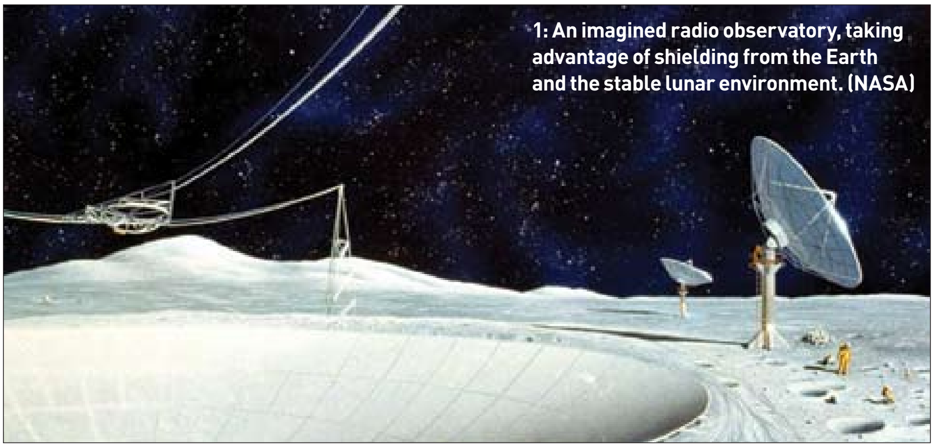
# Astronomy from the Moon

Ian Crawford and John Zarnecki report on an RAS Specialist Discussion Meeting held on 14 December 2007.



1: An imagined radio observatory, taking advantage of shielding from the Earth and the stable lunar environment. (NASA)

**ABSTRACT**

A return to the Moon will confer scientific benefits in several different fields. Although the principal beneficiary is likely to be planetary science, the lunar surface also offers advantages for observational astronomy and future plans for lunar exploration should take these into account.

The recent revival in scientific interest in the Moon is driven largely by the recognition that its ancient surface still has much to tell us about the early history of the solar system. Unravelling this history is primarily the field of the planetary sciences (see *A&G* **49** 1.9–1.12 for a summary of a recent meeting dealing with UK involvement in these aspects of lunar science). However, given the magnitude of the anticipated investment, it is clearly important to determine whether other sciences might also benefit from a greatly expanded programme of lunar exploration. One such potential beneficiary is observational astronomy and this was the subject of a Specialist Discussion Meeting held in the new RAS Lecture Theatre on Friday 14 December 2007.

The first talk was by **Ian Crawford** (Birkbeck College), who described the international context of anticipated future lunar exploration activities. In January 2004 President Bush announced a new US Vision for Space Exploration which has redirected NASA's human spaceflight programme away from activities in Earth orbit and towards the Moon and Mars. In parallel, several other space-faring nations (notably China, India and Japan, plus Europe through ESA) have also become actively engaged in lunar exploration programmes. Recently, an attempt has been made to coordinate all this activity through the development of a Global Exploration Strategy (see http://zuserver2.star.ucl.ac.uk/~iac/GES.pdf). The benefits of UK participation in the GES are summarized in the report of the UK Space Exploration Working Group (http://www.stfc.ac.uk/uksewg) which, among other scientific benefits, identified possibilities for conducting astronomical observations from the lunar surface. Examples include:

- very low-frequency (<20 MHz) radio astronomy, to which the Earth's ionosphere is opaque;
- the possible value of the lunar surface as a platform for long (i.e. several km) baseline optical and infrared interferometers for the study of extrasolar planetary systems;
- studies of neutrinos and high-energy cosmic rays;
- observations of the Earth and its magnetosphere.

For some of these applications the lunar surface is uniquely suited, and while it is probably not as good a site for optical and infrared instruments as the Sun–Earth L2 point, it is still a much better site than the Earth's surface, or even low Earth orbit. A key point is that the Moon is likely to become especially attractive from an operational perspective once a human-tended infrastructure is developed on its surface, even if this is primarily developed in support of other exploration activities. In addition, the Ares V launch vehicle (figure 2), being designed to support renewed human missions to the Moon, will have the capability of launching much larger astronomical instruments to free-flying locations such as L2 than will be possible otherwise.

The next talk was given by **Mario Livio** (STScI, Baltimore), who spoke on "Astrophysics enabled by the return to the Moon". His talk summarized the conclusions of a workshop of that title held at the Space Telescope Science Institute in November 2006 (a summary of which is available at http://zuserver2.star.ucl.ac.uk/~iac/STScI_Report.pdf). Mario identified several important astrophysical observations that can potentially be carried out from the lunar surface. Most promising are:

- low-frequency observations from the far side, to probe structures in the high-redshift ($10 < z < 100$) universe and the epoch of re-ionization;
- lunar ranging experiments to test general relativity and alternative theories of gravity.

Other, more limited, possibilities include:

- a lunar telescope to observe the Earth for better characterization of Earth-like planets;
- a lunar regolith "calorimeter" to study intermediate-energy cosmic rays;
- a small lunar far-UV telescope to study the interstellar medium;
- the longer-term possibility of exploiting the Moon's gravity to construct large-area rotating liquid-mirror telescopes, although it is recognized that this concept requires more study.

Finally, Mario stressed that observations from free space (particularly the Sun–Earth Lagrange points) are considered preferable to the lunar surface for many areas of observational astrophysics, and that efforts should be made to ensure that a return to the Moon enables, rather than precludes, future observations from free space; the heavy lift capacity of the proposed Ares V launch vehicle is especially attractive in this respect.

## Last unexplored wavelength window

Mario was followed by **Heino Falcke** (ASTRON, Netherlands) who gave more details on the value of the Moon as a site for low-frequency radio astronomy – the last unexplored wavelength window into the universe. Some known and potentially promising radio science that could be conducted from the Moon includes:

- studies of the so-called "Dark Ages" of the universe and the epoch of re-ionization;
- a survey of large-scale radio structures (clusters, relics, galactic halos, high-$z$ radio galaxies);
- a survey of local bubble and the local interstellar medium;
- detection of radio bursts from ultra-high-energy cosmic rays and neutrinos striking the

lunar surface;
- detection of radio emission from extrasolar giant planets.

Europe is gaining relevant experience with the low-frequency LOFAR array, but this will only work down to frequencies of about 10 MHz because of the Earth's ionospheric cut-off – progress below 10 MHz, where much interesting science lies, will require a lunar-based dipole array. A lunar LOFAR might contain between 30 and 100 dipoles over a ~100 km baseline, but this could be developed incrementally. Initially, a simple lunar rover, such as ESA's proposed MoonNEXT mission, might deploy two dipoles with a ~10 km baseline to demonstrate the technology. The full array could then be deployed either by advanced robotic missions or by exploiting the infrastructure provided by a renewed human presence. Ultimately the array might be built up to the $10^3$ to $10^5$ dipoles over a more than 100 km baseline that would be required for serious probing of the early universe.

**Mike Lockwood** (RAL) then discussed the potential of using the far side of the Moon to detect the magnetic fields of extrasolar planets. He pointed out that it has been estimated that, provided one had an adequate radio receiver, Auroral Kilometric Radiation (AKR) would be the last detectable signal of Earth as one travelled into deep space. Earth's AKR is gigawatts of power emitted between about $2\times10^4$ and $5\times10^5$ kHz, generated by the cyclotron maser mechanism and ultimately powered by the solar wind. Earth's LF spectrum is similar to that of Saturn, Uranus and Neptune, for which the peak powers are respectively about 5, 0.1 and 0.05 times that of Earth. These non-thermal emissions can give us unique information about the magnetic field of an exoplanet and, indeed, detection and quantification of the field of hot Jupiters is expected to be possible using the LOFAR distributed ground-based array. The peak LF emission for Earth, Saturn, Neptune and Uranus coincides with a minimum in the Jovian spectrum such that Earth is about three times more powerful at $10^5$ kHz and Saturn is roughly 10 times more powerful. Although the emissions from Jupiter-like exoplanets should be detectable from the ground, the emissions from other planets (peaking at $10^5$ kHz) would not penetrate the ionosphere. However, once above the ionosphere, Earth's own AKR becomes a dominant noise source.

The far side of the Moon, at times of full Moon, is the ideal location from which to search for non-thermal radio emissions from other exoplanets because it is shielded from both terrestrial and solar emissions. These emissions would be at frequencies above the solar wind and the (weak) lunar ionosphere cut-off frequencies. Thermal antenna noise is also reduced in the lunar wake region where the solar wind is excluded. Sensitivities allowing detection of 0.1 mJy signals are achievable, whereas a true Earth-like and Saturn-like exoplanet at 10 parsecs would give 0.4 and 2 μJy, respectively. Nevertheless, a far-side lunar LF telescope would allow detection of the magnetic fields of planets other than hot Jupiters: STP studies of Earth's AKR show that it is modulated in frequency and power by the dipole tilt and the amount of ionizing EUV at the base of night-side auroral field lines, and that it is bursty in character because the solar wind has major events such as coronal mass ejections. This gives a modulation at the orbital and stellar activity period that could be used to aid detection and discrimination from emissions of the parent star.

2: The mighty Ares V launch vehicle planned for NASA's future Moon missions would also be an excellent vehicle for launching large space observatories. (NASA)

The theme of low-frequency astronomy was continued by **Graham Woan** (University of Glasgow) who spoke on the influence of environment and scattering on low-frequency lunar radio astronomy. He discussed the possible impact on lunar radio astronomy of the lunar exosphere, local dust environment, surface regolith properties, and terrestrial and solar interference. He identified the following unresolved lunar radio science questions:
- What is the *electron* "weather" really like on the Moon, especially in terms of its diurnal and solar wind-induced variations?
- What are the electrical properties of the regolith at likely radio astronomy sites?
- What is the true low-frequency attenuation factor of the Moon at the surface?
- What is the noise floor like on the dark, far-side surface?
- Can we achieve the dynamic range needed for HI surveying out to $z$~100–1000?

These questions could be addressed by appropriate "site testing" missions to the lunar surface, and radio science and electrical properties experiments should therefore be included in future lunar missions.

## Optical interferometry pros and cons

Moving on from radio astronomy, **Chris Haniff** (Cavendish Laboratory, Cambridge) discussed the pros and cons of the Moon as a platform for optical interferometers. Interferometry is a powerful technique for resolving small angular scales, and has many important astrophysical applications, including the study of extrasolar planetary systems. In recent years considerable progress has been made with ground-based optical interferometry and several major instruments are already in operation or are in the process of development. The main limitations of the Earth's surface for optical interferometry arise from spatial and temporal disturbances in the atmosphere. These disadvantages would be largely absent on the Moon, although active control of (less severe) thermal and mechanical disturbances would probably still be required. The lack of atmosphere would also improve the accuracy with which optical path fluctuations within the instrument itself could be monitored, thereby improving its efficiency. Additionally, operation during the lunar night, or in permanently shadowed localities, where the temperature will be ~100 K, would significantly reduce

**3: Harrison Schmitt exploring the lunar surface during the Apollo 17 mission in 1972. Also shown to scale is the size of the Earth and its magnetosphere in the lunar sky. Future astronauts could both conduct geological fieldwork on the Moon and deploy instruments such as ALIVE and MagEX to study the Earth and its environment. (NASA/GSFC/ Leicester University)**

the thermal background that is a problem for Earth-based interferometry at infrared wavelengths. However, lunar-based operation would also have disadvantages: the slow rotation rate of the Moon ($0.5^\circ\,\mathrm{hr}^{-1}$) means that many telescopes will have to compensate for the slow rate of rotation synthesis, and delay lines based on moveable carriages will probably be needed.

The scale of this hardware would be quite large, and the cost and logistical problems of installing it on the Moon should not be underestimated. For these reasons it is not clear whether a lunar location would offer significant advantages over a free-flying implementation, say at the Sun–Earth L2 point, as is envisaged for instruments such as Darwin (although these would have their own problems, including the need for very accurate pointing and control of the free-flying elements, probably a relatively short (fuel/cryogen-limited) lifetime, and the lack of access to maintenance facilities if required). For these reasons Chris suggested that we follow a developmental roadmap for space-based interferometry:

- develop ground-based interferometry to improve reliability and sharpen the science focus of the technique;
- conduct parallel track studies of lunar and formation flying strategies;
- depending on the outcome of these studies, revisit a possible lunar implementation once ground-based interferometry comes of age.

The next talk was by **Giovanna Tinetti** (UCL), who discussed the Moon as a platform for observing both the Earth and extrasolar planetary systems. For the foreseeable future it will not be possible to spatially resolve extrasolar Earth-like planets, even once these have been definitively detected. Thus any spectra obtained by instruments such as Darwin or TPF will be integrated over an entire hemisphere. A small optical/IR telescope on the Moon could be used to obtain similar disc-averaged spectra of the Earth, permitting studies of the spectral effects of diurnal rotation as different proportions of land, sea, vegetation and cloud cover are brought into view. It would also be possible to study the spectral consequences of phase, seasonal and solar-cycle variations. Such studies would inform the interpretation of similar spectral variations that may be observed for extrasolar planets, as well as providing valuable insights into the Earth's own climate system and radiation balance. The Moon is situated sufficiently far from the Earth to provide just such a holistic view, which is generally lacking in data obtained from Earth-orbiting satellites, and such observations form the basis of the ALIVE (Autonomous Lunar Investigation of the Variable Earth) proposal for an astronaut-deployed Earth-observing lunar telescope (see http://www.lpi.usra.edu/meetings/LEA/whitepapers/Turnbull_Tempe_Abstract.pdf). Finally, Giovanna noted the possible value of the Moon as a site for future interferometric instruments that might one day provide spatially resolved images of extrasolar planets. In particular, she drew attention to a possible lunar version of the New Worlds Observer concept (see http://en.wikipedia.org/wiki/New_Worlds_Mission) in which two or more widely spaced lunar telescopes might be combined with specially shaped orbiting "star shades" to occult the light from the parent star and thus improve the detectability of orbiting planets. While technically challenging, Giovanna expressed the view that the possibility of imaging extrasolar Earth-like planets would be sufficiently exciting to justify the likely expense.

The final talk was given by **Steve Sembay** (Leicester), who described MagEX ("Magnetosheath Explorer in X-rays"; see http://www.src.le.ac.uk/projects/magex ), a proposal for a small X-ray telescope that would make an important contribution to a lunar-based scientific programme. MagEX is an international collaboration between researchers in the USA, the Czech Republic and the University of Leicester in the UK. It 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. 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 neutral particles concentrated in the Earth's magnetosheath. This would provide a three-dimensional view of the dynamic interaction of the solar wind and the Earth's magnetic field. In addition, the telescope would simultaneously observe the interaction of the solar wind with the tenuous lunar atmosphere. The Moon is uniquely well-placed for making observations of this kind, and the installation of MagEX on the lunar surface would make a major contribution to solar–terrestrial physics.

## Conclusions

The consensus of the meeting was that the lunar surface offers significant advantages as an observing platform for some areas of observational astronomy, especially low-frequency radio astronomy and observations of the Earth and its magnetosphere. For optical and infrared astronomy, and especially interferometry at these wavelengths, further studies need to be performed to assess the pros and cons of lunar-based observatories compared with free-flying space-based instruments. In addition, more work needs to be done in characterizing the suitability ("site testing") of the lunar surface for astronomical observations at all wavelengths. However, there was general agreement that opportunities for conducting astronomical observations from the Moon should be allowed for in the developing international strategy for lunar exploration. ●

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