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Lunar Convection

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It has been shown that, if the mean rate of lunar radioactive heat generation is similar to the terrestrial value, and if the moon is relatively undifferentiated, solid-state thermal convection can be expected within the moon. Because of the larger surface-to-volume ratio on the moon, the cold and rigid outer shell is considerably thicker than on the earth; as a result, fragmentation of the shell has not occurred, explaining the lack of lunar seismic activity. Pressure release during convection could produce basaltic magmas consistent with the composition of the rocks returned by Apollo 11. An approximate analysis of lunar convection indicates that the convection velocities within the moon may be large. In this case complete differentiation may have occurred early in the history of the moon; however, there is presently no way to estimate the rate of differentiation so it is not possible to conclude whether convection and differentiation are continuing on the moon.

Studies of the rocks and soils brought back from the moon on Apollo 11 indicate a considerable similarity with oceanic basalts [*Morrison et al.*, 1970; *Turekian and Kharkov*, 1970]. Clearly, the entire moon cannot have the high concentrations of radioactive elements found in these surface rocks. This indicates that a differentiation process has occurred on the moon similar to that which produced the oceanic crust on earth.

Consistent with sea-floor spreading and mantle convection, it has been proposed [*Oxburgh and Turcotte*, 1968] that the oceanic crust is formed from basaltic magmas in the vicinity of ocean ridges. The magmas are a partial melt fraction of peridotite due to pressure release during ascending mantle convection beneath the ridges. We would argue that a similar process has occurred and may still be occurring within the moon and that the surface basalts in the mare regions are a direct result of thermal convection within the moon.

The primary exponent of solid-state convection within the moon has been *Runcorn* [1962, 1967]. He has shown that convection can explain the departures of the lunar surface from hydrostatic equilibrium. *Schubert et al.* [1969] have shown that thermal convection within the moon is to be expected if the mean rate of lunar radioactive heat generation is similar to the terrestrial value and if the moon is relatively undifferentiated. Assuming diffusion creep to be the applicable deformation mechanism, they applied a stability analysis to a number of conduction solutions and concluded that in each case thermal convection would occur.

Turcotte and Oxburgh [1969] have determined the temperature and viscosity profiles within the moon if convection is occurring. They found that the interior of the moon has nearly constant viscosity. The pressures within the moon are too low to cause an increase in viscosity such as occurs on the earth. The ratio of surface area to volume is nearly four times greater for the moon than for the earth, and consequently the cold and rigid outer layer (the lunar lithosphere) is nearly four times thicker. The lunar lithosphere is too thick to have fragmented into plates, and thus there is little lunar seismicity.

RADIOACTIVITY

There is still considerable controversy regarding the concentrations of radioactive elements within the earth; obviously any specification of the distribution of radioactive elements within the moon is speculative. If the earth has reached a steady-state thermal balance, the rate of heat release within the earth is equal to the heat flux to the earth's surface. *Lee and Uyeda* [1965] have concluded that the mean value of the heat flux to the earth's surface is 63 ergs/cm² sec with an error estimate of ±10%. If this surface heat flux is due to a uniform distribution of radioactive elements through the mantle, the required rate of heat generation for a steady thermal balance is $H = 7.8 \times 10^{-8}$ erg/g sec.

We will assume that this is the rate of heat generation throughout the moon. This assumption implies that significant differentiation has not occurred on the moon. If the moon is also in a steady thermal balance, then the mean surface heat flux on the moon is 15.1 ergs/cm² sec. It should be pointed out that a measurement of the surface heat flux on the moon cannot differentiate between various radial distributions of radioactive elements so long as the moon is in a steady-state thermal balance.

The Model

The model that we consider is a rigid spherical shell of thickness δ filled with a fluid of constant viscosity η. Assuming a steady thermal balance with a uniform distribution of radioactivity as proposed above, the thickness of the cold outer shell is approximately 350 km. The interior is a self-gravitating sphere of fluid with uniform heat release and with a radius R = 1400 km.

The stability of such a fluid sphere has been studied by *Backus* [1955], who found that the Rayleigh number

$$Ra = \frac{\alpha \rho H G R^6}{k \kappa \nu} \qquad (1)$$

(G universal constant of gravitation, k thermal conductivity, κ thermal diffusivity, α coefficient of thermal expansion, and ν kinematic viscosity) had a critical value of 2213.9 for a free surface boundary condition and 5758.3 for a fixed surface boundary condition. With the rigid outer shell the fixed surface boundary condition is appropriate for this problem. Although the linear analysis provides information on the stability of the fluid sphere, the results cannot be used to determine the structure of the convection once convection occurs. The linear analysis predicts that the first harmonic, i.e. a single convection cell, is least stable. However, there is no information on how many convection cells will occur in a fluid sphere as the Rayleigh number is increased. Experience with plane geometries favors a single cell at all amplitudes of convection. No research has been carried out on the structure of finite amplitude convection cells for this problem.

The Analysis

In order to estimate the velocities and other properties of the convective flow, we use the boundary-layer theory originally developed by *Turcotte and Oxburgh* [1967]. This analysis is valid if the Rayleigh number is large compared with the critical value and if the Prandtl number is large. A cold thermal boundary layer develops adjacent to the rigid shell. This cold thermal boundary layer separates from the rigid shell and forms a descending plume. The gravitational body force on the cold plume drives the flow. This flow is illustrated in Figure 1.

Using standard boundary layer analysis, the total heat flux to the rigid shell Q is proportional to

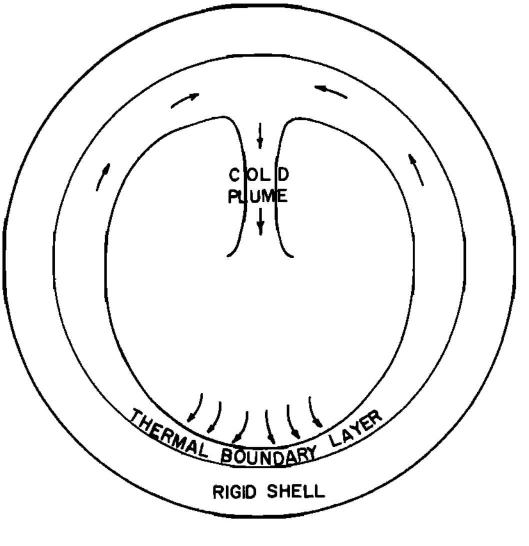

Fig. 1. Model for convection within the moon.

$$Q \approx Rk\ \Delta T\left(\frac{u_0 R}{\kappa}\right)^{1/3} \quad (2)$$

where ΔT is the temperature drop across the boundary layer and u_0 is a mean velocity for the convective flow. The constant of proportionality is of order one. This heat flow must equal the rate of heat generation within the fluid sphere

$$Q \approx R^3 \rho H \quad (3)$$

The fluid within the thermal boundary layer forms the descending plume. A mass-flux balance gives the radius of the descending plume r_p

$$r_p \approx R\left(\frac{\kappa}{u_0 R}\right)^{2/3} \quad (4)$$

The gravitational body force on the plume is balanced against the viscous retarding force on the edge of the plume to give

$$\nu \frac{u_0}{R} \approx \alpha\ \Delta T\ G\rho R^2\left(\frac{\kappa}{u_0 R}\right)^{2/3} \quad (5)$$

Equations 2, 3, and 5 can now be solved to give the mean velocity and temperature difference

$$u_0 \approx \left(\frac{H\rho\alpha G R^4}{c_p \nu}\right)^{1/2} \quad (6)$$

$$\Delta T \approx \left(\frac{R^6 \nu \rho^3 H^5}{k^4 c_p \alpha G}\right)^{1/6} \quad (7)$$

The constants of proportionality should be of order one.

Application to the Moon

If the viscosity of the interior of the moon were known, then the above results could be used to determine properties of the convective flow. On the earth, uplift phenomena have provided information on the viscosity of the upper mantle that can be used in studies of mantle convection; no such information is available about the moon.

We will first plot u_0 and ΔT as given in (6) and (7) against viscosity. For $H = 7.8 \times 10^{-8}$ erg/g sec, $\rho = 3.34$ g/cm^3, $\alpha = 3 \times 10^{-5}$ °K^{-1}, $R = 1.4 \times 10^3$ km, $c_p = 10^7$ ergs/g °K, and $k = 4.2 \times 10^5$ ergs/cm sec °K, the results are given in Figure 2. One of the most important features of this plot is the large velocities. If the viscosity of the interior of the moon was 10^{21} poises, comparable with the upper mantle on earth [*Crittenden*, 1967], the mean velocity would be near 10^2 cm/year. This is nearly two orders of magnitude larger than the velocities associated with mantle convection on earth. In order to have velocities of a few centimeters per year, the viscosity would have to be near 10^{24} poises. In this case, however, the ΔT across the thermal boundary layer would be several thousand degrees. With a temperature-dependent viscosity, this would lead to a large decrease in the viscosity.

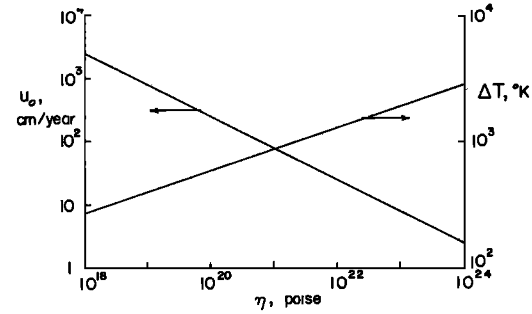

Fig. 2. Dependence of the mean velocity and boundary-layer temperature difference on viscosity.

With large convection velocities complete differentiation of the moon could have been completed in a few billion years. After complete differentiation, the interior of the moon would be barren of radioactivity and convection would cease. If undifferentiated peridotite contains 25% basalt, then it is clear that a differentiated moon would have a layer of basalt 500 km deep. However, there is no way of estimating the rate at which differentiation occurs, so that convection and differentiation may be continuing on the moon.

Because the pressure gradient is so much smaller on the moon, convection may be much less effective in producing partial melting, and thus differentiation, than it is on earth. It is thus possible that differentiation on the moon may be 'complete,' in the sense that it has gone as far as it can, but a much smaller fraction of the material may have been separated on the moon than on earth.

Conclusions

1. Convection within the moon can occur

even though the outer shell of the moon is rigid; such convection would probably not produce seismic activity except during volcanic activity.

2. Convection could be expected to occur throughout the interior of the moon; the pressure inside the moon is not large enough to increase the solid-state viscosity.

3. Pressure release during ascending convection could produce basaltic magmas consistent with the composition of the rocks returned on Apollo 11.

4. Convection velocities within the moon may be considerably larger than those within the earth.

5. There is presently no way to estimate the rate at which differentiation of basaltic magmas takes place; therefore it is impossible to estimate whether differentiation has been completed with a termination of convection or whether convection and differentiation are continuing.

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