LONG-TERM WARMING OF SURFACE AND SUBSURFACE TEMPERATURES OBSERVED AT APOLLO 15 AND 17 SITES: IMPLICATIONS FOR FUTURE LUNAR GEOPHYSICAL MISSIONS. S. Nagihara[1], P. T. Taylor[2], D. R. Williams[2], and Y. Saito[3], [1]Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Goddard Space Flight Center, Greenbelt, MD 20711, [3]Institute of Space and Astronautical Science, Sagamihara, Japan.

Introduction: The Apollo astronauts deployed geothermal heat flow probes as part of the Apollo Lunar Surface Experiment Package (ALSEP) at the landing sites 15 and 17 [1,2]. The heat flow instrumentation at the Apollo 15 site operated from July 1971 through January 1977, and the one at the Apollo 17 site operated from December 1972 through September 1977 [3]. Langseth et al. [4] determined the endogenic (internal) heat flow at the two sites (21 mWm^2 and 16 mW/m^2, respectively), using the data obtained between 1971 and 1974. More recent investigators [5,6] questioned validity of the heat flow determination by suggesting that Langseth et al. did not thoroughly examine the cause of the long-term (multi-year-scale) warming trend that was present in the subsurface temperature records at both sites. It is imperative that researchers understand the cause of the long-term temperature change, because that knowledge will influence the instrument design and the deployment strategy for future heat flow measurements to be carried out on the Moon. The present work reviews the data obtained during the Apollo Heat Flow Experiments (HFE), discusses the potential causes for the long-term warming, and makes suggestions for future missions.

The Apollo HFE Data: The Apollo heat flow probe consisted of two major sections. The lower section (~1-m long) consisted of 8 bridge-sensors utilizing platinum resistance thermometers, while the upper section (~1.5-m long) consisted of a string of 4 thermocouples [1,2]. Two such probes were deployed, a short distance apart, at each of the two landing sites. Except for Probe 2 of the Apollo 15 site, the lower section was fully inserted into the ground, while at least one of the uppermost thermocouples remained on or above the ground. Therefore, we have records of both surface and subsurface temperatures (Fig. 1).

The 1971-1974 data used by Langseth et al. [3] were archived at the National Space Science Data Center at Goddard at the conclusion of the Apollo program. The post-1974 data were long forgotten until the early 2000s, when Yosio Nakamura of University of Texas (UT) and his collaborators at Japan Aerospace Exploration Agency recovered HFE data for some months in 1976 and 1977 from the work tapes stored at UT [6]. There are still two major data gaps in the data: the entire year 1975 and a period between the late 1976-through mid-1977. Taylor, Nagihara, Williams and K. Hills are currently trying to recover these missing data under a LASER award.

The Observed Temperature Fluctuations: As seen in Fig. 1, temperatures of the lunar surface and the very shallow (< ~0.5-m depth) subsurface are dominated by the diurnal solar radiation cycle. At the Apollo 15 site, surface temperature reaches ~360 K at lunar noon and falls to ~80 K before dawn. The annual-seasonal variation can also be observed. The variation coincides with that of the southern hemisphere of the Earth, with highest temperatures occurring in late December and lowest in late June.

Because of the very low thermal conductivity of lunar regolith, the amplitudes of the diurnal and seasonal fluctuations diminish quickly with depth (Fig. 1). At ~1-m depth, only the seasonal fluctuation can be seen with a phase lag (Fig. 2D). Also seen in the subsurface temperature records are (1) a quick fall of the temperature immediately following the installation of the probes, which is due to the dissipation of the frictional heat introduced by drilling, and (2) a slow, monotonic warming throughout the period of the observation, the cause of which has been debated in recent years.

Possible Causes of the Long-term Warming: Three types of explanation can be offered for the long-term subsurface warming observed at the two Apollo sites. First, it is a drift in the thermal characteristics of the instrumentation [7]. Second, the astronauts' activity associated with the ALSEP package deployment altered the radiative properties of the lunar surface [4], for example, by lowering the albedo of the soil. That resulted in greater absorption of the solar heat by the lunar soil. Third, the total radiative energy reaching the lunar surface increased over time at the two sites. Such increase in energy may have been caused by an increase in solar luminosity [8], an increase in radiation from the Earth [9], or the 18.6-year-cycle precession of the lunar orbit [5,6].

The long-term warming trend has been seen on all the subsurface sensors that did not fail [4,6]. The magnitude of the increase is less for deeper sensors. That is an indication that the regolith was responding to heat that entered from the surface. It is difficult to determine whether or not the surface temperature was changing with a long period, because it was dominated by the diurnal cycle. But, one can be almost certain that the surface temperature was influenced by the 18.6-year precession. The difference in the lunar day-time highs between the summer and the winter gradually increased from 1972 to 1974 (Fig. 2A). That is consistent with the changes in solar incident angle expected for the precession, according to the JPL DE405 ephemerals [5,6]. The night-time lows at the lunar surface also show gradual warming trends with some annual fluctuations (Figs. 2B and 2C and [9]). It can be interpreted that overall radiative heat input to the lunar regolith increased annually over the same period. Whether or not the increase is due to the change in the surface albedo or that in solar irradiance may be determined only by realistic energy balance modeling for the lunar surface. In any case, it is difficult to dismiss the observed long-term temperature changes solely due to a drift in the instrumentation, because these changes are systematic and understandable if heat input into the lunar regolith increased over time.

Conclusions: A heat flow probe to be deployed on a future lunar mission would most certainly see multi-year-scale temperature changes down to at least ~2.5-m depth (i.e., the greatest depth penetrated during the Apollo HFE). Therefore, the probe should penetrate deeper to a depth of greater temperature stability (4 to 5 m, [10]). If, however, that is not feasible due to the mass and power constraints of the mission, the internal heat flow may be constrained only by accurately modeling the energy balance of the lunar surface and the subsurface. In enabling such modeling, the probe should be operable for a longer period, ideally ~10 years (i.e., more than the half of the precession period), and the instrumentation should be able to record the depth of each thermal sensor accurately. In addition, *in-situ* thermal conductivity measurement capability will be necessary. Further, it is desirable that the surface instrumentation be equipped with some type of net radiometer that can measure the incoming and outgoing radiation.

References: [1] Langseth M. G. et al. (1972) *Apollo 15 Prelim. Sc. Rept.,* 11-1–123. [2] Langseth M. G. et al. (1973) *Apollo 15 Prelim. Sc. Rept.,* 9-1-23. [3] Bates J. R. et al. (1979) *ALSEP Termination Rept.* [4] Langseth. M. G. et al. (1976) *LPS VII*, 3143-3171. [5] Wieczorek M. A. and Huang S. (2006) *LPSC XXXVII*, 1682. [6] Saito et al. (2006) *Bull. Japanese Soc. Planet. Sc.,16*, 158-164. [7] Peters K. and Langseth M. G. (1975) *LDGO Tech. Rep., 3-CU-4-75*. [8] Miyahara et al. (2008) *GRL, 35*, L02716. [9] Huang S. (2007) *Adv. Space Res., 41*, 1853-1860. [10] Nagihara et al. (2009) *LPSC XXXX*, 1165.

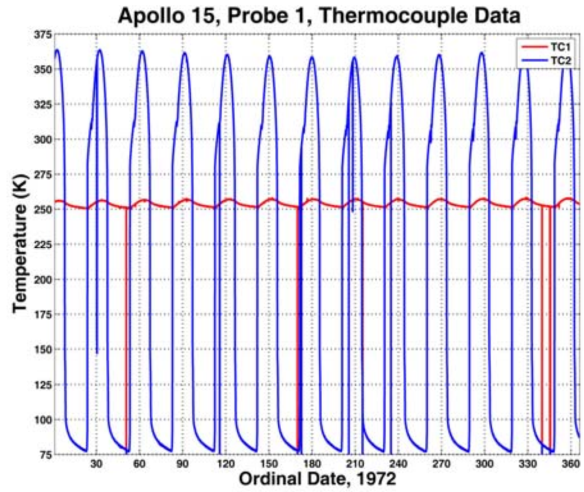

Fig. 1 The thermocouple temperature records for the surface (blue) and 0.4-m depth (red) from Apollo 15, Probe 1 for year 1972.

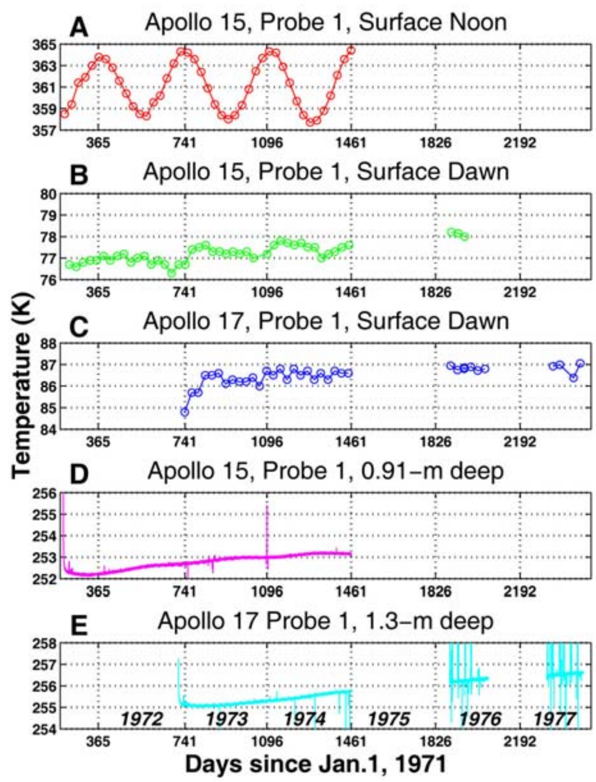

Fig. 2 A: Lunar day-time high temperatures recorded at the surface of the Apollo 15 site. B: Lunar night-time low temperatures recorded at the Apollo 15 site. C: Lunar night-time low temperatures recorded at the Apollo 17 site. D: Temperatures at 0.91-m depth at the Apollo 15 site. E: Temperatures at 1.3-m depth at the Apollo 17 site.