MOONLITE*: THE SCIENTIFIC CASE. I.A. Crawford[1], A.J. Ball[2], L. Wilson[3], A. Smith[4], Y. Gao[5] and the UK Penetrator Consortium[6]. [1]School of Earth Sciences, Birkbeck College, London, WC1E 7HX, UK. [2]Planetary and Space Sciences Research Institute, Open University, Milton Keynes, UK. [3]Department of Environmental Science, Lancaster University, UK. [4]Mullard Space Science Laboratory, University College London, UK. [5]Surrey Space Centre, University of Surrey, UK.[6]www.mssl.ucl.ac.uk/pages/general/news/UKLPC/UKLPC.pdf. *MoonLITE is a UK-led initiative which is currently the focus of a joint UK-NASA study. (Email: i.crawford@ucl.ac.uk).

Introduction: The principal scientific importance of the Moon is as a recorder of geological processes active in the early history of terrestrial planets (e.g. planetary differentiation, magma ocean formation and evolution, etc), and of the near-Earth cosmic environment throughout Solar System history [1,2]. Although the *Clementine* and *Lunar Prospector* missions have in recent years greatly added to our knowledge of the geochemical and mineralogical makeup of the lunar surface, and these observations will soon be supplemented by results from *Kaguya*, *Chang'E*-1, *Chandrayaan*-1 and *LRO*, our knowledge of the interior still largely relies on geophysical measurements made during the Apollo programme. However, these landing sites were all located at low to mid-latitudes close to the centre of the lunar nearside, and were thus unable to provide global coverage. In order to build on the Apollo data-set, and thus advance our knowledge of lunar science, *MoonLITE* [3] will fly 4 penetrators to the Moon for the purpose of conducting a range of *in situ* geophysical and geochemical measurements at widely separated localities.

Scientific objectives: The principal scientific objectives of the MoonLITE penetrator mission are:

- To further our understanding of the origin, differentiation, internal structure and early geological evolution of the Moon;
- To obtain a better understanding of the origin and flux of volatiles in the Earth-Moon system;
- To obtain 'ground truth' geochemical data to complement orbital remote-sensing observations;
- To collect *in situ* surface data that will help in the planning of future lunar exploration.

These top-level science objectives require that the penetrators emplace instruments capable of contributing to at least four different areas of scientific investigation: seismology, heat-flow, geochemical analysis, and volatile detection/characterisation.

Seismology: Seismology is the most powerful geophysical tool available to us for determining the interior structure of a planetary body. However, to-date the only object, other than the Earth, where it has been successfully applied is the Moon, where the Apollo seismometers yielded important information on the Moon's natural seismic activity, and the structure of the lunar crust and upper mantle [4,5]. However, the deep interior of the Moon was only very loosely constrained by Apollo seismology due to the geographically limited coverage of the network (essentially a triangle between the Apollo 12/14, 15 and 16 sites), so the information obtained on crustal thickness and mantle structure may not be globally representative. There is now a pressing need for a more widely-spaced network of lunar seismic stations, including stations at high latitudes and on the farside. Penetrators delivered from orbit are ideally suited as a means of emplacing a global seismometer network, which would address the following scientific questions:

(a) Size and physical state of lunar core: Such knowledge of the lunar core as we have has been obtained from studies of the Moon's moment of inertia and physical librations, and electromagnetic induction studies [6]. These studies favour a small ($R<400$ km) partially liquid core, with suggested compositions ranging from iron-nickel, Fe-FeS alloy, to molten silicates. Confirmation of the size, composition and physical state of a lunar core would have profound impacts on our understanding of the Moon's origin, mantle evolution, and magnetic history. For these reasons, constraining the nature of the Moon's core is a top scientific priority of the penetrator-deployed seismic network.

(b) Deep structure of the lunar mantle**:** One of the main contributions lunar studies can make to planetary science is an enhanced understanding of the internal differentiation processes that occur immediately after the accretion of a terrestrial planet. Magma oceans are likely to have been a common phase in the early evolution of rocky planets, and, in contrast to the more evolved mantles of the larger terrestrial planets, the structure of the lunar mantle may preserve a record of these early times. Seismology may help elucidate these processes by constraining the initial depth of the magma ocean and its mineralogy [7]. Again, new, and more widely spaced, seismic data are now required if this record is to be deciphered.

(c) Thickness of the farside lunar crust: Reinterpretations of the Apollo seismic data have now constrained the thickness of the nearside anorthositic crust to about 30-40 km [6,7]. However, the thickness of the farside crust has not been seismically constrained. Estimates based on gravity data are typically in the range 70-90 km [6], but these are non-unique, and farside seismic measurements are required to determine the average lunar crustal thickness which has significant implications for understanding the bulk composition, and thus origin, of the Moon.

(d) Studies of natural moonquakes: Understanding natural lunar seismicity, and especially the relatively strong (up to magnitude 5) shallow moonquakes, is important both for our knowledge of lunar geophysics and the planning of future exploration activities [8].

Heat-flow: Measurements of surface heat-flow provide valuable constraints on the composition and thermal evolution of planetary interiors. The lunar heat-flow was measured at the Apollo 15 and 17 sites [9]. However, these measurements have been subject to numerous re-interpretations [6], and in any case may not be representative of lunar heat-flow as a whole. An important measurement would be to determine the heat-flow as a function of distance from the Procellarum KREEP Terrain (PKT) on the north-western part of the lunar nearside [10]. Remote sensing measurements have determined that the heat-generating elements (U, Th, K) are concentrated at the surface in this region but a question remains over whether this is a surficial effect (owing to excavation of a global underlying KREEP-rich layer by the Imbrium impact), or whether these elements are indeed concentrated in the mantle below the PKT [6,11]. The latter scenario would predict a much higher heatflow in the PKT than elsewhere, and would have major implications for our understanding of mantle evolution [12]. There is thus a need to extend these measurements to new localities far from the Apollo landing sites (e.g. the polar regions and the farside highlands) and. penetrator deployment of a global heat-flow network would be an attractive means of achieving this.

Geochemistry: The only places on the Moon from which samples have been collected *in situ* are the six Apollo landing sites and the three Soviet *Luna* sample return missions. No samples have been returned from the polar regions or the farside, greatly limiting our knowledge of lunar geological processes. Although additional sample return missions are desirable, this may not be practical in the short term. An alternative would be to make *in situ* geochemical measurements, at least of the abundances of the major rock-forming elements (e.g. Mg, Al, Si, Ca, Fe and Ti). This could be achieved by penetrator-deployed X-ray fluorescence spectrometers. In addition to teaching us much about the geology of the sites that have yet to be sampled, such measurements would provide additional 'ground truth' for the calibration of remote-sensing instruments on forthcoming lunar orbital missions.

Polar volatiles: As is well known, the *Lunar Prospector* neutron spectrometer found evidence for enhanced concentrations of hydrogen at the lunar poles, which has been widely interpreted as indicating the presence of water ice in the floors of permanently shadowed craters [13]. If water ice is present, it is most likely derived from the impacts of comets with the lunar surface. The confirmation of water ice (and other volatiles) at the poles would be important for what it will reveal about the flux and composition of cometary volatiles into the inner Solar System (which is of significant astrobiological interest), and also because such volatiles could be a very valuable resource in the context of future human exploration of the Moon. We consider that volatile detectors, deployed on penetrators and landed within permanently shadowed craters, would be a powerful and economical means of determining whether or not scientifically and operationally valuable deposits of volatiles exist at the lunar poles.

Conclusions: By deploying a range of instruments (including seismometers, heat-flow probes, X-ray spectrometers and volatile detectors) to diverse locations on the Moon from which geochemical and geophysical measurements have not yet been obtained (including the poles and the farside), the MoonLITE penetrators have the potential to make major contributions to lunar science. At the same time, they will provide knowledge (e.g. of lunar seismicity and polar volatile concentrations) that will be of central importance in the planning of future human missions to the Moon, and will also demonstrate a technology that will have wide applications for the exploration of other airless bodies throughout the Solar System.

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