Lunar Science as a Window into the Early Evolution of the Solar System and Conditions on the Early Earth

ABSTRACTS

The Timing and Source(s) of Water Addition in the Lunar Interior

Mahesh Anand (Open University)

Recently, we have witnessed a paradigm shift in our understanding of the history of water on the Moon. Currently, there is less disagreement over the presence of water in the lunar interior as documented by sample analysis. However, uncertainties exist regarding the abundance, distribution, and the source(s) of water in the lunar interior. In addition, it is also not known if the water content of the lunar interior has changed through time.

The giant-impact origin of the Moon is thought to have involved a lunar magma ocean (LMO) phase. Much of any water present during the accretion of the Moon would presumably have been lost to space because of high-temperatures but some primordial water may have been sequestered in minerals and rocks formed by LMO solidification. There is also a possibility that some additional water was accreted to the Moon after the LMO solidification through impacts of meteorites.

Mare basalts (and volcanic glasses) derived by partial melting of the lunar mantle have erupted episodically onto the lunar surface. Any evidence for the presence of water in the lunar mantle is likely to be preserved in mare basalts as water behaves incompatibly during mantle partial-melting and is thus partitioned preferably into the melt. The Apollo and Luna missions collected a range of lunar samples including those of primary LMO products (e.g., anorthosites, Mg-suite rocks etc.) and a variety of mare basalts with crystallization ages predominantly ranging from ~ 3.9 to ~ 3.1 Ga. However, Apollo samples were collected from geographically restricted areas from the equatorial nearside of the Moon. In contrast, lunar meteorites potentially may have originated from areas of the Moon, far away from the Apollo sites and thus provide a wider sampling of the lunar surface. There are a number of lunar basaltic meteorites ranging in age from 4.35 Ga to ~ 2.8 Ga.

By combining age-dating of apatites, from lunar basalts, with measurements of their H-content and H isotopic composition, we can investigate any secular changes in the water content of the lunar interior. By synthesising and modelling of all previously published data on OH contents and H isotope compositions of lunar apatite from mare basalts, we demonstrate that a model of hydrogen delivery into the lunar interior by late accretion of chondritic materials provides a satisfactory explanation to account for the measured "water" content and its hydrogen isotopic composition in mare basalts.

Exploring the Early Bombardment of the Earth and Moon

Bill Bottke (Southwest Research Institute)

The Late Heavy Bombardment refers to a period 4 billion years ago in which the large lunar basins with known ages were produced. The nature of the LHB is debated. One view is that the LHB marked the end of a steadily decreasing bombardment of the inner solar system due to the leftover planetesimals of planet accretion. A second view is that the LHB was a short-lived "cataclysm" of dramatically increased impact rates on the Moon and other inner solar system worlds, possibly produced by a rearrangement of the giant planets. Until recently, we have been unable to distinguish between these two fundamentally different histories of the solar system.

Here I will argue that both schools are probably correct in some fashion, with late-forming lunar basins made by asteroids destabilized by late giant planet migration (e.g., the Nice model). We can show that many LHB-era impactors probably came from an unexpected source, and that they continued to hit Earth, Venus, and Mars well after the last lunar basin formed about 3.7-3.8 billion years ago (Bottke et al. 2012; Nature). In fact, this "late late" bombardment probably pummelled the Earth throughout the Archean and early-Proterozoic eras (1.8-3.8 Gy ago), a formative time for early life and our biosphere. The smoking gun for this bombardment comes from the known terrestrial impact spherule beds: globally distributed ejecta layers created by Chicxulub-sized or larger cratering events. At least seven spherule beds have been found that formed between 3.23 and 3.47 Gyr ago, four between 2.49 and 2.63 Gyr ago, and one between 1.7 and 2.1 Gyr ago. We will show our revised impact rates reproduce impact spherule bed and lunar crater constraints.

Processing of projectiles during high speed impacts: Implications for understanding what we may find on the Moon.

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Harvesting of terrestrial meteorites on the Moon offers the opportunity to examine samples from different eras in the Earth's history. However, whilst terrestrial material will survive an impact on the lunar surface relatively intact (minimum impact speed circa 2 km s^{-1} with a peak around 3 km s^{-1}, see Armstrong 2010 for a discussion), it may well undergo subtle changes as a result. These can introduce shock effects, alter the apparent mineralogy, preferentially influence any organic content and change the detectable biomarkers. Thus whilst material may be recoverable, it may not only have been altered by the length of its residency on the Moon, but will also have undergone a series of changes during the impact which may potentially seriously bias the results.

Accordingly, based on a series of recent light gas gun experiments, we present examples of how impact shock effects can alter the projectile fragments recovered after an impact. The range of effects considered include fragmentation of the projectile (Milner et al., 2006), mineralogical changes on olivines (Wozniakiewicz et al., 2012), introduction of shock defects in calcite (Lindgren et al., 2011), change in apparent carbon amorphous vs. crystalline structure (Fries et al., 2009), changes in organic content of shale (Bowden et al., 2008) and studies of alteration of biomarker content in shale Parnell et al., 2010). Indeed, higher impact speeds of 5 or 6 km s^{-1} may also leave fragments or residues in craters which contain signatures of the original mineralogy (e.g. see Burchell et al., 2008, Wozniakiewicz et al., 2012) and even biological material may survive, albeit in altered or reduced amounts (see Burchell et al., 2010 for a discussion relevant to lunar astrobiology).

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The Lunar Poles: A Record of the Early Earth's Impact History

Ben Bussey (Applied Physics Laboratory)

The Moon is a critical and important target for scientific exploration. It is a miniature planet in that it has experienced most of the geological processes that operate during the formation and evolution Of all the terrestrial planets. Studying the early development of the Earth is problematic because key evidence has been removed by erosion and active crustal recycling and tectonics. In contrast, the Moon retains a record of many of the earliest experiences and events within the Earth-Moon system. A long-term human presence at a lunar pole would permit the study of the early geological evolution of the Earth-Moon system. Some specifics include determining the impact flux history (with the associated planetary survival ramifications), studying the physics of the impact process, and studying the output and processes of the ancient Sun (the Moon preserves in its regolith a record of the solar wind from the last 4.5 billion years.) In addition to improving our understanding of solar evolution, studying the long-term nature of Sun provides critical information on the history of Earth¹s climate.

Accessing the Lunar Record: Implications for Exploration Policy

Ian Crawford (Birkbeck, University of London)

The lunar geological record has much to tell us about the earliest history of the Solar System, the origin and evolution of the Earth-Moon system, the geological evolution of rocky planets, and the near-Earth cosmic environment throughout Solar System history. Although some progress can continue to be made by studying existing lunar samples, gaining proper access to the lunar geological record will require an end to the 40-year hiatus in lunar surface exploration. Renewed exploration will advance our knowledge in key areas by enabling the placing of sophisticated scientific instruments on, and the return of samples from, the surface (and sub-surface) of the Moon, with a particular emphasis on regions not previously visited.

Many of these exploration objectives can be addressed robotically, as reflected by the large number of proposals for lunar surface robotic missions that have been put forward in recent years; the proposed ESA Lunar Lander and NASA MoonRise mission concepts are two well-developed examples (although neither have yet been funded). In the longer term, it seems clear that most of these research objectives would benefit from the scientific infrastructure, on the spot decision making, enhanced surface mobility, and increased sample return capacity that would be provided by renewed human operations on the lunar surface. Indeed, some of the scientific objectives directly relevant to understanding the early Earth (e.g. deep drilling into the sub-surface to extract undisturbed palaeoregolith deposits with their potentially rich record of Solar System history) may be impractical without a human presence (see [1] and references therein for a more detailed discussion of these issues).

In this context it is worth noting that the kind of ambitious exploration programme required to properly access the lunar geological record is currently under active international discussion. In 2007 the World's space agencies came together to develop the Global Exploration Strategy (GES [2]), which lays the foundations for an international programme for the exploration of the inner Solar System. One of the first fruits of the GES has been the development of a Global Exploration Roadmap [3], which outlines possible international contributions to human and robotic missions to the Moon, near-Earth asteroids and, eventually, Mars. Implementation of this roadmap would provide many opportunities for pursuing the science objectives discussed at this meeting. Our understanding of the origin and evolution of the Earth-Moon system, and of the conditions prevailing on the early Earth, would therefore be major beneficiaries of implementing the Global Exploration Roadmap.

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[2] *The Global Exploration Strategy: Framework for Coordination*

(http://esamultimedia.esa.int/docs/GES_Framework_final.pdf).

[3] *The Global Exploration Roadmap*

(http://www.nasa.gov/pdf/591067main_GER_2011_small_single.pdf).

The importance of the Moon as an Isotopic Reference for Earth Evolution

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Studies have long compared the composition of the accessible Earth to chondritic meteorites in order to deduce the make-up of inaccessible terrestrial reservoirs. Notably, the composition of the core and the conditions of its formation are have been inferred form the missing budgets of siderophile elements in the Earth's upper mantle. For lithophile elements (e.g. K), apparent inconsistencies in the combined crust and accessible mantle inventories have been explained as hidden reservoirs, occupying various volumes of the uncharted lower mantle. Fresh impetus to this approach has recently come from the ability to make a range of stable isotopic measurements to high precision. Thus, the superchondritic δ^{30}Si of the Earth's mantle has been attributed to fractionation of Si during core formation. The Moon plays a key reference point in such an analysis. In the case of Si, a value of δ^{30}Si for the Moon within error of the Earth (Armytage et al 2012) suggests that it was formed from the proto Earth, post the major phase of core formation. We have focused on the isotopic budget of the major lithophile element Mg. Although some earlier studies disagreed in the δ^{26}Mg determined for the Earth, more recent work has generally converged to a value ~ -0.20

relative to the commonly used DSM-3 standard. We have documented how diffusive processes can perturb the Mg isotopic composition of mantle xenoliths en route to the surface and we have been able to use Li isotopic measurements to screen for pristine mantle samples. Such filtering, combined with our high precision analyses has allows us to define a mantle value of ^{26}Mg = -0.23±0.01 (2se). In contrast, our average δ^{26}Mg for primitive chondrites is -0.42±0.02 (2se). The lunar reference can play a major role in constraining the origin of this difference. Did the Earth accrete with non-chondritic Mg isotope ratios, as has previously been proposed (Wiechert and Halliday 2007)? In this case the δ^{26}Mg of the Earth and Moon might be the same. Alternatively, does the isotopically heavy composition of accessible Earth imply a hidden, isotopically light reservoir in the deep terrestrial mantle? If this results from crystallization of a magma ocean, post-lunar collision, then the Moon might be expected to have near chondritic δ^{26}Mg. We are currently testing these hypotheses and will (hopefully) present new data on high precision lunar δ^{26}Mg at the meeting.

Delivery of Volatiles to the Earth Before and After Moon Formation”

Alex Halliday (Oxford University)

The mostly widely accepted model for the origin of the Moon is that it formed in a Giant Impact between an Earth that was roughly 90% formed and a Mars-sized impactor sometimes called "Theia", which added most of the remaining 10%. This is based on smooth particle hydrodynamic simulations that need to conserve angular momentum with relatively little overall loss over time. The amount of energy imparted would be significant and some have suggested that Earth could not have acquired and retained its current volatiles until after the Moon formed, adding support to the idea of a subsequent "late veneer". However, there are problems with this Giant Impact model as there are with explaining Earth's volatiles with a late veneer. In particular most of the Moon is derived from Theia in the simulations whereas oxygen isotopes provide evidence that most of the atoms came from Earth. In addition Earth's volatiles as currently known have H/N and H/C ratios that are distinct from those expected from volatile rich chondritic or cometary veneers. The overall patterns of noble gases and major volatiles make more sense as a series of Solar, chondritic and cometary additions punctuated by major differential losses to the core or to space. As such some of the volatiles appear to predate any late veneer and possibly also predate the Giant Impact. The atmospheres of Mars and Venus appear to be broadly similar to this. Some of the new dynamic models that are now being developed for the Giant Impact appear to be more consistent with this. They explain the oxygen isotopic similarity with the Earth and offer a broader array of possibilities for the energy imparted and the amount of mixing and volatile loss that might have been achieved.

The Lunar Regolith as an Archive of Solar System Bombardment

Katherine Joy (University of Manchester)

The Lunar Regolith as an Archive of Solar System Bombardment: The lunar regolith is an important boundary layer between the Moon and surrounding space environment. At any one locality the lunar regolith typically contains a record of diverse rock types mixed by vertical and lateral impacts. It also preserves an archive of material added to the Moon by projectiles, and contains a record of the Moon's interaction with the solar wind, and galactic environment. Temporally constraining this record sheds light on different times in the Moon's past, helping to better understand the geological history of the Moon itself, and the bombardment history of the Moon, Earth and Solar System.

The Lunar Surface Record of Matter Contribution to Planetary Surfaces in the Terrestrial Region

Bernard Marty (Ecole Nationale Supérieure de Géologie, Nancy)

Lunar soils have recorded contributions of ET material (IDPs, micrometeorites and meteorites, cometary matter) to planetary surfaces in the terrestrial region over eons, that were otherwise tectonically erased on Earth. It has been suggested also that ions from the terrestrial atmosphere were implanted on the Moon when the terrestrial magnetic field was weaker than at present. The analysis of volatle elements (C, N, H, noble gases) in lunar soil grains provides an exceptionnal insight into the nature and strength of past fluxes, that permits to test the above possibility.

From Earth to the Moon: Impact Ejection of Intact Rocks from the Surface of our Planet

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We now know that rocks from the surface of Mars are ejected by impacts into interplanetary space. A few have eventually found their way into terrestrial meteorite collections. Although not yet proven, it seems likely that large impacts on the Earth also eject rocks from our planet into interplanetary space. Some of these ejecta must find their way to our Moon, among other places. The requirements for Earth ejection are more stringent than for Mars: Earth’s twice higher escape velocity and 100 times denser atmosphere limit possible ejection to much larger, and therefore rarer, events. Nevertheless, during the Archean era the cratering rate was much higher than at present and a record of impactors up to 70 km in diameter is inferred from thick spherule beds in our most ancient rocks. Because the Moon lacks an atmosphere, Earth ejecta must strike its surface at velocities of more than 2.5 km/sec, rendering it probable that Earth ejecta will be crushed and partially dispersed into the lunar regolith upon landing. Nevertheless, such velocities are too low to either melt or vaporize impacting Earth rocks, especially given the porous, easily crushed, lunar regolith. The Moon's regolith may thus preserve a fragmental record of the Earth's earliest crust.

What was the Earth's surface like in the late Hadean and early Archaean, and can ejected ancient terrestrial material be recognised on the Moon?

Euan G. Nisbet (Dept. Earth Sciences, Royal Holloway, Univ. of London)

It is probable that Earth-sourced ejecta may be present on the lunar surface, but can they be recognised? The late Hadean (pre- 4 Ga) and early Archaean (4.0 – 3.5 Ga) Earth's surface was likely recognisably similar to the modern planet in the presence of oceans and continents, but beyond that comparison is conjecture. The record preserved in the Hadean Acasta Gneiss and in zircons from the Jack Hills of W. Australia indicate that terrestrial continental material was present and should be recognisable, for example via $\delta\,^{18}O$ in zircon. Much of the late Hadean Earth's surface may have been covered by very extensive komatiite flows, and forsteritic olivines from such flows may be identifiable, especially if they retain silicate melt inclusions with modest volatile contents, as in some terrestrial examples that have frozen the contemporary Earth's mantle volatile complement.

Whether signs of life could be found is questionable. The Isua record includes carbon dust with light $\delta^{13}C$, but this may be difficult to differentiate from interplanetary carbon dust. On Earth, the deep phylogeny of bacteria is not inconsistent with one or more bottlenecks caused by major impacts that warmed the oceans $>100^{o}C$, with only hyperthermophiles surviving. Just possibly, traces of a hypothetical pre-bottleneck mesophile biota may be preserved in ejecta that made the transition to the Moon. But whether such traces could survive the aeons of subsequent gardening is unlikely.

Fluid Silicates at the Origin of the Earth-Moon System

Lars Stixrude (University College London)

Partial melting of silicates dominates the chemical evolution of Earth today and was even more important in earlier history of the terrestrial planets. The Earth-Moon system may have begun in a completely molten state, a global magma ocean, extending from the boundary with the iron-rich core to an attenuated rocky atmosphere than may have encompassed the proto-Moon. This initial magma ocean may have left signatures of its presence in the Earth and Moon. However, these signals are still uninterpretable because of a lack of basic knowledge of the behavior of fluid silicates at extreme conditions: very little is known of the physics and chemistry of fluid silicates beyond the conditions of ongoing shallow magma genesis (pressure<3 GPa, temperature less than vaporization). We have begun to attack this problem by constructing a comprehensive thermodynamic model (HeFESTo) of multi-component silicate melting, vaporization, and reaction with iron, and the physical properties of liquid and vapor phases over the entire pressure-temperature range relevant to Earth and the Moon, including impacts and early Earth processes. To help constrain the thermodynamic model, we are performing new first principles quantum mechanical simulations in the range of pressure, temperature, composition relevant to the early Earth that have not yet been explored by experiment or theory. We discuss the implications of our recent finding that the Grüneisen parameter of silicate liquids increases on compression, the predicted melting curve of simplified chemical systems and estimates of whole mantle melting, the density contrast between liquids and coexisting solids, the viscosity of liquid silicates, and the phase equilibria and speciation of liquid-vapor coexistence.

Where was the Moon when the Earth was Young?

Dave Waltham (Earth Sciences, Royal Holloway, University of London)

In order to facilitate discussion at this meeting, this short talk will provide a brief review concerning the early evolution of the Earth-Moon system. The assumptions used are that the Moon was formed at 4.53 Ga as the result of a collision and that it rapidly coalesced just outside the Roche limit. Subsequent evolution was driven by tidal drag which resulted in slowing down of the Earth's rotation and recession of the Moon. The equations governing this evolution were first developed by George Darwin in the nineteenth century but it is only in the last few decades that we have had the data and tidal-drag models needed to implement these equations successfully. Key data was provided by the Apollo missions which gave us rocks which confirm the age of the Moon and its origin in a giant impact and which also provided the means to directly measure the current recession rate of the Moon. However, this recession rate implies a "friction factor" in tidal drag which, in turn, implies that the Moon was formed at around 1.55 Ga. Reproducing the correct 4.53 Ga age therefore requires that tidal-coupling was significantly weaker in the past. Webb (1982) provided an explanation for this is terms of resonance in the ocean-component of the tidal drag. Loosely speaking, the speed of "tidal waves" in the oceans is very similar to the speed at which the tidal-bulge crosses the oceans today and this explains the present strong coupling. As shown by Bills and Ray (1999) this model successfully reproduces the correct age for the Moon, the correct present day recession rate and the observed "bundling" in ancient tidal deposits. Using more generic models, this presentation will show the range of recession histories which are compatible with the constraints set out by Bills & Ray. Even with dramatically reduced tidal-coupling in the past, the resulting models shows rapid, early lunar recession with the Earth-Moon distance reaching 50% of its modern value within 75-200 million years.

POSTERS

Water in the Moon: Insights from SIMS analyses of lunar apatites

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Introduction: The initial studies of Apollo rock samples concluded that the Moon was an anhydrous planetary body [1]. Recently there has been a change of opinion with several research groups detecting variable amounts of H_2O in lunar mare glass beads [2], melt inclusions [3] and hydroxyl in lunar apatites [4-7]. The maximum amount of hydroxyl detected thus far has been from mare basalt 12039 [7,8]. These authors measured the D/H ratio of lunar apatites, with δD values ranging from -215 ‰ to +1010 ‰ in the case of mare basalts and from +240 ‰ to +340 ‰ in the case of highlands anorthosite clast 14305. Here we report δD values and hydroxyl contents of apatite grains from two Apollo mare basalt samples and two Mg-suite rock samples.

Analytical Methods: Apollo thin sections were mapped with the FEI Quanta SEM at the Open University using gentle beam conditions of 0.6 nA and 20 kV. Apatite grains were identified by short exposure (<20 s) spot analyses. The samples were then analysed using the Cameca NanoSIMS 50L at the Open University. Apatite grains were analysed using a large Cs^+ primary beam of ~250 pA current, rastering over an area of 10x10 µm. Analyses lasted 20 minutes, and were preceded by a 2 minute pre-sputter. Charge compensation was provided by the electron gun. Negative secondary ions $^1H^-$, $^2D^-$ and $^{18}O^-$ were collected from a central 5x5 µm area at a mass resolving power of ~5000.

Results: The average $*D_{SMOW}$ for mare basalts analysed was 842 ± 90 ‰ with an average OH concentration of 1662 ± 26 ppm. The Mg-suite rock samples have an average $*D_{SMOW}$ of 484 ± 102 ‰ and an average OH concentration of 287 ± 16 ppm.

Discussion: The D/H ratios of the apatite grains analysed in this study lie distinctly outside of the terrestrial range indicating that it is unlikely we have analysed terrestrial contamination. Our results clearly show that there is a discrepancy between the 'water' content of the highlands Mg-suite and the mare basalts, with the crustal rocks being much drier than the basalts. The highest δD values of between ~1000 to 1100 ‰ obtained from the mare basalt samples are in the range previously reported [7,8]. We suggest that these relatively high D/H ratios may have been artefacts of D/H fractionation due to H_2 degassing from the basaltic magmas [9].

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Geoscience., 4, 79-82 [8] Greenwood, J. P. et al. (2012) *LPSC XLIII* Abstract # 2089. [9] Ustunisik, G. et al. (2011) *Am. Min*., 96, 1650-1653.

What can you tell from a piece of the moon the size of your fingernail? Lynch 002 – a new lunar meteorite from the Nullarbor Desert, Australia.

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Lynch 002, weighing 36.5 g, was found during systematic open-plain searching in the Nullarbor Desert of Western Australia in September 2010. It is only the second lunar meteorite to be found on the Australian continent.

Our section of Lynch 002 displays a complex, highly brecciated texture and is polymict, containing diverse lithic and single mineral clasts, glass spherules, agglutinates, and melt both as cross-cutting veins, and a cement to the fine matrix. The sample is moderately to highly weathered with a dark brown/black desert varnish crust of up to 125 micrometers thickness. No fusion crust remains. Cracks and fissures are widespread, many are filled with Ca carbonate.

Mare basalt and finely crystalline feldspathic impact melt breccia fragments form the largest clasts, up to ~ 1 mm in size. KREEP-rich clasts (with intergrown skeletal K-feldspar, silica and micrometer-scale REE-Y-Zr-rich phases), and pyroxferroite remnants (hedenbergite, fayalite and silica) are also abundant, with grains of high and low-Ca pyroxene, typically of 200 micrometers size. High-alumina silicon-poor (HASP) glassy spherules up to ~150 micrometers in diameter show Na-rich (1 % wt) and Na-poor compositions.

The finer indurated matrix is composed primarily of plagioclase and high and low-Ca pyroxene. Fe-Ti oxide grains are fairly abundant, baddeleyite and silica are also found. Irregular Fe-Ni metal grains reach a few tens of micrometers in size. Melt veins are pervasive and range in width from a few micrometers to irregular patches almost 1mm across. The coarser melt veins are vesicular for much of their length, partially fill open fracture voids, and contain small blebs of Fe-Ni metal. Many of the veins show complex cross-cutting relationships between surrounding material, and with other melt veins.

Replicate oxygen isotope analyses were carried out on an acid washed, bulk sample, giving: $\delta^{17}O = 3.638, 3.470$ $\delta^{18}O = 7.005, 6.676$ $\Delta^{17}O = -0.005, -0.002$ (all values in per mil)

Lynch 002 is a highly brecciated meteorite containing diverse lunar lithologies and mineral phases, reflecting a wide range of igneous activity and multiple phases of impact and regolith processing, even within a centimetre-size sample.

Investigating the Distribution and Source(s) of Lunar Volatiles

James Mortimer, M. Anand, I. Gilmour, C. T. Pillinger (Open University)

In recent years, the search for lunar volatiles (including water), has attracted renewed interest; new analyses of lunar glasses and apatite crystals suggest initial magma volatile contents (prior to degassing) many times higher than previously reported [1], with some possibly even reaching terrestrial-like volatile abundances [2].

Alongside these discoveries, several spacecraft have carried out remote experiments on the lunar surface, with equally encouraging results. The Moon Mineralogy Mapper (M^3) spectrometer on-board Chandrayaan-1 detected absorptions of wavelengths associated with the presence of either OH or H_2O groups within the upper layers of the lunar regolith [3]. Most recently, the LCROSS mission documented water and other hydrocarbons and volatiles within impact ejecta near the lunar south pole [4].

But in what form do these surficial volatile compounds exist? And where did these volatiles at the lunar surface come from? Are they indigenous (i.e. coming from the original regolith-forming bedrock), or are they exotic, introduced to the lunar surface by comet/meteorite impacts, or by the solar wind? And finally, is there any heterogeneity in volatile abundance across the lunar surface, or are they evenly distributed?

This new study will apply a geochemical perspective to the search for answers to these fundamental questions about the lunar surface and its volatile budget, using stable isotopes of carbon and hydrogen to 'fingerprint' volatiles found in returned lunar soils. It is hoped that better constraints on the nature of surficial lunar volatiles will complement the ongoing research into lunar mantle volatiles, to build up a coherent, holistic overview of the Moon and its resource potential, and so provide information about the formation of volatiles on/delivery of volatiles to planetary surfaces.

[1] Greenwood, J.P., et al., *Hydrogen isotope ratios in lunar rocks indicate delivery of cometary water to the Moon.* Nature Geoscience, 2011. 4: p. 79-82.

[2] Boyce, J.W., et al., *Lunar apatite with terrestrial volatile abundances.* Nature, 2010. 466(7305): p. 466-469.

[3] Pieters, C.M., et al., *Character and Spatial Distribution of OH/H2O on the Surface of the Moon Seen by M3 on Chandrayaan-1.* Science, 2009. 326(5952): p. 568-572.

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The Moon as a Planetoid

Graham Oram (U3A)

The poster suggests a new model for the origin of a stony planet. The model envisages a planetary seed (TNO) captured into an inner solar system orbit where it grows by addition of refractory materials from the primordial sun's accretion disk. The conversion of kinetic energy to heat from impact with an ever larger planetoid makes a near surface magma ocean.

This model is highly unstable, hot and heavy on the outside, cold and light on the inside, it will invert itself. However there are two stable states; a small planetoid with a shallow magma ocean has a thin iron shell that when set lets internal gases escape. A large planetoid has a fluid magma ocean all the way to the core. Intermediate sizes are a bomb. The poster suggests the Earth and Moon is a stable binary of a large and a small planetoid. The LHB began when this binary exploded a passing intermediate planetoid at 3.9 Ga.

The event makes two different lunar hemispheres. Iron fragments make lunar craters with mascons, stony fragments make craters without mascons. The fragments that missed will return to Earth orbit. Large fragments of the core are NEOs still in orbit close to the original planetoid orbit. The small fragments are meteorites, are sample of a planetoid interior, are examples of the lunar interior. These planetoid fragments will bring metals to the Earth's surface and gases to its atmosphere.

The poster shows how all the different types of meteorite are related to the thermal metamorphism of the primordial chondrite material in the planetoid interior. Chondrules are impact melts generated during accretion. The lunar seismic model defines the different zones and permits an overall density calculation. The lunar core at 800km or 1000km below the surface gives a range from 3400 to 3600kgm^{-3}, with wriggle room for a closer result. The Moon is a fossilized retarded little brother. This model also applies to Mars and Venus

Lunar impact basins: A window into basin formation in the Solar System

Ross Potter (Lunar and Planetary Institute)

Impact cratering is a fundamental geological process which is ubiquitous throughout the Solar System. However, the cratering process for the largest impact structures, basins, remains poorly understood. The Moon is the ideal laboratory to study this process due to the well preserved state of many of its basins. We numerically model lunar basin-forming impacts with the aim of elucidating the formation and structure of these basins. By investigating a number of impact parameters and comparing model results to photogeologic, spectroscopic and gravity data, we primarily find that thermal conditions at the time of impact greatly influence basin formation and structure. Compared to today, both the Earth and Moon are likely to have been hotter during their first billion years of existence. Our results may therefore provide insight into basin formation not only on the Moon but also on the early Earth and throughout the Solar System.

Testing moon-dust for traces of life

Max Wallis (Cardiff University)

Litho-panspermia envisages that material blasted off Earth by mega-impacts contains viable spores as well as non-viable biomaterials. In the 5% of ejecta accreted by the Moon, potential detection of viable or inactivated spores would provide evidenc on the ejection efficiency and survival problems. Given the significant shower of terran meteorites on the Moon from the 65 Myr Chicxulub event, practical schemes to search for traces of life in Moondust should be drawn up.