A/AC.105/C.1/2024/CRP.14*

29 January 2024

English only

Committee on the Peaceful Uses of Outer Space
Scientific and Technical Subcommittee
Sixty-first session
Vienna, 29 January–9 February 2024
Item 11 of the provisional agenda**
Long-term sustainability of outer space activities

Protection of Astronomy and Science on the Moon

The present conference room paper contains information received from the International Astronomical Union, Square Kilometre Array Observatory, European Organisation for Astronomical Research in the Southern Hemisphere, European Astronomical Society, Open Lunar Foundation, For All Moonkind, Secure World Foundation and International Institute of Space Law. The information was reproduced in the form it was received.

* Reissued for technical reasons on 9 February 2024.
** A/AC.105/C.1/L.412.

Protection of Astronomy and Science on the Moon

Summary

The Moon offers unique opportunities for major observational discoveries in astronomical science. Cheaper launch to the Moon and the development of lunar infrastructure enable these opportunities, but many planned and potential activities are, in some instances, incompatible with the critical need for these scientific facilities to be free from noise and interference.

A process for the allocation, coordination around, and protection of lunar sites is needed to assure successful multiple long-term and sustainable scientific uses of the Moon and its orbital environment.

This paper defines the terms of the problem for the consideration and awareness by the Committee.

I. Introduction and Background

1. The International Astronomical Union (IAU) was founded in 1919. Its mission is to promote and safeguard the science of astronomy in all its aspects, including research, communication, education and development, through international cooperation. Its individual members are professional astronomers from all over the world, at the Ph.D. level and beyond, who are active in professional research, education and outreach in astronomy. The IAU has a total membership of 12,761. The IAU has been an observer at COPUOS since 1995.

2. The IAU Working Group on Astronomy on the Moon was established in 2023, and is chaired by Dr. Richard Green from the University of Arizona, along with Dr. Martin Elvis of the Harvard Smithsonian Center for Astrophysics, and Christopher Johnson, Director of Legal Affairs and Space Law at the Secure World Foundation serving as co-chairs. The Working Group is constituted as part of the IAU standing Commission C.B7 for Protection of Existing and Potential Observatory Sites.

3. The IAU Working Group on Astronomy on the Moon has the following Terms of Reference:

(a) Develop scientific information and policy recommendations to support those working, in particular at ITU-R, to protect the ability to make radio astronomical observations unique to the Shielded Zone of the Moon (SZM);

(b) Lead and collaborate on identifying, prioritizing and developing policy to protect sites of extreme scientific value for other astronomy-related observational facilities (e.g., IR interferometry, gravitational wave interferometry);

(c) Inform policy makers and agencies about cis-lunar astronomy needs and immediate threats;

(d) Support the IAU in their efforts at the United Nations COPUOS and other bodies to promote an international policy that includes lunar astronomical site protection.

4. This paper is specific to the astronomical needs for utilization of the Moon. We note many previous presentations to the STSC from, e.g., the Moon Village Association GEGSLA (A/AC.105/C.1/2023/CRP.), towards developing a plan for sustainable use of the Moon. The needs of astronomy add an additional dimension, broadly consistent with any policy framework to be developed.

II. Astronomy and Science Opportunities on the Moon

5. A variety of unique scientific and astronomical activities can be conducted on the lunar surface. These include cosmology, planetary sciences and fundamental physics activities.

A. Cosmology: Probing the Cosmic Dark Ages

6. Ultra-low frequency radio observations in the shielded zone on the far side of the Moon probe the original building blocks of the galaxies – myriads of clouds of pristine hydrogen, which would be detected as absorbing shadows against the cosmic microwave background as early as three million years after the Big Bang. Mapping the elusive fluctuation signal from the Dark Ages of the Universe before any stars or galaxies were formed would herald a new era of ultraprecision cosmology, opening the possibility of discovering new physics.

B. Exoplanets: Characterizing Planets in Other Solar Systems

7. From the Moon, long periods of continuous viewing enable the monitoring of the atmospheres of exoplanets as they transition through day and night around their host stars. The sharp resolution achieved by a numerous array of large telescopes can enable searches for biosignatures in the atmospheres of Earth-like planets. Exoplanet magnetic fields, potentially vital to shielding life from harmful radiation and preventing planetary atmospheric loss, can also be detected and monitored.

C. Fundamental Physics: New Frontiers in Gravitational Wave Astronomy

8. Gravitational waves propagate through the Universe from the mergers of extremely dense objects like white dwarfs, neutron stars and black holes. Detectors on the Moon would be sensitive to lower frequencies than those on Earth, allowing the exploration of mergers of intermediate-mass and seed black holes, as well as white dwarfs, throughout much of the Universe. Frequent detections with identifications of the sources can test Einstein's Theory of Relativity.

III. Observational Techniques and Special Sites

A. Lunar Farside Radio Quiet Zones

9. The far side of the Moon always faces away from Earth and is thus the only truly radio-quiet location in the inner solar system, as it is shielded by the Moon itself from radio-frequency interference coming from powerful Earth-based transmitters. This enables the sensitive detection of ultra-low-frequency radio signals, by placing large arrays of simple antennas on the far side of the Moon. In the long term, this research demands highly specific sites. The physics of the Dark Ages of the Universe tells us that eventually we will want to build an array of antennae spanning some 200 km, for which there are few sites on the far side. Those would need to be allocated for scientific use and protected against Unintended Electromagnetic Radiation, from sources such as electric motors and unshielded circuits.

B. Infrared Telescopes

10. Distortions in the high-redshift cosmic microwave background and the composition of the atmospheres of exoplanets are measured in infrared wavelengths, beyond those accessible to the James Webb Space Telescope (JWST). To suppress the

thermal noise that would swamp the faint cosmic signals, the telescope and instruments must operate under very cold conditions. On the Moon, the permanently shadowed regions (PSRs) on crater floors have been shielded from direct illumination by the Sun for some 4 billion years, making them extremely cold, ~ -250C (~25 K), similar to the JWST or colder. These sites provide the stable cooling crucial to the functioning of these devices without complex mechanical solutions. However, many of these craters are also attractive for extraction of frozen water ice, an activity incompatible with the low dust, low noise environment required for telescope operation.

C. Interferometry

11. One mode of detection of gravitational waves and the combining of light from distributed telescopes to achieve greatly enhanced resolution rely on the technique of interferometry. Light waves are combined in a vacuum to measure the passage of a gravitational wave distorting the Moon's surface by an amount 1,000 times smaller than the size of an atomic nucleus. The Moon is intrinsically much more seismically quiet than the Earth and has a natural (near-)vacuum, so it provides a greatly advantageous platform. Disturbances generated by nearby landings and launches or by heavy equipment for exploration or mining would not be compatible with these sensitive observations.

D. Sites of Exceptional Scientific Importance (SESIs)

12. The Moon presents some of the most promising sites for a next generation of high-performance instruments, protected from radio interference, wind buffeting, gravitational sag, and other constraints imposed by the terrestrial environment. The Moon presents some of the most promising sites for a next generation of high-performance instruments. Broadly, there are two classes of lunar SESIs for astronomy: the radio-quiet farside sites and the cold traps. The mountainous farside has only a few locations that are smooth and large enough to accommodate arrays of antennae spanning some 200 km. Permanently shadowed regions (PSRs) also known as "cold traps" can passively cool infrared and X-ray telescopes without energy-expensive chillers. Only a dozen or two cold traps sustain temperatures below 25 K and most are small, about 1 km in diameter.

IV. Policy and Regulatory Needs to Protect Science and Astronomy on the Moon

13. The ability to utilize the unique advantages of science on the Moon, including astronomy, will depend on the development of internationally accepted methods to communicate, signal intentions between actors, foster coordination and due regard between relevant users and stakeholders, avoid harmful interference, and in allocating and protecting specific sites from interfering activities.

14. In short, some of the most important and pioneering scientific missions on the Moon can only take place in specific locations and under specific conditions, and can only take place if they are protected from interference – even from other peaceful uses.

15. Such a process of transparent and internationally-accepted coordination and protection for science is needed by the time the current phase of governmental and non-governmental demonstrations and prototyping of launch, delivery, and deployment is complete.

16. The IAU will work with other organizations with complementary interests to encourage COPUOS's thinking and planning on this complex issue.

17. The following pages contain an annex of technical aspects of astronomy and science opportunities on the Moon.

Technical Annex

I. Astronomical Opportunities on the Moon

A. Low-Frequency Radio Astronomy and the Need for Protected Sites on the Moon

1. The far side of the Moon is the only truly radio-quiet location in the inner solar system. The Moon is tidally locked to the Earth so that one side always faces away from our home world. On the far side, two thousand miles of rock blocks off any interfering signals arising from anthropogenic sources on Earth as well as the auroral kilometric radiation (AKR) arising from the Earth's magnetic field energized by the solar wind and from solar radio bursts at night.

2. The Moon has effectively no ionosphere, which on Earth serves to distort, refract, and absorb low frequency radio radiation at 50 MHz (below the FM band). The Moon's subsurface – which electromagnetically couples with radio antenna beams – is highly anhydrous, i.e. dry, and electrically stable (unlike Earth), making low frequency radio observations more accessible.

3. Thus, the Moon is the ideal location to open the last of the electromagnetic windows to the Universe at low frequencies and thus e.g., probe unexplored epochs of the early Universe including the so-called Dark Ages, prior to the formation of the first stars and galaxies.

4. Several exciting and forefront science cases have been described in United States National Academy of Sciences Decadal Surveys for low radio frequency observations. The first involves distinctive measurements of the magnetic fields associated with potentially habitable exoplanets. AKR emissions emitted by nearby exoplanets are the only way to directly measure magnetic fields that may be crucial to the formation of life. AKR emission arises from maser instabilities in cyclotron radiation which means that the frequency is directly proportional to the magnetic field strength. Using arrays with a few hundred low frequency dipole antennas laid on the lunar surface operating as an interferometer, radio observations are predicted to have the sensitivity to detect numerous exoplanets within 30 light years of Earth. The Planetary Science Decadal advocated for *search[es] for magnetospheric activity at exoplanets with remote sensing of phenomena associated with magnetic fields, potentially including radio emission.*

5. A second science case involves observations of the Dark Ages and Cosmic Dawn, the time during the formation and birth of the first stars and galaxies. The United States Astro2020 Decadal Survey cosmology panel sees *21 cm mapping of the Dark Ages and reionization era as both the discovery area for the next decade and as the likely future technique for measuring the initial conditions of the Universe*. The science is compelling and unique, with the potential to revolutionize cosmology by exploring a new frontier to the beginning of the Universe.

6. The Dark Ages ($z > 30$) have no stars or galaxies but space is filled with neutral hydrogen that emits redshifted 21-cm radiation. The sweet spot for observing hydrogen in absorption against the cosmic microwave background (CMB) is at the epoch when the diffuse intergalactic hydrogen medium was cooler than the CMB photons, between a redshift of 30 and 100. The corresponding frequencies of the 21 cm line in absorption are from 50 to 15 MHz, and effectively unobservable from the Earth.

7. At these low radio frequencies, the first goal will be to detect the integrated signal with a simple dipole antenna, enabling the first direct measurement of the Dark Ages of the Universe. Far side radio interferometers, with thousands of dipoles, will

subsequently probe the building blocks of the galaxies, myriads of clouds of pristine hydrogen, as absorbing shadows against the cosmic microwave background just a million years after the Big Bang.

8. Such observations enable measurements of the nature of dark matter, scale dependence of primordial fluctuations and deviations from Gaussian statistics, and primordial gravitational waves linked to inflation. Mapping the elusive fluctuation signal from the dark ages would herald a new era of ultraprecision cosmology, just as detection of the cosmic microwave background in 1964 by Penzias and Wilson led to the discovery of the CMB fluctuations by the COBE satellite in 1990 that transformed cosmology into a precision science.

9. Facilitated by NASA's Commercial Lunar Payload Services (CLPS) programme – synergizing NASA's Artemis human exploration programme – the first radio telescope observations from the Moon are planned for 2024. CLPS allows rapid acquisition of lunar delivery services from commercial companies for payloads that advance capabilities for science. The first radio telescope on the Moon, *Radio wave Observations at the Lunar Surface of the Electron Sheath* (ROLSES), is slated for delivery to the lunar south pole by Intuitive Machines' NOVA-C lander. ROLSES consists of four 2.5-m monopole antennas and a radio spectrometer that was built by the NASA Goddard Space Flight Center. Science goals include the first measurements of the electron sheath density from ~1-3 m above the lunar surface, detection of Earth's AKR, solar and other radio emission from the lunar surface, the Galactic spectrum at <30 MHz, and aid in development of lunar radio arrays.

10. The first radio telescope to the lunar farside will be the *Lunar Surface Electromagnetics Experiment at Night* (LuSEE-Night) manifested for launch in 2025/26 on the CLPS lander built by Firefly Aerospace. LuSEE-Night (6-m cross-dipole antennas) will observe at 1-50 MHz corresponding to the Dark Ages. A communication satellite will be placed in lunar orbit to relay data to the Earth along with a radio beacon to calibrate the radio antenna beam. The mission is a novel collaboration between NASA (led by UC-Berkeley PI S. Bale) and the United States Department of Energy (DOE) (liaison Anže Slosar at Brookhaven National Lab).

11. The European Space Agency (ESA) intends to use the European Lunar Lander to set up a low frequency radio telescope tripole antenna in a permanently shadowed dark crater at the Lunar South pole.

12. The Hongmeng project (also known as the Discovering the Sky at the Longest wavelength or DSL project) has been proposed by a team of scientists from the National Astronomical Observatories, the National Space Science Center, and the Innovation Academy of Microsatellites of the Chinese Academy of Science. This is a lunar orbit satellite array, including one mother satellite handling the communication and control, and 9 daughter satellites for low frequency radio astronomy observation.

13. The Hongmeng project aims to map the sky at frequencies below 30 MHz, and also carry out global spectrum measurement in the 0.1-120 MHz band to probe the cosmic dark ages and cosmic dawn. These satellites will fly along the same orbit as a linear formation, with the mother satellite at one end of the array, and the farthest satellite at 120 km away. The planned orbit has an inclination angle of 30 degree and an altitude of 300km. Observations are usually made when the satellites are on the part of orbit shielded from the Earth by the Moon, while data is transmitted back to Earth when it is on the part of the orbit visible from the Earth. The regular inter-satellite communication is carried out in the Ka band. The threats to its operation is primarily radio transmission at frequencies in the 0.1-120 MHz range from spacecraft or facilities in cislunar space.

14. The technology for these various projects is challenging but feasible, and the potential science return is compelling. All are pathfinders towards obtaining a definitive signal of highly redshifted brightness fluctuations from atomic hydrogen, the precursor of all structure in the universe. Forming structures in the Dark Ages are uniquely probed using the power spectrum measured by very large interferometric

arrays such as FarView. NASA, ESA and the Chinese National Space Agency (CNSA) are each planning radio interferometers, with hundreds or thousands of dipole antennae deployed over tens of km for the mid-2030's. The ultimate goal will be deploying millions of dipoles over hundreds of kilometres.

15. There will inevitably be competition from commercial activities. The number of key scientific sites is very limited, and so international coordination will be required. This becomes all the more urgent due to the imminent exploitation of NASA's SLS, an expendable vehicle capable of 100 ton-scale deliveries to low earth orbit. The projected costs of lunar payload deliveries are rapidly dropping via a new generation of large load recyclable launchers that include SpaceX's Starship and Blue Origin's New Glenn spacecraft.

16. As an example, the Large-scale Array for Radio Astronomy on the Farside (LARAF) project has been proposed by a team of scientists from the National Astronomical Observatories, Chinese Academy of Science and the Beijing Institute of Spacecraft System Engineering. This is a low frequency radio astronomical array on the lunar farside, which will discover and observe celestial objects in the 0.1–50 MHz band, and test techniques for future very large arrays aimed at measuring primordial fluctuations during the cosmic dark ages. The proposed array has one master station and 20 distributed stations, each with 10~20 antennas, and the array has a maximum baseline of about 10 km, connected via power line and optical fiber. The array is to be deployed on the far side of the Moon, in a mid-latitude flat site. A tentative candidate site at longitude 171.4947° west and latitude 32.7393° south has been proposed, though other sites are also under consideration. The main threat to its operation is the radio transmission at frequencies in the 0.1–50 MHz range from lunar farside surface or cislunar space, while excessive lunar dust produced by activity in nearby sites may also affect its operation.

17. Thus, radio observations from the Moon are no longer science fiction but science fact as we enter a new era of exciting science investigations from our nearest neighbour in space. To fully realize the potential of radio astrophysics and cosmology from the Moon, it is essential to maintain the radio-quiet of the far side. We must prevent contamination of the radio spectrum at low frequencies as recently seen on Earth from Starlink satellites. For instance, Di Vruno et al. (2023) observed bright radio leakage from Starlink power supplies and other unshielded electronics at 150 MHz. This would be a disaster for sensitive radio telescopes on the Moon. It is within the purview of the ITU to regulate this Unintended Electromagnetic Radiation, but preserving large, flat sites for extensive interferometric arrays requires an international process of allocation and protection that falls under the remit of COPUOS.

B. Infrared Astronomy: the Moon as a unique, future platform

18. The JWST is fully demonstrating the power of infrared astronomy from space in all the fields of astrophysics, from solar system objects, exoplanets, star forming regions, to the most distant galaxies.

19. To go beyond the current capabilities of this telescope, it will be necessary to notably increase the collecting area (> 6.5 m diameter) and to extend the spectral coverage well beyond 28 µm. Larger ground-based telescopes are in service and bigger ones are already in construction with the Thirty Meter Telescope planned for Mauna Kea plus the Giant Magellan Telescope and the European Extremely Large Telescope in Chile.

20. However, even on the best sites on Earth to explore the heavens, the image quality and the field size remain dependent on the adaptive optics systems capabilities. The spectral coverage is limited to the atmospheric windows which are never perfectly clean. The sensitivity, particularly to go towards the longer wavelengths, is affected by the temperature of the telescope which in average is

around 5°C or more. On the other hand, a space telescope bigger than JWST, due to the current capabilities of the launchers cannot be considered.

21. Only the Moon could combine the advantages of space (image quality and transparency) and of the ground to support a large structure. But in addition, the Moon offers extremely cold sites with the presence at the lunar poles of permanently shadowed craters where the temperature in a few locations can be as low as 18 K. These spots are giving the chance of passive cooling of a large telescope more efficiently than at a distant orbital position that is still irradiated with sunlight, such as that of JWST at L2. These sites must be protected in priority to keep intact their exceptional properties.

22. Subtle distortions of the Cosmic Microwave Background spectrum in the mid-infrared yield information about the earliest formation of structure in the Universe. These could be detected in the far infrared with an array of cooled, moderate aperture telescopes with specialised detectors. Arrays of cooled telescopes of very large aperture and/or wide area distribution provide the sensitivity and angular resolution to probe the molecular transitions in the infrared characterizing the atmospheres of exoplanets and enabling the search for chemical transformations caused by the presence of life.

23. The main threat comes from the projects of economic utilization of the Moon which implies the building of a Moon base to explore the physical, mineral, and chemical resources of the Moon. The lunar poles represent a tempting location for such operations by the presence of water ice, making it possible to produce the water needed for a human settlement. Sometimes called a “Moon Village”, it supposes the construction of a landing pad, of roads, of shelters for propellant, food and material, of housing for the residents, and a large area levelling for all these settlements. The subsequent exploration and exploitation of the mineral resources will imply drilling, excavation, mining, storage, and possible processing of the extracted material.

24. All these projected activities at the lunar poles would necessarily require many launches and landings. Such projects would need to be closely controlled and limited in the case of the astronomical use of the same sites.

25. In contrast to activities that require intense astronaut involvement, the deployment and the operation of a 13-m telescope such as ALLURE (Astronomical Large Lunar Infrared Explorer) as described in: “Infrared Astronomy beyond JWST: the Moon perspective” (Phil. Trans. R. Soc. A, special issue – to be published soon) can be only robotic. That prospect would allow site placement distant from human activities that can loft dust and gasses disruptive to sensitive observations.

C. Gravitational Wave Astronomy on the Moon

26. Our Moon is the most promising location for building gravitational-wave detectors and ushering in the revolution of multi-messenger astrophysics.

27. Predicted by Albert Einstein a century ago, the detection of gravitational waves by LIGO (Laser Interferometer Gravitational-wave Observatory) detectors for the first time in 2015 was awarded the Nobel Prize in Physics. Gravitational waves, unlike electromagnetic waves (radio, light, X-ray), are practically invisible, thus their detections require some of the highest precision experiments in all of science and engineering.

28. A next-generation gravitational-wave detector called LILA (Laser Interferometer Lunar Antenna) is being proposed around the rim of a large crater on the Moon. Our Moon is seismically much quieter than the Earth, especially at low frequencies to detect gravitational waves. This allows a detector to avoid the worst of the seismic noise, which currently limits the low end of the frequency range over which a terrestrial detector (such as LIGO) can see gravitational waves. It also lacks human interference.

29. A detector like LILA would, unfortunately, be easily disturbed by human activities, such as mining the Moon, or nearby landings on the lunar surface. Such activities must thus be kept far away from LILA, as well as similarly sensitive experiments. Such issues have already been seen with LIGO, which regularly experiences interference from logging and trains, even though the train tracks are around three kilometres from the closest part of the detector. This direct interference limits the astrophysical window we can achieve with gravitational waves.

30. Therefore, a site for LILA would require both isolation and protection from other interfering activities, highlighting the need for an international process.

II. Sites of Extreme Scientific Interest (SESIs) for Astronomy on the Moon

31. The Moon presents some of the most promising sites for a next generation of high-performance instruments, protected from radio interference, wind buffeting, gravitational sag, and other constraints imposed by the terrestrial environment. The Moon presents some of the most promising sites for a next generation of high-performance instruments. Broadly, there are two classes of lunar SESIs for astronomy: the radio-quiet farside sites and the cold traps.

A. The Lunar Farside's Radio Quiet Zone

32. The predicted part-in-a-million signal from the Dark Ages and the scale of emerging structure tells us that eventually we will need the sensitivity and angular resolution of an extensive array of antennae spanning some 200 km. The mountainous farside has only a few locations that are smooth and large enough to accommodate arrays on this scale. Preserving these sites for the future deployment of these large antenna arrays is essential for the long-range plans for cosmology and exoplanet characterization.

B. Cold Traps: Permanently Shadowed Lunar Regions

33. Permanently shadowed regions (PSRs) also known as "cold traps" are unique locations for infrared and X-ray telescopes. Lunar "cold traps" are polar craters on the lunar surface whose interiors have been shielded from direct illumination by the Sun for some 4 billion years making them very cold, ~ -250C (~25 K), similar to the JWST or colder. These sites provide the stable cooling crucial to the functioning of these devices without complex mechanical solutions, such as a JWST-like special-purpose sunshield. Only one or two dozen cold traps sustain temperatures below 25 K and most are small, about 1 km in diameter. Moreover, as discussed below, many of them seem to contain water, making them likely targets of competing (and even incompatible) pursuits, such as mining.

C. Seismically Quiet Cold Traps for Gravitational Wave Detectors

34. Gravitational waves are generated by extreme events in the Universe: merging pairs of black holes a bit more massive than the Sun, or neutron star-black hole pairs. The spacetime distortions caused by the passage of a gravitational wave are 1,000 times smaller than the size of an atomic nucleus, so great care is needed to minimize vibrations experienced by gravitational wave detectors.

35. Operating at cryogenic temperatures, in a vacuum, and in seismically quiet environments, far from traffic and other human generated motions all help. These conditions are difficult to create on Earth, but are all available in the cold traps on the Moon.

36. Although the Moon features some seismic activity, it is far quieter than Earth, making it a greatly superior location for gravitational wave instruments.

37. Two types of gravitational wave detector have been proposed for the Moon:

(a) An array of seismometers to sense the distortion of the Moon from the passage of gravitational waves. These would be best placed in the coldest cold traps at < 50 K inside PSRs. As before, other missions, particularly for mining, may also want to use these cold traps;

(b) A gravitational wave interferometer, similar to the Earth-based LIGO detectors, would require long baselines (~40 km) to probe the gravitational wave frequencies between LIGO/VIRGO/KAGRA and LISA, although not all concepts require cryogenic conditions. The three largest cold traps are just large enough and are cooler than 75 K. Of these three, only Faustini seems to be water poor, so may be the only site to avoid mining disturbances.

38. In sum, the conditions at these two types of lunar SESIs, the farside and select cold traps, present extraordinary opportunities for astronomical research, but are also rare and fragile.