Lunar Science as a Window into the Early History of the Solar System

A White Paper submitted in response to ESA's Call for Proposals for Cosmic Vision L2/3 Science Themes

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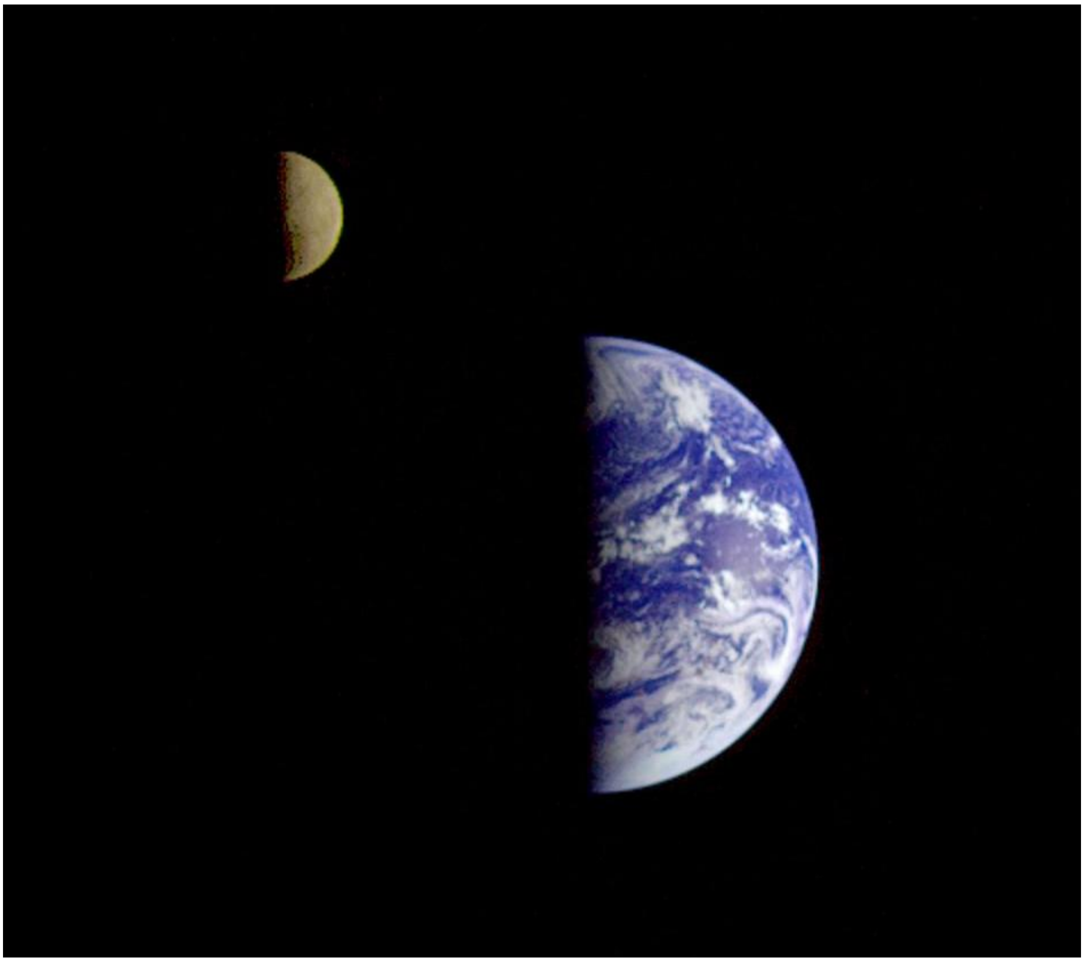
(For full list of contributors and endorsers see overleaf)



Frontispiece: The Earth and Moon photographed together by the Galileo spacecraft from a distance of 6.2 million km. The binary nature of the Earth-Moon system means that the Moon's history is intimately connected with that of our own planet (NASA).

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EXECUTIVE SUMMARY

We propose a Cosmic Vision 'Science Theme' of using lunar science as a window into the early history of the Solar System. The near surface lunar environment contains a rich record of inner Solar System history. Accessing this record will directly address key elements of ESA's Cosmic Vision themes, especially Theme 1 ('Planets and Life') and Theme 2 ('How does the Solar System Work?'). In particular, the main areas of lunar science that will inform our understanding of inner Solar System evolution, and the past habitability of our own planet, are the following:

- *The bombardment history of the inner Solar System*. The lunar surface preserves a unique record of the bombardment history of the inner solar system, important for understanding the emergence of life on Earth, dating the surfaces of terrestrial planets and asteroids, and constraining the orbital evolution of the giant planets.

- *The record of lunar and extra-lunar processes recorded in the lunar regolith*. The lunar regolith is a unique witness to over 4 Ga of Solar System history and records changes in solar activity, the population of small bodies in the Solar System, and the passage of the Solar System through Galaxy. The regolith may further contain unique samples of Earth's early surface and atmosphere not obtainable in any other way.

- *Studies of volatiles at the lunar poles*. Water and other volatiles at high lunar latitudes may reveal the nature and sources of compounds that enabled life on Earth, as well as providing a model for processes of water formation and migration on other airless bodies.

Implementation will require spacecraft to land on the lunar surface in order to make *in situ* measurements at, and/or return samples from, localities that have been carefully selected with specific scientific objectives in mind. For the Cosmic Vision L2/3 mission opportunities we propose the development of a scientific infrastructure that would enable us to address these scientific objectives. Such a lunar exploration infrastructure would also address other areas of high scientific importance, including studies of the evolution of the Moon itself as a planetary body, and geophysical, astrophysical and astrobiological investigations conducted on its surface. Here we propose two, mutually complementary, strands: (i) a mission based around multiple penetrators for the characterisation of lunar polar volatiles and (ii) a sample return mission to address the lunar impact chronology and records of the near-Earth Solar System environment preserved in regolith deposits. We consider that the development of such an ambitious lunar science architecture is worthy of consideration for the Cosmic Vision L2/3 mission opportunities. We note that many of the technical developments required for this lunar science programme are relevant for developing Mars Sample Return missions.

1 Introduction

From a planetary science perspective the primary importance of the Moon arises from the fact that it has an extremely ancient surface, mostly older than 3 billion years with some areas extending almost all the way back to the origin of the Moon 4.5 billion years ago (e.g., Hiesinger and Head, 2006; NRC 2007; Jaumann et al., 2012). Its relatively accessible near-surface environment therefore preserves a record of the early geological evolution of a terrestrial planet, which more complex planets such as Earth and Venus have long lost, and of the Earth-Moon system in particular (NRC, 2007; Jaumann et al., 2012). Moreover, the Moon’s outer layers also preserve a record of the environment in the inner Solar System (e.g., meteorite flux, interplanetary dust density, solar wind flux and composition, galactic cosmic ray flux) throughout Solar System history, much of which is relevant to understanding the past habitability of our own planet (e.g., Crawford, 2006; NRC, 2007; Norman, 2009; Cockell, 2010; Crawford et al., 2012; Fernandes et al., 2013). Indeed, 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 owing to active geological and meteorological cycles which have largely erased the geological record from much of Earth history. Fortunately, the binary nature of the Earth-Moon system provides a means of remedying this situation because records of the early space environment shared by the Earth-Moon system will be preserved on the ancient surface of the Moon.

Accessing this rich record of inner Solar System history will directly address key elements of ESA’s Cosmic Vision themes, especially Theme 1 (‘Planets and Life’) and Theme 2 (‘How does the Solar System Work?’) and is a scientifically valuable theme for the Cosmic Vision L2/3 mission opportunities. Implementation will require spacecraft to land on the lunar surface in order to make *in situ* measurements at, and/or return samples from, localities that have been carefully selected with specific scientific objectives in mind. In what follows we describe the nature of the lunar geological record, and how it can inform our knowledge of the early history of the Earth and of the inner Solar System more generally, before going on to outline two possible, but not mutually exclusive, mission scenarios that would be well-suited to address these key scientific questions.

2 The nature of the lunar record

We here elaborate on those aspects of the lunar geological record which will provide key information concerning the evolution of the inner Solar System, including the Earth-Moon system, and the continued habitability of our own planet. Of course, the Moon is also an important object for scientific investigation in its own right, the interior structure of which records early planetary differentiation processes that will have affected all the terrestrial planets but which the more evolved planets have long lost (see, e.g., Jaumann et al., 2012). Moreover, the Moon is a potential platform for low-frequency radio astronomy (Jester and Falcke, 2009) and for biological and astrobiological studies (Cockell et al., 2010; de Vera et al., 2012). Investigation of those other aspects of lunar science, which will largely rely on geophysical, astrophysical, and biological techniques are not directly addressed here (although some will be covered in other White Papers). That said, it is clear that strong synergies exist between the techniques and samples required to access the Moon's record of the inner Solar System environment and those required to understand the evolution of the Moon itself as a planetary body, and that lunar geophysical, astrophysical and astrobiological investigations would benefit from the development of a lunar scientific infrastructure. All these aspects of lunar science could be addressed by a suitable choice of instrument payloads on landed spacecraft.

With these caveats in mind, the main areas of lunar science that will explicitly inform our understanding of inner Solar System evolution are the following:

2.1 The Bombardment History of the Inner Solar System

The Lunar surface preserves a unique record of the bombardment history of the inner solar system, important for understanding the emergence of life on Earth, dating the surfaces of terrestrial planets and asteroids, and constraining the orbital evolution of the giant planets.

The vast majority of lunar terrains have never been directly sampled, and their inferred ages are based on the observed density of impact craters calibrated against the ages of Apollo and Luna samples (e.g., Neukum et al., 2001; Stöffler et al., 2006). However, the current calibration of the cratering rate, used to convert crater densities to absolute model ages, is neither as complete nor as reliable as it is often made out to be. For example, there are no calibration points that are older than about 3.85 Ga, and crater ages younger than about 3 Ga are also uncertain (e.g., Hiesinger et al., 2012). Improving the calibration of the cratering rate would be of great value for planetary science for the following three reasons: (i) It would provide better estimates for the ages of unsampled regions of the lunar surface; (ii) It would provide us with a more reliable estimate of the impact history of the inner Solar System, especially that of our own planet; and (iii) The lunar impact rate is used, with various other assumptions, to date the surfaces of other planets for which samples have not been obtained – to the extent that the lunar rate remains unreliable, so do the age estimates of surfaces on the other terrestrial planets.

Moreover, there is still uncertainty over whether the lunar cratering rate has declined monotonically since the formation of the Moon, or whether there was a bombardment 'cataclysm' between about 3.8 and 4.1 billion years ago characterised by an enhanced rate of impacts (Kring, 2003; Stöffler et al., 2006; Norman, 2009; Morbidelli et al., 2012). Indeed, recent studies of the ages of impact melt samples obtained by the Apollo and Luna missions suggest a very complicated impact history for the Earth-Moon system, with a number of discrete spikes in the impact flux (Fernandes et al., 2013 and references therein). Clarifying this issue is especially important from an astrobiology perspective because it defines the impact regime under which life on Earth became established and the rate at which volatiles and organic materials were delivered to the early Earth (e.g., Maher and Stevenson, 1988; Sleep et al., 1989; Ryder, 2003). Additionally, as the inner Solar System bombardment history is thought to have been governed, at least in part, by changing tidal resonances in the asteroid belt (Gomes et al., 2005; Morbidelli et al., 2012; Bottke et al., 2012), improved constraints on the impact rate will lead to a better understanding of the orbital evolution of the early Solar System. This in turn will have implications for our understanding the habitability of planets within the 'habitable zones' of *other* planetary systems as a function of their age and the locations of any giant planets that may be present (Brock and Melosh, 2012; Johnson et al., 2012).

Obtaining an improved lunar cratering chronology requires the sampling, and radiometric dating, of surfaces having a wide range of crater densities, supplemented where possible by dating of impact melt deposits from individual craters and basins (Stöffler et al., 2006; Fernandes et al., 2013). In practice this will require robotic sample return missions to key localities from which samples have not yet been returned. Examples sites include the farside South Pole-Aitken basin (the dating of which will help determine whether or not most lunar basins formed in a single 'cataclysm'; e.g., Kring, 2003; Jolliff et al., 2010) and, at the other end of the age spectrum, young basaltic lava flows in Oceanus Procellarum on the nearside (where the dating of individual lava flows with ages in the range 1.1 to 3.5 Gyr would provide data points for the as yet uncalibrated 'recent' portion of the inner Solar System cratering rate; e.g. Stöffler et al., 2006; Crawford et al., 2007).

2.2 Treasures in the regolith

The lunar regolith is a unique witness to over 4 Ga of Solar System history and records changes in solar activity, the population of small bodies in the Solar System, and the passage of the Solar System through Galaxy. The regolith may further contain unique samples of Earth's early surface and atmosphere not obtainable in any other way.

The lunar regolith is known to contain much that is of interest for studies of Solar System history. For example, studies of Apollo samples have revealed that solar wind particles are efficiently implanted in the lunar regolith (McKay et al., 1991; Lucey et al., 2006), which therefore contains a record of the composition and evolution of the Sun throughout Solar System history (e.g., Wieler et al., 1996; Chaussidon and Robert, 1999; Hashizume et al., 2000). Recently, samples of the Earth's early atmosphere may have been retrieved from lunar regolith samples (Ozima et al., 2005; 2008), and it has been suggested that samples of Earth's early crust may also be preserved there in the form of terrestrial meteorites (Gutiérrez, 2002; Armstrong et al., 2002; Crawford et al., 2008; Armstrong, 2010). Meteorites derived from elsewhere in the Solar System may also be found on the Moon, preserving a record of the dynamical evolution of small bodies throughout Solar System history (Joy et al., 2011; 2012). Last but not least, the lunar regolith may contain a record of galactic events, by preserving the signatures of ancient galactic cosmic ray (GCR) fluxes, and the possible accumulation of interstellar dust particles during passages of the Sun through dense interstellar clouds (Crozaz et al., 1977; McKay et al., 1991; Crawford et al., 2010). Collectively, these lunar geological records would provide a window into the early evolution of the Sun and Earth, and of the changing galactic environment of the Solar System, that is unlikely to be obtained in any other way. Much of this record has clear astrobiological implications, as it relates to the conditions under which life first arose and evolved on Earth.

From the point of view of accessing ancient Solar System history it will be desirable to find layers of ancient regoliths (*palaeoregoliths*) that were formed and buried billions of years ago, and thus protected from more recent geological processes, (e.g., Spudis, 1996; Crawford et al., 2007, 2010; Fagents et al., 2010; Rumpf et al., 2013; see Figure 1 of Crawford et al., 2010 for a pictorial representation of the process). Locating and sampling such deposits will therefore be an important scientific objective of future lunar exploration activities.

2.3 Volatiles at the lunar poles

Water and other volatiles at high lunar latitudes may reveal the nature and sources of compounds that enabled life on Earth, as well as providing a model for processes of water formation and migration on other airless bodies.

The lunar poles potentially bear witness to the flux of volatiles present in the inner Solar System throughout much of Solar System history (e.g., NRC, 2007). In 1998 the *Lunar Prospector* neutron spectrometer found evidence of enhanced concentrations of hydrogen at the lunar poles (Feldman et al., 1998), which was widely interpreted as indicating the presence of water ice in the floors of permanently shadowed polar craters. This interpretation was supported by the LCROSS impact experiment, which found a water ice concentration of 5.6 ± 2.9 % by weight in the target regolith at the Cabeus crater (Colaprete et al., 2010). It seems likely that this water is ultimately derived from the impacts of comets and/or hydrated meteorites on to the lunar surface (Anand, 2010). In addition to ice in permanently shadowed craters, infra-red remote-sensing observations have found evidence for hydrated minerals, and/or adsorbed water or hydroxyl molecules, over large areas of the high latitude (but not permanently shadowed) lunar surface which may be due to oxidation of solar wind hydrogen within the regolith (Pieters et al., 2009; Liu et al., 2012).

As discussed by Anand (2010) and Smith et al. (2012), obtaining improved knowledge of the presence, composition, and abundance of water (and other volatiles) at the lunar poles is important for several reasons:

- It is probable that the ice in permanently shadowed regions is ultimately derived from comet and/or meteorite impacts. Even though the original volatiles will have been considerably reworked, it remains probable that some information concerning the composition of the original sources will remain (Zhang and Paige, 2009). Among other things, this may yield astrobiologically important knowledge on the role of comets and meteorites in delivering volatiles and pre-biotic organic materials to the terrestrial planets (Chyba and Sagan, 1992; Pierazzo and Chyba, 1999; Zhang and Paige, 2009).

- The processes involved in the creation, retention, migration, and destruction of OH and H_2O across the surface of the Moon are likely to be common on other air-less bodies, and quantifying them on the Moon will give us better insight into the volatile history and potential availability of water elsewhere in the inner Solar System.

- Lunar polar ice deposits are of considerable astrobiological interest, even if they do not retain vestigial information concerning their ultimate sources. This is because any such ices will have been continuously subject to irradiation by galactic cosmic rays and, as such, may be expected to undergo organic synthesis reactions (e.g., Lucey, 2000; Crites, et al., 2011). Analogous reactions may be important for producing organic molecules in the icy mantles of interstellar dust grains, and on the surfaces of outer Solar System satellites and comets, but the lunar poles are much more accessible than any of these other locations.

- The presence of water ice at the lunar poles, and even hydrated materials at high-latitude but non-shadowed localities, could potentially provide a very valuable resource (e.g., rocket fuel, habitation resources) in the context of future lunar exploration activities (e.g., Spudis and Lavoie, 2011).

Confirming the interpretation of the remote sensing measurements, and obtaining accurate values for the concentration of polar ice and high latitude surficial OH/H_2O will require *in situ* measurements by suitably instrumented and landed spacecraft, and we outline some possibilities below.

3 Strawman mission proposals

In this section we outline a scientific infrastructure that would enable us to address the scientific objectives described above and which we consider suitable for consideration within ESA's Cosmic Vision framework for implementation by either the L2 or L3 mission opportunities. There are two, mutually complementary, strands: (i) a mission based around multiple penetrators for the characterisation of lunar polar volatiles, and (ii) a sample return mission to address the lunar impact chronology and records of the near-Earth Solar System environment preserved in regolith deposits.

3.1 Penetrator Mission

Volatile detectors deployed on penetrators (emplaced ballistically into the lunar sub-surface), and landed within permanently shadowed craters (and/or the surrounding non-shadowed but apparently nevertheless volatile enhanced areas), would be a powerful and economical means of determining whether or not scientifically and operationally valuable deposits of volatiles exist at the lunar poles. One of the implications of the LCROSS and other recent spacecraft results is that such volatiles may be distributed very inhomogeneously in the lunar polar regions, and a mission with multiple penetrator capability would enable additional sampling of this distribution, which would be important in terms of understanding sources/sinks of polar volatiles.

Here we propose a mission that involves the delivery of a minimum of four penetrators into the lunar surface at multiple locations. Each penetrator will be ~0.5 m long and ~13 kg mass (similar to the JAXA Lunar-A mission concept; Mizutani et al., 2005). Each penetrator will consist of a supporting structure, a power system, communications system, data handling system, and payload. They will be delivered to the Moon by a spacecraft bus that will enter lunar orbit and act as a communications relay (as described by Smith et al., 2012). Provisionally, it is anticipated that two of the penetrators will be placed in permanently shadowed regions, one into a high-latitude non-permanently shadowed locality where remote sensing indicates the presence of surficial volatiles, and one penetrator at a low latitude site (either an Apollo landing site or the location of the Sample Return component discussed in Section 3.2.1) to act as a volatile-poor control.

Direct communication between these penetrator and Earth cannot be guaranteed and a lunar polar orbiting relay communications satellite (Orbiter) is therefore required. The Orbiter will carry the four penetrators and their descent modules (DMs) into lunar orbit prior to their release. This Orbiter may also act as a communications relay for the sample return component discussed in Section 3.2.1 if a farside locality is selected.

This element of the proposal closely follows that of the LunarNET proposal submitted to the Cosmic Vision M3 opportunity that has been described in detail by Smith et al. (2012). Detailed information relating to the mission profile, technological readiness, and spacecraft system requirements, for which there is insufficient space to describe here, will be found in that publication. Here we concentrate on the modified scientific payload tailored to address the scientific objectives outlined in Section 2.

The penetrator deployment is shown schematically in Figure 1, and example model payload instruments are listed in Table 3-1.

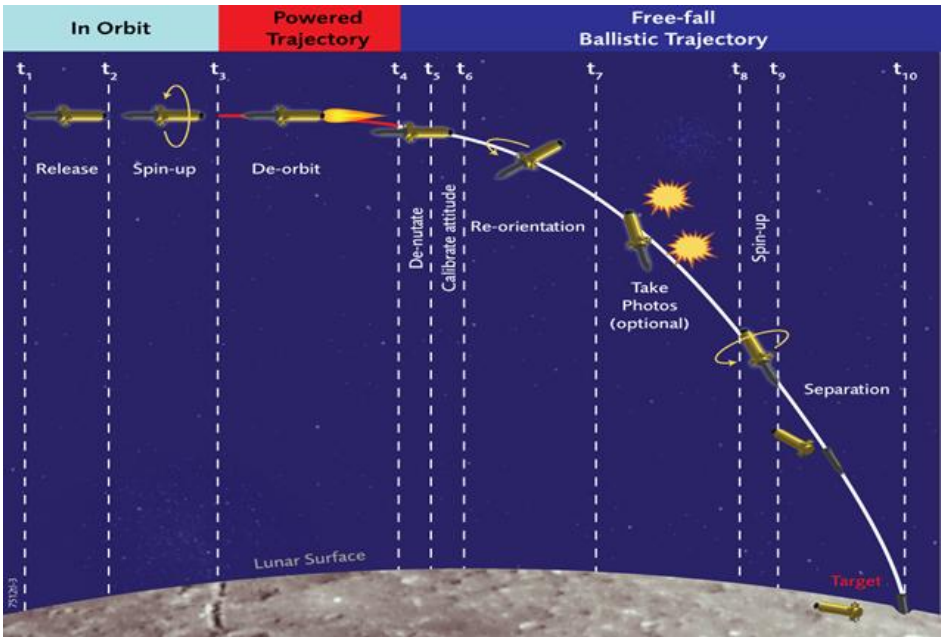

Figure 1. *Provisional Descent Sequence (Courtesy Astrium)*

Table 3-1: Proposed Penetrator Payload Instruments (for full details see Smith et al., 2012)

Instrument	**Acro-nym**	**Mass [kg]**	**Size [cm^3]**	**Power [W]** ***[W hr]***	**Total Data Volume [kbit]**	**Technical Readiness Level (TRL) Heritage ***
Accelerometer (8 sensors)	ACCL	0.07	2.4	0.8 to 1.2 *0.17*	1 Mbit	TRL 6-8 Off-the-shelf components, Lunar A, Pendine
Descent camera	DC	0.160	27 3×3×3 cm	0.160 *0.015*	~ 10 Mbits after compression	TRL 7+ general camera technology TRL 2 for proposed design
Magnetometer	MAG	0.07	200 10×10 ×2	0.15 - 0.4	~1 Mbit (0.06 kbps)	TRL 5: Pendine trials
Mass Spectrometer	MSPC	0.75	1000 10×10 ×10	3-6	~0.2 Mbits	TRL 4/5: Rosetta / Beagle2
Engineering Tiltmeter	ETLT	0.010	25	0.1	1 kbit	TRL 6-8, Huygens, Mars 96
Water/Volatile Detector	BIOC	0.750	1000	3	TBD	TRL 4-8: DS-2, Huygens, ExoMars, Pendine
X-Ray Spectrometer	XRS	0.260	160	4 *24*	0.1 Mbits	TRL 7 : Mars 96
Microscopic Imager	MICI	TBD	TBD	TBD	TBD	
Radiation Monitor	RADM	TBD	TBD	TBD	TBD	MoonLITE

*Pendine refers to UK penetrator trials conducted in 2009 (see Smith et al., 2012).

3.2 Sample Return

In order to address the lunar chronology questions identified in Section 2, and to identify extra-lunar materials in the regolith (e.g., solar wind particles, cosmogenic nuclides produced by galactic cosmic rays, meteoritic fragments, etc.), we propose a mission element able to return of the order of 1-10 kg (TBC) of rock and soil samples to Earth. Mobility is highly desirable in order to secure a diverse set of samples, and we propose that two options be considered: (i) inclusion of a rover with a 5-10 km range, and (ii) a lander that is able to 'hop' to multiple (at least three) localities separated by tens or hundreds of km. A drilling capability would also be desirable to obtain samples from a vertical stratigraphic column. A possible mission architecture is described in Section 3.2.2, after we first discuss scientifically valuable landing sites for sample return.

3.2.1 Sample return sites.

We tentatively identify two sites for a sample return mission: (i) the young basaltic lava flows of Oceanus Procellarum at low latitudes on the nearside, and (ii) the farside, high southern latitude, Schrödinger Basin, which can be used to sample the South-Pole Aitkin basin as well as providing additional science opportunities. In addition to both being high priority science targets (e.g., Crawford et al., 2007; Kring and Durda, 2012 respectively), these two localities may be seen as bracketing relatively 'easy' and 'difficult' sample return locations and thereby constrain the spectrum of lunar sample return options. In the sub-sections below we outline the scientific advantages of each location and then summarise mission architectures required.

3.2.1.1 Oceanus Procellarum

Oceanus Procellarum consists of a patchwork of discrete lava flows with different compositions and estimated ages ranging from about 3.5 to 1.2 Gyr (Wilhelms, 1987; Hiesinger et al., 2003; Fig. 2). This is a far greater range of ages than any basalt samples collected by the Apollo missions (which occupy the narrow age range 3.8 to 3.1 Gyr).

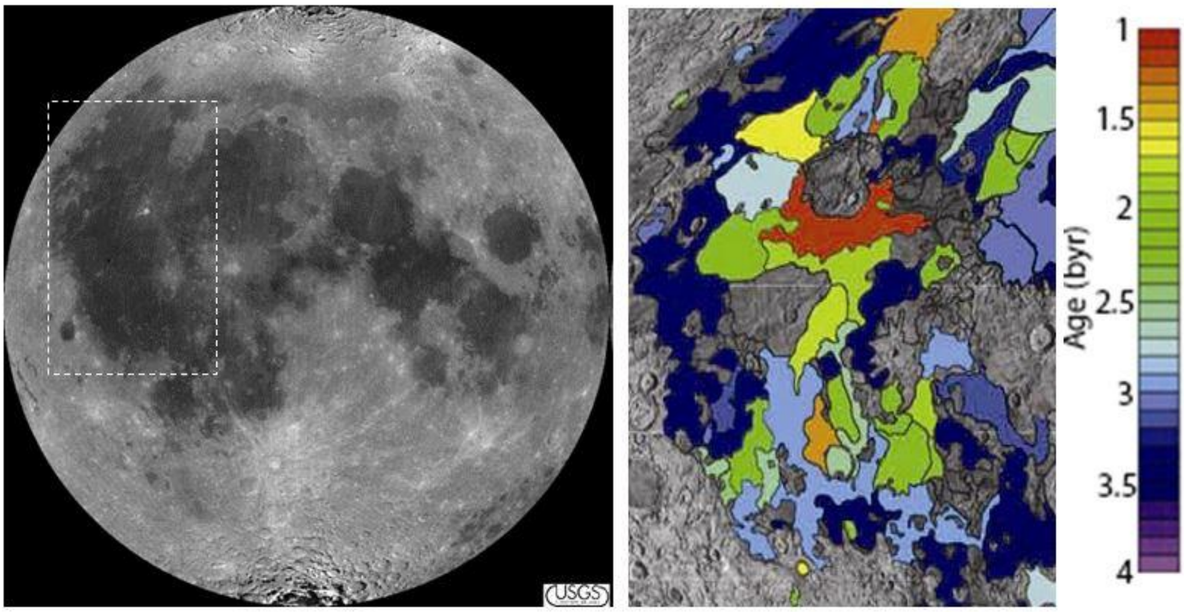

Figure 2. (left) Albedo map of the near side of the Moon. Dashed box represents region of Oceanus Procellarium mare basalts shown at right. (right) Absolute model ages of lava flows in Oceanus Procellarum, as mapped by Hiesinger et al. (2003). Sample return from one or more of these lava flows would verify these ages, with the benefits described in the text. (Image courtesy of Dr. H. Hiesinger; © AGU).

Collecting samples from one or more of these different lava flows, and returning them to Earth for radiometric dating, will directly lead to an improvement in the calibration of the lunar cratering rate for the last three billion years (see Stöffler et al., 2006). The post 3 Ga lunar cratering rate is poorly calibrated (as a result of Apollo not having visited younger surfaces), but this is the cratering rate that is used, with assumptions, to date cratered surfaces elsewhere in the Solar System (most notably the surface of Mars). Thus, better constraining the lunar cratering rate in this time interval is of importance to planetary science generally, not merely in the context of lunar geology Moreover, extra-lunar materials collected form regoliths developed on top of lava flows of different ages (and palaeoregoliths trapped between them) will make it possible to determine how the flux and composition of solar wind particles, galactic cosmic ray particles, and meteoritic impacts have varied with time. Finally, although not directly related to the theme of this White Paper, we note that geochemical analysis of these basaltic samples would also yield information on the magmatic history of the Moon, and thus lunar mantle evolution, extending our understanding of lunar geological and thermal evolution to more recent times than is possible using the Apollo and Luna sample collections.

3.2.2.2 South Pole Aitkin Basin sample return

The South Pole Aitkin (SPA) basin is the largest (~2500 km in diameter) and oldest recognized impact basin on the Moon. Its deep structure, which may have sampled the lunar mantle, and subsequent modification provides a unique sampling site for accessing a record of the Moon's early geological evolution and its impact history (e.g., Duke, 2003; Jolliff et al., 2010). As SPA is the Moon's oldest known impact structure, directly measuring its age would help constrain the bombardment history of the entire inner Solar System, including that of the Earth (e.g. Norman, 2009; Fernandes et al., 2013, and references therein). Moreover, dating SPA, and younger craters and basins within it, will further elucidate the extent to which the early bombardment history of the Earth-Moon system was stochastic (or 'saw-toothed', Morbidelli et al., 2012) with significant implications for the habitability of the early Earth. Last but not least, dating SPA is important because it provides temporal information for the thermal evolution of the lunar curst, and an upper age limit for the addition of a 'late veneer' to the lunar mantle (i.e. later impacts will not deliver volatiles and platinum group elements to the mantle because it will have been sealed by a thick crust).

As discussed in Section 2.1, addressing these questions will require the return of samples from SPA for analysis in laboratories on Earth. The primary mission objective is therefore to return ~1-10 kg (TBC) of lunar regolith from within SPA to determine the age of SPA itself, and ideally also younger craters and basins located within it, SPA is thought to have had a large melt sheet that forms much of the present day floor of the crater, although this melt sheet has been modified by more recent geological processes (magmatism, younger impact basins). Survival of SPA impact melt breccias in present day regolith (after mixing with ejecta from younger impacts) estimated to be ~75-80 % (e.g., Petro and Pieters, 2004), and some regions of the basin preserve this record better than others.

There are a number of suitable landing sites for SPA sample return, however, Schrödinger basin, which is a large impact basin located on the western rim of SPA (centered at 75°S, 132.5°E; Fig. 3) has been identified as particularly ideal site to both sample SPA impact products, and also address other numerous key questions in lunar and planetary science (e.g., Bunte et al., 2011; O'Sullivan et al., 2012; Kring and Durda, 2012). These include dating the age of Schrödinger itself in addition to SPA which, as one of the *youngest* lunar basins (Wilhems, 1987), would further constrain the basin-forming impact chronology. In addition, the floor of Schrödinger contains presumed young pyroclastic deposits (Fig. 3). Not only would sampling these materials provide valuable information on late-stage lunar volcanism, but palaeoregoliths covered by the pyroclastic deposit may contain information on the extra-lunar environment (e.g., solar wind, cosmic rays, meteoritic debris) from a well-defined time horizon.

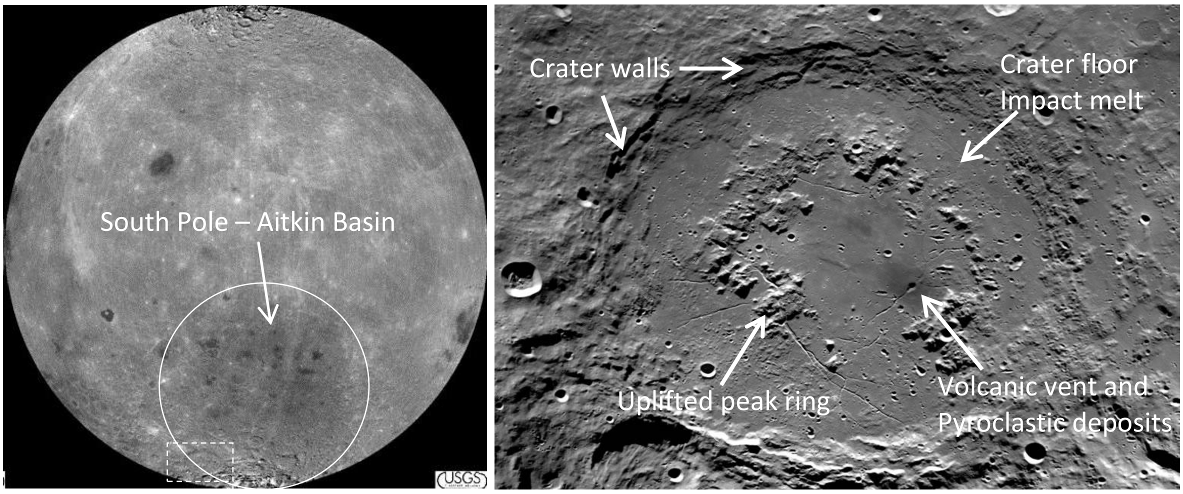

Figure 3. (left) Albedo image of the farside of the Moon. Dashed box shows location of the Schrödinger basin close to the South Pole. (right) Close up albedo map of the Schrödinger basin, which is 315 km in diameter. Some major geological features indicated. .

3.2.3 Sample return mission architecture

3.2.3.1 Moon Near Side Architecture (MNSA)

For the Moon Near Side Architecture, two main strategies can be envisaged and are reported Table 3-2.

Table 3-2: Mission Architecture Elements	
Strategy 1	Strategy 2
Carrier Spacecraft	Lunar Lander
Lunar Lander	Lunar Ascent Vehicle
Lunar Ascent Vehicle	

Both strategies nominally rely on a Soyuz-Fregat (TBC) launch to perform the injection to Geostationary Transfer Orbit (GTO), but the possibility of using a more powerful launch vehicle (e.g., Ariane 5) will be investigated in future studies with a view to enhancing the capabilities of the landed elements. The two strategies differ with regards to the mission element performing the transfer from Earth to Low Lunar Orbit (LLO, about 100-150 km altitude) as well as the return journey. In fact, for the first strategy, the transfer in both directions is performed by a Carrier Spacecraft, while in the second case the Earth to Moon transfer is performed by the Lunar Lander and the return journey by the Lunar Ascent Vehicle itself (accommodating also the Earth Re-Entry Vehicle). Both strategies will be thoroughly traded-off during future mission studies. As example, here only one will be discussed more in detail.

Strategy 1 foresees that, once delivered to GTO, the Carrier Spacecraft (CS) will carry the Lunar Lander (LL) and the Lunar Ascent Vehicle (LAV) to LLO. Therefore, the LL will separate from the CS and will descend using a dedicated chemical propulsion stage. Once on surface, lunar samples, for a total mass in the order of 1-10 kg (TBC), will be collected and stored into the LAV. The mode of sampling will be assessed during future studies, but we currently envisage a sieved and/or cored sample of regolith containing mm to cm-sized 'rocklets' suitable for dating and mineralogical and geochemical analyses; one or more core samples (depth TBD) would also provide valuable stratigraphic information about the regolith and implanted volatiles. Possible mobility requirements will also be assessed during future studies and could involve either a rover or a hopper capable of multiple landings. The final choice will depend on several factors among which: available launch vehicle, mass and power resources, and sampling site(s) location(s). During surface operations, the CS orbiting around the Moon will deliver a set of Penetrators in predefined locations to enable further scientific investigation

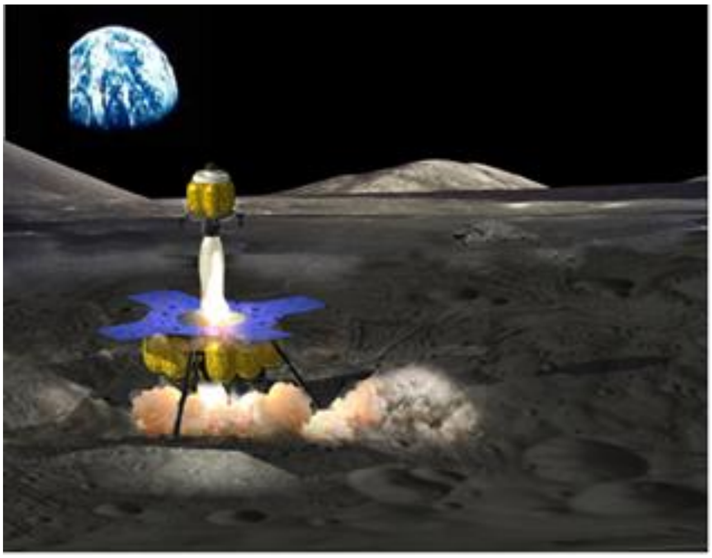

Figure 4. The LAV takes off from the lunar surface (Astrium)

After completion of sample acquisition and storage, the LAV will take off from the LL leaving behind the sampling equipment, the landing stage, and some scientific instruments (Fig. 4). Once in lunar orbit, the sample container will be ejected, captured by the CS and transferred into the Earth Re-Entry Vehicle. The CS will capture the sample container and use the same propulsion system as used for the outward journey to return to Earth.

A preliminary assessment of this Architecture allows for a LL of 665 kg (including 384 kg of propellant), LAV of 145 kg (including 66 kg of propellant), and a CS of 1937 kg (including 1509 kg of propellant for the two transfers, and 206 kg for four Descent Modules transporting the penetrators). More accurate mass break downs can be determined once the landing site and staging strategy are analysed during future mission studies. Trade-offs on the overall architecture will also need to be performed in the next study phases and might result in significant mass savings or enhanced mission capability. Last but not least, it has to be noted that such a mission will also directly demonstrate key technologies for Mars Sample Return (MSR), as the proposed Architecture is very similar.

3.2.3.2 Moon Far Side Architecture (MFSA)

Also for this Architecture, two possible strategies can be envisaged and they are reported in Table 3-3 below. As the lunar farside is never visible from Earth a relay element, which could be either located in LLO or in EML-2, is needed in order to support communications.

Table 3-3: Mission Architecture Elements	
Strategy 3	Strategy 4
Carrier/Orbiter Spacecraft	Deployed human spaceflight infrastructure in Earth-Moon Lagrange Point 2 (EML-2)
Lunar Lander	Lunar Lander
Lunar Ascent Vehicle	Lunar Ascent Vehicle

The strategy 3, is similar to the one presented for the MNSA, with a CS aimed at performing the transfer from Earth to Moon and return as well as delivering the set of Penetrators, but also providing communication services between the surface elements and the Ground Station(s), a LL descending on lunar surface, and a LAV hosting the collected samples and bringing them back to orbit, where they will be transferred into the Earth Re-Entry Vehicle of the CS to be transported to Earth.

Of significant interest is also the strategy currently under investigation from NASA (Alkalai et al., 2012) which foresees the exploitation of a human spaceflight infrastructure in EML-2 to perform the rendezvous with the orbiting LAV and make easier the securing of the sample container. In fact, the implementation of such an approach could be advantageous because:

- The propellant mass required to return to Earth would be saved;
- The Orbiter would be not needed, as the communications with Earth could be enabled via the EML-2 infrastructure.
- The Earth Re-Entry Vehicle would be not needed, as the Sample Container would be secured in the EML-2 infrastructure;
- Teleoperations from EML-2 to lunar surface could be performed, this increasing the mission success probability;
- Owing to the saved mass, the LAV could be bigger and accommodate a larger quantity of samples, increasing the scientific return.

As for the MNSA, both the presented strategies will be investigated during future studies (including consideration of a more powerful launch vehicle), in order to identify the associated benefits and risks.

3.2.3.3 Surface mobility requirements

In order to address the top-level science questions it is essential that samples be collected from a diverse range of localities separated by tens, or even hundreds, of km (see Figs. 2 and 3 for the scale of separation of geological units in Procellarum and Schrödinger, respectively). A rover capable of collecting rock and soil samples from a radius of a few tens of km from the landing site would be extremely valuable from this point of view. Surface mobility would also enable the sampling of ejecta from small craters that will have naturally excavated to a range of depths below the surface, thereby providing important stratigraphic information. In addition to collecting samples, and transferring them to the sample return vehicle, such a rover could be instrumented to obtain contextual information for the samples (e.g., by multi-spectral imaging, *in situ* mass spectrometry, X-Ray fluorescence/diffraction, and/or Raman-LIBS instruments). In addition, a rover could use ground penetrating radar to image shallow subsurface structure (e.g., a 1 GHz radar, easy to accommodate on a small rover, could determine internal regolith structure, to a depth of about 2 m), which would help with sample site selection/local context and regolith depth/age determination. We note that even a smaller range rover would be useful to support sample collection from outside areas contaminated by the landing, which would be especially important when considering samples containing volatiles. The Mobile Payload Element, designed in the context of ESA's proposed Lunar Lander (Haarmann et al., 2012), provides an example of a small (~14 kg) autonomous and innovative rover that could satisfy this requirement.

Despite the advantages of a rover, for some of the scientific objectives outlined above (especially in the Oceanus Procellarum mission case) a sample collection range of 50 to 100 km might be preferable. As this may be beyond the practical range of a rover that could be landed within the mass constraints, we propose that the possibility of having the lander 'hop' to multiple locations separated by tens or hundreds of km will be investigated as part of an industrial pre-phase A study of the sample return architecture.

Accessing palaeoregolith deposits, either trapped between lava flows in Oceanus Procellarum, or beneath pyroclastic deposits in Schrödinger, may require a drilling capability to be included. Determining whether or not drilling will actually be required, and if so the probable depth, will depend on whether plausible palaeoregolith outcrops can be identified in high-resolution Lunar Reconnaissance Orbiter Camera (LROC) images (see discussion by Crawford et al., 2009). The practicality of including a drilling capability will likewise be studied during an industrial pre-Phase A study should the mission concept be deemed worthy of further study.

4 Conclusions

We have proposed a Cosmic Vision 'Science Theme' of using lunar science as a window into the early history of the Solar System. The near surface lunar environment contains a rich record of inner Solar System history. Accessing this record will directly address key elements of ESA's Cosmic Vision themes, especially Theme 1 ('Planets and Life') and Theme 2 ('How does the Solar System Work?'). Implementation will require spacecraft to land on the lunar surface in order to make *in situ* measurements at, and/or return samples from, localities that have been carefully selected with specific scientific objectives in mind.

For the Cosmic Vision L2/3 mission opportunities we propose the development of a scientific infrastructure that would enable us to address these scientific objectives. There are two, mutually complementary, strands: (i) a mission based around multiple penetrators for the characterisation of lunar polar volatiles and (ii) a sample return mission to address the lunar impact chronology and records of the near-Earth Solar System environment preserved in regolith deposits. We consider that the development of such an ambitious lunar science architecture is worthy of careful consideration for the Cosmic Vision L2/3 mission opportunities.

References

Alkalai, L. et al., 2012. ORION/MOONRISE: Joint human-robotic lunar sample return mission concept, LEAG Meeting, GSFC.

Anand, M., 2010. Lunar water: a brief review. *Earth Moon Planets*, 107, 65-73.

Armstrong, J.C., 2010. Distribution of impact locations and velocities of Earth meteorites on the Moon. *Earth Moon Planets*, 107, 43-54.

Armstrong, J.C., Wells, L.E. and Gonzales, G., 2002. Rummaging through Earth's attic for remains of ancient life. *Icarus*, 160:183-196.

Bottke, W.F., et al., 2012. An Archaean heavy bombardment from a destabilized extension of the asteroid belt, *Nature*, 485, 78-81.

Brock, L.S., Melosh, H. J., 2012. Impact Exchange of Material Between Planets of Gliese 581, LPSC, 43, 2467.

Bunte, M. K., et al., 2011. A sortie mission to Schrödinger Basin as reconnaissance for future exploration. *GSA Special Papers* 483, 533-546 doi: 10.1130/2011.2483(32).

Chyba, C.F., Sagan, C.,1992. Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: an inventory for the origins of life. *Nature*, 355, 125-132.

Chaussidon, M., Robert, F., 1999, *Nature* 402, 270-273.

Colaprete, A., et al., 2010. Detection of water in the LCROSS ejecta plume. *Science*, 330, 463-468.

Cockell, C.S., 2010. Astrobiology – what can we do on the Moon? *Earth, Moon Planets* 107, 3-10.

Crawford, I.A., 2006. The Astrobiological Case for Renewed Robotic and Human Exploration of the Moon. *Internat. J. Astrobiology*, 5, 191-197.

Crawford I.A., Fagents S.A., and Joy K.H. 2007. Full Moon Exploration: valuable (non-polar) lunar science facilitated by a return to the Moon. *Astronomy and Geophysics*, 48: 3.18–3.21.

Crawford, I.A., Joy, K.H., Fagents, S.A., Rumpf, M.E., 2009. The importance of lunar palaeoregolith deposits and the role of Lunar Reconnaissance Orbiter, LRO Targeting Meeting, Tempe, Arizona; Abstract # 6007.

Crawford, I.A., Baldwin, E.C., Taylor, E.A., Bailey, J. and Tsembelis, K., 2008. On the survivability and detectability of terrestrial meteorites on the Moon. *Astrobiology*, 8, 242-252.

Crawford, I.A., Fagents, S.A., Joy, K.H., Rumpf, M.E., 2010. Lunar palaeoregolith deposits as recorders of the galactic environment of the Solar System and implications for astrobiology. *Earth Moon Planets*, 107, 75-85.

Crawford, I.A., et al., 2012. Back to the Moon: the scientific rationale for resuming lunar surface exploration. *Planet . Space Sci*., 74, 3-14.

Crites, S.T., et al., 2011. In-situ production of organic molecules at the poles of the Moon, AGUFM.P13D1730C.

Gomes, R., et al., 2005. Originof the cataclysmic late heavy bombardment period of the terrestrial planets, *Nature*, 435, 466-469.

Crozaz, G., et al., 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.,* A285, 587-592.

De Vera, J.-P., et al., 2012. Supporting Mars exploration: BIOMEX in Low Earth Orbit and further astrobiological studies on the Moon using Raman and PanCam technology; *Planet. Space Sci*., 74, 103-110.

Duke M.B. 2003. Sample return from the lunar South Pole-Aitken Basin, *Advances in Space Research* 31, 2347–2352

Fagents, S.A., Rumpf, M.E., Crawford, I.A. and Joy, K.H., 2010. Preservation potential of implanted solar wind volatiles in lunar paleoregolith deposits buried by lava flows. *Icarus*, 207, 595-604.

Feldman, W.C., et al., 1998. Fluxes of fast and epithermal neutrons from Lunar Prospector: evidence for water ice at the lunar poles. *Science*, 281, 1496-1500.

Fernandes, V.A., et al., 2013. The bombardment history of the Moon as recorded by ^{40}Ar-^{39}Ar chronology, *Meteotitics and Planetary Science*, 48, 241-269.

Gutiérrez, J.L., 2002. Terrene meteorites in the moon: relevance for the study of the origin of life in the Earth. ESA SP-518, 187 – 191.

Haarmann, R., Jaumann, R., et al., 2012. Mobile Payload Element (MPE): Concept study for a sample fetching rover for the ESA Lunar Lander Mission, *Planet. and Space Sci*., 74, 283-295.

Hashizume, K., et al., 2000. Solar Wind Record on the Moon: Deciphering Presolar from Planetary Nitrogen, *Science*, 290, 1142-1145.

Hiesinger, H., Head, J.W., 2006. New views of lunar geoscience: an introduction and overview. *Rev. Min. Geochem*., 60, 1-81.

Hiesinger, H.J. *et al*., 2003. Ages and stratigraphy of mare basalts in Oceanus Procellarum, Mare Nubium, Mare Cognitum, and Mare Insularum, *J. Geophys. Res*., 108 (E7), 1-27.

Hiesinger, H., van der Bogert, C.H., Pasckert, J.H., Funcke, L., Giacomini, L., Ostrach, L.R., Robinson, M.S., 2012. How old are young lunar craters? *J. Geophys. Res.,* 117, E00H10.

Jaumann, R., et al., 2012. Geology, geochemistry and geophysics of the Moon: status of current understanding. *Planet. Space Sci.,* 74, 15-41.

Jester, S., Falcke, H., 2009. Science with a lunar low frequency array: from the dark ages of the universe to nearby exoplanets. *New Astronomy Reviews*, 53, 1-26.

Johnson, B.C., et al., 2012. A self-consistent model of the circumstellar debris created by a giant hypervelocity impact in the HD 172555 system *Astrophysical Journal*, 761, Issue 1, article id. 45.

Jolliff, B. L., et al., 2010. MoonRise: Sampling South Pole-Aitken Basin as a Recorder of Solar System Events. American Geophysical Union, Fall Meeting 2010, abstract #P43A-01.

Joy, K.H., et al., 2011. Re-examination of the formation ages of the Apollo 16 regolith breccias. *Geochimica et Cosmochimica Acta*, 75, 7208-7225.

Joy, K.H., et al., 2013. Direct detection of projectile relics from the end of the lunar basin-forming epoch. *Science*, 336, 1426-1429.

Kring, D.A., 2003. Environmental consequences of impact cratering events as a function of ambient conditions on Earth, *Astrobiology*, 3, 133-152.

Kring, D.A., Durda, D.D., eds., 2012. A Global Lunar Landing Site Study to Provide the Scientific Context for Exploration of the Moon, LPI Contribution. 1694, LPI, Houston, TX, 688 pp.

Liu, Y. et al., 2012. Direct measurement of hydroxyl in the lunar regolith and the origin of lunar surface water, Nature Geoscience, 5, 779-782.

Lucey, P.G., 2000. Potential for prebiotic chemistry at the poles of the Moon. *Proc. SPIE*, 4137, 84-88.

Lucey, P.G., et al., 2006. Understanding the lunar surface and space-Moon interaction. *Rev. Min. Geochem*. 60, 82–219.

Maher, K.A., Stevenson, D. 1988. Impact frustration of the origin of life, *Nature*, 331, 612-614.

McKay, D.S., et al., 1991. The lunar regolith. In: Heiken, G.H., Vaniman, D. and French, B.M. (Eds.), *The Lunar sourcebook: A user's guide to the Moon*, Cambridge University Press, pp. 285-356.

Morbidelli, A., et al., 2012. A sawtooth-like timeline for the first billion years of lunar bombardment, *Earth Planet. Sci. Lett*., 355, 144-151.

Neukum, G., Ivanov, B. A., Hartmann, W. K., 2001. Cratering Records in the Inner Solar System in Relation to the Lunar Reference System. *Space Science Reviews*, 96, 55-86.

Norman M. D. 2009 The Lunar Cataclysm: Reality or "Mythconception"? *Elements*, Vol. 5, 23–28.

Petro, N. E., and Pieters C. M.,2004. Surviving the heavy bombardment: Ancient material at the surface of South Pole-Aitken Basin, *J. Geophys. Res*., 109, E06004, doi:10.1029/2003JE002182.

Mizutani, H., et al., 2005. Lunar-A mission: outline and current status*., J. Earth System Science*, 114, 763-768.

NRC, 2007. *The Scientific Context for Exploration of the Moon*. National Research Council, National Academies Press, Washington DC.

O'Sullivan K.M., et al., 2011. Calibrating several key lunar stratigraphic units representing 4 billion years of lunar history within Schrödinger Basin. In *Recent Advances in Lunar Stratigraphy*, D.A. Williams and W. Ambrose (eds.), pp. 117–128, *Geol.Soc.Am. Special Paper 477*, Boulder, CO.

Ozima, M., et al., M., 2005. Terrestrial nitrogen and noble gases in lunar soils. *Nature* 436:655-659.

Ozima, M., et al., 2008. Toward prescription for approach from terrestrial noble gas and light element records in lunar soils understanding early Earth evolution. *Proc. Nat. Acad. Sci.* 105:17654–17658.

Pierazzo, E., Chyba, C.F., 1999. Amino acid survival in large cometary impacts. *Meteorit. Planet. Sci*., 34, 909-918.

Pieters, C.M. et al., 2009. Character and spatial distribution of OH/H_2O on the surface of the Moon seen by M^3 on Chandrayaan-1. *Science*, 326, 568-572.

Rumpf, M.E., Fagents, S.A., Crawford, I.A., Joy, K.H., 2013. Numerical modeling of lava-regolith heat transfer on the Moon and implications for the preservation of implanted volatiles'', *Journal of Geophysical Research (Planets)*, 118, 382-397.

Ryder G., 1990. Lunar samples, lunar accretion and the early bombardment of the Moon. *EOS* **71**, 313-323 .

Ryder, G., 2003. Bombardment of the Hadean Earth: wholesome or deleterious? *Astrobiology*, 3, 3-6.

Sleep N.H., Zahnle K.J., Kasting K.F. and Morowitz H.J., 1989. Annihilation of ecosystems by large asteroid impacts on the early Earth, *Nature*, 342, 139-142.

Smith, A., et al., 2012. Lunar Net—a proposal in response to an ESA M3 call in 2010 for a medium sized mission, *Experimental Astronomy*, 33, 587-644.

Spudis, P.D., 1996. *The Once and Future Moon*. Smithsonian Institution Press, Washington D.C.

Spudis P. D. and Lavoie A. R. 2011. Using the resources of the Moon to create a permanent, cislunar space faring system. AIAA SPACE 2011 Conference & Exposition. AIAA 2011-7185.

Stöffler, D., et al., 2006. Cratering History and Lunar Chronology, *Rev. Min. Geochem*., 60, 519 – 596.

Wieler, R., Kehm, K., Meshik, A.P., Hohenberg, C.M.,1996. Secular changes in the xenon and krypton abundances in the solar wind recorded in single lunar grains. *Nature*, 384:46-49.

Wilhelms, D.E. 1987. *The Geologic History of the Moon*, USGS Professional Paper No. 1348.

Zhang, J.A., Paige, D.A. 2009. Cold-trapped organic compounds at the poles of the Moon and Mercury: implications for origins, *Geophys. Res. Lett*., 36, L16203.