THREE DEPLOYMENT OPTIONS FOR THE HEAT FLOW COMPONENT OF THE LONG-LIVED LUNAR GEOPHYSICS INSTRUMENT PACKAGE. Shaopeng Huang[1], Walter S. Kiefer[2], Clive R. Neal[3], Norbert Kömle[4], Marek Banaszkiewicz[5], Mark Wieczorek[6], Satoshi Tanaka[7] [1]Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1005, USA (shaopeng@umich.edu); [2]Lunar and Planetary Institute, Houston, TX 77058, USA; [3]Dept. Civil Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA; [4]Institut für Weltraumforschung, Österreichische Akademie der Wissenschaften, Graz, Austria; [5]Space Research Centre, Warsaw, Poland; [6]Institut de Physique du Globe de Paris, Paris, France; [7]Institute of Space and Astronautical Science, Sagamihara-shi, Japan.

Introduction: To deepen our understanding of the geology and geophysics of the Moon and to resolve ambiguities in the interpretation of some existing lunar data, a long-lived Lunar Geophysics Instrument Package (L-GIP) which includes a heat flow component has been proposed [1].

Lunar heat flow carries rich information about the evolution history, thermal structure, and bulk chemical composition of the Moon. However, any individual heat flow measurement is subject to site-specific perturbations associated with the local settings. A representative and well constrained global mean relies heavily on the number and spatial distribution of the contributing measurements.

So far only two heat flow values have been obtained on the Moon – 21 mW/m^2 from the Apollo 15 landing site in Hadley Rille and 14 mW/m^2 from the Apollo 17 landing site in Taurus Littrow [2]. These two lunar heat flow values are less than a quarter of the global terrestrial mean of 87 mW/m^2 [3], yet significantly higher than the prediction with respect to the small size and commonly accepted chemistry of the Moon. There are concerns that the existing measurements are not globally representative because they are located at geographical/geological boundaries [4-6]. An important objective of the prospective L-GIP is to obtain heat flow measurements from other regions of the Moon.

Heat flow is measured as the product of the thermal conductivity and vertical temperature gradient in the subsurface. As such, a lunar heat flow measurement requires penetration into the regolith layer. In this study we examine three deployment methods – onsite drilling, gravitational penetration, and lander-attached deployment – to deploy heat flow instruments in strategic locations across the lunar surface so as to maximize the global representativeness of the measurements. The methods are applicable to both manned and robotic missions.

Onsite Drilling: This approach would be similar to the one taken by the Apollo 15-17 missions. The deployment of the Apollo heat flow experiment involved drilling two boreholes by astronauts into the lunar regolith at each landing site. The boreholes are around 100 meters away from a lunar module and several meters away from any other lunar surface experiment instruments [2] (Fig. 1). Each borehole received a heat flow probe designed for measuring subsurface temperature gradient and thermal conductivity. The reason for a heat flow probe to be located a certain distance away from the lander and other instruments is to reduce the perturbations from unwanted shadowing and other sources of noise. The Apollo heat flow probes were connected by cables to an electronic box where raw data were initially processed before being transmitted to Earth by the ALSEP central station powered by a radioisotope thermoelectric generator.

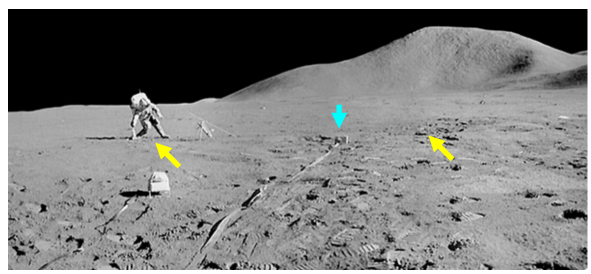

Fig. 1: Heat flow experiment deployment at the Apollo 15 landing site. Photo credit: NASA. Yellow arrows show the locations of the heat flow probes inserted into boreholes. Blue arrow points to the electronic box connected to the probes by cables. Visible beside the astronaut are the drill (left) and drill rack (right).

Onsite drilling is the only method that has been successfully applied for planetary (Earth excluded) heat flow measurement. The principal advantage of this approach is that it builds on the heritage of the Apollo heat flow experiment. However, an application of this deployment method in an unmanned mission will require a robot that can walk away from the lander and perform the tasks that were performed by Apollo astronauts. Additionally, the frictional heat generated directly by drilling and the exploration activities around the borehole can permanently change the radiation property of the regolith surface, and cause transient thermal perturbation in the subsurface,

Gravitational Penetration. This method is to deploy the heat flow experiment mainly by gravitational force via free-fall from a high altitude. One or more penetrator probes would be dropped during descent and land a short distance from the main lander. This method shares the same design idea as the recently canceled Japanese mission Lunar-A [7]. Because a specific heat flow probe will be much slimmer than a Lunar-A penetrator which is a missile-shaped carrier for both heat flow instrument and seismometer, this approach is expected to be more effective for delivering a L-GIP heat flow penetrator than for inserting a Lunar-A penetrator.

The principal advantage of the penetrator approach is that it allows the heat flow experiment to be deployed at a greater distance from the main lander without human or robotic activity within the vicinity of the heat flow probe, and thus avoids the thermal perturbations associated with exploration activities. A second potential advantage is that if the mass and budget margins are sufficient, it may be possible to use two or more penetrators to measure the heat flow at a given landing site and thus derive a better average value for the location.

However, there are also several potential concerns about using a penetrator. First, an instrumented panetrator must withstand the penetrating impact. Second, a radio system is required for the penetrator probes to transmit their data to the lander or to a lunar orbiter for further transmission to Earth. We must assure line-of-sight communication from the penetrator to the main lander in various topographic environments. Third, the insertion of the penetrator into the regolith compresses the regolith and thus modifies its density and thermal conductivity [8]. Additionally, dissipation of the penetrator's kinetic energy will locally heat the regolith, although the perturbation from such a thermal pulse will decay exponentially with time.

An alternative deployment design of the gravitational penetration approach would be to deploy the heat flow probes after landing rather than to release them from the spacecraft during its descent. If a heat flow probe is shot upward from the lander to a certain altitude, the gravitational free fall penetration effect should be the same as it is released from spacecraft from the same altitude. However the risk for the lander to lose the penetrator probe could be greatly reduced if the lander would do a quick topographic survey after landing and decide accordingly where the penetrators should be located. It would then launch the heat flow probes with a calculated angle to ensure the probes will be within the radio communication range when they fall back to the surface.

Lander-Attached Deployment: This third approach uses either a drill or telescopic injection system attached to the main lander and deploys the heat flow probe(s) close to the lander. The lander will contain a robotic arm to emplace the heat flow probe(s) several meters away, but remain connected to the probe(s) via a wire spool for electrical power and communications. Additional measurements can be made by the thermal sensors embedded into a leg or spike of the lander or other instruments.

The design of the heat flow instrument for this approach can benefit from the existing model of the thermal probe MUPUS-TP on board the European Rosetta spacecraft [9] and the Heat flow and Physical Properties Package (HP^3) instrument that is being developed for ExoMars mission [10]. The MUPUS-TP probe is to be inserted into regolith about one meter from the lander by a deployment device involving a recoilless hammering mechanism. The HP^3 is to be accommodated in a mole, a self-penetrating device that could hammer its way several meters below the surface.

The major concern about a lander-attached deployment is the effects that the lander will have on the near-surface thermal structure of the landing site. The lander can alter the radiation energy budget of the landing site dramatically, and consequently change the surface temperature around it. The temperature change on the surface will propagate downward to the subsurface as transient perturbation [11]. Because of the extremely low thermal diffusivity of the regolith, the transient perturbation will be long-lasting[12]. It might take years for the subsurface temperature field beneath the immediate vicinity of the lander to establish a new equilibrium with the modified surface environment.

There is little doubt that the lander-attached deployment approach is most secure and likely cost effective. However, the correction for the landing and drilling/injection induced perturbations will be a challenging task in the data reduction phase. On the positive note, the noise of the heat flow experiment with this approach would be a signal for the study of exploration-induced thermal environmental change, which has its own significance in lunar exploration.

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