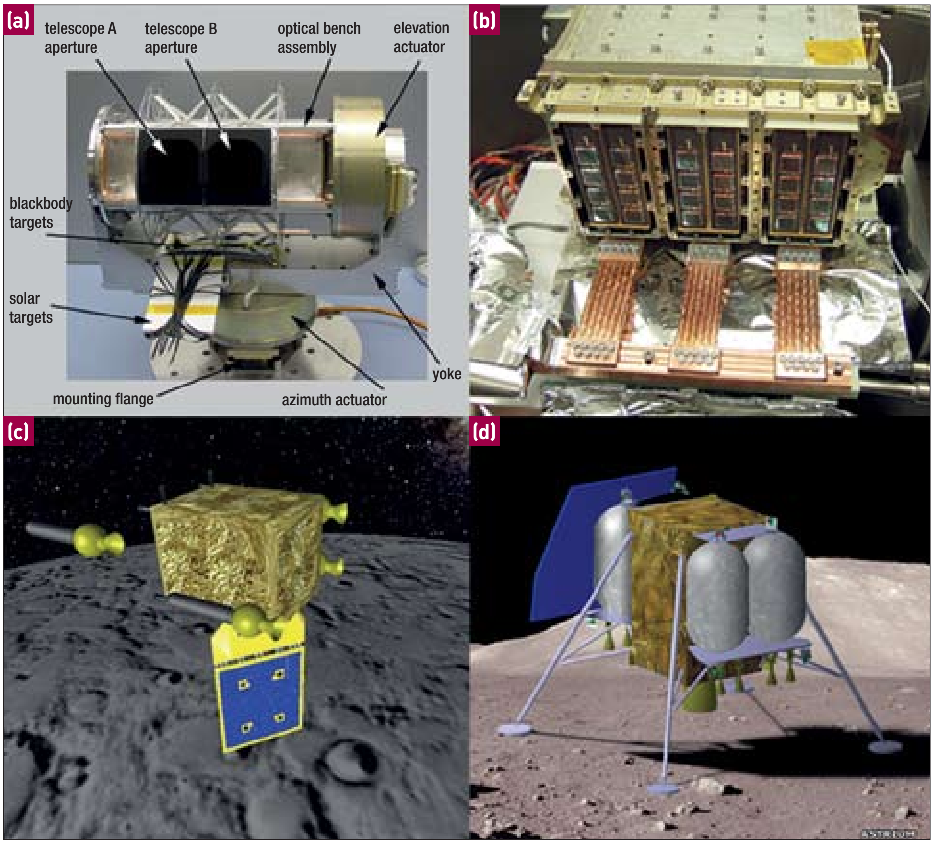
Exploring the Moon: a UK perspective

Abstract

The principal scientific importance of the Moon is as a recorder of geological processes in the early history of the terrestrial planets, and of the near-Earth cosmic environment for the past 4.5billion years. Within the context provided by the recently agreed Global Exploration Strategy, the UK planetary science community has much to contribute to the interpretation of this unrivalled archive of solar system history.

Ian Crawford, Mahesh Anand, Andrew Ball and Katherine Joy report on a UK community meeting on lunar exploration, held at the Open University on 24 and 25 September 2007.



1: A montage of images showing some of the present, and anticipated future, lunar missions with UK involvement discussed at the meeting. (a): DIVINER, a radiometer that will fly on NASA's LRO mission with UK involvement from the University of Oxford. (NASA). (b): C1XS , an X-ray spectrometer being built at RAL for India's forthcoming Chandrayaan-1 lunar mission. (RAL). (c): MoonLITE, a proposed lunar geophysics penetrator mission led by the Mullard Space Science Laboratory and Surrey Satellite Technology Ltd. (MSSL). (d): Artist's conception of the MoonTwins lander proposed by EADS-Astrium, which may form the baseline for ESA's NEXT lunar mission. (ASTRIUM)

In January 2004, President Bush announced a new "Vision for Space Exploration", which has refocused NASA's objectives towards human and robotic missions to the Moon and Mars, and the European Space Agency's Aurora programme has established similar objectives for Europe. This renewed interest in the Moon on both sides of the Atlantic, and the emergence of other space-faring nations interested in the Moon – notably China, India and Japan – has put lunar science firmly back in the limelight after the long hiatus that followed Apollo. Interest in the exploration of the Moon includes astronomical, geological, commercial, resource utilization and strategic considerations, as well as its use as a potential stepping stone for the future human exploration of the solar system. It is in this international context that this UK community meeting was organized. The intention was to demonstrate the strength and diversity of the UK lunar scientific community, to stimulate its further development, and to highlight opportunities for future UK involvement in lunar exploration. The meeting attracted 30 contributed talks, 10 poster presentations and more than 90 registered participants, demonstrating the strength of interest in lunar science in the UK. The meeting was also picked up by BBC Radio 4's *Today* programme.

International context

After a brief introduction by Brenda Gourley, Vice Chancellor of the Open University, the first full talk was given by **Keith Mason**, Chief Executive of STFC. Keith outlined the prospects for UK participation in space exploration and presented the conclusions of the UK Space Exploration Working Group (http://www.stfc.ac.uk/uksewg), which recommended increased UK investment in this area and to which STFC is clearly sympathetic. With regard to lunar exploration in particular, he drew attention to opportunities that may arise from cooperation with the US following the signing of a joint statement of intent between NASA and BNSC in April 2007, and highlighted the proposed MoonLITE mission (see below) as one such possible area of cooperation.

Then **Ian Crawford** (Birkbeck) summarized the scientific case for lunar exploration. The primary scientific importance of the Moon lies in the record it preserves of the early evolution of a terrestrial planet, and of the near-Earth cosmic environment throughout solar system history. This record may not be preserved anywhere else, and gaining proper access to it will require future robotic and human missions. Key tasks for future exploration include: sampling a representative range of lunar lithologies, better calibration of the inner solar system bombardment history, emplacement of global geophysical (e.g. seismic and heat-flow) networks, confirmation and characterization of polar volatiles, identification and sampling of buried regolith deposits (which may contain ancient solar wind, galactic cosmic rays and, more speculatively, meteorites from the early Earth), and assessment of the value of the lunar surface as a platform for astronomical observations. Some of the knowledge gained will be of astrobiological importance, as it will help improve our knowledge of the conditions under which life took root on Earth.

Next **Ben Bussey** (APL, Johns Hopkins University) brought the meeting up to date with NASA's plans for renewed human exploration of the lunar surface, including NASA's current architecture for returning to the Moon in the 2020 timeframe and establishing a permanently occupied lunar base near the south pole, and the scientific and technical rationale for this site. He also described his work, using data from the Clementine and SMART-1 missions, on the illumination conditions of the lunar poles, which has not only led to the identification of permanently shadowed craters (where water ice may reside), but has also identified places that experience permanent (or near permanent) sunlight – excellent sites for future outposts relying on solar power. Finally, he described his involvement with two radar instruments that will fly on the Chandrayaan-1 and Lunar Reconnaissance Orbiter (LRO) missions in 2008 with the aim of confirming the presence of water ice in permanently shadowed polar craters.

UK plans

The session after lunch concentrated on possible UK involvement in future lunar missions. **Colin Pillinger** (OU) began the session with a description of his "Beagle 2 on the Moon" concept. In 2007, NASA's Planetary Programs Office solicited proposals for a "Lunar Sortie" initiative to identify science and technology opportunities that could "piggy-back" on the exploration programme. NASA's Johnson Spacecraft Center submitted a bid suggesting that parts of the UK's Beagle 2 technology could contribute to the furtherance of NASA's lunar programme. In particular it was recognized that the Beagle 2 science package would be an ideal payload for determining the existence and nature of lunar polar volatiles, supporting international exploration objectives and world-class science.

This talk was followed by three talks describing different aspects of the UK's MoonLITE concept: a proposal for a small lunar orbiter equipped with four penetrators designed to emplace a geophysical network on the lunar surface. First, **Alan Smith** (MSSL) gave an update on the status of the UK Penetrator Consortium, which is developing both the penetrator design and the selection of instruments. As currently envisaged, each penetrator will carry a micro-seismometer, a heat flow experiment and a geochemical package. The principal scientific objectives are to determine: the size and physical state of the Moon's core; the deep structure of the lunar mantle; the thickness of the farside crust; the nature and causes of natural moonquakes; the composition and thermal evolution of the Moon's interior; and the existence, nature and origin of polar ice deposits. **Yang Gao** (SSC/SSTL) then presented the preliminary MoonLITE mission definition and system design studies. These have progressed to the point where a launch date of 2012 would be realistic given a decision to proceed in the near future. Yang also briefly described a parallel study, MoonRaker, which would place a single soft lander on the surface; however, currently the MoonLITE concept is preferred. Finally, **Phil Church** (QinetiQ) described QinetiQ's penetrator design work, and hydrocode simulations of penetrator impacts, in preparation for experimental trials scheduled to begin in the first quarter of 2008.

After the coffee break, **Kelly Geelen** (Astrium) described work on the MoonTwins concept – a candidate NEXT mission within ESA's Aurora programme. MoonTwins would land two landers on the Moon, one on each pole, and would emplace geophysics instruments at each, while at the same time demonstrating key technologies (e.g. precision landing and hazard avoidance) required for the later Mars sample return mission. Since the meeting it has become clear that ESA has not selected MoonTwins as a candidate NEXT mission, although much of the work done will feed into a related lunar lander concept that will be carried forward.

The next talk was by **Mark Sims** (Leicester) who outlined possible opportunities for the UK with the Chinese lunar exploration programme. In particular, there may be opportunities for including Beagle 2 instruments, especially the PAW instruments, on the proposed Chang'e II lunar rover. This UK heritage could greatly augment Chang'e II's capability for geological investigations and the evaluation of lunar resources.

Neil Bowles (Oxford) then described his group's involvement with the Diviner instrument on LRO. Diviner is a two-telescope, nine-channel radiometer with internal calibration black-body and solar targets. Key science goals include global day/night surface temperature maps, measurements of global rock abundance, surface properties and the search for near-surface and exposed ices.

The final talk in this session was by **Derek Pullan** (Leicester), who described a concept for an Autonomous Robot Scientist (ARS). Currently, robots require frequent ground-based intervention which inevitably slows up a mission and restricts overall potential scientific output; the ARS addresses the need for greater rover autonomy. The initial phase of ARS has been funded under the STFC CREST initiative and has developed a methodology for the scientific assessment of geological parameters based on established human field practice that will be of value for future robotic missions to the Moon and Mars.

Day one was rounded off by a public lecture given by **Nigel Mason** (OU) on understanding the origin of life on Earth and the prospects for life elsewhere in the universe. As he noted, lunar exploration may yield much that is relevant to this quest.

Lunar science

The second day began with a review by **Larry Taylor** (University of Tennessee) on the properties of the lunar soil and its implications for *in situ* resource utilization. Space weathering of lunar regolith has produced myriads of nanophase-sized metallic Fe grains set within mineral grains and silicate glass ("agglutinates"). This has endowed the soil with several remarkable and potentially useful electrical and magnetic properties. For example, it is possible to melt lunar soil (at 1200–1500 °C) in a few minutes in a normal kitchen-type 2.45 GHz microwave oven. Thus microwave processing of lunar regolith could be used to manufacture building materials and construct paved roads on the Moon. Also, the magnetic properties of lunar dust are such that magnetic air filtration systems may be plausible as a means of controlling dust within lunar habitats.

Larry's talk was followed by a session on lunar science and the next contribution was by **Lionel Wilson** (University of Lancaster) on the influence of volcanic intrusions on the density of the lunar crust. The density structure of the lunar crust and mantle exerts a key control on the fate of melts rising from the mantle. The low density of the anorthositic crust acts to hinder the rise of dense mafic melts to the surface, but a possible feedback mechanism exists in which intrusions of magma failing to reach the surface add to the bulk density of the crust over geological time, progressively alleviating the problem. Studies of lunar graben show that stalled igneous intrusions (dykes) are indeed common in the lunar crust, which is consistent with this scenario. **Martin Knapmeyer** (DLR Berlin, Germany) then spoke on the location accuracy of deep moonquakes. The Apollo passive seismic experiment resulted in the detection of more than 12 000 seismic events; however, the spatial distribution of these clusters still poses some questions, the most important of which is why does the lunar far side appear to be almost aseismic? He argued that the apparent aseismicity of the far side is an artefact caused by the nearside distribution of the Apollo seismometers. A global seismic network, with at least one station on the lunar far side, is needed for reliable locations for deep moonquakes, which would form the basis for the investigation of the deep lunar interior.

After coffee, **Ray Burgess** (University of Manchester) described the new perspectives being opened up on lunar chronology through the study of lunar meteorites. There are now more than 40 lunar meteorites known, many derived from regions of the Moon not covered by the Apollo and Luna missions. Study of these samples extend conclusions drawn from the Apollo collection in important ways. For example, Ar–Ar ages of impact melt clasts record multiple major impact events between 1.0 and 3.9 Ga, rather than clustering around the 3.8–3.9 Ga ages of Apollo impact melts. Similarly, the crystallization ages of basaltic lunar meteorites span the range 1.5–4.2 Ga, much larger than the roughly 3.1–3.9 Ga span of the Apollo basalt samples, indicating that lunar volcanism spanned a longer period of time than previously thought. In addition, it is possible to identify the launch craters of lunar meteorites by matching remote sensing geochemical measurements of young craters with the measured compositions of specific lunar meteorites.

Then **Mahesh Anand** (OU) discussed evidence for pre-Imbrium impact-induced volcanism, arguing that some of the earliest (c.4.2 Ga) basaltic volcanism on the Moon may have been triggered by decompression melting in the mantle following pre-Imbrium giant impacts. This may be a plausible source of magma before the accumulation of radiogenic heat, and/or the convective overturn of a stratified mantle, which are generally invoked as sources of melting for later lunar magmatism.

There then followed three talks on specific lunar meteorite samples. The first was by **Katherine Joy** (Birkbeck), who described the petrography of lunar meteorite NWA 4472. This meteorite is a 64.6 g lunar KREEP-rich breccia that is likely to have been launched from the lunar near-side, from a location within the Th-rich Procellarum KREEP Terrane. Analyses of the mineral chemistry of several clasts within the breccia, made using electron microprobe techniques, allow better understanding of its petrogenesis and clast provenance.

Sara Russell (Natural History Museum) then summarized her work on rare earth element concentrations in relict anorthite crystals from two lunar highland meteorites: Dhofar 081 and NWA 482. These meteorites represent more primitive lunar material than the ferroan anorthosite (FAN) samples collected by Apollo, and point to some complexity in the global magma ocean theory: either there was a global spatial heterogeneity that survived the magma ocean event, or the FAN samples have experienced more geological processing than previously supposed and the relict grains represent an earlier generation of anorthite production. Forthcoming lunar remote sensing missions that map the compositional heterogeneity of the lunar highlands may cast more light on this question.

In the last talk of this session, **John Bridges** (University of Leicester) described his characterization of the KREEP and regolith components of three lunar meteorites (Y983885, Y981031, NWA 773). Y983885 and NWA 773 contain significant geochemical signatures of KREEP, which is unusual for highland regolith breccias. On the basis of Th concentrations in Y983885 – which are used as a proxy for KREEP – this meteorite may have a NW near-side provenance. NWA 773 is a unique lunar meteorite with affinities to both the Mg-suite and VLT basalts; the olivine-rich component comprises 38% of the meteorite and is one of the most primitive lunar samples. One explanation for the KREEP signature of the olivine-rich lithology is formation through limited fractionation of a KREEP-basalt, followed by the addition of trapped KREEP liquid.

Future instruments

After lunch, discussion turned to instruments for future lunar missions. The first talk was by **Manuel Grande** (Aberystwyth) on the C1XS X-ray fluorescence spectrometer being built in the UK (at the Rutherford Appleton Laboratory) for the Chandrayaan-1 mission in 2008. C1XS is designed to measure absolute and relative abundances of major rock-forming elements (principally Mg, Al, Si, Ti, Ca and Fe) in the lunar crust with spatial resolution of ~25 km. C1XS will arrive at the Moon in the run up to the maximum of the solar cycle, and the high incident X-ray flux coupled to an orbit optimized for science, means that it should obtain composition data accurate to better than 10% of major elemental abundances over the entire surface. Hence C1XS will be well-placed to make significant contributions to lunar science. In particular, the ~25 km spatial resolution enables C1XS to address several smaller-scale geological issues that will also refine our understanding of lunar geological evolution.

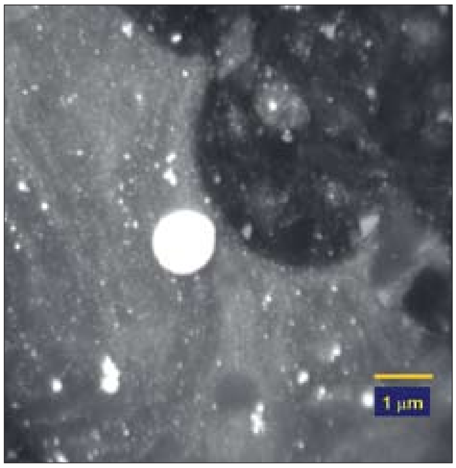
Dave Rothery (OU) spoke about that value of experience gained from C1XS for the interpretation of X-ray data obtained by the MIXS instrument on the Bepi-Colombo mission to Mercury. A significant obstacle in the way of quantitative use of elemental abundance data from MIXS is that detected X-ray fluorescence depends on both viewing geometry and the physical properties (grain size, shape, roughness, sorting and packing) of the regolith. Laboratory experiments are underway, but C1XS data from areas of the Moon (where, unlike

2: Earth over Plaskett crater, taken by Clementine (false colour montage). (LPI/NASA)

Poster presentations

As well as the oral contributions, the following poster presentations were also made:

- **Katherine Joy** (Birkbeck) produced a public outreach poster to accompany the STFC's collection of Apollo rock samples, borrowed for the occasion;
- **Roberto Bugiolacchi** (UCL) displayed a poster describing his work on the compositional and temporal variation of basalts in Mare Imbrium;
- **Ruth Carley *et al.*** (Edinburgh) described their work on the magnetization of the lunar crust;
- **Ian Crawford** (Birkbeck) and **Kelly Geelen** (Astrium) presented a concept for a lunar sample return mission for ESA's NEXT mission opportunity;
- **Lydia Hallis *et al.*** (OU) described their analysis of Apollo 11 and 12 mare basalts;
- **Barry Kellett *et al.*** (RAL) presented some new work on understanding anomalous lunar crustal magnetism;
- **Andy Morse *et al.*** (OU) described possible applications of the Beagle 2 Gas Analysis Package for a lunar mission;
- **Elizabeth Muller *et al.*** (OU) presented their work on lunar meteorite MIL05035;
- **Ingrid Peate** and **Geb Thomas** (University of Iowa) presented a methodology for evaluating the effectiveness of rover-based geology in the context of lunar exploration;
- **Larry Taylor** (Tennessee) and **Mahesh Anand** (OU) presented their poster on how better knowledge of lunar regolith properties will enable *in situ* resource utilization.



2: Back-scatter electron image of lunar agglutinatic glass showing white metallic iron grains, commonly called nanophase iron (np-Fe). This np-Fe affects the spectral reflectance of lunar regolith, and also imparts magnetic properties to the lunar soil with potentially very useful applications for ISRU activities.

Mercury, we have independent measurements of elemental abundances and surface properties) will also contribute to a better understanding of X-ray fluorescence at Mercury.

Alan Weston (NASA Ames Research Center) then made the case for small lunar robotic missions to deliver scientifically and technically useful payloads to lunar orbit and the lunar surface. He presented results showing that spacecraft within a budget of $100m, and that could be launched on one of the next-generation affordable launch vehicles, could deliver payloads of 5–50 kg to the lunar surface or 10–200 kg payload to lunar orbit. These smaller payloads would be capable of covering most of the functions of lunar missions that are needed prior to human arrival, as identified in NASA's Lunar Robotic Architecture Study. The key advantages would be reduced cost and schedule. The final talk before tea was given by **David Lawrence** (Los Alamos National Laboratory) who described the application of neutron spectroscopy to the detection of lunar polar hydrogen deposits. Full characterization of the polar deposits for exploration and scientific purposes requires landed missions in the permanent shade. A variety of tools and instruments should be used to make measurements, including neutron spectroscopy; a field-tested thermal and epithermal neutron detector with a mass of <500 g would easily fit within the envelope of a landed polar mission. The development and deployment of such instruments would fit in well with the future goals of the UK lunar programme (e.g. MoonLITE) and thus provide an exciting opportunity for future US/UK collaboration.

The final session began with **Phil Bustin** (LogicaCMG) describing lunar drilling technologies, summarizing recent scientific interest in deep drilling on the Moon and Mars (e.g. boreholes to 100 m or kilometre depths, such as may be required for sampling buried palaeoregoliths on the Moon, and searching for extant, subsurface organisms on Mars), and presenting a possible roadmap for developing the necessary technology with Earth-based tele-robots. He emphasized synergies with equivalent plans for terrestrial drilling developments.

Lunar-based astronomy

The next talk was given by **Ian Crawford** (standing in for Peter Wilkinson from Jodrell Bank) on lunar-based astronomy. Although not quite as good as the Sun–Earth L2 point for some astronomical instruments, the Moon nevertheless remains a very good astronomical site (much better than low Earth orbit), and the lunar farside is probably uniquely suited to long-wavelength radio astronomy. Lunar telescopes might become especially attractive from an operational point of view if a human-tended infrastructure were to be developed on the Moon in support of other lunar exploration goals.

This theme was continued by **Andrew Read** (Leicester) who spoke on a concept for a lunar X-ray telescope called MagEX, (Magnetosheath Explorer in X-rays). The primary science goal of MagEX is to study soft X-ray emission from the solar wind charge-exchange process that occurs between the solar wind and geocoronal neutrals that are concentrated in the Earth's magnetosheath. The proposal has been submitted to NASA's Lunar Sortie Science Opportunities (LSSO) programme and has been accepted for an initial technical feasibility study funded by NASA. It would make an important contribution to a lunar-based scientific programme.

Vojko Bratina (Italian Space Agency) then discussed the Moon as a platform for observing the Earth. The Moon can be an excellent platform for future Earth observation as it ensures continuous full-disc coverage that enables many Earth-viewing applications. For example, a Moon-based Earth Observatory would provide observations on the input of energy to the Earth's atmosphere, with the opportunity to obtain data from Earth and Sun simultaneously in order to better understand Earth's climate.

The meeting concluded with a talk from **Sue Horne** (STFC), who reiterated the opportunities for developing UK lunar science within the STFC planetary science programme.

In conclusion, the meeting clearly succeeded in demonstrating the high level of interest in lunar science in the UK. There was a broad consensus that the UK is well placed to benefit from, and contribute to, the exciting developments in lunar exploration that are envisaged in the context of the developing Global Exploration Strategy (http://zuserver2.star.ucl.ac.uk/~iac/GES.pdf). ●

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FURTHER INFORMATION

The full abstract book of this meeting, which contains more information and references to the relevant literature, can be downloaded from **http://www.open.ac.uk/planetarygeology/p8_1.shtml**