The Moon and the early Earth

Meeting report:

Ian Crawford summarizes a joint RAS/Geological Society Discussion Meeting which examined what the Moon can tell us about the origin and early evolution of our own planet.

1: The Earth and Moon photographed 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)

For the past 4.5 billion years the Earth and Moon have essentially comprised a binary planet system, unique in the inner solar system (figure 1). 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 the first thousand million years of Earth history. Fortunately, the binary nature of the Earth–Moon system provides a means of remedying this situation because records of the early environment shared by the Earth–Moon system are likely to be preserved on the ancient surface of the Moon. This was the topic of an RAS Specialist Discussion Meeting held, in collaboration with the Geological Society of London, on 9 November 2012.

Early bombardment

The meeting was opened by **Dr Bill Bottke** (Southwest Research Institute) who presented recent work on the early bombardment history of the Earth and Moon. The Late Heavy Bombardment (LHB) 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 (e.g. Kring 2003; figure 2). One view is that it marked the end of a steadily decreasing bombardment of the inner solar system by 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. Bill argued that both views 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; Gomes *et al.* 2005). 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 (Ga) (Bottke *et al.* 2012). In fact, this "late late" bombardment probably pummelled the Earth throughout the Archean and early-Proterozoic eras (1.8–3.8 Ga), 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 Ga, four between 2.49 and 2.63 Ga, and one between 1.7 and 2.1 Ga. Statistically, one would expect that, for a declining impact population, the later impacts would be found on the Earth rather than the Moon because of the Earth's larger surface area; comparison of the Earth and Moon impact rates broadly support the Nice Model of asteroid orbits perturbed by giant planet orbital migration in the early solar system.

Lunar regolith

The theme of using the Moon to record the bombardment history of the inner solar system was continued by **Dr Katherine Joy** (University of Manchester). Katie pointed out that the lunar regolith is an important boundary layer between the Moon and surrounding space environment, and that at any one locality the lunar regolith typically contains a record of diverse rock types mixed vertically and laterally by 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 the Moon's past and on the bombardment history of the Moon, Earth and solar system. Recent work on ancient (>3.4 Ga) regolith breccias returned by the Apollo missions 40 years ago (figure 3) has led to the probable identification of fragments of the impactors which produced the lunar impact basins (Joy *et al.* 2012). These ancient impactor fragments have a generally chondritic composition and are not as diverse as those found in younger (<3.4 Ga) regolith breccias and soils from the Moon, or that presently fall as meteorites to Earth. This suggests that primitive chondritic asteroids were common on Earth–Moon-crossing orbits during the latter stages of the basin-forming epoch.

The Moon as recorder

The importance of the Moon as a recorder of key information central to a proper understanding of our own planet was reiterated by **Dr Ben Bussey** (Applied Physics Laboratory, Johns Hopkins University). The Moon should be seen as a miniature planet that has experienced most of the geological processes that operated during the formation and evolution of all the terrestrial planets. Unlike Earth, the Moon retains a record of many of the earliest events within the Earth–Moon system. Specific scientific objectives include determining the impact flux history (with the associated planetary habitability ramifications; figure 2), studying the physics of the impact process, and studying the output and processes of the ancient Sun (as the lunar regolith preserves a record of the solar wind from the past 4.5 billion years). As well as improving our understanding of solar evolution, studying the long-term nature of the Sun will also provide critical information on the history of Earth's climate. Ben argued strongly that a long-term human presence on the Moon would facilitate these investigations, and identified a human outpost at the Moon's south pole as the most desirable exploration objective from a scientific perspective. He drew an analogy with the way in which Antarctic bases have facilitated research on our own planet that could probably not have been done in any other way, and argued that similar scientific benefits could be expected from a lunar polar outpost.

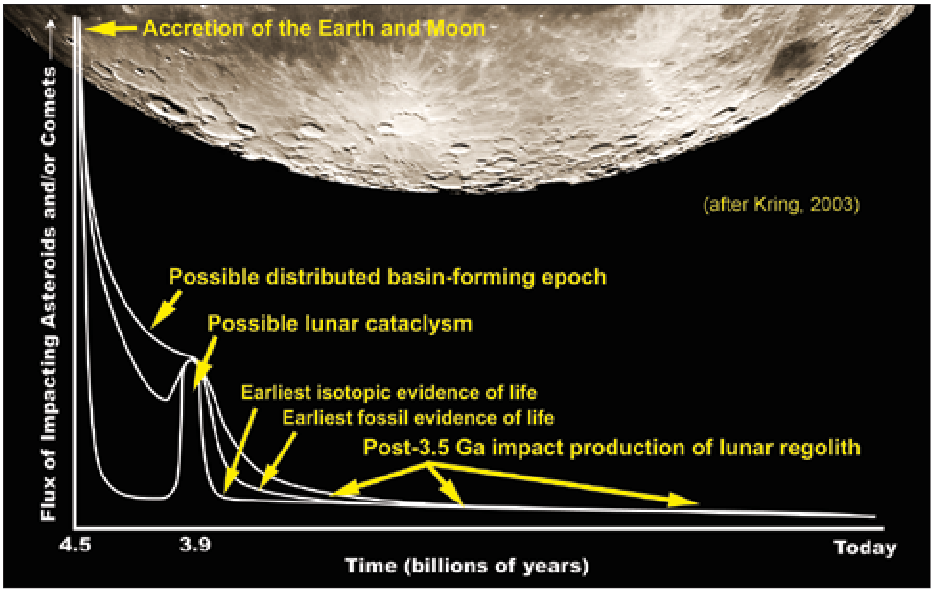
Earth ejecta

Among the geological records that may provide important information about our own planet that might be found on the Moon are fragments of Earth's early crust ejected by giant meteorite impacts billions of years ago, that land on the Moon as terrestrial meteorites (Armstrong *et al.* 2002). Discussion of this topic occupied most of the remainder of the morning session, and was initiated by **Prof. Jay Melosh** (Purdue University) who addressed the impact ejection of intact rocks from the surface of our planet. We now know that rocks from the surface of Mars are ejected by impacts into interplanetary space and a few eventually find their way into terrestrial meteorite collections. Moreover, magnetic domain studies of the martian meteorite ALH84001 (Weiss *et al.* 2000) imply that its interior has never been heated above 40 °C since before it left Mars, indicating that ejection from a planetary surface need not result in significant alteration of mineralogical (or even biological) records within meteorites exchanged between planets.

Although not 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 higher escape velocity and denser atmosphere limit possible ejection to much larger, and therefore rarer, impact 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 (Johnson and Melosh 2012). Because the Moon lacks an atmosphere, Earth ejecta must strike its surface at velocities of more than 2.5 km s^{-1}, 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 (e.g. Crawford *et al.* 2008). The Moon's regolith may thus preserve a fragmental record of the Earth's earliest crust.

High-speed impacts

This theme was picked up by **Prof. Mark Burchell** (University of Kent), who addressed the processing of projectiles during high-speed impacts and the implications for understanding what we may find on the Moon. While terrestrial material will survive an impact on the lunar surface relatively intact (with a probable impact speed of around 3 km s^{-1}; Armstrong 2010), it may nevertheless undergo subtle changes as a result. In particular, these could influence the mineralogy and any organic content (if present). Based on a series of recent light gas gun experiments, Mark presented examples of how impact shock effects can alter the projectile fragments recovered after an impact at speeds of a few km s^{-1}. In addition to fragmentation of the projectile, these include changes to mineral structure, the abundance of amorphous vs crystalline carbon, and organic and biomarker content. However, although such changes are observed, signatures of the original mineralogy of the projectile, and even biological material entrained within it, may survive impact with the lunar surface, albeit in altered or reduced amounts (see Burchell *et al.* 2010 for a discussion relevant to lunar astrobiology).



2: Schematic illustration of current uncertainty in the lunar cratering rate, represented by three different curves prior to about 3.8 Ga. Determining whether there was, or was not, a "Late Heavy Bombardment" spike at about 3.9 Ga is important both for our understanding of conditions on the early Earth, and for constraining models of giant planet orbital dynamics. The answer is up there on the Moon! (Image courtesy of Dr D A Kring, LPI)

Lunar soil

The next talk was given by **Prof. Bernard Marty** (Ecole Nationale Supérieure de Géologie, Nancy) who noted that lunar soils have recorded contributions of extraterrestrial material (e.g. interplanetary dust particles [IDPs], meteorites, micrometeorites and cometary matter) to planetary surfaces in the inner solar system over billions of years, and that these records have been tectonically or otherwise erased on Earth. In particular, 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 (e.g. Ozima *et al.* 2005). The analysis of volatile elements (C, N, H and noble gases) in lunar soil grains provides an exceptional insight into the nature and strength of past fluxes that permits us to test the above possibility. Bernard argued that similar volatile abundances in lunar meteorites (at least some of which presumably originated from the far side) and Apollo soil samples argues against a terrestrial source and are more likely to have been delivered to the lunar surface by IDPs. Potentially, therefore, the study of lunar soils provides a means of monitoring the changing flux and composition of IDPs, and their role in delivering water and other volatiles to the inner planets, as a function of time (Füri *et al.* 2012).

Earth on the Moon

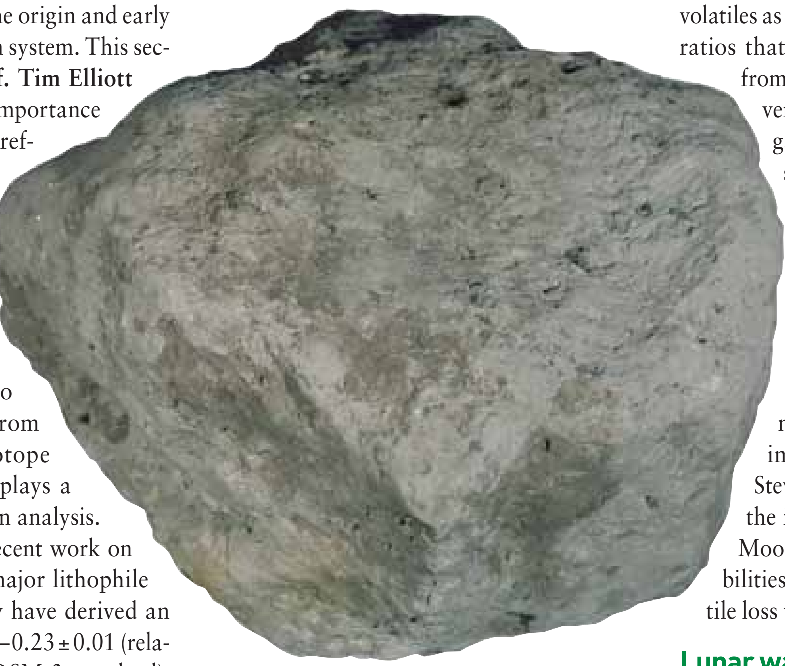
The final talk of the morning was given by **Prof. Euan Nisbet** (Royal Holloway), who described the nature of the Earth's surface during the late Hadean and early Archaean, and asked whether ejected ancient terrestrial material could be recognized on the Moon. In the late Hadean (>4 Ga) and early Archaean (4.0–3.5 Ga) the Earth's surface was likely to be recognizably similar to the modern planet in the presence of oceans and continents, but beyond that is conjecture. The record preserved in the Hadean Acasta Gneiss, and in zircons from the Jack Hills of Western Australia, indicate that terrestrial continental material was present and should be recognizable, for example via δ^{18}O in zircon. Much of the late Hadean Earth's surface may have been covered by extensive komatiite lava flows, and forsteritic olivines from such flows may be identifiable. Whether signs of life could be found is more questionable. The Isua record from Greenland includes carbon dust with light δ^{13}C, but on the Moon this may be difficult to differentiate from interplanetary carbon dust. On Earth, the deep phylogeny of bacteria is consistent with one or more bottlenecks caused by major impacts that warmed the oceans >100 °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. Euan argued that it is unlikely that such traces of early Earth life could survive the aeons of subsequent meteoritic gardening on the lunar surface. However, as pointed out during the discussion, any such material buried below the surface (e.g. in palaeoregolith deposits buried by younger lava flows; see Fagents *et al.* 2010) would stand a much better chance of being preserved (but locating it would be challenging).

Earth evolution

The first few talks after lunch dealt with what the Moon can tell us about the origin and early evolution of the Earth–Moon system. This section was kicked off by **Prof. Tim Elliott** (Bristol) who addressed the importance of the Moon as an isotopic reference for Earth evolution. Studies have long compared the composition of the accessible Earth to chondritic meteorites in order to deduce the make-up of inaccessible terrestrial reservoirs. Fresh impetus to this approach has come from high-precision stable isotope measurements. The Moon plays a key reference point in such an analysis. Tim described his group's recent work on the isotopic budget of the major lithophile element Mg, for which they have derived an Earth mantle value of $^{26}\mathrm{Mg} = -0.23 \pm 0.01$ (relative to the commonly used DSM-3 standard). In contrast, the average $\delta^{26}\mathrm{Mg}$ for primitive chondrites is -0.42 ± 0.02. 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? In that case the $\delta^{26}\mathrm{Mg}$ 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 $\delta^{26}\mathrm{Mg}$. Further work on lunar samples will help distinguish between these possibilities.

Fluid silicates

Tim was followed by **Prof. Lars Stixrude** (UCL) who discussed the role of fluid silicates at the origin of the Earth–Moon system. Partial melting of silicates dominates the chemical evolution of Earth today and was even more important in the earlier history of the terrestrial planets. The Earth–Moon system may have begun in a completely molten state following a giant impact, and a global magma ocean, extending from the boundary with the iron-rich core to an attenuated rocky atmosphere may have encompassed the proto-Moon. This initial magma ocean may have left signatures of its presence in both the Earth and Moon. However, these signals cannot be interpreted because of a lack of basic knowledge of the behaviour of fluid silicates at extreme conditions. This problem is being attacked by constructing a comprehensive thermodynamic model describing the physical properties of silicate liquid and vapour phases over the pressure–temperature range relevant to the Earth and Moon, including impacts and early Earth processes. To help constrain the thermodynamic model, new first principles quantum mechanical simulations are being performed in the range of pressure, temperature and composition relevant to the early Earth that have not yet been explored by experiment or theory. First results show that a putative magma ocean was characterized by low viscosity, even at the pressure at the core–mantle boundary, and vigorous turbulent convection. Predictions of the thermodynamics of silicate liquids at high pressure show that the isentropic gradient in the magma ocean was much steeper than previously thought, making complete melting of the Earth–Moon system likely (Stixrude *et al.* 2009, Karki and Stixrude 2010).



3: Apollo 16 sample 60016. An example of a lunar regolith breccia studied by Joy *et al.* (2012) who identified within it chondritic remains of basin-forming impactors which struck the Moon during the Late Heavy Bombardment about 4 Ga. The sample is ~18 cm across. (NASA)

Giant impact

The next speaker was **Prof. Alex Halliday** (Oxford) who discussed the delivery of volatiles to the Earth before and after the formation of the Moon. 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%. 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. Some of the Earth's volatiles appear to predate any late veneer, and possibly also predate the giant impact. Some of the new dynamic models that are now being developed for the giant impact (e.g. Canup 2012, Ćuk and Stewart 2012) are better able to explain the isotopic similarity of the Earth and Moon, and offer a broader array of possibilities for the amount of mixing and volatile loss that might have occurred.

Lunar water

The topic of lunar volatiles was developed by the next speaker, **Dr Mahesh Anand** (Open University), who discussed the timing and sources of water addition in the lunar interior. Mahesh began by noting that recently we have witnessed a paradigm shift in our understanding of the history of water on the Moon. However, uncertainties exist regarding the abundance, distribution, and the source(s) of water in the lunar interior, and it is 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 the 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. 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

4: Artist's vision of astronauts supervising a drill, which would permit access to the subsurface, for example to extract buried palaeoregolith samples containing ancient solar wind and galactic cosmic-ray records; an example of how science will benefit from returning humans to the Moon. (NASA)

Apollo and Luna missions collected a range of lunar samples, including a variety of mare basalts with crystallization ages predominantly ranging from ~3.9 to ~3.1 Ga. By combining age-dating of apatites, from lunar basalts, with measurements of their H-content and H isotopic composition, it is possible to investigate secular changes in the water content of the lunar interior. By synthesizing and modelling of all previously published data on OH contents and H isotope compositions of lunar apatite from mare basalts, Mahesh argued that a model of hydrogen delivery into the lunar interior by late accretion of chondritic materials and degassing of mare magmas provide a satisfactory explanation to account for the measured "water" content and its hydrogen isotopic composition in mare basalts (Tartèse and Anand 2012).

Earth–Moon distance

The penultimate talk was given by **Dr Dave Waltham** (Royal Holloway) who addressed the question: "Where was the Moon when the Earth was young?" An answer to this question is important for an understanding of the types of early terrestrial records (crustal meteorites, atmospheric gases, etc) that might be found on the Moon. It is assumed that the Moon formed at 4.53 Ga as the result of a giant impact, 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 19th century, but it is only in the last few decades that we have had the data and tidal-drag models needed to solve these equations successfully. Key data were provided by the Apollo missions, which gave us rocks that confirm the age of the Moon and its origin in a giant impact, and which also provided the means to measure directly the current recession rate of the Moon. However, this observed recession rate 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) and others provided an explanation for this in terms of resonance in the ocean-component of the tidal drag, i.e. the natural frequency of oscillations in the modern ocean basins is similar to the frequency at which tides are driven on the, relatively slowly rotating, modern Earth. 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, Dave illustrated the range of recession histories which are compatible with the modern recession rate, the age of the Moon and the limited constraints provided by ancient tidal-deposits. Even though these models have dramatically reduced tidal-coupling in the past, the results show very rapid early lunar recession, with the Earth–Moon separation reaching 100 to 200 000 km within 5 million years (c.f. a present separation of 384 000 km).

Human exploration

Prof. Ian Crawford (Birkbeck) brought the meeting to a close with a talk entitled "Accessing the lunar record: implications for exploration policy". As amply demonstrated by the earlier talks in the meeting, 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, and the early history of our own planet. Although some progress can continue to be made by studying existing lunar samples, Ian argued that 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 subsurface) of the Moon, with a particular emphasis on regions not previously visited. Although some of these exploration objectives can be addressed robotically, in the longer term 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 subsurface to extract undisturbed palaeoregolith deposits; figure 4) may be impractical without a human presence (Crawford *et al.* 2012). The kind of ambitious exploration programme required to access the lunar geological record properly is currently under international discussion in the form of a Global Exploration Roadmap (ISECG 2011), which outlines possible international contributions to human and robotic missions to the Moon, asteroids and, eventually, Mars.

Conclusions

Overall, the meeting (which was attended by more than 90 planetary- and geo-scientists) successfully demonstrated that the Moon still has much to tell us about the origin and evolution of the Earth–Moon system, including conditions on the early Earth relevant to past habitability. When combined with other planetary science, astrobiological and astronomical reasons for wanting to explore the Moon (see Crawford *et al.* 2012, and references therein), the scientific case for pursuing a programme of lunar exploration, such as advocated by the Global Exploration Roadmap, appears compelling. There is little doubt that improved knowledge of our own planet would be one major beneficiary of such an exploration programme. ●

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