Why we should build a Moon village

Ian Crawford explains how science would benefit from a human outpost on the Moon.

The director general of the European Space Agency, Jan Wörner, has suggested that the creation of a human–robotic lunar outpost would be a logical next step in human space exploration (e.g. Wörner & Foing 2016). The creation of such a Moon village (figure 1) would offer significant scientific opportunities by providing an infrastructure on the lunar surface, analogous to the way that human outposts in Antarctica (figure 2) facilitate research activities across multiple scientific disciplines on that continent. In the case of a Moon village, scientific fields that might benefit include planetary science, astronomy, astrobiology, life sciences and fundamental physics (e.g. Taylor 1985, Ehrenfreund *et al.* 2012, McKay 2013, Crawford & Joy 2014). In addition, a Moon village would help assess the economic potential of lunar resources, while also acting as a market for them (e.g. Crawford 2015).

The extent to which different scientific fields would benefit from a lunar outpost would, in part, depend on its location and on the length of time for which it is occupied. Some of the scientific areas discussed below are more dependent on these factors than others. For example, science questions related to the lunar poles would clearly benefit more from a polar Moon village than an equatorial one. Nevertheless, the kind of transportation and other infrastructure required to establish a Moon village would likely facilitate human and robotic operations at locations that may not be local to the village itself. Moreover, in the fullness of time, just as in Antarctica today, we might envisage multiple such outposts at different locations.

With these caveats in mind, we here address the major areas of science that would benefit from the scientific infrastructure represented by a Moon village.

"The lunar geological record still has much to tell us about the early solar system"

Planetary science

As discussed by Crawford & Joy (2014), the lunar geological record still has much to tell us about the earliest history of the solar system, the origin and evolution of the Earth–Moon system, the geological evolution of rocky planets, and the near-Earth cosmic environment throughout solar system history. Having humans operating on the lunar surface would enable much better access to this record, especially if supported by a scientific infrastructure such as that envisaged for the Moon village. A much wider range of rock and soil samples could be collected, analysed (and, if necessary, shipped to Earth), and the base would support implementation of complex exploratory activities such as subsurface drilling.

Specific planetary science activities that would benefit from such a lunar surface infrastructure include (see e.g. NRC 2007, Crawford & Joy 2014, Neal *et al.* 2014, and references cited therein) inner solar system bombardment history, impact cratering processes, the lunar interior including volatile content, regolith processes and serendipitous discoveries.

The lunar cratering rate is used to estimate the ages of cratered surfaces throughout the solar system, but it is not well calibrated (e.g. Robbins 2014). Improving this calibration is a key objective of planetary science, and requires sampling impact melt deposits from multiple (ideally hundreds) of impact craters of a wide range of ages. In addition, recovering fragments of the impacting bodies would reveal how and if the population of impactors has changed with time (Joy *et al.* 2012, 2016). Accessing these materials requires a significant transportation infrastructure (such as pressurized rovers; figure 3) on the lunar surface, a significant sample return capacity and, ideally, *in situ* analytical instruments.

Impact cratering is a fundamental planetary process, but our understanding of it is limited by lack of access to pristine craters of a wide range of sizes. The lunar surface

1 (Left) Artist's impression of a Moon village. (ESA)
2 (Below) The Amundsen–Scott research station at Earth's South Pole. Such outposts provide a scientific infrastructure that supports research in multiple disciplines (e.g. astronomy, atmospheric science, biology, glaciology, geology, magnetospheric physics, meteoritics and zoology) on the Antarctic continent that would be difficult or impossible to sustain otherwise. Lunar research stations will fulfil the same function on the Moon. (NSF)
3 (Right) The Lunar Electric Rover, under development by NASA. Many lunar science activities will require the ability to move away from the outpost, requiring pressurized rovers, but conversely a lunar outpost will provide the facilities to maintain, recharge and upgrade such vehicles. (NASA)

clearly exhibits the required diversity of craters. Using these craters to improve our knowledge of impact cratering processes requires visiting many craters of a wide range of sizes and ages to conduct sampling, geophysical surveys and, possibly, subsurface drilling.

The Moon provides an excellent example of a small rocky body that largely preserves its internal structure from shortly after its formation. As such it can provide insights into the early geological evolution of larger and more complicated planets. To better understand the structure, composition and evolution of the lunar interior requires emplacement of geophysical tools (e.g. seismic networks and magnetic surveys), as well as sampling a wide range of lunar crustal and volcanic rocks of diverse ages and compositions. Such studies would also help constrain theories of lunar origin.

"The Moon could be a useful platform for astronomical observations"

There is now convincing evidence that water ice exists within permanently shadowed polar craters, and that hydrated materials also exist at high-latitude (but not permanently shadowed) localities (see Anand 2010 for a review). In addition to their possible value as resources (discussed below), such deposits would inform our knowledge of the role comets and meteorites have played in delivering volatile substances to the terrestrial planets. Determining the nature and extent of these volatiles requires surface activities (including sampling and near-surface drilling) at polar and high-latitude locations.

The lunar surface is a natural laboratory for understanding space weathering and regolith processes throughout the solar system, through time. Access to regoliths of different composition, thickness and latitude are required to improve our knowledge of these processes.

Humans are unique in our ability to recognize the significance of new observations or phenomena, even if they were not anticipated. Having humans living and working on the lunar surface for long periods is likely to result in unanticipated discoveries that might not otherwise be made. Although unquantifiable, such discoveries may ultimately prove to be among the most significant to result from a lunar outpost.

Astronomy

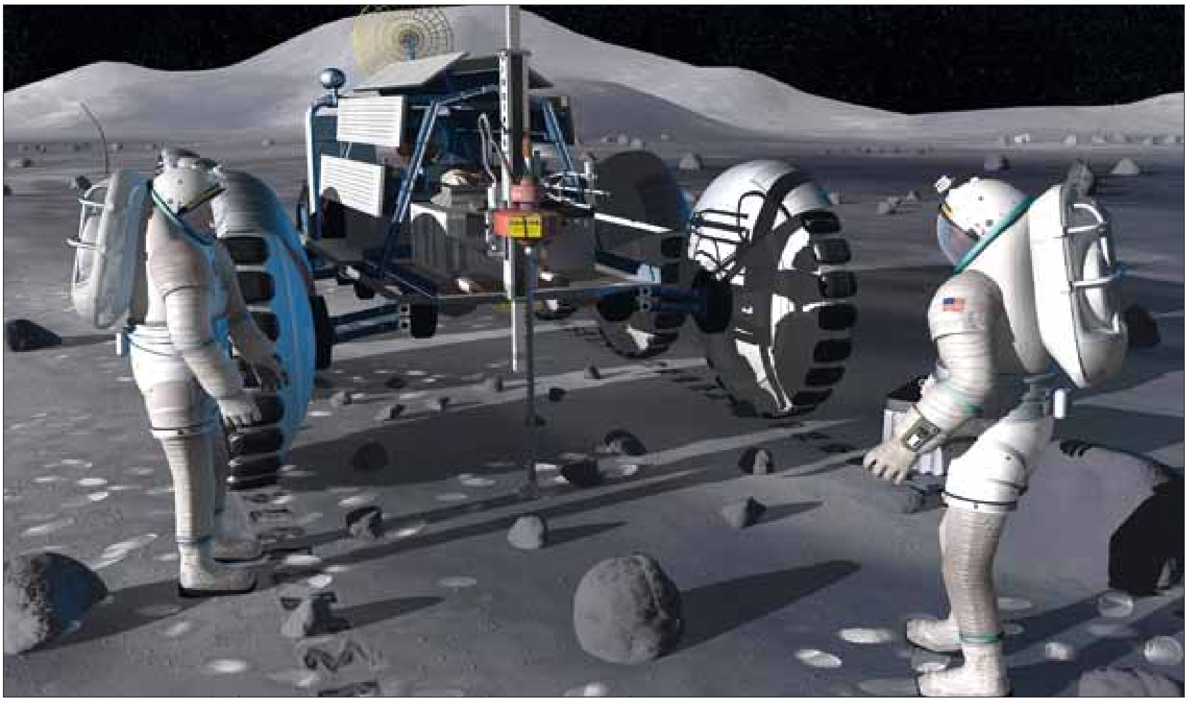
The lunar surface is a potentially useful platform for astronomical observations (e.g. Burns *et al.* 1990, Crawford & Zarnecki 2008), and establishing the equipment required for such observations would be facilitated by a human and robotic infrastructure on the Moon. Key aspects include low-frequency radio astronomy, optical and infrared astronomy, high-energy astrophysics and fundamental physics.

Radio wavelengths longer than about 10 m cannot penetrate the Earth's ionosphere, yet much valuable scientific information is expected to lie in this low-frequency range (e.g. Jester & Falcke 2009). The lunar farside, which is permanently shielded from the Earth, is probably the best location in the inner solar system for such observations and a human infrastructure on the Moon would assist in the setting up of the necessary equipment (although care would also be required to ensure that human operations do not degrade the natural radio-quietness of the location).

Although the Moon could in principle provide a platform for optical and infrared telescopes, there is a consensus that free-flying satellites (e.g. at the Earth–Sun L2 point) probably provide better platforms for such activities (Lester *et al.* 2004). It is certainly true that some aspects of the lunar surface environment (e.g. dust and, in most locations, extreme diurnal temperature ranges) are not ideal for astronomical observations at these wavelengths. Nevertheless, access to a scientific infrastructure able to emplace, maintain and upgrade such instruments (the value of which has been demonstrated by multiple HST servicing missions) might compensate for these disadvantages. Moreover, the stability of the lunar surface may be enabling in the context of building optical/IR interferometric arrays, and permanently shadowed polar craters might enable passive cooling of IR instruments. The pros and cons of the lunar surface for optical/IR astronomy still need to be properly assessed and a lunar outpost would at least facilitate such an assessment.

As the lunar surface is not shielded by either an atmosphere or a magnetic field (other than the Sun's heliospheric magnetic field) it is an attractive location from which to study the flux and composition of primary cosmic rays. This can also be done in free space, but the existence of a human and robotic infrastructure on the lunar surface may facilitate the installation of the required instrumentation. Similar arguments apply for gamma-ray and X-ray observations.

Although not a major driver for lunar exploration, several areas of fundamental physics research may benefit from the scientific infrastructure represented by a lunar



4 Several lunar science objectives require accessing the subsurface and may require drilling to depths of tens or hundreds of metres (e.g. Crawford *et al.* 2010). A lunar outpost would provide the background supporting infrastructure required to enable such activities, just as Antarctic research stations are required to support scientific drilling on that continent. (NASA)

outpost. These include testing General Relativity through improved lunar laser ranging measurements (Currie *et al.* 2010), tests of quantum entanglement over the Earth–Moon baseline (Schneider 2010), and searches for exotic particles (e.g. strange quark matter, dark matter, etc) interacting with the lunar surface (Banerdt *et al.* 2007).

Astrobiology

Astrobiology is usually defined as the study of the origin, evolution, distribution and future of life in the universe. As the Moon has presumably never had any indigenous life of its own, at first sight a scientific lunar infrastructure might not seem especially relevant to astrobiology. However, we can identify the following areas of astrobiological research that would benefit from lunar surface operations (e.g. Crawford 2006, Cockell 2010, and references cited therein): the early impact regime at the time when life began on Earth, the evolution of Earth's space environment, samples of early terrestrial planet materials, and the search for extraterrestrial intelligence.

Understanding the extent to which large meteorite impacts may have affected the origin and early evolution of life on Earth is a key aspect of astrobiology. It would be addressed on the Moon as part of the wider calibration of inner solar system cratering rate discussed above, and would require sampling of ancient impact melt deposits in the age range 4.5–3.8 Gyr.

As discussed by Crawford *et al.* (2010), buried ancient regoliths are expected to contain records of the solar wind and galactic cosmic ray (GCR) fluxes throughout solar system history, both of which would inform our understanding of the past habitability of the Earth. Accessing such palaeoregoliths would require extensive fieldwork and, possibly, drilling to depths of tens or hundreds of metres (figure 4). This is the kind of large-scale exploratory activity that would be greatly facilitated by a human infrastructure on the Moon, just as Antarctic research stations are required to support scientific drilling on that continent, for example, to sample biological diversity in subglacial lakes.

In addition, as pointed out by Armstrong *et al.* (2002) and Gutiérrez (2002), the lunar surface may contain fragments of the early Earth, and possibly also of Mars and Venus, that predate the oldest existing surfaces on those planets. Finding such material, especially for the early Earth, could help constrain the timing of the origin and early evolution of life on our planet and would be of considerable astrobiological significance. Finding such materials on the Moon would likely require extensive exploratory activities and would be aided by a Moon village.

"Microorganisms may still be present within the remains of crashed space vehicles"

There is also the possibility that molecules derived from the Earth's atmosphere may be preserved in the lunar regolith (Ozima *et al.* 2008, Terada *et al.* 2017). If these can be identified in, and extracted from, ancient palaeoregolith layers, then they have the potential to provide insights into the evolution of Earth's atmosphere with time. Accessing them will require the same sort of capabilities required for extracting solar wind and GCR records from palaeoregolith layers as discussed above.

Lunar ices also have astrobiological significance. Lunar polar ices exposed to GCRs may be expected to form organic molecules (Lucey 2000). Sampling of polar ices, as described above, would indicate the extent to which this process occurs and its relevance to abiotic syntheses of organic molecules in planetary and interstellar ices.

In addition, microbial spores, and conceivably even live microorganisms, may still be present within the remains of space vehicles (including Apollo lunar module ascent stages) that have crashed onto the Moon (Glavin *et al.* 2010). Sampling such localities, and determining what, if any, viable organic material has survived for decades on the lunar surface would provide key information regarding the survival of life in the space environment relevant to fundamental biology, planetary protection and panspermia.

At the other end of the astrobiology spectrum, a scientific infrastructure on the Moon could help constrain the prevalence of technological civilizations in our galaxy. There are two main routes to this: SETI could make use of radio astronomical facilities established on the Moon (e.g. Maccone 2004) or, more speculatively, the lunar surface might be searched for artefacts of extraterrestrial origin (Arkhipov 1998, Rose & Wright 2004). Both would benefit from a human-tended infrastructure, but the latter (speculative though it is) would probably require such an infrastructure because of the large surface areas that would need to be searched to place any meaningful limits on the existence of any such artefacts.

Life sciences

The lunar surface provides multiple opportunities for research in the life sciences (e.g. Gronstal *et al.* 2007, Cockell 2010, Carpenter *et al.* 2010, Green 2010). Most of these studies are not dependent on the physical

5 Tim Peake operates the Muscle Atrophy Research and Exercise System (MARES) on the ISS. MARES is an ESA experiment for research on human physiology in microgravity. A lunar outpost would extend such experiments to low, but non-zero, gravity, potentially providing insights relevant to human health on Earth (e.g. Green 2010) as well as long-term goals for future space exploration. (ESA/NASA)

location of a human-tended outpost, although some would require a prolonged presence. Gronstal *et al.* (2007) have reviewed the kind of laboratory equipment that would be required for such investigations, from which it is clear that a human-tended outpost would greatly facilitate this work (and would, of course, be essential for human studies). Specific areas of lunar life science investigations include life in lunar gravity and within the lunar radiation and dust environment.

Although a lot of research has now been performed on the response of life, including human beings, to microgravity (e.g. Seibert *et al.* 2001, Horneck *et al.* 2003; figure 5), no comparable data exist for prolonged exposure to low, but non-zero, gravity. A lunar outpost would permit such studies on life forms ranging from individual cells to entire organisms (Cockell 2010). Fundamental insights into biological processes may be expected from such studies, in addition to knowledge that may be beneficial for human health on Earth (e.g. Green 2010) and the future exploration of space.

In addition to the low gravity, the lunar surface presents a challenging radiation and dust environment, and life science studies in this environment would also be expected to yield both fundamental biological knowledge and knowledge with potential medical applications (e.g. Cockell 2010, Carpenter *et al.* 2010, Green 2010, Loftus *et al.* 2010, Durante 2012). And if humans are to have a long-term future on the Moon, and on other planetary surfaces, then growing food will at some stage become necessary. A lunar outpost would facilitate the necessary research.

Lunar resources

There is growing interest in the future use of lunar resources, both to support lunar exploration itself and as a contribution to a developing space economy. A self-sustaining Moon village would very likely rely on lunar resources such as locally derived water and oxygen (Anand *et al.* 2012, Crawford 2015), but equally the infrastructure provided by an outpost of this kind would facilitate prospecting for additional resources. Indeed, a Moon village could help kick-start a space economy by providing a market for commercial space resource companies while at the same time providing infrastructure to support their activities. Although not strictly a scientific benefit of a Moon village *per se*, there is little doubt that, in the longer term, science will benefit from the development of a space economy built on the use of space resources (e.g. Elvis 2016, Metzger 2016).

Conclusion

By analogy with scientific outposts in Antarctica, a human–robotic outpost on the Moon would enable multiple scientific opportunities owing to the lunar surface infrastructure that it would provide. Scientific fields expected to benefit from such an infrastructure include planetary science, astronomy, astrobiology, the life sciences and fundamental physics. In addition, a Moon village would help initiate the utilization of lunar resources, and perhaps help kick-start a space economy. Although beyond the scope of this paper, a Moon village would also offer important societal and cultural benefits to humanity, especially if, as envisaged, it is developed as a truly global endeavour (e.g. White 2014). Moreover, although not explicitly identified as an objective in the current Global Exploration Roadmap (ISECG 2013), an international Moon village would clearly be consistent with this roadmap, and more especially with the over-arching aims of the Global Exploration Strategy (ISECG 2007). The whole scientific community, and indeed the world community more generally, has the greatest possible interest in seeing this initiative succeed. ●

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REFERENCES

Anand M 2010 *Earth Moon Planets* **107** 65
Anand M *et al.* 2012 *Planet. Space Sci.* **74** 42
Arkhipov A V 1998 *J. Brit. Interplanetary Soc.* **51** 181
Armstrong J C *et al.* 2002 *Icarus* **160** 183
Banerdt W B *et al.* 2007 *Nuclear Physics B Proc. Supp.* **166** 203
Burns J O *et al.* 1990 *Scientific American* **262(3)** 18
Carpenter J *et al.* 2010 *Earth Moon Planets* **107** 11
Cockell C S 2010 *Earth Moon Planets* **107** 3
Crawford I A 2006 *Internat. J. Astrobiology* **5** 191
Crawford I A 2015 *Prog. Phys. Geog.* **39** 137
Crawford I A & Joy K H 2014 *Phil. Trans. Royal Soc.* **A372** 20130315
Crawford I A & Zarnecki J 2008 *Astron. & Geophys.* **49** 2.17
Crawford I A *et al.* 2010 *Earth Moon Planets* **107** 75
Currie D G *et al.* 2010 AGU Fall Meeting 2010, abstract P51C-1467
Durante M 2012 *Planet. Space Sci.* **74** 72
Ehrenfreund P *et al.* 2012 *Adv. Space Res.* **49** 2
Elvis M 2016 *Space Policy* **37** 65
Glavin D P *et al.* 2010 *Earth Moon Planets* **107** 87
Green D A 2010 *Earth Moon Planets* **107** 127
Gronstal A *et al.* 2007 *Astrobiology* **7** 767
Gutiérrez J L 2002 *Proc. First European Workshop on Exo-Astrobiology* ESA **SP-518** 187
Horneck G *et al.* (eds) 2003 *HUMEX: Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions* ESA **SP-1264**
ISECG 2007 *The Global Exploration Strategy: Framework for Coordination* http://esamultimedia.esa.int/docs/GES_Framework_final.pdf
ISECG 2013 *The Global Exploration Roadmap* http://www.globalspaceexploration.org/web/isecg/news/2013-08-20
Jester S & Falcke H 2009 *New Astron. Rev.* **53** 1
Joy K H *et al.* 2012 *Science* **336** 1426
Joy K H *et al.* 2016 *Earth Moon Planets* **118** 133
Lester D F *et al.* 2004 *Space Policy* **20** 99
Loftus D J *et al.* 2010 *Earth Moon Planets* **107** 95
Lucey P G 2000 *Proc. SPIE* **4137** 84
Maccone C 2004 in *Life in the Universe* Seckbach J *et al.* (eds) (Springer) 303
McKay C 2013 *New Space* **1** 162
Metzger P T 2016 *Space Policy* **37** 77
Neal C R *et al.* 2014 *Space Policy* **30** 156
NRC 2007 *The Scientific Context for Exploration of the Moon* (National Research Council, National Academies Press, Washington DC)
Ozima M *et al.* 2008 *Proc. Nat. Acad. Sci.* **105** 17654
Robbins S J 2014 *Earth Planet. Sci. Lett.* **403** 188
Rose C & Wright G 2004 *Nature* **431** 47
Schneider J 2010 *EPSC* abstract 202
Seibert G *et al.* (eds) 2001 *A World Without Gravity* ESA **SP-1251**
Taylor G J 1985 The need for a lunar base: answering basic questions about planetary science, in *Lunar Bases and Space Activities of the 21st Century* Mendell W W (ed.) (Houston, TX) 189
Terada K *et al.* 2017 *Nature Astronomy* **1** 26
White F 2014 *The Overview Effect: Space Exploration and Human Evolution*, 3rd edition (AIAA)
Wörner J & Foing B 2016 The "Moon Village" concept and initiative, Annual Meeting of the Lunar Exploration Analysis Group, LPI Contribution no. 1960, id.5084