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How a Laboratory on the Moon should be equipped

Christiane Heinicke[a]*, Steven Jaret[b], Jens Ormö[c], Miranda Fateri[d], Nina Kopacz[e], Mickael Baqué[f], Cyprien Verseux[g], Bernard Foing[h], Alberto Razeto[j]

[a] *University of Bremen, Center of Applied Space Technology and Microgravity (ZARM), Germany,* christiane.heinicke@zarm.uni-bremen.de
[b] *Stony Brook University, United States,* steven.jaret@stonybrook.edu
[c] *Centro de Astrobiologia (INTA-CSIC), Spain,* ormoj@cab.inta-csic.es
[d] *DLR, German Aerospace Center, Germany,* miranda.fateri@dlr.de
[e] *Utrecht University, The Netherlands,* k.a.kopacz@uu.nl
[f] *DLR Institute for Planetary Research, Germany,* mickael.baque@dlr.de
[g] *Concordia Station, Antarctica,* cyprien.verseux@gmail.com
[h] *ESA/ESTEC, ILEWG & VU Amsterdam, The Netherlands,* bernard.foing@esa.int
[j] *Concordia Station, Antarctica,* alberto.razeto@concordiastation.aq
* Corresponding Author

Abstract

The Moon is at the center of attention in many current plans for spaceflight activities, particularly manned missions. Significant progress has recently been made in the transportation to the Moon, and several institutes work on systems and system components to support human life on the surface of the Moon. One of these activities is project MaMBA (short for Moon and Mars Base Analog) which is located at the ZARM in Bremen and is dedicated to creating a full-scale, technologically functioning habitat.

Unlike MaMBA, most of these projects focus on habitability alone – neglecting scientists' desire to perform meaningful analyses, using the advantages of human presence at the location of interest. This approach is concurrent with how most spaceflight missions have been implemented in the past, adding scientific instruments after most of the engineering work is already finished. This often limited scientific studies to relatively scattered, insular topics.

One of the main goals of project MaMBA is therefore to create a base that allows scientists to comprehensively study the most relevant areas of interest. Our focus is the in-base laboratory, and any equipment that should be available inside the habitat, but we also take into consideration instrumentation that may more efficiently be placed outside the habitat and/or on-board of rovers. The purpose of the habitat laboratory is to perform some basic investigations; in-depth analyses of selected samples are supposed to remain within the responsibility of Earth-based laboratories. However, the base may help chose which samples should be sent to Earth for further analysis.

The authors of this paper represent different disciplines with a particular interest in scientific exploitation of the Moon. These represented disciplines are: geology, materials science, astrochemistry, astrobiology, medicine, and astronomy. We will present what we deem some of the most important questions that could be addressed on the Moon, and how these may be addressed efficiently instrument-wise. We will consider synergies between the different disciplines, saving weight and space wherever possible, and make recommendations for a to-be-built lunar base. While the direct addressee of our recommendations is the MaMBA laboratory, most of them are also applicable to general non-terrestrial surface laboratories.

Keywords: lunar laboratory, Moon base, prototype, MaMBA

1 Introduction

A large number of robotic and human missions to the Moon have been announced in the media by different entities for the next decade or so, beside NASA, ESA, and Roscosmos, also countries like China, India, and Israel. And even though the projected short timelines are often questionable, there is an undeniable push towards a return of humans to the Moon.

From a scientific standpoint, sending humans to the Moon opens up many possibilities for investigations and analyses that would otherwise be impossible or at least impractical. We have therefore gathered a team of scientists from different fields to discuss the options of having a laboratory on the lunar surface as part of a habitat, specifically the fields of geology, materials sciences, astrochemistry, astrobiology, medicine, and astronomy.

Previous sampling of lunar materials during the Apollo missions have been with the intent of conducting all analyses back on Earth. However, the location of a laboratory at a lunar base would allow for faster and more efficient analyses, effectively enabling a much larger number of samples to be investigated.

Of course, such a Moon laboratory faces certain limiting factors such as mass and volume of equipment, energy supply, need for various consumables (e.g., gases, liquids), and qualifications of the staff. For this reason, we focus on equipment that already has reached some minimization, for instance for robotic missions, and does not require whole teams of trained personnel.

Instead, the laboratory would have three primary purposes: (1) conduct experiments utilizing the lunar reduced-gravity environment (and prepare experiments to be placed outside the laboratory), (2) conducting analyses of samples of lunar rock and regolith in high numbers, (3) perform preliminary analyses and filtering of samples to be sent to Earth for more detailed, specialized analysis.

The objectives are true for all disciplines included in this paper, although at varying degrees. For example, the number of rock samples analyzed with astrobiological goals is perhaps rather small, and the focus of astrobiology is more on utilizing the unique lunar environment for unprecedented experiments. For geologists, the focus is more on investigating the existing lunar environment—using standard geological methodology to understand the Moon's mysterious origin and evolution.

In general, the logic of this paper follows this structure: Each of section 2-7 is dedicated to a specific discipline, and will start with an overview of open questions in its field. We then suggest instrumentation that we deem suitable for addressing those questions. The disciplines are sorted such that we start from the "dead" geology via "increasing chemical complexity" to "living organisms".

Astronomy and medicine at the end are somewhat outsiders here: Astronomy, as it does not use typical laboratories but rather outdoor equipment, but we believe that their requirements for running telescopes etc. on the Moon (likely to be mostly trouble-shooting, maintenance and repairs) should be accounted for nonetheless. Medicine, on the other hand, has a two-fold interest: medical research and maintaining crew health. Due to constraints in space and time, we have not included medical research in this paper, but "only" the facilities necessary for the treatment of medical emergencies. Since the main purpose of this short paper is to ignite discussion, rather than provide final answers, we believe that there will be plenty of opportunities to appropriately include medical research, particularly in an extended version of this paper we are currently planning. Likewise, we are planning to include geophysical research in the future, rather than restricting ourselves to pure geology.

Finally, in section 8, we summarize the instrumentation recommendation for all disciplines, identifying synergies and overlaps, and in section 9 we will make recommendations for a lunar laboratory.

2 Geology

2.1 Open questions and investigations of interest

The Lunar Exploration Analysis Group (LEAG) has a long legacy of providing guidance and direction for future lunar science and exploration. Based on their 2016 roadmap [1] (and drawing on the US National Research Council's reports), they define several priorities for the immediate future of lunar science and exploration. The important science questions they define are:

1. Understand the formation, evolution, and current state of the Moon
2. Understand the dynamical evolution and space weathering of the regolith
3. Understand lunar differentiation
4. Understand volcanic processes
5. Understand the impact process
6. Determine the stratigraphy, structure, and geological history of the Moon
7. Understand the formation of the Earth-Moon system
8. Understand the impact history of the inner Solar System as recorded on the Moon

2.2 Desired instrumentation

The above objectives should be, at least partially, reached by analysis already on the Moon before any eventual sample transfer to laboratories on the Earth. This allows for initial screening of important material to minimize shipments. In addition, the science objectives guiding additional sampling can be let to evolve already on site leading to a faster collection of high quality data.

Furthermore, some of the analyses, particularly those involving determining the effects of space weathering and precise measurements of lunar volatile contents would be more precisely determined from the Moon itself. Space weathering effects (such as the flux of micrometeorite impacts or changes to the magnetic field) need to be measured on the Moon. Likewise, chemical analyses of volatiles measured from a base on the Moon would not risk complications of terrestrial contamination.

2.2.1 Laboratory instrumentation

The field sampling and swift feedback from the lunar lab will help decide the course of the ongoing and future sampling. Therefore the laboratory should be designed for rapid, one may see it as preliminary, analyses.

For geologists, it is often important to quickly determine the general type of lithology, its relation to other lithologies in the area, and potential significance for the objective, be it general or highly specific. Given the aforementioned broader science questions for the Moon, and bearing in mind the concept of the lab as a place for swift determinations before more detailed analysis can be made on Earth of selected samples, we here suggest the lab to be equipped with, at least, the following instruments.

Firstly, it should be possible to visually inspect the rocks directly in hand specimen. This will require tools for the sampling itself, e.g., hammers, chisels, hand-operated core drillers, and pocket lens, as well as sample bags and containers for safe and clean transport to the lab and storage within the lab. Ideally this would include facilities for mineral separation (sieves, crushers, density separation, magnetic separators). This will allow scientists in the lunar base to quickly assess the samples collected and prepare them for either further analysis on the Moon or select portions to return to Earth. For example, if precise geochemistry or geochronology is to be done on Earth, the individual mineral grains could be picked on the Moon thereby drastically reducing the volume to be returned to Earth. Other equipment could include hand-held petrophysical tools such as susceptimeters and even artificial intelligence (AI) systems designed to aid in the sample selection (see articles on the Cyborg Astrobiologists by McGuire et al. [2]).

Secondly, the samples, when arriving to the lab, should be possible to be swiftly analyzed directly under binocular magnifiers, and with tools such as fluorescent light etc. This will assist in identifying important mineral resources (e.g., trace elements) which are often housed in small phases not clearly visible to the naked eye, or are in phases that fluoresce under UV light. Having such equipment will help researchers assess whether how best to use the collected samples in further analyses. At this stage it is also important to have the capacity to cut and polish rocks of up to hand specimen dimensions (i.e., a cubic dm).

A further step would be to have an equipment for semi-automated thin section production. For the analysis of thin sections and cut-and-polished rock slabs optical microscopes for both translucent and reflected light are needed.

If further analysis of mineralogy and microstructures are needed there should also be a Scanning Electron Microscope coupled with an Energy Dispersive X-Ray (SEM-EDX). The ability to generate quick rough (even semi-quantitative) chemical analyses will help ensure that a variety of compositions are returned to Earth and that we are making the best use of the samples being collected.

The above would serve as a generic "base lab" for answering a variety of geologic questions. Some of the objectives above would require more specialized equipment as outlined in the following section.

2.2.2 Instrumentation on the lunar surface

1) Space weathering: Studies of space weathering and effect of micrometeorite impacts on the lunar surface. This is a major question regarding the Moon and directly relates to our ability to identify surface mineralogy via remote spectroscopic measurements. Therefore, having direct measurements would complement our set of remote observations. The first question centers on quantifying the micrometeorite flux over time. This could be achieved through a small particle counter placed outside the lab on the lunar surface. Secondly, it would be useful to have portable Analytical Spectral Devices (ASD)-type spectrometers that could be taken outside the lab to measure the spectra of rocks in situ. Ideally a portable ASD would allow for repeated measurements of the same surfaces over time to track their spectral changes due to solar wind and micrometeorite impacts.

2) Of the stated objectives above, many can be answered in terrestrial laboratories with samples returned from the Moon. The primary objective for this lunar-based laboratory should be for rapid analyses and screening of samples as an initial step before other more-detailed investigations such as those done in a terrestrial laboratory. However, one critical question involves lunar volatile content, which may be better answered in a lunar-based lab. One complication with lunar volatile studies is the potential for terrestrial contamination. Therefore measuring volatile abundances directly on the Moon would greatly reduce the likelihood of such contamination and lead to more robust interpretations. For this, Secondary Ion Mass Spectrometers (SIMS) would provide the most precise measurements of lunar rocks.

3 Materials Science

For this paper, we restrict our research interest to investigating the material properties of lunar regolith, with the primary aim of closing the gaps left by the Apollo missions which were largely focused on physical and chemical characteristics of the regolith. In order to aid future development for in-situ resource utilization on the Moon, particular with the goal of creating structures, it should be the primary focus to understand the local resources.

This limitation is of course debatable, as it might be worthwhile to also investigate the behavior of materials brought from Earth in the lunar environment, like alloys, solar panels, and components of the base or spacecraft. We will therefore consider including a broader scope in future compilations of scientific equipment.

3.1 Basic laboratory equipment

A lunar laboratory with the focus on material science should initially support analyzing the materials on-site. The first step would be towards the in-situ analyses of resources such as lunar regolith and rocks. Towards this goal, a closed visual analysis of the samples is necessary using microscopy (visible, polarized, Scanning Electron Microscopy (SEM)). These microscopy devices enable analysis of regolith regarding its geometry, sphericity, chemical composition and minerals.

In the next step, quantitative analysis of the regolith and crushed rocks requires sieving the soil into different particle sizes and distributions (using different mesh-sieves).

Wet sieving would also be necessary in order to remove the dusty part of regolith from the bigger particles.

For sieving purposes, rocks could be crushed using a jaw crusher or a ball mill device.

Moreover, a scale would be necessary in order to provide the mass fraction of particles and rocks. Sieving could be implanted using a shaker at different frequencies. This shaker could be further applied to compacting/tapping the regolith to study the effect of lunar soil compressibility and cohesion under reduced gravity. For pouring the regolith, basic equipment from the chemical lab such as beakers and funnels are necessary.

In order to shape the regolith into solid objects and study the sintering behavior of the lunar soil on-site, an oven and corresponding molds (crucibles) are needed. This oven should reach temperatures above ~1200 ℃ which is the melting temperature of regolith for the most studied areas on the Moon so far. [3]

A Differential Scanning Calorimeter (DSC) device could provide more detailed information regarding the melting behavior of the regolith on-site. In order to shape regolith into a denser form, a press device is required before sintering/melting it in the oven.

Furthermore, volume analysis of the formed geometries is required. This could be done using different methods such as envelope density measurement devices.

Chemical analysis and crystal structure of the lunar soil as well as the sintered/molten shaped products could be done using Energy-dispersive X-ray spectroscopy (EDX) and X-Ray Diffraction (XRD). Mechanical testing devices such as a compressive and flexural strength analyzer would be needed in order to evaluate the shaped products' properties. Hardness evaluation of the final samples would also be required. Ultimately spectrometers which could determine the absorption, reflection, and transmission of regolith and the shaped products at different wavelengths would be needed.

3.2 Summary of recommended instrumentation

1. Microscopy (visible, polarised, Scanning Electron Microscopy (SEM)).
2. Sieving machine (dry and wet)
3. Shaker
4. Jaw crusher/Ball mill
5. Oven
6. Press
7. Differential Scanning Calorimetry (DSC)
8. Energy-Dispersive X-ray spectroscopy (EDX)
9. X-Ray Diffraction (XRD)
10. Compressive and flexural strength analyzer
11. Hardness testing device
12. Spectrometer instrument

In addition, the following consumables are recommended as direct contact with the regolith must be avoided:

1. Lab gloves (standard + heat resistive)
2. Safety goggles
3. Mask
4. Lab coat

4 Astrochemistry

4.1 Open questions and investigations of interest

The Moon has been collecting organic material from carbonaceous chondrites, asteroids, comets, and interplanetary dust particles (IDPs) for over four billion years. As such, it tells the story of the evolution of carbon compounds throughout a large part of the Solar System's history.

4.1.1 The source of organic molecules on the Moon

The lunar rocks returned by the Apollo missions were analyzed in the 1970s for their carbon containing compounds (see Gibson et al., 1972 [4] for a review). In that time, it was rather difficult if not impossible to distinguish whether they were of exogenous or terrestrial origin. More recently the Apollo 17 samples have been revisited with new instrumentation and techniques [5], [6]. With the development of compound-specific isotopic measurements, it is now possible to distinguish with more accuracy between the different sources of organic compounds contained in the Apollo samples [7].

Continued investigations into organic content of meteorites and comets [8], [9], prompts the search for organic matter on the Moon with new fervor. The ongoing analysis of lunar regolith will help distinguish more precisely the origin of organic compound content, be it from meteoritic infall, solar wind (thought to have delivered acid-hydrolysable precursors to amino acids [10]), or terrestrial contamination.

Studying lunar samples on the Moon has the advantage of being less prone to contamination by terrestrial organic molecules. With scientists being involved in the entire process of sample collection, preparation, and analysis, the inevitable contamination history can be well documented and understood.

4.1.2 Survivability of organic molecules during meteoritic impact

A topic of interest relating to astrobiology explores the probability of survival of organic compounds when delivered by meteoritic impact. This question has already been explored for the Earth [11], though the conditions here are obviously quite different. If such compounds could survive an impact on the Moon, which does very little to slow down an impactor, it would indicate the survivability of impact on many other bodies in the Solar System, and suggest the possibility of transference of organic material between bodies. Whether the ingredients necessary for life, namely prebiotic compounds and water, were delivered to bodies in the Solar System other than the Earth is an important question in the search for extraterrestrial life.

The aforementioned recent studies of Apollo 17 regolith samples show evidence of organic compounds of meteoritic origin, suggesting they may survive impact events on the Moon, as may volatiles [12].

4.1.3 The preservation of organic molecules at depth

A great topic of interest in carbon chemistry on extraterrestrial bodies is that of photolysis induced by UV and cosmic radiation, most studied in the context of Mars. Since the Viking landers, there have been many laboratory studies concerning the degradation of organic molecules by radiation on simulated planetary surfaces [13], [14], [15]. Constraining the causes and rates of this degradation and comparing with influx rates allows for an estimation of the timescale of preservation of organic molecules on a given body.

By looking at molecules on the surface and at depth, we can study how UV affects molecules in the first millimeter of regolith, how solar cosmic rays affect the first two centimeters of regolith, and how galactic cosmic rays affect the first two to ten meters of regolith. A depth profile of organic carbon content can be created in a way which would be unfeasible with a meteorite, which is constrained in size, or on Earth, where a significant portion of ionizing radiation is attenuated.

Another advantage in studying photochemistry on the Moon is that any metal-catalyzed effects are easier to distinguish since much of the minerals are dehydrated. Whereas ice photochemistry has been extensively studied in laboratories on Earth (see Cottin et al., 1999 [16] or Öberg et al., 2016 [17] for a review), metal photochemistry and catalysis is understudied and might play a significant role in the degradation of organic compounds on the Moon.

4.2 Desired instrumentation

4.2.1 Consumables

Organic extraction from lunar regolith requires some basic equipment and consumables. Organic solvents such as chloroform and methanol will be needed, as well as acetone and ethanol for cleaning. Syringes with micro-pore filters will be required to remove any metals from the organic extractions for further analysis.

4.2.2 Equipment

The instruments required include those for measuring environmental conditions such as a thermometer and radiometer.

As some larger kerogen-type molecules can be difficult to extract from a mineral matrix, an accelerated solvent extraction (ASE) system will be necessary, complete with high heat and pressure source. A centrifuge and a nitrogen or vacuum drying system is also needed to remove solvents from the extractions. An oven and a fume hood would be useful for drying and manipulating samples.

Analysis of the organic content of a regolith is best achieved with a combination of spectroscopy and mass spectrometry. Both Fourier transform infrared (FTIR) and Raman spectroscopy would be good candidates. Gas chromatography mass spectrometry (GC/MS) would be suitable, both for small organic compounds and larger polycyclic aromatic hydrocarbons and kerogen type molecules. It would be best with a tandem MS system, as the amount of different organic compounds in one sample may be large, and a column may not be enough to achieve good separation. Alternatively this can be substituted by liquid chromatography mass spectrometry (LC/MS) coupled with high performance liquid chromatography (HPLC).

5 Astrobiology

5.1 Open questions and investigations of interest

While presumably devoid of life, the Moon could allow for valuable astrobiology investigations [18–20]. Those mainly pertain to: i) the limits for life beyond Earth, ii) the search for extra-terrestrial life, iii) the origins and early development of life, iv) biological life-support systems (BLSS), and v) microbiome evolution and containment.

5.1.1 Limits for life beyond Earth

Studies on life's limits would benefit from the Moon's lack of magnetic field and atmosphere, which results in high vacuum and unattenuated fluxes of UV and ionizing radiation [21]. Such radiation cannot be reproduced in ground-based facilities [22] and is affected by Earth's magnetic field in low Earth Orbit (LEO). Exposure experiments on the Moon could thus yield insights into the habitability of extra-terrestrial environments, planetary protection, and the likelihood of lithopanspermia [18].

5.1.2 Search for extra-terrestrial life

A laboratory on the lunar surface would also allow for assessing the stability of biosignatures under extra-terrestrial environments [23,24], and the testing of life-detection instruments and protocols foreseen for Mars.

5.1.3 Origin and early development of life

Due to its lack of plate tectonics, and wind or water-driven weathering, the lunar surface may have preserved fragments of the early Earth and Mars, landed there after impact ejection [25,26]. Their analysis may help elucidate the evolution of those planets' habitability, and possibly contain traces of early life forms [25]. Besides, prebiotic molecules—either indigenous or deposited by meteorites or interstellar dust particles—may be preserved in permanently shadowed ice [27]. This record may help understand the emergence of life from abiotic chemistry.

5.1.4 Biological life support systems

The Moon could be used as a testbed for BLSS. A lunar BLSS could reduce the costs of long-term missions, and some Moon-specific BLSS modules have been proposed [28–30]. Above all, testing full-scale BLSS would be highly valuable in preparation for crewed Mars missions [18]. While a Martian BLSS would best rely on local resources [31] which differ from the Moon's, a lunar BLSS would also have to provide an environment radically different from the outside, be relatively Earth-independent, and function in lower-than-Earth but non-null gravity.

5.1.5 Microbiome evolution and containment

Finally, microorganisms in extraterrestrial habitats can pose a threat to space crews and mission objectives, due to the potential emergence of pathogens [32] and technophiles [33]. Besides, outbound leaks of micro-organisms could contaminate the environment [34–37]. A Moon base could allow for the assessment of microbial communities' dynamics in habitats beyond Earth, in an environment where planetary protection constraints are mild [38] and crewmembers can be evacuated promptly.

5.2 Desired instrumentation

Consumables needed for the above mentioned astrobiology investigations are similar to those used on Earth for microbiology and molecular biology (and possibly others fields of biology, such as plant biology, based on BLSS design; but this is not addressed here). However, given payload weight and waste disposal limitations, reusable versions should be preferred for typically disposable resources (Petri dishes, reaction tubes, etc.).

Overall, hardware should be resistant to the stresses of launch and landing, while working under reduced gravity and not representing hazards in flight. Miniaturized systems [e.g., 39–41] should be favoured to minimize payload weight and volume, reagent consumption, and need for waste disposal. Kits and automated platforms [e.g., 42,43] are desirable for routine tasks, to minimize the need for crew time and training. While those constraints may be seen as harsh, a wide range of biology hardware items meeting them have been developed for previous experiments in LEO (notably on the ISS) and could be used in, or adapted for, a lunar base.

Habitability and biosignature research will require an array of environmental sensors including thermometers, radiometers (for UV and ionizing radiation), and humidity sensors. They will also require analytical instruments such as microscopes (optical, fluorescence, confocal, and potentially SEM and others), spectrometers (UV-Vis-IR, Raman), gas and liquid chromatographs coupled with mass spectrometers (GC/MS and LC/MS), nucleic acid sequencing facilities, and biosensor arrays (or biochips) allowing, for instance, immunoassays. Equipment primarily aimed for geology research could be used for studies on molecule- and microbe-mineral interactions. Exposure experiments could also be equipped with in situ monitoring and measurement devices.

The sensors, sequencing facilities, microscopes, and other analytical devices mentioned above would serve as well for experiments involving actively growing microorganisms—mainly BLSS and microbiome studies. Those will also require microbiology and molecular biology hardware, similar in function to that of a terrestrial laboratory but adapted to the constraints mentioned above. They will also require a sterilisable and contained workplace, such as a glovebox system [42,44,45]. This setup could be used for non-biological research, for instance that involving lunar dust.

Equipment needed for prebiotic chemistry research was described in section 4 (Astrochemistry).

6 Astronomy

The Moon provides a unique environment for astronomy, with no atmosphere, large cold polar craters in permanent darkness and polar peaks of perpetual sunlight, no ionosphere, and, as confirmed recently, abundant ice. It is seismologically stable and the lunar far side is the most radio-quiet area in the inner solar system. It has great potential for the future for infrared astronomy and for cosmology, as a space-like environment where one can build telescopes.

The cold polar craters on the moon offer an environment beyond anything achievable on the Earth or foreseeably in space: areas of 10 km or more in size, thermally stable at 30K, and within reach of perpetual solar power from the crater rims.

6.1 Open questions and investigations of interest

Astronomy objectives on the Moon range from verifying predictions of inflation, to detecting spectral distortions in the cosmic microwave background (CMB), to detecting the first stars and galaxies, to investigating the physics of super-massive black holes in the centers of active galaxies, and to probing the chemistry of the birthplaces of stars and spectro-images of exoplanets for possible biosignatures.

The main target of current and future CMB experiments is the CMB polarization signal induced by gravity waves at the onset of inflation. Yet there is no guaranteed prediction of such a signal, therefore we need to search for primordial non-gaussianity (PNG) in order to robustly test the theory of inflation.

Radio interferometer arrays on the far side of the Moon are the unique way to work towards this goal, by probing the dark ages at red-shifts of around 50, when the best probe of cold hydrogen clouds, the precursors of the galaxies, is the 21cm line of atomic hydrogen which however is red-shifted by the expansion of the universe to the decametric band.

Another goal in cosmology will be to detect the first stars, galaxies and active galactic nuclei in the Universe at the end of the dark ages, when the very first stars formed. The science reach includes detection of the first galaxies and the physics of accreting supermassive black holes and their nearby surroundings (dust torus, broad emission line region), the astrochemistry of the first episodes of chemical enrichment of the universe, and unparalleled opportunities for direct detection, imaging and spectroscopy of exoplanets and their atmospheres, analyzing their morphology and searching for biosignatures.

6.2 Suggested external equipment

Due to the immense technological challenge we believe a lunar astronomy program should be staged.

Precursor external equipment: A number of landers, rovers and robotic assets are to be emplaced in the next decade (Lunar Robotic Village) prior to the installation of human bases and laboratories. We expect a series of enhanced external packages of experiments to the ALSEP deployed by Apollo astronauts or other packages deployed by large robotic landers. An example was demonstrated by ExoGeoLab pilot project [46,47].

Precursor telescope elements will include a lunar Pancam for geological context and for supervision of astronauts and rovers. A telescope could allow far distance supervision of astronauts or rovers for sample selection and acquisition, as was demonstrated with telescopes on board ExoGeoLab lander in campaigns at Eifel region [48].

A series of telescopes could monitor the sun in white light, H Alpha and Ca II line. Also Extreme UV telescopes (as onboard EIT SOHO, PROBA2) will be of great interest, in particular from quasi eternal sunlight.

A telescope observing the Earth will have great interest for global mapping, radiation budget, but also for outreach showing the changes due to Earth rotation, cloud cover, illumination phases, seasonal effects, and even long term effect due to man-induced climate change.

A planetary telescope could attain high resolution to monitor solar system planets. A very low frequency radio telescope could monitor the Sun and Jupiter bursts.

A network of radio dipoles would have the ability to gain significant sensitivity to provide new constraints on cosmology.

A first step needs a modest optical telescope (say 40cm-50cm) fully robotized and remotely operated with a simple focal instrument: a wide angle multi-filter camera covering the visible and near IR: say 400nm-800nm. The program would be to do transit photometry of exoplanets in special cases where the angular resolution of a 50cm aperture, i.e. 0.2 arcsec at 500nm gets better resolution than the rather modest multi-telescope of the PLATO project as envisaged by ESA. The goal would be to better follow-up of already discovered exoplanetary systems like it has been the case of the multi-site photometry of the TRAPPIST-B exoplanetary system.

In a second stage, two movable telescopes would be added to the first to constitute an interferometric array operating in the UV wavelengths (200-350nm where classical optics can be used). The reason is the gain in angular resolution for given baselines in comparison with ground operated interferometers and an astrophysical niche that will not be accessible otherwise than from space. With 1000m distance between the 3 telescopes and using intensity interferometry that does not need any delay lines and at 200nm one will access 20 microarcsecond angular resolution which is a factor 50 better than the best operating terrestrial interferometers and very likely for the next two decades.

6.3 Role of the Moon laboratory

A moon laboratory plays a key role in lunar habitation road map and for detailed planning for the complex infrastructure necessary to do astronomy on the Moon. It can support construction of support facilities, undertake site searches, investigate power and computing requirements, and plan transport logistics both to and on the moon. Most of the construction is likely to be done robotically, and astronauts in the lunar base can help in maintenance and repairs of both telescopes/interferometers and rovers.

7 Medicine

There are two types of medical interest in a mission to the Moon: health care to the benefit of the astronaut(s) at the time of treatment and clinical research that benefits future generations of astronauts rather than the individual.

7.1 Health issues and med. emergencies to prepare for

Ball and Evans [49] identified the following major health and medical issues during spaceflight:

- Radiation exposure
- Hearing deterioration
- Cardiovascular problems
- Muscle degradation
- Bone loss
- Neurovestibular problems
- Habitability
- Extravehicular activity risk
- Psychological issues

The majority of these issues can be mitigated by proper planning and preparation. However, “severe emergency medical events such as a traumatic injury, toxic exposure, or acute cardiopulmonary decompensation will probably occur on a long-duration space mission” [49]. A medical bay inside an extraterrestrial habitat should therefore include at least five distinct but connected compartments that meet the criteria of functionality, efficiency, and convenience.

The five compartments or working areas are: (1) infirmary, (2) operating room, (3) airlock to the operating room, (4) post-operative hospitalization ward, (5) examination room, possibly for radiological examinations, laboratory analyses and dental treatments.

7.1.1 Ambulance/Infirmary

Area used for medications of various kinds and small surgery, which hosts the supply of drugs (possibly sorted alphabetically in mobile desk with sliding drawers). It should be equipped with an examination table, a small scialitic lamp, and contain tools such as monitors for vital parameter measurements with defibrillation pads, electrocardiograph, ultrasound; and consumables such as bandages, sterile gauze, sterile gloves, suture threads, surgical instruments, disinfecting and sterilizing liquids.

7.1.2 Clean area

Area used for dressing before the operating room, with automatic door and closed cycle ventilation system with forced air inside, a sink for hand washing with sterilants, a wardrobe with sterile uniforms and shoes for the operating room (for example plastic clogs to be sterilized after use) to be worn before entering the operating room. In this area, surgical instruments (and sterile gloves and suture threads) should be stored, washed and sterilized with pressure steam autoclave. There should be a sliding window with positive pressure for the passage of the surgical instruments necessary for surgery.

7.1.3 Operating room

This room or separable area should be accessed from the filter area. The ventilation system should be closed circuit with forced ventilation. The room should contain an operating table at the center. The minimally indispensable equipment includes: machine for assisted ventilation under general anesthesia, monitor of vital functions during surgery (saturation of O_2, electrical activity of the heart, respiratory rate, blood pressure), aspirator for liquids with graduated vacuum container, semiautomatic defibrillator, mono / bipolar electrosurgical unit, machinery for infusion of pump liquids. At least one central scialitic lamp with the possibility of adjusting the light intensity on the Kelvin scale. It would be useful if a closed circuit camera system was installed on the lamp for the eventual transmission of images in telemedicine to a specialized center for distance consulting. Medication for induction of general anesthesia, as well as intubation material (laryngoscopes, set of cannulae for intubation); either a closed circuit or cylinders that can provide medicinal gases (O_2, Nitrogen, Air) and for maintaining deep anesthesia.

7.1.4 Post-surgery

To save space, the crew quarters should have the function to be repurposed as hospitalization beds, with a monitor for vital functions, the possibility to mount supports for limbs in case of orthopedic operations, machinery for forced automatic ventilation (C-PAP). In addition, the laboratory may provide a trolley equipped

Table 1: Summary of the lab equipment suggested for the four research disciplines discussed within this paper (medicine is listed separately in table 3). The top category lists the equipment that is requested by more than one discipline. The second category comprises equipment specific to only one discipline. Note that this table does not include specialized equipment for specific experiments. “m.d.” = measurement device.

	Geology	Materials Science	Astrochemistry	Astrobiology
MULTI- PURPOSE EQUIPMENT	Microscopes (translucence, reflection, fluorescence, SEM-EDX)	Microscopes (visible, polarised, SEM-EDX)		Microscopes (optical, fluorescence, confocal, SEM)
		Spectrometers (absorption, reflection, transmission)	Spectrometers (FTIR or Raman)	Spectrometers (UV-Vis-IR, Raman)
			Mass spectrometers GC/MS or LC/MS	Mass spectrometers GC/MS or LC/MS
		Scales	Scales	Scales
			Glovebox	Glovebox
			Centrifuge	Centrifuge
	Sieves	Mesh-sieves Wet sieves		
	Crushers	Crushers Jaw or ball mill device		
SPECIFIC EQUIPMENT	Rock cutter+polisher	X-Ray Diffractometer	Accelerated Solvent Extraction system	Nucleic acid sequencing device
	Thin section production	Shakers	Nitrogen or Vaccum Drying System	Biosensor arrays
	Binocular magnifiers	Envelope density m.d.		Environmental sensors (temperature, radiation, humidity)
	Pocket lens	Differential Scanning Calorimeter		
	Density separators	Oven (1200°C)		Incubator
	Magnetic separators			
	Susceptimeters	compressive + flexural strength m.d.		
		hardness m.d.		

with sterile gauze, disinfecting liquids, sterile surgical instruments, gloves, plasters, sterile probes, catheters, infusion fluids.

7.1.5 Laboratory/Radiology

A key piece of equipment would be a (portable) X-ray machine with computerized image acquisition. The medical laboratory requires the possibility to perform analyzes on blood and urine equipped with centrifuge, various reagents, micropipettes, test tubes, blood gas analysis machine, a slit lamp for eye exams, ideally a dental chair complete with scialitic light, an aspirator, micromotor, turbine, ultraviolet light, X-ray illuminator for radiological examinations of the dental arches. Cabinet with drawers and compartments for dental material (surgical instruments, tips for micromotor and turbine, material for dental reconstruction, fillings, glues, suction cannulas).

For the case of exposure to ionizing radiation, a large supply of filgrastim or pegfilgrastim, potassium iodide and EPO would be useful.

Frequent dehydration can lead to frequent cases of renal lithiasis so it is useful to always have hydrochlorothiazide available to combat calciuria and the necessary to perform shock wave lithotripsy, as well as cystoscope and ureteroscope.

8 Overview and synergies between disciplines

We summarize the laboratory equipment recommended in sections 2-5 in table 1. As the primary purpose of this paper is to compile a list of the “most wanted” laboratory equipment, we have left out the outdoor facilities suggested by astronomy. Moreover, the table only contains research equipment; medical supplies are listed in the separate table 3 (note that in the future, medical research should be added to the categories in table 1, plus perhaps geophysics and other disciplines).

Table 2: Equipment recommended for a scientific moon laboratory. 1 – must have, 2 – necessary, 3 – nice to have, C – Consumables.

Priority	Equipment
1	Optical microscope
	Fluorescent microscope
	SEM-EDX
	UV-Vis-IR spectroscope
	Raman spectroscope
	Gas chromatograph + MS
	Crushers
	Sieves
	Scales
	Environmental sensors
	Glovebox
2	Rock cutter + polisher
	Thin section cutter
	XRD
	Shaker
	Strength and hardness m.d.
	Centrifuge
	DNA sequencer
	Biosensor arrays
	Oven
	Binocular magnifiers
	Pocket lens
3	Translucence, reflection, confocal microscope
	Absorption, reflection, transmission spectrometer
	Envelope density m.d.
	Differential scanning calorimeter
	Accelerated solvent extraction system
	Nitrogen or vaccum drying system
	Density separators
	Magnetic separators
	Susceptimeters
C	Glassware
	Organic solvents
	Reagents
	Safety equipment
	Additional supplies
	Storage containers
	Sample bags

We identified 8 categories of instrumentation that are required by more than one discipline (presented in table 1 as section multi-purpose equipment). We suggest that these are included in any research laboratory on the Moon. The second half of the table (labeled "specific equipment") contains instrumentation that was only mentioned by one discipline—although this categorization does not necessarily represent the importance of those instruments for each discipline.

This representation has been attempted in table 2, where the equipment from sections 2-5 is sorted according to relevance. Highest priority (1) in a lunar lab should have the equipment from the multi-purpose category in table 1 ("must have"). For example, this category comprises microscopes, which are needed by all disciplines but astrochemistry, and the microscopes in "high" demand are optical, fluorescent microscopes and SEM. The other type of instrument required by several disciplines (astrobiology, astrochemistry, materials sciences) are spectrometers, particularly a combination of UV-Vis-IR and Raman spectrometers. In addition, both geology and materials sciences would benefit from crushers and sieves, and astrobiology and astrochemistry would benefit from a gas chromatograph coupled with a mass spectrometer.

The second category in table 2 "necessary" contains equipment from table 1 that was named by only one discipline, but that we consider an essential part of a lunar laboratory for that discipline.

Category 3 ("nice to have") on the other hand, should be considered to be included in the laboratory, but it may be worthwhile to rank its instruments according to scientific benefit and mass—and determine a cut-off based on this ranking.

Finally, category C contains consumables that are likely to be needed by one or more disciplines. These consumables are: glassware such as beakers and petri dishes needed by every discipline but geology; organic solvents such as chloroform and alcohols (for astrobiology and astrochemistry), reagents and nutrient solutions (astrobiology), and some additional supplies such as funnels and syringes. Moreover, geologists will need a collection of storage containers and sample bags. Another type of consumable may more may not be required in a lunar lab: safety equipment such as gloves, goggles and perhaps even gloves. These pieces should be considered, but they might be found to be superfluous, if all hazardous materials are being handled inside the glovebox.

Medical supplies suggested for the laboratory are listed in table 3. They are listed separately, as the supplies we are considering are intended for treatment of medical problems, rather than prophylactic treatment or medical research. Nevertheless, as the laboratory is likely to be the cleanest module in a lunar habitat, we felt it was appropriate to include (emergency) medicine in the equipment of the laboratory.

9 Recommendations for a Moon laboratory

1 We recommend to include in a Moon laboratory the scientific instrumentation as listed in table 2, sections 1 and 2, plus the consumables in section C of the same table. It should be noted however, that this paper is presenting ongoing work, therefore this list is not (yet) exhaustive.

Table 3: Equipment for medical emergencies. 1 – to be stored in the lab, 2 – could be stored somewhere else, C - consumables.

Priority	Equipment
1	monitors for vital parameters
	defibrillator
	ultrasound
	machine for assisted ventilation under general anesthesia
	electrocardiograph
	sterile surgical tools
	steam autoclave
	aspirator for liquids with graduated vacuum container
	scialitic lamp, possibly with camera for telemedicine
	mono / bipolar electrosurgical unit
	machinery for infusion of pump liquids
2	supports for limbs after orthopedic operations,
	machinery for forced automatic ventilation (C-PAP)
	drawers, racks
	trolley
	operating table
	examination table
C	Easily accessible drugs (TBD)
	Restricted-access drugs (TBD)
	bandages
	sterile gauze
	sterile gloves
	suture threads
	disinfecting and sterilizing liquids
	infusion fluids
	wardrobe with sterile uniforms and shoes
	medicinal gases (O2, Nitrogen, Air)
	anesthesic gases
	intubation material
	catheters

2 We recommend to include all medical equipment listed in table 3. For safety reasons, we suggest to store all medical equipment in a separate rack/ storage space within the laboratory.

3 To save launch mass, we suggest to design racks in a way that they can be re-purposed as examination/ operating table.

4 We recommend to balance the equipment of table 2, section 3 with other specialized equipment that may be developed in the future, and make the final selection based on science priorities at the time of actual launch.

5 In order to accommodate changing needs, we recommend to reserve a reasonable fraction of laboratory space for future experiments of currently unknown nature (in addition to the dedicated space for the equipment mentioned above).

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