Fly me to the Moon?

MIKE LOCKWOOD

is in the School of Physics and Astronomy, University of Southampton, Highfield, Southampton, SO17 1BJ, UK, and the Space Science and Technology Department, STFC/Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK.
e-mail: M.Lockwood@rl.ac.uk

The revival of interest in lunar and planetary exploration is prompting astronomers to re-evaluate the advantages of observatories on the Moon. But the debate is much more than one of science versus money, and goes to the inspirational heart of space exploration.

During my teens, I watched the Apollo missions live on black-and-white TV. That humans were walking on the Moon was no surprise to me — I was, after all, a member of a post-war generation brought up on comic-strip heroes such as Dan Dare and Buck Rogers — but I vividly remember how my parents were both stunned and emotional. Then, some years later, as a fresh PhD graduate, I too was filled with awe and excitement watching (on colour TV, by then) the launch of Space Transportation System One in April 1981 — a space truck and bus that would be used to first build the International Space Station (ISS) and then shuttle scientists back and forth to it. So, when I arrived for work at NASA's Marshall Space Flight Center in 1984, I was surprised to find a simmering discontent among many of its staff. I had been aware of the debate about manned missions versus free-flying robotic spacecraft, but did not realize the depth of feeling about scientific missions that had been sacrificed to the inspirational power of the Shuttle/ISS vision. The arguments were about cost-effectiveness and astronaut safety (arguments thrown into new light by the recent safety record of the Shuttle). Now the same debate has arisen in relation to the use of the Moon as a base for astronomical observations. There is no doubt about the scientific merits of Moon-based over Earth-based observatories — the question is whether to build it using men or machines, and whether the returns, both scientific and political, justify the costs[1].

Following the Apollo landings, enthusiasm for a lunar astronomical observatory (using electromagnetic waves of many wavelengths, gravitational waves, energetic particles and so on) reached a peak — not surprising, given that much of the enabling technology had by then been developed and proved. The main advantage of a lunar site is that it gives long intervals of continuous viewing of the sky without the spectral and resolution limitations imposed on observations made through the atmosphere with Earth-based telescopes. But since then, many techniques have been developed for ground- and satellite-based astronomy that make the Moon a much less obvious choice[2]. The development of adaptive optics, for one, has greatly reduced the atmospheric turbulence problem for ground-based observatories, but the available spectrum will always be limited.

The advantages of being above Earth's atmosphere are also are enjoyed by satellite-based telescopes. However, the Moon has an added advantage in that it acts as an excellent heat sink, providing an important benefit for observations where radiation balance is a factor. Another potentially important advantage of the Moon over the Earth or satellites is that it has a solid surface with very low seismic activity. It has long been understood that this would be extremely helpful for optical and submillimetre interferometry[3]. The aim here is to position multiple telescopes large distances apart (baselines of even hundreds of kilometres have been proposed) but know their separation to an accuracy of a small fraction of a wavelength — which is therefore much more demanding for optical and submillimetre observations than using the longer-wavelength radiowaves. On the ground, optical fibre links have been used to overcome seismic and other problems (for example, the OHANA network of 7 Mauna Kea telescopes giving 800-m baselines), but there are great technical challenges in the areas of accurate station-keeping and baseline determination for proposed satellite-based interferometers (such as SIM PlanetQuest, Darwin and Terrestrial Planet Finder).

At wavelengths of 3–30 μm, space-based detection of an Earth-like extrasolar planet, in the glare of its parent star, would require baselines of between about 75 m and 200 m, whereas kilometre-scale separations would be needed for general astrophysics[4]. Satellite-based measurements have the useful feature that the baseline is easily varied. But for the longer baselines in particular, it has been argued that building and supporting an array of telescopes on the Moon is technically much easier. Even so, it should be noted that some studies have questioned this; for example, tidal- and micrometeorite-induced disturbances, and large temperature swings from day to night could have considerable effect on the measurements[5]. There are also special problems associated with dust and electrostatic charging as the Moon passes through the tail of Earth's magnetosphere[6] — charging causes the dust to adhere and also throws it up in fountains[7].

Such problems are not 'show-stoppers', *per se*, but they do represent as yet unsolved technical challenges. In the view of many experts, the balance in technological difficulty and cost has clearly swung in favour of satellite observations[2]. Studies show that the key factor is whether or not transportation costs to the Moon are included in the facility costs or considered to be infrastructure costs that lie elsewhere[8]. It is not surprising, then, that the prevailing view is strongly reminiscent of the past discussions about the ISS. That is, if a lunar base were established for reasons other than science then we would undoubtedly want to use it for optical and submillimetre interferometry, but that if we are discussing science as the rationale for building the base in the first instance, then satellite constellations in halo orbits around the L2 Lagrange point offer a more cost-effective route. Indeed, there are now about 50 proposed L2 missions. Yet there is one important possibility that connects the two alternatives — the fact that a base on the Moon would also provide new opportunities for astronauts to travel to, maintain and upgrade satellite observatories at the L2 point.

The story is somewhat different when it comes to low-frequency radio astronomy, where the Moon has other important advantages. Taking a radio observatory above the Earth's ionosphere will open up an unexplored part of the electromagnetic spectrum between about 30 kHz and 10 MHz. Here, the Moon has two principal advantages over satellites. Firstly, the radio noise environment on the farside of the Moon is uniquely low. The largest sources of noise are Earth's auroral zones, which emit gigawatts of power in non-thermal radio emissions called auroral kilometric radiation (AKR)[9]. Going to the farside would allow us to use the Moon itself as a shield from these emissions. It has been estimated that, even at a very low frequency of 50 kHz, the noise at farside locations 45° from the limb (the edge of the lunar disc as seen from the Earth) would be attenuated by at least ten orders of magnitude compared with elsewhere in near-Earth space[10]. The second advantage is that the lunar surface allows the construction of a dense but large antenna array to give sufficient sensitivity and angular resolution, which would not be viable in space.

The reason why astronomers are excited about such a possibility is that low-frequency radio is the only part of the electromagnetic spectrum that they have not used to image the Universe, and the dominance of different emission and absorption processes will give an entirely new view. Both the plasma frequency and the gyrofrequency of many astronomical objects will fall in the waveband revealed. This will open up new perspectives on phenomena involving and producing energetic particles (such as galactic cosmic rays). It could reveal fossil radio galaxies (telling us about the active phases of galactic nuclei and about the intergalactic magnetic field), very-high-redshift (z) galaxies (including proto-galaxies at $z > 4$) and give new studies of millisecond pulsars. The observatory would also probe structures in the interstellar medium, and could be used in combination with direction-finding meteor studies of extrasolar material by the tristatic high-latitude EISCAT radar to study at the origins of our and other solar systems.

The Apollo missions captured the imagination of a generation. Could a Moon-based telescope do the same again?

Finally, a Moon-based low-frequency observatory could provide a potent tool in the search for Earth-like extra-solar planets. It has been predicted that bursts of AKR would be the last detectable signature of the Earth seen by a probe travelling into deep space. Moreover, the magnetic field required to generate this signal is almost certainly a prerequisite for a planet to support advanced lifeforms as it protects against the inevitable flux of cosmic rays and other harmful particle radiations produced by the parent star. Although the cyclotron maser mechanism responsible for this non-thermal radio emission is not yet fully understood, AKR can certainly tell us about the strength and size of the magnetic field of a planet outside our Solar System, and hence if it is genuinely Earth-like[11]. Detection of such signals may prove difficult owing to the need to distinguish stellar and planetary emissions from the background arising from interstellar and interplanetary space — but we cannot develop the techniques required until we have observations of the nature of the low-frequency background. The facility would also be very valuable indeed for studies of the Sun and heliosphere and its interactions with interstellar space.

So the scientific case for a lunar low-frequency radio telescope is very strong, but is such a base practically feasible, or even possible? Much of the construction and maintenance of a large radio array on the farside of the Moon could be carried out robotically, but it is not clear that it could be completed without any direct human intervention. And if constructed solely by robots, does the absence of humans boldly going where no-one has gone before — replaced by robot controllers sheltering safely within the Earth's biosphere — undermine the case in the public's imagination? Yet if practical or political considerations dictate that astronauts are integral to the project, it raises a further issue — not of financial cost, but of human cost.

Even accounting for the recent Shuttle accidents, few people realize just how dangerous a place space is. All life on Earth is protected from hazardous radiation by the twin shields of its atmosphere and its magnetic field. These radiations include galactic cosmic rays (for which the open magnetic field of the Sun provides some additional, but variable, shielding) and solar energetic particles produced by solar transients such as flares and coronal mass ejections as well as by longer-lived coronal features called co-rotating interaction regions. The mass spectra of these particle fluxes show that the protons are usually accompanied by heavier nuclei, including helium, oxygen, carbon and even iron, and these are very damaging for life. They not only break molecular bonds in DNA (as can, for example, X-rays) but they also cause nuclear reactions within molecules (causing carbon atoms, for example, to transmute into oxygen and nitrogen atoms). Cells also undergo 'apoptosis' (pre-programmed cell death). The results range from long-term damage such as cataracts and cancers and more rapid ageing (partly due to the loss of 'telomere' caps on the ends of DNA chains), through to acute effects of radiation sickness and dehydration, which can kill within a few days.

That all the Apollo astronauts who ventured beyond this protection managed to return safe and sound is purely a matter of luck (see Fig. 1). No manned missions have ventured beyond the Earth's magnetic field since. Observations in interplanetary space since 1965 have shown that, even behind a viable shield of 100 kg m^{-2}, doses of solar energetic particles that would cause cancer, severe radiation sickness and almost instant death in humans have been present for, respectively, 1.75%, 0.55% and 0.05% of the time and that the chances of encountering them during a journey to, and stay on, the Moon lasting 100 days would be 13%, 5% and 0.5% (M. Lockwood and M. A. Hapgood, submitted to *Astron. Geophys.*). Such a trip behind the same shield would also give an average dose of galactic cosmic rays of 10 r.e.m. (this figure should be compared with safe lifetime limits estimated to be about 30 and 15 r.e.m. for men and women, respectively). More frequent but shorter trips would reduce the risks per trip but increase the costs. The cosmic-ray dose could be reduced by scheduling missions at sunspot maximum, but this would increase the risk of the solar events. In fact, because the cosmic-ray flux is continuous whereas the solar particles are in discrete bursts, it is likely that missions will be at solar maximum because astronauts cannot remain behind a shield for the entire mission. This will place huge importance on reliable predictions of the solar events so that refuge behind an adequate shield can be sought in time.

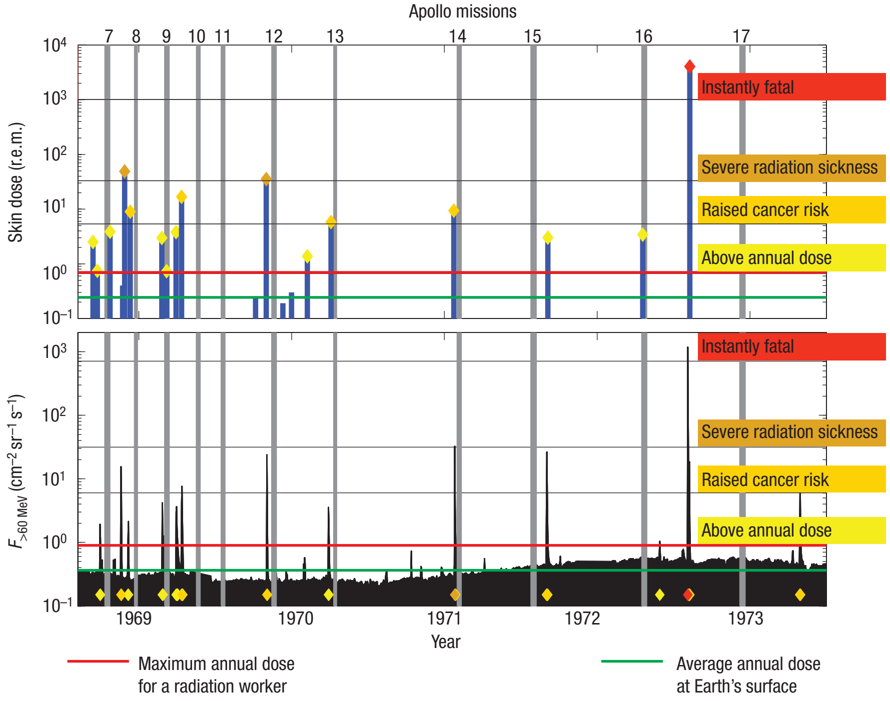

Figure 1 The radiation hazards during the Apollo missions. The lower panel shows the measured flux of protons at energies above 60 MeV ($F_{>60\ \mathrm{MeV}}$) in near-Earth space. The solar-cycle variation of the continuous (black) background of galactic cosmic rays can be seen, along with discrete events of solar energetic particles (SEPs). The upper panel gives estimated skin doses of the SEP events (in r.e.m. behind 100 kg m^{-2} of shielding). The vertical grey bars show when Apollo missions were at risk. The horizontal green lines give the typical annual dose at the Earth's surface, and the purple lines give the upper limit for an industrial worker dealing with radiation. Individual SEP events coded in yellow gave more than the permitted maximum annual dose; those in orange would give significantly enhanced long-term cancer risk; those in brown would cause severe radiation sickness and those in red would cause death within a few days. Note the very large SEP event between the last two missions. (Image from M. Lockwood and M. A. Hapgood, submitted to *Astron. Geophys.*).

Yet even if the risks could be minimized, it is difficult to know if they could be made acceptable to the public. An historical perspective is supplied by the acclamation with which the Admiralty and the public greeted Captain James Cook on his return from his first circumnavigation in 1771, despite the loss of almost half of Endeavour's crew (a loss that Cook managed to limit because he cunningly induced his crew to demand sauerkraut and lime juice to avoid scurvy by making them mandatory only for his officers). But times and attitudes have changed radically and, for sure, we would demand better odds and better protection for their modern-day counterparts. Indeed, it could take just one potential 'crew-killing' event (such as the radiation spike that occurred in the months between Apollo 16 and Apollo 17, see Fig. 1), to dampen the public's enthusiasm for human space exploration.

Although we may not like it, this debate raises issues well beyond the purely scientific[12]. Since humans last visited the Moon, the balance of the options has swung away from lunar observatories in many cases. But this trend won't necessarily continue into the future. My own view is that the case for a low-frequency radio telescope on the farside of the Moon, in particular, has grown considerably over time and will continue to do so. Advances in medical and electromagnetic protection for astronauts are possible, but for the foreseeable future we will certainly need to make maximum use of robots and, where human travel is unavoidable, models and predictions of the Sun and inner heliosphere to avoid the worst radiation hazards. There will be many applications in research disciplines other than astronomy; nevertheless, if humankind returns to the Moon, the cost will ensure that the main drivers will be political rather than scientific. For me, the central question is this: will modern pragmatism and accounting systems stifle the spirit of unbridled optimistic confidence, captured in the famous words of JFK's superb speechwriter, Ted Sorensen? "We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard". What price can one put on inspiration like that?

References

1. Lowman, P. D. Jr & Lester, D. F. *Phys. Today* **59,** 50–54 (2006).
2. Lester, D. F., Yorke, H. W. & Mather, J. C. *Space Policy* **20,** 99–107 (2004).
3. Tifft, W. G. *Astronaut. Aeronaut.* **4,** 40–53 (1966).
4. Lawson, P. R. in *Aerospace Conf. IEEE Proc.* Vol. **4**, 2005–2011 (IEEE, 2001).
5. Bely, P. Y. *et al. Proc. SPIE* **2807,** 59–73 (1996).
6. Hapgood, M. A. *Annales Geophys.* (in the press).
7. Stubbs, T. J., Vondrak, R. R. & Farrell, W. R. *Adv. Space Res.* **37,** 59–66 (2006).
8. Friedman, E., Ebbets, D. & Kilston, S. in *Workshop On Science Associated With The Lunar Exploration Architecture* (Tempe, Arizona, February, 2007); available via <http://tinyurl.com/yu5t76>.
9. Mutel, R. L. Gurnett, D. A. & Christopher I. W. *Ann. Geophys.* **22,** 2625–2632 (2004).
10. Takahashi, Y. D. *New Astronomy from the Moon: A Lunar Based Very Low Frequency Radio Array* Thesis, Univ. Glasgow (2003); available at <http://www.astro.gla.ac.uk/users/yuki/thesis/YukiThesis.pdf>.
11. Janhunen, P., Olsson, A., Karlsson, R. & Griessmeier, J.-M. Preprint available at <http://arxiv.org/abs/astro-ph/0305458> (2003).
12. Close, F., Dudeney, J. R. & Pounds, K. W. *The Scientific Case for Human Space Exploration* (Royal Astronomical Society, London, 2005); available via <http://tinyurl.com/2hvbc5>.