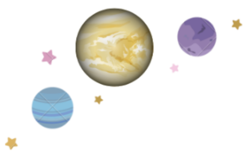
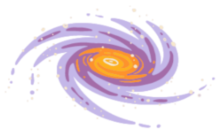
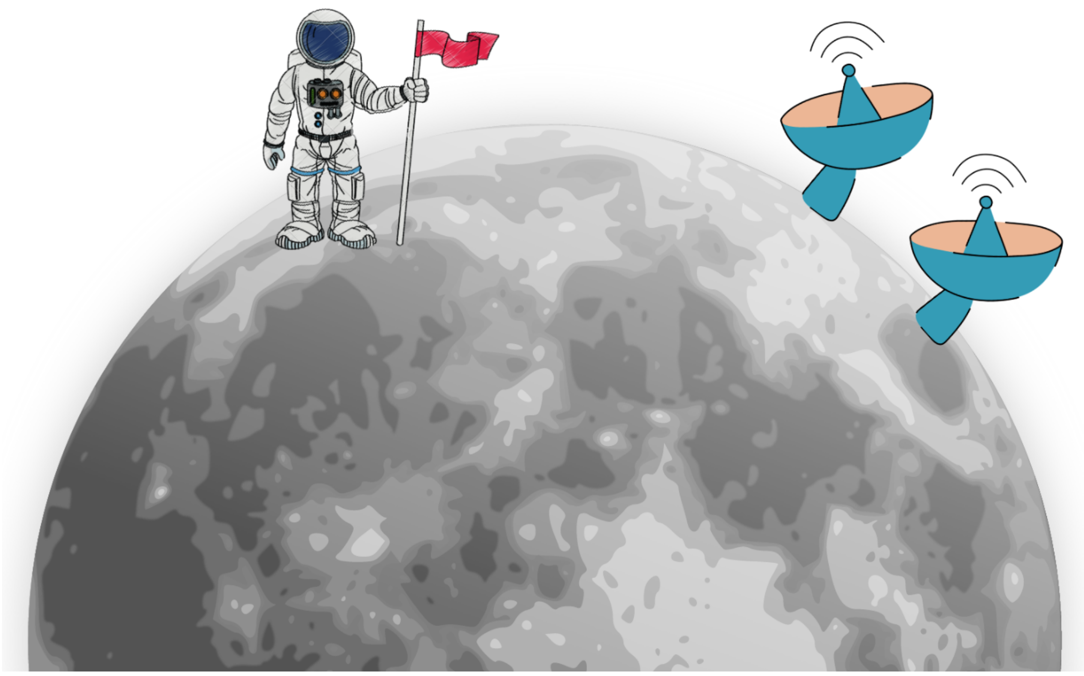




ASTRONOMY FROM THE MOON

...seeks a new lunar policy



Lorena Nicotera, University of Groningen, MSc Astronomy

International Astronomical Union

Executive summary

The Moon is a unique site for a variety of astronomical observations enabled by the rare characteristics of individual sites. For example, the farside of the Moon is shielded from radio interference by radio sources on Earth and in Earth's orbits. Being a radio quiet environment, it represents the perfect location to perform low frequency radio observations that could lead to the detection of the very faint atomic hydrogen signal belonging to the "Dark Ages", before stars and galaxies formed. This is of extraordinary importance for cosmology and fundamental physics research. However, science experiments require extremely sensitive instrumentation so that electronic\noise leakage from other sources could severely limit the scientific value of the farside. Meanwhile, the presence of water and minerals on the Moon has attracted commercial attention and enlarged the number of players interested in outer space raw materials. Space agencies and private companies are currently refining their plans for a long term return to the Moon over the next decades. The lunar sites with extraordinary scientific value often overlap with those that have the most concentrated valuable resources. Their extraction requires intense mining activities with harmful impact on the neighboring environment. Astrophysical observations from the Moon and extraction-oriented operations have great potential to conflict with one another. This is where the International Astronomical Union (IAU) comes into play, demonstrating that good astronomical sites are rare, no matter where they are located, so the rare ones on the Moon should be protected by a dedicated international policy. The purpose of this project is to analyze the current outer space legal and policy framework to clarify the modalities allowed for modern operations on the Moon. A particular focus is on the opportunities and threats carried by the US-led Artemis Programs. On the one hand, their international partnerships with technologically advanced private companies can facilitate the delivery of scientific experiments on the Moon. But on the other hand, they have introduced a controversial way to interpret the principles written in the Outer Space Treaty, the international outer space constitution. The main finding of this analysis is that the international outer space law does not include any provision that explicitly protects lunar locations for their scientific potential; therefore, astronomers should urgently act to defend their objectives on the Moon. I advise the IAU to take a leading position in raising a decisive awareness for the needed preservation of high valuable lunar sites for science. For example by considering the possibility of creating an ad hoc working group for lunar matters. The IAU should be the place for collecting consensus among the astronomical community on the list of lunar sites with priority for protection in the near and long term. Moreover, the IAU should create agreement on the technical requirements for all operational instruments, as an aggregate, not to interfere with the target signal of the sensitive experiments. It would be appropriate for the IAU to set up an interface with commercial industry and space agencies and talk to them on behalf of science to make sure their plans are aware of the scientific issues. Then, the IAU should align with other professional scientific societies to approach the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) to get consideration of the protection of astronomy from the Moon by the Committee.

Acknowledgements

I am deeply grateful to my supervisors, Dr. Richard Green and Dr. Martin Elvis, for giving me the opportunity to work on this challenging and captivating project. Their expert guidance and their invaluable advice have inspired me throughout this study.

I would also like to thank my SBP supervisor, Dr. Marlies Westerhof, for encouraging me and providing valuable suggestions and feedback.

I express my sincere appreciation to my scientific supervisor, Dr. Jake Noel-Storr, who has supported me all along.

I also want to thank all the people who contributed to the realization of this project giving much appreciated insights.

A special thanks to Saul G. who has always believed in me and encouraged my perspective.

Table of contents

Chapter 1: Introduction

In this chapter, I define the project framework, outline its scope, characterize the company profile, its internal structure and the context wherein it is actively involved. Then I pose the main questions that have driven the whole project and explain my approach in addressing them to finally come up with useful recommendations and a strategy implementation.

1.1 Project framework

This internship is undertaken in the context of the specialization Science, Business & Policy of the master's degree program in Astronomy, University of Groningen.

The main purpose of this internship is to integrate policy aspects with scientific based knowledge in a way to achieve around 30% of science research and a remaining 70% of policy tasks.

The final product will be an advice to the International Astronomical Union to what regulations they need to ask for the protection of the most valuable lunar sites for scientific experiments.

The internship took place in the period between 09/01/2023 to 30/06/2023 for a total of 24 weeks, in collaboration with:

Name	Institute	Function	Role in supervision
Dr. Richard Green	Steward Observatory University of Arizona	Astronomer & Assistant Director for Government Relations	Daily supervisor
Dr. Martin Elvis	Center for Astrophysics | Harvard & Smithsonian	Senior Astrophysicist	Daily supervisor
Dr. Jake Noel-Storr	University of Groningen	Astronomy Lecturer	Science supervisor
Dr. M. D. D. Westerhof	University of Groningen	Lecturer	SBP supervisor
MSc. Saskia Grooters	University of Groningen	Lecturer	SBP supervisor

1.2 International Astronomical Union

Founded in 1919, the International Astronomical Union (IAU)[1] is an organization that connects together professional astronomers worldwide, at a PhD level and beyond, to create international collaborations and advance scientific research. At present, it counts 12,784 members, including junior memberships. The IAU is a place for exchanging ideas, sharing knowledge and promoting astronomy as a tool for global development and innovation. To fulfill its mission, the IAU programs periodic meetings, assemblies and symposia to discuss the present and future prospects of astronomy. It also coordinates international outreach campaigns with the direct involvement of amateur astronomers and the general public as an opportunity to spread astronomical education and prepare the next generation of scientists.
A key goal of the IAU is the safeguarding of astronomical sites and hence it is actively engaged with policy makers who are committed to astronomical matters. In this context, the IAU is directly linked with the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) as an official observer organization.

The IAU is organized into different Working Groups, Divisions and Commissions. A comprehensive list of these is provided in Appendix A. The three major areas of action are: the advancement of astronomical knowledge, education and communication, and using astronomy for development. These three main activities and their individual scopes are summarized in the schema in Figure 1, below.

Advance Astronomy

Facilitation of sharing astronomical knowledge

Coordination of professional tasks and interactions with other fields at the professional level

Safeguard the science of astronomy in terms of dark and quiet skies, astronomical standards, etc.

Interface with other scientific unions, neighbouring fields, industry, culture and society

Hosting informal discussions on the future international large-scale facilities

Astronomy as a tool for Development

Stimulation of scientific, technological and cultural development through the use of astronomy

Fostering inclusiveness in the advancement of astronomy

Promotion of astronomical contribution to UN Sustainable Development Goals (SDGs)

Establishment of interdisciplinary partnerships around science for development

Education / campaigns

Training young astronomers at university level

Engagement with the public through astronomical events

Providing open databases and public-friendly access to astronomical information

Coordination of awareness campaigns (i.e. for the protection of dark and quiet skies)

Use of astronomy to stimulate teaching and education at school level

Figure 1. List of the main activities of the IAU per individual objective.

[1] www.iau.org

At the very beginning of its operation, the IAU was mainly focused on scientific activities; however, with time, it has acquired a more multidisciplinary character with enlarged connections with science, industries and society. It has also activated a strategic plan to further expand its portfolio and its impact on global development.

The IAU is currently active on several policy fronts, especially to address the issue of satellite constellations in low Earth orbits (LEO), that have the potential to severely impact astronomical observations. The mission of the IAU CPS[2] (i.e. the “IAU Centre for the protection of the dark and quiet sky from satellite constellation interference”) is to work towards mitigation measures to minimize the impact of large satellite constellations on astronomy and on the night sky.

Good astronomical sites are rare, no matter where they are located, so protecting the very special ones on the Moon is an appropriate scope for the IAU, as it requires international policy. The IAU should be looking at the possibility of creating an ad hoc working group for lunar astronomical matters. In particular, the IAU is now seeking to raise a decisive awareness on the needed protection of astronomy from the Moon to the competent authorities, so as to help stimulate the activation of a protection protocol. In this context, the large size and influence of the IAU is likely to play a significant role. I summarize in the list below the distinctive resources of the IAU and I rate them as high H, medium M or low L, according to their relevance in the context of taking lunar astronomy issues to the next level:

★ Large dimension	H		
★ Collaborations with scientists worldwide	H		
★ High science profile of members	H		
★ Interdisciplinary partnerships	H		
★ Long time experience in policy matters	H		
★ Connections with commercial industries	H		
★ Direct communication with the UN COPUOS	H		
★ Plans to expand its portfolio	H		
★ Sustainable purposes		M	
★ Interface with society			L

[2] cps.iau.org

1.2.1 Commission for protection of existing and future observatory sites

The IAU *Commission for protection of existing and future observatory sites*[3], hereafter referred to as Commission B7 (as in the IAU structure, Appendix A), actively works to control the harmful impact of light pollution on existing and potential astronomical sites. Its key science objective is to defend important dark sky sites worldwide, including professional observatories (Hawaii, continental Spain, the Canary Islands, North America, South Africa, Chile & Australia).

Therefore, in the view of expanding IAU portfolio, the activities aimed at the protection of scientifically valuable lunar sites fall naturally in Commission B7, as a coherent extension of its mission.

1.3 Project scope

Several astrophysical objectives could benefit from the environmental characteristics offered by some unique locations of the lunar farside and the lunar poles, considered as sites with extraordinary scientific importance (SESIs). In particular, very sensitive experiments in the context of cosmology cannot be made elsewhere on Earth, due to human made radio interference (RFI) and the allocation of radio frequencies to services other than astronomy.

However, the current radio quietness of the lunar farside SESIs is threatened by the future commercial missions on the Moon, driven by the value, and possible profitability, of lunar resources in the long-term lunar exploration plan. In fact, the advanced technology and expertise of humankind, in combination with the very ambitious aspirations, have made space travel significantly easier and going to the Moon is likely to become economically and technically feasible for several purposes. This will result in overcrowding the outer space landscape and producing destructive interference among conflicting activities in the next decades. Consequently, this calls for an urgent intervention of the astronomical community to defend their golden opportunities of doing astrophysics from the Moon.

The ultimate purpose of this internship is to come up with some useful advice for the IAU on the course of actions they should soon pursue to ask for a new policy that protects the most valuable SESIs from the harmful effects of commercial operations and preserve them for scientific research with potential unprecedented outcomes.

The main points addressed in the analysis presented in this report can be summarized into the following seven research questions:

Science

- Why do astronomers want to do observations from the Moon?
- What are the threats to scientific experiments on the Moon?
- What are the technical requirements for the mitigation of radio interference?

[3]https://www.iau.org/science/scientific_bodies/commissions/B7/

Policy/Legal

- What are existing policies upon the use of lunar space?
- What are the different interpretations of the current regulations covering the access to lunar resources? And what are the implications of the different interpretations of the laws?
- What actions will astronomers need to take to preserve the most valuable SESIs from the harmful interference of commercial and other governmental activities?
- How are decisions being made in an international context? Who has the greatest influence?

The end product would be useful material to guide the IAU into an astronomy negotiating position and urge the UN COPUOS to consider the issue of the lunar astronomical science protection.

1.4 Methodology

For the purpose of this project, I will perform first a scientific and later a policy analysis in multiple steps and with individual outcomes.

Scientific background ($\sim 30\ \%$)

I will start with a literature review of the main lunar features to map the most valuable and resource rich lunar sites. In parallel, I will research the advantages of putting telescopes on the Moon to tackle some of the major astrophysical questions, and thus I will survey the most promising and interesting missions planned to be brought to the Moon in the next decades.

I had the golden opportunity to participate in the conference about the future prospects of astronomy from the Moon at the Royal Society, in London, of which my supervisor was one of the organizers. There I met and talked with influential people in the lunar scientific and policy framework that provided me with very useful information.

Among the different possible observations that could benefit from the lunar environment, low frequency radio experiments are the ones with the clearest potential to bring a real breakthrough in our knowledge of the early cosmic epochs. Therefore, I decided to put my focus on this specific science objective, which is also the most widely investigated. In addition, I attended some meetings with researchers at the Kapteyn Institute, University of Groningen, to collect more information on the current status of a lunar project they have been working on (Astronomical Lunar Observatory - ALO).

To conclude my scientific analysis I will make a list of the most valuable lunar sites (especially) for cosmology research, indicating a priority flag connected with the necessity to protect them from alternative commercial uses. To provide some visual references, I will produce images of lunar locations using the available data products of the Camera (LROC) that has been orbiting the Moon onboard the Lunar Reconnaissance Orbiter (LRO) since 2009.

Policy context ($\sim 70\ \%$)

First of all I will investigate, through literature review, the international legislation that currently governs the use of outer space. I will focus on recognising the conflicting and shared points of the different sets of provisions and identifying eventual principles that could refer to the protection of scientific objectives on other utilizations.
Afterwards, I will analyze the diverse national interests in commercial operations on the lunar surface and in lunar orbits, threats to sensitive science experiments. Therefore, I will perform an actor analysis in the domain of lunar exploration and resource exploitation and an internal analysis of the IAU to place its scope in the overall scenario.

My supervisor introduced me to some members of the International Academy of Astronautics (IAA) that had recently created a committee devoted to the protection of the lunar farside. I attended the first meeting of this international committee, where I learned about the interdisciplinary efforts of science, technical, legal and policy communities to address the serious issue of a necessary new governance for lunar activities.

In the end phase I will integrate science and policy outcomes to profile my final advice.

Chapter 2: The Moon

In this chapter I provide some useful information about the distinctive structures of the lunar surface and I summarize the most important lunar resources as well as their different applications. I explain that lunar resources are either tangible elements with strategic multi-use value or, especially for science, optimal environmental characteristics that offer the opportunities to push the limits of our understanding in specific fields, including astrophysics.

2.1 Overview

To give some historical context, lunar studies have for a long time been limited to observations from Earth, orbiting spacecrafts or lunar landers. But on July 20, 1969 humans were able to close that distance with the American Space Mission Apollo 11[4] (of the National Aeronautics and Space Administration - NASA) and for the very first time in history, humans could walk on another "world" (Figure 2). In a total of six missions (Apollo 11- 12- 14- 15- 16- 17) landed in different sites of the lunar nearside (Nunn et al., 2020), the Apollo program collected hundreds of kilograms of lunar material that represent the basis of our physical and historical knowledge of our natural satellite. The age of the Moon, its temperature, the geological processes and its chemical enrichment were all derived from the lunar rocks collected in those first landing sites. And they still keep revealing new useful information[5]. The Apollo missions enabled not only scientific breakthroughs, but they were also politically and socially meaningful. They demonstrated the capabilities of humankind to break barriers and they opened up the idea that technology can shorten distances and govern the unknown.

The Moon is the brightest and the most noticeable object in the night sky, our closest celestial body and Earth's natural satellite. The unique characteristic of the Moon is that it rotates once around its axis in exactly the same time it orbits around the Earth, every 28 days. This phenomenon is known as synchronous rotation, a natural consequence of the tidal locking induced by the gravitational attraction of the Earth on the Moon. And this results in the same side of the Moon to be always facing the Earth, the lunar nearside[6].

One of the greatest mysteries has always been "what the hidden face of the Moon would look like". Human progress has made giant steps forward and modern satellites allowed astronomers to map the farside of the Moon, (e.g. LRO, 2009 - present), showing that it is quite different from the nearside. At present, there is even a Chinese mission, Chang'e 4, operational at the Aitken Basin, one of the largest craters on the farside, where it landed in 2019, and was the very first in history to do so (Jingye Yan et al., 2023)

[4]www.nasa.gov/specials/apollo50th/missions
[5]https://www.ornl.gov/news/50-years-after-nasas-apollo-mission-moon-rocks-still-have-secrets-reveal
[6]https://moon.nasa.gov/moon-in-motion/earth-and-tides/tidal-locking/

The lunar farside is a “radio quiet” environment as it is shielded from human made radio signals including TV, airplanes and all different kinds of telecommunications by 80 dB[7] (i.e. 100 million-fold); therefore, it offers the perfect view on the most faint radio signals of the universe, dating backward to its origins. Further curiosity comes from the fact that the near- and the far-sides of the Moon appear very different from one another, both on a visual and a geochemical basis.

Figure 2: One of the first steps on the Moon, from the Apollo 11 mission. *Image Credit: NASA*

2.2 Structures on the lunar surface

For some reference scaling, the Moon has a mass that accounts for $1/81$ and a radius of approximately $1/4$ of those of Earth, respectively. Thus, lunar gravity is $1/6$ that of the Earth. As a result the Moon has a very tenuous atmosphere, insufficient to shield its surface from bombardments by asteroids or to mitigate the impact of the solar wind (Benna et al., 2015). This is crucial for its geological and mineral composition. The frequent collisions of external bodies - asteroids and comets - has cratered the lunar surface in its evolution and covered its top layer with an unconsolidated mixture of powdery dust and pieces of rock that together form the lunar regolith (Lucey et al., 2006). The regolith is $\sim\ 20\,m$ thick (McKay et al., 1991) and its finest ($sub\ -\ cm\,size$) fraction is called lunar soil.

[7]dB: the decibel logarithmic scale is widely used to measure signal ratios.

Furthermore, meteoroids hitting the lunar surface, in combination with the tidal stresses caused by the gravitational pull of the Earth, result in moonquakes (Watters et al., 2019), analogous to terrestrial earthquakes. During the Apollo missions, five seismometers were placed in different lunar sites, and they recorded a seismic energy about 80 times weaker than that on Earth (Albee A.L., 2003).

Some of the largest topographic features on the lunar surface are the lunar maria (“seas'') that are named after their ocean-like appearance. They are vast and flat solidified basaltic lava flows, products of a past intense volcanic activity that occurred on the Moon for billions of years (Haskin and Warren, 1991), due to the concentrations of radioactive elements (thorium Th and uranium U).

The dominant chemical materials of mare basalts are magnesium (Mg), iron (Fe) and titanium (Ti), with a very low fraction of calcium (Ca) and aluminum (Al) (Crawford I.A., 2015). Lunar maria fill up huge basins (from $700\ to\ 3000\ km$ diameter) that formed some billion years ago during a period of major bombardment by asteroid-sized bodies (Buratti B.J., 2002). Maria reside especially on the lunar nearside (Figure 3) and they are clearly distinguishable by the naked eye as they appear circular, some of them also interconnected, darker and less elevated than other regions (hence called *lowlands*). Conversely, the remaining areas are the light-coloured *highlands*, considered as the original crust of the Moon and that have been characterized as rich in Ca, Al, silicon (Si) and oxygen (O), while relatively poor in Mg and Fe (Crawford I.A., 2015). Some lunar maria coincide with “lunar mascons”, that are high mass concentrations, resulting in much stronger gravitational fields than the rest of the lunar crust. These positive gravitational anomalies may have originated from denser deposits of lava material in craters or rather due to some iron-rich concentrations (Bell T.E., 2006). Their main impact is that mascons cause most low lunar orbits to be unstable (Konopliv A.S. et al., 2001). Accordingly, the number of stable lunar orbits is very small and they occur at four specific inclinations: 27º, 50º, 76º, and 86º, usually referred to as “frozen lunar orbits”, where spacecraft can stay indefinitely (Bell T.E., 2006). It might also happen that satellites, for specific operational reasons, need to orbit at unstable orbital inclinations, in this case frequent orbital corrections are necessary.

Distinctive features of the lunar landscape are combinations of mountains and craters. The latter are round depressions present almost everywhere on the lunar surface and forged by the crashing of massive bodies. These are especially numerous on the lunar farside and the ones with the greatest concentrations of valuable resources are especially those of the lunar south pole (Figure 4). As the axis of the Moon is closely (1.5 deg) perpendicular to the direction of the solar illumination, some of these craters reside in permanently shadowed regions (PSRs), that are never directly illuminated by the Sun. Their floors have been dark for over billions years and are extremely cold, $T < 50\ Kelvin\ (K)$ (Crawford I.A., 2015). Crater sizes can reach up to a few tens to a few hundred km.

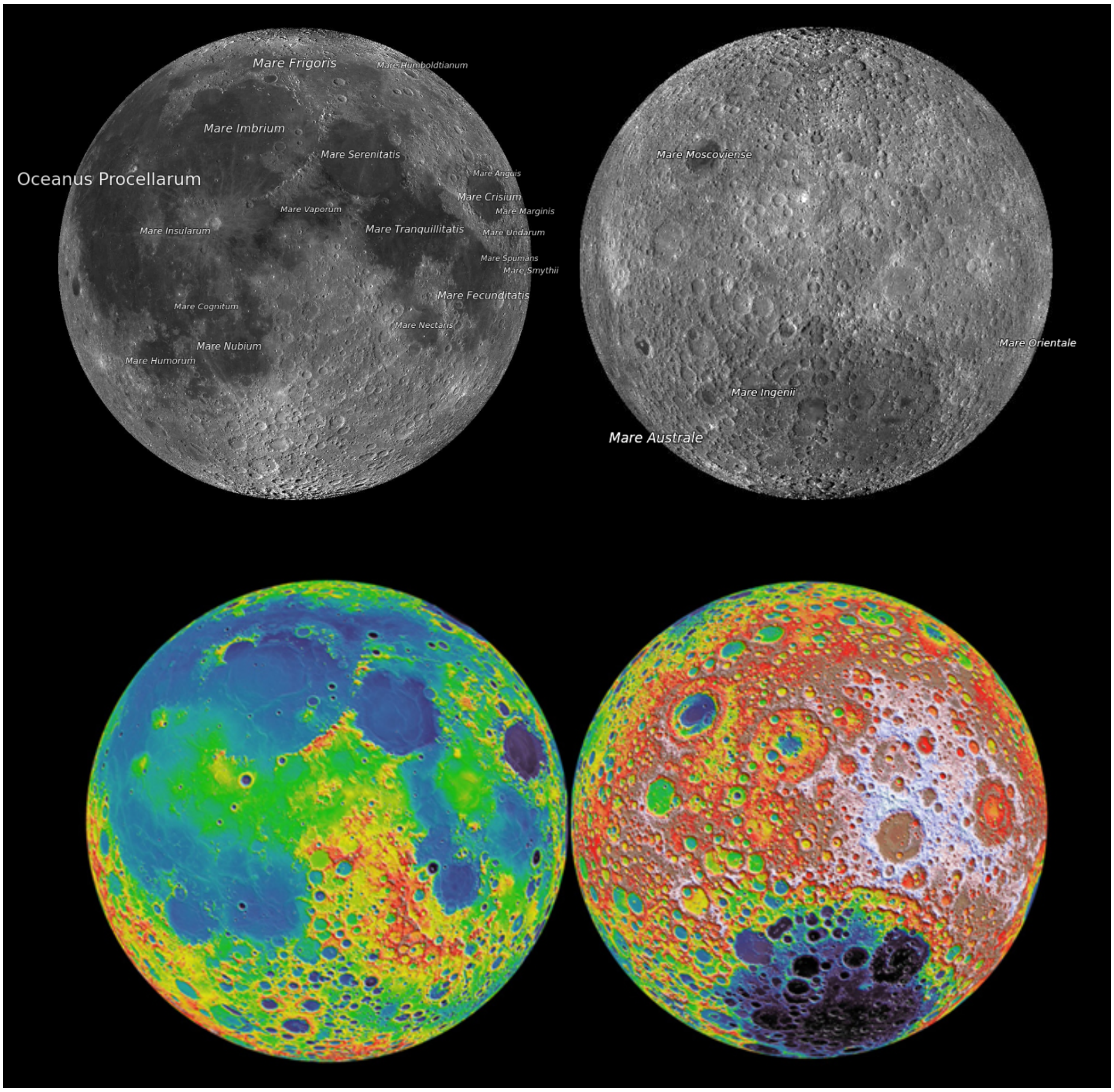


Figure 3: Top maps. View of the nearside and the farrside of the Moon from the left to the right respectively. I produced these images using the Lunar Reconnaissance Orbiter Camera, LROC WAC Mosaic + NAC data products (quickmap.lroc.asu.edu)[8]. The overplotted nomenclature indicate the locations of lunar maria; Oceanus Procellarum is so called for its very big size (more than $2500\ km$ diameter) compared to the other maria. Bottom maps. Topography of the nearside (left) and farside (right) of the Moon. The white and red colors represent high terrains while the blue and purple are low terrains. Image credit: NASA/GSFC/MIT/LOLA.

[8]https://quickmap.lroc.asu.edu/layers?extent=90%2C-22.7823941%2C270%2C35.1257609&id=lroc&showTerrain=true&queryFeature=0&queryOpts=N4IgLghgRiBcIBMKRAXyA&layers=NrBsFYBoAZIRnpEoAsiEIHYFcA2vIBvAXwF1Siylw4pZYEQBmOOJ9GAOgE40d9K5QaSA&proj

2.3 Lunar resources

The Moon is a treasure trove of science; it offers optimal locations to make important discoveries about the history of the universe, as well as resources, like water ice (Shuai Li et al., 2018) and minerals upon which modern lunar industries can start.

2.3.1 Lunar raw materials

The information provided by numerous remote sensing missions on the lunar surface (Crawford I.A., 2015), in combination with Apollo and Luna missions around 40 years ago (Heiken et al., 1991; Jolliff et al., 2006), revealed that the Moon is naturally provided with valuable raw materials, not uniformly distributed across the whole area and with the potential for different uses. The main application for such lunar resources is the "In Situ Resource Utilization" (ISRU), that would facilitate long-lunar exploration as well as support future missions in deep space (i.e. onto Mars). And this would surely benefit either scientific experiments or commercial activities on the lunar surface and in cis-lunar[9] space. Eventually, lunar resources could be directly brought to the Earth's surface and contribute to its global economy, but this scenario is conceived for specific elements only.

The most important among the lunar materials that are suitable for ISRU is water, available on the Moon in different forms and shapes. Whether it originates from the Moon itself or from external sources is still an open question that raises interdisciplinary scientific interests. Water is present as water ice in the cold PSR craters at the lunar poles (Feldman et al., 1998). Furthermore, lunar soil is enriched with volatiles, materials that the solar wind deposits on the lunar surface as a consequence of its lack of an atmosphere, albeit at low concentrations. Volatiles include hydrogen (H), helium (He), carbon (C), nitrogen (N) and more, which can be used for ISRU activities. Water may also form when hydrogen from the solar wind combines with the oxygen extensively present in lunar regolith (Pieters et al., 2009). Water is undoubtedly a critical resource for supporting human life, but it is also extremely valuable to create rocket fuel out of its hydrogen or oxygen components. The data provided by the instruments onboard LRO has revealed a low to medium concentration of ice blocks in PSRs ($1 - 10$ wt %[10]), whereas larger quantities (up to 30 wt % deposits) are those of granular solid ice mixed in with regolith in PSRs (Shuai Li et al., 2018). The most efficient techniques to extract water from the lunar soil are currently under investigation and they are crucial to really define the long term lunar presence.

The surface of the Moon also contains heavy elements like Fe, that comes from the impact of asteroids, or Mg, Al, Si and Ti. These are very useful raw materials to facilitate the building and maintenance of structural components or entire facilities in Earth's orbit, such as solar power cells. These elements require a lot of energy to be launched from the Earth's surface to the orbits, so there is a major energy saving in taking them from the Moon ("Commercial space

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[9]Vicinity of both Earth and Moon

[10]Weight %, Wt % = (mass of solute/mass of solution) x 100%

mining: Economic and legal implications" - Vidya Sagar Reddy Avuthu). This represents a key opportunity that has encouraged many companies worldwide to consider extracting and using lunar resources to support operations in Earth orbits.

The Moon also possesses reservoirs of Th and U (Lawrence D.J. et al., 2000), that could serve as radioactive fuel for space-based activities.

The case of the isotope Helium - 3, that the solar wind deposits into the lunar soil, is different from other elements. It is seen as a potential fuel for nuclear fusion reactors therefore, economically valuable to be imported to the Earth's surface (Elvis M., Krolikowski A. & Milligan T., 2021). It is available in small quantities in the lunar maria and more highly concentrated in a few regions including craters Grimaldi and Riccioli, Mare Moscoviensis, the southern-western part of Oceanus Procellarum, the northern-western part of Mare Tranquillitatis, and the northern-eastern part of Mare Fecundidatis (Kim K.J. et al., 2019). However, its concentration on the Moon stays still relatively low (Crawford I.A., 2015), and it would require continuous extraction activities to be possibly sufficient to meet the Earth's energy needs, assuming its efficiency in the reaction is confirmed.

Other potential elements worthy of consideration to introduce to the Earth are platinum group materials as well as rare-Earth elements, mostly concentrated in the KREEP (potassium K, rare Earth elements REE and phosphorus P) zone of the Oceanus Procellarum (Jolliff B.L. et al., 2000). These are called rare-Earth elements not because they are not available on Earth but as their terrestrial extraction is environmentally costly. Nowadays, their importance for technology, in particular for semiconductors, gives REEs a crucial value (Crawford I.A., 2015) and drives a rising desire for consistent supplies that might come from the Moon in the near future.

Surely our knowledge of the lunar environment is still incomplete and further exploration could reveal the presence of other natural resources on the Moon, with the potential to support human operations and benefit the global economy.

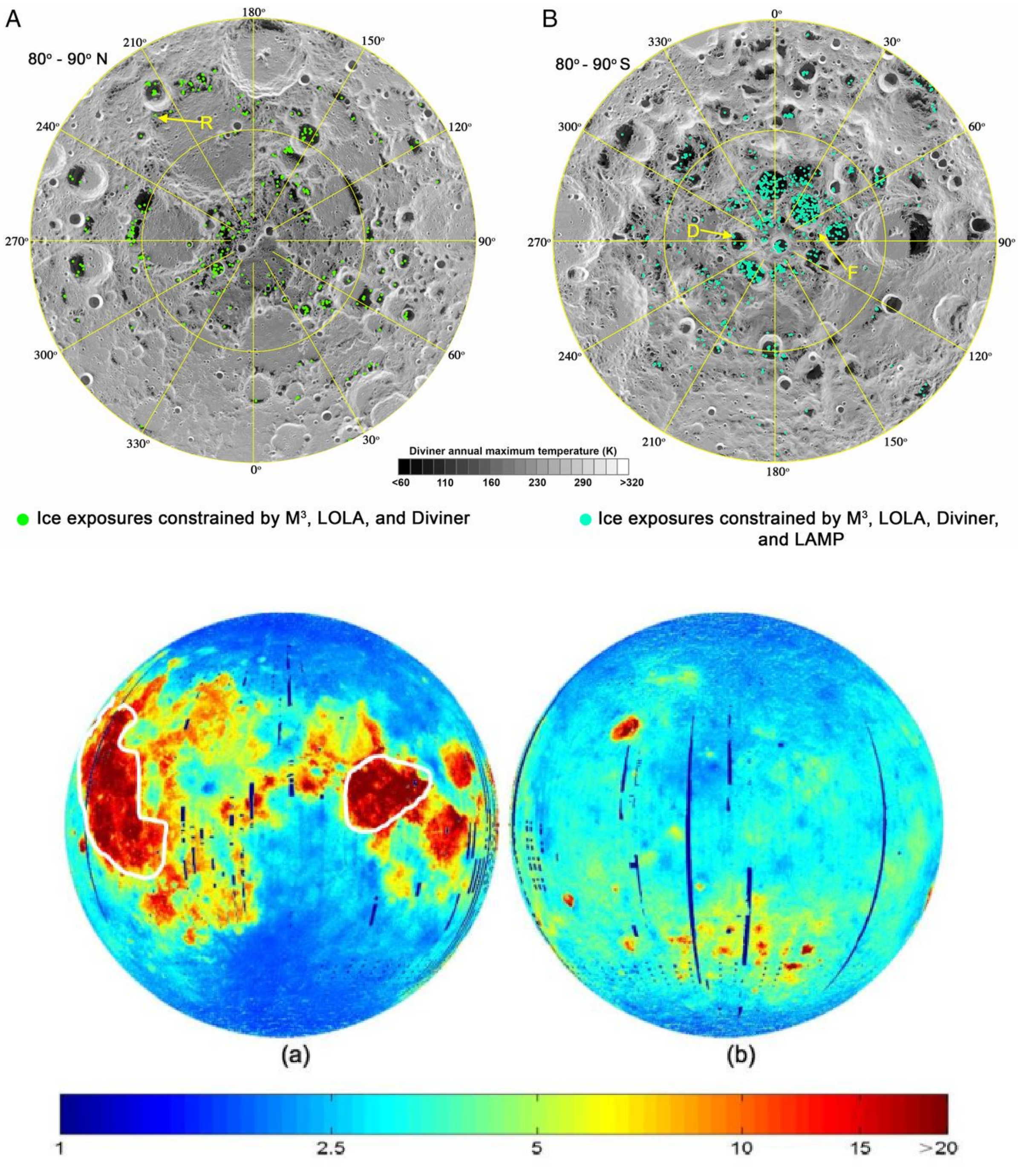

Figure 4. Top panel: Maps of the lunar poles made with LRO Diviner + LAMP +LOLA data. The green and cyan dots indicate the distribution of water-ice in the northern- and southern polar regions from left to right. Credit: Shuai Li et al., 2018. Bottom panel: Maps of the near- (left) and far- (right) side concentrations of He-3 (parts per billion by mass) in the lunar regolith. The white contours delineate the concentrations of Oceanus Procellarum (left) and Mare Tranquillitatis (right) Credit: Crawford I.A., 2015.

2.3.2 Lunar sites of extraordinary scientific interest

Very important and unique lunar resources are not materials but rather locations, and these are the ones scientifically critical.

The Peaks of Eternal Light, near the lunar poles, are among the most attractive sites for astronomy (Elvis M., Milligan T. & Krolikowski A., 2016). These regions are almost continuously illuminated by the Sun and never shadowed by any part of the Moon; therefore, they could be used to collect solar power consistently and distribute it to lunar experiments (Ross A. et al., 2020). Moreover, these Peaks offer the opportunity to continuously observe the Sun using radio telescopes (Elvis M., Milligan T. & Krolikowski A., 2016).

The most scientifically valuable locations are the cold traps in the PSRs at the lunar poles. These regions are the dark floors of craters whose rims, instead, are continuously exposed to sunlight (they are peaks of eternal light). The traps can extend for a maximum of around $50\ km$ in diameter, more than the rims, and their temperature is extremely cold (below $90\ K$, or even below $50\ K$ in the coldest traps). For these reasons most of them contain water ice signatures (Li S. et al., 2018). Such a combination of dark and cold traps and illuminated rims make lunar craters at the poles absolutely optimal for scientific experiments, according to their scientific objectives. In fact, at these very low temperatures, they offer natural cooling for a range of scientific missions such as far-infrared telescopes, that need to be kept cool enough in order not to interfere with the target radiation (Elvis M., Krolikowski A. & Milligan T., 2021). Moreover, ultra-cold conditions of the coldest traps are crucial to build radio interferometer facilities, to test fundamental physics (Burrage C. et al., 2015). On the other hand, the low temperatures of the coldest traps make them retain specific volatiles; which means such locations are alluring to both scientists and commercial actors.

In addition, the farside of the Moon is composed of large areas of smooth terrain, perfect to place sensitive radio telescopes for cosmology purposes (described in subsection 3.4) (Burns J.O. et al., 2021). For instance, in order to detect the faint neutral hydrogen signal from the early cosmic epochs, a telescope needs to have a very sensitive resolution, defined as the ratio of the target wavelength (in this case $21\ cm$) to the diameter of the telescope. And for cosmology studies, an array of around $200\ km$ across would create optimal expectations (Elvis M., Krolikowski A. & Milligan T., 2021). However, large areas of smooth terrain on the lunar farside are few. The most prominent are: Apollo, Hertzsprung, Korolev, Mare Moscoviensis, Mare Ingenii and Mendeleev (Figure 5). In particular, the most promising site for cosmology is Mare Moscoviensis although this same location also has high concentrations of Helium-3 (Kim K.J. et al., 2019) hence providing an example of conflicting goals. Mining operations in such a site would likely cause electromagnetic noise, making it useless for cosmology.

Other interesting locations are the lunar pits, circular features said "to provide a window into the subsurface" (Keller J.W. et al., 2016). These pits are protected from radiation and meteorites and they have a relatively constant temperature therefore, they could be potential good locations for human bases, and even settlements aimed at long-duration lunar missions. These pits are quite rare, especially those close to other resources. Some of the best lunar pits have been found at the Marius Hills in Oceanus Procellarum (Kaku T. et al., 2017).

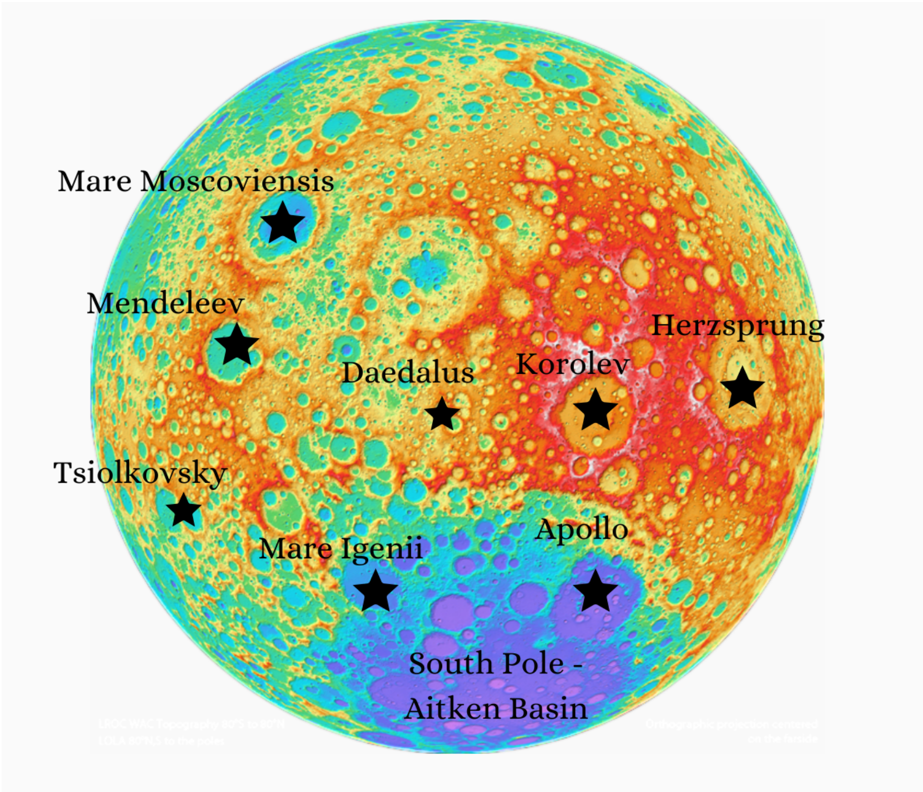

Figure 5. Topographic map of the lunar farside with LRO LOLA data which highlights the distribution of mountainous terrain and craters. Marked and labeled are the sites with the highest value for science. Credit: (LeConte Z.A. et al., 2023)

2.3.3 Cultural heritage

There are lunar locations that meet UNESCO requirements[11] to be considered as "Lunar Heritage Sites" (Elvis M., Krolikowski A. & Milligan T., 2021), with an intrinsic value that goes beyond any science or commercial interests and that should, on its own, lead to keeping lunar integrity untouched.
Among them there certainly are the six Apollo mission landing sites, as well as places chosen for other landings, successful or not. Some of them could eventually become tourist locations. NASA's Artemis Accords (discussed in subsection 5.3), incorporate a provision[12] to preserve them, giving specific instructions to the distance allowed for instrumentation to operate.

More generally, the whole Moon can be considered a huge natural resource of all humankind, that should be preserved *as is* for future generations (Moon Treaty, Article 11[13]).

2.3.4 Conclusions

It is of greatest importance to bear in mind that the Moon is not a place of unlimited or uniformly distributed resources; instead, they are typically concentrated in a small number of specific sites that extend for a few km across, hence they are relatively rare (Elvis M., Krolikowski A. & Milligan T., 2021).

Moreover, many unique locations on the Moon are objects of conflicting interests. In fact, the coldest traps of PSRs, at lunar poles, are optimally suitable for astronomical observations of the early universe, as well as deposits of water ice and volatiles with strategic ISRU and commercial values. If mining operations were undertaken in such areas, they would pollute and change environmental characteristics, leaving no more space for any scientific aspiration.

The variety of actors with diverse and incompatible goals in the context of lunar activities is likely to raise several issues with a lasting impact in the ethical, legal and societal areas (Elvis M., Krolikowski A. & Milligan T., 2021).

[11] https://whc.unesco.org/en/criteria
[12] NASA. 2011 NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts. [cited 2020 Sept 2]. See https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf
[13] https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/moon-agreement.html

2.4 Artemis Program

Through the Artemis Program, NASA is leading a sustained manned return to the Moon that will mark a new era of lunar exploration and economy, with unprecedented scientific and commercial objectives. The breakthroughs that the Artemis plan is bringing to the Moon are not a series of isolated missions but, instead, building a community on another cosmic shore. The primary intention is to establish a permanent human-robot presence on and around the Moon by building the Artemis Base Camp[14] at the lunar south pole, where no astronaut has landed before, while placing the Gateway space station[15] in lunar orbit. They will enable long-term activities to allow for a deep investigation of the lunar surface[16]. The location chosen for the Artemis Base Camp is not fortuitous; but is instead resource rich (i.e. power and water).
The main goals of NASA's Artemis Programs include: restarting human lunar exploration by sending the first woman and first person of color to the Moon; assessing human abilities to survive in a partial gravity environment; testing new technologies and capabilities to prepare for future Mars' exploration; extracting and using critical resources on the Moon that are needed for deep space exploration (e.g. learning how to purify water ice into drinkable water) and making scientific discoveries in different fields. All these may be achievable on the basis of global alliances. These programs also seek American leadership in lunar exploration and economy while expanding commercial and international partnerships.

To deliver scientific instruments and other technologies to the lunar surface, NASA has started a collaboration with several American companies (i.e. Astrobotic Technology, Blue Origin, Ceres Robotics, Deep Space Systems, Draper, Firefly Aerospace, Intuitive Machines, Lockheed Martin Space, Masten Space Systems, Moon Express, Orbit Beyond, Sierra Nevada Corporation, SpaceX and Tyvak Nano-Satellite Systems to date) through the Commercial Lunar Payload Services (CLPS) initiative[17]. The first CLPS payloads serve to characterize the lunar environment and test instrumentation to prepare for future experiments, whereas the awaited human return to the lunar surface is predicted by 2025[18].

The core elements of the deep space transportation system are shown in Figure 6. The Space Launch System (SLS)[19] is NASA's new powerful rocket that will send astronauts to a lunar orbit aboard NASA's Orion[20] spacecraft. Then, through the Gateway, astronauts will be transferred to a human landing system (HLS) in order to be sent to the lunar surface. In 2022, Artemis I[21] was the first, successful, uncrewed flight to test the SLS and Orion spacecraft together. Artemis II will be the second test mission, this time carrying a crew of four astronauts, recently designated[22].

[14]nasa.gov/artemis/2020/10/28/lunar-living-nasas-artemis-base-camp-concept
[15] www.nasa.gov/gateway
[16]www.nasa.gov/specials/artemis
[17]www.nasa.gov/content/commercial-lunar-payload-services
[18]https://www.nasa.gov/feature/artemis-iii
[19]www.nasa.gov/exploration/systems/sls
[20]www.nasa.gov/exploration/systems/orion
[21]www.nasa.gov/artemis-1
[22]https://www.nasa.gov/specials/artemis-ii/

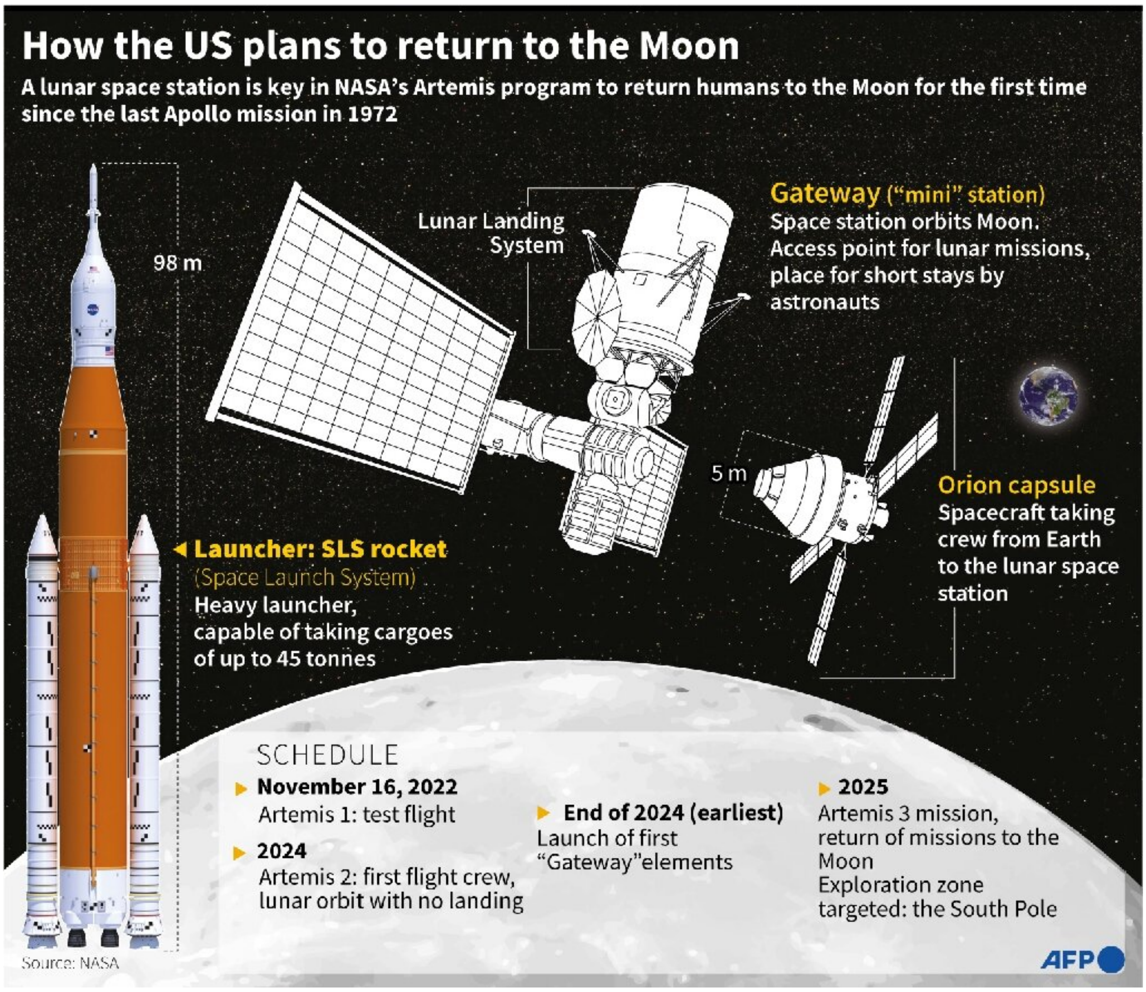

Figure 6: The core elements[23] of the deep transportation system and the first milestones of the Artemis program. Image credit: NASA

The exploration of the Moon is not a single country ambition, but a shared effort. In their articulated lunar plan, NASA is supported by other space agencies including: the Canadian Space Agency (CSA), the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). Some clarification about the position of ESA with respect to the Artemis Programs will follow in subsection 5.4.

[23] www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

Chapter 3: Astrophysics from the Moon

The idea of putting a telescope on the Moon is not new. Already in the late 1830s, despite the fact that going to the Moon was considered very difficult, astronomers realized that its lack of atmosphere would allow a pristine view of the cosmos (Silk J., 2022). With the Apollo missions 11 to 17 (and minus Apollo 13), over a century later, the in situ exploration of the lunar environment started and the idea of lunar telescopes finally became a plausible concept. But the available technology could not allow much more than a geophysical characterisation of the Moon Itself. Now that NASA has the mandate to return astronauts to the Moon, under the Artemis Programs, and thanks to technological improvement, the astronomical community has begun to reconsider the value of putting telescopes on the Moon instead of in space.

In this section I analyze the benefits that the lunar environment has to offer for observations at different wavelengths, for different science objectives. Some of this information, I gathered directly from the authors of the missions at the Royal Society, in February 2023 (Phil.Trans.R.Soc A proceedings[24]). First, I briefly introduce the theoretical background behind each science research, the current detection techniques and facilities from Earth and in space. Then I explain why going to the Moon may represent such a great improvement and I point at the specific lunar sites that are most suitable for different experiments. In each subsection, for individual scope, I include a table with the planned missions in the near/far future, providing information about their observational frequency window and their main science cases. A more in depth focus is on probing cosmology from the Moon, using low frequency radio observations that are not possible elsewhere on Earth.

3.1 Gravitational wave astronomy

Gravitational Waves (GWs) are among the most avidly investigated astrophysical messengers as they carry unique information about the universe, not accessible in other ways. Unlike electromagnetic radiation, they travel through space undisturbed, weakly interacting with the matter they encounter, thus preserving important information.
GWs are produced by supernova explosions, colliding neutron stars, merging black holes, even the Big Bang; therefore they can really reveal how the most violent phenomena in the universe start and evolve. However, the size of GW effects is extremely small thus, hard to track. It took some fifty years of effort before the first detection of GW from a merging black-hole binary by the Laser Interferometer Gravitational-Wave Observatory (LIGO), a Nobel Prize-winning event in 2015 (Abbott B. P. et al., 2016).

Currently operating ground-based GW facilities are LIGO (Aasi J. et al., 2015), Virgo Interferometer (Acernese F. et al., 2015) and the Kamioka Gravitational Wave Detector (KAGRA) (Akutsu T. et al., 2019). Their sensitivities span frequencies between 10 Hz and the kHz regime, allowing the detection of GWs emitted by astrophysical sources with masses from 1 to 100 $M_{\odot}$[25]. These ground-based detectors cannot work at lower frequencies due to the coupling

[24]https://royalsociety.org/science-events-and-lectures/2023/02/astronomy-moon/
[25]Mass of the Sun, $M_{\odot}$ = 1.989 x 10^{30} kilograms

of the GW signal with the Earth's seismic noise. Instead, the next GW observatory will be LISA (Laser Interferometer Space Antenna) mission, operating from space, that will cover frequencies below $0.1\,Hz$ (Amaro-Seoane P. et al., 2017). This is expected to achieve extraordinary sensitivity in tracking inspiraling and merging massive black holes with masses from 10^3 to 10^7 $M_{\odot}$. But the aformentioned facilities do not cover the deci-Hertz regime, considered as a window of astrophysical source richness (Amaro-Seoane P. et al., 2021), thus leading to a need to bridge this gap.
The proposed next generation terrestrial GW detection facilities are the Cosmic Explorer (CE) and the Einstein Telescope (ET) (Punturo M. et al., 2010), designed to push to lower frequencies (Dwyer S. et al., 2015). But these very ambitious projects have a number of limitations. In fact, they require very large infrastructure and a challenging technology to operate well underground, resulting in a lot of R&D effort and higher risks associated with their deployment. Specifically, when going to low frequencies, efficient techniques for isolation and monitoring of the signal as well as mitigation of the background become crucial. Being able to handle such issues from Earth is not easy.

Where else shall we go? The idea of lunar GW detectors was developed in the 1960s and the first GW detection facility was brought to the Moon with the Apollo 17 program, in 1972. However, its design did not allow it to achieve the projected sensitivity, due to problems with lunar gravity. Instead, it collected very important geophysical data on the surface of the Moon and its seismic measurements are still extensively used in present models (Coughlin and Harms, 2014).
Thanks to the rapidly advancing technology, every ten years the concept of a GW detector on the Moon has been investigated and it now seems an excellent candidate observatory to benefit from the advantages of the lunar environment. The lack of atmosphere, ocean tides or a significant ground motion result in a much lower background noise compared to that of Earth (by 6 orders of magnitude, a million-fold) (Harms J. et al., 2020). This means from the Moon it could be possible to achieve the highest sensitivity for the detection of deci-hertz GWs. The most suitable sites for GW interferometer observatories on the Moon are large ($\geq 50\,km$) craters in PSRs at lunar poles (Amaro-Seoane P. et al., 2021) as for their good vacuum conditions and a cold stable temperature ($T < 40$ K) that translates into the lowest background noise. Among them, *Faustini crater* seems to be an optimal location for placing a GW detector also because it is water-poor and therefore, less appealing to commercial interests (Elvis M., 2023).

In 2020, NASA and ESA called for lunar missions to bring science to the Moon and different concepts of lunar GW detectors have been proposed. A list of them is given in Table 1, below, while I briefly describe each of them in Appendix C.

Table 1. Gravitational Wave proposed missions on the Moon

Mission	Expected Activation	Frequency band	Science cases	Location
LGWA: Lunar Gravitational Wave Antenna (Harms J. et al., 2020)	2032	$1\,mHz - 1\,Hz$	White dwarfs; Neutron stars; Black holes; ~ $10^{3} M_{\odot}$	PSR (Lunar South Pole)
LSGA: Lunar Seismic Gravitational wave Antenna[26]	Timeline TBD	$10^{-3} - 10^{-2}\,Hz$	Compact binary coalescences; White dwarf mergers; Jet gravitational waves; Type IA supernovae	PSR
GLOC: Gravitational-Wave Lunar Observatory (Jani K. et al., 2021)	Still uncertain	$0.1 - 5\,Hz$	Dark matter density; Neutron stars; Type IA supernovae; Dark sirens; Tests of general relativity	PSR
LION: Laser Interferometer on the Moon (Amaro-Seoane P. et al., 2021)	2050s	$0.7\,Hz - 10\,kHz$	Massive black holes; Track seed black holes at $z > 100$; Search for new exotic objects	Shoemaker crater

[26] ideas.esa.int/apps/IMT/UploadedFiles/00/f_1365a252b41c3b9829533dc65cc707f6/LSGA_3jul2020_final.pdf)

3.2 Optical - Infrared (OIR) regime

The universe reveals different characteristics at different wavelengths of light. Individual telescopes are designed to study the cosmos to provide the most complete information possible and allow us to learn about the full variety of astrophysical processes. The Hubble Space Telescope (HST)[27] is the most famous example of an “optical” instrument designed to perform observations in the visible regime ($400 - 700\ nm$) as well as the adjacent similar ultraviolet (UV) and near-infrared (NIR) ones. Its imaging capabilities have allowed scientists to study very distant stars and galaxies as well as the planets in our solar system.

Phenomena hidden by dusty clouds can only be accessed via the long and penetrating IR wavelengths ($1\ \mu m - 1000\ \mu m$). In the IR range very cold objects appear like interstellar gas, planets, asteroids, forming stars (and many more). Furthermore, IR astronomy can provide information about the formation of the first stars and galaxies in the early epochs. This is because we live in an expanding universe that stretches the light traveling through it: looking deep in space is looking back in time.

IR emission from astrophysical sources is readily observable from Earth only at near- and mid-infrared wavelengths ($< 3\mu m$). Instead, far IR (FIR) observations ($\sim 3\mu m\ -\ > 25\ \mu m$) are much more powerful if conducted in space as IR light is mostly blocked by Earth's atmosphere. Moreover, terrestrial FIR frequency windows are vastly affected by the background radiation produced by telescopes and the atmosphere themselves.

In December 2021, the James Webb Space Telescope (JWST)[28] was launched. This is the largest IR instrument in space, with a $6.5\ m$ primary mirror, thus it marked a new era for an unprecedented view in cosmic history. Among its most dramatic science cases are: (1) the detection of the atmospheres of exoplanets to search for life elsewhere in the universe, (2) studying the first light sources to probe the formation of the first stars, galaxies and black holes, and (3) the exploration of star and galaxy evolution through cosmic time (Deming D. et al., 2009).

But what is the future of OIR astronomy beyond the JWST? NASA has started the evaluation of some “flagship” scale future projects to understand the advantages and feasibility associated with each proposal.

The Habitable Worlds Observatory (HWO)[29] is the OIR space mission of the future, to be placed near the Sun-Earth Lagrangian L2 point. This is the successor of the LUVOIR and HabEx mission concept studies, developed in preparation for Astro2020. It is designed as a multiwavelength space observatory with a $6,0\ -\ 6,5\ m$ aperture, like JWST, but with radically improved optical imaging quality and equipped with a coronagraph to block light from host stars and thus

[27] www.nasa.gov/mission_pages/hubble
[28] https://webb.nasa.gov/content/science/index.html
[29] https://www.space.com/habitable-worlds-observatory-first-glimpse

image and study exoplanets directly. However, space facilities suffer from size limitations and impractical operational requirements.

On Earth, the largest ever OIR facility is the Extremely Large Telescope (ELT), provided with a $39\ m$ primary mirror with some 36 times the light collecting ability of JWST or HWO. ELT is now under construction at its chosen location in Chile's Atacama Desert[30]. It is expected to demonstrate great capabilities in studying habitable exoplanets, unveiling the nature of dark matter and of dark energy. However, ELT's big limitation is being on the ground.

Instead, an intriguing new location for a future OIR observatory is on the Moon. The low lunar seismic activity, the lack of an atmosphere as well as a lower gravity than that of Earth are significant advantages. In particular, the PSRs at the lunar poles offer good conditions to accommodate next generation OIR telescopes as their floors are never illuminated by the Sun directly but their rims are "peaks of eternal light" with almost continuous solar power available (chapter 2). Therefore, OIR instruments would benefit from the vicinity of solar power and the passive cooling by the extremely low and stable temperatures ($T < 40\ K$) inside craters. The latter is an essential condition for FIR observations to eliminate the bright IR background, unavoidable on Earth (Elvis M., 2023). Moreover, PSRs offer areas large enough to host sensitive instruments; a $100\ m$ OIR telescope is perfectly feasible on the Moon.

Not all lunar craters are suitable for science objectives; they need to meet the following requirements (Elvis M., 2023):

- A slope $< \sim 25\ degree,\ and\ preferably < 15\ deg$ to allow the operation of rovers;
- A low dust environment;
- The lowest feasible lunar latitude, to maximize their sky coverage (Cannon K.M. et al., 2020);
- A good compactness for landing infrastructure and instrument assembly;
- A crater diameter of $\sim 25\ km$ and a crater depth $\sim 5\ km$ (Labeyrie A., 2021);
- A modest range of temperatures to ease engineering design.

In addition, FIR telescopes require a temperature $< 50\ K$ to remain signal-limited out to $\sim 200\ \mu m$.

Ultimately, the multi-billion dollar costs of the largest ground- and space- based telescopes make it plausible that lunar telescopes could be feasible, assuming that human bases are already in place.

The most promising future OIR missions are summarized in Table 2. Moreover, I provide some additional descriptions for each in Appendix C.

[30] elt.eso.org

Table2. OIR planned missions for the next decades.

Mission	Expected Activation	Observational band	Primary mirror diameter	Science cases	Location
E-ELT[31]: European Extremely Large Telescope	2027	$0.47—2.45\ \mu m$	$39\ m$	Search for habitable exoplanets; Investigation of the nature of dark matter and dark energy; Observations of stars in the Milky Way, black holes and distant galaxies	Chile's Atacama Desert
HWO [29]: Habitable Worlds Observatory	2040s	$0.09\ -\ 1.35\ \mu m$	$6.5\ m$	Search for Earth-like exoplanets and signs of life; Formation and evolution of stars, planets and galaxies; Solar System characterisation	Sun-Earth Lagrange 2 point (L2)
ALLURE: Astronomical Large Lunar UV to mid-infraRed Explorer (Jean-Pierre Maillard, Royal Society 2023)	Under investigation	$0.2\ -\ 200\ \mu m$	$13\ m$	Under investigation	Hermite or Shackleton craters
ELLIT: Extremely Large Lunar Telescope (Maillard J.P., 2020)	Under investigation	$0.4\ -\ 1.35\ \mu m$	$39\ m$	Formation and evolution of planetary systems; Tracking water and organic molecules in protoplanetary disks;	Lunar crater

[31] https://www.eso.org/sci/facilities/eelt/docs/e-elt_executivesummary.pdf

				Looking at distant light sources	
LOUPE: Lunar Observatory for Unresolved Polarimetry of the Earth **(Klindžić et al., 2020)**	2020s	$0.4 - 1\,\mu m$	small	Observing the Earth as a "dot"	Near side of the Moon

3.3 Far-infrared / submillimeter range

The FIR and submillimeter frequency window, between $100\,\mu m$ and several mm, is of great importance for cosmological observations of the Cosmic Microwave Background (CMB), leftover radiation from the Big Bang that fills the entire universe (Mather et al., 1990). This represents the youngest cosmic light detectable with telescopes and thus the first ever light that could travel freely through the universe. It dates from some 380,000 years after the Big Bang (z ~ 1100), which means that the universe became transparent (neutral) at this redshift. Between then and now the CMB was stretched by the expansion and cooled. The first spectroscopic analysis of the CMB was made in 1989 by the COBE[32] mission and revealed a CMB perfect blackbody spectrum with a peak at $2.7\,K$. The homogeneity and isotropy of the CMB seen at large scales, breaks at very small scales that, instead, show tiny temperature fluctuations of the order of $milli - K$. These are predicted by the standard cosmological model to have driven large structure formation.

FIR observations of the CMB are crucial as very small fluctuations of the CMB from the perfect blackbody would provide important clues about the thermal history of the universe, the inflation (described in subsection 3.4.1), the nature of dark matter and primordial correlation functions at scales inaccessible to other tracers (Chluba J. et al., 2019).
The FIR can only be observed from space, due to the limitations imposed by the Earth's atmosphere. These observations could especially benefit from an infrared site on the Moon; the cold landscape of lunar craters offers large areas with optimal conditions to accommodate a large array of FIR telescopes. The proposed lunar FIR mission for cosmological purposes is called Multi-SIMBAD, whose details are given in Table 3 below and a more complete description is provided in Appendix C.

[32]https://science.nasa.gov/missions/cobe

Table 3. Far-Infrared proposed mission on the Moon

Mission	Expected Activation	Observational band	Science cases	Location
Multi-SIMBAD: Multi - Spectroscopic Interferometer for Microwave BAckground Distortions **(Maillard J.P., 2020)**	Under investigation	$100\,\mu m - mm$	Spectroscopy of the CMB	Lunar crater on the farside

3.4 Low radio frequencies

Radio waves span from tens of meters to $1\ mm$ in length and up to $300\ GHz$ in frequencies. They have revealed a great portion of the "invisible Universe" and will continue to advance our knowledge of it. Among the most significant discoveries of radio astronomy are: the detection of radio galaxies and quasars, the detection of the hydrogen spectral line at a wavelength of $21\ cm$ (Ewen and Purcell, 1951), of the CMB (Dicke et al., 1965) and the discovery of pulsars (Hewish et al., 1968).

Radio waves have the ability to easily penetrate the Earth's atmosphere thus they can be observed from the ground using radio telescopes. Several of them are currently operational, either individual large antennas such as China's FAST Telescope[33] and the Green Bank Observatory (GBO)[34] in West Virginia, or multiple element interferometers that, depending on the distance between their components, can allow very high angular resolution. Examples of the best known facilities that use interferometry are the Karl G. Jansky Very Large Array (VLA)[35] in New Mexico, the Murchison Widefield Array (MWA)[36] in Australia or the Atacama Large Millimeter/submillimeter Array (ALMA)[37] in the Atacama desert, Chile.

The use of many small and cheap antennas is a promising method to build a high resolution, high sensitivity telescope for low-frequency radio observations. The Low-Frequency Array (LOFAR)[38] is one of the largest terrestrial radio infrastructure networks, operating at the lowest frequencies, $30 - 240\ MHz$ (Gunst A.W. and Bentum M.J., 2010). Most of its stations are located in the Netherlands, a few in Germany and Poland while France, Ireland, Latvia, Sweden, and the United Kingdom host one antenna each. Italy and Bulgaria will follow. Key science projects of

[33]fast.bao.ac.cn
[34] greenbankobservatory.org
[35] http://www.vla.nrao.edu/
[36] www.mwatelescope.org
[37]https://www.eso.org/public/teles-instr/alma/
[38]www.astron.nl/telescopes/lofar

LOFAR include the detection of the highly redshifted 21 cm signal of neutral hydrogen from the Epoch of Reionization (EoR), a big survey of the low-frequency sky up to $z \geq 6$, and searches for pulsars and transient sources. These are also the targets of the Square Kilometer Array Observatory (SKAO)[39], a next-generation radio astronomy-driven Big Data facility composed of hundreds of dishes and thousands of antennas located in Australia and South Africa. With an unprecedented sensitivity and spatial resolution, SKAO is expected to push beyond LOFAR capabilities (Offringa A., 2012).

However, over the last decades, human technological progress has caused increasing radio-frequency interference (RFI), hard to mitigate. Consequently, ground-based radio observations are highly affected by man-made radio transmitters (notably Earth's radar, radio, TV emissions, airplanes, and orbiting internet constellations) that are much stronger than the weak celestial signals. Other big limitations are the effects caused by the Earth's auroral kilometric radiation and the Earth's ionosphere (Meyer-Vernet and Perche, 1989).

Additionally, most of the radio frequencies are just not accessible to radio astronomy from Earth because they were allocated by the International Telecommunication Union (described in subsection 5.3.1) to other services. Radio astronomy has 1.8 % of allocated frequencies below 40 GHz from Earth (Gyula Jozsa, IAA committee meeting, March 2023).

The Moon, instead, is a stable place with no weather and no atmosphere. In particular, the lunar farside is a region of extraordinary scientific value as it is sheltered over much of its surface from human-made RFI (by about 80 db) (Elvis M., 2022), a big enemy of extremely sensitive experiments. During the lunar night[40], it is also protected from the Sun. Therefore, radio telescopes on the Moon's farside would have many advantages and open up a range of wavelengths that astronomers have not explored yet.

The idea of placing radio facilities on the farside of the Moon has been around for a long time and renewed interests have periodically emerged until the current century. At present, there are several valuable concepts for low-frequency radio missions in cislunar space; these are listed in Table 4 and briefly described in Appendix C. The main purpose of such experiments is to map the 21 cm signal from the Dark Ages, prior to the formation of any sources of light. This signal, free from contamination by astrophysical sources, would provide unique information of the early epochs of cosmic history and the nature of dark matter particles.

The locations for very sensitive radio experiments have to be carefully chosen; LeConte Z.A. et al., 2023 performed a preliminary study of suitable lunar sites for hosting large radio facilities suitable to measure the primordial spatial fluctuations. For this purpose, a 10 $arcsecond$ spatial resolution is required and so a 200 km baseline[41] radio interferometer.

The candidate sites have been selected considering:

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[39]www.skao.int
[40]The Moon takes 28 days to complete a rotation around its axis. The lunar day is approximately 14 days long and the lunar night is again of the same duration.
[41]The baseline length is the longest linear distance achievable on that site.

- ❖ Slope constrained size: at a higher slope threshold (~24°) a site becomes more accessible as well as the achievable baseline increases;
- ❖ Point spread function (angular resolution): a larger baseline provides a smaller angular resolution;
- ❖ Roughness: the smoother the surface, the better;
- ❖ Topographic features: special features may represent terrain obstacles.

After all these aspects are considered, there is a small number of locations, all with a dimension > $100\ km$, ideal for sensitive experiments, and these are: Apollo, Hertzsprung, Mare Ingenii and Mare Moscoviensis, with Tsiolkovsky and Daedalus suitable for smaller arrays ($\sim 100\ km$).

The rarity of such extraordinary lunar locations will result in a high competition in the next decades, therefore the need for protection and cooperation among different actors.

3.4.1 Cosmology

One of the major frontiers of modern astronomy and fundamental cosmology is the study of the Dark Ages as a unique tool to advance our understanding of the formation and evolution of large scale structures as well as probe inflation, a leading paradigm for describing the early instants of the universe (Adams et al., 1993).

In agreement with our best accredited cosmological model, ΛCDM (described in Appendix B), approximately $10^{-36}\ to\ 10^{-32} s$ after the Big Bang, the universe expanded exponentially in a process called the "inflationary phase". This scenario was proposed to solve some early cosmic mysteries including the homogeneity and isotropy of the universe on large scales, its flatness and the absence of magnetic monopoles (Guth A., 1981). There are different inflationary models under verification; the simplest slow roll inflation theory implies that the exponential expansion of the universe started with quantum fluctuations in a primordial inflation field, and produced a global stretch making it all appear uniform, low density and flat. The quantum fluctuations of the inflation field got stretched in the same way and imprinted on larger scales, thus scale-invariant. These in turn represent the seeds of the distributions of galaxies and galaxy clusters as we see them today. Freely propagating in the inflationary background, these primordial quantum fluctuations are considered to follow a Gaussian distribution. The best way to study them is through the power spectrum of the CMB anisotropies (Xingang Chen, 2010) that is consistent with their gaussianity (Planck Collaboration, 2015) however, with a much smaller fraction of non Gaussian components (Celoria M., 2018). The origin of the inflation field is still not known. Therefore, the search for primordial non-gaussianities would be a robust complementary probe of an alternative to the standard inflationary model.

In the Dark Ages there were no sources of light and the universe was filled primarily with neutral hydrogen HI, which eventually served as raw material for the first stars. The "spin-flip" transition of neutral hydrogen emits a photon with a rest frame wavelength of $21\ cm$, corresponding to a frequency of $\nu = 1420\ MHz$ (Muller & Oort, 1951). Its signal is generated by a weak hyperfine transition that can be detected even with a simple radio dipole experiment. However, the highly redshifted $21\ cm$ signal from the Dark Ages becomes extremely hard to track; due to the expansion of the universe its wavelength appears much elongated ($6.5 - 17.0\ m$) and its frequency in a much lower band ($17.6 - 46.1\ MHz$).

There are two ways of observing the $21\ cm$ signal: as a sky averaged global signal or as spatial fluctuations. The method consists in measuring the neutral hydrogen spin temperature (Ts) against the CMB radiation temperature (Tr) (Furlanetto et al., 2006). The hydrogen gas clouds at very high redshifts ($z \sim 30\ to\ 100$) have $Ts < Tr$ as no stars, galaxies or quasars have formed yet; in this case the $21\ cm$ signal is seen in absorption against the CMB.

The ΛCDM cosmological model predicts an absorption feature in the global $21\ cm$ spectrum, called the "Dark Ages trough", at ν ≈18 MHz. This traces the density field of the early universe in the absence of light sources (Flöss et al., 2022) (Figure 7). It is purely cosmological and can be analytically derived starting from the initial conditions of the ΛCDM model, to which it is very sensitive. Any deviation of the observed global signal from the currently accepted predictions would be a direct measure of the breakdown of the standard cosmological model of known physics; resulting in the necessity to challenge it with new physics. Another predicted absorption feature in the $21 - cm$ spectrum is the "Cosmic Dawn trough", starting at ≈ $50\ MHz$. This corresponds to the formation of the first stars accompanied by a much faster gas cooling than the CMB radiation (Burns J.O. et al., 2017).

Recently, the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) has claimed to have detected the presence of a strong absorption feature in the $21 - cm$ spectrum at $\approx 78\ MHz$ ($z \approx 17$), the window where the Cosmic Dawn trough is predicted (Bowman et al., 2018). This result has been later disputed (Singh et al., 2022).

Spatial fluctuations in the Dark Ages $21 - cm$ signals are direct tracers of the underlying matter distribution (Zaldarriaga, Furlanetto & Hernquist, 2004). In particular, $21\ cm$ line maps and tomography in the frequency window $10 - 50\ MHz$ would represent the "richest of all cosmological data sets", sampling a large number (trillions) of independent modes that describe primordial density fluctuations, inaccessible in other ways (Morabito L.K. & Silk J., 2021) and invaluable to understanding the earliest matter distribution and the beginning of creation. Furthermore, they could provide clues about the nature of dark matter, the matter power spectrum spectral index, non-Gaussianity (Munoz et al., 2015b), the curvature of the universe and the mass of the neutrino (Mao et al., 2008).

Tracking the highly redshifted $21 - cm$ signal of the Dark Ages is not an easy task for observers on Earth as its frequency falls in the window where human-generated interference is great (Elvis M., 2022), in addition to the distortions produced by Earth's ionosphere. Ground-based observations of the Dark Ages signal would require an effective antenna diameter of $79 < D\ (km) < 208$ to achieve the appropriate resolution (LeConte Z.A. et al., 2023).

Instead, a lunar platform, on the lunar farside, would allow the access to the earliest universe and complement the studies of next generation telescopes on the ground (i.e. SKA[42]) and in

[42]https://www.skao.int/en/explore/science-goals/164/probing-cosmic-dawn

space (JWST). For $21 - cm$ observations, the access to small scales ($k \sim 10\,Mpc^{-1}$)[43] is critical; this might be achieved from a lunar site.

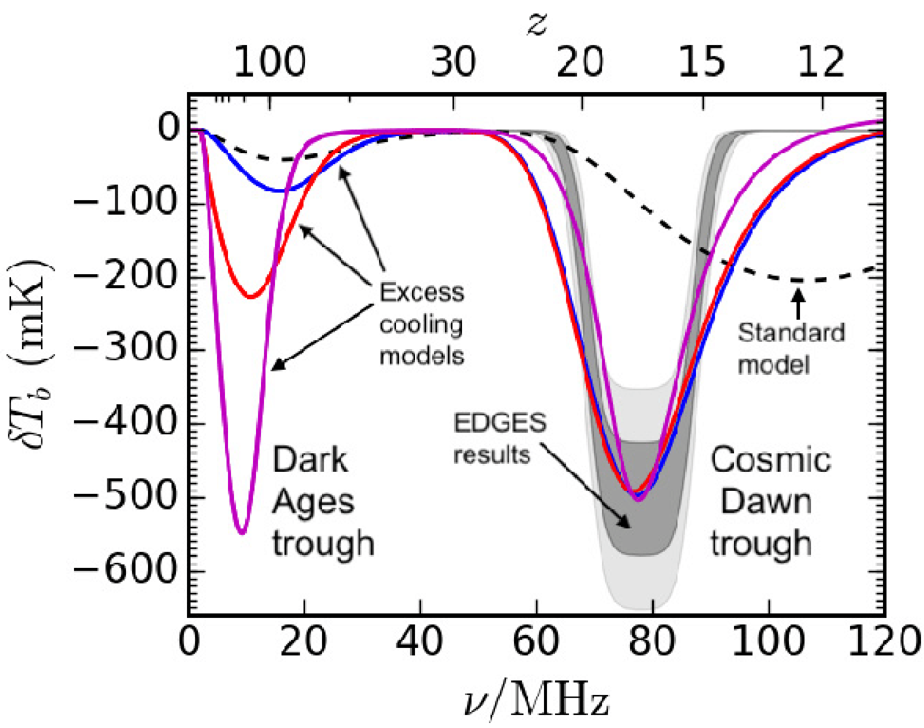

Figure 7: The Dark Ages 21-cm absorption trough is a sensitive probe of cosmology. The black dashed curve shows the brightness temperature (relative to the radio background) in a standard cosmological model. Credit: (Burns J.O. et al., 2021)

Galactic emission

It is important to mention that the farside of the Moon is not completely radio quiet due to the bright galactic radio emission which becomes stronger at lower frequencies, $\sim a\,few\,to\,a\,few\,hundreds\,MHz$ (de Oliveira-Costa A. et al., 2008). The radio sky, in this band, is dominated by the synchrotron radiation of relativistic cosmic ray electrons that spiral in the magnetic field of the galaxy, undergoing energy loss. This creates a bright and unavoidable foreground contamination for cosmological measurements. Therefore, in order to intercept signals at high redshifts, like the $21\,cm$ signature of the Dark Ages, up to $z \sim 100$, mitigation and separation techniques become critical (Bale S.D. et al., 2023).

In such a situation, careful considerations are necessary to avoid producing an extra amount of harmful noise artificially, and individual experiments should estimate their noise requirements before they cannot operate for the predicted purposes. A general criterion could be that the

[43] 1 Megaparsec = 3.086E+19 km

contribution from all artificial farside sources of emission must not exceed 10% of the natural contribution of radio noise by the Galactic emission at low frequencies (Burns J.O., private communication). This criterion is analogous to the limit to the artificial light contribution defining dark-sky ground-based observing sites defined by the IAU.

3.4.2 Lunar low frequency radio missions

Table 4. Low frequency planned lunar missions.

Mission	Expected Activation	Observational band	Science cases	Location
ROLSES: Radio Wave Observations at the Lunar Surface of the Photoelectron Sheath (MacDowall R. J. et al., 2020)	2023	$10\ kHz - 1\ MHz$ and $300\ kHz - 30\ MHz$	Measurements of the photoelectron plasma sheath on the Moon; Estimation of RFI	Oceanus Procellarum
LuSEE: Lunar Surface Electromagnetic Experiment (Bale S.D. et al., 2023)	2025, 2026	$10 - 50\ MHz$	Measurements of the pristine radio sky of the lunar farside	Schrödinger Basin
DAPPER: Dark Ages Polarimeter Pathfinder (Burns J.O. et al., 2021)	2023 to 2026	$17 - 110\ MHz$	Probing the Dark Ages; verify the recent EDGES results for Cosmic Dawn	Lunar orbit
DSL (or Hongmeng): Discovering the Sky at the Longest wavelength (Yuan Shi et al., 2021)	2026 (TBC)	$1 - 30\ MHz$	Map of the sky and survey of the major sources at this frequencies; explore Dark Ages and Cosmic Dawn	Lunar orbit (Inclination of 30º)

FARSIDE[44]: Farside Array for Radio Science Investigations of the Dark ages and Exoplanets	Late 2030s	$0.1 - 40\ MHz$	Search for radio signatures by energetic particle events in near stellar systems; Search for habitable exoplanets; Solar system observations; Measurement of the Dark Ages global $21 - cm$ signal at redshifts $z \sim 50 - 100$	Lunar farside
FarView[45]	2030s	$5 - 40\ MHz$	Probing the Dark Ages and investigate the formation of the first stars, galaxies, and accreting black holes	Lunar farside
ALO: Astronomical Lunar Observatory (Wolt et al., 2021)	2030s	$7 - 70\ MHz$[46]	Measurements of the global $21 - cm$ signal and its fluctuations for probing Dark Ages and the Cosmic Dawn	Lunar farside
LCRT[47]: Lunar Crater Radio Telescope	Under investigation	$6 - 30\ MHz$	Probing Dark Ages and Cosmic Dawn	Inside a crater on the lunar farside

[44]science.nasa.gov/science-pink/s3fs-public/atoms/files/FARSIDE_FinalRpt-2019-Nov8.pdf
[45] https://www.nasa.gov/directorates/spacetech/niac/2021_Phase_I/FarView/
[46]Updated information gathered from a scientist working on the project
[47]www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/lunar_crater_radio_telescope

Chapter 4: Threats to science objectives

In this chapter I elaborate on: (1) the interests of the most developed spacefaring states in commercial space activities and (2) the role of non-traditional players in an evolving space exploration landscape. Furthermore, I investigate the threats that the developing space economy can represent to lunar astronomical science.

4.1 Human activities on the Moon

The Moon is receiving growing attention particularly because it is an optimal location to test and develop advanced technologies and capabilities for deep space exploration. This will result in a lunar economy with many opportunities associated with instrumentation, transportation, resource extraction, communication and navigation services. The three main kinds of human activities perceived are described below.

4.1.1 Mining. Water and minerals are the most desirable targets of contemporary lunar ambitions of both government and commercial organizations. These are critical resources to sustain a long-term robotic and manned presence on the Moon, and their wide applicability in space operations, described in subsection 2.3, can turn into lunar industry segments with valuable profitability. Although the commercial use of lunar resources may take some time to develop, the local use of such resources is likely to be a key component of near-term plans.

There are more than 70 nations with space programmes worldwide. The United States (US), through the Artemis Programs, has a leading position in mining activities. SpaceX[48], the company set up by Elon Musk in 2002, supports NASA by providing affordable space transport services based on reusable rockets. They have plans to maximize the utilization of space materials to prepare for future missions to Mars (Pomeroy C. et al., 2019). Another American entrepreneur, Jeff Bezos, founder of Amazon, shares an interest in the lunar market, so he started Blue Origin[49] for launching vehicles into space at reduced cost. Recently, NASA selected Blue Origin to build a Moon lander for the Artemis V[50] mission.

Luxembourg, with a big space industry in satellite communication services to date, is putting great efforts towards innovative access to space. It is seeking to create a vibrant network of space companies and attractive space economy segments and establish a manufacturing system that purely relies on raw materials of celestial bodies ("Commercial space mining: Economic and legal implications" - Vidya Sagar Reddy Avuthu). Both the US and Luxembourg, through national laws, have given rights to their commercial entities to extract, use and sell space resources[51].

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48 www.spacex.com

49 Spencer Soper, “Bezos Sells $1 Billion a Year in Amazon Stock for Space Project,” Bloomberg, April 6, 2017, https://www.bloomberg.com/news/articles/2017-04-05/bezos-hopes-big-windows-will-give-space-tourism-a-boost

50 https://spacenews.com/nasa-selects-blue-origin-to-develop-second-artemis-lunar-lander/

51 www.ft.com/content/af15f0e4-707a-11e7-93ff-99f383b09ff9

However, these are to be framed with respect to international treaties that comprise outer space law (described in chapter 5).

Another big spacefaring state is India, with its own lunar program aimed at studying water traces and cold traps (Krolikowski A. & Elvis M., 2022).

4.1.2 Settlement. In addition to the US planned Artemis Base Camp, another lunar base project is that of China and Russia called International Lunar Research Station (ILRS)[52], expected in the 2030s. Furthermore, ESA wishes to establish a "Moon Village[53]" served by local resources. The purposes associated are large-scale scientific experiments, testing technologies and capabilities required for deeper space missions, exploitation of resources and even lunar tourism. Missions for settlement are led by space agencies with multiple roles for private companies.

4.1.3 Militarization. Outer space has been for a long time a place for extending rivalries. The most popular example is that of the space race between the Soviet Union and the United States during the Cold War. Since then, orbits around large bodies, including the Moon, have been also considered for their military potential and outer space has been militarized with the introduction of surveillance and communication networks; however, not weaponized (yet).
At present, there are several concepts of space weapons also known as anti-satellite weapons[54] (ASTAT); these include any kind of ground-, sea- or air- based technology able to degrade or destroy a working enemy satellite or interfere with its operations. ASTAT can be non-destructive, like cyberattacks or lasers, but there are also destructive concepts based on high-speed physical collisions[55]. With a facilitated access to cis-lunar space, a scenario of hidden weapons in lunar orbits is not excluded but also easier to track. However, "conflict" need not be military, it could be a legal/governance conflict that can be resolved peacefully. The potential for conflict over highly concentrated resources, notably on the Moon, has the potential to become a real threat.

4.2 Network of navigation and communication satellites

The growing number of government and commercial lunar missions, planned to be operational in the next decades, need continuous navigation and communication services, for proper positioning and connectivity with the Earth. This has encouraged space agencies and private companies to project constellations of telecommunications and navigation satellites (Nav/Comm) around the Moon.

Among them, ESA is busy working on its Moonlight[56] programme, consisting of a network of lunar satellites that will offer communication and navigation systems to serve all present and

[52]www.news4jax.com/tech/2021/03/10/china-russia-agree-to-build-lunar-research-station/
[53]www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village
[54]https://www.ucsusa.org/sites/default/files/2019-09/intro-to-space-weapons.pdf
[55]https://swfound.org/news/all-news/2022/06/swf-releases-new-infographic-on-anti-satellite-weapons-and-space-sustainability/?utm_source=VisualCapitalist-Web&utm_medium=Branded-Content-VisCap&utm_campaign=VC-SecureWorldFoundation
[56]https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Moonlight

future missions around the Moon or on the surface. The first of these satellites, called the Lunar Pathfinder[57], is planned for launch in 2026 through the CLPS awarded to Firefly Aerospace.

Furthermore, the American company Lockheed Martin, has recently announced a similar project called Parsec[58] service. The first of its lunar satellites are expected to be launched in 2025.

NASA is working on a satellite network project, called Lunar Geophysical Network (LGN)[59], as part of its New Frontiers program. This has a completely different purpose; in fact, LGN will perform geophysical observations of the lunar structure, internal and superficial, to understand the processes of formation, differentiation and persistence (or not) of internal dynamics in planetary evolution. This is because the Moon preserves records of the near-Earth cosmic environment in the young history of the Solar System therefore, it is a natural target to study the earliest stages of terrestrial planet evolution (Crawford I.A., 2004), a primary scientific value of the Moon. LGN is designed as a set of four landers to be deployed in different locations across the lunar surface, including the farside. These will all be equipped with the same scientific instruments plus solar power cells. The spacecraft that will carry and deploy the landers on the Moon, will later remain on a 250 km circular polar orbit and serve as a relay communication satellite to receive data from the unit placed on the farside and transmit it to Earth. The landers are expected to have a relatively long duration, from 6 to 10 years, to allow maximum collection of information for important science achievements. Eventually, additional units could be added during the mission as an outcome of new commercial partnerships.

4.3 Future lunar landings

The Moon has become a very desirable destination for institutional and commercial organizations. In the international scene, space agencies, commercial companies and industry are teaming together to define common profit from a landmark lunar exploration.

In the graph in Figure 8 below, I provide an overview of the lunar missions that have been recently undertaken and the ones planned for the coming years. This is an updated schema of the one available on the official ESA website[60].

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[57]https://bsgn.esa.int/2023/03/17/who-will-deliver-lunar-pathfinder-to-the-moon-orbit
[58]https://crescentspace.com/
[59]https://science.nasa.gov/science-red/s3fs-public/atoms/files/Lunar%20Geophysical%20Network.pdf
[60]www.esa.int/ESA_Multimedia/Images/2019/07/Lunar_missions_overview

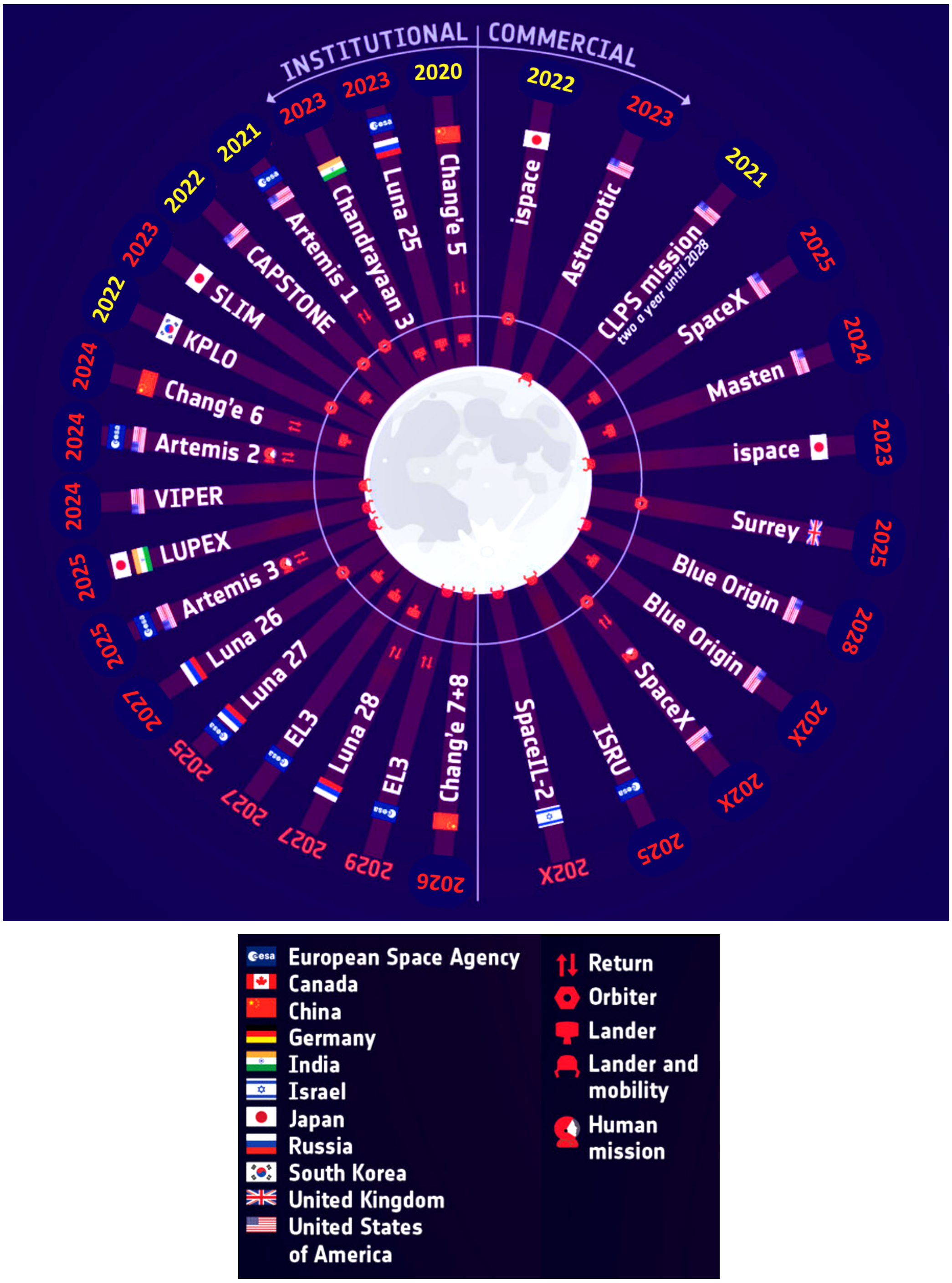

Figure 8. Top panel: Overview of the recently undertaken (yellow) and future planned (red) lunar missions divided into two main categories, institutional and commercial, according to their scopes. Bottom panel: Legend of the players and modalities for these missions. Credit: ESA

4.4 Impact on lunar astronomical science

The best mining locations on the Moon often coincide with the most valuable locations for scientific experiments, notably the cold traps in the PSRs at the lunar poles (chapter 3). Resource extraction operations and the placement of sensitive telescopes are prima facie conflicting goals. Unregulated mining activities on the Moon are likely to throw up enormous amounts of dust and rocks up to great heights in the Moon's reduced gravity; on the other hand, the dust will settle quickly without an atmosphere to keep it up. This is deleterious for the operation and integrity of any components of scientific instruments, such as mechanisms or exposed optical surfaces. For GW observatories that measure tiny vibrations, the seismic noise induced by extraction activities are particularly harmful.

Detecting the $21 - cm$ signature from the Dark Ages requires the most radio silent environment possible; the lunar farside is the only place that could allow that. In general, the targets of opportunity for astrophysics (cosmology) at low frequencies are in the range $50 - 100\,MHz$ (chapter 3). While relay communication satellites operate at GHz or above ranges thus, do not create major radio interference, the main issue of concern is the leakage of electronic noise from instruments either onboard satellites, of surface facilities and from power supplies. Their architecture and operational mode should be properly designed not to interfere with the signal of interest. For instance, electronics components should be properly enclosed within Faraday cages[61] to reduce their radio emission. However, the chance to completely avoid RFI leakage from electronics seems rare and with the upcoming overcrowding on the farside of the Moon, and all the instrumentation associated, the radio noise is likely to worsen significantly.

Furthermore, some minor level of RFI is produced by the diffraction of human made FM frequency waves ($88 - 108\,MHz$) around the limb of the Moon (Bassett et al., 2020).

[61]https://ceptech.net/resources/understanding-emi-rfi-shielding-to-manage-interference/

Chapter 5: Cis-lunar policy framework

In this chapter, I elaborate on a policy and legal analysis of outer space activities. First I investigate the actors interested in lunar operations. Then, I examine the main international laws and their implications in the contemporary lunar exploration landscape. Then, I focus on the innovation and "controversiality" of the US-led Artemis Accords, to understand the possibilities and challenges they introduce. The core questions to address in this section are:

- To what extent do the Artemis Accords respect the framework established by previous regulations?
- Are the new planned lunar activities in line with the main principles of international outer space law? Or do they violate/misinterpret laws for private gain?
- Are new principles needed to preserve the most valuable lunar sites for scientific experiments?

5.1 Actor analysis

The domain of lunar exploration and resource exploitation has evolved in a complex net of interconnected interests. The necessity for action to protect SESIs from the harmful effects of commercial activities is a delicate matter that involves various actors in several fields. These all have different levels of influence and interest in a new space governance regime. The main actors individuated are reported in the schema in (Figure 9) and their relationships indicated with the colored arrows. In addition, they are listed in Appendix E, in an order that reflects their interest in the preservation of SESIs.

Space agencies have multiple objectives on the Moon; on the one hand, they aim at testing their capacities to sustain long-term lunar exploration, relying mostly on lunar resources. For this purpose, they partner with private companies, key players in the emerging lunar economy, for transport and extraction services. On the other hand, space agencies might support scientific research for unprecedented discoveries. Therefore, they are interested in valuable lunar locations for opposing purposes but mostly seeking to maximize the utilization of raw materials on the Moon as an opportunity for future deep space missions.

In the lunar exploration framework, the UN COPUOS is the only authority with decisional power that could regulate the utilization of lunar resources for common benefit and with the view of protecting highly valuable lunar sites for science.

The IAU shares its interests in the preservation of SESIs with other organizations representing the astronomical community. However, unlike the others, the IAU is global. The IAU has only recently decided to actively investigate lunar preservation. The IAU, being the largest astronomical organization, being world-wide, being involved in space policy matters for a long time, and being already connected with the UN COPUOS, is likely to play an influential role in getting the protection of lunar astronomy considered at the highest policy levels. In this context, the cooperation of different organizations is key to eliciting the science needs and communicating them to commercial actors and policy makers, with the view of achieving a potential agreement.

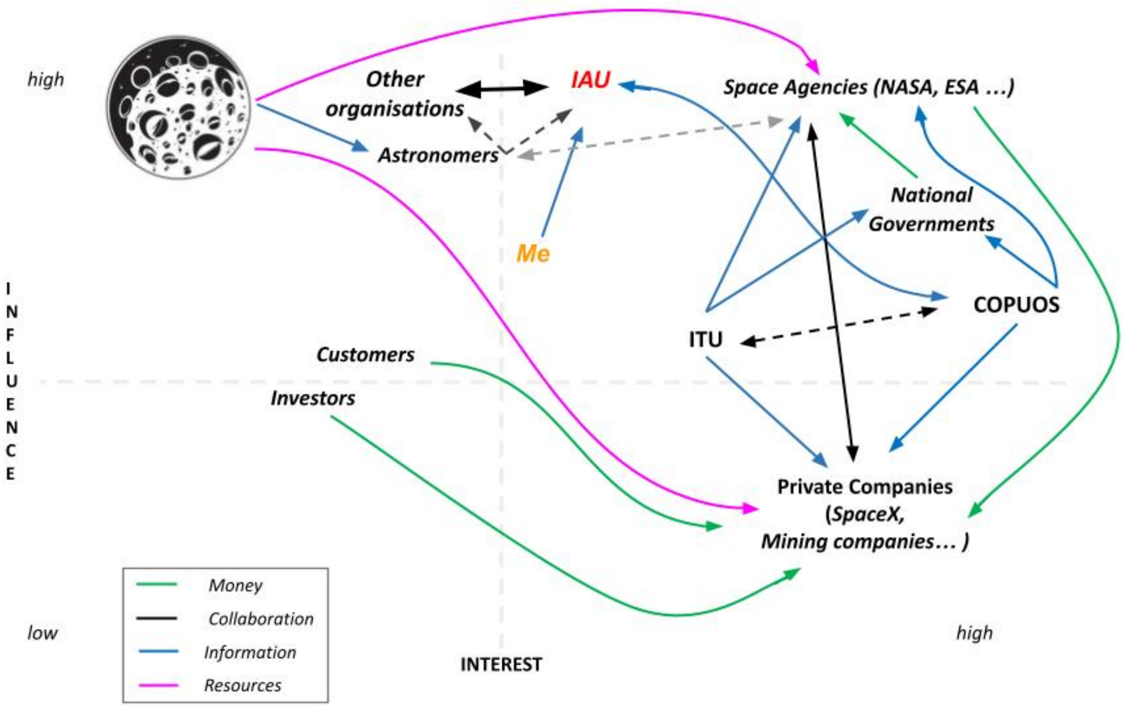

Figure 9: Influence and interest for different lunar actors. Each has individual levels of influence and interest in the protection of lunar sites for scientific instruments. Some of the stakeholders are passively/oppositely involved in the matter. Dotted lines are used when actors/organizations are part of other organizations. The dashed line between astronomers and space agencies is gray because only a fraction of astronomers work for space agencies, most of them work for universities and non-profits.

5.1.1 Space sustainability rating

Some of the driving motivations of company actions are attracting investors. Nowadays, many venture capital companies are more sustainability-oriented, therefore, it is to the operating company's advantage to show they are taking a sustainable approach in their operations so as to be more attractive to investors and customers.

An interesting concept, at the moment more relevant in LEO, is the "space sustainability rating". This implies that space actors get voluntarily rated on the basis of how good space citizens they are being, which means reliable, respectful of others and with the least possible impact on astronomy. By analogy, it could be used as an incentive to create a sustainable cis-lunar environment.

5.2 Overview - Policy

There is an existing, articulated, legal/policy framework around the use of outer space, the modalities allowed for extraterrestrial missions, and the use of the resources of celestial bodies. The 1967 Outer Space Treaty (OST) has governed space (and thus lunar) exploration for decades and continues to be the main international legal regime for space. The 1979 Moon Agreement consolidated principles in the OST; however, it is not in force anymore. In the specific case of radio frequency allocation, particularly in geostationary equatorial orbit (GEO), the rules of the International Telecommunication Union (ITU - RR) complete the regulatory picture. The Rescue Agreement, The Liability Convention and The Registration Convention are regulations that recall and re-elaborate principles included in the OST. The renewed interests in both robotic and human long term presence on the Moon pose challenges for the whole system. The 2020 US-led Artemis Accords have introduced a level of "controversial" innovation and uncertainties in the lunar governance. To what extent the Artemis Accords will be disruptive is difficult to assess because some principles in the Artemis Accords, even if grounded in the OST, seem to be vague and thus open to different interpretations. To better understand the Artemis Accords changes and how they challenge the existing legal regime it helps to first analyze the lunar sets of regulations individually.

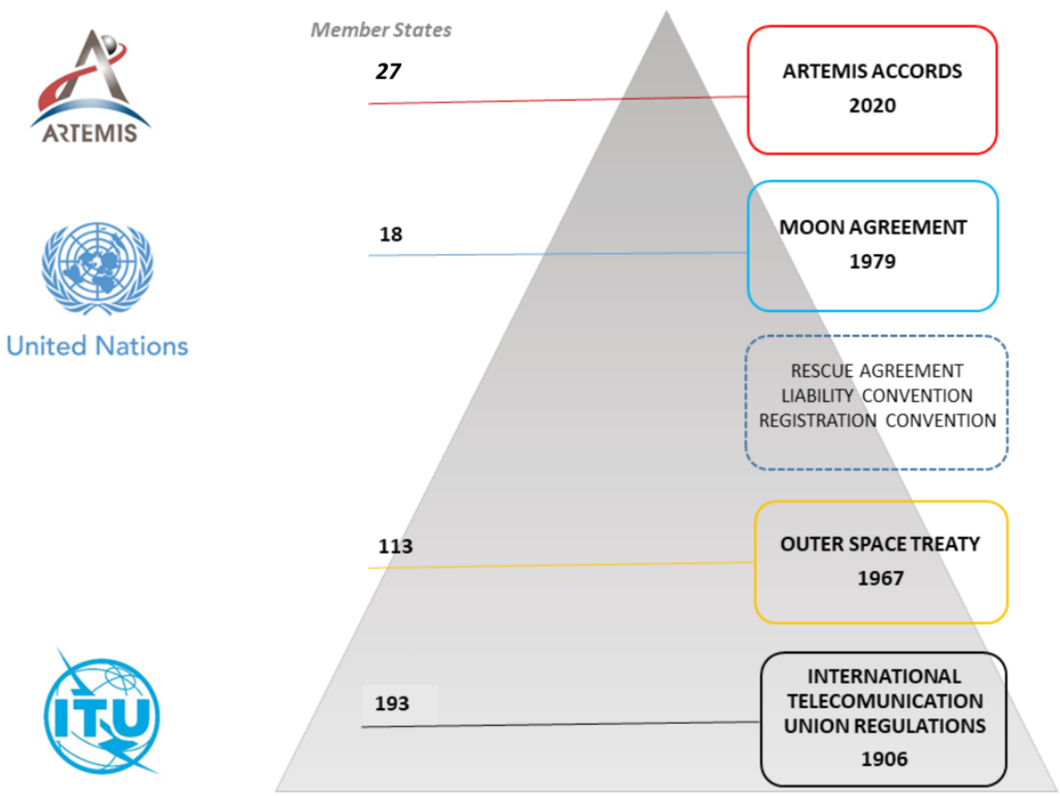

Figure 10: The main collections of provisions that represent the International legal/policy framework for outer space governance in the radio frequency regime.

5.3 Individual Agreements

5.3.1 International Telecommunication Union Radio Regulations

The International Telecommunication Union (ITU)[62] is the UN specialized agency for communication technology and the governance of the worldwide use of radio frequencies for different applications.
It was founded in 1865 as an autonomous organization, cooperating with governments and the private sector to facilitate connectivity in international communication networks. It is based in Geneva and it currently counts 193 Member States as well as a membership of 900 companies, universities, and other organizations.

The international regulations that coordinate the global use of the radio spectrum are collected in the **ITU Radio Regulations (RR)[63]**, which represents an international Treaty.

Among the different areas of application of ITU's work there is the allocation of radio frequencies to radio astronomy as well as the participation in assigning satellite orbits. Radio astronomy has 1.8% of allocated frequencies below $40\ GHz$ from Earth as most of the radio spectrum is distributed to other services (Gyula Jozsa, IAA committee meeting, March 2023). The situation is opposite on the Moon. In fact, ITU recognises the unique value of the lunar farside as a shielded zone from human RFI as well as for the lack of an atmosphere; therefore, it is an ideal place for astronomical observations in the low radio frequency range, $20 - 1000\ MHz$. Article 22 (sections 22.22 to 22.25) [64] of the ITU RR declares it an "area with great potential" and claims its protection from radio noise. This provision entitles radio astronomy, and other space research, to use all radio frequencies on the lunar farside, with the only admitted exceptions being radio communication satellites to transmit data to Earth. Thus, the official question ITU is trying to address concerns the coordination of frequencies for transmitters in the shielded zone of the Moon that should not interfere with the sensitive experiments. Some useful information comes from the Chinese mission, Chang'e 4, the first to land on the farside of the Moon in 2019. The frequency range used to communicate data back to Earth was around $11\ GHz$, above the desirable band for astronomical observations. Similarly, NASA's lunar Gateway must meet technical requirements to avoid producing any radio noise in the target range.
However, as experts in the field have pointed out, a more serious issue is the leakage of radio frequency interference from electronics either onboard satellites or of surface facilities and power supply (Burns J.O., IAA committee meeting, March 2023). Therefore, it is crucial to know the noise level that can be tolerated before the experiments cannot be conducted anymore.

[62]www.itu.int
[63]www.itu.int/hub/publication/r-reg-rr-2020/
[64] life.itu.int/radioclub/rr/art22.pdf

Considerations

The only optimal place to conduct low frequency radio observations of the early universe is the Moon. However, the artificial electromagnetic interference (EMI) from any instrumentation, that will sum to the unavoidable galactic foreground, can be harmful to the signal detections. There are two crucial steps that must be undertaken very soon:

- ★ Astronomers need an agreement on the upper limit on the aggregate level of artificial EMI that their experiments could tolerate before these are considered unsuccessful.
- ★ The scientific community, the competent authorities and ITU should collaborate to set up technical standards for human activities on the lunar surface and in lunar orbits.

5.3.2 Outer Space Treaty

The Outer Space Treaty (OST)[65] is formally known as the T*reaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon And Other Celestial Bodies*. It was established in 1966 by the United Nations General Assembly (UNGA) and was first signed by the Russian Federation, the United Kingdom and the United States of America in January 1967. It became active in October 1967 and still represents the basic framework for developing the law of outer space. The OST is currently agreed by 113[66] countries across the world (Table 5); these will be later referred to as “States Parties to the Treaty” (or simply “States”).

The OST comprises seventeen articles that promote "peaceful purposes" for outer space missions and the "non-appropriation of celestial territories" by any country. These principles are elaborated in Appendix D, using key words that highlight their context; their complete text can be found on the official UNODA web page[67].

The principles of the OST were written when space travel was still in its infancy. Therefore, they are formulated as general principles and do not specify how to practically implement these principles to space resource utilization (Krolikowski A. & Elvis M., 2022). Therefore, they require further clarification to serve as governing regulations for individual activities and the Artemis Accords (claim to) do that.

[65]www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html
[66]https://treaties.unoda.org/t/outer_space
[67] United Nations Office of Disarmament Affairs. https://treaties.unoda.org/t/outer_space

Considerations

On the one hand, Article II of the OST literally states "*Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.*". On the other hand, there is no prohibition on putting installations on the Moon. This pair of statements makes it obvious to ask: for how long are States Parties to the Treaty entitled to use their installations on the Moon before it becomes appropriation?

Article XII states the principle of free access to all facilities on the Moon (of all States), based on the value of reciprocity. But Article IX, instead, concerns the necessity to avoid harmful interference between States and their activities, saying they all should act with "due regard" to one another. This means there are specific conditions to access others' spaces, but specifying no mechanism for resolving disagreements. In this blurry framework: what is the limit of free access and what is considered harmful interference?

The OST does not include any clear provision that protects the scientific value of outer space locations from being damaged by alternative utilization.

★ The values of peaceful exploration, non-appropriation of resources and "due regard" in provision IX, could be used as the bases for defining a process for the protection of SESIs. In this context, it is crucial to ask for a UN COPUOS resolution as a practical realization of what is stated in the OST.

5.3.3 The Moon Agreement

The Moon Agreement was considered to be the second important Treaty in the legal regime for the use of celestial bodies, orbits and trajectories within the Solar System. It was negotiated by the United Nations in 1979 and entered into force for the signatory States only in 1984 to consolidate the ban of military applications and national sovereignty of outer space territories, stated into the OST. Principles in the Moon Agreement were in perfect continuity with those in the OST. International cooperation, clear communication and mutual assistance were the main promoted values for achieving a peaceful and safe cis-lunar exploration and utilization for all mankind. The twenty-one Articles of the Moon Agreement are listed and briefly described in Appendix D; for the complete text refer to the link[68]. However, the Moon Agreement is not operational anymore (Krolikowski A. & Elvis M., 2022).

[68]https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/moon-agreement.html

5.3.4 Artemis Accords

On 13 October 2020, eight founding members signed the Artemis Accords. Later, other states joined and as of June, 2023, there are 27 signatory States (Table 5). The Artemis Accords are multi-lateral agreements among the US and other countries and they are crafted to govern civil exploration and regulate the use of space resources for a common benefit, but clearly affirming the US leadership. They are non-binding, so not legal provisions (as of yet!).

The Artemis Accords represent a modern effort of promoting a space policy based on international space law but that, at the same time, reflects the aspirations and potentialities of a technologically advanced society. These provisions are presented as an operationalisation of the obligations contained in the OST, however, in a deep analysis, they appear highly innovative. The thirteen sections included in the Artemis Accords are listed and briefly elaborated in Appendix D, while the complete expression can be found in one of the indicated links[69].

5.4 Artemis Accords compared with other space Agreements

5.4.1 Artemis Accords vs. Outer Space Treaty

US-led Artemis principles are presented as simple, intuitive and universal; they are grounded in the OST, as they attempt to strengthen and implement its obligations. However, they introduce a certain degree of innovation that can be read in a quite “controversial” tone.

While in Section 10 of the Artemis Accords, on “Space resources'', it is stated that resource extraction and utilization should not translate into any kind of national appropriation, in accordance with the OST, the following section, on “Deconfliction of Space Activities'' (11), introduces the ambiguous concept of “safety zones''. In a safety zone the recipient Signatory State is allowed to conduct its planned activities without any external interference, but still communicating all relevant information to the others. That mechanism attempts to efficiently regulate the use of outer space resources in a globally agreed environment and to prevent harmful interference among operations. However, it generates substantial room for ambiguity and disparity. Safety zones may be used to legitimize effective private ownership of the resources within the safety zone. Because lunar resources are concentrated (Chapter 2) safety zones can be used to exclude others. Arguably, this quasi-property is possible within the OST (Elvis M., Milligan T. & Krolikowski A., 2016), incompatibly with the principles in the OST. Furthermore, they are likely to favor the highly established and emerging spacefaring states, with lower or no regard for the less developed ones, again deviating from the “common benefit” and “equality” values stated in the OST.

★ A point of continuity between the OST and the Artemis Accords is a lack of a clear coordination of space activities with prioritization of scope per location. The protection of lunar locations for science objectives is neither stated nor inferable in any section.

[69] www.nasa.gov/specials/artemis-accords/index.html,
www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf

★ There should be zones exclusively dedicated to science in global agreement. And they should be regulated in the Artemis Accords, like they do with safety zones

5.4.2 Artemis allies and non-allies

NASA’s Artemis Programs intend to affirm a leading position of the US in the new emerging lunar economy, while reinforcing international partnerships[70]. Currently, the US is the world’s most developed nation in commercial space exploitation and with the most ambitious space policy goals to date. Not surprisingly, the Artemis Programs have provoked mixed reactions among different countries, as a reflection of their individual stake in outer space activities.

On the one hand, the operations promoted by the Artemis Programs will have major benefits for active spacefaring states that can count on developed private firms to advance emerging lunar industries. Their activities are facilitated by the Artemis Accords and the national appropriation of the extracted resources legitimized. Therefore, in the near future, Signatories of the Accords will have early access to the lunar exploitation business.

On the other hand, the diverging position of states that are less operational in space and not sustained by services from private companies will see minor/no gains. In addition to the minor or non-spacefaring States, two major spacefaring states, Russia and China, stand out as the most committed opponents of the “US-centered” Artemis Programs, and are sharing efforts to establish their own lunar base (Krolikowski A. & Elvis M., 2022).

An intriguing case is that of Australia[71], which is a signatory of two opposite sets of agreements, which raised curiosity about, and criticism of its position. Australia’s decision to join the Artemis Accords seems logical in the view of seeking visibility for its space capacities and the prospect of economic profits for that mining nation. However, Australia might need to revisit its permanence in the Moon Agreement and give notice of withdrawal under Article 20, since the other States Parties to the Artemis Accords might consider its double commitment controversial (Tronchetti & Liu, 2021).

Germany, a big spacefaring nation, has not signed the Artemis Accords, consistent with a spreading European trend. Actually, there is a fragmented response to the Artemis Accords in Europe as a few EU countries have signed the Accords (Table 5).

ESA is not empowered to sign the Artemis Accords, as they are at the national level, not the organizational level. However, ESA has signed with NASA a Memorandum of Understanding (MoU)[72]: the two big space agencies will join efforts in launching the Lunar Gateway, with three flight opportunities for European astronauts.

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[70]https://www.nasa.gov/specials/artemis/

[71]https://www.internationalaffairs.org.au/australianoutlook/australia-between-the-moon-agreement-and-the-artemis-accords/

[72]https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Gateway_MoU_and_Artemis_Accords_FAQs

Table 5: Nations that signed the main agreements for outer space exploration and utilization, as of March 2023.

1967 Outer Space Treaty	1979 Moon Agreement	2020 Artemis Accords
113 States Parties	Armenia Australia Austria (EU) Belgium (EU) Chile Kazakhstan Kuwait Lebanon Mexico Morocco Netherlands (EU) Pakistan Peru Philippines Saudi Arabia Turkey Uruguay Venezuela	Australia* Bahrain Brazil Canada* Columbia Czech Republic (EU) Ecuador France (EU) India Israel Italy (EU)* Japan* Luxemburg (EU)* Mexico New Zealand Nigeria Poland (EU) Republic of Korea Romania (EU) Rwanda Saudi Arabia Singapore Spain (EU) Ukraine United Arab Emirates* United Kingdom* United States of America*, **
		**Leading State *Founding members

In response to the necessity of clarifying the contemporary framework for the use of outer space resources, in 2022 UN created a new Working Group on the Legal Aspects of Space Resource Activity under COPUOS. Within a 5-year-mandate, it is expected to address space resource issues unresolved by the OST by studying modern space-related operations of an innovative nature[73].

[73]https://www.thespacereview.com/article/4534/1

Considerations

The Artemis Accords are controversial with respect to the OST and the Moon Agreement as they tend towards legitimizing the national appropriation of outer space resources through the mechanism of safety zones, originally proposed to prevent harmful interference.

In this way the Accords encourage the domination of developed spacefaring states in the emerging lunar economy, leaving all the others behind.

The US clearly has a leading position in the space resource exploitation arena and a lot to gain from the Artemis Accords. In the next half-decade, the US and its partner nations, including powerful private firms performing on their behalf, are likely to start an unprecedented utilization of outer space resources and to begin to create flourishing lunar industries. Accordingly, there is also a robust opposition to the US-centered Artemis programs in the name of a more equal share of resources[74].

The Artemis Programs are presented as a policy breakthrough for both science and commercial activities on the Moon, but a clear coordination and prioritization of scope per location is not explicitly included. The long-term permanence on a celestial body, like the Moon, does imply the need of certain resources, including water or regolith, to be used in situ. Therefore commercial activities are crucial to support any outer space missions. However, the concentration of such resources in unique lunar sites should not completely obscure the possibility of pursuing scientific objectives.

★ In the framework of the Artemis Accords, the establishment of SESIs by a process to be determined by the States should be allowed. Therefore, exclusive zones should include internationally recognized scientific activities.

5.5 Artemis Programs from different perspectives

The Artemis programs are committed to an imminent exploitation of lunar resources to sustain a long-term robotic and human presence on the Moon. They carry both opportunities and threats, summarized in the schema below (Figure 11), in social, ethical, political and also scientific frameworks.

[74] https://www.northumbria.ac.uk/about-us/news-events/news/expert-comment-why-many-countries-are-refusing-to-sign-moon-exploration-agreement/

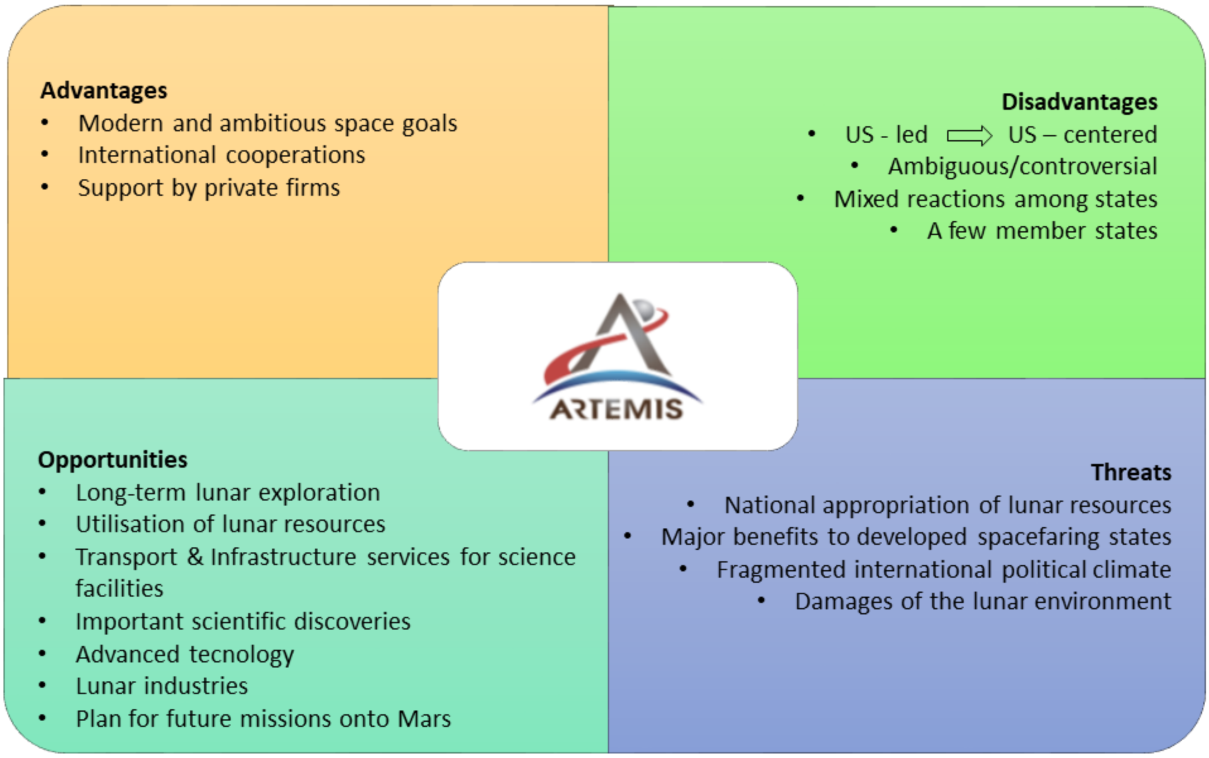

Figure 11: Advantages, Disadvantages, Opportunities and Threats of the Artemis Accords

The entry of the private sector into space operations has significant benefits including: (1) the growth of the national economy; (2) the provision of scientific, including astronomical, facilities on the Moon; (3) other infrastructure on the Moon; (4) the provision of communication and network services; (5) the provision of technologies to extract and use the resources in situ, essential for long-term exploration and science experiments on the Moon.

On the other hand, the US-promoted operations for national interests are likely to create disparities and political tension among states. The biggest risk associated is the effective ownership of valuable resources for national economic and strategic gains.

Moreover, commercial activities could be harmful for the local environment and, if not well regulated, they will cause changes of lunar territories and the loss of their intrinsic and scientific value. The counter argument is that there is no "environment" on the Moon; it is a dead rock.

★ With a very ambiguous plan of actions, the Artemis Accords need to be elaborated more clearly.

Chapter 6: Summary - Integration of science and policy

The Moon offers great opportunities for astrophysical research. The lunar farside is the perfect place for performing cosmological measurements of the 21 cm hydrogen signal of the Dark Ages to study the epochs before the formation of stars and galaxies. This is extremely important to understand processes in cosmic evolution and test the physical model we currently use to describe our universe - the “concordance cosmology”. The potential cosmology achievements might also be a breakthrough for fundamental physics, elucidating the nature of Dark Energy. Furthermore, the coldest traps of permanently shadowed craters at the lunar poles are optimal locations to host future IR facilities of large dimensions; the very low temperatures of such regions create natural cooling that is essential for a range of scientific missions such as far-infrared telescopes or radio interferometers. Additionally, PSRs, with a much lower seismic noise than that of Earth, offer the advantage to achieve the highest sensitivity for the detection of deci-hertz GWs.

The places with the most valuable scientific importance on the Moon are few and they tend to coincide with the sites of the most concentrated valuable resources. These are, nowadays, the targets of a variety of actors, from space agencies who seek to test technologies and capabilities for deep space exploration, to private entities who envision the profitability of the emerging lunar market. Scientific and commercial activities cannot readily share spaces. They need to have their own “exclusive zones” to avoid interfering with each other. Furthermore, the mechanisms of all missions are likely to break the radio silence of the farside, hindering the much desired science purposes.

The current law of outer space, represented by the OST, does not pay particular attention to the preservation of SESIs for scientific objectives. Whereas, the Artemis Accords focus on the appropriation and utilization of resources, giving major consideration to commercial rather than scientific activities. In a potentially overcrowded lunar landscape, a new governance structure is needed, tailored to the contemporary situation, to clarify and coordinate all conflicting lunar operations. The UN COPUOS should soon consider this issue and adopt a course of actions for preserving unique areas for lunar science.

6.1 The most valuable lunar sites for science identified to date

Following the studies of Le Conte et al., 2023 and Elvis M., 2023, a preliminary list of lunar sites of greatest interest to astronomy, for different studies, is given in Table 6. They need protection against alternative uses. The priority flag is assigned considering different criteria: sites with flag 1 have the best geological/environmental conditions to host sensitive experiments and facilitate instrument operationality thus, the most urgent to protect. I have also considered the concentration of resources (water and minerals) in them: when sites are very highly concentrated in essential materials they are more likely to be dedicated to commercial activities so I put a flag 2; however, if they are also extremely valuable for science a delicate negotiation is required.

Table 6: Lunar sites to be preserved for lunar science, with details about location, size and science scope. The priority flag is meant to highlight the ones that must be devolved to science soon (Flag 1), the others can be negotiated (Flag 2).

Lunar Site	Science Objective	Diameter (km)	Presence of resources	Location	Priority Flag
Mare Moscoviensis	Cosmology	276	Helium-3, FeO	Farside	1
Korolev crater	Cosmology	437	-	Farside	1
Mendeleev crater	Cosmology	325	-	Farside	1
Schrödinger basin	Low frequency radio measurements	316	Water	South Pole	1
Faustini crater	Gravitational Waves	42	-	South Pole	1
Shoemaker crater	Gravitational Waves	52	Water	South Pole	2
Hermite crater	OIR	109	-	Farside	1
Shackleton crater	OIR	21	Water	South Pole	2
Peaks of Eternal Light	Solar Panels	-	-	-	1
Stable lunar orbits	Multiple: Nav/comm	-	-	-	1

Chapter 7: Recommendations & strategies for implementation

The advice to the IAU given below is based on (1) a combination of the scientific findings, (2) the analyses of the legal and policy framework around the utilization of outer space, (3) the nature of the IAU portfolio, and (4) the identification of the diverse players interested in lunar operations for conflicting goals. This is a complex context with economic, political, social and cultural implications, beyond the scientific considerations. Furthermore, the technical requirements established in the advice follow the conversations with expert scientists in the field (Burns J.O., personal communication).

For specific requests of the company, the advice is formulated in more general so less prescriptive terms. The main reason is that the communication with the UN COPUOS, the highest possible policy level, is delicate and must be mediated with a gentle tone to be more effective for considerations and resolution.

7.1 Final Advice

My final advice to the IAU covers four points:

- The keynote of the whole picture is the need for a rational **classification of lunar sites**. Some could be used for extraction of resources, while the scientifically most valuable need to be protected for science. Therefore, the IAU should be the place for collecting the consensus among the whole astronomical community upon the highest priority objectives achievable from the Moon, and the site criteria that allow these objectives to be realized, in both near- and long-term scenarios. This will result in a selection and prioritization of the prime sites that need to be devoted to sensitive experiments, and protected from alternative activities.

  The scarcity of optimal places could be mediated through the IAU, for example, by assigning a specific time duration to individual experiments and make the scientific facilities be applicable for different purposes and used by different science missions (when possible), for the common benefit. After all, astronomy is for all and requires global efforts.

  To conclude my analysis of the science, a preliminary list of the lunar locations with the highest scientific value for astronomy is presented (chapter 6). A more carefully considered and detailed list needs to be agreed upon by astronomers, through the IAU, as the actual highest priority one so then, they can start a process for protection.

- The **UN COPUOS** is the international body able to provide a modern interpretation of the OST with respect to the preservation of scientific sites and therefore produce regulations to protect science objectives from the Moon. The IAU should make common cause with other scientific organizations and even take a leading position to urge the UN COPUOS, through the IAU's observer status, to activate a process for the protection of SESIs.

- A possible criterion for the favorable conditions for sensitive observations could be that the **artificial contribution must not exceed 10% of the natural contribution of radio noise** by the Galactic emission at low frequencies. This is a general requirement that concerns the *cumulative* impact of all artificial farside sources of emission, i.e. the aggregate effect of all missions.

  However, more precise conditions should be soon identified by the relevant astronomy community. Therefore, the IAU should promote the importance that single experiments are aware of the radio interference they can tolerate before they exceed their allotted fraction of the emission. When such estimates are available, the IAU should work with the ITU to set them as official requirements.

  The constraints to respect for maximizing profit are many and might not be all known as of now. For instance, to **keep the lunar farside radio quiet,** so as not to create interference with the very sensitive experiments, technical requirements are: putting Faraday screens around the electronics and restrictions on landing sites. Another general requirement is the dust control of every operation.

- An "Astronomy Impact Factor"? By analogy to the space sustainability rating in LEO, discussed in subsection 5.1.1, the IAU should provide or support a system of comparative ratings to lunar projects based on their impact on astronomy so as to push them to become “space-sustainable”.

7.2 Future implementation

Three are the main points for the implementation of the advice; these are shown in Figure 12 and described below.

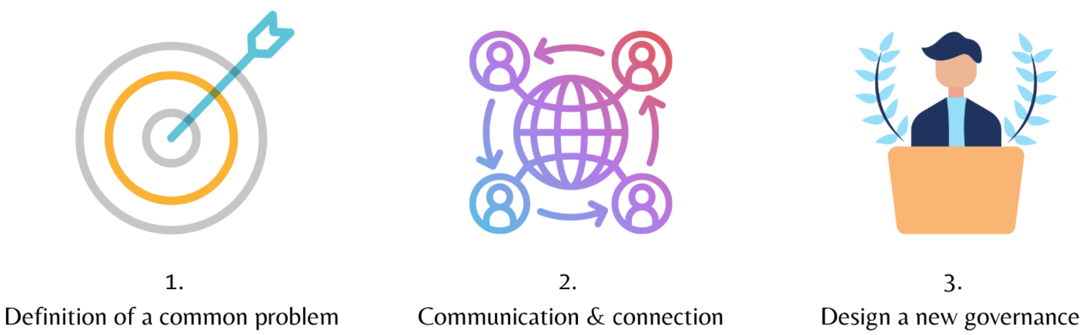

Figure 12: Three main steps for the strategy implementation

First phase: science to science

There are important steps that should be undertaken inside the astronomical community itself. Astronomers who want to be actively involved in the preservation of lunar SESIs should soon: (1) agree on the lunar sites that should have priority for protection against alternative uses; (2) cooperate to define technical requirements for sensitive lunar experiments before they become obsolete.

In this context, I advise the IAU to take a leading position, for example by forming a dedicated working group to study lunar matters. This could be set up within the Commission B7, as a natural extension of its mission for the protection of existing and potential astronomical observatories. The members of this new working group would be either astronomers that are impacted by the option of lunar science or simply interested in a stake for the preservation of the scientific value of the Moon. To make the process start, Commission B7 should coordinate informal community workshops and conferences for prioritization as well as approach the elective officers of the IAU to stimulate new cooperation with other professional societies interested in the preservation of lunar sites.

Second phase: science to private sectors

The IAU should set up an interface with and talk to commercial industry and space agencies on behalf of science to make sure their plans are aware of the scientific issues. In doing so, the IAU should proceed hand in hand with the IAA, which is already moving some steps forward in raising this awareness in a more multidisciplinary setting.

Third phase: science to governments

The IAU should align with other professional societies (e.g.. the IAA) and non-profits (e.g. For All Moonkind) and take a leading position in approaching the UN COPUOS to get the problem of protecting lunar astronomical science addressed during the 5 year study of the "Working Group on Legal Aspects of Space Resource Activities”.

References

Aasi, J., Abbott, B. P., Abbott, R., Abbott, T., Abernathy, M. R., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R. X., Adya, V., Affeldt, C., Aggarwal, N., Aguiar, O. D., Ain, A., Ajith, P., Alemic, A., Allen, B., Amariutei, D., … Zweizig, J. (2015). Advanced LIGO. *Classical and Quantum Gravity*, *32*(7), 074001. https://doi.org/10.1088/0264-9381/32/7/074001

Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R. X., Adya, V. B., Affeldt, C., Agathos, M., Agatsuma, K., Aggarwal, N., Aguiar, O. D., Aiello, L., Ain, A., Ajith, P., … Zweizig, J. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters*, *116*(6), 061102. https://doi.org/10.1103/PhysRevLett.116.061102

Acernese, F., Agathos, M., Agatsuma, K., Aisa, D., Allemandou, N., Allocca, A., Amarni, J., Astone, P., Balestri, G., Ballardin, G., Barone, F., Baronick, J.-P., Barsuglia, M., Basti, A., Basti, F., Bauer, Th. S., Bavigadda, V., Bejger, M., Beker, M. G., … Zendri, J.-P. (2014). *Advanced Virgo: a 2nd generation interferometric gravitational wave detector*. https://doi.org/10.1088/0264-9381/32/2/024001

Adams, F. C., Bond, J. R., Freese, K., Frieman, J. A., & Olinto, A. v. (1993). Natural inflation: Particle physics models, power-law spectra for large-scale structure, and constraints from the Cosmic Background Explorer. *Physical Review D*, *47*(2), 426–455. https://doi.org/10.1103/PhysRevD.47.426

Akutsu, T., Ando, M., Arai, K., Arai, Y., Araki, S., Araya, A., Aritomi, N., Asada, H., Aso, Y., Atsuta, S., Awai, K., Bae, S., Baiotti, L., Barton, M. A., Cannon, K., Capocasa, E., Chen, C.-S., Chiu, T.-W., Cho, K., … Zhu, Z.-H. (2018). *KAGRA: 2.5 Generation Interferometric Gravitational Wave Detector*. https://doi.org/10.1038/s41550-018-0658-y

Arden L. Albee, in. (n.d.). Lunar Rocks. In *Encyclopedia of Physical Science and Technology (Third Edition), 2003*

Amaro-Seoane, P., Audley, H., Babak, S., Baker, J., Barausse, E., Bender, P., Berti, E., Binetruy, P., Born, M., Bortoluzzi, D., Camp, J., Caprini, C., Cardoso, V., Colpi, M., Conklin, J., Cornish, N., Cutler, C., Danzmann, K., Dolesi, R., … Zweifel, P. (2017). *Laser Interferometer Space Antenna*.

Amaro-Seoane, P., Bischof, L., Carter, J. J., Hartig, M.-S., & Wilken, D. (2021). LION: laser interferometer on the moon. *Classical and Quantum Gravity*, *38*(12), 125008. https://doi.org/10.1088/1361-6382/abf441

Bale, S. D., Bassett, N., Burns, J. O., Jones, J. D., Goetz, K., Hellum-Bye, C., Hermann, S., Hibbard, J., Maksimovic, M., McLean, R., Monsalve, R., O’Connor, P., Parsons, A., Pulupa, M., Pund, R., Rapetti, D., Rotermund, K. M., Saliwanchik, B., Slosar, A., … Suzuki, A. (2023). *LuSEE “Night”: The Lunar Surface Electromagnetics Experiment*

Bassett, N., Rapetti, D., Tauscher, K., Burns, J., & Hibbard, J. (2020). *Ensuring Robustness in Training Set Based Global 21-cm Cosmology Analysis*. https://doi.org/10.3847/1538-4357/abdb29

Benna, M., Mahaffy, P. R., Halekas, J. S., Elphic, R. C., & Delory, G. T. (2015). Variability of helium, neon, and argon in the lunar exosphere as observed by the LADEE NMS instrument. *Geophysical Research Letters*, *42*(10), 3723–3729. https://doi.org/10.1002/2015GL064120

Bowman, J. D., Rogers, A. E. E., Monsalve, R. A., Mozdzen, T. J., & Mahesh, N. (2018). An absorption profile centred at 78 megahertz in the sky-averaged spectrum. *Nature*, *555*(7694), 67–70. https://doi.org/10.1038/nature25792

Buratti, B. (2002). High-Resolution 0.33–0.92 µm Spectra of Iapetus, Hyperion, Phoebe, Rhea, Dione, and D-Type Asteroids: How Are They Related? *Icarus*, *155*(2), 375–381. https://doi.org/10.1006/icar.2001.6730

Burns, J. O. (2021). Transformative science from the lunar farside: observations of the dark ages and exoplanetary systems at low radio frequencies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *379*(2188), 20190564. https://doi.org/10.1098/rsta.2019.0564

Burns, J. O., Bradley, R., Tauscher, K., Furlanetto, S., Mirocha, J., Monsalve, R., Rapetti, D., Purcell, W., Newell, D., Draper, D., MacDowall, R., Bowman, J., Nhan, B., Wollack, E. J., Fialkov, A., Jones, D., Kasper, J. C., Loeb, A., Datta, A., … Bicay, M. (2017). A Space-based Observational Strategy for Characterizing the First Stars and Galaxies Using the Redshifted 21 cm Global Spectrum. *The Astrophysical Journal*, *844*(1), 33. https://doi.org/10.3847/1538-4357/aa77f4

Burns, J. O., MacDowall, R., Bale, S., Hallinan, G., Bassett, N., & Hegedus, A. (2021). Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions. *The Planetary Science Journal*, *2*(2), 44. https://doi.org/10.3847/PSJ/abdfc3

Burrage, C., Copeland, E. J., & Hinds, E. A. (2015). Probing dark energy with atom interferometry. *Journal of Cosmology and Astroparticle Physics*, *2015*(03), 042–042. https://doi.org/10.1088/1475-7516/2015/03/042

Cannon, K. M., & Britt, D. T. (2020). Accessibility Data Set for Large Permanent Cold Traps at the Lunar Poles. *Earth and Space Science*, *7*(10). https://doi.org/10.1029/2020EA001291

Celoria, M., & Matarrese, S. (2018). *Primordial Non-Gaussianity*.

Chen, X. (2010). Primordial Non-Gaussianities from Inflation Models. *Advances in Astronomy*, *2010*, 1–43. https://doi.org/10.1155/2010/638979

Chen, X., Yan, J., Deng, L., Wu, F., Wu, L., Xu, Y., & Zhou, L. (2021). Discovering the sky at the longest wavelengths with a lunar orbit array. *Philosophical Transactions of the Royal Society A:*

Mathematical, Physical and Engineering Sciences, *379*(2188), 20190566. https://doi.org/10.1098/rsta.2019.0566

Chluba, J., Kogut, A., Patil, S. P., Abitbol, M. H., Aghanim, N., Ali-Haimoud, Y., Amin, M. A., Aumont, J., Bartolo, N., Basu, K., Battistelli, E. S., Battye, R., Baumann, D., Ben-Dayan, I., Bolliet, B., Bond, J. R., Bouchet, F. R., Burgess, C. P., Burigana, C., … Zannoni, M. (2019). *Spectral Distortions of the CMB as a Probe of Inflation, Recombination, Structure Formation and Particle Physics*.

Coughlin, M., & Harms, J. (2014). Upper Limit on a Stochastic Background of Gravitational Waves from Seismic Measurements in the Range 0.05–1 Hz. *Physical Review Letters*, *112*(10), 101102. https://doi.org/10.1103/PhysRevLett.112.101102

Crawford, I. A. (2015). Lunar resources. *Progress in Physical Geography: Earth and Environment*, *39*(2), 137–167. https://doi.org/10.1177/0309133314567585

de Oliveira-Costa, A., Tegmark, M., Gaensler, B. M., Jonas, J., Landecker, T. L., & Reich, P. (2008). A model of diffuse Galactic radio emission from 10 MHz to 100 GHz. *Monthly Notices of the Royal Astronomical Society*, *388*(1), 247–260. https://doi.org/10.1111/j.1365-2966.2008.13376.x

Deming, D., Seager, S., Winn, J., Miller-Ricci, E., Clampin, M., Lindler, D., Greene, T., Charbonneau, D., Laughlin, G., Ricker, G., Latham, D., & Ennico, K. (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*(883), 952–967. https://doi.org/10.1086/605913

Dicke, R. H., Peebles, P. J. E., Roll, P. G., & Wilkinson, D. T. (1965). Cosmic Black-Body Radiation. *The Astrophysical Journal*, *142*, 414. https://doi.org/10.1086/148306

Dwyer, S., Sigg, D., Ballmer, S. W., Barsotti, L., Mavalvala, N., & Evans, M. (2015). Gravitational wave detector with cosmological reach. *Physical Review D*, *91*(8), 082001. https://doi.org/10.1103/PhysRevD.91.082001

Elvis, M. (2022). Protection of Unique Astronomical Sites on the Moon. The American Astronomical Society's Committee on Light Pollution, Radio Interference and Space Debris (AAS LPRISD) submits the following response to Request for Information; Cislunar Science and Technology Subcommittee, 40282 Federal Register / Vol. 87, No. 128 / Wednesday, July 6, 2022

Elvis, M. (2023). Protecting Sites of Extraordinary Scientific Importance to Astronomy on the Moon. *Bulletin of the AAS*, *55*(2). Retrieved from https://baas.aas.org/pub/2023n2i364p04

Elvis, M., Krolikowski, A., & Milligan, T. (2021). Concentrated lunar resources: imminent implications for governance and justice. *Philosophical Transactions of the Royal Society A:*

Mathematical, Physical and Engineering Sciences, *379*(2188), 20190563. https://doi.org/10.1098/rsta.2019.0563

Elvis, M., Milligan, T., & Krolikowski, A. (2016). The peaks of eternal light: A near-term property issue on the moon. *Space Policy*, *38*, 30–38. https://doi.org/10.1016/j.spacepol.2016.05.011

Ewen, H. I., & Purcell, E. M. (1951). Observation of a Line in the Galactic Radio Spectrum: Radiation from Galactic Hydrogen at 1,420 Mc./sec. *Nature*, *168*(4270), 356–356. https://doi.org/10.1038/168356a0

Feldman, W. C., Maurice, S., Binder, A. B., Barraclough, B. L., Elphic, R. C., & Lawrence, D. J. (1998). Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles. *Science*, *281*(5382), 1496–1500 https://doi.org/10.1126/science.281.5382.1496

Flöss, T., de Wild, T., Meerburg, P. D., & Koopmans, L. V. E. (2022). The Dark Ages' 21-cm trispectrum. *Journal of Cosmology and Astroparticle Physics*, *2022*(06), 020. https://doi.org/10.1088/1475-7516/2022/06/020

Furlanetto, S. R., Peng Oh, S., & Briggs, F. H. (2006). Cosmology at low frequencies: The 21cm transition and the high-redshift Universe. *Physics Reports*, *433*(4–6), 181–301. https://doi.org/10.1016/j.physrep.2006.08.002

Furlanetto, S. R., Zaldarriaga, M., & Hernquist, L. (2004). Statistical Probes of Reionization with 21 Centimeter Tomography. *The Astrophysical Journal*, *613*(1), 16–22. https://doi.org/10.1086/423028

Gunst, A. W., & Bentum, M. J. (2010). The LOFAR phased array telescope system. *2010 IEEE International Symposium on Phased Array Systems and Technology*, 632–639. https://doi.org/10.1109/ARRAY.2010.5613300

Guth, A. H. (1981). Inflationary universe: A possible solution to the horizon and flatness problems. *Physical Review D*, *23*(2), 347–356. https://doi.org/10.1103/PhysRevD.23.347

Harms, J., Ambrosino, F., Angelini, L., Braito, V., Branchesi, M., Brocato, E., Cappellaro, E., Coccia, E., Coughlin, M., Ceca, R. della, Valle, M. della, Dionisio, C., Federico, C., Formisano, M., Frigeri, A., Grado, A., Izzo, L., Marcelli, A., Maselli, A., … Votta, R. (2021). Lunar Gravitational-wave Antenna. *The Astrophysical Journal*, *910*(1), 1. https://doi.org/10.3847/1538-4357/abe5a7

Harms, J. (2022). *Seismic Background Limitation of Lunar Gravitational-wave Detectors*. https://doi.org/10.1103/PhysRevLett.129.071102

HEWISH, A., BELL, S. J., PILKINGTON, J. D. H., SCOTT, P. F., & COLLINS, R. A. (1968). Observation of a Rapidly Pulsating Radio Source. *Nature*, *217*(5130), 709–713. https://doi.org/10.1038/217709a0

Izumi, K., & Jani, K. (2021). *Detection Landscape in the Deci-Hertz Gravitational-Wave Spectrum*. https://doi.org/10.1007/978-981-15-4702-7_50-1

Jani, K., & Loeb, A. (2020). *Gravitational-Wave Lunar Observatory for Cosmology*. https://doi.org/10.1088/1475-7516/2021/06/044

Jolliff, B. L., Hughes, J. M., Freeman, J. J., & Zeigler, R. A. (2006). Crystal chemistry of lunar merrillite and comparison to other meteoritic and planetary suites of whitlockite and merrillite. *American Mineralogist*, *91*(10), 1583–1595. https://doi.org/10.2138/am.2006.2185

Jolliff, B. L., Gillis, J. J., Haskin, L. A., Korotev, R. L., & Wieczorek, M. A. (2000). Major lunar crustal terranes: Surface expressions and crust-mantle origins. *Journal of Geophysical Research: Planets*, *105*(E2), 4197–4216. https://doi.org/10.1029/1999JE001103

Kaku, T., Haruyama, J., Miyake, W., Kumamoto, A., Ishiyama, K., Nishibori, T., Yamamoto, K., Crites, S. T., Michikami, T., Yokota, Y., Sood, R., Melosh, H. J., Chappaz, L., & Howell, K. C. (2017). Detection of Intact Lava Tubes at Marius Hills on the Moon by SELENE (Kaguya) Lunar Radar Sounder. *Geophysical Research Letters*, *44*(20), 10,155-10,161. https://doi.org/10.1002/2017GL074998

Keller, J. W., Petro, N. E., & Vondrak, R. R. (2016). The Lunar Reconnaissance Orbiter Mission – Six years of science and exploration at the Moon. *Icarus*, *273*, 2–24. https://doi.org/10.1016/j.icarus.2015.11.024

Kim, K. J., Wöhler, C., Berezhnoy, A. A., Bhatt, M., & Grumpe, A. (2019). Prospective 3He-rich landing sites on the Moon. *Planetary and Space Science*, *177*, 104686. https://doi.org/10.1016/j.pss.2019.07.001

Klindžić, D., Stam, D. M., Snik, F., Keller, C. U., Hoeijmakers, H. J., van Dam, D. M., Willebrands, M., Karalidi, T., Pallichadath, V., van Dijk, C. N., & Esposito, M. (2021). LOUPE: observing Earth from the Moon to prepare for detecting life on Earth-like exoplanets. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *379*(2188), 20190577. https://doi.org/10.1098/rsta.2019.0577

Konopliv, A. (2001). Recent Gravity Models as a Result of the Lunar Prospector Mission. *Icarus*, *150*(1), 1–18. https://doi.org/10.1006/icar.2000.6573

Krolikowski A., Elvis M. (2022). *Space Resources and Prospects for Contested Governance*. 1–17.

Labeyrie, A. (2021). Lunar optical interferometry and hypertelescope for direct imaging at high resolution. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *379*(2188), 20190570. https://doi.org/10.1098/rsta.2019.0570

Lawrence, D. J., Feldman, W. C., Barraclough, B. L., Binder, A. B., Elphic, R. C., Maurice, S., Miller, M. C., & Prettyman, T. H. (2000). Thorium abundances on the lunar surface. *Journal of Geophysical Research: Planets*, *105*(E8), 20307–20331. https://doi.org/10.1029/1999JE001177

Le Conte, Z.A., Elvis, M., and Gläser, P.A., (2023). Lunar Far-Side Radio Arrays: A Preliminary Site Survey. Royal Astronomical Society Techniques and Instruments, in press.

Li, S., Lucey, P. G., Milliken, R. E., Hayne, P. O., Fisher, E., Williams, J.-P., Hurley, D. M., & Elphic, R. C. (2018). Direct evidence of surface exposed water ice in the lunar polar regions. *Proceedings of the National Academy of Sciences*, *115*(36), 8907–8912. https://doi.org/10.1073/pnas.1802345115

Lucey, P. (2006). Understanding the Lunar Surface and Space-Moon Interactions. *Reviews in Mineralogy and Geochemistry*, *60*(1), 83–219. https://doi.org/10.2138/rmg.2006.60.2

Maillard, J.-P. (2021). Is the Moon the future of infrared astronomy? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *379*(2188), 20200212. https://doi.org/10.1098/rsta.2020.0212

Mao, Y., Tegmark, M., McQuinn, M., Zaldarriaga, M., & Zahn, O. (2008). How accurately can 21 cm tomography constrain cosmology? *Physical Review D*, *78*(2), 023529. https://doi.org/10.1103/PhysRevD.78.023529

Mather, J. C., Cheng, E. S., Eplee, R. E. , Jr., Isaacman, R. B., Meyer, S. S., Shafer, R. A., Weiss, R., Wright, E. L., Bennett, C. L., Boggess, N. W., Dwek, E., Gulkis, S., Hauser, M. G., Janssen, M., Kelsall, T., Lubin, P. M., Moseley, S. H. , Jr., Murdock, T. L., Silverberg, R. F., … Wilkinson, D. T. (1990). A preliminary measurement of the cosmic microwave background spectrum by the Cosmic Background Explorer (COBE) satellite. *The Astrophysical Journal*, *354*, L37. https://doi.org/10.1086/185717

McKay, D. S. et al. The lunar regolith in *Lunar sourcebook* Ch. 7, 285–356 (Cambridge University Press, 1991).

Meyer-Vernet, N., & Perche, C. (1989). Tool kit for antennae and thermal noise near the plasma frequency. *Journal of Geophysical Research*, *94*(A3), 2405. https://doi.org/10.1029/JA094iA03p02405

Morabito, L. K., & Silk, J. (2021). Reaching small scales with low-frequency imaging: applications to the Dark Ages. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *379*(2188), 20190571. https://doi.org/10.1098/rsta.2019.0571

MULLER, C. A., & OORT, J. H. (1951). Observation of a Line in the Galactic Radio Spectrum: The Interstellar Hydrogen Line at 1,420 Mc./sec., and an Estimate of Galactic Rotation. *Nature*, *168*(4270), 357–358. https://doi.org/10.1038/168357a0

Muñoz, J. B., Ali-Haïmoud, Y., & Kamionkowski, M. (2015). Primordial non-gaussianity from the bispectrum of 21-cm fluctuations in the dark ages. *Physical Review D*, *92*(8), 083508. https://doi.org/10.1103/PhysRevD.92.083508

Nunn, C., Nakamura, Y., Kedar, S., & Panning, M. P. (2022). A New Archive of Apollo's Lunar Seismic Data. *The Planetary Science Journal*, *3*(9), 219. https://doi.org/10.3847/PSJ/ac87af

Offringa, A. R., van de Gronde, J. J., & Roerdink, J. B. T. M. (2012). *A morphological algorithm for improving radio-frequency interference detection*. https://doi.org/10.1051/0004-6361/201118497

Pieters, C. M., Goswami, J. N., Clark, R. N., Annadurai, M., Boardman, J., Buratti, B., Combe, J.-P., Dyar, M. D., Green, R., Head, J. W., Hibbitts, C., Hicks, M., Isaacson, P., Klima, R., Kramer, G., Kumar, S., Livo, E., Lundeen, S., Malaret, E., … Varanasi, P. (2009). Character and Spatial Distribution of OH/H_2O on the Surface of the Moon Seen by M ^{3} on Chandrayaan-1. *Science*, *326*(5952), 568–572. https://doi.org/10.1126/science.1178658

Planck Collaboration, Ade, P. A. R., Aghanim, N., Armitage-Caplan, C., Arnaud, M., Ashdown, M., Atrio-Barandela, F., Aumont, J., Baccigalupi, C., Banday, A. J., Barreiro, R. B., Bartlett, J. G., Bartolo, N., Battaner, E., Benabed, K., Benoit, A., Benoit-Levy, A., Bernard, J.-P., Bersanelli, M., … Zonca, A. (2013). *Planck 2013 results. XXII. Constraints on inflation*. https://doi.org/10.1051/0004-6361/201321569

Pomeroy, C., Calzada-Diaz, A., & Bielicki, D. (2019). Fund Me to the Moon: Crowdfunding and the New Space Economy. *Space Policy*, *47*, 44–50. https://doi.org/10.1016/j.spacepol.2018.05.005

Punturo, M., Abernathy, M., Acernese, F., Allen, B., Andersson, N., Arun, K., Barone, F., Barr, B., Barsuglia, M., Beker, M., Beveridge, N., Birindelli, S., Bose, S., Bosi, L., Braccini, S., Bradaschia, C., Bulik, T., Calloni, E., Cella, G., … Yamamoto, K. (2010). The Einstein Telescope: a third-generation gravitational wave observatory. *Classical and Quantum Gravity*, *27*(19), 194002. https://doi.org/10.1088/0264-9381/27/19/194002

Ross, A., Ruppert, S., Gläser, P., & Elvis, M. (2021). *Towers on the Peaks of Eternal Light: Quantifying the Available Solar Power*.

Shi, Y., Xu, Y., Deng, L., Wu, F., Wu, L., Huang, Q., Zuo, S., Yan, J., & Chen, X. (2021). *Imaging sensitivity of a linear interferometer array on lunar orbit*. https://doi.org/10.1093/mnras/stab3623

Joseph Silk. (2022). *Back to the Moon: The Next Giant Leap for Humankind*. Princeton University Press.

Singh, S., T., J. N., Subrahmanyan, R., Shankar, N. U., Girish, B. S., Raghunathan, A., Somashekar, R., Srivani, K. S., & Rao, M. S. (2021). *On the detection of a cosmic dawn signal in the radio background*.

Watters, T. R., Weber, R. C., Collins, G. C., Howley, I. J., Schmerr, N. C., & Johnson, C. L. (2019). Shallow seismic activity and young thrust faults on the Moon. *Nature Geoscience*, *12*(6), 411–417. https://doi.org/10.1038/s41561-019-0362-2

Wolt M.K., Falcke H., Brinkerink C., Vecchio A., Boonstra A.J., Bentum M., Koopmans L., Rothkaehl H., Ping J., Chen L., Huang M., Burns J., Cecconi B., Zarka P., Bergman J., Carpenter J. Astronomical Lunar Observatory, URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Vidya Sagar Reddy Avuthu. (2017). *Commercial space mining: Economic and legal implications*.

Yan, J., Wu, J., Gurvits, L. I., Wu, L., Deng, L., Zhao, F., Zhou, L., Lan, A., Fan, W., Yi, M., Yang, Y., Yang, Z., Wei, M., Guo, J., Qiu, S., Wu, F., Hu, C., Chen, X., Rothkaehl, H., & Morawski, M. (2022). *Ultra-Low-Frequency Radio Astronomy Observations from a Selenocentric Orbit: first results of the Longjiang-2 experiment*.

Glossary

- *Asteroids*

These are rocky, small and solid bodies with irregular shapes. They are composed of leftover material from the formation of the solar system and its planets around 4.6 billion years ago.

- *Auroral kilometric radiation*

It is an intense radio emission from planetary magnetospheres.

- *Blackbody*

It is an object that absorbs electromagnetic radiation, at all frequencies, falling on it.

- *Black hole*

It is a region of space-time so massive and dense that nothing, even light, can escape its strong gravitational effects.

- *Cosmic rays*

They are hIgh energy particles, either atomic nuclei or electrons, that travel through space at nearly the speed of light. Being charged, their paths are deflected by magnetic fields.

- *Cosmology*

It is the field of astrophysics that studies the origin and evolution of the universe.

- *Dark energy*

It is an unknown form of energy responsible for the accelerating rate at which the universe is expanding.

- *Dark matter*

It is a component of the universe that accounts for approximately 85% of the total matter of the universe. Unlike normal matter, dark matter does not absorb, reflect, or emit electromagnetic radiation.

- *Exoplanet*

It refers to any planet that does not belong to the Solar System.

- *General relativity*

Also known as Einstein's theory of gravity, it is a theory that describes the gravitational field and the mathematical equations it obeys.

- ☐ *Ionosphere*

It is the upper part of the Earth's atmosphere, between 80 and about 600 km. Here the ultraviolet and X-ray solar radiation ionizes the atoms and molecules hence creates a layer of electrons.

- ☐ *Lagrangian points*

They are positions in space where a small mass object can stay in equilibrium under the gravitational influence of two more massive orbiting bodies.

- ☐ *Magnetosphere*

It is the region of space around an astronomical object where charged particles are highly affected by the object's magnetic field.

- ☐ *Maser*

It stands for Microwave Amplification by Stimulation Emission of Radiation and it is a natural source of stimulated spectral line emission mostly in the microwave band.

- ☐ *Meteoroids*

They are rocky objects in space, significantly smaller than asteroids.

- ☐ *Neutron stars*

They are the remnants of the explosive evolution of very massive stars and are characterized by a very high density matter, composed primarily of neutrons.

- ☐ *Plasma*

It is the fourth fundamental state of matter, composed of charged particles in any combination of ions or electrons.

- ☐ *Protoplanetary disk*

It is a rotating circumstellar disc of dense gas and dust around a freshly formed star.

- ☐ *Pulsars*

They are special types of neutron stars that emit periodic bursts of radio waves, X-rays and gamma rays.

- ☐ *Quasar*

Extremely luminous active galactic nucleus (AGN).

☐ *Redshift*

It is a parameter that astronomers use to measure how the universe is expanding thus determining the distance to our universe’s most distant (and therefore oldest) objects.

☐ *Solar wind*

It is a flow of charged particles continuously released from the upper region of the solar atmosphere, called the corona.

☐ *Supernovae*

They are violently exploding stars whose luminosity can briefly outshine the entire galaxy the reside in. This very luminous explosion happens when the star has reached the end of its life.

☐ *Synchrotron emission*

It is the radiation emitted by relativistic cosmic ray electrons spiraling in the galactic magnetic field and accelerated by supernova explosions.

☐ *White dwarf*

It is a stellar corpse with roughly the mass of the Sun and the size of the Earth; a degenerate electron gas supports it against the crush of gravity.

APPENDIX A: IAU Organization

The IAU management and oversight is provided by an Executive Committee of Elected Officers: President, President-Elect, General Secretary, Assistant General Secretary, 6 Vice Presidents representative of the world astronomy community, and Advisors who are past elected executives.

The Executive Committee constitutes ad hoc Working Groups to address key priorities, currently:

- Executive Committee WG Astronomy for Equity and Inclusion
- Executive Committee WG Dark and Quiet Sky Protection
- Executive Committee WG Exoplanetary System Nomenclature
- Executive Committee WG Global Coordination of Ground and Space Astrophysics
- Executive Committee WG IAU EC WG for Professional-Amateur Relations in Astronomy
- Executive Committee WG Junior Members
- Executive Committee WG Planetary System Nomenclature (WGPSN)
- Executive Committee WG Small Bodies Nomenclature (SBN)
- Executive Committee WG Women in Astronomy

The main work of the society is done by its volunteer members through the organization of Divisions:

- Division A Fundamental Astronomy
- Division B Facilities, Technologies and Data Science
- Division C Education, Outreach and Heritage
- Division D High Energy Phenomena and Fundamental Physics
- Division E Sun and Heliosphere
- Division F Planetary Systems and Astrobiology
- Division G Stars and Stellar Physics
- Division H Interstellar Matter and Local Universe
- Division J Galaxies and Cosmology

The Divisions then form and sponsor Commissions for long time-scales and the Commissions form Working Groups for shorter timescales to focus on specific topics:

Commissions	Commission Name	Parent Division(s)
A1	Astrometry	A
A2	Rotation of the Earth	A
A3	Fundamental Standards	A
B1	Computational Astrophysics	B
B2	Data and Documentation	B
B3	Astroinformatics and Astrostatistics	B

B4	Radio Astronomy	B
B5	Laboratory Astrophysics	B
B6	Astronomical Photometry and Polarimetry	B
C1	Astronomy Education and Development	C
C2	Communicating Astronomy with the Public	C
C3	History of Astronomy	C
C4	World Heritage and Astronomy	C
D1	Gravitational Wave Astrophysics	D
E1	Solar Radiation and Structure	E
E2	Solar Activity	E
E3	Solar Impact Throughout the Heliosphere	E
F1	Meteors, Meteorites and Interplanetary Dust	F
F2	Exoplanets and the Solar system	F
F3	Astrobiology	F
G1	Binary and Multiple Star Systems	G
G2	Massive Stars	G
G3	Stellar Evolution	G
G4	Pulsating Stars	G
G5	Stellar and Planetary Atmospheres	G
H1	The Local Universe	H
H2	Astrochemistry	H
H3	Planetary Nebulae	H

Inter-Division Commissions

Commission Name		Primary Division	Parent Division(s)
A4	Celestial Mechanics and Dynamical Astronomy	A	A, F
B7	Protection of Existing and Potential Observatory Sites	B	B, C
H4	Stellar Clusters through-out Cosmic Space and Time	H	G, H, J
J1	Galaxy Spectral Energy Distributions	J	D, G, H, J
J2	Intergalactic Medium	J	B, H, J
X1	Supermassive Black Holes, Feedback and Galaxy Evolution		D, J
X2	Solar System Ephemerides		A, F

Commission Working Group	Parent Commission
Theory of Earth Rotation and Validation (IAU / IAG Joint WG)	A2
Historic Radio Astronomy	B4
High-Accuracy Stellar Spectroscopy	B5
Spectroscopic and Radiative Data for Molecules	B5
Site Protection	B7
Technical Working Group	B7
Astronomy for Equity and Inclusion	C1
Network for Astronomy School Education (NASE)	C1
Theory and Methods in Astronomy Education	C1
CAP Conferences	C2
CAP Journal	C2
Outreach Professionalization & Accreditation	C2
Public Outreach Information Management	C2
Science Communication Research in Astronomy	C2
Johannes Kepler	C3
Astronomical Heritage in Danger	C4
Classical Observatories from the Renaissance to the 20th Century	C4
Heritage of Space Exploration	C4
Solar Irradiance	E1
Meteor Shower Nomenclature (MSN-WG)	F1
Stellar Spectral Libraries	G1
Reference Library of Galaxy Spectral Energy Distributions (RELIGAS)	J1

APPENDIX B: Deeper scientific background - The cosmological model

The standard cosmological Λ-Cold Dark Matter (Λ-CDM) model, provides the best description of the observed universe in agreement with a large set of astronomical observations.

This model assumes that the universe is flat and composed of a small fraction of baryonic (ordinary) matter and a higher fraction of dark matter (DM) plus a dominant presence of dark energy, the latter with a dominant influence in the accelerated expansion of the universe, at a rate that is described by the Hubble parameter H_0. The DM particles interact only through gravitational interaction and have small kinetic energy, thus they are considered 'cold'.

According to the standard cosmological model, the universe was born with the Big Bang approximately $13.7\ billion\ years$ ago, when it was extremely hot and infinitely dense.

Immediately after the Big Bang ($10^{-36}\ to\ 10^{-32} s$), the very hot universe expanded exponentially, in the so-called *'inflation'* and started to cool enough to create a vast sea of neutral atoms (almost only hydrogen, H) out of the decoupled protons and electrons. The earliest radiation signature we have of the youngest universe is the Cosmic Microwave Background that dates $380.000\ years$ after the Big Bang. This radiation is observed as a $2.7\ K$ thermal blackbody radiation that fills homogeneously the entire universe and its anisotropies at small scales provide information about the very early cosmic stages.

The particle coupling, in the colder expanded universe, began the "Epoch of Recombination" (at z ~ 1100s).

Whereas the Cosmic "Dark Ages" (at z ~ 30-80) refer to the period prior to any star or galaxy formation and they are named so because of the absence of any light sources; the universe was filled with neutral hydrogen atoms.

Later, around 600 million years after the Big Bang, the first stars and galaxies formed, starting the era of the "Cosmic Dawn" (z ~ 30).

The radiation emitted by star forming processes began to ionize neutral hydrogen, "Epoch of Reionization'' (EoR) (30 < z < 6) making the universe "observable" as illuminated. The ionized universe is well constrained by astrophysical research.

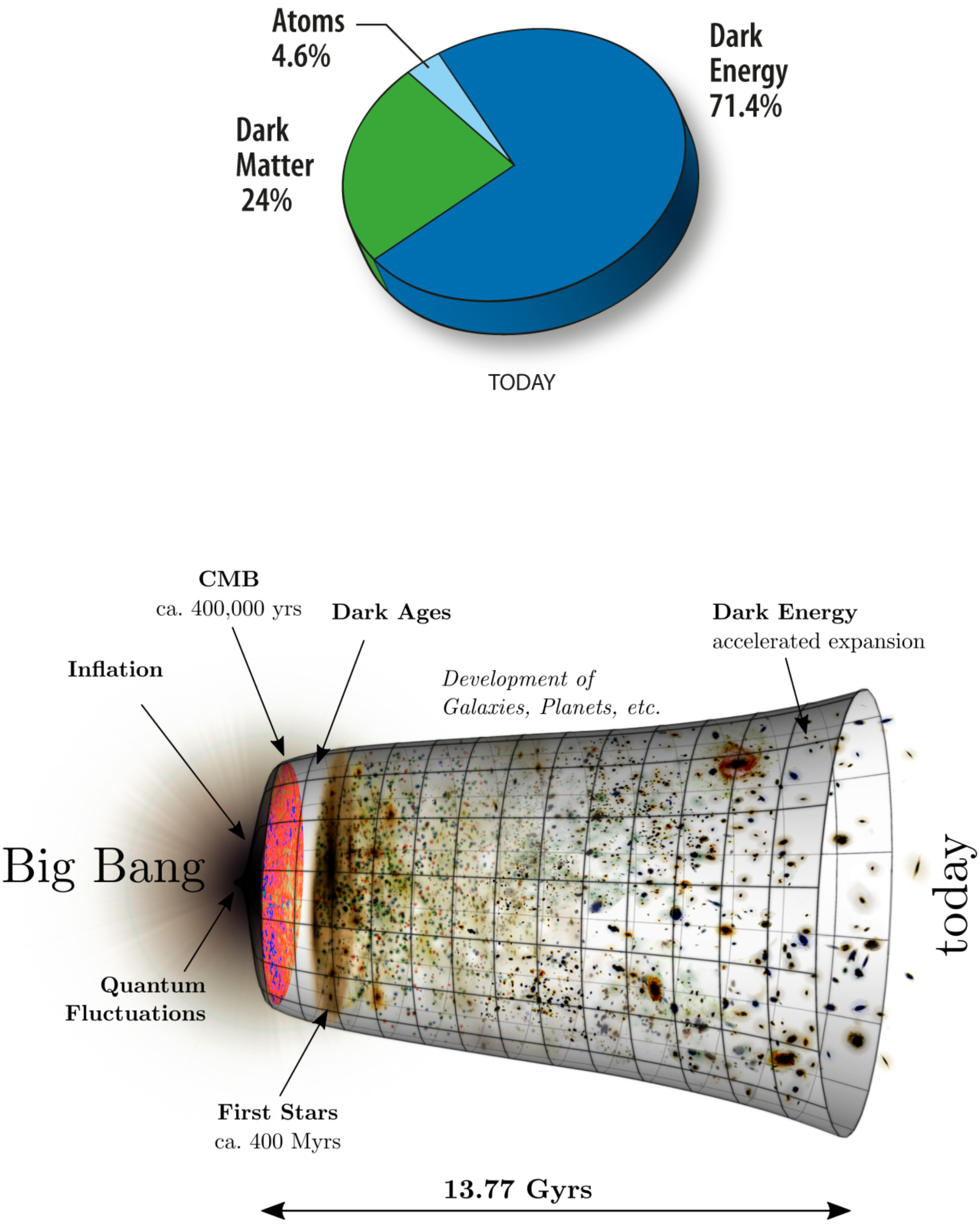

Figure: A.1: Top panel: Components of the universe at the present era. Bottom panel: Diagram of the evolution of the universe from the Big Bang explosion to the present epoch. Credit: NASA/WMAP Science Team.

APPENDIX C: Deeper Scientific Background - Lunar Missions in the next decades

Gravitational Wave lunar missions

How to detect GWs from the Moon? When they pass through an elastic body, like the Moon, they induce quadrupolar vibrations at all frequencies with resonant amplification at those specific modes corresponding to the normal modes. This process is highly dependent on the internal structure of the body and the desired goal is to be able to detect deviations from quadrupolar vibrations.

★ Lunar Gravitational Wave Antenna (LGWA)

LGWA is a European project, based on the deployment of an array of four seismometers on a PSR of the lunar south pole (Harms J. et al., 2021). It adopts the idea to use inertial acceleration measurements to detect GWs with a conceivable observation band from $1\ mHz$ to a few Hz (Harms J., 2022). LGWA design consists of one detector to be placed in the center and the other three around it; this allows for a consistent background reduction to well disentangle the GW signal from environmental noise.
But how to power such an experiment in a PSR? This is still an open question and ongoing considerations are delaying the mission. One possibility could be to install solar panel stations with laser power beaming or microwave power beaming shooting inside the shadowed places.
The science cases of LGWA are expected to be compact binaries in the range ($1\ mHz$ – $1\ Hz$) including white dwarfs, neutron stars and black holes, with highest sensitivity up to redshift $z \sim 24$ and mass 10^3 $M_\odot$, filling the gap between LISA science and the terrestrial telescopes'.

★ Lunar Seismic Gravitational wave Antenna (LSGA)

The LSGA detector concept is based on a large multi-sensor network with a chosen configuration (Izumi K., Jani K., 2021) of two $50\ km$ long fiber optics cables disposed in an L-form attached to a central interrogator unit using a narrowband laser light source. This design is suitable to achieve very high sensitivity in a range of very low frequencies,$10^{-3} - 10^{-2}\ Hz$.
LSGA would perform laser-interferometric measurements of the seismic strain of the Moon caused by GWs (Harms J., 2022). This facility could advance the scope of GW astronomy significantly; however, issues related to the power supply, calibrations, deployment by rovers and data volume still need to be well assessed for a realistic timeline determination.
LSGA applicability is associated to different science goals: GW detections for a broad set of phenomena including compact binaries, white dwarf mergers, Jet GWs and the search of type IA supernovae; a detailed seismological study of the Moon and a precise determination of its inner structure with a bonus scientific goal of tracking ultra high energy cosmic ray.

★ Gravitational-wave Lunar Observatory for Cosmology (GLOC)

The Gravitational-Wave Lunar Observatory for Cosmology (Jani K., Loebb A., 2021) is expected to have maximum potential for GW detections at frequencies near $0.1\ to\ 5\ Hz$, providing the opportunity to study the strongest fundamental cosmology.

Its technology follows that of the third generation terrestrial CE and ET and its design is based on the idea of a triangular geometry GW interferometer with an arm length of $40\ km$: the three end stations at the triangle vertices will host a laser, a mirror and a suspension. This setup is optimized to limit the background seismic noise and could be tested already with the future Artemis missions in this decade.

GLOC could provide an unprecedented access to over 70% of the observable universe including the possibility to probe the early epochs. GLOC's most important science cases[75] would be: measuring the dark matter density of exotic objects like neutron stars, studying type IA supernovae mechanisms, tracking dark sirens and allowing strongest tests of general relativity.

Significant limitations for GLOC are represented by the feasibility and costs.

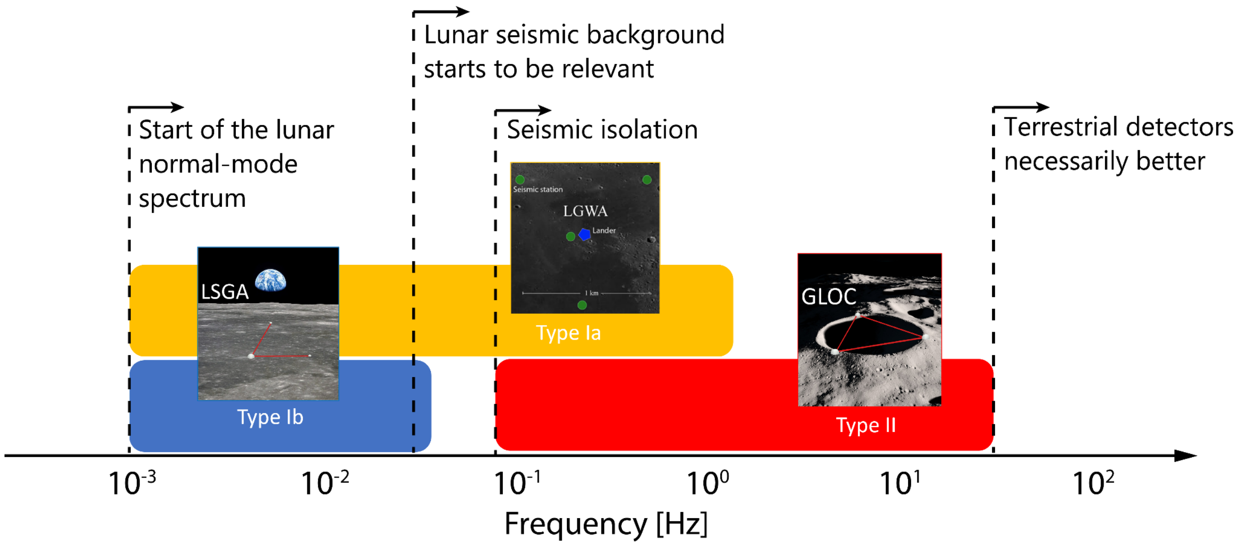

Figure A.2: LSGA, LGWA and GLOC are three different complementary concepts in terms of observation bands. Credits: Harms J., 2022.

[75]www.lpi.usra.edu/announcements/artemis/whitepapers/2084.pdf

★ Laser Interferometer on the Moon (LION)

Similarly to LIGO, Virgo and KAGRA, but with the advanced technology of the third generation terrestrial GW facilities, the design choice for LION[76] consists of three interferometers in a triangular configuration, an arm length of $40\,km$, and three end stations (Figure A.3). The highest sensitivity to be achieved between $0.7\,Hz\ and\ 2\,Hz$. Its broad frequency range may allow the opportunity to observe more massive black holes, study gravity in the strong field regime, track seed black holes at redshifts more than 100 and detect new astrophysical sources. LION could reach its full potential if operating in combination with the third generation detectors on Earth and in space. The power supplier of such a mission could possibly be a solar panel array of a few tens of square meters placed on mountains close to the chosen site.

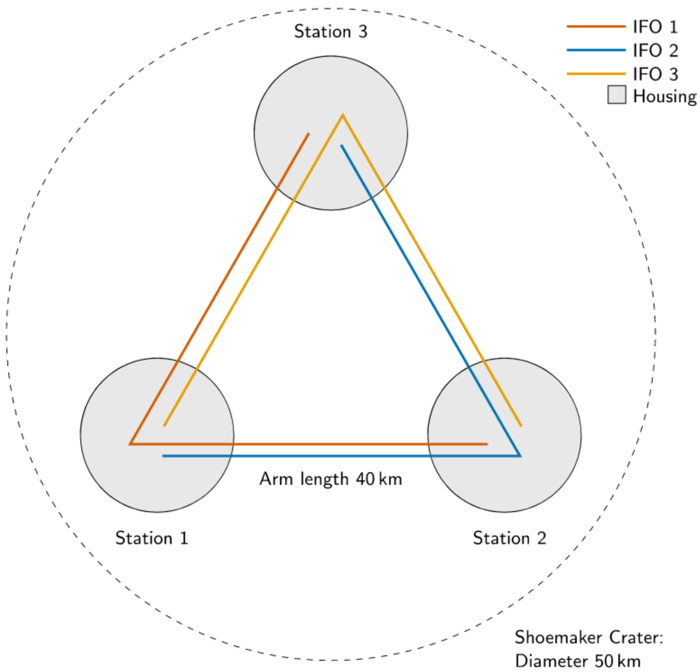

Figure A.3: Design of LION detector with three interferometers and end test stations. The arms are all 40 km in length. The end stations contain isolation platforms and suspension systems for the core and auxiliary optics. Credits: Amaro-Seoane P. et al, 2021.

[76] iopscience.iop.org/article/10.1088/1361-6382/abf441/pdf

Optical/infrared lunar missions

★ Astronomical Large Lunar UV to mid-infraRed Explorer (ALLURE)

It is a proposed IR lunar telescope with a $13\ m$ primary multi-mirror on axis, for a total of 18 hexagonal mirrors. This should be assembled on Earth and then moved to a selected cold lunar crater at a temperature of $26\ K$ for performance in the IR domain $0.2 - 200\ \mu m$ (Jean-Pierre Maillard, Royal Society, 2023). Optimal sites for ALLURE are the Hermite or Shakleton lunar craters at the North and South lunar pole respectively; a double location could allow a full sky coverage. This conceptual mission is expected to be less costly and easier to maintain than the space telescope HabeX. The mission will be equipped with a UV coronograph, near- and mid- IR cameras, near-IR spectrometer and a mid-IR integral field spectrometer.
The science advantages of this proposal are under investigation and they would be better assessed by international collaborations of space agencies.

★ Overwhelming Lunar Telescope (OWL)/ Extremely Large Lunar Telescope

The original project of the European Southern Observatory was OWL, a $50 – 100\ m$ aperture instrument for visible and IR astronomy scopes. However, it was soon abandoned due to the excessive costs and technological challenges and replaced with the project of a $39\ m$ mirror, the ELT, now under construction on Cerro Armazones in the Atacama Desert of northern Chile (Maillard J.P., 2020). Its main objectives are the detection of rocky exoplanets and characterisation of their atmospheres and superficial composition. Furthermore, it will make observations to identify water and organic molecules in protoplanetary disks around forming stars and look at distant objects like the first stars, galaxies, and black holes to clarify their relationships.
A potential lunar version of the ELT would be an Extremely Large Lunar Telescope (ELLIT) (Maillard J.P., 2020), with the advantages of a very large aperture and the strategic location in a cold polar lunar site. However, its major disqualifying points are the impact and costs for its full implementation on the lunar surface. Deeper considerations are ongoing.

Figure A.4: Representation of the design of the European ELT. Credit: ESO/L. Calçada/ACe Consortium

★ Lunar Observatory for Unresolved Polarimetry of the Earth (LOUPE)

The proposed LOUPE instrument is a small, robust spectro-polarimeter to accompany an orbiting, landing or roving mission on the near side of the Moon, a stable vantage point from which LOUPE can observe the Earth at all times in a wavelength range $400–1000\ nm$ (Meinke et al., 2022). In fact, its science scope is monitoring the Earth "as a dot", from far away, so observing the Earth as an exoplanet. The basic idea is to collect information in a single 'dot' including spectral flux and polarization data of the sunlight reflected by Earth's oceans, continents, biomarkers and clouds and use the properties of Earth as benchmark data to be able to identify those of exoplanets by analogy. Polarimetry is a promising method in this context (Keller et al., 2010; Williams and Gaidos, 2008).
LOUPE is designed to be small and consists of a hyperspectral imager, based on the Hyperscout detector (built by the Dutch Cosine company) with the addition of a patterned liquid crystal, a polariser and a microlens array, as shown in Figure A.5. This mission will be crucial to test numerical codes currently used to simulate the rocky exoplanet signals and improve strategies for future planet observatories. Furthermore, data of the total flux reflected by the Earth and its spectral and temporal variations provide information on the Solar energy the Earth absorbs, which is useful material for climate research.

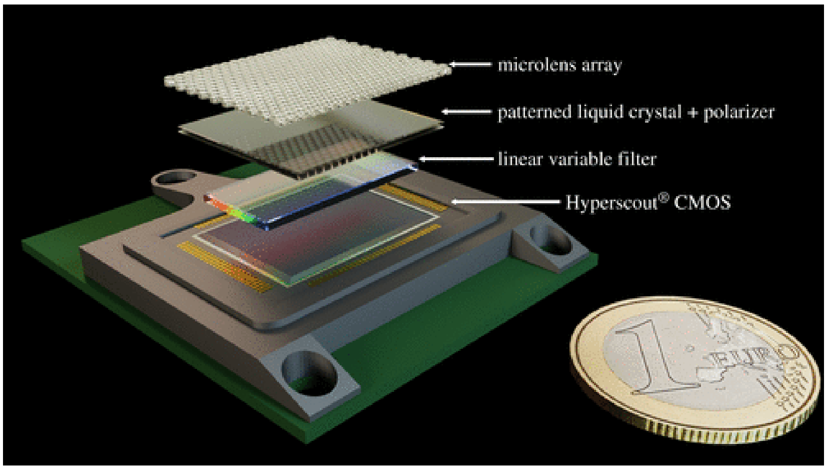

Figure A.5: Structure of LOUPE. Size compared to a coin. Credits: Stam D.M., Royal Society, 2023.

Far-infrared lunar mission

★ Multi-SIMBAD (Spectroscopic Interferometer for Microwave BAckground Distortions)

The Multi-SIMBAD mission is aimed at making spectroscopy of the CMB and it is based on the concept of the space mission SIMBAD (planned to be placed at L2), but consisting of an array of small telescopes instead of a single in space large one (Maillard J.P., 2020). Multi-SIMBAD includes several identical $1.5\,m$ cryo-cooled telescopes at $2.5\,K$ with an imaging Fourier transform spectrometer in each unit. These should be installed all together in a cold lunar crater, an optimal site for the system to achieve an efficient angular resolution (around 1°).
The feasibility of this project is promoted by the total building on Earth of each SIMBAD unit, no mounting, manpower for installation or servicing needed. They will only need to be transported to the Moon and arranged by a lander; they will be equipped with an antenna to transfer data directly to Earth. One negative aspect of this mission is the limited scope of a spectroscopic analysis of the CMB and no alternative applicability.

Low frequency radio missions on the Moon

★ Radio Wave Observations at the Lunar Surface of the Photoelectron Sheath (ROLSES)

The Moon's surface is electrostatically charged and this may affect structures and humans on the lunar surface. The primary objective of ROLSES is the investigation of the effects of solar wind and ultraviolet light, which are known to charge the dusty lunar surface and transport dust around. To this end, ROLSES will perform measurements of the photoelectron plasma sheath, $1\ to\ 3\ m$ above the surface, and assess the frequencies at which incoming radio waves get attenuated by the sheath (Burns J.O. et al., 2021). The information about the lunar surface charging has a great importance for charging exploration vehicles (Zimmerman et al., 2011 and Poppe & Horányi, 2010).
In addition, ROLSES (in a 14 day mission) will measure the temporal and spectral characteristics of terrestrial RFI from the Moon, to confirm the efficiency of putting radio observatories on the nearside for imaging solar radio bursts. ROLSES is the first NASA funded payload that will be taken to the Moon, in June 2023. This will be transferred by the commercial lander NOVA-C provided by Intuitive Machines[77]Houston, Texas; the chosen landing site is the Oceanus Procellarum near Vallis Schröteri (Schroter's Valley), on the lunar nearside. This facility is designed as a two dipole antennas system to detect radio waves in two frequency bands, $10\ kHz$ – $1\ MHz$ and $300\ kHz$ – $30\ MHz$, and providing radio spectra from $10\ kHz$ – $30\ MHz$.

★ The Lunar Surface Electromagnetic Experiment (LuSEE)

Currently known as "LuSEE Night", this NASA low frequency radio mission is planned to land on the Schrödinger Basin, on the farside of the Moon, between 2025 and 2026.
Its main purpose is making sensitive measurements of the radio sky, up to $50\ MHz$, to characterize the pristine electromagnetic environment of the farside in absence of man made radio noise. To this end, it will perform during lunar nights when the Sun is below the horizon (Bale S.D. et al., 2023). Its design is based on dipole antennas placed on a carousel (red items in the drawings on the right), solar arrays (in blue) and a battery system (gold box). The LuSEE objective is extremely relevant also for the following and more ambitious low frequency lunar missions.

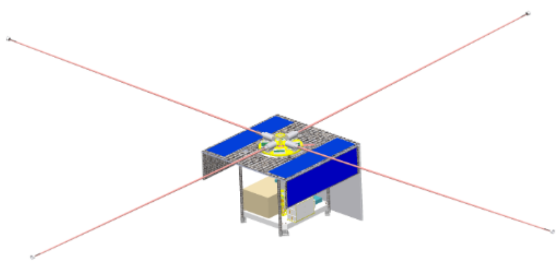

Figure A.6: Sketch of the LuSEE Night system consisting of dipole antennas on a carousel, solar arrays and a big battery. Credit: Bale S.D. et al., 2023

[77]www.intuitivemachines.com/lunarlander

★ Dark Ages Polarimeter PathfindER (DAPPER)

This is the first (and only) concept of a radio telescope in low lunar orbit. DAPPER will measure the all-sky averaged spectrum of the $21 - cm$ signal from the DA and Cosmic Dawn in a frequency range $10 - 110\ MHz$ (Burns J.O. et al., 2021). It is intended as a precursor telescope that will open an era of cosmology from the Moon. The instrument is designed to overcome the major ever challenge for cosmological measurements, the interference from the galactic foreground emission. The techniques it will apply to separate the $21 - cm$ signal from the galactic emission are differences in spectral shape, spatial structure and polarization.
The design of this mission is based on two simple antennas, a STACER (Spiral Tube & Actuator for Controlled Extension Contraction) antenna to operate at the low frequency part of the band and a Patch antenna in the high end of the band.

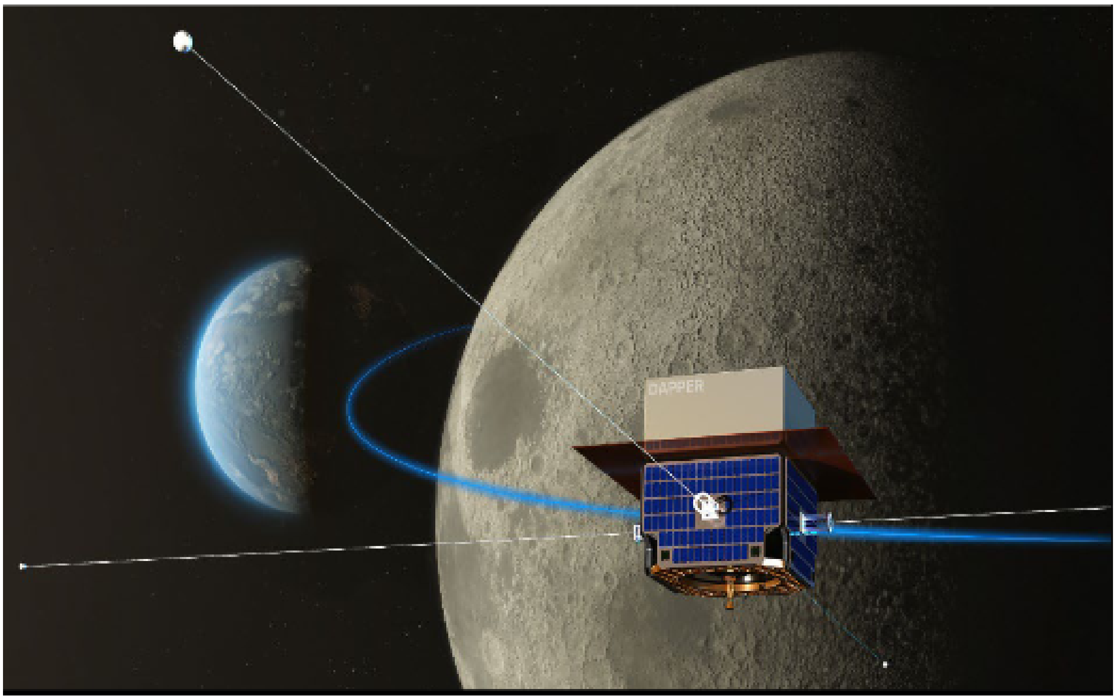

Figure A.7: Artistic representation of a radio telescope, DAPPER, in lunar orbit. Credit: (Burns J.O. et al., 2021)

★ Discovering the Sky at the Longest wavelength (DSL)

This is the only formulated concept of a linear array of micro-satellites orbiting the Moon. The architecture of this system is characterized by a mother satellite and some 3 to 8 daughter satellites all to be placed on the same circular lunar orbit. While the smaller ones (daughter) will make the actual observations in the portion of the orbit which is not affected by the Earth RFI, the big (mother) one will collect such data and transmit it back to Earth.
The mission will serve several scopes including map the sky at low frequencies ($1 - 30\ MHz$), crucial for the future lunar cosmology experiments, and explore the Dark Ages and Cosmic

Dawn by making high precision measurements of the global $21 - cm$ spectrum. DSL is expected to make observations over 3 to 5 years (Yuan Shi et al. 2021).
The precise timeline for this mission is not publicly available yet, but the technologies required for it are currently being developed (Xuelei Chen et al., 2023).

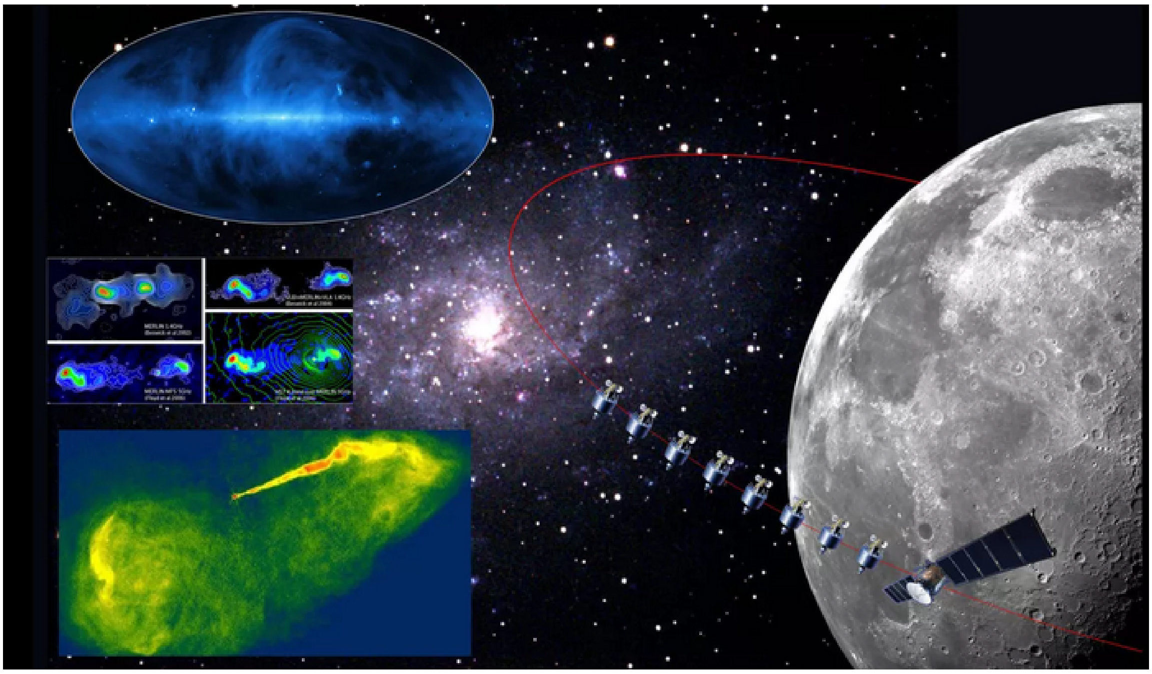

Figure A.8: Artistic representation of a lunar array on a lunar orbit. Image credit: NAOC/Xulei Chen.

★ The Farside Array for Radio Science Investigations of the Dark ages and Exoplanets (FARSIDE)

FARSIDE is the first concept of a low frequency radio interferometric array to be placed in a crater on the lunar farside. Its architecture consists of 128 dipole antennas to be distributed over a $10\ km$ diameter in a four arm spiral configuration (Figure A.8), connected to the Lunar Gateway, or an alternative relay communication satellite (at Moon-Earth L2), for data transmission (Burns J.O. et al., 2019). The array is planned for operations over five years, imaging the entire sky within a frequency range of $0.1 – 40\ MHz$. The variety of science targets for FARSIDE includes the monitoring of near stellar systems in search for radio signatures of coronal mass ejections and energetic particle events and characterisation of magnetospheres for the nearest candidate habitable exoplanets. It will also track similar activities in our own solar system. Another main objective is the measurement of the DA global $21 - cm$ signal at redshifts $z \sim 50 – 100$, a very appropriate scope for a large radio interferometer array on the lunar farside. The FARSIDE payload mass is estimated to be $1750\ kg$ and it is expected to be delivered to the Moon by a commercial lander like the Blue Origin's Blue Moonlander.

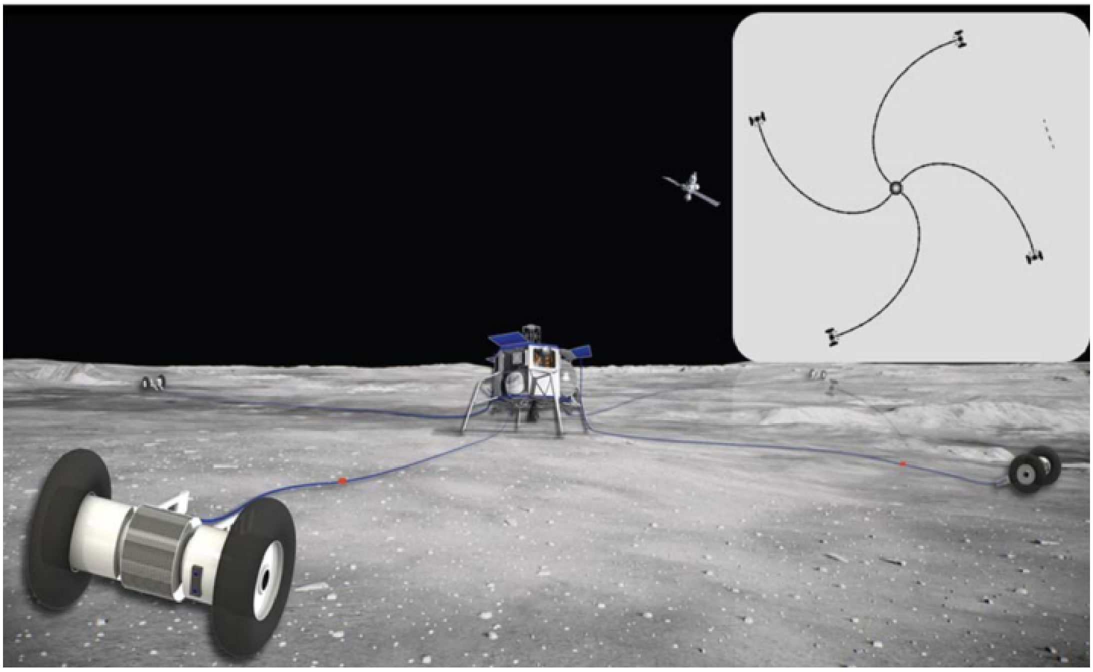

Figure A.9: FARSIDE architecture. Credit: Burns J.O. et al., 2019.

★ FarView

This is a large low frequency radio observatory to be completely built on-situ, using lunar regolith materials. Its design is based on an array of $\sim 100,000$ dipole antennas to be located on a $\sim 20 \times 20\, km$ area, with an observation window of $5 - 40\, MHz$. $FarView$[45] science is focused on the exploration of Dark Ages by detecting the highly redshifted hydrogen $21 - cm$ line with unprecedented sensitivity.

The completely ISRU based manufacturing, efficient and less costly than launches from the Earth, represents both innovation and incentive. For its perspective, this mission has recently been awarded a NIAC grant and in the early 2030s it will start to be constructed.

★ Astronomical Lunar Observatory (ALO)

This ESA mission is intended to perform low frequency radio observations using an interferometric distributed array of multi-elements radio antennas on the lunar farside, a relay satellite for communication and the connection with 4 receivers placed far away, nicely isolated and provided with different technologies for system controls (Wolt et al., 2021). ALO's observational range is $7 - 70\ MHz$. The design of such a mission is still under development, with the idea of future additions to the first architecture. Furthermore, it is still debated

whether to locate the observatory in a lunar crater or rather on the surface of the lunar farside. The crater is shielded from RFI but affected by diffraction effects from the rims.
ALO's main science case is the measurements of the global $21\ cm$ signal and its fluctuations to study Dark Ages and the Cosmic Dawn hence probe the standard cosmological model and eventually discover new physics in the early cosmic history.
The most optimal scenario would be to perform observations during the lunar night; however, this could result in power issues. It seems a more plausible scenario to make observations during the lunar day as the batteries could easily be powered by solar panels.

- ★ Lunar Crater Radio Telescope (LCRT)

NASA proposed the lunar $LCRT$[47] to observe ultra-long-wavelength radio waves ($10\ -\ 50\ m$) for probing the cosmic Dark Ages. LCRT would be a $1\ km$ diameter facility, the largest filled-aperture radio telescope in the Solar System, to be located inside a crater of the lunar farside, powered by solar panels on crater rims. It could potentially enable tremendous scientific discoveries in cosmology. The feasibility and the technical challenges associated with such a huge experiment are under investigation, before any timeline decision.

APPENDIX D: Deeper Legal/Policy context

Principles of the Outer Space Treaty

I. Outer space exploration shall be carried out in the **interest of all countries**.

II. Celestial bodies, and in general outer space, shall **no**t be subject to **national appropriation** by any means.

III. Outer space missions shall be carried out for **peaceful purposes** and based on security, international cooperation, mutual assistance, and global interests.

IV. It is **forbidden to hide nuclear weapons** on celestial bodies or in outer space orbits.

V. All possible **assistance shall be offered to astronauts** of all State Parties to the Treaty in case of emergency/necessity.

VI. States Parties to the Treaty have the **responsibility for national activities** in outer space, either carried on by governmental agencies or by non-governmental entities.

VII. When launching objects in space, each State Party to the Treaty is **internationally liable for damage** to another State Party caused by such objects or component parts.

VIII. A State Party to the Treaty shall retain **jurisdiction and control over its objects** launched into outer space.

IX. All State Parties to the Treaty shall **avoid** their **harmful contamination** and adverse environmental changes on Earth due to the introduction of extraterrestrial matters.

States Parties to the Treaty shall carefully analyze the possible **adverse interference** of their planned outer space activities on other State Parties, hence conduct operations in outer space "with due regard to the corresponding interests of all other States Parties to the Treaty". Moreover, they can **request consultation** should they think another State Party's activities are not in line with the peaceful purposes and global interests.

X. The international collaboration among State Parties to the Treaty shall be based on the **equality of any requests** and by agreements between the States concerned.

XI. States Parties to the Treaty shall **inform** the Secretary-General of the United Nations (UN) as well as the public and the international scientific community **on their findings and results** of their missions.

XII. All facilities and equipment on the Moon or other celestial bodies, belonging to a State Party to the Treaty, shall be open to representatives of other States Parties on the basis of **reciprocity**.

XIII. The provisions of this Treaty shall apply to the activities of States Parties to the Treaty either if they undertake activities in outer space individually or within joint organizations between different States Parties.

XIV. Any country can **sign the Treaty anytime**. There is a legal procedure in multiple steps for it to become a State Party.

XV. Any State Party to the Treaty may propose **amendments to this Treaty**.

XVI. Any State Party to the Treaty may **withdraw from the Treaty**.

XVII. This Treaty shall be deposited into the archives of the Depositary Governments and certified copies shall be transmitted to the Governments of the signatory and acceding States.

Principles of The Moon Agreement

I. The regulations contained into the Moon Agreement apply to the **Moon and other celestial bodies in the solar system**, including orbits and trajectories around them.

II. The lunar exploration and utilization shall be carried out in **accordance with international law** for cooperation and peace of all States Parties to the Agreement.

III. Lunar exploration and utilization shall be carried out exclusively for **peaceful purposes** and States Parties shall **no**t place **military weapons** on the lunar surface, in lunar orbits or other trajectories.

IV. **The Moon is a common heritage of all mankind** and its exploration shall be for global interests with no discrimination based on the economic or scientific development of specific countries. States Parties shall cooperate and provide assistance to each other.

V. States Parties shall **inform** the UN Secretary-General as well as the public and the international scientific community **on their findings and results** of their missions and provide all relevant information at precise moments.

VI. States Parties shall all have **equal freedom in the scientific investigation** on the Moon. They shall have the right to **collect materials** or samples of the Moon only **for scientific purposes** and keep them at the disposal of the interested States Parties for doing science. Minerals and other substances may be directly used on the Moon to support the missions.

VII. States Parties shall act carefully **not to change or disrupt the lunar environment** in the exploration and utilization of the Moon. They shall also avoid adverse effects that could be caused by the use of extraterrestrial material on Earth.

"States Parties shall report to other States Parties and to the Secretary-General concerning areas of the moon having special scientific interest in order that, without

prejudice to the rights of other States Parties, consideration may be given to the designation of such areas as international scientific preserves for which special protective arrangements are to be agreed upon in consultation with the competent bodies of the United Nations".

(The text in italics is the official language used in Section 3 of the Article VII of the Agreement. It is faithfully reported here to potentiate the context and better support the discussion).

VIII. States Parties are allowed to carry out activities for lunar exploration **anywhere on the lunar surface or below** it, with respect to the provisions of this Agreement. Activities of one State Party shall not interfere with the ones of the others. If this is likely to happen a consultation is needed for keeping safety and peace.

IX. When a State Party installs a station on the Moon, it shall **not impede the access** to those areas of the personnel and equipment of other States Parties.

X. States Parties shall adopt all practicable measures to **safeguard the life and health of astronauts** on the Moon.

XI. The Moon and its natural resources are the **common heritage of mankind** and thus they can**no**t be subject to **national appropriation** by any claim of sovereignty. Placing facilities on the Moon does not create any right of ownership to any State Party. The exploration and utilization of the Moon shall be **equally allowed to all States Parties** without any discrimination. Natural resources discovered on the Moon shall be used in accordance with appropriate procedures. This provision is intended to **promote good governance for the safe exploitation of lunar resources**, with the view of expanding the opportunities connected with their application, and equitable sharing among all involved States Parties.

XII. States Parties are responsible for **controlling their facilities** and personnel on the Moon. In cases of emergency, States Parties may use instruments or supplies of others.

XIII. A State Party shall readily inform others and the UN Secretary-General about events of **space objects** launched or not by itself.

XIV. States Parties have the **responsibility of national activities on the Moon** carried on either by governmental agencies or non- governmental entities. They shall ensure that all their national missions are in accordance with the international outer space law.

XV. State Parties shall **respect the provisions** of this Agreement in all their activities and they shall allow other States Parties to visit their facilities at agreed moments, to prevent interference or other issues.

XVI. Any **international intergovernmental organization** conducting space activities shall respect the provisions of this Agreement (except from Articles XVII to XXI).

XVII. States Parties may propose **amendments** to the Agreement.

XVIII. States Parties shall periodically **review the Agreement** and join review conferences with other States Parties and the UN Secretary General.

XIX. This Agreement shall be open for **signature by all States** at United Nations Headquarters in New York and shall be **ratified** by signatory States.

XX. There is a specific timeline procedure that applies when a State Party **withdraws** from the Agreement.

XXI. This Agreement shall be deposited with the UN Secretary-General and certified copies shall be transmitted to all signatory and acceding States.

Sections of The Artemis Accords

1. PURPOSE AND SCOPE

The Artemis Accords are the legal vehicles upon which the Artemis Programs rely to achieve an **unprecedented long-term sustainable celestial exploration** based on peace and prosperity for all humankind. With "celestial" is intended a number of target locations including the Moon, Mars, comets, and asteroids, either their surfaces and subsurfaces as well as orbits around them, the Lagrangian points for the Earth-Moon system, and trajectories in between.

2. IMPLEMENTATION

All outer space activities shall be carried out in **accordance with international space law** and shall be regulated by appropriate instruments that clarify the made agreements and the scopes.

3. PEACEFUL PURPOSES

All outer space activities shall be for **peaceful purposes**, in accordance with the international space law.

4. TRANSPARENCY

The Signatory nations shall conduct all outer space operations with **transparency and respect to** their **national regulations**. The Signatories are committed to **communicating their mission outcome**, in accordance with Article XI of the OST.

5. INTEROPERABILITY

The Signatories shall use **current interoperability standards** for space-based infrastructure and, where not existing, establish and follow appropriate standards.

6. EMERGENCY ASSISTANCE

The Signatories are committed to **provide assistance to the personnel** in need.

7. REGISTRATION OF SPACE OBJECTS

The Signatories involved in cooperative outer space activities shall determine the **modality for registering** relevant space objects.

8. RELEASE OF SCIENTIFIC DATA

The Signatories are committed to communicate scientific information to the public. They may decide the **appropriate timeline for the public release of data**.

9. PRESERVING OUTER SPACE HERITAGE

The Signatories shall adopt rules and procedures to **preserve outer space heritage**.

10. SPACE RESOURCES

Resources in outer space shall be extracted and used *in situ* to **support space activities** and their utilization shall **no**t imply any **national appropriation**, as stated in Article II of the OST. The Signatories shall inform the UN Secretary-General, the public and the international scientific community of their extraction operations. Furthermore, the Signatories are cooperatively engaged in further developing international regulations for the extraction and utilization of space resources.

11. DECONFLICTION OF SPACE ACTIVITIES

The Signatories shall conduct space activities following OST regulations, with the view of achieving a long term sustainable lunar exploration and utilization. Therefore the Signatories shall communicate in a clear way to **avoid any** eventual **harmful interference** among each other. This translates into the necessity of coordinating and mutually respecting the so-called "**safety zones**". These are areas of the lunar surface, temporarily assigned to a Signatory for specific operations; their size and duration depend on the scope of the application.

12. ORBITAL DEBRIS

The Signatories shall adopt all appropriate practices to **mitigate orbital debris** and reduce the generation of new harmful debris during space activities.

13. FINAL PROVISIONS

The Signatories are committed to periodically review the implementation of the principles and evaluate future cooperation.

The original text of the Artemis Accords is maintained by the Government of the United States of America, a copy transmitted to the UN Secretary-General and circulated to all the members of the Organization.

APPENDIX E: Deeper elaboration of the actor analysis

- **International Astronomical Union**

The IAU has lately committed to the cause of a new urgent policy that protects SESIs from the harmful interference of commercial activities on the Moon. The policy hub of the IAU has direct connections with the UN and it also punctually communicates with private companies to validate the advantages astronomy could benefit from these external collaborations.

The IAU wishes to soon come up with a strategic policy plan to go ask the approval of new lunar regulations to the UN.

★ **I** am helping the company profile the necessary actions and a good strategy to get the protection of lunar astronomical science considered soon at the highest policy levels, for resolution.

- **Other Organizations** - (IAA, Secure World Foundation, For All Moonkind, Open Lunar Foundation, Moon Village Association…)

There are a lot of organizations inter-operating to identify the most probable scenario for the future of lunar exploration and exploitation. They aim to influence the possible direction of lunar missions in order to prevent any loss of value of the Moon as a human heritage and place with the most unique scientific potential.

- **Major National Space Agencies** (ESA, NASA, JAXA, ….)

National Space Agencies are among the main players in the long-term lunar exploration and utilization of resources. They are both interested in commercial activities and scientific research on the Moon. On the one hand they seek to explore their capacities in sustaining life in an extraterrestrial environment. On the other hand, they want to support science discoveries. They collaborate with the whole scientific community as well as establish commercial partnerships with powerful private firms.

- **Astronomers**

Astronomers, in specific fields of research, have always aspired to do science from the Moon as certain lunar locations are unique to advance our knowledge of the universe. Therefore, the whole scientific community, through international cooperations, is looking at the needed measures that could be taken to bring their experiments to the next level.

- **National governments**

They decide to be bound by certain collaboration/international agreements through national regulations for governmental and commercial space activities. They realize that the emergent lunar economy carries a lot of opportunities for global economic growth, with a lot of job possibilities associated.

- **The Committee on the Peaceful Uses of Outer Space (COPUOS)**

It is the UN body responsible for space-related coordination and governance for a peaceful use of outer space with shared benefits. UN COPUOS implemented treaties and agreements (OST, Rescue Agreement, Liability Convention, Registration Convention, Moon Treaty) to promote international cooperation and solve legal issues arising from space exploration and exploitation. It includes a Scientific and Technical Subcommittee and a Legal Subcommittee (LSC).

The UN COPUOS is the only authority with decisional power, therefore the only that could approve a new policy for the regulation of space resource utilization with the view of protecting SESIs.

- **International Telecommunication Union (ITU)**

This agency has an important role in the landscape of protecting SESIs from radio-interference. It collaborates with the scientific community and the actively involved organizations to find and set technical standards that must be met to keep the lunar farside a radio quiet environment.

- **Private Companies**

In their space exploration plan, the most developed spacefaring states are supported by private entities with advanced capacities for making good profit on the nascent lunar market. Their fundamental goal is to extract and sell lunar resources, provide communication and transportation services and advanced technologies. Private firms are mostly US-led and their operations can have highly harmful consequences on the most valuable lunar sites.

- **Entrepreneurs, enthusiasts**

Private investors may try to understand how to contribute and profit from the emerging lunar economy.

- **Customers**

Buyers of space resources may include **private companies** or **hybrid public-private organizations** that envision flourishing lunar industries in a new, facilitated, outer space utilization.