PHILOSOPHICAL TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Introduction

Check for updates

Cite this article: Silk J, Crawford I, Elvis M, Zarnecki J. 2021 Astronomy from the Moon: the next decades. *Phil. Trans. R. Soc. A* **379**: 20190560.
http://dx.doi.org/10.1098/rsta.2019.0560

Accepted: 12 October 2020

One contribution of 16 to a discussion meeting issue 'Astronomy from the Moon: the next decades'.

Subject Areas:
observational astronomy, space exploration

Keywords:
lunar astronomy, telescopes, infrared, optical and radio lunar exploration

Author for correspondence:
Joseph Silk
e-mail: joseph.silk@physics.ox.ac.uk

Astronomy from the Moon: the next decades

Joseph Silk[1,2,3], Ian Crawford[4], Martin Elvis[5] and John Zarnecki[6]

[1]Department of Physics, The Johns Hopkins University, 3400 N. Charles Street, Baltimore MD 20218, USA
[2]Department of Physics, University of Oxford, 1 Keble Rd, Oxford, OX1 2JD, UK
[3]Institute d'Astrophysique, 98bis Blvd Arago, 75014 Paris, France
[4]Department of Earth and Planetary Sciences, Birkbeck College, University of London, Malet Street, London, WC1 7HX
[5]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge 02138-1516, UK
[6]School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

JS, 0000-0002-1566-8148; IC, 0000-0001-5661-7403; ME, 0000-0001-5060-1398

There is increasing interest in returning astronauts to the lunar surface. The US Administration has recently re-orientated NASA's planning towards the Moon, and the Director General of ESA has advocated the creation of a human–robotic outpost on the Moon (a 'Moon Village') as the next major step in space exploration. The Chinese National Space Administration has announced plans for a lunar base. There are multiple scientific reasons for wishing to resume the robotic and human exploration of the lunar surface, ranging from lunar geology to astrobiology. There are also potentially wider societal and geopolitical benefits, including the provision of a focus for international cooperation, and an inspirational stimulus for scientific and technical education. In the longer term, lunar resources might enable human operations deeper into the Solar System, which themselves may be expected to yield scientific and societal benefits.

Observational astronomy is one of the main scientific fields that will benefit from renewed operations on the lunar surface. Potentially, this could result in a huge science impact at a relatively low additional cost. In order to have an impact on planning for future lunar

THE ROYAL SOCIETY PUBLISHING

royalsocietypublishing.org/journal/rsta *Phil. Trans. R. Soc. A* **379**: 20190560

operations, now is the optimal time to generate science input to these plans. This themed issue of *Phil. Trans. A* develops some of the preparatory science activities, telescope design and lunar infrastructure needs of lunar astronomy. It was originally intended to include the proceedings of a Royal Society Discussion Meeting scheduled for Spring 2020 but subsequently postponed. Many of our invited speakers have contributed articles. Participants include cosmologists, low-frequency radio astronomers, infrared and far-infrared astronomers, and engineers specializing in lunar logistics and infrastructure.

The goal is to define the science reach of lunar-based astronomy, to define the appropriate infrastructure for lunar astronomy, and to study interactively how cosmology, astronomy and lunar infrastructure developments interface with, and motivate, telescope site selection and design, as well as to inspire agency planning for lunar exploration. There are interactions between theorists and radio astronomers, seeking to test inflation, infrared astronomers seeking to explore exoplanets, and the first stars and supermassive black holes, while lunar geologists and lunar engineers will inform and reinforce thinking on telescope design, as will the dialogue between analysis of the many astrophysical foregrounds (ranging from radio sources to the diffuse infrared background and zodiacal light) and limitations of lunar construction and deployment. Some of the ideas presented here develop standard technology in a lunar context, others are more futuristic. But all merit serious discussion.

One of the principal benefits of the lunar surface for astronomy would be for low-frequency radio astronomy from the radio-shielded far side. Radio waves with wavelengths longer than about 20 m cannot penetrate the Earth's ionosphere, and so must be observed in space, yet are expected to be a rich source of astrophysical information—including highly red-shifted 21 cm lines absorbed against the Cosmic Microwave Background by hydrogen clouds shortly after the Big Bang. Probing the dark ages before cosmic dawn is the only way to unleash the trillions of potentially observable modes from 21 cm observations, essentially the available information content for cosmological model determination, and that may be compared to millions of independent modes in the Fourier power spectrum in the CMB or hundreds of millions of galaxy modes in deep galaxy surveys. Only then can we aspire to approach the ultimate precision in cosmology that will provide the means of falsifying inflation. The goal will be to search for small-scale angular anisotropies in the cold hydrogen absorption signal generated in the dark ages, that of tiny deviations from Gaussianity, a rich and robust primordial relic of an inflationary beginning.

The possibility for passive cooling of IR instruments in permanently shadowed ultracold lunar craters near the lunar south pole, with crater rims in perpetual sunlight and the provision of a solid substrate on which to mount optical/IR/farIR instruments, will enable telescopes of up to 100 m diameter to dramatically improve the yield of habitable zone exoplanets that can be explored for biosignatures. The most practical means of directly imaging exoplanets within 100 pc of the Earth could be achieved with kilometre-scale interferometric baselines. Access to the infrastructure provided by human activities on the lunar surface would greatly aid in the maintenance and upgrading of astronomical instruments compared to free-flying satellites. The lunar surface lends itself to studies on the interface between astrophysics and fundamental physics (e.g. by facilitating emplacement on the lunar surface of instruments to study ultrahigh energy cosmic rays, general relativity, low-frequency gravitational waves in the LIGO-LISA frequency gap, and even quantum entanglement over the Earth–Moon baseline). Developments on the Moon are surely the next frontier for humankind and space exploration, but to couple this with an exploration of the wider universe would provide an even more compelling vision for justifying such an immense and expensive venture.

We believe that by providing a sufficiently detailed strategy, it is entirely feasible that the advisory committees appointed by the space agencies will be persuaded to include these options in their forward planning as a key element, rather than as a highly compromised and descoped afterthought. The science returns can uniquely address possibly the most important problem in cosmology, namely understanding how the Universe began. They may also shed light on a key question in astrobiology, namely is life unique to our local environment. These questions are intimately related, and we hope to provide the unifying basis for profound multidisciplinary discussions of broad interest to humanity on topics such as the inflationary origin of the universe, whether structure formation began via the first stars or via the first massive black holes, and whether exoplanets exhibit spectroscopic biosignatures in their atmospheres.

There is an ongoing dialogue as to whether space agencies should focus on Mars or on the Moon, and whether free-flying space telescopes can address the most profound questions in cosmology and in exoplanet research, such as whether we are alone in the Universe. Lunar astronomy provides an alternative strategy that deserves to be discussed in more detail than has hitherto been done, as long-term space agency planning is being formulated.

The articles in this issue begin with the case for observations of the dark ages as well as exoplanets via low-frequency radio observations from the lunar far side (by Jack Burns [1]). Dark ages probes by a lunar orbiting array are described by Xuelei Chen *et al*. [2], and the role of lunar telescopes in advancing cosmology is developed by Joseph Silk [3]. Leah Morabito [4] (with Silk) explores the reach of a lunar radio array for low-frequency imaging, and Kris Adami (with Eman Farhat) [5] describes technological aspects of a lunar interferometer. Spectroscopy of the cosmic microwave background has been largely unexplored for 40 years, and Jean-Pierre Maillard [6] argues that a dark lunar polar crater would be an ideal site for a microwave telescope with a Fourier Transform Interferometer to peer back to the first months after the Big Bang.

One pathway to detecting exoplanet biosignatures would be with a 100 m infrared telescope (Jean Schneider *et al*. [7]). The possibilities for ultrahigh-resolution imaging of the nearest exoplanets with a lunar hyper-telescope array in the optical/IR are described by Antoine Labeyrie [8]. The case is made for constructing a large telescope observatory using lunar regolith (Nick Woolf and Roger Angel [9]), along with the design for a diffraction-limited 20 m lunar telescope (Ryker Eads and Roger Angel [10]).

The lunar surface has a complex history of bombardment by the solar wind, galactic and solar cosmic rays, and meteorites over billions of years. Ian Crawford *et al*. [11] review the rich astrophysical records retained in the lunar surface. Robotic exploration to enable science from the lunar surface is described by Armin Wedler *et al*. [12] and human habitat issues are reviewed by Christiane Heinicke and Bernard Foing [13]. Dora Klindzic *et al*. [14] explain how a remote Earth-like planet would be viewed in exoplanet searches. In the final contribution, Martin Elvis *et al*. [15] note that the best lunar astronomy sites are quite few in number and have other possible uses, so astronomers need to engage in influencing a system of governance and justice for lunar exploitation. The history of proposals for astronomy on the Moon is reviewed in a complementary article by discussion meeting panelist Bernard Foing (submitted to *Proc. R. Soc. A*).

It is important to recognize that lunar science would also span materials science, fluid dynamics and fundamental physics. Astronomy can coexist with all of this—and indeed might even benefit from common facilities—including infrastructure, power, data analysis and servicing. The synergy between these science and infrastructure activities will provide an essential focus for a feasible scientifically driven international space programme. We realize that science is not the only driver for lunar exploration. However, not only can science benefit, but it can contribute to new horizons that have fascinated humanity over recorded history. A staged lunar astronomy programme would provide an improved understanding of our cosmic origins, at a level that is beyond the reach of any planned telescopes, whether on Earth or in space.

We thank Alice Power and her editorial team for a highly efficient collaboration in helping us produce this issue.

Data accessibility. This article does not contain any additional data.
Authors' contributions. All authors contributed equally to this article.
Competing interests. We declare we have no competing interests.
Funding. We received no funding for this study.

References

1. Burns JO. 2021 Transformative science from the lunar farside: observations of the dark ages and exoplanetary systems at low radio frequencies. *Phil. Trans. R. Soc. A* **379**, 20190564. (doi:10.1098/rsta.2019.0564)

2. Chen X, Yan J, Deng L, Wu F, Wu L, Xu Y, Zhou L. 2021 Discovering the sky at the longest wavelengths with a lunar orbit array. *Phil. Trans. R. Soc. A* **379**, 20190566. (doi:10.1098/rsta.2019.0566)
3. Silk J. 2021 The limits of cosmology: role of the Moon. *Phil. Trans. R. Soc. A* **379**, 20190561. (doi:10.1098/rsta.2019.0561)
4. Morabito LK, Silk J. 2021 Reaching small scales with low-frequency imaging: applications to the Dark Ages. *Phil. Trans. R. Soc. A* **379**, 20190571. (doi:10.1098/rsta.2019.0571)
5. Adami KZ, Farhat IO. 2021 Low-frequency technology for a lunar interferometer. *Phil. Trans. R. Soc. A* **379**, 20190575. (doi:10.1098/rsta.2019.0575)
6. Maillard J-P. 2021 Is the Moon the future of infrared astronomy? *Phil. Trans. R. Soc. A* **379**, 20200212. (doi:10.1098/rsta.2020.0212)
7. Schneider J, Silk J, Vakili F. 2021 OWL-Moon in 2050 and beyond. *Phil. Trans. R. Soc. A* **379**, 20200187. (doi:10.1098/rsta.2020.0187)
8. Labeyrie A. 2021 Lunar optical interferometry and hypertelescope for direct imaging at high resolution. *Phil. Trans. R. Soc. A* **379**, 20190570. (doi:10.1098/rsta.2019.0570)
9. Woolf N, Angel R. 2021 Pantheon habitat made from regolith, with a focusing solar reflector. *Phil. Trans. R. Soc. A* **379**, 20200142. (doi:10.1098/rsta.2020.0142)
10. Eads RW, Angel JRP. 2021 A 20 m wide-field diffraction-limited telescope. *Phil. Trans. R. Soc. A* **379**, 20200141. (doi:10.1098/rsta.2020.0141)
11. Crawford IA, Joy KH, Pasckert JH, Hiesinger H. 2021 The lunar surface as a recorder of astrophysical processes. *Phil. Trans. R. Soc. A* **379**, 20190562. (doi:10.1098/rsta.2019.0562)
12. Wedler A *et al.* 2021 German Aerospace Center's advanced robotic technology for future lunar scientific missions. *Phil. Trans. R. Soc. A* **379**, 20190574. (doi:10.1098/rsta.2019.0574)
13. Heinicke C, Foing B. 2021 Human habitats: prospects for infrastructure supporting astronomy from the Moon. *Phil. Trans. R. Soc. A* **379**, 20190568. (doi:10.1098/rsta.2019.0568)
14. Klindžić D *et al.* 2021 LOUPE: observing Earth from the Moon to prepare for detecting life on Earth-like exoplanets. *Phil. Trans. R. Soc. A* **379**, 20190577. (doi:10.1098/rsta.2019.0577)
15. Elvis M, Krolikowski A, Milligan T. 2021 Concentrated lunar resources: imminent implications for governance and justice. *Phil. Trans. R. Soc. A* **379**, 20190563. (doi:10.1098/rsta.2019.0563)

royalsocietypublishing.org/journal/rsta *Phil. Trans. R. Soc. A* **379**: 20190560