Protecting Sites of Extraordinary Scientific Importance on the Moon: The Case of Astronomy

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Abstract

The imminent return to the Moon by multiple space agencies and commercial companies has spurred astronomers to reconsider the Moon as a site for ambitious telescopes. There are several concepts that use the rare properties of special sites on the Moon to undertake astronomical observations not possible elsewhere. These include the well-known radio quiet zone of the lunar farside, the coldest cold traps for far-IR telescopes, and large permanently shadowed regions for cryogenic gravitational wave detectors. For each application there are surprisingly few of these "sites of extraordinary scientific importance." A first inventory of them is given here. Because these sites are easily degraded by other activities, they will need protection against other uses if the discovery potential they enable is to be kept for humanity. Initial policy approaches to achieve this protection when involving multiple parties are outlined.

1. Introduction

Astronomers were unprepared for the sudden emergence of internet constellations of thousands of satellites in low Earth orbit (LEO).[1] On the Moon we have the chance to anticipate the threats to "sites of extraordinary scientific importance" (SESIs). Astronomy provides an important example of how scientific lunar sites can be surprisingly rare and small. Like many rare environments, these special sites for astronomy can be easily ruined for scientific use. Unlike biological planetary protection, the degradation of astronomy sites is in principle reversible. Alternative uses for many of these sites have already been recognized. If these other uses have great support (e.g., for life support, or profit) then the reversibility of the disturbances may be only theoretical. Some of these other uses can threaten specific science objectives Moon-wide.

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1 Lawrence, A., 2021, Losing the Sky, *Photon Productions*, ASIN: B08W9NR7DX.

Interest in the Moon as a location for astronomical observatories is growing. In early 2021 a volume of the Philosophical Transactions of the Royal Society was devoted to astronomy from the Moon.[2] Further ideas for new classes of lunar-based telescopes have emerged in just the subsequent two years. This is a sea-change from the mostly negative position in 2007 detailed in a National Academies report.[3] Now, however, current and planned telescopes in free space are already large and costly, making the lunar surface seem less of a stretch; multiple players have developed strong plans for a sustained return to the Moon, including a human presence. These changes have ignited astronomers' creativity.

In this paper the concepts for lunar telescopes are first explained and then their site requirements outlined. In most cases there are only a handful of potential sites, making them SESIs. Ways to mitigate the degradation of these SESIs, in both the technological and policy realms, are explored. The paper is written with the hope of explaining the astronomy to the policy and legal communities, and the policy/legal issues to the astronomers.

2. The Moon as a Unique Location for Astronomy

The concepts for astronomy from the Moon developed so far, and their preferred, rare locales, span at least four distinct areas.

2.1. Far-side Radio Telescopes for Cosmology and SETI

The faint signal from neutral hydrogen atoms (HI) out of the "Dark Ages" can inform us about the time before there were any stars or galaxies (at redshifts, $z \sim 30\text{-}80$). With sufficient angular resolution the highly redshifted HI can test the inflation model of cosmology.[4] At these high redshifts the signal, which was emitted at a wavelength of 0.21 m, lie in the wavelength range 6.5 – 17.0 m (frequency range 17.6 – 46.1 MHz) where human-generated interference is greatest. Earth-based telescopes designed to detect this signal are heavily limited by this interference.[5]

2 Silk, J., Crawford, I., Elvis, M., and Zarnecki, J. (eds), 2021, Astronomy from the Moon: The Next Decades, *Phil. Trans. Roy. Soc., A*, 379, Issue 2188.

3 National Research Council 2007. "The Scientific Context for Exploration of the Moon." Washington, DC: *The National Academies Press*. https://doi.org/10.17226/11954.

4 Silk, J., 2016," Challenges in Cosmology from the Big Bang to Dark Energy, Dark Matter and Galaxy Formation", *Proceedings of the 14th International Symposium on Nuclei in the Cosmos (NIC2016*), id.010101, 13 pp.

5 Burns, J.O., et al., 2021, "Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions", *The Planetary Science Journal*, 2, 44.

The far-side of the Moon is shielded by about 80 dB from radio interference (RFI) from Earth's radar, radio, and TV emissions, making this location better than anywhere else in the Solar System.[6]
The same quiet radio environment is equally beneficial for sensitive searches for technosignatures of alien civilizations, to determine whether we are alone in the Galaxy. The microwave 1 – 10 GHz range has the lowest background for Earth-based searches, but in space this window expands to 1 – 100 GHz.[7]
For cosmology an array of telescopes ~200 km diameter is needed to obtain the necessary 10 arcsecond resolution at these wavelengths. There are only a few sufficiently large, smooth sites for such a telescope on the Moon's mountainous far-side.[8]

2.2. Infrared Telescopes for Searching for Life on Exoplanets

The signatures of life should be imprinted on the infrared spectra of planets outside our Solar System ("exoplanets").[9] Most of these signatures are very faint. The James Webb Space Telescope may find a few,[10] and its proposed successor recommended in the 2020 Decadal Survey may find two dozen. To really know if we are rare, and perhaps alone in our Milky Way galaxy, a much bigger telescope will be needed.
An infrared telescope must be cryogenically cold to keep its own emission low so that the weak cosmic signal can be discerned. In space this requires complex heat shields – Webb deployed five tennis-court-sized reflective shields to keep the telescope and instruments cold enough. Larger shades are for now impractical, though they may become feasible as launch capabilities increase. The Moon, instead, has "cold traps" that are kilometers across in craters near the two poles. The floors of these craters are never illuminated by the Sun directly and so are always at the low, cryogenic, temperatures needed. These regions are called "Permanently Shadowed Regions" (PSRs). A few may be ideal places from which to conduct a broad search for life in the Universe.[11]

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6 I.e., 100 million-fold quieter.

7 Tarter, J.C. and Rummel, J., 2008, "Exobiology and SETI from the Lunar Farside", *AIP Conference Proceedings*, 207, 99 (1990); https://doi.org/10.1063/1.39361; Heidmann, J., 1998, "SETI from the moon: an invitation to COSPAR", *Advances in Space Research*, Volume 22, Issue 3, p. 347-351.

8 LeConte, Z., Gläser, P.C., and Elvis, M., 2023, RAS Techniques & Instruments, submitted.

9 Seager, S., 2010, "Exoplanet Atmospheres: Physical Processes", *Princeton Series in Astrophysics*, 18. ISBN-13: 978-0691146454.

10 D. Deming, S. Seager, J. Winn, et al., 2009, "Discovery and Characterization of Transiting Super Earths Using an All-Sky Transit Survey and Follow-up by the James Webb Space Telescope ", *Publications of the Astronomical Society of the Pacific*, 121:952–967.

11 Schneider, J., Silk, J., and Vakili, F., OWL-Moon in 2050 and beyond, *Phil. Trans. Roy. Soc., A*, 379, Issue 21880187.

2.3. Radio interferometers to Image the Event Horizon of Black Holes

In 2019 the release of the first image of the shadow of a supermassive black hole by the Event Horizon Telescope team made headlines around the world.[12] Impressive as that image of Messier 87 and its Sagittarius A* 2022 successor[13] are, they lack the detail to test precisely both Einstein's General Relativity and theories for how black holes accelerate tight jets of plasma to near light-speed.[14] Moreover, without higher resolution images, we are limited to just these two black holes.

Getting off-Earth is the only path to longer baselines and so higher angular resolution, potentially making dozens, or more, black hole shadows accessible. Even one antenna placed on the Moon would pick out the effects of General Relativity cleanly.[15]

2.4. Gravitational Wave Antennas to see Mergers of Black Holes Throughout the Universe

The dramatic birth of gravitational wave (GW) astrophysics in 2016[16] led directly to strong new tests of General Relativity and the realization that the range of black hole masses is much broader than we knew. Between the few kilometers long Earth-based antennas (LIGO, VIRGO, KAGRA) that cover the 10 Hz to kHz band,[17] and the million kilometer long European LISA instrument planned for the 2030s that will cover the <0.1 Hz band,[18] there is a gap. Building on the pioneering Apollo 17 experiment led by Joe Weber,[19] several teams have realized that the Moon offers a path to bridging that gap.

12 Event Horizon Telescope Collaboration, 2019, "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole", *Astrophysical Journal Letters*, Volume 875, L1.

13 The Event Horizon Telescope Collaboration. 5/12/2022. "First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way." *The Astrophysical Journal Letters*, 930, L12.

14 Punsley, B., and Chen, S., 2021, "Did the Event Horizon Telescope Detect the Base of the Submilliarsecond Tubular Jet in M87?", *The Astrophysical Journal Letters*, Volume 921, Issue 2, id.L38.

15 Johnson, M.D., et al., 2020, "Universal Interferometric Signatures of a Black Hole's Photon Ring", arXiv:1907.04329v2. Johnson, M.D., et al., 2019, "Studying black holes on horizon scales with space-VLBI", Astro2020: Decadal Survey on Astronomy and Astrophysics, APC white papers, no. 235; *Bulletin of the American Astronomical Society*, Vol. 51, Issue 7, id. 23.

16 Abbott, B.P., Abbott, R., Abbott, T.D., et al., 2016, "Observation of Gravitational Waves from a Binary Black Hole Merger", *Physical Review Letters*, Volume 116, Issue 6, id.061102.

17 Abbott, B.P., Abbott, R., Abbott, T.D., et al., 2020, "Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA", Living Reviews in Relativity, Volume 23, Issue 1, article id.3.

18 Amaro-Seoane P., et al., 2017, "Laser interferometer space antenna", arXiv:1702.00786v3.

19 Giganti, J.J., et al., "Lunar surface gravimeter experiment", 1977cpmd.rept.....G.

The concepts fall into two types:[20] those that use the GW-induced motion of the Moon's surface, and those that are isolated from any surface motion. All gravitational wave antennas are exquisitely sensitive to vibrations. The interferometers need a good vacuum, cold temperatures, and low seismic activity: the Moon supplies all three – at present.
The number of sufficiently large PSRs for these detectors is limited.

3. Site Requirements for Astronomy from the Moon

The requirements for each of the astronomical sites for these telescopes are quite specific.

3.1. Farside Radio Telescopes for Cosmology

1. ~200 km baselines to obtain diffraction limit of ~10 arcsec for the 21 cm HI line at high redshifts ($30 < z < 80$). Some eight farside sites are sufficiently large;
2. Slope gradients <~25 degrees on meter scales (set by rover capabilities when deploying the many antennae, e.g., the VIPER rover is designed to work well up to 15 deg, with 25-30 deg. being challenging, but contingently possible [Andrews 2020];
3. Smooth terrain with minimal boulder fields (D>~1 meter) to simplify deployment and minimize the traversed path for a rover, and so the length of cable that needs to be carried;

There are only three sites on the lunar far-side that are both large and appear smooth enough to be a site for the ultimate "Dark Ages" telescope.

3.2. Radio Telescopes for SETI

Heidmann[21] says

> the minimum requirements we need for a future farside site [for SETI are]:
>
> 1. to be in the equatorial lunar region, for all-sky access;
> 2. to be as close as possible to the visible side for logistic and communication reasons;
> 3. to be inside a strongly walled crater to escape any lunar ground RFI;
> 4. large enough to permit the deployment of future radioastronomical paraphernalia.

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20 Harms, J., 2021, "Seismic Background Limitation of Lunar Gravitational-wave Detectors", arXiv:2205.07255.

21 Heidmann, J., 1998, "SETI from the moon: an invitation to COSPAR", *Advances in Space Research*, Volume 22, Issue 3, p. 347-351.

> It happens that these very clear, simple and reasonable criteria lead to a practically unique candidate: the 100 km diameter Saha crater, with a 3000 m high circular rim, at 10 28 E, 28 S.

It would be prudent to search for back-up sites. If there are none, then Saha crater will be a high priority for protection as a SESI.

3.3. Radio Interferometers to Image the Event Horizon of Black Holes

These telescopes work at millimeter and sub-millimeter wavelengths, and so much higher frequencies (~100 – 1000 GHz), where RFI is unimportant, so that a farside location is not required. An antenna in geostationary orbit (GEO), or at the Earth-Moon L1 Lagrange point would also be suitable. A human-tended base would allow servicing more readily than in orbital space. If the lunar surface has suitable infrastructure developed on it, then deploying an antenna there may be simpler and cheaper than at the alternatives.
A Moon-based extension to EHT needs:

1. the ability to view a large fraction of the sky, including both Sgr A* at the Galactic Center (Dec = -29) and M87 (Dec = +12);
2. a direct view of the Earth for high data rate (~100 GB/s) transmission.

Unlike the other lunar telescope concepts, these criteria would be easily met with any roughly equatorial, nearside, location. The wide ~250 C day/night temperature swings[22] may be lessened for the antenna by the use of a radome.

3.4. Large Aperture Far Infrared Telescopes

Telescopes now under construction will have primary mirrors up to ~40 meters in diameter. Building the next generation will be challenging.[23] The 100-meter diameter "Overwhelmingly Large" telescope (OWL) is the largest optical/infrared telescope concept that has been studied for construction on Earth.[24] Wind buffeting limited the maximum diameter, and an impractically large secondary mirror was imposed by the short focal length needed to

22 Williams, J.-P., Greenhagen, B. T., Paige, D. A., Schorghofer, N., Sefton-Nash, E., Hayne, P. O., et al. (2019). "Seasonal polar temperatures on the Moon". *Journal of Geophysical Research: Planets*, 124, 2505. https://doi.org/10.1029/2019JE006028.

23 McPherson, A., Gilmozzi, R. and Spyromilio, J., 2007, "Recent Progress Towards the European Extremely Large Telescope (E-ELT)", The Messenger, 148, 2.

24 Brunetto, E.T., et al., "Progress of ESO's 100-m OWL optical telescope design", Second Backaskog Workshop on Extremely Large Telescopes. Edited by Ardeberg, Arne L.; Andersen, Torben. Proceedings of the SPIE, Volume 5382, pp. 159-168 (2004).

overcome excessive flexing in Earth gravity.[25] On the Moon there is no atmosphere and so no wind, and gravity is ~1/6 of Earth's. These properties make the Moon a promising location of the next generation of bigger telescopes.

A lunar telescope should avoid large temperatures changes to maintain the figure of the mirror, which is possible in the PSRs. Moreover, the low temperatures (T(max) <~50 K) achievable in some of the PSRs near the lunar poles[26] can effectively eliminate the bright infrared background that is unavoidable on Earth (at ~300 K) out to far infrared wavelengths (>~60 microns.) Not all PSRs will be suitable.

The chosen site must also:

1. be accessible to wheeled rovers which requires slopes <25 deg, and preferably <15 deg,[27] or to hoppers or elevators;
2. be in a low dust environment. Hence avoid areas with human activity and, to be forward-looking, PSRs with potential for mining, i.e., water free PSRs;
3. be located at the lowest feasible lunar latitude, to maximize sky coverage; given that the PSRs are in deep craters, the area of sky visible (the "field of regard") may well be restricted;[28]
4. have strong crater walls to carry the load of a suspended dish if that is the chosen design. Weak rims may be common,[29] and regolith near the poles may be looser than at the Apollo sites.[30] Old craters should be more compacted than young ones due to having experienced more impacts.

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25 Maillard, J.-P., 2021, "Is the Moon the future of infrared astronomy?" Philosophical Transactions of the Royal Society A, Volume 379, Issue 2188, article id.20200212.

26 Paige, D.A., et al., 2010, "Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region", *Science*, 330, 479.

27 Cannon, K.M., and Britt, D.T., 2020, "Accessibility Data Set for Large Permanent Cold Traps at the Lunar Poles", *Earth and Space Science*, 7, e2020EA001291. https://doi.org/ 10.1029/2020EA001291

28 E.g., for a field of regard of half angle 30° a telescope at the pole can steer to 1/4 of the sky; this fraction increases to almost 1/3 of the sky at 80° deg latitude, an increase of nearly 30%.

29 Bickell, V.T., and Kring, D., 2020, "Lunar south pole boulders and boulder tracks: Implications for crew and rover traverses", *Icarus*, 348, 113850.

30 Metzger, P.T., Anderson, S., and Colaprete, A., 2018, "Experiments Indicate Regolith is Looser in the Lunar Polar Regions than at the Lunar Landing Sites", *Earth & Space 2018 Conference* (ASCE), eprint: arXiv:1801.05754.

Additionally, for some truly ambitious designs[31] they must:

5. have a crater diameter of ~25 km primary mirror diameter;
6. have a crater depth ~5 km.

3.5. Gravitational Wave Detectors

The requirements for gravitational wave detectors are somewhat distinct from those of the radio and infrared electromagnetic telescopes. Gravitational wave detectors need:

1. a seismically quiet environment or, at a minimum, warning of planned seismic noise generating activities with a significant duty cycle of "quiet time".
2. PSRs for surface-isolated designs (e.g., LION[32]), with:
   a. diameter >~50 km to accommodate an equilateral triangle with 40 km long sides;
   b. thermally stable at cryogenic temperatures (<~50 K);
   c. accessible to rovers or, potentially, hoppers, or elevators;
   d. away from PSRs with valuable resources (primarily water) to avoid future active mining.

There are only three PSRs that are cold and large enough: Shoemaker, Haworth and Faustini craters. Of these, Faustini appears to be relatively water-poor, and Shoemaker particularly water-rich.[33]

4. Mitigation and Limitation of Threats to Lunar Astronomy Sites

Astronomers' first reaction might be to want a ban on all non-scientific activities on the Moon. However, this is neither practicable, nor will it lead to the best astronomy. Construction of these large observatories will not be possible without the infrastructure that will be built for a human presence and for mining. Astronomers will need to work with other stakeholders to implement reasonable standards and to develop policies to make the standards accepted and adhered to.

Potential actions fall into two categories: research and development (R&D) into mitigation, and standards setting for allowable thresholds. Policy will

31 Labeyrie, A., 2021, "Lunar optical interferometry and hypertelescope for direct imaging at high resolution", Philosophical Transactions of the Royal Society A, Volume 379, Issue 2188, article id.20190570.

32 Amaro-Seoane, P., et al., 2021, "LION: laser interferometer on the Moon", *Class. Quantum Grav*. 38 125008.

33 Sanin, A.B., Mitrovanov, I.G., Litvak, M.L., et al., 2017, "Hydrogen distribution in the lunar polar regions", *Icarus*, 283, 20.

then involve setting up mechanisms for coordinating R&D, setting standards, and achieving compliance with technical standards.

4.1 Research and Development Actions

For each of the telescope concepts, specific R&D topics will divide into two types:

4.1.1 Refinement of candidate SESIs

For example:
Ice Favorability Index (IFI) maturation. Refined surveys for “dry” cold traps in PSRs would be valuable as they will not become mining sites. An “Ice Favorability Index” (IFI) is used to prioritize water prospecting sites.[34] The data and theory behind the IFI can be refined.
Traversability studies. Not all promising SESIs may be reachable with rovers,[35] and so may be eliminated from further study.
Sky visibility studies. Not all promising SESIs for crater-based telescopes will have good sky visibility due to high horizon terrain.
A thorough data-based catalog of SESIs and their properties will enable other studies to be optimized.

4.1.2 Mitigation techniques

These will include:
Radio Interference: techniques to suppress side-lobes, harmonics, and electronics noise both in the vicinity of the astronomical site and from orbit; optical (laser) communication as an alternative. Accurate prediction of orbits for temporal mitigation could be developed.
Water mining: Develop techniques to minimize dust, vibration.
Large landers – Investigate ways to manufacture landing pads to eliminate regolith debris ejection. Sites for landing pads may be quite restricted at the high illumination regions (colloquially called the “Peaks of Eternal Light”) near the lunar poles.[36] Investigating their preferred locations and spacing will be essential. Can landers be made movable, without using rockets, to allow others to use the same pad? Are there other ways to reduce regolith debris?
Major Human and Robotic Activity – develop automated systems to alert scientific instruments to imminent activity. Develop wheels and suspension systems that transmit less vibration to the lunar surface.

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34 Cannon, K.M., and Britt, D.T., 2020, “A geologic model for lunar ice deposits at mining scales”, Icarus, 347, 113778.
35 Cannon, K.M., and Britt, D.T., 2020, “Accessibility Data Set for Large Permanent Cold Traps at the Lunar Poles”, Earth and Space Science, Volume 7, Issue 10, article id. e01291.
36 Elvis, M., Milligan, T., and Krolikowski, A., 2016, “The Peaks of Eternal Light: a Near-Term Property Issue on the Moon”, Space Policy, Volume 38, p. 30-38.

4.2 Technical Standards Actions

R&D efforts are useful only if useful site protection standards can be developed and agreed upon.

Specific standards may include:
Radio Interference: As with the ITU allocation of orbital slots and frequencies for satellites in geosynchronous orbit (GEO), allocation of radio transmission frequencies will help. These allocations may include well-defined limits on allowable side-lobes, harmonics, and stray noise from electronics. Both in situ and orbital transmissions will need to be controlled.
Water mining: Establish limits to dust and vibration levels that can be tolerated at the astronomy sites. These will depend on the level of disturbance they pose to the scientific activity. The limits may be temporal. I.e. certain mining activities (e.g. drilling) may only be allowed at certain times. Notifications would be best if provided in advance, e.g., mining machinery operating shifts, vehicle maneuvers. These may be supplemented by real time alerts if unanticipated activities occur. Should some PSRs that are SESIs be declared off-limits to non-science users?
Large landers: Landing pad activities will need an allocation mechanism for their use, including landing times and time spent on each pad (rather like gates and time slots at airports).[37]
Major Human and Robotic Activity: Advance notification could prevent damage to delicate instruments; after-the-fact notification could allow identification and editing out of lunar created noisy data. Limits to vibration measured at the astronomical sites may be needed.
It would be helpful if organizations developing technical standards work in coordination with the International Astronomical Union (IAU) Centre for the Protection of the Dark and Quiet Sky[38] (CPS), hosted at the NSF's National Optical-Infrared Research Laboratory (NOIRLab)[39] to establish well-vetted technical standards that would protect these lunar sites.

4.3 Policy Standards Approaches

Treaties establishing appropriate standards of behavior that include all active lunar players appear to be a remote possibility, given the geopolitical situation, at least on the roughly decade timescale on which action is first needed. The 1967 Outer Space Treaty[40] has wording that could form the

37 Montes, J., Schingler, J.K., and Metzger, P., 2020, "Pad for Humanity: Lunar Spaceports as Critical Shared Infrastructure", ASCE Earth & Space 2020. https://www.openlunar.org/library/pad-for-humanity.
38 https://cps.iau.org.
39 https://noirlab.edu/public/.
40 Formally the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies". (http://www.unoosa.org/oosa/SpaceLaw/outerspt.html, accessed 2022 July 18).

basis for further elaboration that may include the protection of scientific sites on the Moon (OST Article IX[41]). On the other hand, restricting access to others is not allowed by the OST, so long as "reasonable advance notice" is given (OST Article XII[42]). The ITU[43] Radio Regulations are an applicable treaty with the US as signatory, and they include protection of lunar radio-quiet zones.

There do exist laws that govern resolution of certain disputes in space – though they are more focused on Earth and its orbit. As such, we have a foundation for addressing and resolving conflicting uses of resources through adoption of "customary laws" applicable to signatories. Recently, tentative arguments have been advanced toward explicitly expanding this approach to establish a lunar "customary law" regime.[44]

Although the United States is not a party to the Moon Agreement (because of specific language not relevant here), the Moon Agreement nonetheless contains useful conceptual language to apply for purposes of protecting sites of the Moon, including lunar orbits, within this protection (see Art. I, § 2). More importantly, the United States' efforts to protect certain aspects of the Moon for scientific research would be consistent with the much more recent United Nations Long-Term Sustainability of Outer Space Activities guidelines.[45]

One approach would be for the United States-led Artemis Accords[46] to be interpreted to cover protection of SESIs. At present "Section 10 – Space

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41 OST Article IX: "*A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the moon and other celestial bodies, would cause potentially **harmful interference** with activities in the peaceful exploration and use of outer space, including the moon and other celestial bodies, may request consultation concerning the activity or experiment. (Emphasis added)*.

42 OST Article XII: "*All stations, installations, equipment and space vehicles on the moon and other celestial bodies **shall be open** to representatives of other States Parties to the Treaty on a basis of reciprocity. Such representatives shall give reasonable advance notice of a projected visit, in order that appropriate consultations may be held and that maximum precautions may be taken to assure safety and to avoid interference with normal operations in the facility to be visited." (Emphasis added)*.

43 United Nations International Telecommunication Union. https://www.itu.int (Accessed 18 July 2022).

44 Johnson-Freese, J., and Weeden, B., "Application of Ostrom's Principles for Sustainable Governance of Common-Pool Resources to Near-Earth Orbit," *Global Policy*, vol. 3, no. 1, pp. 72–81, Feb. 2012.

45 https://www.unoosa.org/oosa/en/ourwork/topics/long-term-sustainability-of-outer-space-activities.html [accessed 15 September 2022].

46 The Artemis Accords: Principles For Cooperation In The Civil Exploration And Use Of The Moon, Mars, Comets, And Asteroids For Peaceful Purposes https://www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf [accessed 29 September 2022].

Resources" appears to consider as a resource only material. A resource can also include locations. The "Peaks of Eternal Light" are an example, with the high solar illumination there being the value. SESIs are also resources, with their enabling of astronomy being the value. Similarly, "Section 11 – Deconfliction of Space Activities" notes in paragraph 11 that "[t]he Signatories commit to use safety zones ... *in a manner that encourages scientific discovery*" (emphasis added). The Artemis Accords could then be used to develop community standards. The Artemis Accords do not, however, include important State Parties, notably China and Russia.

Singam[47] suggests an alternative approach of extending the Liability Convention[48] when considering biological planetary protection. Gathering scientific data from a site could be argued to create property in the Lockean sense of improving the value of the land. Loss of the ability to gather this data would then be an infringement of property rights and could fall within the Liability Convention's "damage to property" for which the "launching state" is liable (Article I)[49] This approach may not seem to allow making use of this interpretation prior to any actual scientific activity on a site. If the damage is reversible, as it is in principle in the case of astronomy, then the damage will be more difficult to assess. Singam suggests that introducing the concept of "material risk" from actions would be sufficient to counter this objection.

Some form of authority that licenses lunar activities will be needed. This may well be more like the ITU than any more general "lunar government"; indeed a heavier regulatory regime may encourage violations and defections.

5. Conclusions

The great promise of locations on the Moon for deploying breakthrough astronomical telescopes is becoming clear. At the same time astronomers are realizing that the specific sites of extraordinary scientific importance (SESIs) for these telescopes are surprisingly few and that the special properties of these rare sites are easily disrupted. SESIs will be threatened by sustained

47 Singam, C. A. K. (2022). Ethical and legal considerations in preventing the contamination of space (IAC-22-E7,3,1,x73386). In *Proceedings of the 73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022*. International Astronautical Federation.

48 2777 (XXVI). Convention on International Liability for Damage Caused by Space Objects. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/liability-convention.html.

49 "Article I. For the purposes of this Convention: (a) The term "damage" means loss of life, personal injury or other impairment of health; or loss of or damage to property of States or of persons, natural or juridical, or property of international intergovernmental organizations; (b) The term "launching" includes attempted launching; (c) The term "launching State" means: (i) A State which launches or procures the launching of a space object; (ii) A State from whose territory or facility a space object is launched."

human activity on the Moon including mining. The threats to the SESIs are both in situ and orbital.

Fortunately, there are prudent steps we can take to mitigate, or eliminate, many and perhaps all these threats to SESIs. A dual-pronged approach is needed, encompassing both research and development of solutions, and agreement on technical standards that can enable these solutions to be implemented. Policy approaches that can create agreement and compliance with these standards will be needed.

Astronomy is only one example of science that is enabled by the Moon. Other fields include[50] solar system formation, lunar origin and structure, exoplanet geophysics, astrobiology, earth science, and heliophysics. Similar surveys of sites for other scientific uses of the Moon, should be made. A unified database of all the resulting sites would be a valuable tool for protecting the sites of extraordinary scientific interest on the Moon.

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50 Kring, D.A., and Durda, D.D. (eds), 2012, “A Global Lunar Landing Site Study to Provide the Scientific Context for Exploration of the Moon”, LPI Contribution No. 1694, LPI-JSC Center for Lunar Science and Exploration, A Member of the NASA Lunar Science Institute.