Astrobiology on the Moon

Meeting report

Ian Crawford and Charles Cockell report on an RAS Specialist Discussion Meeting held on Friday 14 May 2010.

1: The only known inhabited planet rises over the surface of the Moon, as photographed from Apollo 8 in December 1968. (NASA)

Although the Moon has, almost certainly, never supported any life of its own, lunar exploration will nevertheless reveal much of astrobiological interest. As the Earth's closest celestial neighbour it retains a unique record of the inner solar system environment under which life evolved on our planet. The Moon can also provide knowledge essential for the long-term exploration of space, including information on the survival of both microorganisms and humans in space, and the spread of microbial contaminants in extreme planetary conditions. This meeting addressed these different aspects of lunar astrobiology in the context of future lunar exploration activities.

The first talk was given by **Charles Cockell** (Open University), who summarized the potential of the Moon for astrobiological studies. This includes geological studies of its ancient surface, which preserves a record of the meteorite impact flux in the Earth–Moon system, with its potential both to "frustrate" biological evolution but also to deliver volatiles and organic molecules to planetary surfaces and create new habitats for microorganisms. The lunar surface may also preserve fragments of Earth's early crust in the form of meteorites blasted off our planet's surface by giant impacts, and which may therefore contain a biological record of the early Earth.

In addition to these geological aspects, the Moon offers the potential for a number of biological studies, especially relating to studies of microorganism survivability at sites of previously crashed and soft-landed spacecraft. These will permit a number of investigations relevant to planetary protection (e.g. for future exploration of Mars) including: developing strategies for minimizing microbial loads on spacecraft; monitoring the spread of biological contaminants outside of human habitats; understanding survivability of microorganisms and spores as a function of time; and assessing the potential of the Moon as a safe and sterile location for the study of materials returned from other parts of the solar system. Cockell also highlighted the value of the Moon for perfecting techniques for the human exploration of the solar system, including studies of the physiological consequences of long-term exposure to low (but non-zero) gravity, the development of bio-regenerative life-support systems, and the development of effective dust mitigation strategies. On the latter point, he highlighted work that his group is doing on the use of cyanobacteria in practical space applications, such as using microbial filaments to trap and contain dust which might form the basis for dust control on other planetary surfaces.

Lunar Lander

The next talk was given by **James Carpenter** (European Space Agency), who described ESA's on-going Lunar Lander study and its applications to astrobiology. This proposed mission, which has just entered phase B1, would place a small lander (total mass about 60 kg) close to the

2: The Gas Analysis Package (GAP) developed for the Beagle2 mission. Such an instrument, incorporated into future lunar missions, would be ideal for detecting and characterizing volatile and organic substances in the lunar regolith. (Everett Gibson/OU/Beagle2)

lunar south pole, to help prepare for sustainable future human exploration. With this in mind, the scientific payload will address questions related to lunar dust properties and toxicity, radiation monitoring and mitigation (including improved "space weather" forecasts), and *in situ* resource utilization (ISRU). A particularly important objective of the mission is to improve current understanding of the response of biological systems to the *integrated* lunar environment (i.e. enhanced radiation doses, from both solar particle events and galactic cosmic rays, low gravity, and possible dust toxicity), such that risk assessment for humans on the lunar surface can be improved. The necessary measurements can be performed only on the lunar surface. However, it will be important to build a community in support of this precursor mission, and its objective to prepare for human exploration of the Moon, leading up to a decision on implementation at the ESA Ministerial Council Meeting in 2012.

The discussion of future lunar missions was continued by **Everett Gibson** (NASA Johnson Space Centre) who outlined the Lunar Beagle concept, an off-shoot of the ill-fated Beagle2 Mars mission applied to lunar science. Many of the instruments designed, built and flight-qualified for Beagle2 are directly relevant to lunar science. Foremost among these is the Gas Analysis Package (GAP), developed at the Open University, which is ideally suited for compositional and isotopic studies of volatiles in the lunar regolith. These include both solar wind-implanted volatiles, and those delivered to the lunar surface by meteorites and comets, including possible deposits of water ice in shadowed polar craters. The latter may preserve a record of the contribution of comets to the volatile and organic inventory of the Earth (and perhaps also Mars) and thus is of clear astrobiological relevance. Moreover, characterization of the extent and composition of lunar volatiles is important in the context of future human exploration activities, for which they may become an important *in situ* resource. Other Beagle2-derived instruments which could be applied to the Moon include the mole (for heat-flow measurements and the collection of subsurface samples), and the X-ray spectrometer (for determining the chemical composition of the local regolith). The package could also include instruments to characterize the lunar exosphere before this is disturbed by future human activities. Gibson concluded by pointing out that the Lunar Beagle instruments could either be deployed as a soft-landed payload on a precursor robotic mission, or as an ALSEP-like package deployed by astronauts.

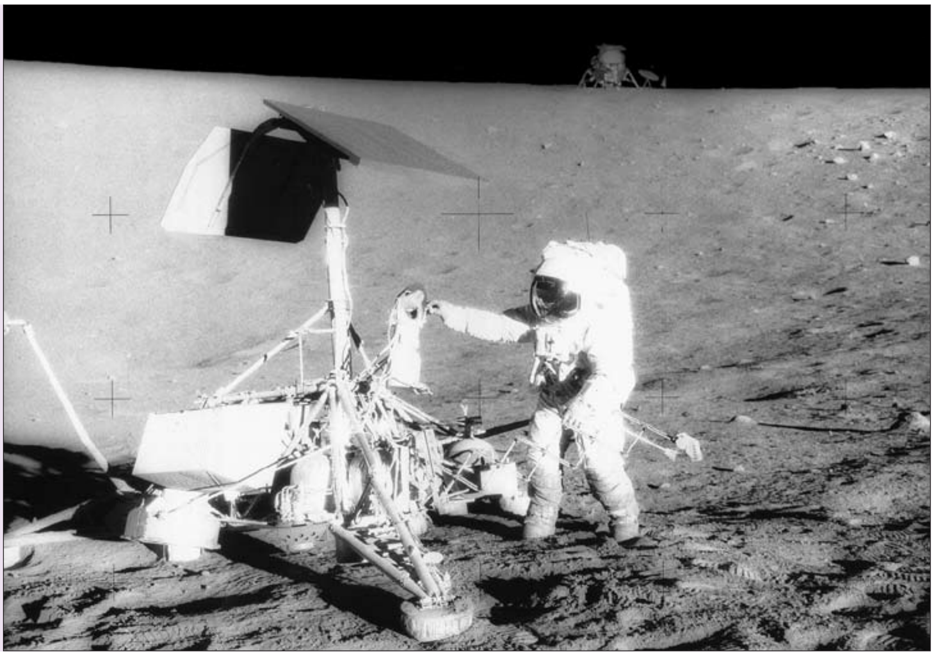
Terrestrial meteorites

After a break for coffee, **John Armstrong** (Weber State University) outlined the chances of finding terrestrial meteorites on the Moon. The Earth's own geological record for the first billion years of its history is largely missing, because the planet is geologically active. Yet this time interval is crucial for understanding the conditions under which life originated and took root on our planet. Strange though it may seem, probably the best place to find samples of the Earth's crust dating from this early time is the surface of the Moon. Many fragments of Earth's crustal materials blasted into space by giant impacts will have struck the Moon, and many may be preserved there as terrestrial meteorites.

The extent to which terrestrial meteorites will survive impact with the lunar surface depends on the vertical component of their velocity on impact which, for oblique impacts, is much less than their interplanetary velocity. Armstrong presented models showing that a significant fraction of terrestrial meteorites would hit the lunar surface with vertical velocity components less than $1\,\mathrm{km\,s^{-1}}$, which suggests that a substantial fraction of them will survive. His models indicate that about 7 parts per million of the lunar regolith might be derived from the Earth, with moderately enhanced concentrations at the poles relative to equatorial latitudes. Finding such samples on the Moon will be challenging, but it may be possible to identify them through spectral signatures unique to terrestrial materials. The importance of these materials for understanding the early Earth is such that a thorough search is warranted.

Mark Burchell (University of Kent) continued with the theme of impacts in his talk, which considered the survival of organic materials in impacts with the lunar regolith. Complex organics are widely distributed in the solar system, existing in both meteorites and comets. Both these sources were likely to have been important for delivering pre-biotic organic molecules to the early Earth (and Mars), but the reactive surface environment of the Earth does not preserve a long-lived record of them. The Moon is much more stable in this respect, and may preserve a record of meteoritic and cometary organics extending over much of solar system history, but only if it can be demonstrated that these complex molecules will survive lunar impact.

Experiments performed with a light gas gun at the University of Kent have demonstrated that complex biomarkers (e.g. n-alkanes, steranes, hopanes, β,β-carotane, α-carotane) within organic-rich shale projectiles survive impacts into sand at velocities of $2\,\mathrm{km\,s^{-1}}$. It was also found that the thermal history of the impactor event is recorded in changed ratios of key biomarker molecules. These results suggest that meteoritic and cometary organic molecules will survive impact with the Moon and could be



3: An Apollo 12 astronaut stands next to Surveyor 3 in November 1969. Study of the survival of microorganisms, bacterial spores, and/or complex organic molecules within and around old spacecraft hardware on the lunar surface would add to our understanding of the survival of life in extreme environments, and assist in the development of planetary protection protocols. (NASA)

identified in regolith samples (e.g. using instruments such as those planned for ESA's Lunar Lander and Lunar Beagle). These results also give some confidence that biomarkers in samples from the early Earth, carried to the Moon in terrestrial meteorites as described above, will likewise survive impact with the lunar surface and may be detectable in any such samples identified by future exploration activities.

Water on the Moon

The next talk was given by **Mahesh Anand** (Open University), who summarized the current state of knowledge regarding water on the Moon. Within the last year or two there have been important developments in this area, deriving both from discoveries by the latest generation of orbital remote-sensing instruments and from careful laboratory studies of lunar samples. Recent infrared remote-sensing observations, reported in three separate papers in *Science* last year, have revealed the spectral signature of water (and/or the hydroxyl radical), over widespread areas of the lunar surface, extending from the poles to at least mid-latitudes. The nature of this water is unclear, but its ultimate origin is likely to be due to the reduction of iron oxides in the surface regolith by solar-wind hydrogen. Prior to these results, the expectation had been that water on the Moon would only be present as ice in permanently shadowed polar craters, further evidence for which was provided by the LCROSS impact in October 2009. Given the likely mobility of water molecules in the regolith, the probability of some of this water migrating to the poles and getting caught in cold traps appears high, strengthening the case for larger deposits of polar ice.

In parallel with these discoveries, petrological studies of lunar samples have revealed that many of these are not as devoid of water as originally thought, with both volcanic glasses and hydrated minerals within lunar basalts (notably apatites) showing evidence for water at the level of hundreds of ppm to several tenths of a percent by weight. The implication is that the lunar mantle is not as dry as previous models supposed, with implications both for theories of lunar origin and possibly for the sources of the newly observed surficial water. A wetter Moon would greatly facilitate ISRU during future lunar missions, and enhances the opportunities for astrobiological investigations on the lunar surface.

The final talk of the morning session was given by **Ian Crawford** (Birkbeck College), who discussed the importance of lunar palaeoregolith deposits as recorders of astrobiologically important solar system history. Studies of Apollo samples revealed that solar wind particles are efficiently implanted in the lunar regolith, providing a possible window on the early evolution of the Sun that is not otherwise available. Regolith particles also contain a record of cosmic-ray fluxes, and thus a record of galactic events which may have affected the Earth (such as nearby supernova explosions, or passages through dense interstellar clouds and attendant collapse of the heliosphere). Recently it has been suggested that samples of the Earth's early atmosphere may also be preserved in the lunar regolith, along with samples of our planet's early crust in the form of terrestrial meteorites (discussed above). This is a potentially very rich record, of clear astrobiological significance.

“Solar wind particles are implanted in the lunar regolith, providing a possible window on the early evolution of the Sun”

However, the present surficial regolith has undergone continual processing by meteorite impacts for the last three to four billion years, and the record it contains is therefore an average over this time. From the point of view of accessing ancient, well-preserved records of solar system and galactic history, it will be most desirable to find ancient regoliths (“palaeoregoliths”) which have been undisturbed since their formation. Palaeoregoliths are expected to be preserved beneath younger lava flows, and recent results from the radar sounder instrument on the Japanese Kaguya mission appear to confirm their existence. The records preserved in palaeoregolith layers will be especially valuable because they will come from well-defined time horizons, dated by the ages of the under- and over-lying lava flows. Sampling such palaeoregolith deposits will therefore be an important objective of future lunar exploration activities. As such sampling will require extensive field excursions, and/or subsurface drilling, it would be greatly facilitated by a renewed human presence on the Moon.

Biological contamination

In the afternoon session the talks became focused on more explicitly biological issues. The first talk after lunch was by **Danny Glavin** (NASA Goddard Spaceflight Centre), who developed the case for biological contamination studies of lunar landing sites. Such studies are particularly important in the context of future human missions to Mars. Is it possible for humans to visit a body and not contaminate it with our organic material? How well will we be able to control contamination once humans are present? The answers to such questions may be learned on the Moon, both by studying the fate of microorganisms carried to the Moon on earlier crashed and soft-landed space probes (many

4: Treasures in the regolith: the lunar soil is an efficient collector of everything which falls on to it from outside, including solar wind particles, galactic cosmic rays, micrometeorites, interstellar dust particles, and possibly samples of the Earth's early crust and atmosphere. Recovering ancient (palaeo-) regoliths would yield a rich record of solar system history of relevance to galactic astronomy, solar–terrestrial physics and astrobiology. (NASA)

of which have now been on the surface for almost half a century), and by performing active biological experiments. Although the survival of bacteria on surface seems unlikely, the question of survival in permanently shadowed regions, below the surface, or within spacecraft hardware remains to be determined.

It will be especially important to assess the degree to which biological contamination extends from sites of human activity on hostile planetary surfaces. This applies not just to microorganisms, whose survival may be unlikely, but to bacterial spores (which are known to be highly resistant to the space environment), and non-living (but biologically derived) organic molecules. Assessing the rate at which the latter may migrate from sites of human activity will be especially important when it comes to searching for biomarkers on Mars. Because the internationally agreed planetary protection protocols are weak for the Moon (COSPAR Category I), experiments along these lines are possible there in a way that will not be possible on Mars: the Moon is the obvious test bed for these studies.

The next talk was given by **David Loftus** (NASA Ames Research Centre) on the chemical reactivity of lunar dust. He began by reviewing the formation and composition of lunar dust, pointing out that the lunar regolith is a complex material, formed and modified by continuous micrometeorite impacts on the lunar surface. High-velocity impacts induce shock melting and localized vaporization of regolith particles which quickly recondenses, resulting in agglutinates with high surface area, complex shapes and sharp jagged edges. Moreover, a full understanding of the chemical reactivity of lunar dust requires an understanding of UV and other radiation effects on lunar dust, as this affects grain charging and oxidation state. From studies in human epidemiology, animals and mineral chemistry, it is well recognized that chemical reactivity plays a key role in dust toxicity. In preparation for the return of astronauts to the Moon, the Lunar Airborne Dust Toxicity Assessment Group (LADTAG) is working to characterize the chemical reactivity and toxicity of lunar dust. A key aim is to develop a small lightweight instrument for determining the chemical reactivity of lunar dust *in situ*, which could validate ground-based studies of lunar dust chemical reactivity. Such an instrument could be part of a lunar precursor mission, or be used as an astronaut-deployed device for characterizing lunar dust at sortie and habitat sites as part of a comprehensive lunar exploration programme.

Lunar dust toxicity

The topic of lunar dust toxicity was continued by **John Cain** (UK Health and Safety Executive), who reiterated the point that toxicity is related to the composition, size, reactivity and morphology of the dust particles, as well as location and type of deposition in the respiratory tract. The location of deposition depends on particle size, with nanoparticles penetrating deep into the lung. The effects of lower gravity on the Moon may have a significant effect, and this needs to be investigated in future research, as do cellular responses to nanoparticles. It is expected that exposure to lunar dust may cause acute health problems such as respiratory irritation and possible chronic health effects if exposure is long-term. It will therefore be necessary to assess the exposure risks to health based on the length of time an astronaut is exposed, the type of work activity and the control measures in use, etc. In addition to adverse physiological and toxicological consequences, lunar dust is likely to create problems for the operation of equipment and maintaining vacuum seals. For all these reasons, further research on dust characterization, and the development of effective mitigation measures (e.g. through appropriate filtration systems, and careful airlock and spacesuit design), is urgently required.

The final talk of the day was given by **David Green** (King's College, London), on how the UK can lead the terrestrial translation of biomedical advances arising from lunar exploration activities. The translation of knowledge gained in space to terrestrial medicine requires humans in space, not robots! Space exposure is particularly useful for understanding interactions between different aspects of physiology (e.g. between nutrition and exercise), and as a model for accelerated aging (e.g. bone and muscle loss, central nervous system disorders, etc). It also provides useful models of individualized medicine, and improved insights into occupational medicine (including telemedicine) in extreme environments on Earth. A lunar outpost would provide a useful platform for biomedical research in a harsh, low-gravity environment with significant potential for translation to terrestrial medicine. The UK has a world-class biomedical science base, but the relevant research councils do not, as yet, fund space biomedicine research. However, renewed interest in lunar exploration, together with the recent creation of the UK Space Agency, provides new opportunities for UK leadership in this area.

The meeting successfully demonstrated that there are wide-ranging astrobiological aspects to lunar exploration, including a better understanding of the impact and volatile history of the inner solar system, the survival of life in extreme environments and, in the context of human exploration, improved insights into human physiology and medicine with potential benefits here on Earth. Of course, these are not the only reasons for wanting to return to the Moon – the totality of the scientific case for lunar exploration comprises several other areas of planetary science and astronomy (for summaries of previous meetings on these other aspects of lunar science see *A&G* **49** 1.9–1.12 and **49** 2.17–2.19). Considering the totality of the scientific benefits which may be expected, the case for a robust programme of lunar exploration appears to be overwhelming. As this meeting showed, an improved understanding of the origin, evolution, and distribution of life in the solar system would be one beneficial consequence of such a programme. ●

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