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Royal Astronomical Society

The Moon and early Earth

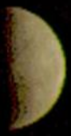
VIRUAL CONFERENCE

29-30 November 2021

For the last 4.5 billion years the Earth and Moon have essentially comprised a binary planet system which is unique in the inner Solar System. During this time life has evolved and prospered on Earth, yet key aspects of our planet's early environment are poorly understood. This meeting will explore how the lunar geological record may be used to elucidate early Solar System processes relevant to understanding the earliest history of our own planet and the conditions under which life originated on it.

Convened by:

- Ian Crawford (Birkbeck College, University of London)
- Professor Mahesh Anand (The Open University)
- Dr Katie Joy (University of Manchester)
- Dr Oliver Shorttle (University of Cambridge)
- Dr Richard Palin (University of Oxford)



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#GSLMoon

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2021 YEAR OF SPACE

Image credit NASA

Contents

CONFERENCE PROGRAMME

The Moon and Early Earth
29-30 November 2021

Day One – 29 November	
Session 1: Bombardment history I – Chair Ian Crawford	
12:25	**EVENT OPEN**
12:30	Welcome address and Introduction – Ian Crawford
12:40	**Shocked primitive meteorites record widespread collisional reheating from 4.48-4.44 Ga** *Craig Walton, University of Cambridge*
13:05	**High-resolution oblique impact simulations of the formation of the South Pole-Aitken Basin** *Thomas M Davidson, Imperial College London*
13:30	**Atmospheric Erosion by Giant Impacts onto Terrestrial Planets** *Jacob Kegerreis, Durham University*
13:55	**The effect of pre-impact spin on the Moon-forming collision** *Sergio Ruiz-Bonilla, Institute for Computational Cosmology, Durham University*
14:20	**BREAK**
	Session 2: Bombardment history II - Claire Nichols chair

14:45	Old and new issues with the Earth-Moon bombardment history *Simone Marchi, Southwest Research Institute*
15:10	**Effects of Late Accretion Impacts on Early Earth Habitability: Planetary Sterilization and Iron Delivery** *Robert Citron, University of California Davis*
15:35	**The Moon's First Billion Years: Maybe Not So Hadean After All** *Nicolle Zellner, Albion College*
16:00	**Flash poster talks** **Earth's Twin Children, The Moon And Vesta, Preserve Its Earliest Records** *Donald Wise, University of Massachusetts* **We're drifting apart… Quantifying Lunar recession since 4.25 billion years ago** *Hannah Davies, University of Lisbon* **Impact Melt Scaling in Planetary Collisions** *Auriol Rae, University of Cambridge* **Using Deep Moonquakes To Constrain Lunar Tectonic Stresses** *Alice Turner, University of Oxford* **Poster session**
16:25	**BREAK**
	Session 3: Bombardment history III / Space agency presentations - Chair Nicolle Zellner
16:50	**Crustal porosity reveals the bombardment history of the Moon** *Ya Huei Wang, Massachusetts Institute of Technology*

17:15	**Implications of a Moon-forming impact for the early Earth's oceans on volatile budget** *Hilke E.Schlichting, UCLA*
17:40	**A Cataclysmic Impact Origin of Life?** *Gordon Osinski, University of Western Ontario*
18:05	**ESA to the Moon** *James Carpenter, European Space Agency*
18:30	**Returning to the Moon to Stay: NASA's Artemis Program** *David Draper, NASA Headquarters, Office of the Chief Scientist*
18:55	**DISCUSSION**
19:30	**END**

Day 2 – 30 November	
Session 4: Lunar geology Chair - Ana Cernok	
12:25	**EVENT OPEN**
12:30	Welcome address and Introduction
12:40	**Constraining the early isotope evolution of the Moon** *Joshua Snape, University of Manchester*
13:05	**Lunar Granulites: Recording High Temperature Metamorphism within the lunar crust** *John Pernet-Fisher, University of Manchester*

13:30	**Protosolar hydrogen source for water in the Moon and the Early Earth** *Alice Stephant, Istituto Nazionale di Astrofisica*
13:55	**Assessing the survivability of biomarkers within terrestrial material impacting the lunar surface** *Samuel Hickson Halim, Birkbeck, University of London*
14:20	**BREAK**
	Session 5: Orbital evolution - Chair Alice Stephant
14:45	**The Moon-Forming Impact and its Influence on Obliquity Stability** *David Waltham, Royal Holloway University of London*
15:10	**Long-term Earth-Moon evolution with high-level orbit and ocean tide models** *Brian Arbic, University of Michigan*
15:35	**Milankovitch cycles in 2.46 billion-year-old banded iron formations provide a robust estimate of the Earth-Moon distance** *Margriet Lantink, Utrecht University*
16:00	**A tectonically active early Earth driven by the tidal recession of the Moon** *Simon James Lock, Caltech*
16:25	**BREAK**
	Session 6: Magnetic fields and astrophysical records – Chair Mahesh Anand
16:50	**The Paleoinclination of the Ancient Lunar Magnetic Field from an Apollo 17 Basalt** *Claire Nichols, University of Oxford*

17:15	**When The Moon Had a Magnetosphere** *James Green, NASA*
17:40	**Absence of a long-lived lunar paleomagnetosphere: Opportunities for future exploration** *John A.Tarduno, University of Rochester*
18:05	**Relaxing the Assumption of a Constant Sun over Time to Understand the Effect on Cosmic Ray Exposure Age** *Prabal Saxena, NASA Goddard/CRESST II/UMD-CP*
18:30	**Lunar palaeoregolith deposits as recorders of astrophysical processes relevant to Earth’s habitability** *Ian Crawford, Birkbeck, University of London*
18:55	**DISCUSSION**
19:30	**END**

DAY 1 – 29 November

Session 1: Bombardment history I

Shocked primitive meteorites record widespread collisional reheating from 4.48-4.44 Ga

Craig Walton

University of Cambridge

Asteroid collision rates increase during solar system reorganisation, such as in the wake of Earth's Moon-forming impact, or giant planet migration. Evidence for these collisions is brought to Earth by meteorites, which can preserve impact-reset radioisotope mineral ages. However, as meteorites often preserve numerous mineral ages, their interpretation is controversial. Here, we combine analysis of phosphate U-Pb ages and mineral microtextures to construct a simplified collision history for the Chelyabinsk ordinary chondrite meteorite. We show that phosphates in this meteorite experienced both recent fracturing and partial Pb-loss at 1 +/- 56 Ma, suggesting recent separation from the Chelyabinsk parent body asteroid after a minor collision. Phosphate textural-age relationships also indicate complete early Pb-loss during the deformation and recrystallisation of phosphates at 4,479 +/- 12 Ma, revealing massive collisional reheating at this time. Our results support an interpretation of the the wider chondritic phosphate texture-age record where energetic collisions widely affected the inner Solar System from 4.48-4.44 Ga. This event could reflect giant planet migration, or debris scattering in the wake of Earth's Moon-forming impact.

High-resolution oblique impact simulations of the formation of the South Pole-Aitken Basin

Thomas M Davison

Imperial College London

Gareth S Collins (Imperial College London)

The ~2500-km diameter South Pole-Aitken (SPA) basin is the oldest and largest known impact structure in the Solar System. The effects of this giant impact event on the Moon were profound. The crater dominates the topography, crustal structure, subsurface density distribution and surface composition of the lunar farside and South Pole [1–3]. Understanding the SPA basin-forming impact is key to unlocking much of the Moon's history and evolution and is a major objective of NASA's Artemis III mission.

Previous 2D numerical simulations of the SPA impact [4] showed that its consequences are sensitive to the thermal state of the Moon at the time of impact and hence how soon after the Moon's formation the collision occurred. Those simulations determined the likely impact energy, maximum depth of excavation, melt production and final surface distribution of crustal and mantle materials under the simplifying assumption of a vertical impact. SPA's elliptical planform and asymmetric surrounding topography, however, imply that the impact was oblique, with a trajectory approximately south to north [1].

Here we show results from high-resolution iSALE3D simulations of the formation of the SPA basin as an oblique impact in which we represent the Moon with a compositionally distinct crust, mantle, and core, and track the fate of the metallic core and silicate mantle of the impactor. Preliminary results confirm that the proximal SPA ejecta is dominated by material from the upper 200 km of the mantle [5]; and that in a 45° impact, more than 50% of the impactor core is found in the ejecta deposited on the downrange side of the basin [6].

[1] Garrick-Bethell I, Zuber MT. (2009) Icarus 204:399–408

[2] Moriarty DP, Pieters CM. (2018) JGR-Planets 123:729–47

[3] James PB, et al. (2019) GRL 46:5100–6

[4] Potter RWK et al. (2015) GSA Spec. Pap. 518:SPE518-06

[5] Melosh HJ, et al. (2017) Geology 45:1063–6

[6] Wieczorek MA, et al. (2012) Science 335:1212–5

Atmospheric Erosion by Giant Impacts onto Terrestrial Planets

Jacob Kegerreis

Durham University

Vince Eke (Durham University), David Catling (University of Washington), Richard Massey (Durham University), Luis Teodoro (BAERI/NASA Ames), Kevin Zahnle (NASA Ames)

Giant impacts dominate many planets' late accretion and evolution, including the Earth's, and can build, erode, or completely destroy a young atmosphere. We examine the mechanisms by which atmosphere can be eroded by giant impacts, based on high-resolution 3D smoothed particle hydrodynamics simulations.

In the Moon-forming collision, only around 10% of the atmosphere would have been lost from the immediate effects of a "canonical" impact, up to about 60% in more violent scenarios.

We find a new scaling law to predict the loss of atmosphere from planetary collisions for any speed, angle, impactor mass, target mass, and body compositions, in the regime of broadly terrestrial planets with relatively thin atmospheres. Different collision scenarios lead to extremely different behaviours and consequences for the planets. In spite of this complexity, the fraction of lost atmosphere is fitted well by a power law, and is independent of the total system mass for a constant impactor:total mass ratio. We find no evident departure from the trend at the extremes of the parameters explored. Slow impactors can also deliver a significant mass of atmosphere, but always accompanied by larger proportions of their mantle and core.

Animations of some of the 10^8 particle simulations are available here, coloured by their internal energy (related to the temperature):
astro.dur.ac.uk/~cklv53/research/atmos_fid_1e8_u_anim.mp4

The effect of pre-impact spin on the Moon-forming collision

Sergio Ruiz-Bonilla

Institute for Computational Cosmology, Durham University

V. R. Eke (Durham University), J. A. Kegerreis (Durham University), R. J. Massey (Durham University), L. F. A. Teodoro (BAERI/NASA Ames Research Center & University of Glasgow)

Explaining the Earth and Moon's isotopic similarity is a major challenge for giant impact models of lunar formation. We find that changing only the initial spin of the impactor can lead a collision to create a self-gravitating clump of material in a stable orbit in addition to the debris disk, which might help to alleviate the so-called isotopic crisis.

The final stage of planet formation involves giant impacts between planet-sized bodies, which are usually studied using simulation techniques such as smoothed particle hydrodynamics (SPH). We simulated the hypothesized collision between the proto-Earth and a Mars-sized impactor, Theia, that created the Moon for a variety of pre-impact spins of the impactor. Collisions that differ only in the impactor's initial spin reveal a wide variety of outcomes: a merger, a grazing hit-and-run, or the creation of an orbiting proto-Moon.

Among the resulting debris disc in some impacts, we find a stable self-gravitating clump of material. It is roughly the mass of the Moon, and has its internal composition resolved for the first time: the clump has ~29% of its mass coming from the proto-Earth's mantle, ~1% from Theia's iron core, and the remaining ~70% from Theia's mantle. The mass fraction of proto-Earth material increases linearly towards the surface of the clump. Roughly equal amounts of Theia and proto-Earth are found at the surface of the clump, quite different from the overall 70:30 split. Further thermodynamical evolution studies are needed to determine if this is a fingerprint we can observe today.

Session 2: Bombardment history II

Old and new issues with the Earth-Moon bombardment history

Simone Marchi

Southwest Research Institute

D. Nesvorny (SwRI), WF Bottke (SwRI)

The ancient (3.5 – 4.5 Ga) Earth-Moon bombardment history has been subject to intense scrutiny since the Apollo-Luna exploration of the Moon (e.g., Tera et al., 1974). In particular, the presence of a putative spike of lunar impacts at ~ 4 Ga, the so-called late heavy bombardment, has become one the most debated issues in planetary science. Several impact models have been recently proposed that seemingly fit available lunar constrains (e.g., cratering, highly siderophile elements; Bottke et al., 2012; Morbidelli et al., 2012; Marchi et al., 2014; Brasser et al., 2020), with the latest dynamical models to disfavor the existence of a late spike of impacts (Nesvorny et al., 2017, Morbidelli et al., 2018).

Lunar constraints, however, are limited. In particular, cratering data for terrains with known radiometric ages is only available for a handful of Apollo-Luna landing sites, ~ 3.5-4 Ga. In addition, cratering data is from small impactors (producing 1 km craters), thus extrapolation to larger projectiles is not straightforward. This raises the question: what else can be done to test Earth-Moon bombardment models?

In this paper, we test available impact flux models using the oldest evidence of collisions on Earth. In recent years, new evidence has been gathered on the number and magnitude of terrestrial collisions 2.4-3.2 Ga thanks to impact-generated spherule layers. We find that available impact flux models produce too few collisions on Earth compared to impact spherule layers (Marchi et al., 2021), as well as too few lunar basins (Nesvorny et al., 2017). This conclusion suggests current Earth-Moon impact models may require significant revisions.

Bottke et al., Nature 485, 2012; Brasser et al., Icarus 338, 2020; Marchi et al., Nature 511, 2014; Marchi et al., Nature Geoscience in press, 2021; Morbidelli et al., EPSL 355, 2012; Morbidelli et al., Icarus 305, 2018; Nesvorny et al., AJ 153, 2017; Tera et al., EPSL 22, 1974.

Effects of Late Accretion Impacts on Early Earth Habitability: Planetary Sterilization and Iron Delivery

Robert Citron

University of California Davis

Sarah Stewart [University of California Davis]

Late accretion onto the Hadean Earth, as constrained by the bombardment history of the Earth-Moon system, likely included a number of large impacts that could have inhibited or enhanced early habitability. Sufficiently large impacts could have sterilized the early Earth (via ocean vaporization, surface heating, or global surface melting), constraining the timing of the origin of precursors to present-day life. Alternatively, large impacts have been proposed as a catalyst for the emergence of life, delivering iron necessary to enable a reducing atmosphere favorable to the development of RNA precursors. However, despite the importance of large impacts (1000-3000 km diameter) to early habitability, only limited studies have explored their efficiency in sterilizing the early Earth or delivering reducing iron. We present 3D numerical simulations of impacts on the early Earth quantifying their effects on habitability. We find that sterilization via ocean vaporization requires a projectile >700 km in diameter, whereas sterilization via global surface melting requires a projectile 2000-2700 km in diameter. We also find that reducing environments favorable for the emergence of life are less likely to arise following large impacts than previously suggested, because >80% of the projectile iron is sequestered in the crust/mantle where it is not available to reduce surface water and form a reducing atmosphere. Although the largest expected late accretion impact (~ 1 lunar mass) could have reduced an entire ocean mass of water, such impacts would also have melted the entire surface, potentially sequestering delivered iron prior to its interaction with surface water. The hypothesis that life emerged in the aftermath of large late accretion impacts requires an efficient mechanism of harnessing the reducing power of iron sequestered in the crust/mantle or an origin of life pathway that operates in more weakly-reducing post-impact environments that utilize smaller quantities of impact-delivered iron.

The Moon’s First Billion Years: Maybe Not So Hadean After All

Nicolle Zellner

Albion College

As Earth’s nearest neighbor, the Moon’s impact flux is applied to Earth, as well as to other planetary bodies in the inner solar system. However, the characteristics of the impact flux, especially during the first billion years of Earth’s history, have been debated by scientists for decades. Even after analyses of lunar impact samples, for example, uncertainties around its profile have persisted: did the impact flux taper off after final planetary accretion and sweep-up of debris or was there a short-lived influx of impactors at ~3.9 billion years ago? Advances in acquiring, analyzing, and interpreting lunar (and other) data are allowing us to refine our interpretations of the nature and extent of the impact flux, from shortly after the solar system formed to the present. These data are allowing us to better understand how impacts may have influenced (or not) Earth’s biological and geological activities. In particular, because of evidence that indicates early Earth possessed the conditions that promoted habitability, impacts may not have been frequent or frequently intense.

Posters

Earth’s Twin Children, The Moon And Vesta, Preserve Its Earliest Records

Donald U. Wise

University of Massachusetts at Amherst, USA

This proposal changes the focus of lunar origin from impact-generated, debris cloud reassembly to whole-body fission from the impacted Early Earth. ++++ Ever since its origin, an apparent fatal flaw of “excess” angular momentum (AM) has made fission “impossible.” It required ~ 2x more AM/g than that in the present E-M System and had no specific mechanism for its removal. That mechanism, discovered in 2012, has become an integral part of current lunar origin models but the fact that it also removed fission’s fatal flaw continues to escape general notice. ++++ Following giant impact homogenization, differentiation of the global, magma ocean slowly accelerated the rotation rate of the Early Earth toward instability. At ~ 50 Ma, viscous fission spun off both the Moon and Vesta from opposite ends of the Earth as essentially unchanged samples of its extant crust and upper mantle. As twins, they share many features: a latitudinally-zoned geology generated by initial stretching and near-isotopic identity of short-lived O17 ratios in lunar samples and Vesta-sourced, HED meteorites. ++++ Immediate tidal entrapment of the nascent Moon in close orbit, in accord with the new mechanism, generated a massive, high temperature atmosphere that engulfed both E & M to erase much of that early record and transfer most “excess” AM to the Sun before lunar escape at ~ 200 Ma. Vesta’s early escape and small size limited the amount of its resurfacing while slow subsidence of its severed umbilical cord formed the great Rheasilvia Basin as its navel. The anomalous Procellarum Basin is the lunar equivalent of that birth certificate. ++++ With this origin model, the older surfaces of both twins become surviving remnants of the pre-lunar Earth’s surface with much new data to interpret and explore.

We’re drifting apart… Quantifying Lunar recession since 4.25 billion years ago

Hannah Davies

University of Lisbon

Dave Waltham (Royal Holloway University of London), Mattias Green (Bangor University)

It has become increasingly clear that Lunar recession through time is not constant. As Earth’s surface changes due to the action of plate tectonics and the supercontinent cycle, altering the morphology of ocean basins and eustasy, it affects the energetics of the tide and therefore strength of Lunar recession. Here we quantify Lunar recession through time using numerical models of the tide.

We used OTIS (Oregon State Tidal inversion software) tidal modelling results from the present day back to 1500 Myr, and at 3.9 Ga (Ga = Giga-annum) to calculate k2/Q (k2 = love number & Q = quality factor). Furthermore, we also estimate k2/Q for the period of Earth before oceans formed (before 4.25 Ga). Geodynamic reconstructions were used to obtain data back to 1500 Myr. However, to obtain tidal modelling data for 3.9 Ga, we use two methods, an ensemble of potential topographies of the Archean Earth to establish a statistically significant approximation, and topographic reconstruction of Venus with present day ocean volume imposed on it. The orbital parameters in the tidal modelling and k2/Q calculations were validated using geologically constrained Lunar semi-major axes for 55, 570, 1400, and 2480 Myrs ago.

Our hypothesis was that k2/Q remains roughly constant throughout the period from 4250 – 500 Myrs ago, remaining at 0.006 (±0.002) where it secularly increases from 500 – 0 Myrs ago, showing peaks where open ocean resonance occurs (e.g., 380 Ma and 0 Ma). The data shows an average of k2/Q for the period of 600 – 1500 Ma of 0.008 (±0.004) and for 3.9 Ga of 0.005 (±0.002). Combining those gives an average result of 0.006 (±0.002) confirming our hypothesis with current data. For the period before ocean formation, we estimate k2/Q to be 0.02 (±0.04). Hence, we cannot yet reject the hypothesis that k2/Q was very low, prior to the emergence of oceans, but we can set an upper limit of, at most, 2-3 times the present day k2/Q.

Impact Melt Scaling in Planetary Collisions

Auriol Rae

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J. Itcovitz (University of Cambridge), O. Shorttle (University of Cambridge)

The early history of the Earth-Moon system was dominated by impact cratering events, including, but not limited to the formation of the Moon itself. Following the moon-forming impact, the Earth and, to a lesser extent, the Moon experienced a number of smaller, though still large impacts which are likely to have supplied the so-called ‘late-veneer’. These impacts would have had the potential to melt significant fractions of the target body, including the formation of magma oceans. The amount of melt produced by an impact, along with the impactor composition, plays an important role in the evolution of planetary composition. In this study, we determine how impact melt volumes on Earth scale as functions of impactor velocity, impactor mass, and the target geotherm using the finite-difference shock physics code, iSALE. We compare our methodology and results to the volumes predicted by smooth particle hydrocode (SPH) simulations and consider the relationship between melt-scaling in these planetary-scale collisions and smaller impacts. Our results demonstrate the sensitivity of impact melt scaling to impact parameters and to model-based choices including: the type of model, equations of state, and the method of defining ‘melt’.

Using Deep Moonquakes To Constrain Lunar Tectonic Stresses

Alice Turner

University of Oxford

J. C. Hawthorne (University of Oxford)

Deep moonquakes have the potential to provide unique insight about the stresses acting in the deep lunar interior. Any tectonic stresses are remnants from the moon's early history and lunar mantle evolution, as earth-like convection does not occur on the moon. Here we use deep moonquake observations to constrain the tectonic stress near the A01 moonquake nest. To do so, we note that some deep moonquakes appear to slip backwards. There are two models for these backwards slipping events: there could be a large tectonic stress driving deep moonquakes that varies in space or a large tidal stress that changes in time. To discriminate between these two models, we note that the tectonic stress model implies only one slip direction: forward or back, while the tidal stress model could allow more slip directions: any combination of forward, back, left, or right. We determine the range of slip directions in the A01 nest by applying principal component analysis to the collection of seismograms. We find around 12% of the energy in the seismogram is generated by a second slip direction, which suggests that the tidal stress drives deep moonquakes and the tectonic stress near the A01 nest can be no larger than 0.1 MPa.

Session 3: Bombardment history III / Space agency presentations

Crustal porosity reveals the bombardment history of the Moon

Ya Huei Huang

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology

Jason M. Soderblom (Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology); David A. Minton (Department of Earth, Atmospheric, and Planetary Sciences, Purdue University); Masatoshi Hirabayashi (3Department of Aero

The lunar cratering record is one of the most valuable geological records in the Solar System. Interpreting this record, however, has proven challenging, especially those derived from the heavily cratered lunar highlands, which is considered incomplete because the highlands are thought to have reached an equilibrium state of crater distribution. Fortunately, a crater is not the only record an impact imparts on a crust — it also modifies the structure of the underlying crust.

Data from the Gravity Recovery and Interior Laboratory mission reveal significant amounts of crustal porosity on the Moon. Recent research has shown a clear correlation between this porosity and large lunar basins. The evolution of crustal porosity, however, is less understood. Here we propose a model that accounts for the porosity distribution in the lunar highlands. We find that both the initial porosity of basins and their cratering history are sufficient to explain most of the variation of porosity in the crust. Most porosity in a planetary crust is initially generated by basins, and subsequent impacts reduce this porosity. We conclude that the present-day surface with the lowest porosity, ~9–10%, is the oldest. Using this model, we are able to derive a more complete bombardment record from the deep-lying porosity of the lunar crust.

This model also provides insight into the historic lunar crust. We find that the ancient lunar crust was likely highly porous. This condition provides additional insulation, supporting a prolonged solidification of the lunar anorthositic crust.

Implications of a Moon-forming impact for the early Earth's oceans on volatile budget

Hilke E. Schlichting

UCLA

Previous works examining the volatile loss caused by the impact shock in the moon-forming impact find atmospheric loss of at most 20-30 per cent and essentially no loss of oceans. However, giant impacts also result in thermal heating, which can lead to significant atmospheric escape via a Parker-type wind. I will explain how H2O and other high-mean molecular weight outgassed species can be efficiently lost through this thermal wind if a hydrogen-dominated atmosphere is present. I will demonstrate that a giant impact during terrestrial planet formation can remove several Earth oceans' worth of H2O, and other heavier volatile species, together with a primordial hydrogen-dominated atmosphere, thereby substantially altering the final volatile inventory of terrestrial planets. These results may offer an explanation for the observed depletion in Earth's light noble gas budget and for its depleted xenon inventory, which suggest that Earth underwent significant atmospheric loss by the end of its accretion.

A Cataclysmic Impact Origin of Life?

Gordon Osinski

University of Western Ontario

C. S. Cockell (University of Edinburgh), A. Pontefract (Georgetown University/University of Western Ontario), H. M. Sapers (York University)

The dating of Apollo samples and lunar meteorites reveals that impact cratering rates during the first half a billion years of solar system evolution were significantly higher than the present-day. It has been widely proposed that this led to the impact frustration of life, either precluding its existence entirely, or extinguishing its presence, perhaps multiple times. This gains support from studies of the destructive environmental and biological effects of meteorite impact events, due, to a large extent, to the discovery of the ~200 km diameter Chicxulub impact structure, Mexico, and its link to the Cretaceous – Paleogene mass extinction event. The impact frustration of life, however, is at odds with evidence that the origin of life on Earth likely occurred prior to ~3.8 to ~3.9 Ga, and potentially back to ~4.1 Ga, potentially during the highest rates of impact bombardment. We propose that this conundrum can be explained by considering the beneficial effects of meteorite impacts for microbial life. Based on studies of the terrestrial impact record, these beneficial effects range from generating conditions conducive for the origin of life (e.g., clays that form catalysts for organic reactions) to varied habitats for life that persist long after an impact event, including impact-generated hydrothermal systems, endolithic habitats in shocked rocks and impact glasses, and impact crater lakes. Indeed, meteorite impacts can generate many of the previously proposed environments for the origin of life on Earth, including subaerial and submarine hydrothermal vents, hydrothermal–sedimentary settings, and impact analogues for volcanic pumice rafts and splash pools. In summary, we suggest that a paradigm shift is needed in terms of our view of the biological consequences of impact events such that impact craters, long seen as cataclysmic destructive events, may represent the most likely site(s) for the origin of life on Earth and beyond.

ESA to the Moon

James Carpenter

European Space Agency

The world is going back to the Moon with multiple missions from public and private actors from around the world planned in the coming years. Europe, through ESA, is going too with international partners, participation in the Artemis human lunar programme and the development of a large lunar lander. These activities will create new opportunities for science at the Moon.

This presentation will provide an overview of ESA's present lunar activities and the plans for the future exploration programme.

Returning to the Moon to Stay: NASA’s Artemis Program

David Draper

NASA Headquarters, Office of the Chief Scientist

James Green (NASA Headquarters, Office of the Chief Scientist)

NASA’s Artemis Program will return US astronauts to the lunar surface after more than fifty years since the final Apollo mission. Unlike that initial era, dominated by the geopolitics of the US-USSR Cold War, there is now a robust coalition of partners from governments, academia, and the commercial sector working together to achieve this next giant leap.

NASA’s first Artemis astronauts will land in the vicinity of the lunar south pole, a high-value area for science and exploration priorities. Precursors to these landings are in active development. In the coming year, the first missions in NASA’s Commercial Lunar Payload Services (CLPS) program will deliver science and exploration payloads to the lunar surface. Astronauts are actively training to conduct surface science operations under the challenging conditions expected to prevail near the lunar poles, especially the very low lighting angles. International partners such as the United Kingdom, Japan, Canada, Italy, and many other countries have indicated support through signing the Artemis Accords, and are also very active in preparing their complementary lunar missions. This talk will highlight some of the questions that these mission campaigns will help answer, such as the nature of lunar polar volatiles and the impact history of the inner Solar System.

Together, all these entities are collaborating for common goals, bringing a wide range of talents and experience to this unifying effort. The Artemis Generation needs skills and abilities from nearly all walks of life to enable this enterprise. Come join the grand adventure.

Day 2 – 30 November

Session 4: Lunar geology

Constraining the early isotope evolution of the Moon

Joshua Snape

University of Manchester

Wim van Westrenen (Vrije Universiteit Amsterdam), Alexander Nemchin (Curtin University)

In this study, we have performed a series of high pressure and temperature experiments, to investigate the trace element partitioning behaviour for minerals predicted to have formed during the crystallisation of the Lunar Magma Ocean (LMO). The focus of this work has been particularly on determining partition coefficients for parent-daughter pairs of radiogenic elements, for LMO-relevant conditions. We have compared our experimental datasets with previous studies for the same minerals and elements, and established a current best estimate for the partition coefficient of each element for the evolving mineral compositions predicted by recent LMO models. These coefficients have then been combined with the LMO model predictions, so as to model the evolving parent-daughter ratios in the LMO residual melt and crystallising components, for the four main radiogenic isotope systems that have been studied in lunar samples (Rb-Sr, Sm-Nd, Lu-Hf and U-Pb). The calculated 87Rb/86Sr, 147Sm/144Nd, and 176Lu/177Hf ratios are consistent with predictions for the mantle sources of lunar basalts and evolved lithologies. By contrast, it is difficult to explain the wide range of 238U/204Pb source ratios predicted from the Pb isotopic compositions of basaltic lunar samples. Based on current constraints, the most likely explanation for this observation is that the Moon experienced a significant loss of volatiles (including Pb), towards the end of LMO crystallisation, resulting in the dramatic U-Pb fractionation evidenced by recent sample analyses. Two potential mechanisms for this volatile loss are: (1) catastrophic degassing of the LMO, as has been described in recent magma ocean models, or (2) a large basin-forming impact(s), such as has been proposed to form the putative Procellarum basin. Distinguishing between these two degassing mechanisms is challenging, but may become less ambiguous with the return of new lunar samples, particularly those from the lunar farside.

Lunar Granulites: Recording High Temperature Metamorphism within the lunar crust

John Pernet-Fisher

University of Manchester

M. E. Hartley (Manchester) K. H. Joy (Manchester)

Metamorphic rocks on the Moon are an important yet under-studied suite of lithologies that have been identi-fied in the Apollo and lunar meteorite collections. These rocks, with granoblastic and poikilitic textures, are generally referred to as granulites. They are considered to represent the products of high-temperature (>1000 oC) thermal metamorphism that resulted in the recrystallization of primary and secondary highland lithologies. As such, the genesis of the granulite suite may represent an analogue for early metamorphic processes on the early Earth.

We report major and minor element systematics for a suite of Apollo 16 and 17 granulites in order to constrain the conditions within the crust that resulted in such high temperature metamorphism. Specifically, we aim to assess whether the granulites formed as a result of burial of the protolith by impact melt sheets or contact metamorphism of the protolith due to the emplacement of magma chambers or upwelling plutons within the lunar crust.

Pyroxene crystals within granulite samples preserve minor and trace element zoning. Experimentally derived dif-fusion rates for Ti in low Ca-pyroxenes, combined with two-pyroxene thermometry, indicates that the granulite samples investigated here were held at peak metamorphic temperatures of ~1000 oC, over timescales ranging from 450 to ~16,000 years. Additionally, we modeled the thermal gradients within highland lithologies that would result following either the emplacement of impact melt sheets at the lunar surface, or the intrusion of magmatic plutons within the crust. This modeling indicates that melt sheets >200 m thick can generate the necessary metamorphic conditions for granulites to form. Melt sheets with these thicknesses are found at impact crater > 60 km in diameter. Thus, granulites have the potential to form at the majority of impact craters found on the Moon. Consequently, lunar granulites may represent a minor, yet ubiquitous lithology within the crust.

Protosolar hydrogen source for water in the Moon and the Early Earth

Alice Stephant

Istituto Nazionale di Astrofisica

Mahesh Anand (the Open University) ; Xuchao Zhao (the Open University) ; Ian Franchi (the Open University)

The origin of endogenous water in the Moon has been a matter of long-standing debate, because of the hydrogen isotopic heterogeneities recorded by lunar samples (i.e., ~-300‰ to ~+300‰). Given the binary nature of the Earth-Moon system, the current assumption is that Moon's water originated mainly from the early Earth. Indeed, the current best estimate of the hydrogen isotopic composition of the Moon is similar to that of the present-day bulk-silicate Earth. We have measured the hydrogen isotopic composition of nominally anhydrous minerals from Apollo samples representing all of the major lunar lithologies. Our results suggest that lunar hydrogen isotopic composition heterogeneities can be reconciled in the context of a global-scale degassing of the lunar magma ocean and a light hydrogen isotopic composition for the proto-Moon is estimated (-444±46‰). Our favoured interpretation is that the light hydrogen isotopic composition of the proto-Moon also fingerprints the hydrogen isotopic signature of the early Earth. This hydrogen isotopic composition for the proto-Moon and the Early Earth is lighter than the chondritic hydrogen isotopic ratio, arguing for incorporation of D-poor nebular hydrogen in the building blocks of terrestrial planets in the early stage of the Solar System formation.

Assessing the survivability of biomarkers within terrestrial material impacting the lunar surface

Samuel Hickson Halim

Birkbeck, University of London

Ian A. Crawford (Birkbeck, University of London), Gareth S. Collins (Imperial College London), Katherine H. Joy (University of Manchester), Thomas M. Davison (Imperial College London).

We investigate the potential for terrestrial material (i.e., terrestrial meteorites) to be transferred to the Moon by a large impact on Earth and subsequently survive impact with the lunar surface, using computer modelling. Due to the near constant geological activity in the history of the Earth, organic and biological markers (biomarkers) are effectively non-existent in the geological record >3.8 billion years ago. The lunar surface has experienced much less alteration by erosional processes than the Earth, so could act as a “collection plate”, preserving a record of early Earth which the Earth itself no longer retains. Three-dimensional impact simulations show that a typical basin-forming impact on Earth can eject a small but significant mass of solid fragments at speeds sufficient to transfer from Earth to the Moon. We then use two-dimensional modelling to simulate terrestrial material impacting the lunar surface, tracking both pressure and temperature within the meteorite. Assuming that they survive launch from Earth, we show that some biomarker molecules within terrestrial meteorites are likely to survive impact with the Moon, especially at the lower end of the range of typical impact velocities for terrestrial meteorites (2.5 km/s). The survival of larger biomarkers (e.g., microfossils) is also assessed, and we find limited, but significant, survival for low impact velocity and high target porosity scenarios. Biomarkers within terrestrial meteorites that experience long durations of elevated temperatures will experience greater proportions of mass loss (thermal degradation). Shortly after impact, thermal degradation of biomarkers depends heavily upon where the meteorite lands, whether it is buried or remains on the surface, and the related cooling timescales. We conclude that terrestrial meteorites on the Moon, if they can be located, may preserve evidence of Earth’s earliest biosphere.

Session 5: Orbital evolution

The Moon-Forming Impact and its Influence on Obliquity Stability

David Waltham

Royal Holloway University of London

It is often reported that a large Moon aids axial stability, climate stability and hence habitability. This presentation shows that this assumption should be reassessed.

It is widely accepted that, without our Moon, Earth's axis would be unstable due to a three-fold drop in tidal forces and, hence, a three-fold drop in Earth's axial precession rate. Slower precession, in turn, allows chaotic, resonant interactions with the other planets of the Solar System.

It is also widely accepted that tidally driven recession of the Moon, and slowing of Earth rotation, reduce Earth's axial precession rate through time and that, as a result, resonant interactions and axial instability will set in, anyway, in 1 or 2 billion years' time.

It is less widely appreciated that larger moons slow precession more and, hence, instability sets in sooner.

There is therefore an apparent contradiction between two perfectly correct statements:

1. Removing our Moon causes instability (implying that a large moon aids stability).
2. Having a larger moon leads to earlier onset of instability (implying that a large moon is bad for stability).

Resolving this contradiction is straightforward. The first statement is irrelevant because having a large moon for 4.5 billion years, which magically disappears, is not the same as never having a large moon at all. The second statement is incomplete because it ignores the increase in system angular momentum that tends to accompany increases in moon-mass.

A better approach is needed. In this talk, I look at numerical models of the moon-forming impact and what they predict about the relationship between moon-mass and angular-momentum. This allows simulation of a population of Earth-Moon-like systems and evaluation of their stable-axis lifetimes. The results show unambiguously that "Earths" accompanied by small moons tend to have stable axes for longer than "Earths" with large moons.

Long-term Earth-Moon evolution with high-level orbit and ocean tide models

Brian Arbic

University of Michigan

James G. Williams [NASA JPL], Houraa Daher [University of Miami], Joseph K. Ansong [University of Ghana], Dale H. Boggs [NASA JPL], Malte Mueller [Norwegian Meteorological Institute], Michael Schindelegger[University of Bonn], Jacqueline Austermann [Colum

Tides and Earth-Moon system evolution are coupled over geological time. Tidal energy dissipation on Earth slows Earth's rotation rate, increases obliquity, lunar orbit semi-major axis and eccentricity, and decreases lunar inclination. Tidal and core-mantle boundary dissipation within the Moon decrease inclination, eccentricity and semi-major axis. Here we integrate the Earth-Moon system backwards for 4.5 Ga with orbital dynamics and explicit ocean tide models that are ``high-level" (i.e., not idealized). To account for uncertain plate tectonic histories, we employ Monte Carlo simulations, with tidal energy dissipation rates (normalized relative to astronomical forcing parameters) randomly selected from ocean tide simulations with modern ocean basin geometry and with 55, 116, and 252 Ma reconstructed basin paleogeometries. The normalized dissipation rates depend upon basin geometry and Earth's rotation rate. Faster Earth rotation generally yields lower normalized dissipation rates. The Monte Carlo results provide a spread of possible early values for the Earth-Moon system parameters. Of consequence for ocean circulation and climate, absolute (un-normalized) ocean tidal energy dissipation rates on the early Earth may have exceeded today's rate due to a closer Moon. Prior to ~3 Ga, evolution of inclination and eccentricity is dominated by tidal and core-mantle boundary dissipation within the Moon, which yield high lunar orbit inclinations in the early Earth-Moon system. A drawback for our results is that the semi-major axis does not collapse to near-zero values at 4.5 Ga, as indicated by most lunar formation models. Additional processes, missing from our current efforts, are discussed as topics for future investigation.

I am giving a virtual talk at Harvard University, on the capacity development work that I do in Africa, on Nov 29 at noon-1 PM US eastern time. Other than that, I would be free to give a talk at other times on Nov 29 or 30.

Milankovitch cycles in 2.46 billion-year-old banded iron formations provide a robust estimate of the Earth-Moon distance

Margriet Lantink

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Joshua Davies (Department of Earth Sciences, University of Geneva, Switzerland; Département des sciences de la Terre et de l'atmosphère, Université du Québec à Montréal, Montréal, Québec, Canada) and Frederik J. Hilgen (Department of Earth Sciences, Utrec

Tidal dissipation of energy within the ocean and Earth causes a gradual decrease in the Earth's spin velocity and causes the Moon to gradually move away from Earth. Backward projection of the present-day rate of lunar retreat, however, implies a Roche limit encounter of the Moon already ~1.5 Ga, which is incompatible with its 4.5 Ga age. Thus, over Earth's history, average rates of tidal dissipation must have been lower yet of which the details are highly uncertain. To empirically reconstruct this past evolution and test different theoretical models, the sedimentary record of the changing Milankovitch cycle periods (precession, obliquity and eccentricity) may be used. In particular for the older (Precambrian) part of the geological record, this method provides a valuable alternative for counting fossil growth bands, as such bioarchives become increasingly rare with age, and represents a potentially more robust approach than counting tidal laminae. Here we present results of cyclostratigraphic analysis and high-precision TIMS U-Pb zircon dating of ~2.46 Ga banded iron formation from Western Australia, which demonstrate the presence of climatic precession- and eccentricity-related cycles, allowing for a robust reconstruction of the shorter Earth-Moon distance and daylength based on their increased period ratio. Our results extend firm evidence for the past trajectory of lunar retreat and corresponding tidal dissipation history by more than 1 Gyr further back in time.

A tectonically active early Earth driven by the tidal recession of the Moon

Simon James Lock

Caltech (shortly moving to the University of Bristol)

Paul Asimow (Caltech)

How and when Earth developed its dichotomy of felsic continents and mafic seafloor is an enduring mystery. Earth's earliest crust was likely basaltic, but evidence from the earliest rocks and zircons suggests that the first felsic lithologies emerged within ~100 Myrs of the Moon-forming impact. In the absence of modern-day subduction, it is unclear how these first felsic materials were produced.

After the Moon-forming giant impact, Earth was rapidly rotating, with a day between ~ 5 and 2.5 hrs. Earth was significantly oblate, with a ratio of polar to equatorial radii between 0.9 and 0.5, with a very different physical structure (e.g., internal pressure, surface gravity) than at present. As the Moon receded from Earth, the planet's spin period increased and its shape changed dramatically, becoming roughly spherical within a few 10s Myrs.

We used petrological, tidal evolution, and planetary structure calculations to determine the effect of Earth's distorted and changing shape on the early crust. We find that the composition and thickness of a terrestrial crust formed by decompression melting of the primitive mantle varied with latitude due to the varying surface gravity. We demonstrate that the change in shape of Earth caused by lunar tidal recession drove extensive deformation of this early crust during the first few 10s Myr after the giant impact. There would have been extension in polar regions and convergent tectonics in the equatorial regions at rates potentially higher than those forming the Himalayas today. Such substantial deformation could have forced hydrated crust to depth, driving secondary melting and the production of more evolved magmas. A tectonically active early Earth could explain the diversity of lithologies recorded in the early zircon and rock records, and additional constraints on the rate of lunar tidal recession are needed to understand Earth's earliest surface environment and evolution.

Session 6: Magnetic fields and astrophysical records

The Paleoinclination of the Ancient Lunar Magnetic Field from an Apollo 17 Basalt

Claire Nichols

University of Oxford

Benjamin Weiss (MIT), Brenna Getzin (MIT), Harrison Schmitt (University of Wisconsin-Madison), Annemarieke Béguin (NTNU, Trondheim), Auriol Rae (University of Freiburg, University of Cambridge), Jay Shah (MIT)

Paleomagnetic studies of Apollo samples indicate that the Moon generated a magnetic field for at least 2 billion years. However, the geometry of the lunar magnetic field is still largely unknown because the original orientations of essentially all Apollo samples have not been well-constrained. Determining the direction of the lunar magnetic field over time could elucidate the mechanism by which the lunar dynamo was powered and whether the Moon experienced true polar wander. Here we present measurements of the lunar magnetic field 3.7 billion years ago as recorded by Apollo 17 mare basalts 75035 and 75055. We find that 75035 and 75055 record a mean paleointensity of ~ 50 μT. Furthermore, we could infer from 75055 and the layering of its parent boulder that the inclination of the magnetic field at the time was 34±10◦. Lunar paleodirectional data enables a test of whether the Moon's dynamo was described by an equivalent selenocentric axial dipole (SAD) relationship and to assess the implications for the dynamo mechanism and the possibility of true polar wander. Our recovered inclination is consistent with a SAD field geometry: a dipole in the center of the Moon and aligned along the spin axis. These results have implications for the lunar dynamo driving mechanism, which may also be relevant for considering how Earth's magnetic field was generated prior to inner core nucleation.

When The Moon Had a Magnetosphere

James Green

NASA Headquarters

Detailed analysis of Apollo lunar samples reveals that the Moon generated its own global magnetic field by an internal core dynamo, lasting from ~4.25 to ~2.5 billion years ago (Ga). At its peak intensity, about 4 Ga, the surface field intensity may have reached 110 μT (nearly twice that of Earth's present-day field), which it largely maintained for ~100 million years. At the time of peak lunar magnetic intensity, the Moon was also very volcanically active, generating a tenuous atmosphere and, it is believed, was at a geocentric distance of ~18 Earth radii (R_E) from Earth compared to ~60 R_E today. Solar storms are well known for stripping a planet's atmosphere over time and only a strong intrinsic magnetosphere would be able to provide maximum protection. To understand the extent to which the expected Earth-Moon coupled magnetospheres work together to protect the atmospheres of both Earth and the early Moon, simplified magnetic field modeling within a simulated magnetopause are presented. These results indicate that at times when the Moon is on the dayside of the Earth, no matter which polarity, the lunar magnetosphere would provide a significant additional buffer from the expected intense solar wind, reducing the Earth's atmospheric loss to space. In addition, during times of opposite magnetic polarity the two closely spaced magnetospheres will reduce the size of the Earth's polar cap "open" field lines thereby reducing atmospheric escape into solar wind but allowing some of the Earth's atmospheric volatiles to evaporate into the lunar environment and vice versa.

Absence of a long-lived lunar paleomagnetosphere: Opportunities for future exploration

John A. Tarduno

University of Rochester

Rory D. Cottrell (University of Rochester), Kristin Lawrence (Planetary Science Institute), Richard K. Bono (University of Liverpool), Wentao Huang (University of Rochester**, Institute of Tibetan Plateau Research; Chinese Academy of Sciences), Catherine*

Understanding whether the Moon had a long-lived magnetic field is crucial for determining how the lunar interior and surface evolved, and in particular for assessing whether a paleomagnetosphere shielded the regolith. Magnetizations from some Apollo samples have been interpreted as records of a global lunar magnetic field between ~4.2 and ~1.5 Ga that would have created shielding, but the inferred paleofields are too strong to be generated by the small lunar core. New paleointensity data from an Apollo impact glass associated with a young 2 million-year-old crater records a strong Earth-like magnetization, providing evidence that impacts can impart intense signals to samples recovered from the Moon, and other planetary bodies (Tarduno, Cottrell, Lawrence et al., Science Advances, 2021). This observation provides motivation for future lunar collections to constrain impact size - magnetization scaling relationships. Moreover, new data from silicate crystals bearing magnetic inclusions from Apollo samples formed at ~3.9, 3.6, 3.3, and 3.2, Ga are capable of recording strong core dynamo-like fields but do not, indicating the lack of a global magnetic field (Tarduno, Cottrell, Lawrence et al., Science Advances, 2021). Together, these new data indicate that the Moon did not have a long-lived core dynamo. As a result, the Moon was not sheltered by a sustained paleomagnetosphere, and the lunar regolith should hold buried 3He, water, and other volatiles resources acquired from solar winds and Earth's magnetosphere over some 4 billion years. These findings highlight the opportunity to learn about the evolution of the solar wind and Earth's earliest atmosphere during future lunar exploration. This could in turn provide key data to better understand how Earth evolved as a habitable planet despite the expected extreme solar forcing during its first billion years (Tarduno, Blackman, Mamajek, Phys. Planet Inter., 2014).

Relaxing the Assumption of a Constant Sun over Time to Understand the Effect on Cosmic Ray Exposure Age

Prabal Saxena

NASA Goddard/CRESST II/UMD-CP

Natalie Curran (Catholic U./CRESST/NASA GSFC), Vladimir Airapetian(American U./NASA GSFC), Rosemary Killen (NASA GSFC), Ian Crawford (Birbeck University of London)

Cosmic ray exposure ages are a key geological tool that are important in the studies of meteorite orbital and parent body history, dating of lunar craters and constraints on the dynamics of the lunar crust and regolith. The method for calculating the cosmic ray exposure (CRE) age and depth of burial requires a number of assumptions and models of production rates for the various cosmogenic nuclides. New research suggests that one of the primary assumptions - that the flux of primary cosmic rays has been constant in time - is probably wrong. It relies on the assumption that the Sun was constant through time with respect to the ability of the heliosphere to influence the flux and spectra of incident galactic cosmic rays (GCRs) and with respect to the number of solar energetic particles (SEPs) the Sun emitted. Recent research based on observations of the evolution of rotation of solar analogues with age suggests that the Sun likely rotated faster in the past, and consequently may have possessed higher solar wind velocities and densities, a greater frequency of coronal mass ejections, and a larger heliosphere - all of which evolved over time.

We explore how the Sun may have evolved over time in order to determine how galactic cosmic ray and solar energetic particle flux and spectra changed over time for different scenarios. We examine potential GCR incidence histories and apply them to the cosmic ray production rate equation to produce new production rate estimates on the Moon for key cosmogenic nuclides of elements such as Neon and Argon for a select set of samples in order to understand their influence on CRE age estimates. Accurate CRE age estimates will be critical for samples that are currently being opened and obtained in the future.

Lunar palaeoregolith deposits as recorders of astrophysical processes relevant to Earth's habitability

Ian Crawford

Birkbeck, University of London

Katherine Joy (University of Manchester)

The lunar surface has been exposed to the space environment for billions of years and during this time has accumulated records of a wide range of astrophysical phenomena, including ancient solar wind and the cosmogenic products of galactic cosmic rays. Owing to the Moon's relatively low level of geological activity, absence of an atmosphere, and, for much of its history, lack of a magnetic field, the lunar surface is ideally suited to collect these astronomical records. Importantly, the Moon exhibits geological processes able to bury, and thus both preserve and 'time-stamp', these records. A key concept here is that of a 'palaeoregolith' -- ancient regoliths that were exposed to the solar wind at discrete times in the past and then covered up, and thus preserved, by later geological processes. We argue here that locating and sampling such palaeoregolith deposits will yield important information on the near-Earth cosmic environment that may have influenced the conditions under which life originated and evolved on Earth.

GSL CODE OF CONDUCT FOR MEETINGS AND OTHER EVENTS

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