The heat flow of the Moon: influence of long term orbital signals
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Introduction

In the past decades, numerous efforts have been made to estimate planetary heat flows [1]. Planetary cooling is what drives the evolution of a planet, and the measured heat flow constrains models of both thermal evolution and planetary bulk composition.

As part of the Apollo program, heat flow experiments were carried out during Apollo 15 and 17 missions. These experiments measured both surface and subsurface temperatures, and analysis of the 4 years of data provided estimates of the near surface temperature gradient, thermal diffusivity, thermal conductivity and heat flow [2]. A striking result was the large difference in measures between the two experiments: 21 and 16 mWm$^{-2}$ at Apollo 15 and 17 landing site, respectively. This variation has been explained by differences in radioactive elements abundance between the two regions. Unfortunately, both landing sites are on the edge of an anomalous thorium-rich geochemical province, the Procellarum KREEP terrane, and this has made estimation of the Moon’s global heat flow difficult [3].

Langseth and coworkers analyzed the heat flow experiment data in two steps [2]. First, the thermal diffusivity was calculated from the attenuation of the annual thermal wave’s amplitude with depth. Density and thermal capacity from returned samples were then used to deduce the thermal conductivity. The annual signal, due to the eccentricity of the Earth’s orbit about the Sun, and the daily thermal waves were then subtracted from the temperature profile to estimate the mean temperature gradient, and the heat flow was finally calculated by multiplying the mean thermal gradient and thermal conductivity.

As an example, it can be seen from Figure 1 that the Apollo time series appear to possess a modulation of the annual signal that was not considered in the original analysis. As shown below, this is likely a result of the 18.6 years precession of the lunar nodes which has previously been neglected. A long-term temperature increase is also observed in the data that is still not well understood. Here we deal with the question of whether or not this long term increase could be a result of the 18.6 year precessional signal. Furthermore, whether the modulation of the annual signal seen in Figure 1 affects the estimation of the thermal diffusivity or not will be investigated. To do so, we use a thermal model of the lunar regolith that takes into account both thermal conduction and the radiative transport of energy [4].

Figure 1: Apollo 15 surface temperature evolution during the complete span of the mission. Plotted are the maximum temperatures encountered during each luna- tion as inferred from the thermocouples suspended about the lunar surface. We can see an increase of 2K in the amplitude of the annual thermal wave during this three years period.

Our model

The first tens of centimeters of the lunar crust are very porous [5], and in this region, the radiative transfer of energy is non-negligible. Most studies use a term proportional to $T^3$ in the thermal conductivity to simulate radiative transfer effects [6, 7]. However, this is correct only when the regolith is in radiative equilibrium, which is not always the case close to the surface where the temperature changes rapidly. Here we use a model that considers radiative and conductive heat transport [4] to fully take into account this non-linear behavior.

The radiative transfer equation is an energy equation that takes into account scattering and absorption of the incident solar flux in the regolith as well as thermal emissions from the subsurface. The main parameters are the extinction length $E$, which is the total decrease in incident power per unit length, and the single-scattering albedo $w$, which is the proportion of extinction due to scattering. The catch of the model is the assumption that all particles behave independently, therefore it does not account for coherent effects. Although coherence has been argued to be minimal in the lunar regolith [8], this remains uncertain and it should be kept in mind when discussing the results.
Lunar heat flow

The coupled system of equations is then solved using a finite difference algorithm. The solar radiation input is estimated using the JPL ephemerides DE405 to provide solar zenith angle and distance between the Sun and surface. We obtain subsurface temperature time-series, such as in Figure 2, that show a clear, long-period, modulation of the yearly signal. Even when taking into account non-linear radiative transfer effects, no long-term temperature increase is seen and its origin has to be found elsewhere. We have searched for longer periodic signals in the JPL ephemerides but have found none. The most likely explanation for this phenomena, as discussed by [2], are albedo changes and regolith compaction of the surface by the astronauts activity when emplacing the experiment, or the expected re-equilibration process due to the presence of the relative high conductance thermal probe [2].

Re-estimation of the lunar heat flow

Using these tools, it will be possible to re-estimate the heat flow. We will start by estimating the thermal diffusivity of the regolith from the attenuation of the annual thermal wave using time domain fits of temperature evolution at different depths instead of a Fourier analysis as done by Langseth et al. [2]. With phase and amplitude variations with depth being directly dependent on thermal diffusivity, we will be able to obtain an improved estimate of this parameter. Assuming a value for the density and heat capacity we will obtain the corresponding value of the thermal conductivity. Next, we will subtract the daily and annual thermal wave from the initial temperature profile, taking into account the 18.6 years amplitude modulation, to derive the mean temperature gradient. From that, the heat flow follows in the same way as in the Apollo data analysis. We note that the Fourier analysis of 3.5-year of temperature data may bias the amplitude of the annual signal owing to the short duration of the time series. Therefore we hope our time-domain inversion process will avoid this caveat.

Perspectives

Up to now, no study has shown whether or not longer period signals than daily and annual have a strong impact on heat flow inversion. After assessing the accuracy of our time-domain inversion approach, the actual Apollo data will be inverted in the same way. We do not expect large changes in the heat flow, in comparison to the previous work of [2], but it is possible that small biases could make the difference between the Apollo 15 and 17 results either smaller, or larger.

References


Figure 2: Temperature time series at 5 cm depth showing the 18.6 year amplitude modulation of the annual signal.