsistent with the splashing model because it hints that chondrules and matrix were made together from a single reservoir prior to accretion. Complementarity is clearly an important constraint on chondrule formation, but an accepted mechanism for its origin is still awaited.

Complementarity in nucleosynthetic anomalies: Budde et al. [7] have extended the work of [6] by showing that bulk CVs have normal isotopic ratios for tungsten and molybdenum, yet chondrules and matrix carry complementary depletions and excesses, respectively, in s-process nuclides. This remarkable discovery is hard to reconcile with splashing because chondrules from a molten planetesimal would be expected to have the same uniform isotopic ratios as those in all differentiated meteorites. Also the chondrules are variably depleted in the s-process carrier, yet with splashing more uniform depletion might be expected.

Discussion: The splashing model can be reconciled with so many chondrule-forming constraints that the claim that it cannot explain complementarity needs careful scrutiny. A problem is that the dynamics of plume evolution and the state of the molten planetesimal interiors prior to splashing are poorly understood and difficult to simulate numerically [e.g. 8, 9]. Perhaps the 'dirty plume' scenario, which is invoked here for 'relict grains', may yet provide a way of creating complementary relations between chondrules and matrix. Perhaps a nucleosynthetic carrier phase in the dust was selectively incorporated into (or rejected by) the molten droplets. The possibilities offered by the splashing model, particularly in plume dynamics, need to be more fully explored before the significance of complementarity for the model can be understood.

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NUCLEOSYNTHETIC AND MASS-DEPENDENT TITANIUM ISOTOPE VARIATIONS IN INDIVIDUAL CHONDRULES OF ORDINARY CHONDRITES. M. Schönbächler[1], K. K. Bauer[1], M. A. Fehr[1], N. Chaumard[2] and B. Zanda[3], [1]Institute for Geochemistry and Petrology, ETH Zürich, Switzerland (mariasc@ethz.ch); [2]WiscSIMS, Department of Geoscience, University of Wisconsin-Madison, USA; [3]IMPMC-MNHN, UMR-CNRS-7590, Paris, France

Introduction: Chondrules formed during the early stages of solar system evolution in the protoplanetary disk. For this reason, they carry invaluable information about the conditions in the solar nebula and protoplanetary disks in general. Their old formation ages (4564.7-4567.3 Ma e.g., [1]) coincide with the earliest stages of planet formation, and as such chondrules may provide constraints on the planet formation process itself. The origin of chondrules is debated. Various models have been proposed, which broadly can be divided in two groups: (i) chondrule formation during collisions of planetesimals, or (ii) in the solar nebula using shock waves or lightening.

In this study, we separated individual chondrules from the ordinary chondrites (OC) Tieschitz (H/L3.6), Parnallee (LL3.6) and Saratov (L4) and used nucleosynthetic Ti isotope variations to determine their genetic relationship within a single meteorite and between different OC groups. This provides useful information about mixing and transport processes in the protoplanetary disk. Titanium isotopes are powerful tracers because Ti is a refractory element that displays well-documented nucleosynthetic variations in ^{46}Ti and ^{50}Ti in solar system materials, which are of different nucleosynthetic origin [2,3]. Moreover, we also determined the mass-dependent Ti isotope composition to quantify possible fractionation processes during chondrule formation and parent body metamorphism. Experiments have shown that Ti isotope fractionation can occur, for example, during evaporation of perovskite in a vacuum furnace [4].

Analytical methods: Separated chondrules and chondrule fragments were characterized using CT scanning. Fourteen chondrules were selected for mass-independent Ti isotope analyses, while seven of these were also analyzed for mass-dependent Ti isotope compositions. The chondrules were powdered and dissolved by Parr bomb acid digestion. Titanium was separated using a three-step column chemistry procedure [5]. The Ti isotope compositions were determined on a Neptune Plus MC-ICPMS. For the mass-independent analyses, the data were internally normalized to ^{49}Ti/^{47}Ti = 0.749766 [6]. Terrestrial standard rocks and bulk rocks of several OCs (St. Severin, Richardton, Allegan) were analyzed to assess data accuracy and precision. For mass-dependent analyses, we employed the ^{47}Ti-^{49}Ti double spike method of [7].

Results and Discussion:

Nucleosynthetic Ti isotope variations. The fourteen chondrules from Tieschitz (H/L3.6), Parnallee (LL3.6) and Saratov (L4) span a range of nucleosynthetic Ti isotope compositions with ε^{50}Ti from -1.1 to +0.1. The data scatter around the value for bulk ordinary chondrites (ε^{50}Ti =-0.5 ± 0.2). Each meteorite exhibit chondrules with various distinct Ti isotope compositions, that are resolved from each other and with a similar spread around the bulk OC value. This entails that each chondrule has sampled a unique, but yet similar mix of precursor materials. This is difficult to reconcile with chondrule formation from molten planetesimals, but is consistent with formation during collisions of partially molten bodies [8]. The precursor material of OC chondrules is clearly distinct from that of carbonaceous chondrites. For example, the isotopic composition of a chondrule separate from the carbonaceous chondrite Allende display a distinct positive composition (ε^{50}Ti = +4.6 ±0.1) [7]. This further substantiates the previous observation that each chondrite class accreted a unique mixture of chondrules that were little mixed with those of other chondrite classes [9]. This indicates that chondrule formation was on-going in relatively isolated regions in the protoplanetary disk.

Mass-independent Ti isotope variations. These data are very uniform for all analyzed chondrules and overlap with those of terrestrial basalts. Thus, no significant stable isotope fractionation has taken place in the solar nebula and during chondrule formation. The exception are chondrules from the most strongly metamorphosed sample analyzed: Saratov chondrules are depleted in heavy isotopes (δ^{49}Ti/^{47}Ti = -0.4 to -0.6 relative to other chondrules and the terrestrial basalts). These variations are best explained by the crystallization of Ti-bearing chondrule mesostasis that resulted in loss of heavy Ti isotopes.

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CONSTRAINING THE COOLING RATES OF CHONDRULES. S. C. Stockdale[1], I. A. Franchi[1], M. Anand[1,2] and M. M. Grady[1,2], [1]School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK. [2]Department of Earth Sciences, Natural History Museum, London, SW7 5BD, UK. Email: Shannon.Stockdale@open.ac.uk

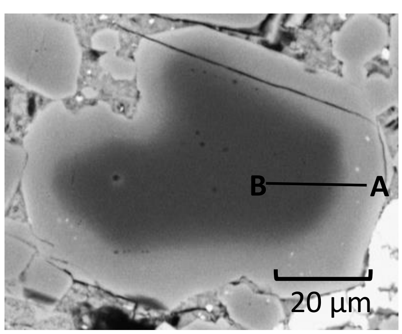
Introduction: The cooling rate of chondrules is one of the important constraints on chondrule formation and can be used to distinguish between competing chondrule formation mechanisms. These mechanisms range from shockwaves in the solar nebula[1] to collisions between planetesimals[2]. Dynamic crystallisation experiments are the most widely cited methods of determining chondrule cooling rates and have provided cooling rates from 1 to 3000 Kh^{-1}[3,4]. This is a very large range and in order to assess whether this is a true representation of chondrule cooling rates in the early solar system, it should be validated or constrained by using a more direct method.

Many type II, FeO-rich chondrules contain MgO-rich relict olivine grains inherited from the precursor assemblage. Minor element concentrations of these grains bear a strong relationship to type I chondrules and therefore they likely originate from previous generations of these chondrules[5]. These are important features as they can allow us to determine the cooling rate of their hosts[6].

During sub-solidus cooling, partial equilibration occurs between the relict grain and overgrowth crystal which creates diffusion profiles for a range of major, minor and trace elements. The amount of re-equilibration is dependent upon the cooling rate of the chondrule. Relatively broad diffusion profiles could indicate slower cooling rates as more equilibration has occurred. Narrow diffusion profiles should indicate faster cooling rates as there was less time for equilibration.

Methods and results: Relict grains have been identified and characterised using Back Scattered Electron (BSE) imaging, Energy Dispersive X-ray Spectroscopy (EDS) mapping and EDS point analyses on an FEI Quanta 200 3D FIB-SEM. In BSE images, relict grains appear as dark patches within relatively bright phenocrysts. Preliminary diffusion profiles have also been measured for Fe and Mg using EDS point analyses with a spacing of 2 μm, a counting time of 240 s and an accelerating voltage of 10 kV. Measured diffusion profiles (e.g. Fig. 1) are narrow, several micrometres across, indicating rapid cooling took place.

a)



b)

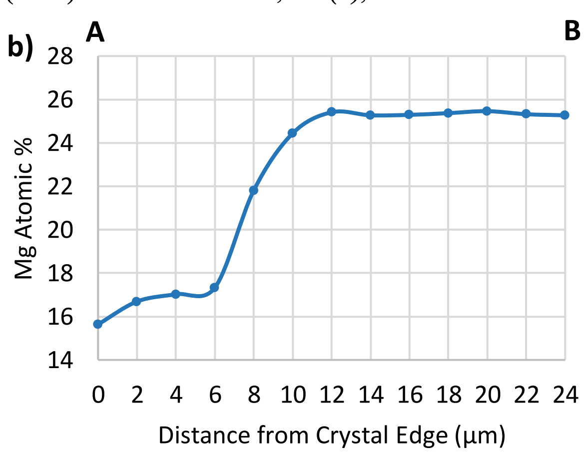


Figure 1 – a) BSE image of an olivine phenocryst containing a relict grain from a chondrule in ALHA 77307 showing the location of **b)** Mg diffusion profile AB measured using EDS point analyses.

Discussion and future work: The cooling histories of chondrules are likely to be complex and may not be resolvable with the relatively large excitation volume of the EDS point analyses. In order to see this complexity and unravel possible multiple heating events, a technique with high spatial resolution must be employed. NanoSIMS combines high spatial resolution (~300 nm) with high sensitivity which will allow us to measure accurate diffusion profiles for a range of major, minor and trace elements. Therefore, we will use the Cameca NanoSIMS 50L at The Open University to measure diffusion profiles for a range of elements (e.g. Mg, Fe, Ca, Cr, Mn, Ti, Al, Ni, and V) between relict grain and overgrowth. A binary element diffusion model will be developed[7], and used in conjunction with these diffusion profiles to obtain temperature-time paths from which cooling rates can be extracted. These cooling rates can then be used to evaluate the current models of chondrule formation.

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MEAN ATOMIC WEIGHT OF CHONDRULES AND MATRICES IN SEMARKONA, ALLENDE AND SHARPS METEORITES. M. Szurgot, Lodz University of Technology, Center of Mathematics and Physics, Al. Politechniki 11, 90 924 Lodz, Poland (mszurgot@p.lodz.pl).

Introduction: Knowledge of mean atomic weight is important to characterize minerals and rocks, planets, moons, and asteroids [1-3]. The aim of the paper was to determine and analyze mean atomic weight of chondrules and matrices of three chondrites: Semarkona (LL 3.0), Allende (CV 3), and Sharps (H3.4 or H/L 3.4).

Results and discussion: Literature data on mean bulk elemental and oxide composition of meteorites, and composition of chondrules and matrices [4-6] have been used to calculate mean atomic weight (*Amean*) using the following formula:

$$Amean = \sum wi/ \sum (wi/Ai), \quad (1)$$

where *wi*(wt%) is the mass fraction of *ith* element and *ith* oxide, and *Ai* is atomic weight of *ith* element and *ith* oxide.

Table 1 and Fig. 1 present *Amean* values calculated for Semarkona, Allende, and Sharps meteorites, and for their chondrules and matrices. Chemical composition of meteorites, and their constituents used in calculations does not include H_2O.

Table 1. Mean atomic weight of chondrules, matrices, and Semarkona, Allende and Sharps meteorites.

Meteorite/ Class	*Amean* Chondrules	*Amean* Meteor-ite	*Amean* Matrix
Semarkona LL3.0	20.5-21.9	**23.2**	23.7-24.1
Allende CV3	21.5	**23.8**	24.5
Sharps H 3.4	20.7-21.2	**24.7**	25.2

Data reveal that *Amean's* values follow the inequality:

$$AChondrules < AMeteorite < AMatrix. \quad (2)$$

Table 1 and Fig. 1 show that mean atomic weight of matrices is higher than chondrules and meteorites.

Data on bulk composition reveal that:

$$ASemarkona(23.2)<AAllende(23.8)<ASharps(24.7). \quad (3)$$

Semarkona chondrules exhibit *Amean* values:

$$IB(20.5) < IA(21.1) < IIB(21.7) < IIA(21.9). \quad (4)$$

FeO poor chondrules (type I) have lower *Amean* values than FeO rich (type II) chondrules (*AmeanIIA - AmeanIA* = 0.8, *AmeanIIB - AmeanIB* = 1.2), and olivine rich chondrules (subtype A) have higher *Amean* than pyroxene rich (subtype B) chondrules (*AmeanIIA - AmeanIIB* = 0.2, *AmeanIA - AmeanIB* = 0.6). Silicates of meteorites, matrices and chondrules exhibit much smaller *Amean* values (21.3-23.8) than Fe,Ni metal (56.2-57.8). Effect of Fe content on *Amean* is expressed by *Amean(Fe/Si)* dependence (Fig. 1).

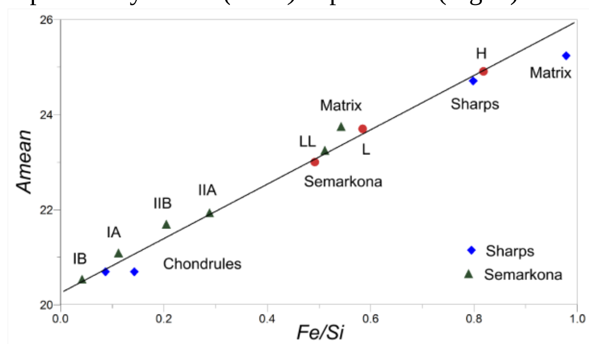

Fig. 1 Relationship between *Amean* and *Fe/Si* atomic ratio for Sharps, Semarkona and H, L, LL chondrites.

Fe/Si atomic ratio satisfactorily predicts *Amean* values by *Amean(Fe/Si)* dependence established for OC's [3] (Fig. 1), which is given by the equation:

$$Amean= 5.72 \cdot Fe/Si + 20.25. \quad (5)$$

Amean value predicted by *Fe/Si* ratio for Semarkona whole rock is 23.2, and for Sharps whole rock is 24.2.

Conclusions: Mean atomic weights of matrices are higher than chondrules, and higher than meteorites. FeO poor chondrules have lower *Amean* values than FeO rich chondrules. *Amean(Fe/Si)* dependence predics precisely mean atomic weight of ordinary chondrites, chondrules, and matrices. *Amean* data indicate that Sharps is rather H than H/L chondrite.

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O-ISOTOPE FEATURES OF CHONDRULES FROM RECENT SIMS STUDIES. T. J. Tenner[1], T. Ushikubo[2], D. Nakashima[3], D.L. Schrader[4], M.K. Weisberg[5,6], M. Kimura[7], and N.T Kita[8]. [1]Los Alamos National Laboratory, NM, USA (tenner@lanl.gov). [2]JAMSTEC, Kochi, Japan. [3]Tohoku University, Miyagi, Japan. [4]Arizona State University, AZ, USA. [5]Kingsborough Community College and Graduate Center, CUNY, NY, USA. [6]American Museum of Natural History, NY, USA. [7]Ibaraki University, Mito, Japan. [8]University of Wisconsin-Madison, WI, USA.

Overview: Oxygen isotope ratios of chondrules are an important tool for cosmochemical research, as they reveal how early Solar System materials were processed and transferred. In particular, chondrules dominate the volume of unequilibrated meteorites (20-80%; [1]). Oxygen is prevalent in chondrules, which is expected as it is the third most abundant element in the Solar System, after hydrogen and helium [2]. Therefore, that oxygen has three isotopes, ^{16}O, ^{17}O, and ^{18}O (99.757, 0.038, and 0.205 atom %, respectively; [3]), with relatively large mass differences, is useful, as they fractionate due to many processes chondrules have experienced. O-isotope ratios record primary, high-temperature signatures of chondrule formation, and are also susceptible to secondary processing that occurred on the parent asteroid by thermal metamorphism and/or aqueous alteration. Often, primary and secondary features coexist within chondrules, and decoding respective O-isotope signatures is not straightforward. To this extent, recent advances of *in situ* O-isotope analysis by secondary ion mass spectrometry (SIMS) has increased our understanding of chondrule processing. Specifically, SIMS now has the ability to interrogate O-isotope signatures of individual grains in chondrules (1-15 μm spot analyses), with sub-per-mil precision [4] in $\delta^{17,18}O$ (‰) = $[(R_{sample}/R_{VSMOW}) - 1] \times 1000$, where R = $^{17,18}O/^{16}O$, and VSMOW: [5].

The focus of this review is to highlight recent chondrule O-isotope findings by SIMS. First, we discuss interphase O-isotope relationships within chondrules, and what they reveal with respect to internal homogeneity during chondrule formation. This includes definitions of host O-isotope ratios (i.e. the value of the final chondrule melt), and identifying relict grains that formed in a prior heating event, survived the final chondrule-forming event, and retained distinct O-isotope signatures from their initial formation. Additionally, some chondrules have heterogeneous isotope ratios, where neither host nor relict signatures can be properly determined. Furthermore, differences in O-diffusion rates of chondrule phases can be used to assess the level of disturbance a chondrule has experienced. Chondrule plagioclase and glass have fast O-diffusion rates during thermal metamorphic conditions, relative to olivine and pyroxene [6]. In turn, recent SIMS studies provide evidence that chondrule plagioclase and glass show O-isotope overlap with coexisting olivine and pyroxene as chondrites approach petrologic type 3.00, but that plagioclase and glass deviate in their O-isotopes relative to coexisting olivine and pyroxene with increasing levels of thermal metamorphism.

In addition to interphase relationships we compare the range of host and relict O-isotope ratios of chondrules from different chondrite types, emphasizing mass-dependent versus mass-independent fractionated O-isotope signatures. We highlight the slope-1 ($\delta^{18}O$ vs. $\delta^{17}O$) primitive chondrule mineral (PCM) line defined by SIMS chondrule phenocryst data from the primitive Acfer 094 chondrite [7], and show that chondrule data from other carbonaceous chondrites fall onto this trend.

Finally, we discuss relationships between O-isotope ratios of chondrules and their major element characteristics. For example, among LL3 ordinary chondrites, FeO-poor chondrules show that host O-isotope ratios fractionate mass-dependently as a function of bulk silica, likely through open-system evaporation and condensation effects [8]. In addition, recent studies of several carbonaceous chondrites reveal that the abundance of mass-independent fractionated ^{16}O among chondrules is linked to chondrule Mg#'s (= mol.% MgO/[MgO + FeO]). As chondrule Mg# is directly related to redox conditions when chondrules formed, by metal-silicate phase equilibria [9], inferences can be made with respect to proportions of various chondrule precursors, such as oxidizing ^{16}O-poor H_2O ice [10] and reducing ^{16}O-poor gas [11], which controlled O-isotope ratios of chondrules and the redox states they have recorded.

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THE CHONDRITIC ASSEMBLAGE. B. Zanda[1,2] P.-M. Zanetta[1,3], H. Leroux[3], C. Le Guillou[3], É. Lewin[4], S. Pont[2], D. Deldicque[5] and R. H. Hewins[2,1], [1]IMPMC – MNHN, UPMC & CNRS, 61 rue Buffon, 75005 Paris, France (brigitte.zanda@mnhn.fr); [2]Dept. of Earth & Planetary Sciences, Rutgers University, 610 Taylor Rd., Piscataway, NJ; [3]UMET, University of Lille & CNRS, F-59655 Villeneuve d'Ascq, France; [4]ISTerre (OSUG : Univ. Grenoble-Alpes & INSU-CNRS), Grenoble, France; [5]École Normale Supérieure, UMR 8538, 75231 Paris CEDEX 5, France.

Introduction: Chondritic meteorites comprise components formed or processed at high temperature embedded in a volatile-rich fine-grained matrix. The origin of matrix and its relationship with other chondritic components are poorly understood. It is highly susceptible to parent-body processes and hence better studied in the most pristine chondrites (type≈3.0), in which it has been shown to be a complex assemblage of hydrous and anhydrous silicates, amorphous material, opaque minerals, presolar grains and organics. Presolar grains have been inherited from the interstellar medium and possibly other components of the matrix, but others may be the product of nebular condensation or high temperature processing and recycling.

Understanding the links between chondritic components is critical to our vision of the protoplanetary disk (PPD) as a chondrule-matrix genetic relationship would indicate accretion to have taken place shortly after these components formed and thus preclude their transport within the disk. Chondrules and matrix may have formed independently [1]. However, the discovery of chemical relations between chondrules and matrix within a given chondrite has led several authors [2-4] to suggest they actually formed simultaneously from the same reservoirs, the compositions of which would be chondritic (CI) in terms of major elements such as Si and Mg [2,4] and more or less depleted in volatile elements depending on the chondrite group [3]. Because obtaining a reliable bulk composition of chondrules within a chondrite is difficult, most arguments developed by these authors are based on comparing matrix composition to that of the bulk rock.

Complementarity in volatile elements. [3] compared bulk and matrix compositions in carbonaceous chondrites (CCs) and showed them to mimic one another: if the bulk is highly depleted in volatiles (CVs), so is the matrix, but to a lesser extent. In contrast, when the bulk is less depleted (CMs), then matrix is even less so. [3] concluded this pattern indicated that these rock components had formed simultaneously from the same reservoir.

Complementarity in major elements [4] and subsequent work by this group argue that all CCs exhibit CI chondritic ratios of the major elements Si, Mg (Fe…), but that each group has a specific matrix composition, with a lower Mg/Si ratio than that of the bulk. This would imply that in each CC group, the composition and proportion of chondrules are exactly suited to those of their embedding matrix to reach a chondritic bulk. They make the case that /Si distribution cannot result from parent body processes, and hence that chondrules and matrix must have been formed simultaneously from a reservoir of CI composition.

Results and discussion: In [5], we showed that the similarity in volatile depletion patterns for matrix and bulk in CCs might be explained by parent-body alteration in the course of which the matrix, originally CI in composition, would have lost some of its volatiles to the chondrules. In the cases where the matrix comprises most of the rock (CMs) the resulting volatile depletion of the matrix would have been slight, whereas in the cases where matrix is significantly less abundant than chondrules (CVs and COs) its volatile depletion would have been much more important.

Here we discuss the case of the major elements and contend that [4] and most of the work arguing for complementarity between matrix and chondrules is based on matrix analyses performed by EMP, a method that may be precise but not necessarily accurate because the beam has to analyze a mixture comprising crystals of varying density. In fact, matrix analyses performed by LA-ICP-MS [3] yield chondritic Mg/Si ratios. Such published data are however rare in the literature and we feel that they should be confirmed and supplemented. We are currently developing a new method for sample analysis adapted from techniques of multiple component analysis in order to obtain an improved estimate of the bulk chemistry of the matrix. Our technique is based on coupling X-ray maps obtained at low voltage on a FESEM with an EMP calibration. Preliminary results will be presented at the meeting.

Conclusion: Complementarity between the high-T and the low-T fractions of the chondritic assemblage would have important implications for our undertanding of the PPD. There is an obvious need for new accurate analyses of the matrices of primitive chondrites.

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