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Citation

Heinicke, C., & Foing, B. A. C. H. J. S. (2021). Human habitats: prospects for infrastructure supporting astronomy from the moon. *Philosophical Transactions A: Mathematical, Physical And Engineering Sciences*, *379*(2188). doi:10.1098/rsta.2019.0568

PHILOSOPHICAL TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Opinion piece

Cite this article: Heinicke C, Foing B. 2021 Human habitats: prospects for infrastructure supporting astronomy from the Moon. *Phil. Trans. R. Soc. A* **379**: 20190568. http://dx.doi.org/10.1098/rsta.2019.0568

Accepted: 30 July 2020

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

Subject Areas:
space exploration, mechanical engineering

Keywords:
space exploration, human and robotic partnership, astronomy, Moon

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Human habitats: prospects for infrastructure supporting astronomy from the Moon

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There is strong interest in lunar exploration from governmental space agencies, private companies and the public. NASA is about to send humans to the lunar surface again within the next few years, and ESA has proposed the concept of the Moon Village, with the goal of a sustainable human presence and activity on the lunar surface. Although construction of the infrastructure for this permanent human settlement is envisaged for the end of this decade by many, there is no definite mission plan yet. While this may be unsatisfactory for the impatient, this fact actually carries great potential: this is the optimal time to develop a forward-looking science input and influence mission planning. Based on data from recent missions (SMART-1, Kaguya, Chang'E, Chandrayaan-1 and LRO) as well as simulation campaigns (e.g. ILEWG EuroMoonMars), we provide initial input on how astronomy could be incorporated into a future Moon Village, and how the presence of humans (and robots) on the Moon could help deploy and maintain astronomical hardware.

This article is part of a discussion meeting issue 'Astronomy from the Moon: the next decades'.

1. Introduction

The Moon provides a unique environment for astronomy, with no atmosphere and no ionosphere. There are large

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cold polar craters that are thermally stable at below 100 K and that lie in permanent darkness yet within reach of nearly perpetual sunlight at surrounding peaks on crater rims [1–6]. The Moon is seismologically stable and the lunar far side is the most radio-quiet area in the inner Solar System [7,8].

It would be regrettable to pass up the opportunity and not make use of these unique advantages of a lunar platform for astronomy, especially given the prospect of sending humans to the Moon, which is arguably riskier than sending astronomical hardware and would, collaterally, lower the costs of set-up and maintenance of such hardware.

Yet, as conducive as the lunar conditions are to conducting astronomical observations on the lunar surface, as challenging they are to the engineer designing and testing the hardware necessary to perform these observations. The list of materials that can withstand the ultra-high-vacuum environment and the extreme temperatures and temperature gradients is limited. The exposure to space radiation is equally hard on materials and on electronics [9]. Likewise, the lunar dust is a menace for any movable parts and surfaces that must not be obscured. Studies of the reflector arrays placed on the Moon by the Apollo astronauts have shown that their reflectivity and their thermal performance have degraded to a small fraction of their original performance over the decades, and it is suspected that this is due to electrostatically charged dust stirred by micrometeorites and impact ejecta [10,11]. This will also likely be an issue for telescopes.

Given these environmental challenges for observatories on the Moon, one might wonder if the Moon really offers an advantage over observatories on Earth or in space. Indeed, the answer is not clear-cut but depends on the type of observatory (e.g. [12]). Already back in 1994, when NASA considered nine lunar telescopes as science payload [13], it was acknowledged that some of them could be placed in Earth orbit more easily (e.g. [14]). However, especially in the case of large instruments such as low frequency radio telescopes and interferometers at short wavelengths, the seismically stable lunar surface enables precision structures with baselines of several hundred metres, if not kilometres [14]. Furthermore, very low frequency (VLF) observations (below 30 MHz) are made possible by the Moon which shields against most of the radio noise from Earth and the Sun, but the shield is most effective only on or close to the lunar surface [15].

Besides, astronomy is not alone in its quest to solve the problems around infrastructure on the Moon: lunar rovers and structures that are intended to keep humans alive on the Moon share the same problems and many of the solutions can also likely be shared. For example, one of the most obvious strategies for preventing dust from entering a human habitat will benefit astronomy as well: concentrating operations on areas whose surface has been compacted and freed from loose dust [12]. Technological developments that need to be made for the safe set-up and maintenance of hardware on the Moon can happen in parallel. Moreover, robots can perform the set-up of astronomical hardware, maintenance tasks such as removing dust from telescopes, and *in situ* repairs. Humans on the other hand can help with these tasks either directly or by supervising, controlling and repairing the deployed robots.

With this paper, we provide initial input to how this collaboration between humans and robots could be achieved and how hardware for astronomy could be developed conjointly with robotic hardware and human support structures. We first provide an overview of hardware that should be considered for astronomy on the Moon (§2). This is held very brief, as more inspiration can surely be drawn from the other papers in this issue. We then outline (§3) the composition of a Moon Village [16,17] adapted to support astronomical research and how humans in particular can contribute to this research on the Moon. We end this paper with a brief outlook (§4) on the open research questions that should be addressed in order to exploit any synergetic effects of a joint human and robotic presence on the Moon on the conducting of astronomy from the Moon.

2. Overview of staged deployment of astronomy hardware on the Moon

The perspectives for astronomy from the Moon have been discussed at various symposia and community workshops over the past decades (e.g. [18–24]). Back in the late 1980s and early 1990s, NASA selected and studied five major candidate experiments for their scientific potential and adequacy to emplacement on the Moon [20,25] as part of their strategy for lunar observations: (a) a lunar very-low-frequency radio array; (b) an optical interferometer; (c) a submillimetric interferometer; (d) a large-lunar-telescope and (e) a lunar-transit-telescope (LTT). Around the same time, the ESA Lunar study group [23] distinguished three main areas (Science of the Moon, Science from the Moon and Science on the Moon) and proposed a sequence of events for a renewed lunar exploration programme.

Data from SMART-1 were already used in 2005–2007 for characterizing the lunar environments and sites for a possible robotic village, human bases and observatories (in particular at Moon poles) [3,6,26–28]. Since then, orbiters from various nations have provided a wealth of data relevant to site selection, notably the Lunar Reconnaissance Orbiter (LRO) [29–38], the Chandrayaan-1 and 2 orbiters [39–41], the Kaguya [42–44] and Chang'E missions [45–47].

Owing to the immense technological challenge, we believe a lunar astronomy program should be three-staged, with some elements being brought to the Moon before the set-up of the actual large astronomical observatory hardware.

(a) Stage 1 with astronomy guest instruments

Astronomy instruments can be carried on board orbiters, surface landers and rovers. The Apollo 15 and 16 missions were the first to use a remote sensing X-ray fluorescence spectrometer experiment for investigating the chemistry of about 10% of the Lunar surface.

More recently, instruments onboard SMART-1 and the Chandrayaan-1 and 2 orbiters performed Solar X-ray observations. Lunar orbiter instruments also performed Earth and astronomical observations. Since December 2013, the Chang'E 3 lander has been operating the Lunar Ultraviolet Telescope, observing the Earth environment as well as mapping galactic sources and measuring their UV variability [48,49]. The Chang'E 4 far-side lander carries a VLF experiment [50], and the NCLE Low Frequency experiment in the 80 kHz to 80 MHz range has been operating from Queqiao, the data relay orbiter of Chang'E 4 on the far-side halo orbit [51].

We expect that on the upcoming landers and rovers from international agencies or commercial initiatives there will be astronomy precursor telescopes. For example, the International Lunar Observatory Association is developing a 1 kg precursor telescope to start with Moon Express [52], with follow-up plans for a 2 m radio dish and a small optical telescope to be placed on Malapert Mountain. At the same time, the Indian Institute of Astrophysics in Bengaluru is developing a small near-UV imager that the launch company OrbitBeyond would carry on its first mission [53]. Future precursor telescope elements could include a lunar Pancam [54,55], supporting geological studies and cosmic observations. They could also contribute to the remote supervision of operations of rovers and later astronauts at far distances, similar to the demonstrator setup on board the ExoGeoLab lander (figure 1) in the International Lunar Exploration Working Group (ILEWG) EuroMoonMars campaigns in the Eifel region [56]. ESA is selecting proposals for a large lunar lander [57] in 2020, which may include rovers and small telescopes such as e.g. [58].

(b) Stage 2 astronomy dedicated instruments from robotic village

For the second stage, astronomical telescopes can be emplaced in a robotic village facility with assets at different places on the lunar surface or in lunar orbit, and will make use of specific advantages of the Moon as an observing platform for:

- Solar telescopes in white light, H Alpha, Ca II, Mg II lines, VUV continuum and lines, extreme UV (as the Extreme-UV Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory (SOHO) [59], or the Sun Watcher using APS and Image Processing instrument (SWAP) on PROBA2 [60]), X-rays, Gamma-rays and also in radio frequencies even inaccessible from Earth. In particular, we can envisage a suite of multifrequency instruments measuring continuously the Sun from the lunar South Pole regions in quasi eternal sunlight, as a reference for observations on Earth or Earth orbit, and as well for other observing sites in the Solar System. These will be also an asset for a self-sufficient space weather warning system for lunar equipment and astronauts. These can be completed with particle sensor telescopes monitoring the solar wind, coronal mass ejections and flares.

- Earth observing telescopes (for global mapping, radiation budget, but also for outreach showing the changes due to Earth rotation, cloud cover, illumination phases, seasonal effects, the Earth as a reference for exoplanetary studies and even long-term effect due to man-induced climate change). These could be complementary to and help cross-calibration for the observations obtained by Earth orbiting satellites, and with varying phase angles compared to the NOAA/NASA Deep Space Climate Observatory (DSCOVR, [61]) Earth observations from Sun-Earth L1 point.
- High-resolution monitoring of Solar System planets, in particular the multi-spectral daily and long-term monitoring at diffraction-limited 1 m class planetary telescopes of dynamics in the atmosphere of giant planets, that is only currently possible with the HST at very restricted times of observations.
- VLF radio to monitor Jupiter radio bursts and galactic sources, at long wavelengths absorbed by Earth ionosphere and requiring large antennas.
- Hyper-energy particle astronomy telescopes, with VLF antenna detecting Cherenkov showers created in the lunar regolith by most energetic cosmic ray particles (above the 10^{18} eV = Eev range) [62], that is 10 000 higher than Large Hadron collider energies, with the current record holder detected on Earth atmosphere Cherenkov at 320 EeV.
- Robotic network of radio dipoles to gain significant sensitivity to provide new constraints on cosmology (for verifying predictions of inflation, to detecting spectral distortions in the cosmic microwave background, to detecting the first stars and galaxies, to investigating the physics of super-massive black holes in the centres of active galaxies).
- Large telescopes and interferometers in the infrared to probe the chemistry of the birthplaces of stellar systems and spectro-images of exoplanets with starlight nulling techniques for possible biosignatures [63–65].
- Modest optical-UV-near IR telescope fully robotized and remotely operated with a simple focal instrument (for stellar activity, variability, seismology studies and for transit photometry of exoplanets with a partly better resolution than the rather modest multi-telescope of the PLATO project as envisaged by ESA [66]). There is consensus that such a telescope may actually be better placed in space, but if the infrastructure of a human outpost was on the Moon already, it would actually allow easier set-up, maintenance and upgrade, similar to the HST [16] (see also §3 for the benefit of a serviceability similar to the HST).

NASA recently selected the Lunar Crater Radio Telescope [67] for a feasibility study. The LCRT is a concrete proposal for a robotically set up VLF telescope that can reach frequencies of interest to cosmologists. China’s Chang’E-program contains a future sample return mission from the near side. Following that, China will have all the flight and landing capabilities necessary to set up its planned research station at the South Pole in the 2030s [68].

(c) Stage 3 with Moon Village crew-tended astronomy telescopes

This will be made possible with astronauts available from a semi-permanent outpost, base or Moon Village for assisting the deployment of large infrastructures, their maintenance and replacement/modernization of instrumentation:

- Developing interferometer telescopes: two movable telescopes would be added to the first to constitute an interferometric array operating in the UV wavelengths (200–350 nm where classical optics can be used). With a 1000 m distance between the three telescopes and using intensity interferometry that does not need any delay lines and at 200 nm one will access 20 microarcsecond angular resolution which is a factor 50 better than the best operating terrestrial interferometers and very likely for the next two decades [69–72].

- Expanding the network of VLF radio telescopes (increasing the sensitivity for 21 cm cosmology at redshifts 100–1000, or for studying extragalactic and galactic sources, and detecting exo-Jupiters).
- Deploying large liquid mirror telescopes for deepest sensitivity in extragalactic and cosmological lines of sight for the study of emission by first stars and structures in the universe. Borra *et al.* [73] have studied the feasibility and scientific potential of zenith observing liquid mirror telescopes having 20–100 m diameters located on the Moon.
- Installing large infrared and sub-millimetre telescopes, including in permanently shaded regions where passive cooling might be achieved.
- Archeoastronomy: one can also measure samples in the sub-surface to perform and find fingerprints of past events such as isotopic signatures of nearby supernovae or novae, or meteoritic samples from asteroids, comets and planets from past bombardment, or even from the early Earth [74–76].

(d) Preparing astronomy: multi-staged approach with field campaigns in lunar-like environments

The International Lunar Exploration Working Group (ILEWG) with its Mars counterpart IMEWG founded the EuroMoonMars initiative, which developed a precursor lunar lander ExoGeoLab on which a robotic telescope was installed that could be remotely controlled from a near-by Moon habitat or from Earth [77].

The EuroMoonMars team organized field campaigns in Moon-Mars analogue environments in specific locations of technical, scientific and exploration interest. The EuroMoonMars campaigns consist of research activities for data analysis, instruments tests and development, field tests in Moon-Mars analogues, pilot projects, training and hands-on workshops and outreach activities. A number of EuroMoonMars campaigns were conducted using telescope instruments [78].

The campaigns started with EuroGeoMars2009 (Utah MDRS, 24 January–1 March 2009), a collaboration of ILEWG, ESA ESTEC, NASA Ames, VU Amsterdam and GWU [79,80]. During these campaigns dedicated to MoonMars simulations, the crew had access to the Elon Musk telescope at MDRS where they performed imaging, stellar variability studies and spectrometry. Beside astronomy, special procedures were tested for addressing the issues of dust and contamination.

Currently, ILEWG is collaborating with the International Moonbase Alliance (IMA) [81] and the Hawaii Space Exploration Analog and Simulation (HI-SEAS) on a series of EuroMoonMars, IMA and HI-SEAS (EMMIHS) campaigns, at the HI-SEAS analogue facilities in Hawaii at 2500 m in elevation. As of 2018, IMA, an organization dedicated to building sustainable settlements on the Moon, has been organizing regular analogue missions. During EMMIHS campaigns, the analogue astronauts have performed tests for operating portable telescopes using EVA suits and helmets. Such simulations also allow to test designs and protocols for construction, operations and to address potential problems, like lunar dust. We also can make use of lunar environment and soil resources for material for construction of large structures, including with techniques of three-dimensional manufacturing.

In Europe, the LUNA facility [82] will soon provide a controlled environment for similar tests and help developing protocols for astronaut operations in lunar conditions.

3. Support infrastructures

Prior to the installation of human bases and laboratories, it is likely that a number of landers, rovers and robotic assets are emplaced on the lunar surface, possibly within the ongoing ‘Lunar

Figure 1. The robotic telescope on the ExoGeoLab lander adapted to lunar landscape (picture EuroMoonMars ISAE). (Online version in colour.)

Decade' [83–85] (Lunar Robotic Village [86–90]). We expect that these partly autonomous and partly remotely operated devices will carry a series of external packages of experiments similar to the ALSEP deployed by Apollo astronauts [91] or other packages deployed by large robotic landers. Examples of such a package were demonstrated by the ExoGeoLab pilot project [56,92] and the ROBEX and ARCHES projects [93–95].

Indeed, robots can likely take over a large part of the exploratory and scientific activities on the Moon. The Russians examined the Moon with their Lunokhod rovers back in the 1970s, and Mars is home to a number of rovers that have been operated successfully over several years. If successful, the Japanese Hayabusa2 will be the first to return a sample from an asteroid. Meanwhile, back on Earth, researchers at the German Aerospace Center demonstrated that robots can perform certain geology-related tasks better than (human) geologists [93], and NASA researchers have tested an all-terrain rover that could be used to assemble a habitat [96].

Nevertheless, the history of robotic exploration is full of mishaps that likely could have been avoided or at least corrected had a human been present. Some of the rovers on Mars got stuck in the soft Martian sand multiple times, with one such 'embedding' eventually leading to the Spirit rover's end of service [97]. The Philae lander on Churyumov–Gerasimenko had the opposite problem, bouncing off the comet during landing and ending up in a location where its solar panels were blocked off from sunlight, ultimately leading to the premature end of its mission [98,99]. On the other hand, the Hubble Space Telescope had been designed specifically to be 'visited in space by astronauts to perform repairs, replace parts and update its technology with new instruments' ([100], also see [101]), and therefore its life could be extended considerably through several service missions during which astronauts successfully replaced electrical parts and scientific equipment.

It is therefore easy to imagine that the existence of a Moon Village inhabited by humans would lead to a prolonged life of any robots operating in its relative vicinity, and ultimately to a more robust and reliable scientific output. In the two upcoming subsections we will discuss what

Figure 2. Artistic rendering of what a (part of a) Moon Village could look like: a habitat under a radiation shield in the centre, small rovers roaming the surface autonomously, a small telescope in the background on the left, and solar panels to supply everything with electricity. Image credit: Space is More. (Online version in colour.)

equipment is required to enable humans to survive on the Moon and some recent advancements, followed by an outline of how humans could support the deployment and maintenance of astronomical hardware, both directly and through the operation and maintenance of robots. This outline is by no means intended to be a comprehensive review; rather our intention is to illustrate one possible way in order to inspire more ambitious astronomical projects.

(a) Human habitats and their periphery

Human explorers require a more intricate compilation of support systems than their robotic counterparts. They require a so-called habitat, a vessel that protects them from the low-pressure, high-radiation environment of the lunar surface and the extreme temperature swings between day and night. Over the past decade, a number of test habitats have been built in various parts of the world. They typically provide room for four to six inhabitants. However, it is important to note that the vast majority of these habitats are designed for simulation purposes only, and are often not intended to function as a prototype of an actual extraterrestrial habitat.

Some of the designs that are closest to a potentially operational base are the HESTIA habitat at JSC from the Gemini-era [102], the Habitat Demonstration Unit [103,104] that was used during the 2011 field season of the Desert RATS [105] and is now in use for multi-week simulations under the name 'HERA' [106], and the Moon and Mars Base Analog (MaMBA, figure 2 and [107]), whose first module has recently been tested for usability at the ZARM in Bremen and which is expected to be expanded soon.

Other habitats have been used as facilities to test life support systems with humans in the loop, such as the Japanese Closed Ecology Experiment Facilities (CEEF, [108]) or the Soviet Bios-3 facility [109]. A more recent example for a life support system testing facility is the Chinese Lunar Palace 1 which has been in use since 2014 [110].

Aside from the shelter itself, a habitat for humans requires various peripheral systems in order to provide long-term subsistence: electrical power systems, bioreactors, ISRU-facilities for processing the lunar regolith, pressurized surface suits and pressurized vehicles for excursions, and communication systems. Some test habitats that are set up outside of laboratory halls already have their independent power supply (typically solar panels such as at HI-SEAS [111,112]), and others have tested complete mission scenarios involving suits, suit ports and vehicles (HDU during the above-mentioned D-RATS field testing in 2011 [104], the Inflatable Lunar-Martian Habitat (ILMH [113]) at the University of North Dakota).

Unfortunately, most of these habitats only have a very rudimentary workshop and scientific laboratory, if any. Sometimes the reason is that the inhabitants are not supposed to make any (major) repairs on the habitats they live in, in any case, a decently sized and equipped workshop is often not part the habitat design. One exception to this problem is the above-mentioned MaMBA-design that dedicates a complete module (out of six) to the workshop. Indeed, experience from long-term analogue missions has shown that crews will spend a significant amount of time on repairs and constructing improvised new equipment; it would be unjustifiable to not equip them with the appropriate tools (and space) for this!

Apart from the work-shop module, the MaMBA-design envisions a radiation shield of the shape of a large hall, rather than simply burying the habitat in regolith. The advantage of a large hall is simple: it provides extra shelter from the harsh radiation for rovers and outdoor tools that can be stored there while not in active use, while at the same time still allowing access to the outer shell of the habitat for repairs. Laser-melting and the three-dimensional printing of such structures from local materials is the focus of ongoing research that has made promising progress in the past few years [114–119]. One variation of printing three-dimensional structures that could be important for astronomy is the potential to use the same printers for grading the lunar surface and for compacting into pathways such that less dust can be raised by rovers, micrometeorites, or landing vehicles in the vicinity of any astronomy equipment.

(b) Human support of the set-up of astronomy hardware

As mentioned previously, humans can share some of the manual work to be performed on the surface with robots. The question of which tasks are better performed by humans and which by robots is a matter of ongoing debate; however, it is generally agreed that robots are better suited for repetitive tasks or tasks that require high precision or repeatability, whereas humans are better at improvising and reacting to unforeseen situations.

We deem it therefore likely that robots would be used to (1) survey prospective telescope and antennae sites, (2) prepare the erection site as described in the previous section, (3) erect or three-dimensional print structures from local regolith, (4) unload the pieces of equipment from the lander, (5) transport them from the landing site to the prepared site for the final set up, perhaps remove any restraints that secured the load during the launch, and (6) position the parts in their intended location, especially for the heavier pieces and items that need to be positioned precisely, such as lunar radio arrays, and (7) perform the initial checks of proper operation, particularly of electrical systems, (8) perform regular maintenance tasks that can be automated.

Humans on the Moon could then take over (1) supervision of robotic performance, (2) partial control of robotic movements (a remotely operated rover is usually faster than an autonomous rover; the Apollo astronauts in the Lunar Rovers went farther than the Curiosity rover in its currently 8 years of service), (3) steps during the assembly that are also complex to implement with robots, (4) run the final checks while in contact with support personnel back on Earth, (5) perhaps the performance of some complex maintenance tasks.

In addition to these foreseeable tasks that would be planned and tested on Earth before the first item for the telescope or antenna would even leave Earth, humans would contribute to the construction and operation of the astronomy equipment by (1) responding to any rover accident or malfunctions that would be difficult or impossible to resolve without human intervention, such as the embedding of a rover wheel, (2) repairing either the rover or the astronomy hardware, and replacing parts of it, (3) build new equipment, tools or other hardware parts that had not been anticipated before the start of the mission in order to improve or re-enable the operation of the rover and the astronomy hardware, (4) execute changes to the astronomy hardware as requested by ground personnel, especially if these changes are not implemented in the rover.

(c) Human-enabled astronomy research

Beside the set-up of telescopes and observatories, astronomy research may be conducted indirectly through the study of the lunar regolith, as mentioned in §2*c*. The regolith may contain meteorites which have not been altered by the Earth atmosphere, or conversely, meteorites from the early Earth that may contain samples of the Earth's primitive atmosphere (e.g. [74–76,120, 121]). Humans are quite good at spotting the unusual; AI/deep learning is likely to improve rapidly in the near future, but this will be of no avail due to a lack of good, large training sets.

Furthermore, anomalous isotopic abundances in the lunar regolith that stem from supernovae, as well as the mentioned meteorites may be buried under a surficial layer of regolith [74]. The Heat Flow and Physical Properties Package (HP^3) on the InSight mission to Mars has demonstrated (unfortunately) that robotic drilling can be problematic [122], hence human support for drilling on the Moon would be beneficial.

4. Outlook and open research questions

A lunar habitat has the potential to support not only the mere survival of humans on the Moon, but it can serve as a base camp for various activities on the lunar surface, including those that enable astronomy research from the Moon. Moreover, much of the developments that need to be done today in order to arrive at a functional habitat prototype in the not-too-distant future, overlaps with the likely needs of an astronomy facility, be it a telescope, interferometer or radio array. Some subsystems could possibly be developed and verified together, as was tested during EuroMoonMars campaigns at MDRS Utah with Elon Musk Observatory [79], ESTEC, Eifel and Lunares Poland Moonbase [77,78] IMA HISEAs Hawaii Moonbase [81,123] or during DLR telerobotic campaigns at Etna (ROBEX 2017, ARCHES 2021, [95,124]), and with the MaMBA project [107].

In any case, it is absolutely paramount that such complex systems be tested together. In order to ensure that, say, a large telescope can indeed by deployed by humans collaborating with rovers in the harsh lunar environment, the necessary activities should simulated together and under as realistic conditions as possible (e.g. the humans wearing surface suits that limit their mobility in a realistic way, and in a dusty environment that is potentially hazardous to the rover hardware).

These joint simulations and their preparation will help answer the following questions that pertain to conducting astronomy from the Moon:

- *Location*. How closely to a habitat or a landing platform could a telescope or other astronomy hardware be installed (before problems arise due to dust levitation from near-by landings or astronaut and rover traverses or due to signal interferences)?
- *Operational*. What tasks can be done on Earth, which are better performed on the Moon (finding a balance between the two extremes of operating everything remotely and conducting all activities including data analysis locally)?
- *Human robotic partnership*. What is better done by robots, what is easier with humans; what can be automated, where is it better to rely on remotely operated rovers?
- *Synergies*. What are the sub-systems needed by both humans and astronomy and can each benefit from a system developed for the other (data transmission; monitoring of the lunar surface and lunar orbit, especially with regard to space weather; stress on materials due to temperatures, radiation, and vacuum)?
- *Preparation*. How can the set-up and operation of astronomy hardware be tested effectively on Earth (benefit of optimizing hardware for use on the Moon for astronomers, benefit of a true use-case for engineers who develop habitats and periphery; option to improve designs that are found to be problematic in the other domain)?

To prepare for this lunar astronomy staged approach, we use data from previous missions (such as SMART-1, LRO), simulation facilities (such as MAMBA), and ILEWG EuroMoonMars field campaigns. It is our hope that by joining human and robotic forces with the knowledge gained from decades of experience with large astronomy facilities in remote regions of the Earth, we can push the frontier of our knowledge about the universe toward the Moon and gain more insights than if we stayed on Earth or tried to go to the Moon alone.

Data accessibility. This article has no additional data.

Authors' contributions. C.H. conceived and designed the outline of the manuscript, and drafted most of the manuscript. B.F. expanded the outline and broadened the theme, wrote large parts of §2 and critically revised

the full manuscript. All authors gave final approval for publication and agree to be held accountable for the work performed therein.

Competing interests. We declare we have no competing interest.

Funding. This paper was made possible through the support of the Klaus Tschira Foundation gGmbH.

Acknowledgements. We would like to thank Joe Silk, Farrokh Vakili, Kris Adami and Armin Wedler for their insights into cosmology and astronomy from the Moon. We thank Ian Crawford and an anonymous reviewer for helping us improve this manuscript.

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