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Life Sciences Investigations for ESA's First Lunar Lander

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Abstract Preparing for future human exploration of the Moon and beyond is an interdisciplinary exercise, requiring new technologies and the pooling of knowledge and expertise from many scientific areas. The European Space Agency is working to develop a Lunar Lander, as a precursor to future human exploration activities. The mission will demonstrate new technologies and perform important preparatory investigations. In the biological sciences the two major areas requiring investigation in advance of human exploration are radiation and its effects on human physiology and the potential toxicity of lunar dust. This paper summarises the issues associated with these areas and the investigations planned for the Lunar Lander to address them.

Keywords Moon · Exploration · Radiation · Dust · Toxicity

1 Introduction

Ensuring the long term health of human explorers on the surface of the Moon, or any other deep space environment, during and following long duration missions poses a major challenge for the future of human space exploration. Major uncertainties exist as to the nature of deep space environments and their effects on human physiology, and there are a

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number of potential risks to human health. Of these radiation, of both solar and galactic origins, may be the most significant and represent a limiting factor for the duration of future deep space exploration missions by humans (White and Averner 2001). For exploration of the Moon an additional hazard may be posed by toxic lunar dust. A sustainable human exploration programme requires that the effects of these hazards are properly characterized and their effects understood, in order that they can be accounted for in the design and planning of future missions. Important steps in achieving this can be achieved through unmanned precursor missions.

The European Space Agency (ESA) is preparing an unmanned Lunar Lander mission, as a precursor to future human exploration of the Moon and beyond for a nominal launch in 2018. At the time of writing this mission has been studied to Phase A level in three parallel industrial activities and is looking forward to the initiation of the Phase B1 level design. Illustrations of the lander designs emerging from the Phase A mission studies are shown in Fig. 1. The mission is part of a wider programme that seeks to prepare Europe for participation in future human exploration efforts by developing and demonstrating new technologies, increasing knowledge of deep space environments, such as the Moon, in areas important for planning and preparing human exploration activities, and gaining experience of working and operating in the relevant environments. The programme also seeks to bring together the various diverse expertise and disciplines that will be essential if humans are to successfully and sustainably explore beyond Low Earth Orbit (LEO).

The primary technology that needs to be developed in Europe to ensure active participation in future exploration activities has been identified by ESA as being automated soft precision landing with hazard avoidance. The demonstration of this technology is the primary objective for the Lunar Lander mission. Once on the surface of the Moon however the mission provides an opportunity to operate a payload and perform investigations, which are important for human exploration, and which can only be carried out in situ on the surface of the Moon. A number of experiments and instruments are under consideration for the mission and accounted for in the model payload. A brief description of the model payload currently under consideration is given by Carpenter et al. (2010a). Of these investigations a number are selected to make measurements directly related to these areas of radiation and dust as hazards for human exploration.

The selection, design and development of instruments for the mission and their operation are all heavily dependent on the detailed mission scenario and the boundary conditions for

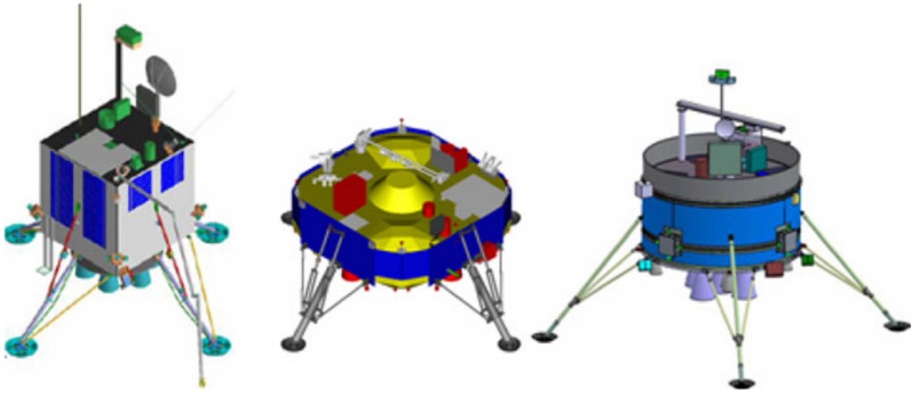

Fig. 1 The three Phase A designs for the MoonNEXT Lunar Lander in the studied Soyuz configuration. From *left* to *right* OHB Systems, Thales Alenia Space, Astrium ST

next phase of the mission design (Phase B1). The details of the baseline mission scenario as it stands and the reasons for their adoption as the baseline for the mission are described in detail by Fisackerly et al. (2010). The scenario has been determined in order to address, as far as is practical, the requirements for human preparatory science (Carpenter et al. 2010b), while taking into account technical and programmatic considerations revealed during the Phase A mission studies. The boundary conditions of the mission scenario must be taken into account when determining which of the many potential mission objectives may be achievable and what a model payload for the mission should be.

A Soyuz class mission launched from Kourou is assumed. The Phase A studies have shown that a mission of this class may be expected to deliver ~60 kg of payload mass to the surface of the Moon. This payload mass includes science instrumentation and any robotics, deployment mechanisms and other servicing elements that are required by the payload. The limitations of payload mass mean that a rover cannot be included in the mission but a high science return relevant to the requirements of exploration preparation can be obtained without mobility (Carpenter et al. 2010a).

It is assumed in Phase B1 that Radioisotope Heating Units (RHUs) are not available for the thermal control of the mission, to enable survival during the lunar night, when temperatures drop below 100 K (e.g. Paige et al. 2009). Mission duration is therefore driven by the illumination characteristics of the landing site and the limitations of thermal design of the lander and landing site selection is driven by the need for favourable illumination conditions to reach a mission duration compatible with the intended investigations. The optimal potential landing sites for mission duration appear to be located at the Lunar South Pole, where the rotational axis of the Moon (tilted 1.54° with respect to the ecliptic plane), coupled with the local topography result in areas for which the duration of illumination far exceeds the 14 Earth day duration of a lunar day, as experienced in equatorial sites (e.g. Bussey et al. 2010; Vanoutryve et al. 2010). The precise locations of these favourable locations are strongly driven by the effects of the local topography on illumination. A mission duration of 6–8 months is expected assuming an optimal landing site close to the South Pole, to be confirmed during the coming mission phases. This selection follows an analysis of illumination conditions at the lunar South Pole (Vanoutryve et al. 2010) using digital elevation model data provided by the Kaguya mission. Similar analyses have also been performed by other authors (e.g. Bussey et al. 2010; Noda et al. 2008).

2 The Lunar Radiation Environment

Radiation at the Lunar surface is dominated by four distinct populations: low energy Solar Wind Particles (SWPs), high energy Galactic Cosmic Rays (GCRs), sporadic high energy particles released during Solar Energetic Proton (SEP) events and secondary radiation generated by the interactions of these primary sources with the lunar surface and subsurface to depths of approximately a meter. Secondary radiation will also be generated by particle interactions with materials in spacecraft and lunar surface infrastructure. In addition ionisation of the surface, to depths of several microns, results from solar UV and X-ray photons (e.g. Vaniman et al. 1991).

SEPs are associated with solar Coronal Mass Ejections (CMEs) and are predominantly protons and He^{2+} nuclei. The energies of these particles are typically between 20 and 80 MeV, although particle energies of GeV can be observed in very large events. Electrons of energies between ~0.5 and 1 MeV usually arrive at 1 AU along magnetic field lines with tens of minutes to hours of a CME event (Posner 2007 and references within). These

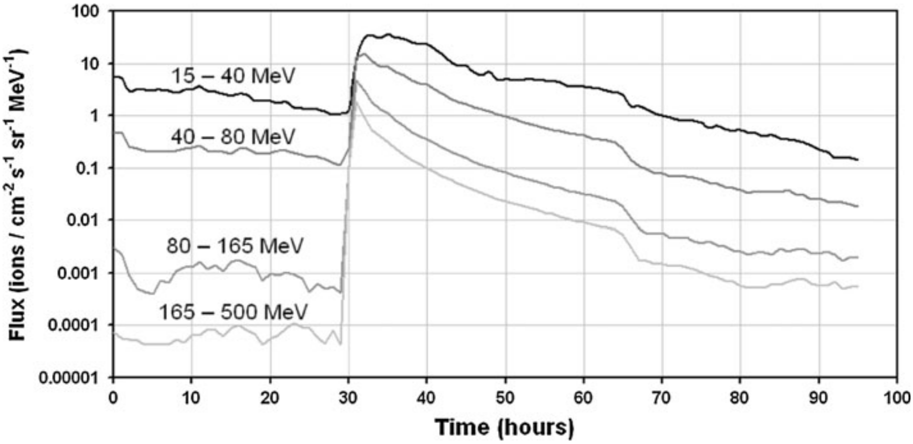

Fig. 2 Proton Flux in four energy bands at 1 AU measured during a typical SEP event by the proton monitor on the NOAA GOES-11 geostationary spacecraft in the period between 00:00 on 19 November 2005 to 23:00 on 23 November 2005. Data shown are hourly averages

electrons precede the arrival of the protons and alpha particles, which usually arrive within several hours to tens of hours, although travel times to 1 AU can be as little as 20 min for flares in the Sun's western hemisphere (Shea and Smart 1996). During an SEP event proton flux can increase by several orders of magnitude over very short time scales, as illustrated in Fig. 2. The distribution of flux between the various energy bands shown in Fig. 2 is also typical, with the majority of particles having energies of <30 MeV and the flux falling rapidly as a function of energy. The precise function describing the flux as a function of energy can be highly variable between events.

After the initial peak in particle flux, which can last for a period of several hours, flux tends to decrease gradually over a period of several days to weeks. Fluxes of the highest energy particles fall off rapidly while fluxes for lower energy particles fall off more gradually.

The penetration of depth of SEPs is typically of the order of cm (0.3 cm Continuous Slowing Down Approximation range for 100 MeV protons in Al increasing to 6 cm for 500 MeV protons) and so the immediate risk from particles to human activities is low when Al shielding is sufficiently thick. The frequency and magnitude of SEP events varies with the solar cycle, with the greatest number of large events occurring around solar maximum.

Galactic Cosmic Rays (GCRs) are particles which originate outside of the solar system, but within our galaxy, and are incident in the inner solar system with an isotropic distribution. Their energies can be as high as 10^{20} eV (Vaniman et al. 1991) but are typically in the range 10^{9}–10^{13} eV (Zombeck 2007). The precise sources for these particles and the reasons for their high energies are not well understood. The GCR population is composed of 85% protons, 11.8% alpha particles, 1% atomic nuclei of $Z > 2$, and 2% electrons and positrons. Of the high-Z particles a significant proportion are found to be rare elements Li, Be, and B, or other minor elements with $Z < 28$. This enhancement is believed to be a result of spallation reactions which occur during collisions with interstellar matter particles during the 10^{7} year typical journey time from source to solar system (Vaniman et al. 1991).

The entry of GCRs into the Solar System is moderated by the interplanetary magnetic field, which is carried by the solar wind. The inward diffusion of GCRs is balanced by the outward convection of the solar wind. The relationship between the density of GCR particles inside the solar system and outside has been modelled by several authors (e.g. Parker 1965; Badhwar et al. 1994) and the results demonstrate a strong dependence on the properties of the solar wind, magnetic field and radius of the heliosphere and thus the level of solar activity is of prime importance. Indeed GCR flux is found to be inversely correlated with the solar cycle, which can be represented by sunspot number.

SEP and GCR particles impacting on the lunar surface will interact with nuclei in the regolith and surface materials and secondary radiation can be produced via processes including neutron capture, inelastic scattering and high energy spallation. The products of these reactions can include neutrons, gamma rays and various nuclear fragments. The precise composition and spectra of secondary emission is a function of the energy of the incident particles and the properties of the local regolith but the dominant products are neutrons.

Observations and of the secondary neutron environment made from orbit around the Moon by Lunar Prospector (Maurice et al. 2000) have been used to inform models of neutron production and the resultant doses received on the surface (Adams et al. 2007). These models indicate that secondary neutron fluxes contribute approximately 18% to the total received doses received behind 1 g cm^{-2} received during periods of solar maximum and approximately 16% during solar minimum. This is comparable to the uncertainties in predictions of GCR fluxes. During a single SEP event in October 1989 the secondary neutron dose was calculated to contribute approximately 2.4% of the total dose associated with the event.

3 Radiation Effects on Lunar Explorers

Lunar astronauts will be exposed to the various sources of radiation, described in the previous section. Protons and HZE particles may have significant biological effects, even at low fluences, and considerable uncertainties exist about the effects of secondary particles (Durante and Cucinotta 2008). The effective dose rates for the 1977 solar minimum and the 1970 solar maximum GCR environments in deep space (Hoff et al. 2002) are reported in Table 1 and compared with the estimated effective dose from albedo neutrons (Adams et al. 2007), generated by interaction of GCR and SEP radiation with the lunar crust. In Table 1 we also report the effective dose from the October 1989 Solar particle event on the Moon behind a shield of 1 g cm^{-2} Al.

The risks to human physiology due to radiation exposure may be categorised as either acute risks, associated with solar particle events, or late stochastic risks, associated with

Table 1 Comparison of the effective dose rates from GCR and albedo neutrons calculated during the 1970 solar max and the 1977 solar min

	GCR		SEP
	1970 solar max (mSv/year)	1977 solar min (mSv/year)	October 1989 (mSv)
Charged particle dose	89	244	964
Albedo neutrons dose	26	28	14
Total	116	282	978

Also shown is a comparison of the effective doses from the SEP in the October 1989 event and the albedo neutrons generated by the SEP during this event. The GCR and SEP effective doses were calculated behind 1 g/cm^2 of aluminium shielding. Adapted from Hoff et al. (2002) and Adams et al. (2007)

chronic exposure to GCR, which may be 100 times greater on the Moon than on the Earth during solar minimum. Acute effects include radiation sickness, which can affect crew health and performance and thus represents the main operational concern related to radiation exposure in a moon mission scenario (NASA, Human Research Program, Evidence Book 2009). In addition radiation damage to cells and the subsequent loss of cells may affect the functional integrity of the central nervous system, again a potentially mission compromising event (NASA, Human Research Program, Evidence Book 2009). Of the chronic stochastic effects the primary concern is the induction of late-occurring cancers (Space Studies Board 2000; Space Studies Board 1996) and this is the primary parameter used to set the maximum allowable doses to astronauts in LEO. Other potential chronic radiation induced physiological problems include cataracts, which appears to progress linearly with exposure time to GCR. Studies have also indicated previously unknown mechanisms of radiation-induced cellular pathologies which follow communication between damaged and undamaged cells and the induction of unstable states leading to the late expression of genetic damage (Cucinotta and Durante 2006).

Uncertainties about the effects of space radiation on human physiology arise primarily because of an inability to create analogous radiation environments on Earth in which to perform appropriate testing. Instead the approach to testing is to use experimental models to estimate the relative effectiveness of the radiation in question and γ-rays. The relative factor used most often is the Relative Biological Effectiveness (RBE). This is defined as the ratio of the dose of a reference radiation to the radiation under study that will produce an equal level of effect for a given experimental observation. Observations show however that RBE is a complex value that can vary by up to two orders of magnitude and is a function of the biological endpoint, cell or animal models, dose, dose rate and type of radiation (National Council on Radiation Protection and Measurements 2000). Additional multiple stressors in the unique environment of the Moon (e.g. reduced gravity) can lead to synergistic or antagonistic effects which can only be investigated in the lunar environment.

Practical limitations on the determination of RBEs mean that values do not exist for many radiation types and environments. In addition for radiation with very high Linear Energy Transfer (LET) values it may be that effects are different from those observed for photons. As a result serious limitations exist in present methodologies for quantifying space radiation effects on biological systems.

The standard approach when using RBE values in the assessment of radiation risks to humans is to is to apply an LET dependent radiation quality factor, Q(L), also called a radiation weighting factor, w_r. This value is the factor by which an absorbed dose (measured in gray, Gy) must be multiplied to obtain a quantity that expresses, on a common scale for all ionizing radiation, the biological damage (measured in sievert, Sv) to the exposed tissue.

RBE values are recommended by the International Commission on Radiological Protection. In proton therapy an RBE of 1.1 is assumed, based primarily on animal data but the RBE values associated with protons and heavier ions in the GCR and SEPs are poorly constrained, and may be modified at low dose rates.

4 Measuring Radiation Effects

Providing a meaningful contribution to improving estimates of the long term effects of the integrated lunar radiation environment is of high priority given the major uncertainties associated with current estimates of radiation risk and the potential implications for human explorers (Durante and Cucinotta 2008). In order to accomplish this, experiments to test the effects of mixed radiation fields and the response of biological systems under stress conditions in the lunar environment are needed. Ground-based experiments are irreplaceable for providing accurate measurements of space radiation effects under well defined conditions (ESA-IBER 2006). However, the lunar radiation environment is characterized by a mixed radiation field, including charged particles from H to Ni at energies from a few MeV/n to TeV/n, neutrons, X-rays, and an unfiltered UV spectrum. Moreover, exposure occurs in severe stress conditions caused by reduced gravity, hypoxia, etc. Only local biological experiments can incorporate all these factors for comparison with the predictions of ground-based experiments and experiments performed in Low Earth Orbit (LEO). Given the importance of improving radiation safety advice for future human explorers and the need to measure effects in situ to properly address the related issues this is considered a high priority objective for the Lunar Lander mission.

An experiment concept under investigation for the Lunar Lander uses cell cultures to characterize radiation response in human physiology. Cell lines can be genetically engineered to constitutionally express fluorescent markers such as Green Fluorescent-Protein (GFP) or luciferase. These markers can monitor transcriptional activity of specific promoters, thus providing real-time information on the viability and metabolic activity of the cells, or allowing live visualization of recruitment of DNA repair proteins to sites of heavy ion hits (Jakob et al. 2009). Fig. 3 shows tracks observed in cells following DNA damage by accelerated Ni ions. The method could be used to provide real-time biodosimetry from patterns of foci, thus addressing specifically the issue of the mixed-radiation field exposure. Moreover they can be used to trace cell division and the resulting progeny. Bioluminescence assays can be applied to monitor a number of transcriptional and metabolic pathways that can be activated in response to radiation and stress, such as the NF-κB pathway (Baumstark-Khan et al. 2005), as well as other endpoints expected to be altered in reduced microgravity, such as the cytoskeleton functional status (Kordyum et al. 2005). Samples in containers with different shielding can be used to single out the radiation effects from the other stress-related response. Telemonitoring and teleoperation will require a very

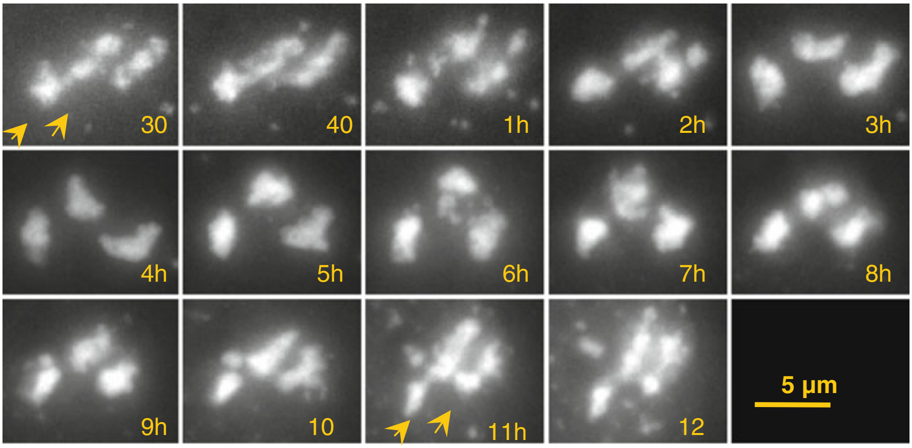

Fig. 3 Examples of tracks observed in human osteosarcoma cells exposed to Ni-ions at the GSI accelerator (Darmstadt, Germany). Two tracks are visible for up to 12 h from the exposure, due to the recruitment of GFP-53BP1 protein to the site of DNA damage

sophisticated technology, particularly considering the mass/volume constraints. Nevertheless, normal human cell lines expressing fluorescent markers are the most promising biological systems for preliminary radiobiology experiments on the Moon, and could provide first information on the cellular response to the complex radiation field under stress conditions.

Considering the size of the cell nucleus and the flux of ions on the moon, it is expected that approximately 2 protons and 0.4 heavier ions per nucleus could be observed per week. Telemonitoring could be able to monitor several hundred cells for extended periods. A minimum duration for exposure for any investigation of this nature is expected to be >1 month with a goal of >1 year. In parallel the radiation environment, including Linear Energy Transfer (LET), spectra, dose and if possible species, must be monitored.

Heritage in the techniques applied exists in ground based observations in accelerator faculties. Adaptation for a lunar mission on this scale is probably feasible in the given time frame but may represent considerable effort. For example the cells need to be maintained by an automated system from integration with the experiment, prior to launch, until the point of exposure to the radiation environment and then kept alive for several weeks during exposure.

5 Lunar Dust Toxicity

During the era of Apollo, in the 1960s and 1970s, the field of dust toxicology was in its infancy and samples of lunar dust were not examined for toxicological effects. The focus was instead on the potential risks due to microbes. In the modern era the toxicity of dust particles has been recognised as an area of high importance for any return to the Moon (Khan-Mayberry 2008). During the brief periods of time spent on the Moon during Apollo it became apparent that lunar dust could pose significant problems for the operations of both people and equipment. Dust was found to adhere to clothing and equipment, it reduced visibility during landings, mechanical devices were severely compromised by lunar dust contamination, optical components were covered with visible dust layers and Apollo astronaut spacesuits became coated with fine-grained dust. Once inside the spacecraft dust caused breathing difficulties and inhibited vision (e.g. Stubbs et al. 2007). Understanding the risks posed by these particles and mitigating exposure to them is of high importance. Understanding these risks requires a proper characterisation of the size, structure and chemistry of grains that pose a potential risk.

Lunar dust originates from the lunar regolith, a layer of rocks and fine grained particles at the lunar surface, whose thickness can vary between approximately 3 and 20 m. The particles that make up the regolith have been generated by billions of years of meteoroid impacts, with subsequent space weathering by thermal cycling, solar wind erosion and impacts leading to comminution and agglutination of original particles. Lunar soils can generally be described by log-normal size distributions with mean diameters typically between 45 and 100 μm; although particles can be at least as small as 10 nm (Greenberg et al. 2007; Liu et al. 2008). Grain morphologies can vary from highly irregular and angular vesicular agglutinates to spherical glass beads, generated during impacts (McKay et al. 1991; Papike et al. 1982).

Dust in the lunar regolith contains a number of minerals including plagioclases, olivine and pyroxene, ilmentite, cristobalite, aptite and metals such as Fe and Ni. The abundances and relative abundances of these, and other, minerals are variable depending on location. In general the basaltic terrains of lunar mare tend to be much richer in ilmenite and olivine whilst the more primitive lunar highlands are dominated by anorthite. At reduced scales the actual compositions of lunar soils are observed to be very localised on a scale of km and less, indicating a limited extent to lateral mixing (Papike et al. 1982). Composition can also vary as a function of grain size; with minerals which favour comminution (e.g. anorthites in feldspars) tending to parent smaller particle sizes than those from olivines and pyroxenes, whose properties are less favourable to comminution. The very smallest particles tend to accumulate into larger agglutinate particles.

It has been identified that lunar dust contains several types of reactive dust. Of these many are in the respirable range, defined previously as those particles with diameters <3.5 μm (Liu et al. 2008) although <10 μm is considered by other authors. Particles <10 μm make up approximately 10% of dust. In addition the surface areas available for chemical reaction are about 8 times that of a sphere of equivalent external size. Of these particles >80 wt% is composed of glass with high abundances of nanophase metallic iron (np-Fe) particles, whose sizes can vary between ~3 and 30 nm.

Small dust particles may be hazardous to human health if they were to enter the lungs, particularly if exposure were for a prolonged period of time, as might be the case for future lunar missions. Impact glass may be easily dissolved in bodily fluids, releasing the np-Fe0 grains, which are very reactive, owing to their redox potential and relatively large surface area per unit mass. In addition the surfaces of particles are unlike any terrestrial analogue and are likely to be highly reactive on account of radicals generated in the highly reducing lunar environment, in which there is no mode for passivation. The extent of this reactivity is key to the toxicity but is not known. Various attempts to reactivate lunar dust and analogues by fracturing and radiation exposure have been attempted but there is no means of verifying the results in the absence of in situ measurements or access to pristine, unpassivated lunar dust. The rate of passivation for particles upon contact with a humid atmosphere like that of a human habitat is not known but may be of the order of a day.

Understanding how these reactive components behave prior to inhalation and then upon contact with a moisture-rich pulmonary environment is important in determining the toxicity of grains to humans and generating risk criteria for lunar dust exposure and lunar dust standards.

Measurements of the size distribution of lunar dust have shown a depletion of particles in the sub micron—nanometer size regime. For example Fig. 4. shows the particle size distribution, measured by Park et al. (2008), for two lunar dust samples from Apollo 11 (10084) and 17 (70051). The distribution has been re-plotted from that of the original paper to show cumulative mass. In both cases, for particles greater than 1 μm the power law describing the curve has a slope of 3. Below 1 μm a roll of in the size distribution is observed. This may be due to limitations in measurement techniques or may represent a real depletion in small particles in the samples, either endemic in lunar soil (perhaps as a result of charging, levitation and transport of lunar dust as away from the surface) or as an artefact of the sampling process or measurement technique. Measurement of the size distribution in situ would provide important information on the prevalence of sub micron particles in the lunar environment, in size regimes of particular importance to human health, but with additional relevance to the design of systems required to operate in the presence of such dust.

Some work has been carried out previously to investigate the toxic effects of lunar dust, for example Latch et al. (2008) exposed macrophages (a type of white blood cell that clears the lung alveoli from foreign material) to terrestrial volcanic ash. Volcanic ash was used as an analogue of lunar dust in respect to its particle size distribution and chemical composition. Aspects of lunar dust particles such as electrical charge and physical structure, which may affect the manner of adhesion to lung tissues, were not considered. In other

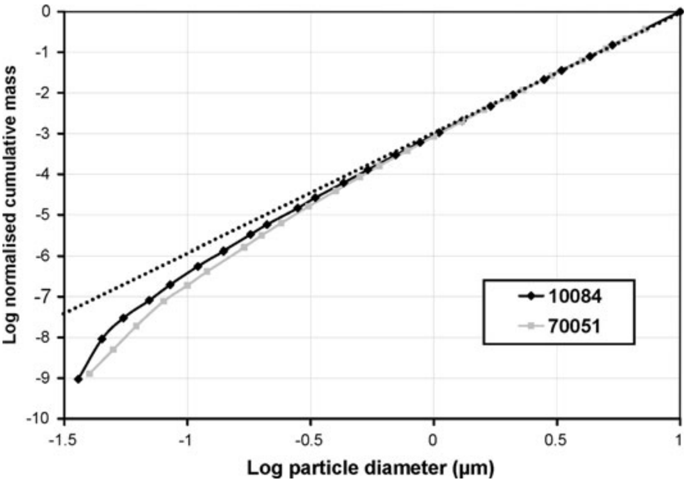

Fig. 4 Log_{10} Cumulative mass fraction as a function of Log_{10} particle diameter, re-plotted from the data presented by Park et al. (2008). Soil 10084 was collected during Apollo 11 and is a fairly typical mature lunar soil. Sample 70051 was collected during Apollo 17 and is an atypical lunar soil. The *dotted line* illustrates a power law with a slope of 3

studies (e.g. Lam et al. 2002) emulsions of dust have instilled in small rodents, however to date the inhalation of aerosols has not been considered.

Peterson et al. (2008) describe studies into the penetration of particles of relevant sizes into the human lung. It has been shown that in lunar gravity, particles are able to penetrate more deeply into the lungs than under terrestrial gravity. It has also been shown that reduced gas density also leads to a deeper penetration of particles, with implications for the conditions generated in a future lunar habitat.

In order to better understand the implications for humans of working in an environment in which lunar dust is prevalent, it is essential to allow the generation of improved analogues for lunar dust, which can be applied in animal models. These analogues should have properties which are better aligned to those aspects of dust that are important for its interaction with human lungs and physiology more generally. At present the best possible samples for use are regolith samples, which have been stored in a nitrogen atmosphere for up to 40 years. Activation of samples has been achieved by crushing or exposure to protons. However there is no way of validating whether these materials, once activated, have the same surface properties as fresh lunar samples and there has been no recreation of the burnt gunpowder smell reported by Apollo astronauts, which indicates that properties are not the same. Under such circumstances the reliability of investigations into toxicology of lunar dust are uncertain. In addition it is important to establish the rate of passivation of particles once in a humid atmosphere, analogous to a habitat.

For in situ measurements on the Moon, to support toxicity studies the following investigations have been identified as being of high prority.

- Investigate the size distribution of dust particles <10 µm. As a goal particles as small as of 10 s of nm should be identified and their abundance determined,
- Image the structure of grains,
- Determine the surface chemical reactivity of dust grains <10 µm,
- Determine the rate of passivation of particles after coming into contact with a humid atmosphere.

6 Measurements to Address the Toxicity of Lunar Dust

An important parameter in determining toxicity is the chemical reactivity of lunar dust. A likely approach to quantifying this is the detection and analysis of radicals on the surfaces of grains. Also of key importance is determination of the passivation rate for particles once they have entered a habitat. Measurements of these properties by the model payload are carried out by an instrument derived from the LunarChem concept (Rask et al. 2009). This instrument measures OH radicals on mineral surfaces using an assay based on detection of OH groups adopted by terephthalate (TA) upon contact with OH radicals on dust grain surfaces.

The size distribution of dust particles is determined via high resolution microscopy which also yields valuable information on the properties of lunar dust relating to structure and shape. Microscopy on the lunar surface is nominally carried out through a combination of optical microscopy and high resolution atomic force microscopy. This provides a dynamic range for characterisation from the mm—nm scales. Such a package has been applied on the surface of Mars as part of the MECA package on the Phoenix mission (Hecht et al. 2008).

Raman spectroscopy and Laser Ionisation Breakdown Spectroscopy can be applied to determine the mineralogical and elemental composition of dust particles. This can provide an insight into the physical properties and toxicity of dust particles but is of lower priority for these investigations. The techniques do however provide a measure of potential resources in the lunar soil at the landing site and provide ground truth for orbital measurements.

Raman Spectroscopy provides detailed information on the mineral assemblages. Identification of the principal mineral phases (i.e. those making up at least 90% of the material in soils, coarse fines and rocks) can allow classification of rocks and define petrogenetic processes. Investigations are also ongoing into the application of Raman spectroscopy for the detection of water in the lunar environment.

Laser Induced Breakdown Spectrometry (LIBS) measures the abundances of major, minor and trace elements down to 100 ppm and thus contributes to understand the local geo-logic/geochemical setting. It allows for depth profiling and removes dust layers on rocks and coarse fines. There are uncertainties as to the application of LIBS in high vacuum environments (Harris et al. 2005) and these must be addressed in advance of the selection of such an instrument.

While Raman and LIBS do not provide the only, or even the best, mechanism for providing mineralogical and compositional information they have several potential advantages over techniques such as X-ray diffractometry and fluorescence spectroscopy. Sample preparation requirements are significantly reduced and analysis can be conducted on small sample areas (<50 μm), while potential sharing of an optical path with a microscope allows the valuable combination of datasets on a common sample.

7 Conclusions

Future exploration of the Moon and other deep space environments by humans will be an interdisciplinary activity requiring the combination of expertise from multiple science and engineering disciplines. ESA's Lunar Lander project, which targets a 2018 launch date, seeks to enable European participation in future international exploration efforts by developing the technologies, experience and expertise required, bringing together the various disciplines and competences where they are needed.

Understanding and mitigating risks to the heath of future astronauts is of key importance to the success of future programmes. Investigations in the model payload for ESA's Lunar Lander are targeted at addressing major unknowns relating to the effects if the lunar environment on human health, in particular radiation effects and the potential toxicity of lunar dust. These investigations require the application of novel experimental methods, which pose a significant challenge. Further information on the model payload's experiments, their methodologies and capabilities will be reported in future papers.

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