THERMAL INSTABILITIES AND THE FORMATION OF LUNAR MARIA*

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Abstract. A model is discussed for a possible type of thermal instability in the outer layers of the Moon. An estimate is made for the temperature differential driving the instability. It is suggested that such an instability may have been involved in the formation of the lunar maria.

This note considers the effect of changes that may occur in the thermal conductivity of the top layers of the lunar surface as a consequence of heat treatment. These changes may in certain circumstances produce instabilities in the thermal flow pattern from internal lunar heat sources. It seems possible that such instabilities could in the past have given rise to the outflows of basaltic lava and thereby formed the lunar marial areas. This suggestion is both adventurous and speculative although there seem at present to be no reasons for discounting its plausibility.

It is known that the thermal conductivity of basalts is between a hundred and a thousand times greater than that of the uppermost fragmented layer of fine material on the lunar surface. Furthermore in the undisturbed state any layer of broken or powdered rock will gradually increase in conductivity as a result of welding or sintering of the contacts between the individual particles or rock. The rate at which such a process takes place will naturally depend on the temperature of the rock layer. In considering the outward flow of heat from the Moon it is clear that the outer layer of broken and powdered rock (which is most likely of a thickness in the metre to subkilometer range) will by virtue of its low conductivity probably give rise to an appreciable fraction of the total resistance to thermal flow in spite of the comparitive thinness of the layer. The temperature difference across any element normal to the lunar surface will depend inversely on the thermal conductivity. A relatively small increase in the conductivity of the surface layer in any region with respect to surrounding regions might therefore decrease the temperature gradient near the surface. If the flow of heat were predominantly from the deep interior the thermal flow lines would concentrate in this area and the process would become unstable since the conductivity of those near-surface areas which are at a high temperature would increase more rapidly than in corresponding regions at the same depth in surrounding regions: this in turn would concentrate more outward heat flow within this area and so produce an instability. It is possible that such an instability could eventually give rise to molten rock at or near the lunar surface.

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Numerous problems arise if we wish to apply the idea to the formation of lunar maria. In the first place it seems likely that there may be possible models for which the mechanism outlined above does not produce unstable conditions essentially this may occur because of the rapid escape of heat. Secondly it may seem unlikely that a relatively narrow top surface layer could have sufficient effect (on what are probably deep-seated processes) to produce the striking differences that are now apparent between upland and maria areas. The first difficulty can only be treated by a detailed analysis of the sources and mechanisms for heat flow and will almost certainly require a detailed computational programme. The second problem will be treated in this paper. Essentially I shall try to show the total temperature difference per unit heat flux across a fragmented surface layer can differ from that across a pure solid basaltic layer by an amount which is sufficient to cause appreciable changes in the internal thermal pattern of the Moon.

I shall consider a fragmented surface layer whose thermal conductivity C_z varies with the depth z. At present I shall not consider the causes for the fragmentation or the scale of depth on which it occurs but assume simply that the value of the conductivity, at all depths within the layer is less than the conductivity C' which relates to the deeper layers. It seems sufficiently exact to regard the heat flow at any given time to be the same at all depths so that for at any point on the lunar surface the heat flux Q will be depth independent. Q is defined as the net heat flow per unit area from all causes. It will be assumed in the analysis that the only appreciable contribution from the flow arises from conduction, although the possibilities of appreciable radiative terms in the uppermost surface layer and convection at deep layers must be examined at a later stage. It will also be assumed that the heat flow takes place in a direction normal to the surface and that the depth of the fragmented layer is small compared with the lunar radius so that the heat flow is essentially one dimensional and the assumptions of a depth-independent flux and a steady-state situation are mutually compatable providing we neglect all heat sources within the layer.

With these assumptions consider now the quantity

$$\theta' = Q \int_{z=0}^{\infty} \left\{ \frac{1}{C_z} - \frac{1}{C'} \right\} \mathrm{d}z. \tag{1}$$

This represents the *difference* of the temperature intervals which would exist through the fragmented layer and that which would be present if all the surface layer had a conductivity C' equal to that of the rock some depth below the layer. It therefore represents the *change* in the temperature interval through the layer which would ensue if the layer were suddenly converted to more solid rock, the heat flux remaining constant. In this context it can be regarded as the driving temperature difference which could produce instabilities. Consider now a whole thermal unit which was responsible for the formation of molten marial material. If θ' is appreciable compared with the total temperature difference between the lunar surface and the maximum temperature of the unit (θ_0) then clearly the process outlined above can have a significant effect on the thermal flow pattern. It may produce instabilities which could eventually result in the flow of lava to the lunar surface. Since we are only concerned with the formation of an instability it need not be assumed that θ' is a large fraction of θ_0 but merely that it is not negligable. The exact value of the ratio of θ' to θ_0 which is required depends on the degree of homogenity over the surface. For an extremely uniform surface the ratio could clearly be very low.

In order to estimate θ' we will assume a conductivity which varies with depth in the fragmented surface layer according to the relation

$$C_z = C_0 [\alpha - (\alpha - 1) \exp\{- \beta z/(\alpha - 1)\}] . \tag{2}$$

This model implies that there is a gradual transition from the fragmented layer to the unfragmented substructure with no discontinuity. In the expression α is the ratio of the conductivity at great depths to that at the surface, as may be readily seen by allowing z to become indefinitely large, i.e.,

$$C' = C_\infty = C_0 \alpha . \tag{3}$$

Further the expression (2) shows that β is simply related to the *conductivity* gradient at the surface. Taking logarithms and differentiating with respect to z, we obtain

$$\beta = \left(\frac{\partial \log_e C_z}{\partial z} \right)_{z=0} . \tag{4}$$

There are no strong reasons for prefering the model specified by Equation (2). An analysis of other reasonable specifications of the variation of conductivity with depth gives results for θ' which do not differ greatly from that in the adopted expression. The actual form of Equation (2) does have some advantages. In the first place it assumes a continuous variation of conductivity with depth. We would not expect such a model to give a good representation of the present situation in marial regions where there may be a more or less sudden conductivity change at the regolith-bedrock interface. However, in the premarial conditions on the moon, before localised melting had taken place near the surface, the top surface structure would probably represent mainly the final stages in the lunar condensation process and the increasing pressure with depth is likely to form an increasing degree of compaction which may be expected to give a conductivity which increases assymptotically to a limiting value as specified by Equation (2). A second advantage of the form of this equation is that the constants C_0, $C\infty = C'$, α and β can be relatively directly related to observation. If the form of Equation (2) is substituted in (1) the following expression results for the temperature differential which drives the instability

$$\theta' = \frac{Q \log_e \alpha}{C_0 \beta} . \tag{5}$$

I shall now briefly consider the most probable value that θ' may take in the early stages of the Moon before the development of the maria. Although at depths of many metres the lunar rock may have been very different in the early stages from its present form (especially in the marial regions) it seems likely that the top surface layers would be relatively similar in structure since in both cases the structure has been the result of micrometeorite churning. For this reason I shall take C_0 to be the *present* value of the conductivity of the uppermost surface. The value of C' I shall take to be that for pure basalt ignoring any effect that the higher temperatures may have at the base of the fragmented layer. The value of β may likewise be assumed to be the same at present as it was before mare formation. I shall use the present value of the flux Q deduced from the Apollo 15 heat flow experiment.

I list now the most values to be substituted in Equation (5) together with their sources:

(a) The flux Q. I take the value from Langseth *et al.* (1972) $Q = 3.3 \times 10^{-2}$ Wm^{-2} although clearly this could have been considerably greater during the early lunar history.

(b) The surface value of the gradient of the logarithm of thermal conductivity. Langseth *et al.* (1972), have as part of their flux measurements determined the conductivities at different depths from which a value for $\beta = 0.9$ m^{-1} can be deduced.

(c) The surface conductivity C_0. Laboratory measurements of lunar fines give for this a value $C_0 = 2 \times 10^{-3}$ Wm^{-1} K^{-1} (Cremers *et al.*, 1970) whereas a very much lower value is implied from the indirect comparison of lunar observations at far infra-red wavelengths with those laboratory lunar rock measurements in the same wavelength range (Ade *et al.*, 1971).

(d) The ratio of bedrock to surface conductivity α. Using a value of 1.3 Wm^{-1} K^{-1} for C' measured by Horai *et al.* (1970) for lunar basalts together with the above value for C_0, α is found to be 6.5×10^2.

These values together with Equation (5) give $\theta' = 110$K. It may be argued that the value for C_0 taken from the laboratory measurements on lunar fines is nearly a factor three less than the value which could be deduced from an extrapolation to the surface of Langseth's subsurface conductivity measurements (Langseth, 1972). On the other had there have been even lower estimates of the surface conductivity (Ade *et al.*, 1971) and in the early stages of thermal evolution higher values of the flux may well have been operative so that the suprisingly high value for θ' deduced above seems not completely unrealistic. Its high value makes worthwhile further investigation of the possibility that this temperature differential θ' may have in the past acted as a driving force to give rise to thermal instabilities of the kind outlined in this paper. More generally, even if the ideas suggested here are shown to be untenable it seems likely that this differential may have had considerable effect on the thermal history of the moon and should be taken into account by those investigating the thermal history of the lunar interior.

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