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Toxicity of lunar dust

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ABSTRACT

The formation, composition and physical properties of lunar dust are incompletely characterised with regard to human health. While the physical and chemical determinants of dust toxicity for materials such as asbestos, quartz, volcanic ashes and urban particulate matter have been the focus of substantial research efforts, lunar dust properties, and therefore lunar dust toxicity may differ substantially. In this contribution, past and ongoing work on dust toxicity is reviewed, and major knowledge gaps that prevent an accurate assessment of lunar dust toxicity are identified. Finally, a range of studies using ground-based, low-gravity, and *in situ* measurements is recommended to address the identified knowledge gaps. Because none of the curated lunar samples exist in a pristine state that preserves the surface reactive chemical aspects thought to be present on the lunar surface, studies using this material carry with them considerable uncertainty in terms of fidelity. As a consequence, *in situ* data on lunar dust properties will be required to provide ground truth for ground-based studies quantifying the toxicity of dust exposure and the associated health risks during future manned lunar missions.

1. Introduction

The current renewed interest in human exploration of the Moon is driven not only by an urge to expand the human presence to other celestial bodies, but also by genuine scientific interest. Many aspects of the origin and evolution of the Earth and the other bodies in our solar system remain unclear. The Moon is thought to hold important information about the time when our own planet was formed, and humans remain capable of much more intelligent and adaptive exploration of the Moon than even the most sophisticated robotic and remote-controlled devices (e.g., Crawford et al., in press). Identification and retrieval of representative or exotic mineral specimens, and drilling deep into the lunar subsurface are examples of tasks for which astronauts are superior to machines. The most compelling argument for human exploration is the unique ability of humans to identify and quickly assess the unexpected, enabling real-time adjustment of a pre-planned exploration strategy.

Although humans have landed on and returned from the Moon during the Apollo era, it is still a formidable challenge to secure the health and safety of astronauts during Moon missions. Challenges for future missions include long-term low- or micro-gravity, radiation exposure, and the maintenance of a number of life support systems during a much longer period than was the case during the Apollo flights (e.g., Cain, 2010, 2011).

One of the biggest challenges may be related to the presence of dust on the lunar surface. The ubiquity of fine dust particles on the surface of the Moon plays an important and often dual role in many aspects of human lunar exploration. On the one hand, identifying the mineralogical and chemical composition of the dust fraction of lunar soils can provide *in situ* geological context for both robotic and human landing sites. In addition, lunar dust

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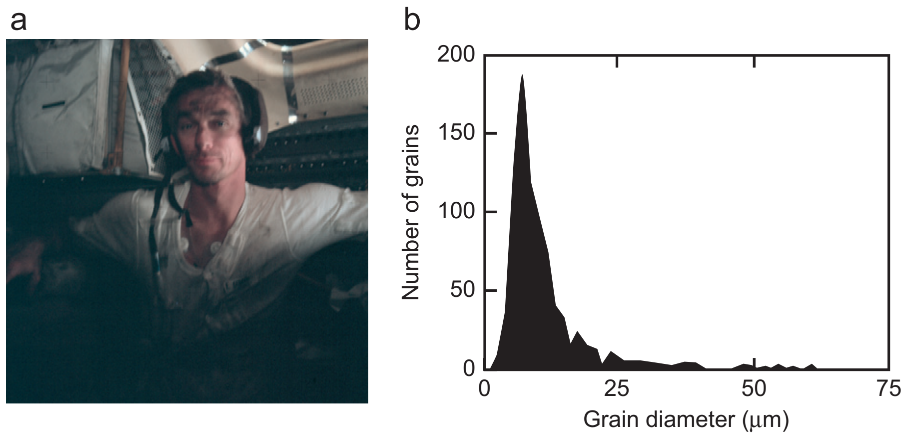

Fig. 1. (a) Apollo 17 astronaut Gene Cernan covered in dust after extravehicular activity on the lunar surface (photograph courtesy NASA). (b) Size distribution of $n=840$ grains recovered from the spacesuit of Apollo 17 astronaut Harrison Schmitt, with a mean of 10.7 μm. Modified from Christoffersen et al. (2009).

may be an ideal starting material for a range of future *in situ* resource utilisation activities on the Moon (e.g., Taylor et al., 2005), and dust is an important component of the lunar exosphere (Horanyi and Stern, 2011).

On the other hand, dust can adversely affect the performance of scientific and life-support instruments on the lunar surface. Fine dust was spread over all parts of the Apollo astronauts space suits, ending up in the habitat (Fig. 1a), resulting in astronaut exposure times of several days. The Apollo astronauts reported undesirable effects affecting the skin, eyes and airways that could be related to exposure to the dust that had adhered to their space suits during their extravehicular activities, and was subsequently brought into their spacecraft (Fig. 1b).

Dust exposure and inhalation could have a range of toxic effects on human lunar explorers, especially if longer exposure times become the norm during future manned exploration missions. There is therefore a need to assess the risks to health. The physical and chemical determinants of dust toxicity for terrestrial materials such as asbestos, quartz, volcanic ashes and urban particulate matter have been studied in great detail, and lunar dust simulant (synthesised from terrestrial volcanic material) has been found to exhibit toxic effects (Lam et al., 2002; Latch et al., 2008; Loftus et al., 2010). Unique features of actual lunar dust (described in more detail in the Composition and size distribution of lunar dust section), resulting from its formation by (micro)-meteoroid impacts and its extended radiation exposure in the absence of oxygen and humidity, could lead to toxic effects significantly exceeding those of simulants made from Earth materials. At present, the formation, composition and physical properties of lunar dust remain incompletely characterised with regard to human health.

In a micro-/hypo-gravity environment the risk of inhalation of dust is increased due to reduced gravity-induced sedimentation. Inhaled particles tend to deposit more peripherally and thus may be retained in the lungs for longer periods in reduced gravity as will be the case in a future lunar habitat (Darquenne and Prisk, 2008; Peterson et al., 2008). Inhalation of particles of varying size may affect the respiratory and cardiovascular systems in deleterious ways leading to airway inflammation and increased respiratory and cardiovascular morbidity (Frampton et al., 2006; Sundblad et al., 2002).

In this contribution, we review our knowledge of the physical chemistry determinants of dust toxicity, of the composition and size of lunar dust, and all aspects related to its toxicity. We identify a number of knowledge gaps that need to be filled to constrain the required extent of mitigation activities protecting astronauts from the potentially toxic effects of lunar dust during and after a stay on the Moon. We also recommend a range of future studies using ground-based, low-gravity, and *in situ* measurements on the lunar surface to better constrain lunar dust toxicity.

2. Physical chemistry determinants of dust toxicity

2.1. What makes a dust particle toxic

Up to the 1980s, fibrous character of asbestos (e.g., Kane, 1996; Mossman et al., 1990; Stanton et al., 1981), crystallinity of silica (e.g., Castranova et al., 1996; IARC, 1997, 2011), and degree of graphitization of carbon (e.g., IARC, 1997, 2010) were considered the main physico-chemical determinants of the pathogenicity of these well-recognised particulate toxicants. Starting in the early 1990s, free radical release has been progressively accepted as a relevant additional factor in causing cell and tissue damage and DNA modifications (Fubini and Hubbard, 2003; Kamp and Weitzman, 1999; Sanchez et al., 2009; Shukla et al., 2003). The triggering or catalysis of these atomic-scale mechanisms by active sites located at the surface of the particles was subsequently elucidated (Fubini and Fenoglio, 2007; Fubini and Otero-Arean, 1999; Pezerat et al., 2007). Several additional aspects of surface chemistry and reactivity, including hydrophilicity/hydrophobicity and contamination by metals, are now also considered to play a role in particle toxicology.

With the advent of nanotechnology, there was an abrupt rise of interest in particle toxicology, because of the general fear that particles would exhibit an increased and/or new form of toxicity when nano-sized. Once again attention was directed to surface properties (e.g., extent and reactivity) as most of the adverse reactions caused by nanoparticles appear to take place at what has been designated as the "bionanointerface" (Fubini et al., 2011; Nel et al., 2009, 2006).

When toxicants act in particulate form, the mechanisms of toxicity are much more complex when compared to molecular toxicants, for the following main reasons:

- It is the *surface* of a particle which is in contact with fluids, cells and tissues.
- The same particle may act in *multiple stages* of the pathogenic process.
- The particle may stay *in vivo* for long periods of time, moving throughout the body.
- The particle may be *modified in vivo*.

The toxic potential of a particle is determined by several features rather than one specific property. It is generally accepted