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The Apollo Lunar heat flow experiment revisited: A critical reassessment of the in-situ thermal conductivity determination

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Abstract

Lunar heat flow was determined in-situ during the Apollo 15 and 17 missions, but some uncertainty is connected to the value of the regolith's thermal conductivity. Different approaches to determine the conductivity yielded discordant results and we have re-investigated likely causes for the observed discrepancies. We find that neither poor coupling between the probe and regolith nor axial heat loss can explain the observed discrepancies. Rather, regolith compaction and compression likely caused a local increase of the regolith's thermal conductivity. We conclude that the corrected lunar heat flow values, which are based on thermal diffusivity estimates sampling a large portion of undisturbed regolith, represent robust results.

1. Introduction

Lunar heat flow has been measured at the Hadley Rille and Taurus-Littrow sites during the Apollo 15 and 17 missions and values of 21 and 16 mW m^{-2} have been obtained [1]. However, some uncertainty is connected to the obtained heat flow values, which is primarily connected to inconsistencies concerning the determination of the in-situ thermal conductivity and some skepticism concerning the merits of the Apollo heat flow measurements exist.

Heat flow probes employed during the Apollo experiments were equipped with platinum resistance temperature detectors, thermocouples, and heaters, the latter of which were operated like classical line heat sources [2,3]. With this setup it was possible to estimate the thermophysical properties of the lunar regolith using four different methods: Active heating experiments and monitoring the thermal re-equilibration of the borestem gave broadly consistent conductivity results, with k ranging from 0.0141 to 0.0295 W m^{-1} K^{-1}. On the other hand, analysis of the decay of periodic temperature perturbations induced by the annual temperature waves and analysis of the propagation of Astronaut induced thermal disturbances also yielded consistent results, but in the range 0.009 to 0.013 W m^{-1} K^{-1}. Furthermore, using the latter approaches, it was found that the regolith's thermophysical properties vary only little with depth, contrary to the results obtained by the active heating experiments. It was concluded at that time that the values obtained by the analysis of transient waves were more reliable, because the small volumes of regolith sampled by the active heating method may have been thermally altered during the drilling process [1]. Here we present a reanalysis of the Apollo active heating experiment data and investigate possible causes for the discordant results obtained using different methods.

2. Modelling

The approach followed by the Apollo active heating experiment to measure thermal conductivity was similar to the standard line heat source method and relied on the controlled injection of heat into the probed medium and interpretation of the temperature rise at the heater as a function of time. A detailed finite difference model was then used to invert the data in a two step process [3]: (1) The slope of the temperature rise ΔT vs. $\ln(t)$ was fitted for large times $t > 1000$ min to obtain the thermal conductivity k of the regolith. (2) The amplitude of ΔT was fitted by adjusting the thermal contact resistance H between probe and regolith.

Here we follow this same approach to invert the self-heating curves and setup a finite element model which captures the main aspects of the Apollo experiment: The model setup is sketched in Fig. 1 and encompasses the probe stem, contact resistance between probe and regolith, a region of compacted regolith as well as the undisturbed regolith. The 1.7 cm long heater is energized at 0.002 W [2] and the temperature rise at its centre is recorded.

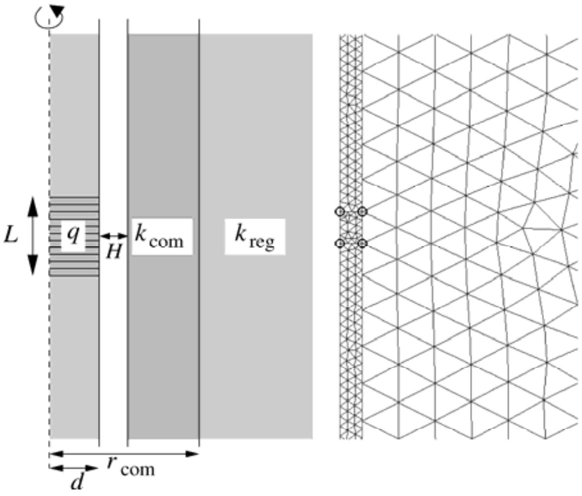

Figure 1: Setup of the finite element model and finite element mesh to invert the self heating curves.

3. Results

We have varied the probe thermal conductivity, heat capacity, and contact conductance H to estimate the robustness of the inverted thermal conductivity values. Varying H between 1.5 and 6 W m^{-2} K^{-1} was found to have a negligible influence (<2 %). Varying heat capacity and thermal conductivity within a factor of two resulted in best fit conductivity estimates that differed by <25%, but probe thermal properties were probably known much better than this generous range. Also, heat dissipation along the electrical connection wires inside the probe was found to be negligible.

Results of including a region of compacted regolith are shown for one measurement in Fig. 2, where the inverted thermal conductivity is given as a function of compaction radius for different compacted thermal conductivities. Thermal conductivities obtained by Apollo are indicated in shades, implying that a compacted region of 3 to 5 cm radius and compacted thermal conductivities of 0.2 to 0.3 W m^{-1} K^{-1} are consistent with the obtained results. This implies a significant disruption of the ambient regolith by the rotary-percussion action of the drill during emplacement of the probes.

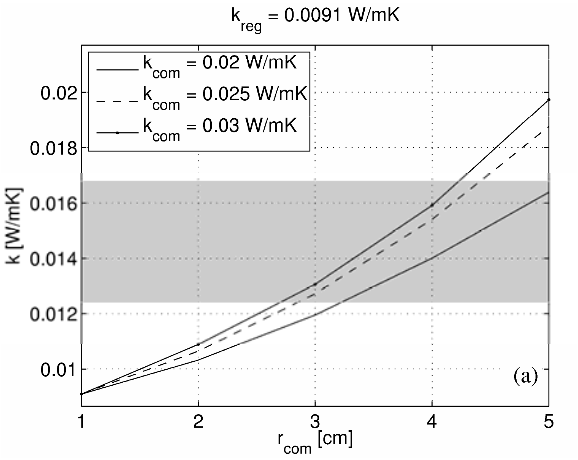

Figure 2: Inverted thermal conductivity as a function of compaction radius for different compacted thermal conductivities.

4. Conclusions

We conclude that regolith compaction and compression likely caused a local increase of the regolith's thermal conductivity by a factor of 2 to 3 in a region which extends at least 3 to 5 cm from the borehole wall. Furthermore, we conclude that the corrected lunar heat flow values, which are based on thermal diffusivity estimates sampling a large portion of undisturbed regolith, represent robust results.

Acknowledgements

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