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Review



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Author for correspondence:

Ian A. Crawford

e-mail: i.crawford@bbk.ac.uk

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The lunar surface as a recorder of astrophysical processes


Ian A. Crawford^{1,2}, Katherine H. Joy³, Jan H. Pasckert⁴ and Harald Hiesinger⁴

¹Department of Earth and Planetary Sciences, Birkbeck College, University of London, Malet Street, London WC1E 7HX, UK

²Centre for Planetary Sciences at UCL/Birkbeck, Gower Street, London WC1E 6BT, UK

³Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, M13 9PL Manchester, UK

⁴Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany

 IAC, 0000-0001-5661-7403; KHJ, 0000-0003-4992-8750; JHP, 0000-0002-1338-5638; HH, 0000-0001-7688-1965

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. These include solar wind particles and the cosmogenic products of solar particle events which preserve a record of the past evolution of the Sun, and cosmogenic nuclides produced by high-energy galactic cosmic rays which potentially record the galactic environment of the Solar System through time. The lunar surface may also have accreted material from the local interstellar medium, including supernova ejecta and material from interstellar clouds encountered by the Solar System in the past. 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. Moreover, the Moon exhibits geological processes able to bury and thus both preserve and ‘time-stamp’ these records, although gaining access to them is likely to require a significant scientific infrastructure on the lunar surface.

This article is part of a discussion meeting issue ‘Astronomy from the Moon: the next decades’.

1. Introduction

There are multiple scientific reasons for wishing to resume the robotic and human exploration of the lunar surface, ranging from lunar geology to astrobiology (for reviews see [1–4]). Other papers in this volume are mostly concerned with the potential of the lunar surface as a platform for astronomical observations of various kinds, whereas in this contribution we argue that the lunar surface itself will have recorded much of astrophysical interest. In this sense, the Moon itself can be viewed as a giant ‘telescope’ which has been observing and recording astrophysical processes ever since it first developed a solid surface some 4.5 billion years ago.

Several factors combine to make the lunar surface an ideal, and perhaps unique, recorder of a wide range of astrophysical processes throughout Solar System history. Primarily, this is because the lunar surface, unprotected by an atmosphere or, for much of its history, a magnetic field, has been directly exposed to the space environment for most of the last 4.5 Gyr. As a consequence, particles and radiation from space have impacted the lunar surface unimpeded, leaving evidence of their presence in the rocks and soils of the lunar regolith. Examples include solar wind particles and cosmogenic products of solar energetic particle (SEP) events, and thus a record of the past evolution of the Sun, and cosmogenic nuclides produced by galactic cosmic rays (GCRs), and therefore a record of the past galactic environment of the Solar System. The lunar surface may also have accreted material from the local interstellar medium, including supernova (SN) ejecta and material from interstellar clouds encountered by the Solar System in its journey around the Galaxy. Equally as important as the collection of these astrophysical records, however, are lunar geological processes which facilitate their long-term preservation. As a relatively low-mass planetary body, whose own internal geological processes largely ceased billions of years ago, the Moon has preserved an ancient surface with some sampled crustal rocks dating from 4.3 to 4.4 Gyr [4]. Crucially, and unlike the possibly equally ancient surfaces of some asteroids, for most of its history the Moon has been sufficiently geologically active to bury, preserve and ‘time-stamp’ ancient astrophysical records in near-surface rocks and soils. Key processes include the covering of old surfaces by lava flows, pyroclastic deposits and impact crater ejecta blankets, and ancient records preserved by these processes may be recoverable by future space missions [1,5].

2. Lunar records of solar activity

Our knowledge of the past evolution of the Sun comes mainly from theoretical modelling (e.g. [6,7]) and observations of other solar-type stars having a range of ages (e.g. [8,9]). These studies indicate that, whereas the overall solar luminosity was probably only approximately 70% of its present value when the Sun formed, its faster rotation would have resulted in greatly enhanced magnetic activity and associated solar wind and UV and X-ray emission. Thus, we expect the luminosity of the Sun to have increased, and the strength of the solar wind and high-energy photon and particle emission to have decreased, throughout Solar System history. Both of these effects will have had implications for the habitability of the terrestrial planets and, in particular, for the environment within which life originated and evolved on Earth [10]. In addition, the decrease in solar magnetic activity has likely resulted in a corresponding increase in the GCR flux in the inner Solar System owing to the shrinkage of the heliosphere [11], which may also have had consequences for biological evolution on Earth.

Although generally accepted, the low total luminosity of the Sun in its early history is difficult to understand given the evidence for liquid water on the surfaces of early Earth and Mars (i.e. the ‘faint-young-Sun’ paradox [12]). Most proposed explanations invoke enhanced greenhouse gas concentrations in the atmospheres of these planets, although difficulties remain with these models [13]. One suggested alternative explanation is that the Sun may have been more massive, and thus more luminous, in the past, but that it lost several per cent of its initial mass in strong solar winds early in its history [14,15]. Observations of limited mass-loss from young solar-type stars have cast doubt on this proposal [16], but direct measurements of the strength of the solar wind through time could in principle settle the issue. In any case, it is clear that obtaining direct

observational evidence of solar activity through time would not only provide important insights into the evolution of the Sun as a star, but also improve our understanding of the evolution of the atmospheres, surface environments and habitability of the terrestrial planets. Here, we argue that the near-surface environment of the Moon has the potential to provide this valuable information.

The Sun is an emitter of both low and high-energy particles which may potentially yield information about solar processes and evolution. Solar wind particles (electrons and protons, alpha particles, and trace heavy ions with energies up to approx. 10 MeV) are emitted constantly from the Sun's corona, varying in intensity with solar activity. Higher energy (approx. $10\text{--}10^3$ MeV) particles, often referred to as solar cosmic rays (SCRs) or SEPs, are episodically emitted during solar flares and coronal mass ejection events and are able to produce a range of cosmogenic nuclides when they impact planetary surfaces (e.g. [17–19]).

Analyses of samples returned by the Apollo and Luna missions have revealed that the lunar regolith is an efficient collector of solar wind particles and cosmogenic nuclides produced by SCRs [5,17,20], and that it, therefore, potentially contains a record of past solar activity (e.g. [21–24]). In this context, determining the time dependence of both the flux and composition of the solar wind would be of interest. Whereas the overall solar wind flux is probably the most direct indicator of solar activity, in practice the surfaces of regolith particles can become saturated with solar wind [25], and the solar wind concentration retained in the regolith is influenced by each individual grain's exposure history (e.g. [25–29]). These factors may make regolith particles insensitive to recording bulk temporal flux variations. However, there is evidence that changes in solar activity also affect the relative abundances of ions in the solar wind owing to differential ionization in the solar wind source regions [30], potentially making the *composition* of the solar wind a proxy for solar activity. In addition, early solar activity, and especially the frequency of coronal mass ejection events, may have been responsible for the wholesale depletion of moderately volatile elements such as Na and K in the surficial regolith, which may also be detectable in lunar samples [31].

The implantation depths of solar wind ions into regolith particles depend on the irradiation energy, the mass of the irradiating particles and the composition (chemistry and mineral lattice structure) of the target material (e.g. [32,33]). To access these records, research has focused on the determination of the light element (H, C, O, N) and noble gas isotope (He, Ne, Ar, Kr, Xe) budgets of small rock fragments or individual mineral grains (e.g. [25,34,35]), and analysis of depth-dependent concentrations of these elements within the grains (e.g. [36]) using noble gas acid-step leaching techniques (e.g. [37]) and secondary ion microprobe analyses (e.g. [38]). However, all these efforts are constrained by the nature of the existing lunar sample collection. Of necessity, samples collected by the Apollo and Luna missions (see [39] for a review) were obtained from the present-day surface of the Moon and most have had a very long, but generally indeterminate, exposure to the solar wind. Moreover, unless they have been deeply buried and recently exhumed, surface samples are unlikely to have sampled the most ancient (i.e. several Gyr-old) solar wind that is of greatest interest in investigating early solar evolution, although progress may be made by studying solar wind trapped in ancient regolith breccias dating from that time [40]. Similar considerations apply to inferring past solar activity from cosmogenic nuclides produced by SCRs (e.g. [17,41]).

A key requirement for further progress would be to obtain independent information on the absolute ages of both the start and end times of solar wind and SCR exposure for a range of samples exposed to the space environment at widely different times in the past. Fortunately, just such 'time-stamped' samples likely exist on the Moon in the form of ancient regoliths (hereinafter 'palaeoregoliths') that were exposed to the solar wind and SCRs at discrete times in the past and then covered up, and thus preserved, by later geological processes. Obtaining such samples would greatly help in reconstructing a record of solar activity through time (although the individual grain exposure histories within sampled palaeoregolith deposits will still need to be considered).

Before leaving this discussion of lunar records of past solar activity, we draw attention to the possibility that the vertical temperature profile in the uppermost few metres of the lunar

regolith may record the history of the solar irradiance over the last several centuries [42]. Such measurements have been applied to reconstructing terrestrial surface temperature changes over similar time scales [43], but implementation on the Moon would yield a measure of solar irradiance variations free of the complexities introduced by Earth's atmosphere and climate. Building on results from the Apollo heat-flow experiments, Miyahara *et al.* [42] calculated that a temperature measurement precision of approximately 0.01°C over a depth range of approximately 10 m would be able to distinguish between different models of the total solar irradiance back to the Maunder Minimum in the mid- to late-seventeenth century. In addition to providing information on very recent solar activity, such measurements may be helpful in understanding the historical evolution of Earth's climate system. Obtaining them will require the drilling of multiple boreholes to approximately 10 m depth (i.e. five times the depths of the Apollo heat-flow measurements of approx. 2 m).

3. Lunar records of galactic processes

As the Solar System has been orbiting the Galaxy for the last 4.6 Gyr it will have experienced a wide range of different galactic environments. The recent review of galactic rotation constants provided by Vallée [44] implies that the Sun traverses the entire spiral pattern of the Galaxy every approximately 720–1760 Myr (where the uncertainty arises from continuing uncertainties in the angular velocity of the spiral arms). As the Galaxy appears to have four major spiral arms [45], this implies spiral arm passages every approximately 180–440 Myr, during which periods the Solar System may have experienced a range of interesting astrophysical phenomena including nearby SN explosions and transits through dense interstellar clouds. Reconstructing this history would provide astronomically valuable information on the structure and evolution of the Galaxy, as well as astrobiologically important information relevant for understanding the past habitability of our own planet [46–49]. Previous attempts to find correlations between spiral arm crossings and Earth's climate and extinction records have been controversial and ambiguous (e.g. [47]), in part be due to a lack of reliable geological records of the Solar System's astrophysical environment.

As reviewed in earlier publications [50,51], the lunar surface is likely to be a much better repository of this information for the same reasons that it will have preserved a record of ancient solar activity—i.e. it has been constantly exposed to the space environment throughout Solar System history, while also manifesting geological processes able to preserve records of this exposure. There are at least three forms that such records might take

- variations in the GCR flux, as recorded in the abundances of cosmogenic nuclides and/or radiation damage preserved in lunar surface rocks and soils
- direct accretion of interstellar matter and/or SN ejecta onto the lunar surface
- variations in the lunar cratering rate driven by gravitational perturbations of the orbits of comets and/or asteroids by changes in the galactic gravitational environment.

(a) Recording variations in galactic cosmic ray flux

Several galactic processes affect the GCR flux in the inner Solar System, operating on a range of time scales [52–54]. On the longest time scales (greater than 1 Gyr), the average GCR flux may reflect the galactic star formation rate, which could provide useful constraints on models of galactic evolution (although it would be necessary to account for an expected secular increase in GCR flux reaching the inner Solar System due to decreasing solar activity [11]). On time scales of the order of a few 100 Myr, the GCR flux is likely to be moderated by an enhanced SN rate, and/or collapses of the heliosphere owing to encounters with dense interstellar clouds, associated with the Sun passing through galactic spiral arms [55–57]. On still shorter time scales (tens of Myr), additional variations in the GCR flux may be expected owing to the oscillation of the Sun about the plane of the Galaxy (with a period of approx. 64 Myr and amplitude approx. 70 parsecs [57]), and possible short-term variations in the size of the heliosphere owing to fluctuations in the

local interstellar medium density [11]. Stochastic events, such as nearby (say, less than or equal to 50 parsecs) SN explosions, may be superimposed on these secular and quasi-periodic galactic influences. For example, Melott *et al.* [58] have considered the GCR flux at the Earth due to a SN at distance of 50 parsecs and find that the GCR flux could be elevated by between one and three orders of magnitude above its current value for several thousand years (see fig. 1 in ref. [58]).

There are at least two ways in which evidence for GCR variations might be recovered from exposed Solar System samples. Firstly, the high-energy GCR particles leave tracks of radiation damage in exposed materials, the density of which is proportional to the GCR flux and exposure duration [5,22,59]. Secondly, when GCRs interact with atomic nuclei in geological materials a variety of cosmogenic nuclides (e.g. ^3He , ^{10}Be , ^{21}Ne , ^{36}Cl , ^{38}Ar) are produced as a result of spallation and neutron capture reactions (e.g. [60]). Typically, these interactions occur within the uppermost metre or so of the exposed surface (e.g. [5,61]). Results of searches for GCR variations based on meteorite samples have proved to be controversial and inconclusive (e.g. [62,63]), in part because they only record an integrated GCR flux since becoming exposed to the space environment. As Wieler *et al.* [62] note ‘because of the limited sensitivity of the time-integrated GCR signals provided by meteorites, it is wise to consider ... also the differential GCR flux signals provided by terrestrial sediment samples.’ Because terrestrial samples can be dated independently of the cosmic ray flux, this is a potentially powerful approach, but is limited by the relatively recent ages of terrestrial sedimentary samples, the complexity of Earth’s geological and erosional history, and by the fact that the primary GCR flux is attenuated by the Earth’s atmosphere and magnetic field. It is here that the lunar geological record may be able to help.

Several cosmogenic nuclides have been measured in lunar samples (e.g. [22,29,33,64]), and in principle the GCR flux could be inferred by measuring the density of cosmic ray tracks and/or the concentrations of cosmogenic nuclides in exposed lunar materials. In practice, there are a number of complications, especially the generally unknown exposure and shielding histories (i.e. burial depths) of existing lunar samples. These uncertainties would be mitigated if the start and end times of the exposure of a given lunar sample, together with its burial history, could be determined independently. This will likely be key to reconstructing GCR records from which the changing galactic environment of the Solar System might be inferred. As for the solar wind history, the recovery of GCR records from buried palaeoregolith layers would be one possibility, although unlike the solar wind case the development of a surficial regolith may not be required to preserve GCR records because they will also occur at approximately metre depths within crystalline rocks.

We note in passing that a nearby SN explosion would also produce an enhancement in the neutrino flux, which in principle might be detected by damage tracks produced in mineral lattices by nuclei recoiling from a neutrino interaction. It has been proposed to search for such signals in terrestrial rock samples [65], but lunar samples would provide a longer temporal baseline and avoid the neutrino background produced in Earth’s atmosphere.¹

(b) Recording the direct accretion of interstellar matter

In its journey around the Galaxy, the Solar System will have been exposed to a range of different interstellar medium densities. As reviewed elsewhere ([66] and references cited therein), at present the Solar System appears to be located close to the boundary of a low density ($n_{\text{H}} \sim 0.1\text{--}0.2\text{ cm}^{-3}$, where n_{H} is the density of hydrogen nuclei) interstellar cloud (the ‘Local Interstellar Cloud’, LIC), which is itself located in the even lower density ($n_{\text{H}} \sim 0.005\text{ cm}^{-3}$) and approximately 100 parsec radius Local Bubble within the Local (Orion) Arm of the Galaxy. As noted by Cohen *et al.* [11], even small changes in the extent of the heliosphere caused by the Solar System moving in and out of low-density clouds like the LIC may have produced variations in the inner Solar System GCR flux on Myr time scales. On longer time scales, and especially during

¹We thank Joe Silk for this observation.

spiral arm passages, much denser interstellar environments are likely to be encountered, possibly resulting in the direct accretion of interstellar gas and dust onto the atmospheres and surfaces of the terrestrial planets [67–70].

In their study of the interaction of the Solar System with interstellar clouds, Yeghikyan & Fahr [68] found that for interstellar densities of $n_{\text{H}} \geq 1000 \text{ cm}^{-3}$ the size of the heliosphere would shrink to less than one astronomical unit, leaving the Earth (and the Moon) directly exposed to interstellar material. The frequency with which the Solar System encounters such dense interstellar clouds is uncertain, with estimates varying between approximately 300 Myr and 3 Gyr [68,70–72]. For both astronomical and astrobiological reasons it would be desirable to reduce this uncertainty, and to determine whether or not encounters with dense interstellar clouds have influenced life on Earth. Pavlov *et al.* [67] calculated that if it took 200 000 years to cross a cloud with $n_{\text{H}} \sim 1000 \text{ cm}^{-3}$ then $\sim 1 \text{ kg m}^{-2}$ of interstellar dust would be deposited on exposed planetary surfaces, where it might be identified by distinctive chemical and isotopic signatures. Given the likely ages and relatively short durations of interstellar cloud encounters, the ancient and relatively undisturbed surface of the Moon appears far more likely to retain a record of such events than the dynamic surface of the Earth, especially if they have been preserved within independently dateable palaeoregolith deposits.

In addition to collecting interstellar dust, it is also possible that airless surfaces such as that of the Moon will provide a record of the gaseous component of interstellar clouds through which the Solar System has passed. One possibility would be interstellar pick-up ions, ionized and accelerated within the heliosphere and then implanted into the surfaces of lunar regolith grains [73]. In addition, now that there is abundant evidence for volatiles trapped in permanently shadowed regions (PSRs) at the lunar poles [74], where temperatures are typically of the order of 40 K [75], it may be worth considering whether directly accreted interstellar gas penetrating the inner heliosphere during interstellar cloud traverses could have become cold-trapped onto PSR surfaces; this might be a fruitful topic for future investigation.

As reviewed elsewhere [51], another component of interstellar material that might be identified on the lunar surface would be ejecta from nearby SN explosions. There has been a long-standing recognition that SN occurring within a few tens of parsecs, and perhaps as distant as 100 parsecs, may deposit debris enriched in radioactive elements within the Solar System (e.g. [76–79]), and evidence for two such events, in the age ranges of approximately 2 and approximately 8 Myr, has been reported from ^{60}Fe deposition in ocean sediments [80–82]. Cook *et al.* [83] argued that the lunar surface has some advantages as a collector of SN ejecta as the much slower rate of surface re-working would allow it to accumulate in more concentrated layers than on Earth, and in 2016 this group [84] identified ^{60}Fe enhancements in Apollo 12, 15 and 16 soil samples (collected from depths a few centimetres or less) consistent with the approximately 2 Myr old SN event recognized in Earth ocean sediments. However, where the lunar record is likely to come into its own is in identifying debris from much older SN events than are likely to be preserved by Earth's dynamic surface environment. It is true that this will be complicated by the short half-lives ($T_{1/2} \leq$ a few Myr) of radioisotopes likely to be present in SN ejecta (see table 1 of Fry *et al.* [79] for a summary), but two such isotopes, ^{146}Sm ($T_{1/2} = 100$ Myr) and ^{244}Pu ($T_{1/2} = 80$ My), are sufficiently long-lived to have recorded one or more spiral arm passages. In addition, careful analysis of the decay products of once-live isotopes in SN ejecta (e.g. ^{26}Al , ^{53}Mn , ^{60}Fe , ^{41}Ca) might also reveal the signatures of ancient SN events. We also note that Siraj & Loeb [85] have recently suggested that SN-accelerated dust grains might leave detectable tracks in mineral surfaces exposed at the lunar surface. Any such detections of SN ejecta would be expected to correlate with evidence for enhanced GCR (and neutrino) fluxes, so these different lines of evidence for ancient SN events would be mutually supportive.

Finally, we briefly mention an even more exotic possibility: recently it has been proposed that geological materials may record interactions with some candidates for dark matter particles [86] and, should the Solar System have encountered variations in the density of such particles in its orbit around the Galaxy, the long-lived lunar geological record would appear ideally suited to recording them.

(c) Recording variations in impact cratering rate

The third category of lunar geological records with the potential to provide insights into galactic processes concerns the changing gravitational environment of the Solar System. It has long been speculated that the changing gravitational potential as the Solar System oscillates above and below the galactic plane, and passes through galactic spiral arms, may perturb the orbits of comets in the Oort Cloud and increase the impact cratering rate in the inner Solar System (e.g. [46,49,55,87–89]). Identifying possible periodicities and/or episodic spikes in the impact cratering rate, which might then be correlated with the Solar System's galactic environment, is problematical primarily because the terrestrial impact record is so sparse [90]. By contrast, the lunar surface holds an essentially complete impact record for most of Solar System history [91]. It follows that, by obtaining and dating samples of impact melt from a sufficiently large number (possibly hundreds) of lunar craters, it ought to be possible to determine unambiguously whether or not temporal variations in the impact flux have occurred and are correlated with galactic structure (although if most of the impactors were from the asteroid belt rather than from comets [92] any galactic signal might be muted). Note that we would expect any galactic periodicity in the cratering rate to be correlated with the GCR flux, which is also recorded on the Moon. Obtaining such a complete impact record for the Moon would also have many other benefits for planetary science, including refining the inner Solar System impact cratering chronology and constraining models of the dynamical evolution of planetary orbits (e.g. [4] and references cited therein).

4. Preserving the record

The Moon will only record a history of past astrophysical processes if evidence for them has reached the surface and then been preserved by lunar geological processes. Before turning to the means of preservation, it is important to consider whether the lunar surface has always been as open to external influences as it is today. There are at least two aspects to consider: the ancient lunar magnetic field, and a possible early atmosphere.

Palaeomagnetic studies of Apollo samples suggest that between approximately 4.2 and approximately 3.6 Gyr ago the Moon had a core-generated magnetic field comparably strong to the Earth's present-day magnetic field (i.e. several tens of μT), which then declined by at least an order of magnitude prior to 3.2 Gyr ago [93]; it may have persisted at this reduced level (approx. $5\mu\text{T}$) until about 2.5 Gyr ago, finally ceasing (less than $0.1\mu\text{T}$) sometime before approximately 1 Gyr ago [94]. As a consequence, at least during the early part of this time period, the Moon's surface would have been partially shielded from the solar wind, so this would need to be taken into account in interpreting the most ancient solar wind records; possibly samples collected close to palaeomagnetic poles, where the magnetic field lines would tend to channel charged particles to the surface, would be preferred for such studies. On the other hand, high-energy GCRs, and uncharged particulate material (e.g. SN ejecta and interstellar dust particles) would not be expected to be significantly affected by an early lunar magnetic field. The presence of an ancient lunar atmosphere would potentially impede a wider range of exogenous material from reaching the surface, including some fraction of the primary GCRs. Given the Moon's low gravity, its only realistic opportunity to accumulate an atmosphere would be during periods of intense volcanic activity when the rate of magmatic degassing might transiently exceed the rate of atmospheric loss. Based on these arguments, Needham & Kring [95] estimated that a transient lunar atmosphere having a surface pressure of up to approximately 9 mbar (i.e. 1.5 times higher than the current atmospheric pressure on Mars) might have persisted for approximately 70 Myr at the peak of mare volcanism. On the other hand, Wilson *et al.* [96] have argued that the intervals between individual mare eruptions (approx. 20 000–60 000 years) would have been too long for such a transient atmosphere to accumulate. In any case, it appears that any ancient lunar atmosphere would only have affected the accumulation of astronomical records on the Moon's surface for geologically brief periods approximately 3.5 Gyr ago.

Assuming that they reach the lunar surface unimpeded, the various astronomical records discussed in this paper will only have survived in detectable quantities if geological processes have acted to preserve them. This is especially true of material deposited directly onto the surficial regolith (e.g. solar wind particles, interstellar pick-up ions and accreted interstellar material) because otherwise these records will be disturbed and diluted by the continuous comminution and overturning (gardening) of the regolith by the unremitting impact of small meteoroids [20]. Owing to the deeper (order metre) penetration depths of GCRs, the record of cosmogenic nuclide formation, required to reconstruct variations in the GCR flux, is probably less sensitive to surficial regolith processing, but any record dating back hundreds of millions of years will still need to be protected from the disturbing effects of larger meteorite impacts. To illustrate this point, consider the solar wind and cosmogenic nuclei extracted from surface regolith samples collected by the Apollo missions. Solar wind and cosmogenic noble gases have been extracted from regolith samples collected at all six landing sites (see [33] for a recent review). However, these regoliths have mostly been developed on surfaces with ages exceeding 3 Gyr (e.g. [97]) so any evidence for temporal variations within them will have been smeared out by impact-induced gardening during these vast spans of time. Some exceptions are provided by samples collected on the ejecta blankets of young impact craters, such as South Ray crater (Apollo 16; estimated age 2 Myr), Cone crater (Apollo 14; 25 Myr) and North Ray crater (Apollo 16; 53 Myr), but these estimated ages [91] are mostly derived from cosmic ray exposure, so are not independent of the GCR fluxes that we seek to determine.

What we really need is to identify materials (e.g. palaeoregoliths) that were once exposed at the lunar surface for a known duration and which were subsequently covered by overlying material so that they have been isolated from the space environment ever since. Fortunately, there are at least three geological processes that will have acted to cover, and therefore preserve, pre-existing surfaces throughout lunar history:

- eruption of low-viscosity basaltic lava flows
- deposition of pyroclastic deposits around sites of explosive volcanism
- emplacement of impact crater ejecta blankets.

There are pros and cons associated with all three preservation mechanisms, which we now discuss.

(a) Lava flows

Basaltic lava flows cover approximately 17% of the lunar surface, mostly on the nearside, and their generally low viscosity and apparently laminar flow [98,99] suggests that palaeoregolith layers may be preserved beneath or between them. Once sampled, basalts can be dated to high accuracy using standard radiometric techniques (e.g. [97]), so the ages of palaeoregoliths trapped between lava flows could in principle be well constrained [5]. However, most mare basalts appear to have been erupted within the relatively narrow time interval between about 3.8 and 3.3 Gyr [100] (although older lava flows may be buried by younger ones now exposed at the surface), and there is no evidence for large-scale basaltic volcanism more recently than approximately 1 Gyr ago. It follows that palaeoregoliths dating from the last approximately 1 Gyr, which more or less encompasses the Solar System's most recent traverse of the galactic disc, are unlikely to be preserved between lunar lava flows unless younger, smaller scale, eruptions have occurred. In this context, it is worth noting that small patches of basaltic lavas, apparently erupted within the last 100 Myr, may have been identified on orbital imagery [101]. However, although these localities could potentially preserve valuable astronomical records from an important time interval, such young lavas are unexpected on the basis of our current understanding of lunar geology and the original interpretation of some of these features has been questioned [102]. Clearly further work to determine whether or not basaltic lava flows with ages less than 1 Gyr exist on the Moon would be desirable.

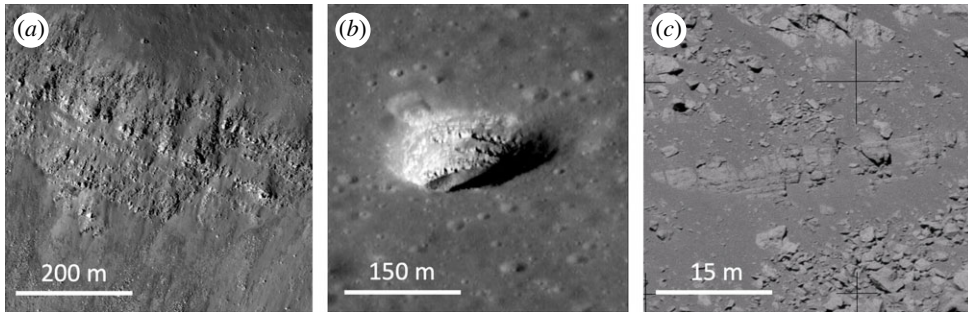


Figure 1. (a) Mare basalt stratigraphy in Mare Serenitatis exposed in the wall of the 16 km diameter impact crater Bessel (21.8° N, 17.9° E; LROC image M135073175R/NASA/GSFC/ASU). (b) Similar layering exposed in walls of a collapse pit in Mare Ingenii on the farside (36.0° S, 166.1° E LROC image M184810930 L/NASA/GSFC/ASU). (c) Metre-scale basalt layers exposed in the wall of Hadley Rille (26.1° N, 3.6° E) photographed by Apollo 15 astronaut David Scott using a 500 mm focal length lens; the outcrop is about 1300 m from the camera (NASA image AS15-89-12104).

Probably the main disadvantage of lunar lava flows as preservers of astronomical records within buried regolith layers is the heating of the regolith substrate by the overlying lava when it is emplaced. Detailed studies of this process [103] indicate that the uppermost approximately 20 cm of regolith covered by a 1 m thick lava flow would likely experience at least partial degassing of implanted volatiles, with thicker lava flows requiring approximately proportional thicker regolith to provide adequate insulation. This sets a lower limit to the thickness of palaeoregoliths able to preserve a good record of solar wind and other implanted volatiles. As regolith production rates are thought to be in the range $1\text{--}5\text{ mm Myr}^{-1}$ (where the lower value is the estimated present-day rate and the higher value relates to fresh basaltic surfaces approximately 3.8 Gyr ago [104,105]), it follows that fresh surfaces would need to be exposed for tens to hundreds of Myr to accumulate regoliths thick enough to shield implanted volatiles from an overlying lava flow. These long regolith accumulation times would lead to a loss of temporal resolution for any astrophysical records they contain. However, it is worth mentioning the recent suggestion [106] that degassing of some mare lavas may result in the formation of metre-thick fragmented layers, ‘auto-regoliths’, on their surfaces. If present, these would assist in the preservation of volatiles should they subsequently be covered by younger lavas. We also reiterate that a thick palaeoregolith is less of a necessity for the preservation of non-volatile records (e.g. heavy nuclei delivered as SN ejecta and some of the less mobile cosmogenic nuclei produced by GCRs) as these may be preserved within layered basalts lacking interbedded regoliths (such as those shown in figure 1).²

We illustrate the concept of palaeoregolith preservation and dating with the aid of a prominent lava flow on the surface of Mare Imbrium (figure 2). Here, a younger lava flow overlies older mare basalts, so we would expect a palaeoregolith layer to be preserved underneath it. This palaeoregolith layer will contain material reaching the surface of the Moon in the time period between the emplacement of the under- and overlying lavas. Ideally, radiometric dating of returned samples would provide these ages, but as none have yet been obtained from this region we have used standard crater size-frequency distribution (CSFD) measurements to model the ages of these flows (for details see electronic supplementary material). Based on our CSFD measurements, the underlying basalts have an absolute model age of $3.30^{+0.04}_{-0.05}$ Gyr, while the overlying lava flow has an absolute model age of $3.03^{+0.12}_{-0.17}$ Gyr. We, therefore, hypothesize that sandwiched between these two lava flows there will be a trapped palaeoregolith layer containing records of the solar wind, SCRs, GCRs and possibly other astronomically valuable records,

²Although insulation provided by even a thin regolith may be helpful in preserving more volatile GCR products (e.g. ^{36}Cl , $^{37,39}\text{Ar}$) and in preventing the annealing of radiation damage tracks (we thank one of our referees, Gregory Herzog, for this observation).

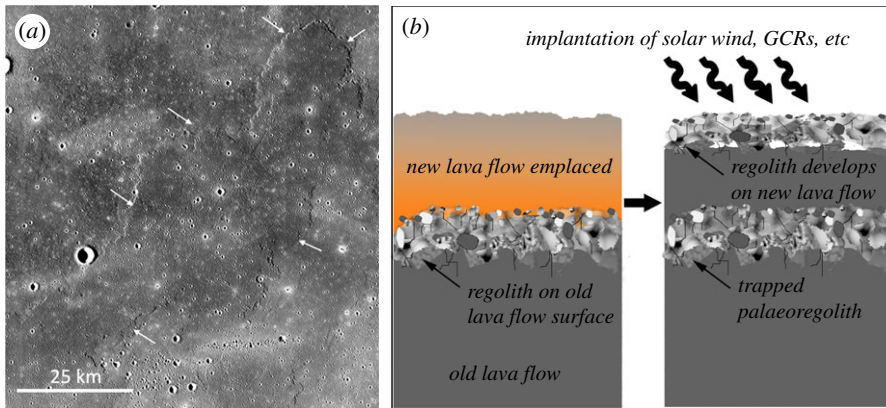


Figure 2. (a) A prominent lava flow (arrows) on the surface of Mare Imbrium (31.5° N, 338.0° E; Kaguya Terrain Camera/JAXA). Based on CSFD measurements (see electronic supplementary material), we obtain an absolute model age of $3.03^{+0.12}_{-0.17}$ Gyr for this lava flow, and an age of $3.30^{+0.04}_{-0.05}$ Gyr for the older lava flows over which it has flowed, so we expect an approximately 3 Gyr old palaeoregolith to be trapped between the two (see text). (b) Schematic illustration of the trapping of a palaeoregolith layer by an overlying lava flow; a palaeoregolith such as this would be expected to contain solar wind, GCR, and other astrophysical records that were implanted during its time on the surface, meanwhile a new regolith develops on the younger lava flow and captures more recent astrophysical records. (Online version in colour.)

that reached the surface of the Moon within the approximately 300 Myr period separating the emplacement of these two lava flows.

Estimating the extent to which any underlying palaeoregoliths will have been heated by overlying lava flows such as this, as well as drawing up plans for sampling them, requires an estimate of the lava flow thickness. In this case, the CSFD of the underlying surface shows that all measured crater sizes have been resurfaced by the upper lava flow, yielding a minimum flow thickness of approximately 20 m (see electronic supplementary material). If emplaced as a single lava flow of this thickness the modelling of Rumpf *et al.* [103] would imply that a palaeoregolith below it would need to be several metres thick in order to prevent thermal degassing of solar wind and other trapped volatiles. Such a thick regolith is unlikely to have been generated in the approximately 300 Myr available given the estimated $1\text{--}5\text{ mm Myr}^{-1}$ regolith formation rates. On the other hand, there is evidence, for example, layers exposed in the wall of Hadley Rille (figure 1c) that some mare basaltic lava flows are built up of multiple thinner (approx. 1 m thick) layers, and if this were the case here it would help reduce the propagation of heat into an underlying regolith [103]; the same would apply if the underlying lava had developed a fragmental ‘auto-regolith’ on eruption [106]. In any case, as stressed above, non-volatile and some GCR-produced cosmogenic nuclides are much less susceptible to thermal disturbance and are likely to be preserved even under such a relatively thick lava flow.

We stress that we have here merely used these Imbrium lava flows as an example. The comprehensive mapping and dating of mare basalts presented by Hiesinger *et al.* [100] indicate that there are hundreds of large (greater than or equal to 50 km in size; fig. 17 of [100]) lava flows on the lunar surface spanning the age range approximately 4.0–1.0 Gyr, and doubtless many thousands of smaller examples such as that discussed here, all with the potential to preserve underlying palaeoregolith layers with a correspondingly wide range of ages. Moreover, as noted above, stacks of layered lava flows (figure 1) have the potential to preserve some astronomically important records (e.g. the GCR flux) in the absence of interleaved palaeoregolith layers. That said, unless evidence for small-scale basaltic volcanism within the last approximately 1 Gyr is confirmed (e.g. [101]), lava flows are unlikely to preserve astronomical records within this timeframe.

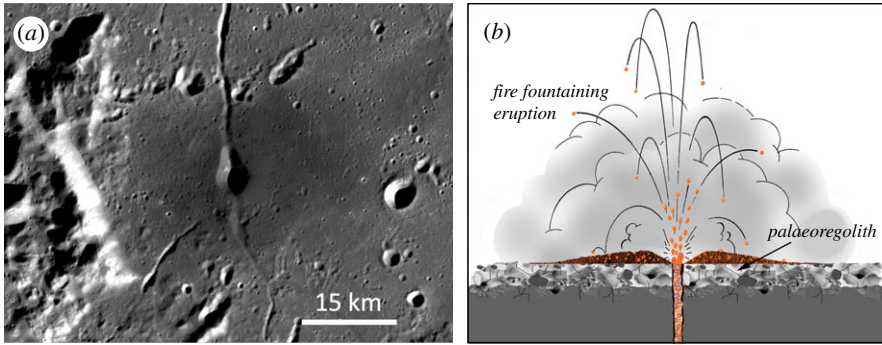


Figure 3. (a) Dark pyroclastic materials surrounding a presumed volcanic vent in the Schrödinger Basin on the lunar farside (75.3° S, 139.2° E; LROC image/NASA/GSFC/ASU). (b) Schematic illustration of a pyroclastic eruption covering a pre-existing regolith to preserve a palaeoregolith underneath (adapted with thanks from LPI CLSE Higher Education Resources). (Online version in colour.)

(b) Pyroclastic deposits

In addition to the effusive eruption of low-viscosity mare basalts, lunar magmatic processes have also resulted in occasional explosive or pyroclastic volcanism [107,108]. The resulting pyroclastic deposits are fine-grained units of basaltic glass fragments mantling surfaces around volcanic vents (figure 3), with sizes ranging from approximately 10 km² to approximately 50 000 km² and thicknesses estimated at several metres [107,109]. McKay [110] has argued that pyroclastic deposits may be the best preservers of palaeoregoliths owing to their relatively gentle mode of emplacement. Moreover, because the small (typically tens of micrometres in diameter) basaltic glass fragments that make up the deposits would have mostly cooled and solidified before impacting the surface, the buried regolith would not be subject to the thermal disturbances associated with burial by active lava flows.

The main disadvantage of pyroclastic deposits in the present context is the ancient, and relatively brief, time periods in which they formed, dating from the main phase of lunar mare volcanism with an estimated age range of 3.8–3.2 Gyr [100,110]. While doubtless preserving valuable records of the early Sun, palaeoregoliths buried by currently identified pyroclastic deposits are, therefore, unlikely to preserve more recent galactic influences on the Solar System. As in the case for basaltic lava flows, a search for more recent pyroclastic deposits would be valuable.

(c) Ejecta blankets and impact melt deposits

Impact cratering has been continuous throughout lunar history [91], so palaeoregoliths covered by crater ejecta blankets and/or impact melt deposits (figure 4) have the potential to preserve records from more recent times than those covered by lava flows or pyroclastic deposits. This will be especially important if we seek well-resolved temporal records for the Solar System's most recent orbit around the Galaxy. Dating the emplacement of crater ejecta blankets could be achieved by sampling and radiometrically dating associated impact melt (e.g. [111–113]). Importantly, such ages would be independent of assumptions regarding the GCR and solar wind fluxes that we wish to reconstruct from the underlying palaeoregoliths. If the pre-existing regolith was developed on a basaltic lava flow, this too could be sampled and dated, thereby locating the palaeoregolith sandwiched between lava flow and ejecta blanket in a well-constrained time window.

Although impact melt deposits have the potential to preserve palaeoregoliths in the same way as lava flows, they suffer from the same potential disadvantage of thermally disturbing volatile

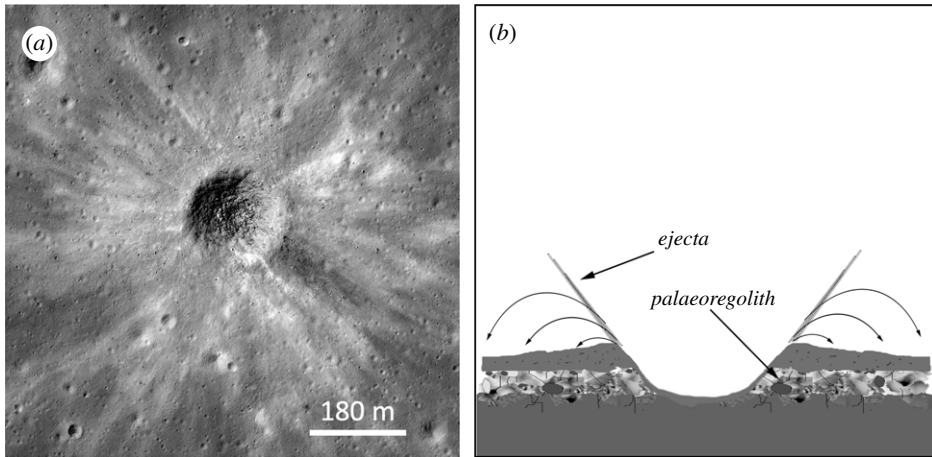


Figure 4. (a) An unnamed fresh 185 m diameter impact crater in Mare Nubium (20.9° S, 350.3° E; LROC image M183588912R: NASA/GSFC/ASU); note the prominent ejecta blanket. (b) Schematic illustration of a crater ejecta blanket covering a pre-existing regolith to preserve a an underlying palaeoregolith.

records. The same may be true of palaeoregoliths buried by thick ejecta blankets from large craters which may contain significant volumes of impact-heated materials [114]. On the other hand, the ejecta of small craters is not thought to be at a high temperature when emplaced, so the main uncertainty in their value as preservers of buried palaeoregoliths is the degree to which the pre-existing surface is mechanically disturbed in the process. As the ejecta is mostly emplaced ballistically [115], this is likely to depend on the size of the impact and the distance from it, and may be quite variable. It is also likely to disturb some records more than others, with very surficial records (e.g. solar wind, pick-up ions and SN ejecta) being more disturbed than deeper-lying cosmogenic nuclides produced by GCR interactions. Further work on the mechanical and thermal effects of impact ejecta emplacement would be desirable.

5. Locating and accessing the record

Gaining access to these astronomical records will present considerable technical challenges. There are two main aspects: identifying the most promising locations where such records are likely to be preserved, and accessing and sampling these locations.

(a) Locating the records

We have argued that the astronomical records we seek will be preserved in sub-surface layers, such as buried palaeoregoliths or lava flows, that were once exposed at the lunar surface. Practical considerations suggest that an initial search must be based on surface features accessible to remote-sensing techniques that are indicative of the likely presence of suitable sub-surface deposits. Examples include the geological mapping and dating of surface lava flows (e.g. [100]), pyroclastic deposits (e.g. [107]), and the ejecta blankets of small Copernican-aged craters. In addition, high-resolution images of the lunar surface have revealed multiple locations where sub-surface layers outcrop in the walls of rilles, craters and collapse pits ([99]; figure 1). Studies of areas where small impact craters have penetrated overlying materials to reveal sub-surface boundaries may also help identify suitable locations [116], as would orbital ground-penetrating radar measurements [117]. Ultimately, it will probably be necessary to visit a sub-set of identified localities with robotic or human explorers employing geophysical techniques, such

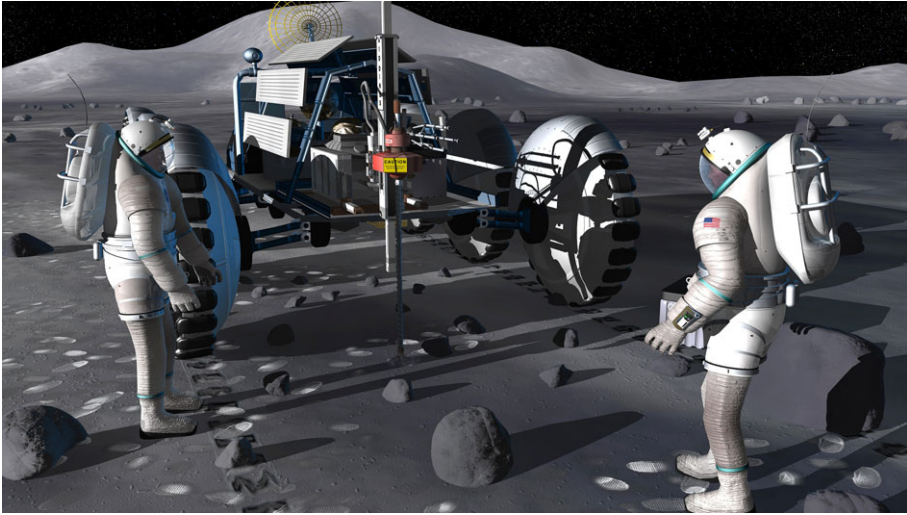


Figure 5. Artist's concept of astronauts supervising a lunar drilling system. Such a capability would permit access to the sub-surface, for example, to extract palaeoregolith samples containing ancient solar wind and GCR records, and is an example of how astrophysics, among other sciences, could benefit from establishing a human-tended research infrastructure on the Moon (image credit: NASA). (Online version in colour.)

as ground-penetrating radar [118,119] or refraction seismology [120], to confirm the existence of suitable sub-surface deposits and to assess the practicalities of sampling them.

(b) Accessing the records

An optimal architecture for accessing and sampling sub-surface deposits would provide for the following capabilities [50,51]:

- ability to deploy equipment at a wide (preferably global) range of locations on the lunar surface
- surface mobility, ideally with a range of several tens of km around a given landing site (for example, this would permit access to the boundaries of lava flows having a wide range of ages; see e.g. the mare basalt maps provided by Hiesinger *et al.* [100])
- detection of sub-surface palaeoregolith deposits (e.g. using ground-penetrating radar or active seismic profiling [119,120])
- access and sampling of outcrops on steep slopes such as crater walls or entrances to collapse pits (e.g. [121])
- drilling from 10s of metres to perhaps approximately 100 m depths (for a review of suitable planetary drilling technology see [122,123])
- return of samples to Earth for analysis; the quantity required will depend on the number and types of sites (e.g. palaeoregolith layers) sampled, but based on the analysis of Shearer *et al.* [124] we estimate this to be approximately 100 kg for each exploration mission or sortie (which would presumably visit multiple individual localities; compare with the 110 kg returned by the Apollo 17 mission).

Although some of these capabilities might be achievable with suitable designed robotic missions (e.g. [121]), as argued elsewhere (e.g. [1,2]) large-scale exploratory activities such as these would be enhanced by renewed human operations on Moon (figure 5). Especially enabling would be the creation of one or more permanently, or semi-permanently, occupied scientific research stations on the lunar surface, as exemplified by the 'Moon village' concept advocated by the

Director General of the European Space Agency [125]. The creation of such an outpost would offer significant opportunities by providing a scientific infrastructure on the lunar surface, just as human outposts in Antarctica facilitate research activities across multiple scientific disciplines [126–128].

6. Conclusion

The Moon is likely to preserve a rich historical record of astrophysical processes relevant to understanding the evolution of the Sun and its changing galactic environment. In order to access these records, it will be necessary to collect samples from sub-surface strata that were directly exposed to the space environment at known times in the past and for known durations. Such geological records undoubtedly exist on the Moon but accessing them will require a greatly expanded program of lunar exploration. Ideally, this will include the eventual establishment of Antarctic-style research stations to support large-scale exploration activities. Such a research infrastructure would also support a wide range of other scientific activities on the Moon [2,4], including, in the present context, observational astronomy and astrophysics.

Data accessibility. Additional data can be found in the associated electronic supplementary material.

Authors' contributions. I.A.C. conceived the paper and drafted most of the manuscript. K.H.J. provided most of the expertise relating to solar wind in the lunar regolith and produced the diagrams illustrating palaeoregolith preservation. J.H.P. and H.H. performed the CSFD measurements of the Imbrium lava flows. All authors provided intellectual content and critically reviewed the whole manuscript prior to submission.

Competing interests. We declare we have no competing interests.

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References

1. Spudis PD. 1996 *The once and future moon*. Washington, DC: Smithsonian Institution Press.
2. Crawford IA, Anand M, Cockell CS, Falcke H, Green DA, Jaumann R, Wieczorek MA. 2012 Back to the Moon: the scientific rationale for resuming lunar surface exploration. *Planet. Space Sci.* **74**, 3–14. (doi:10.1016/j.pss.2012.06.002)
3. Crotts A. 2014 *The new moon: water, exploration and future habitation*. Cambridge, UK: Cambridge University Press.
4. Tartèse R, Anand M, Gattacceca J, Joy KH, Mortimer JI, Pernet-Fisher JF, Russell S, Snape JF, Weiss BP. 2019 Constraining the evolutionary history of the Moon and the inner Solar System: a case for new returned lunar samples. *Space Sci. Rev.* **215**, 54. (doi:10.1007%2Fs11214-019-0622-x)
5. McKay DS, Heiken GH, Basu A, Blanford G, Simon S, Reedy R, French BM, Papike J. 1991 The lunar regolith. In *The lunar sourcebook: a user's guide to the moon* (eds GH Heiken, D Vaniman, BM French), pp. 285–356. Cambridge, UK: Cambridge University Press.
6. Gough DO. 1981 Solar interior structure and luminosity variations. *Sol. Phys.* **74**, 21–34. (doi:10.1007/BF00151270)
7. Guzik JA, Neuforge-Verheecke C, Young AC, Epstein RI, Poulin FM, Schissel JR. 2001 Standard and non-standard solar models. *Sol. Phys.* **200**, 305–321. (10.1023/A:1010398627973)
8. Güdel M. 2007 The sun in time: activity and environment. *Living Rev. Sol. Phys.* **4**, 3. (doi:10.12942/lrsp-2007-3)
9. O'Fionnagáin D, Vidotto AA. 2018 The solar wind in time: a change in the behaviour of older winds? *Mon. Not. R. Astron. Soc.* **476**, 2465–2475. (doi:10.1093/mnras/sty394)
10. Airapetian VS, Glocer A, Gronoff G, Hébrard E, Danchi W. 2016 Prebiotic chemistry and atmospheric warming of early Earth by an active young Sun. *Nat. Geosci.* **9**, 452–455. (doi:10.1038/ngeo2719)

11. Cohen O, Drake JJ, Kóta J. 2012 The cosmic-ray intensity near the Archean Earth. *Astrophys. J.* **760**, 85. (doi:10.1088/0004-637X/760/1/85)
12. Sagan C, Mullen G. 1972 Earth and Mars: evolution of atmospheres and surface temperatures. *Science* **177**, 52–56. (doi:10.1126/science.177.4043.52)
13. Feulner G. 2012 The faint young Sun problem. *Rev. Geophys.* **50**, RG2006. (doi:10.1029/2011RG000375)
14. Graedel TE, Sackmann I-J, Boothroyd AI. 1991 Early solar mass loss: a potential solution to the weak sun paradox. *Geophys. Res. Lett.* **18**, 1881–1884. (doi:10.1029/91GL02314)
15. Whitmire DP, Doyle LR, Reynolds RT, Matese JJ. 1995 A slightly more massive young Sun as an explanation for warm temperatures on early Mars. *J. Geophys. Res.* **100**, 5457–5464. (doi:10.1029/94JE03080)
16. Gaidos EJ, Güdel M, Blake GA. 2000 The Faint Young Sun Paradox: an observational test of an alternative solar model. *Geophys. Res. Lett.* **27**, 501–503. (doi:10.1029/1999GL010740)
17. Reedy RC. 1980 Lunar radionuclide records of average solar-cosmic-ray fluxes over the last ten million years. In *The ancient Sun: fossil record in the earth, moon and meteorites* (eds RO Pepin, JA Eddy, RB Merrill), pp. 365–386. New York, NY: Pergamon Press.
18. Reames DV. 2013 The two sources of solar energetic particles. *Space Sci. Rev.* **175**, 53–92. (doi:10.1007/s11214-013-9958-9)
19. Schmelz JT, Reames DV, Von Steiger R, Basu S. 2012 Composition of the solar corona, solar wind, and solar energetic particles. *Astrophys. J.* **755**, 33. (doi:10.1088/0004-637X/755/1/33)
20. Lucey PG *et al.* 2006 Understanding the lunar surface and space-Moon interaction. *Rev. Min. Geochem.* **60**, 82–219. (doi:10.2138/rmg.2006.60.2)
21. Kerridge JF. 1975 Solar nitrogen: evidence for a secular change in the ratio of nitrogen-15 to nitrogen-14. *Science* **188**, 162–164. (doi:10.1126/science.188.4184.162)
22. Crozaz G, Walker R M, Zinner E, Morrison DA, Poupeau G. 1977 The record of solar and galactic radiations in the ancient lunar regolith and their implications for the early history of the Sun and Moon. *Phil. Trans. R. Soc. Lond. A* **285**, 587–592. (doi:10.1098/rsta.1977.0103)
23. Wieler R, Kehm K, Meshik AP, Hohenberg CM. 1996 Secular changes in the xenon and krypton abundances in the solar wind recorded in single lunar grains. *Nature* **384**, 46–49. (doi:10.1038/384046a0)
24. Wieler R. 2016 Do lunar and meteoritic archives record temporal variations in the composition of solar wind noble gases and nitrogen? A reassessment in the light of Genesis data. *Geochemistry* **76**, 463–480. (doi:10.1016/j.chemer.2016.06.001)
25. Pepin RO, Becker RH, Schlutter DJ. 1999 Irradiation records in regolith materials. I: isotopic compositions of solar-wind neon and argon in single lunar mineral grains. *Geochim. Cosmochim. Acta* **63**, 2145–2162. (doi:10.1016/S0016-7037(99)00002-2)
26. Nishiizumi K, Arnold R, Klein J, Middleton R, Goswami JN. 1985 Cosmogenic nuclides in 15011 rocklets. In *16th Lunar and Planetary Science Conf., Houston, TX, March 1985*, pp. 620–621. (<http://articles.adsabs.harvard.edu//full/1985LPL...16..620N/0000621.000.html>)
27. Jull AJT, Pillinger CT. 1977 Effects of sputtering on solar wind element accumulation. *Proc. Lunar Planet. Sci. Conf.* **8**, 3817–3833.
28. Housley RM. 1980 Toward a model of grain surface exposure in planetary regoliths. In *The ancient sun: fossil record in the earth, moon and meteorites* (eds RO Pepin, JA Eddy, RB Merrill), pp. 401–410. New York, NY: Pergamon Press.
29. Levine J, Renne PR, Muller RA. 2007 Solar and cosmogenic argon in dated lunar impact spherules. *Geochim. Cosmochim. Acta* **71**, 1624–1635. (doi:10.1016/j.gca.2006.11.034)
30. Baker D, Brooks DH, van Driel-Gesztelyi L, James AW, Démoulin P, Long DM, Warren HP, Williams DR. 2018 Coronal elemental abundances in solar emerging flux regions. *Astrophys. J.* **856**, 71. (doi:10.3847/1538-4357/aaadb0)
31. Saxena P, Killen RM, Airapetian V, Petro NE, Curran NM, Mandell AM. 2019 Was the Sun a slow rotator? Sodium and potassium constraints from the lunar regolith. *Astrophys. J.* **876**, L16. (doi:10.3847/2041-8213/ab18fb)
32. Wieler R. 1998 The solar noble gas record in lunar samples and meteorites. *Space Sci. Rev.* **85**, 303–314. (doi:10.1023/A:1005166904225)
33. Curran NM, Nottingham M, Alexander L, Crawford IA, Füre E, Joy KH. 2020 A database of noble gases in lunar samples in preparation for mass spectrometry on the Moon. *Planet. Space Sci.* **182**, 104823. (doi:10.1016/j.pss.2019.104823)

34. Pillinger CT. 1979 Solar-wind exposure effects in lunar soil. *Rep. Prog. Phys.* **42**, 897–968.
35. Palma RL, Becker RH, Pepin FO, Schlutter DJ. 2002 Irradiation records in regolith materials II: solar wind and solar energetic particle components in helium, neon, and argon extracted from single lunar mineral grains and from the Kapoeta howardite by stepwise pulse heating. *Geochim. Cosmochim. Acta* **66**, 2929–2958. (doi:10.1016/S0016-7037(02)00853-0)
36. Grimberg A, Baur H, Bochsler P, Bühler F, Burnett DS, Hays CC, Heber VS, Jurewicz AJG, Wieler R. 2006 Solar wind neon from genesis: implications for the lunar noble gas record. *Science* **314**, 1133–1135. (doi:10.1126/science.1133568)
37. Wieler R, Baur H, Signer P. 1986 Noble gases from solar energetic particles revealed by closed system stepwise etching of lunar soil minerals. *Geochim. Cosmochim. Acta* **50**, 1997–2017. (doi:10.1016/0016-7037(86)90255-3)
38. Hashizume K, Chaussidon M, Marty B, Robert F. 2000 Solar wind record on the Moon: deciphering presolar from planetary nitrogen. *Science* **290**, 1142–1145. (doi:10.1126/science.290.5494.1142)
39. Heiken GH, Vaniman D, French BM (eds). 1991 *The lunar sourcebook: a user's guide to the moon*. Cambridge, UK: Cambridge University Press.
40. Fagan AL, Joy KH, Bogard DD, Kring DA. 2014 Ages of globally distributed lunar paleoregoliths and soils from 3.9 Ga to the present. *Earth Moon Planets* **112**, 59–71. (doi:10.1007/s11038-014-9437-7)
41. Kovaltsov GA, Usoskin IG. 2014 Occurrence probability of large solar energetic particle events: assessment from data on cosmogenic radionuclides in lunar rocks. *Sol. Phys.* **289**, 211–220. (doi:10.1007/s11207-013-0333-5)
42. Miyahara H, Wen G, Cahalan RF, Ohmura A. 2008 Deriving historical total solar irradiance from lunar borehole temperatures. *Geophys. Res. Lett.* **35**, L02716. (doi:10.1029/2007GL032171)
43. Pollack HN, Huang S. 2000 Climate reconstruction from subsurface temperatures. *Ann. Rev. Earth Planet. Sci.* **28**, 339–365. (doi:10.1146/annurev.earth.28.1.339)
44. Vallée JP. 2017 Recent advances in the determination of some Galactic constants in the Milky Way. *Astrophys. Space Sci.* **262**, 79. (doi:10.1007/s10509-017-3058-3)
45. Vallée JP. 2017 A guided map to the spiral arms in the galactic disk of the Milky Way. *Astr. Rev.* **13**, 113–146. (doi:10.1080/21672857.2017.1379459)
46. Raup DM, Sepkoski JJ. 1984 Periodicity of extinctions in the geologic past. *Proc. Natl Acad. Sci. USA* **81**, 801–805. (doi:10.1073/pnas.81.3.801)
47. Overholt AC, Melott AL, Pohl M. 2009 Testing the link between terrestrial climate change and galactic spiral arm transit. *Astrophys. J.* **705**, L101–L103. (doi:10.1088/0004-637X/705/2/L101)
48. Filipovic MD, Horner J, Crawford EJ, Tothill NFH, White GL. 2013 Mass extinction and the structure of the Milky Way. *Serb. Astron. J.* **187**, 43–52. (doi:10.2298/SAJ130819005F)
49. Gillman MP, Erenler HE, Sutton PJ. 2019 Mapping the location of terrestrial impacts and extinctions onto the spiral arm structure of the Milky Way. *Int. J. Astrobiol.* **18**, 323–328. (doi:10.1017/S1473550418000125)
50. Crawford IA, Fagents SA, Joy KH, Rumpf ME. 2010 Lunar palaeoregolith deposits as recorders of the galactic environment of the Solar System and implications for astrobiology. *Earth Moon Planets* **107**, 75–85. (doi:10.1007/s11038-010-9358-z)
51. Crawford IA. 2016 The Moon as a recorder of nearby supernovae. In *Handbook of supernovae* (eds AW Alsabti, P Murdin), pp. 2507–2522. Berlin, Germany: Springer.
52. Forman MA, Schaeffer OA. 1979 Cosmic ray intensity over long time scales. *Rev. Geophys. Space Phys.* **17**, 552–560. (doi:10.1029/RG017i004p00552)
53. Shaviv NJ. 2006 Long-term variations in the galactic environment of the Sun. In *Solar journey: the significance of our galactic environment for the heliosphere* (ed. PC Frisch), pp. 99–131. Dordrecht, The Netherlands: Springer.
54. Scherer K *et al.* 2006 Interstellar-terrestrial relations: variable cosmic environments, the dynamic heliosphere, and their imprints on terrestrial archives and climate. *Space Sci. Rev.* **127**, 327–465. (doi:10.1007/s11214-006-9126-6)
55. Leitch EM, Vasisht G. 1998 Mass extinctions and the sun's encounters with spiral arms. *New Astron.* **3**, 51–56. (doi:10.1016/S1384-1076(97)00044-4)

56. Shaviv NJ. 2003 The spiral structure of the Milky Way, cosmic rays, and ice age epochs on Earth. *New Astron.* **8**, 39–77. (doi:10.1016/S1384-1076(02)00193-8)
57. Gies DR, Helsel JW. 2005 Ice age epochs and the Sun's path through the Galaxy. *Astrophys. J.* **626**, 844–848. (doi:10.1086/430250)
58. Melott AL, Thomas BC, Kachelrieß M, Semikoz DV, Overholt AC. 2017 A supernova at 50 pc: effects on the Earth's atmosphere and biota. *Astrophys. J.* **840**, 105. (doi:10.3847/1538-4357/aa6c57)
59. Crozaz G. 1980 Solar flare and galactic cosmic ray tracks in lunar samples and meteorite: what they tell us about the ancient Sun. In *The ancient sun: fossil record in the earth, moon and meteorites* (eds RO Pepin, JA Eddy, RB Merrill), pp. 331–346. New York, NY: Pergamon Press.
60. Wieler R. 2002 Cosmic-ray-produced noble gases in meteorites. *Rev. Mineral. Geochem.* **47**, 125–170. (doi:10.2138/rmg.2002.47.5)
61. Leya I, Neumann S, Wieler R, Michel R. 2001 The production of cosmogenic nuclides by GCR-particles for 2 pi exposure geometries. *Meteorit. Planet. Sci.* **36**, 1547–1561. (doi:10.1111/j.1945-5100.2001.tb01845.x)
62. Wieler R, Beer J, Leya I. 2013 The galactic cosmic ray intensity over the past 10^6 – 10^9 years as recorded by cosmogenic nuclides in meteorites and terrestrial samples. *Space Sci. Rev.* **176**, 351–363. (doi:10.1007/s11214-011-9769-9)
63. Smith T, Cook DL, Merchel S, Pavetich S, Rugel G, Scharf A, Leya I. 2019 The constancy of galactic cosmic rays as recorded by cosmogenic nuclides in iron meteorites. *Meteorit. Planet. Sci.* **54**, 2951–2976. (doi:10.1111/maps.13417)
64. Lorenzetti S, Busemann H, Eugster O. 2005 Regolith history of lunar meteorites. *Meteorit. Planet. Sci.* **40**, 315–327. (doi:10.1111/j.1945-5100.2005.tb00383.x)
65. Baum S, Edwards TDP, Kavanagh BJ, Stengel P, Drukier AK, Freese K, Górski M, Weniger C. 2020 Paleodetectors for galactic supernova neutrinos. *Phys. Rev. D* **101**, 103017. (doi:10.1103/PhysRevD.101.103017)
66. Crawford IA. 2011 Project Icarus: a review of local interstellar medium properties of relevance for space missions to the nearest stars. *Acta Astronaut.* **68**, 691–699. (doi:10.1016/j.actaastro.2010.10.016)
67. Pavlov AA, Toon OB, Pavlov AK, Bally J, Pollard D. 2005 Passing through a giant molecular cloud: “snowball” glaciations produced by interstellar dust. *Geophys. Res. Lett.* **32**, L03705. (doi:10.1029/2004GL021890)
68. Yeghikyan A, Fahr H. 2006 Accretion of interstellar material into the heliosphere and onto Earth. In *Solar journey: the significance of our galactic environment for the heliosphere and earth* (ed. PC Frisch), pp. 317–348. Dordrecht, the Netherlands: Springer.
69. Yabushita S, Allen AJ. 1989 On the effect of accreted interstellar matter on the terrestrial environment. *Mon. Not. R. Astron. Soc.* **238**, 1465–1478. (doi:10.1093/mnras/238.4.1465)
70. Kokaia G, Davies MB. 2019 Stellar encounters with giant molecular clouds. *Mon. Not. R. Astron. Soc.* **489**, 5165–5180. (doi:10.1093/mnras/stz813)
71. Talbot RJ, Nreman MJ. 1977 Encounters between stars and dense interstellar clouds. *Astrophys. J. Suppl.* **34**, 295–308. (doi:10.1086/190452)
72. Smith DS, Scalo JM. 2009 Habitable zones exposed: astrosphere collapse frequency as a function of stellar mass. *Astrobiology* **9**, 673–681. (doi:10.1089/ast.2009.0337)
73. Wimmer-Schweingruber RF, Bochsler P. 2001 Lunar soils: a long-term archive for the galactic environment of the heliosphere? *AIP Conf. Proc.* **598**, 399–404. (doi:10.1063/1.1434029)
74. Colaprete A *et al.* 2010 Detection of water in the LCROSS ejecta plume. *Science* **330**, 463–468. (doi:10.1126/science.1186986)
75. Paige DA *et al.* 2010 Diviner Lunar Radiometer observations of cold traps in the Moon's south polar region. *Science* **330**, 479–482. (doi:10.1126/science.1187726)
76. Knie K, Korschinck G, Faestermann T, Wallner C, Scholten J, Hillebrandt W. 1999 Indication for supernova produced ^{60}Fe activity on Earth. *Phys. Rev. Lett.* **83**, 18–21. (doi:10.1103/PhysRevLett.83.18)
77. Fields BD, Hochmuth KA, Ellis J. 2005 Deep-ocean crusts as telescopes: using live radioisotopes to probe supernova nucleosynthesis. *Astrophys. J.* **621**, 902–907. (doi:10.1086/427797)
78. Athanassiadou T, Fields BD. 2011 Penetration of nearby supernova dust in the inner Solar System. *New Astron.* **16**, 229–241. (doi:10.1016/j.newast.2010.09.007)

79. Fry BJ, Fields BD, Ellis JR. 2015 Astrophysical shrapnel: discriminating among near-Earth stellar explosion sources of live radioactive isotopes. *Astrophys. J.* **800**, 71. (doi:10.1088/0004-637X/800/1/71)
80. Knie K, Korschinek G, Faestermann T, Dorfi EA, Rugel G, Wallner A. 2004 ^{60}Fe anomaly in a deep-sea manganese crust and implications for a nearby supernova source. *Phys. Rev. Lett.* **93**, 171103. (doi:10.1103/physrevlett.93.171103)
81. Wallner A *et al.* 2016 Recent near-Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe . *Nature* **532**, 69–72. (doi:10.1038/nature17196)
82. Fields B *et al.* 2019 Near-Earth supernova explosions: evidence, implications, and opportunities. Decadal Survey on Astronomy and Astrophysics, science white papers, no. 410. *Bull. Am. Astron. Soc.* **51**, 410.
83. Cook DL *et al.* 2009 ^{60}Fe , ^{10}Be , and ^{26}Al in Lunar Cores 12025/8 and 60006/7: search for a nearby supernova. In *40th Lunar and Planetary Science Conf., Woodlands, TX, 23–27 March 2009*, abstract no. 1129. (<https://www.lpi.usra.edu/meetings/lpsc2009/pdf/1129.pdf>)
84. Fimiani L *et al.* 2016 Interstellar ^{60}Fe on the surface of the Moon. *Phys. Rev. Lett.* **116**, 151104. (doi:10.1103/PhysRevLett.116.151104)
85. Siraj A, Loeb A. 2020 Impacts of dust grains accelerated by supernovae on the Moon. *Astrophys. J.* **895**, L42. (doi:10.3847/2041-8213/ab93d5)
86. Drukier AK, Baum S, Freese K, Górski M, Stengel P. 2019 Paleo-detectors: searching for dark matter with ancient minerals. *Phys. Rev. D* **99**, 043014. (doi:10.1103/PhysRevD.99.043014)
87. Torbett MV. 1986 Dynamical influence of galactic tides and molecular clouds on the Oort cloud of comets. In *The galaxy and the Solar System* (eds R Smoluchowski, JN Bahcall, MS Matthews), pp. 147–172. Tucson, AZ: University of Arizona Press.
88. Matese JJ, Whitman PG, Innanen KA, Valtonen MJ. 1995 Periodic modulation of the Oort cloud comet flux by the adiabatically changing galactic tide. *Icarus* **116**, 255–268. (doi:10.1006/icar.1995.1124)
89. Rampino MR. 2015 Disc dark matter in the Galaxy and potential cycles of extraterrestrial impacts, mass extinctions and geological events. *Mon. Not. R. Astron. Soc.* **448**, 1816–1820. (doi:10.1093/mnras/stu2708)
90. Schmieder M, Kring DA. 2020 Earth's impact events through geologic time: a list of recommended ages for terrestrial impact structures and deposits. *Astrobiology* **20**, 91–141. (doi:10.1089/ast.2019.2085)
91. Stöffler D, Ryder G, Ivanov BA, Artemieva NA, Cintala MA, Grieve RAF. 2006 Cratering history and lunar chronology. *Rev. Min. Geochem.* **60**, 519–596. (doi:10.2138/rmg.2006.60.05)
92. Neukum G, Ivanov BA, Hartmann WK. 2001 Cratering records in the inner solar system in relation to the lunar reference system. *Space Sci. Rev.* **96**, 55–86. (doi:10.1023/A:1011989004263)
93. Weiss BP, Tikoo SM. 2014 The lunar dynamo. *Science* **346**, 1246753. (doi:10.1126/science.1246753)
94. Mighani S, Wang H, Shuster DL, Borlina CS, Nichols CIO, Weiss BP. 2020 The end of the lunar dynamo. *Sci. Adv.* **6**, eaax0883. (doi:10.1126/sciadv.aax0883)
95. Needham DH, Kring DA. 2017 Lunar volcanism produced a transient atmosphere around the ancient Moon. *Earth Planet. Sci. Lett.* **478**, 175–178. (doi:10.1016/j.epsl.2017.09.002)
96. Wilson L, Head JW, Deutsch AN. 2019 Volcanically-induced transient atmospheres on the Moon: assessment of duration and significance. In *50th Lunar and Planetary Science Conf., Woodlands, TX, 18–22 March 2019*, abstract no. 1343. (<https://www.hou.usra.edu/meetings/lpsc2019/pdf/1343.pdf>)
97. Snape JF, Nemchin AA, Whitehouse MJ, Merle RE, Hopkinson T, Anand M. 2019 The timing of basaltic volcanism at the Apollo landing sites. *Geochim. Cosmochim. Acta* **266**, 29–53. (doi:10.1016/j.gca.2019.07.042)
98. Taylor GJ, Warren P, Ryder G, Delano J, Pieters C, Lofgren G. 1991 Lunar Rocks. In *The lunar sourcebook: a user's guide to the moon* (eds GH Heiken, D Vaniman, BM French), pp. 183–284. Cambridge, UK: Cambridge University Press.
99. Robinson MS, Ashley JW, Boyd AK, Wagner RV, Speyerer EJ, Ray Hawke B, Hiesinger H, van der Bogert CH. 2012 Confirmation of sublunarean voids and thin layering in mare deposits. *Planet. Space Sci.* **69**, 18–27. (doi:10.1016/j.pss.2012.05.008)

100. Hiesinger H, Head JW, Wolf U, Jaumann R, Neukum G. 2011 Ages and stratigraphy of lunar mare basalts: a synthesis. *Geol. Soc. Am. Special Paper No.* **477**, 1–51. (doi:doi.org/10.1130/2011.2477(01))
101. Braden SE, Stopar JD, Robinson MS, Lawrence SJ, van der Bogert CH, Hiesinger H. 2014 Evidence for basaltic volcanism on the Moon within the past 100 million years. *Nat. Geosci.* **7**, 787–791. (doi:10.1038/ngeo2252)
102. Qiao L, Head J, Wilson L, Long X, Kreslavsky M, Dufek J. 2017 Ina pit crater on the Moon: extrusion of waning-stage lava lake magmatic foam results in extremely young crater retention ages. *Geology* **45**, 455–458. (doi:10.1130/G38594.1)
103. Rumpf ME, Fagents SA, Crawford IA, Joy KH. 2013 Numerical modeling of lava-regolith heat transfer on the Moon and implications for the preservation of implanted volatiles. *J. Geophys. Res. Planets* **118**, 382–397. (doi:10.1029/2012JE004131)
104. Hörz F, Grieve RAF, Heiken GH, Spudis P, Binder A. 1991 Lunar surface processes. In *The lunar sourcebook: a user's guide to the moon* (eds GH Heiken, D Vaniman, BM French), pp. 61–120. Cambridge, UK: Cambridge University Press.
105. Xie M, Xiao Z, Xu A. 2018 Modeling the growth of regolith on the Moon: implication for the evolution of crater and impactor populations. In *49th Lunar and Planetary Science Conf., Woodlands, TX, 19–23 March 2018*, abstract no. 1992. (<https://www.hou.usra.edu/meetings/lpsc2018/pdf/1992.pdf>)
106. Head JW, Wilson L. 2019 Rethinking lunar mare basalt regolith formation: new concepts of lava flow protolith and evolution of regolith thickness and internal structure. In *50th Lunar and Planetary Science Conf., Woodlands, TX, 18–22 March 2019*, abstract no. 2532. (<https://www.hou.usra.edu/meetings/lpsc2019/pdf/2532.pdf>)
107. Gaddis LR, Staid MI, Tyburczy JA, Hawke BR, Petro N. 2003 Compositional analyses of lunar pyroclastic deposits. *Icarus* **161**, 262–280. (doi:10.1016/S0019-1035(02)00036-2)
108. Head JW, Wilson L. 2017 Generation, ascent and eruption of magma on the Moon: new insights into source depths, magma supply, intrusions and effusive/explosive eruptions (part 2: observations). *Icarus* **283**, 176–223. (doi:10.1016/j.icarus.2015.12.039)
109. Huff AE, Hagerty JJ, Skinner JA, Fortezzo CM, Gaither TA. 2015 Excavation depths of small diameter craters on a pyroclastic deposit near northern Rimae Bode, the Moon. In *46th Lunar and Planetary Science Conf., Woodlands, TX, 16–20 March 2015*, abstract no. 2386. (<https://www.hou.usra.edu/meetings/lpsc2015/pdf/2386.pdf>)
110. McKay DS. 2009 Do lunar pyroclastic deposits contain the secrets of the Solar System? In *Lunar Reconnaissance Orbiter Science Targeting Meeting, Tempe, Arizona, 9–11 June 2009*, abstract no. 6014. (<https://www.lpi.usra.edu/meetings/lro2009/pdf/6014.pdf>)
111. Cohen BA, Swindle TD, Kring DA. 2005 Geochemistry and ^{40}Ar - ^{39}Ar geochronology of impact-melt clasts in feldspathic lunar meteorites: implications for lunar bombardment history. *Meteorit. Planet. Sci.* **40**, 755–777. (doi:10.1111/j.1945-5100.2005.tb00978.x)
112. Zellner NEB, Delano JW. 2015 $^{40}\text{Ar}/^{39}\text{Ar}$ ages of lunar impact glasses: relationships among Ar diffusivity, chemical composition, shape, and size. *Geochim. Cosmochim. Acta* **161**, 203–218. (doi:10.1016/j.gca.2015.04.013)
113. Gombosi DJ, Baldwin SL, Watson EB, Swindle TD, Delano JW, Roberge WG. 2015 Argon diffusion in Apollo 16 impact glass spherules: implications for $^{40}\text{Ar}/^{39}\text{Ar}$ dating of lunar impact events. *Geochim. Cosmochim. Acta* **148**, 251–268. (doi:10.1016/j.gca.2014.09.031)
114. Fernandes V, Artemieva N. 2012 Impact ejecta temperature profile on the Moon: what are the effects on the Ar-Ar dating method? In *43rd Lunar and Planetary Science Conf., Woodlands, TX, 19–23 March 2012*, abstract no. 1367. (<https://www.lpi.usra.edu/meetings/lpsc2012/pdf/1367.pdf>)
115. Melosh HJ. 1989 *Impact cratering: a geologic process*. Oxford, UK: Oxford University Press.
116. Weider SZ, Crawford IA, Joy KH. 2010 Individual lava flow thicknesses in Oceanus Procellarum and Mare Serenitatis determined from Clementine multi-spectral data. *Icarus* **209**, 323–336. (doi:10.1016/j.icarus.2010.05.010)
117. Ono T, Kumamoto A, Nakagawa H, Yamaguchi Y, Oshigami S, Yamaji A, Kobayashi T, Kasahara Y, Oya H. 2009 Lunar Radar Sounder observations of subsurface layers under the nearside maria of the Moon. *Science* **323**, 90–92. (doi:10.1126/science.1165988)
118. Fa W, Zhu M-H, Liu T, Plescia JB. 2015 Regolith stratigraphy at the Chang'E-3 landing site as seen by lunar penetrating radar. *Geophys. Res. Lett.* **42**, 179–187. (doi:10.1002/2015GL066537)

119. Li C *et al.* 2020 The Moon's farside shallow subsurface structure unveiled by Chang'E-4 lunar penetrating radar. *Sci. Adv.* **6**, eaay6898. (doi:10.1126/sciadv.aay6898)
120. Cooper MR, Kovach RL, Watkins JS. 1974 Lunar near-surface structure. *Rev. Geophys. Space Phys.* **12**, 291–308. (doi:10.1029/RG012i003p00291)
121. Kerber L *et al.* 2020 Moon Diver: journey into the ancient lavas of the Moon. In *51st Lunar and Planetary Science Conf., Woodlands, TX, 16–21 March 2020*, abstract no. 1857. (<https://www.hou.usra.edu/meetings/lpsc2020/pdf/1857.pdf>)
122. Zacny K *et al.* 2008 Drilling systems for extraterrestrial subsurface exploration. *Astrobiology* **8**, 665–706. (10.1089/ast.2007.0179)
123. Zacny K *et al.* 2013 LunarVader: development and testing of lunar drill in vacuum chamber and in lunar analog site of Antarctica. *J. Aerosp. Eng.* **26**, 74–86. (doi:10.1061/(ASCE)AS.1943-5525.0000212)
124. Shearer C *et al.* 2007 Analysis of lunar sample mass capability for the lunar exploration architecture. White paper by the NASA Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) (http://www.lpi.usra.edu/lunar/strategies/captem_sample_return.pdf)
125. Woerner J, Foing B. 2016 The 'Moon Village' concept and initiative. In *Annual Meeting of the Lunar Exploration Analysis Group, 1–3 November 2016, Columbia, MD*, abstract no. 5084. (<https://www.hou.usra.edu/meetings/leag2016/pdf/5084.pdf>)
126. Taylor GJ. 1985 The need for a lunar base: answering basic questions about planetary science'. In *Lunar bases and space activities of the 21st century* (ed. WW Mendell), pp. 189–197. Houston, TX: Lunar and Planetary Institute.
127. Ehrenfreund P *et al.* 2012 Toward a global space exploration program: a stepping stone approach. *Adv. Space Res.* **49**, 2–48. (doi:10.1016/j.asr.2011.09.014)
128. McKay C. 2013 The case for a NASA research base on the Moon. *New Space* **1**, 162–166. (doi:10.1089/space.2013.0018)