HEAT FLOW MEASUREMENTS ON MOONS AND PLANETS FOR THE NEXT THREE DECADES. S. Nagihara[1] and K. Zacny[2], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics, Pasadena, CA 91103(zacny@honeybeerobotics.com).

Introduction: Researchers have long recognized the importance of measuring the endogenic (internal) heat flow of the planetary bodies for understanding their origin and thermal evolution. It was more than 40 years ago, when the Apollo astronauts made heat flow measurements at two locations on the Moon [1]. Since then, no more heat flow measurement has been made on the Moon or any other extra-terrestrial body to this day. ESA's *Rosetta* mission had a heat flow probe on its lander, but it did not deploy successfully.

We see two reasons for the lack of progress in accumulating planetary heat flow data since the Apollo program. First, technologies necessary for enabling heat flow measurements on robotic missions had not been fully developed. Second, there have been relatively few landing missions, and heat flow and geophysical measurements were not their primary objective.

We believe that the recent technological advances [2] make it possible to collect high-quality heat flow data on small lander missions. NASA's *InSight* mission is expected to deploy a heat flow probe on Mars in 2018 [3]. In addition, the latest Decadal Survey [4] has recommended the Lunar Geophysical Network (LGN) mission, which will include a heat flow probe as payload, as one of the candidates for the New Frontiers program. Here we discuss the recent advances in planetary heat flow instrumentation and what we may be able to achieve in the next three decades.

Measurement Methodology and Instrumentation: A heat flow probe typically measures conductive heat flow. It can be deployed from a lander or a rover. The probe penetrates into the subsurface and makes two separate measurements: the thermal gradient and the thermal conductivity of the depth interval penetrated. Heat flow is then obtained as the product of these two measurements.

The thermal environment of the surface of most extra-terrestrial bodies is heavily influenced by the insolation. In order to sense the flow of the endogenic heat, the probe should penetrate below the so-called thermal skin depth, where temperature is unaffected by the insolation. The skin depth is a function of the period of the insolation cycles (e.g., diurnal, annual, etc.) and the thermal properties of the surface material (regolith, rock, ice, etc.). The surface materials' texture and composition influence the thermal properties. Therefore, skin depth varies among planetary bodies. For the Moon, a panel of scientists assembled by NASA has recommended 3 m as the target depth of penetration for heat flow measurements [5].

On Earth, rotary or percussive drilling is used to excavate a hole for heat flow probe deployment. The auger or drill pipe is extended until it reaches the desired depth. That is how the Apollo astronauts deployed their heat flow probe [1]. However, such an approach may not work on lander/rover missions mainly due to the limited space available and the complexity of extending the drill pipe, one section at a time.

For future robotic missions to the Moon, we recently developed a compact (shoebox-size), modular heat flow instrumentation that uses a pneumatic excavation system in deploying its probe [6]. In this system, thermal sensors are embedded on a flexible, glass fiber composite stem that spools out like a steel tape measure, as it penetrates deeper into the subsurface (Figs. 1-3). As the stem spools out, it forms a hollow cylinder of ~1.5-cm diameter to gain mechanical strength. When it touches down, it pushes a penetrating cone into the regolith. Simultaneously, Helium gas jets, emitted from the cone tip, blow away loosen material with 1:6000 excavation efficiency in the lunar vacuum (e.g., 1 g of gas capable of lofting 6000 g of regolith particles).

When the cone reaches a depth targeted for thermal measurements, it stops excavating. A short probe attached to the cone tip (Fig. 4) is pushed into undisturbed regolith at the bottom of the hole, and measures the temperature and the thermal conductivity. After that, the probe resumes excavation to the next target depth. By repeating this stop-and-go sequence, we obtain the thermal gradient and the thermal conductivity of the depth interval penetrated. When the probe reaches 3-m depth, the temperature sensors embedded on the fully extended stem monitor long-term stability of the thermal gradient.

The latest prototype of this heat flow probe (Fig. 3) was tested in compacted lunar regolith simulant, NU-LHT-2M, in vacuum and reached 2-m depth in 2 minutes. Its thermal conductivity probe (Fig. 4) has also been tested separately with the JSC-1A simulant in vacuum, and yielded sensitivity down to 0.001 W/mK [7].

Future Applications: This heat flow probe has been developed primarily for the use by the LGN mission [4]. By collecting data at multiple locations on the Moon, we will characterize the geographic variation of heat flow. That will allow us to better contrast the possible difference in subsurface Thorium abundance between the KREEP terrain and the surrounding areas [8], and more tightly constrain the bulk composition of the Moon [9].

The heat flow probe can also dual as a heat source for subliming volatiles in the subsurface. It can be a useful tool for resource prospecting on the Moon.

Another potential destination within the next few decades is Europa. NASA is already planning a lander mission there. Our heat flow instrumentation is a modular system and can be adapted for deployment on the icy satellites. By using a stronger material for the stem and a more robust excavation mechanism (e.g., heaters subliming the ice), it may be able to penetrate into the ice shell. Measurement of the endogenic heat flow on Europa will allow us to further understand the dynamics of the ice shell and the heat budget of the subsurface ocean.

Conclusions: With the recent technological advances, planetary science communities are well positioned for expanding the coverage of heat flow measurements on extra-terrestrial bodies, especially the Moon, in the next three decades.

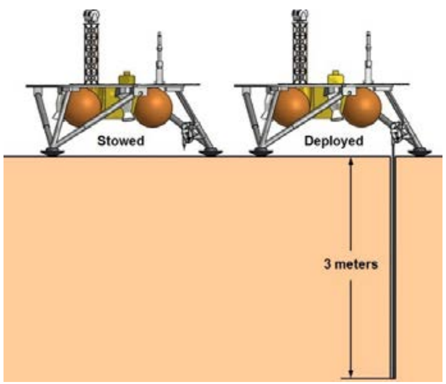

Figure 1: The heat flow probe attached to a leg of a lander in stowed (left) and deployed (right) configurations [6].

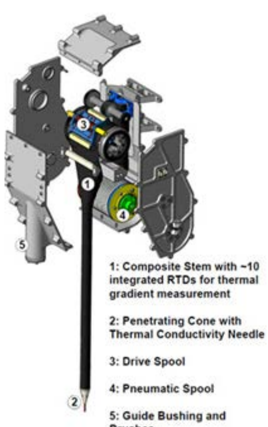

Figure 2: Schematic diagram showing the major components of the planetary heat flow probe [6].

Figure 3: A photograph of the latest prototype of the heat flow system in a stowed configuration.

Figure 4: A photograph of the prototype of the cone tip and thermal conductivity.

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