Day 1, Tuesday, 30.8.2022

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Session 1

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Keynote

When, How and in What Were the Most Volatile Elements Delivered to the Earth?

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In the standard model of terrestrial planet formation, first ~ Mars-sized embryos form by oligarchic accretion of planetesimals, and then on longer timescales the final growth phase is dominated by collisions of embryos. Mars had already reached roughly half its current size within ~2 Ma of Solar System formation. If Mars is typical of embryos, their rapid formation implies that they would have largely formed by accretion of earlier formed planetesimals that, as a result of 26Al decay, would have melted and differentiated. Measurements of achondrites indicate that they generally have very low volatile contents. The meteorite record suggests that planetesimal formation in the inner Solar System ended at ~2 Ma, and those planetesimals that did not differentiate were heavily metamorphosed and degassed. However, dynamical models indicate that the giant planets would have scattered planetesimals from the outer to the inner Solar System as they grew and their orbits evolved. If these scattered outer Solar System planetesimals formed after ~3 Ma, they are likely to have been very volatile-rich. This is the case for the CI, CM and CR carbonaceous chondrites as well as comets, and only relatively small amounts of these objects are needed to account for the volatile inventories of the terrestrial planets. Comparisons of the noble gas abundances/isotopes, and H and N isotopes, suggest that most of the Earth's volatiles were accreted in CI- and/or CM-like bodies, with relatively small contributions from comets and solar/solar wind material. The small solar contributions suggests that the Earth did not acquire a primary atmosphere from the solar nebula, placing limits on how big its building blocks were when the gas disk dissipated. If a late veneer is the explanation for the HSEs, S, Se and Te in the BSE, then most of the Earth's volatiles were accreted prior to the Moon-forming impact. Most estimates of the BSE's H and C contents, and all estimates of its N content are much lower than would be predicted for CI/CM-like sources based on the noble gases. Impact-driven loss of early atmospheres that degassed from impact-generated magma oceans is one possible explanation low H, C and N abundances, but this may be hard to reconcile with the much higher and relatively unfractionated CI-normalized abundances of Ne and Ar that have similar solubilities in silicate melts to CO2 and N2, respectively. Possible alternative explanations for any H, C, and N depletions, relative to the noble gases, in the BSE are significant partitioning into the core or hidden reservoirs in the deep mantle. Equally puzzling is the Ne isotopic difference between the Earth's atmosphere (70-80% chondritic, 20-30% solar) and primitive mantle (solar-like). Taken at face value, it would seem to imply that the bulk of the atmosphere did not degas from the mantle. If correct and most volatiles remained at the surface, this would require that the atmosphere prior to and for some time after Moon-formation was massive enough to prevent significant erosion by impactors large and small.
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scattered outer Solar System planetesimals formed after ~3 Ma, they are likely to have been very volatile-rich. This is the case for the CI, CM and CR carbonaceous chondrites as well as comets, and only relatively

14:40 – 15:00

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Stable isotopes - fingerprints for tracing the origin and history of building blocks and ingredients for life from molecular clouds to planets

Wampfler S[1], Altwegg K[2], Rubin M[2], Haenni N[2], Mueller D[2], Jorgensen J[3]
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Understanding the origin and evolution of the building blocks of planets and minor bodies, and eventually life, is challenging because of the complexity and long time scales involved in the star and planet formation process. Moreover, the most pristine materials in our own solar system, meteoritic inclusions and cometary ices, are present in the form of solids, whereas most of our information on the molecular composition of solar-like star-forming regions stems from observations of species in the gas-phase. Linking the solar system record to processes observed in nascent solar system analogues requires probes that can be used across a wide range of materials, in situ as well as by remote observations.
Stable isotope ratios of volatile elements such as D/H, $^{14}N/^{15}N$, $^{16}O/^{18}O$ etc. can be measured in rocky, icy, and gaseous phases, and are therefore promising tracers for the origin and the evolution of volatiles and organic matter. However, using them as fingerprints for the history of planetary, cometary, and asteroidal building blocks and the delivery of volatiles requires a detailed understanding of the fractionation mechanisms and spatial and temporal evolution of the isotopic ratios during the formation of low-mass stars and their planetary systems.
In this contribution, we will present the current understanding of nitrogen isotopic fractionation in star-forming regions, including new observational data investigating the presence of separate atomic and molecular nitrogen isotopic reservoirs with distinct compositions around young stars. We will also present in situ measurements of the $^{14}N/^{15}N$ ratio by the Rosetta-ROSINA instrument at comet 67P, pointing at a single nitrogen isotopic reservoir in comets, in contrast to the results on protostars and protoplanetary disks. We will then conclude by explaining how a better understanding of the carrier phases of nitrogen may help in reconciling the cometary and interstellar pictures on nitrogen isotopes, and how these results can further contribute to developing the nitrogen isotopic ratio into a key signature for constraining the origin and evolution of different cosmomaterials from molecular clouds to planets.

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The molecular origin of life: interstellar prebiotic chemistry

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The origin of life is intertwined with the emergence of complex organic molecules that act as the chemical building blocks of life. While prebiotic chemistry can take place on planets, for example in their atmospheres or in hydrothermal vents, a fascinating alternative is the production of prebiotic molecules in space.

In this talk, we will take a look at the prebiotic molecules we find in space. We use the ALMA radiotelescope to study the molecules in the gas around infant stars and planet-forming regions [1,2,3,4,5,6]. We find species that can act as building blocks of amino acids, sugars, peptides, and nucleobases. While these molecules are observed in the gas, evidence is found that they originally formed on microscopic ice-coated dust grains. In protoplanetary disks, these dust grains coaggulate together to form larger boulders, planetesimals, and eventually planets. Therefore, these interstellar prebiotic molecules can be inherited on planets, resulting in a rapid development of prebiotic chemistry and thus help kick-start the emergence of life.

[1] Ligterink, N. F. W., et al. "The ALMA-PILS survey: detection of CH3NCO towards the low-mass protostar IRAS 16293− 2422 and laboratory constraints on its formation." Monthly Notices of the Royal Astronomical Society 469.2 (2017): 2219-2229.

[2] Ligterink, Niels Frank Willem, et al. "The ALMA-PILS survey: Stringent limits on small amines and nitrogen-oxides towards IRAS 16293–2422B." Astronomy & Astrophysics 619 (2018): A28.

[3] Ligterink, N. F. W., et al. "The formation of peptide-like molecules on interstellar dust grains." Monthly Notices of the Royal Astronomical Society 480.3 (2018): 3628-3643.

[4] Ligterink, Niels FW, et al. "The family of amide molecules toward NGC 6334I." The Astrophysical Journal 901.1 (2020): 37.

[5] Ligterink, N. F. W., et al. "The prebiotic molecular inventory of Serpens SMM1-I. An investigation of the isomers CH3NCO and HOCH2CN." Astronomy & Astrophysics 647 (2021): A87.

[6] Ligterink, Niels FW, et al. "The prebiotic molecular inventory of Serpens SMM1: II. The building blocks of peptide chains." ACS Earth and Space Chemistry 6.3 (2022): 455-467.

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Tracing Volatiles from Protoplanetary Disks to Planetary Atmospheres

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The bulk composition of a planet-hosting star is thought to reflect the initial chemical composition of the protoplanetary disk from which planets form. However, deviations in the composition of (particularly rocky) planets from their host star are commonplace, and may occur by gas-dust fractionation in the protoplanetary disk and/or over the dynamical process of planet formation. A key distinguishing feature between the formation of a gas giant (e.g. Jupiter) and a rocky planet (e.g. Earth) is devolatilization, i.e., depletion of volatiles, which include both atmophiles (e.g. H, C, N and noble gases) and moderately volatile minerophiles (e.g. O, S, Si, Mg and Fe). This devolatilization mechanism has been observed empirically both in the Solar System and in other planetary systems (e.g. in the atmospheres of polluted white dwarfs), but has yet to be accounted for in most (if not all) existing models of planet formation.

Here, we present a comprehensive interpretation of both nebular (e.g. dust formation, condensation, and evaporation/sublimation) and post-nebular (e.g. energetic accretion and impacts, hydrodynamic escape, and photoevaporation) devolatilization processes as well as our research scheme of incorporating these processes into state-of-the-art planet formation models. Based on our previous empirical studies of these processes, the importance of devolatilized host stellar abundances, along with measured planetary masses and radii, will be demonstrated in constraining the detailed properties of rocky exoplanets including both interiors and atmospheres. Ultimately, by tracing the evolutionary path of both life-critical and rock-essential volatiles (e.g. H, C, O, N, S, Mg, Si and Fe) during planet formation and evolution, this will help us understand why and how our planet becomes habitable and inhabited, and the extent to which we can make testable predications about the habitable conditions of rocky exoplanets apt for life emergence and prevalence in the cosmos.

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Solubility of water in peridotite liquids and the prevalence of steam atmospheres on rocky planets

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Atmospheres are products of time-integrated mass exchange between the surface of a planet and its interior. On Earth and other planetary bodies, magma oceans likely marked significant atmosphere-forming events, during which both steam- and carbon-rich atmospheres may have been generated. However, the nature of Earth's early atmosphere, and those around other rocky planets, remains unclear for lack of constraints on the solubility of water in liquids of appropriate composition. Here we determine the solubility of water in 14 peridotite liquids, representative of Earth's mantle, synthesised in a laser-heated aerodynamic levitation furnace. We explore oxygen fugacities (fO2) between -1.9 and +6.0 log units relative to the iron-wüstite buffer at constant temperature (1900±50 °C) and total pressure (1 bar). The resulting fH2O ranged from nominally 0 to 0.027 bar and fH2 from 0 to 0.064 bar. Total H2O contents were determined by transmission FTIR spectroscopy of doubly-polished thick sections from the intensity of the absorption band at 3550 cm-1 and applying the Beer-Lambert law. The mole fraction of water in the liquid is found to be proportional to (fH2O)0.5, attesting to its dissolution as OH. The data are fitted by a solubility coefficient of ~525 ppm/bar0.5, roughly 25 % lower than for basaltic liquids at 1350 °C and 1 bar. Higher temperatures (rather than more magnesian compositions) result in a significant decrease of water solubility in silicate melts. Because the solubility of water remains high relative to that of CO2, steam atmospheres are rare, although they may form under moderately oxidising conditions on telluric bodies, provided sufficiently high H/C ratios prevail.

16:35 – 16:55

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Interstellar origins of chemical complexity in comets

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It has been speculated that chemically complex molecules could have been delivered to Earth during the Late Heavy Bombardment for further synthesis of biotic compounds on the planet. In my contribution, I will demonstrate the interstellar origins of cometary molecules. I will suggest that the large complex organic reservoirs in comets make them strong candidates for sowing the initial seeds of life on the early Earth. The earliest stage of star formation, the prestellar core, is the birth place of complex organic molecules under interstellar physical conditions. Upon gravitational collapse, a young protostar with a protoplanetary disk is formed. The concurrent heating and UV irradiation boost the production of complex organics. It is thought that the largest reservoir of complex organics is in interstellar ices. Desorption in the warm inner regions around protostars allows us to readily observe these species in the gas. In the outer parts of a protoplanetary disk, solid complex organics become integrated into cometesimals. I will highlight recent observational investigations of complex organics from cores to protostars, including studies of methanol isotopologs in the prestellar core L1544 (Kulterer et al. in prep.) and the comprehensive chemical inventory of the low-mass star-forming region IRAS 16293-2422 (e.g., Jorgensen et al. 2018; Drozdovskaya et al. 2018, 2022). I will bring forward the idea that comets of our Solar System reflect to a degree the complex organic composition of the innate core that birthed our Sun (Drozdovskaya et al. 2019, 2021).

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Geophysical and cosmochemical evidence for a volatile-rich Mars

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Constraints on the composition of Mars principally derive from chemical analyses of a set of Martian meteorites that rely either on determinations of their refractory element abundances or isotopic compositions. Both approaches, however, lead to models of Mars that are unable to self-consistently explain major element chemistry and match its observed geophysical properties, unless ad hoc adjustments to key parameters, namely, bulk Fe/Si ratio, core composition, and/or core size are made. Here, we combine geophysical observations, including high-quality seismic data acquired with the InSight mission, with a cosmochemical model to constrain the composition of Mars.

We employ the InSight seismic data, including a set of geophysical observations (tidal response, mean planetary density and moment of inertia) that sense the large-scale structure of Mars, to determine mantle and core composition. For this, we rely on a geophysical parameterization that provides a unified description of mantle and core phase equilibria and physical properties as a function of composition, temperature, and pressure. Based on the geophysically-determined mantle compositions and mean core properties (radius and density), we further employ a cosmochemical approach by focusing on major elements and the extant correlation between Fe/Si and Fe/Mg that is observed in planetary materials. Quantitative comparison of the geophysical and cosmochemical compositions enables us to restrict the mantle composition of Mars by considering only those compositions that fit both constraints. Finally, we employ the jointly-predicted mantle composition to place constraints on the identities and abundances of light elements in the Martian core. The novelty of our approach lies in the inversion of multiple geophysical observations to derive physically-credible solutions of the interior state of Mars, in conjunction with cosmochemically-plausible bulk chemical compositions.

We find that: 1) mantle FeO content varies in the range 12.5–15 wt%, which is several wt% lower than suggested by canonical models that derive from geochemical analyses of Martian meteorites; 2) a lower mantle FeO content generally correlates with a lower MgO and higher SiO_2 content. The radius range of the liquid core found here is 1790–1870 km and the core density range is 6-6.3 g/m3, as a consequence of the lower mantle FeO content of the mantle. The core compositions most compatible with these numbers, based on thermodynamic solution models constructed from experimental data, are found to encompass 9 wt% S, ≥3 wt% C, ≤2.5 wt% O, and ≤0.5 wt% H, supporting the notion of a volatile-rich Mars. To accumulate sufficient amounts of these volatile elements, Mars must have formed before the nebular gas dispersed and/or, relative to Earth, accreted a higher proportion of planetesimals from the outer proto-planetary disk where volatiles condensed more readily.

17:15 – 17:35

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Life under fire: collisional evolution of the prebiotic Earth

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The Earth likely experienced a greater rate of collisions with extraterrestrial matter in early Solar System history. This is highly relevant for the chemical origins of life, as many types of extraterrestrial matter are enriched in life-limiting elements relative to Earth's crust. I will present results from a continuing effort to interrogate (i) collisional activity in the early Solar System, (ii) the implications of that collisional history for accretion of life-limiting elements to the surface of prebiotic Earth, and (iii) the surface processing of extraterrestrial matter in the context of origin of life chemistry. These topics in turn are investigated with isotopic analyses of meteorites from asteroids that experienced collisions, geochemical measurements of the fine-grained cosmic dust particles that those collisions generated, and simulations of extraterrestrial matter processing and ensuing prebiotic chemistry in closed-basins on prebiotic Earth. Our combined approach leverages astrophysical, geological, and chemical constraints to better understand the role and relevance of collisional bombardment in seeding planets for life.