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THE INTERNAL STRUCTURE OF THE MOON AND THE TERRESTRIAL PLANETS

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I. Introduction

The known internal structure of the Earth is the logical starting point for discussions of the terrestrial planets and the Moon. Until we have direct data, the most reasonable assumption regarding these bodies is that they are similar in composition to the Earth.

Several recent developments in geophysics have immediate implications for the other planets. These are:

1. The evidence that the upper mantle low-velocity zone is essentially a world-wide phenomenon, is more pronounced, and extends much deeper than previously supposed.
2. The development of techniques to detect and interpret the free oscillations of the Earth, thus permitting a direct determination of density.
3. Shock-wave data on rocks at pressures in excess of those existing in the Earth, thereby permitting the free oscillation densities to be interpreted in terms of composition.
4. Laboratory and seismic evidence for abrupt phase changes in the upper mantle, indicating that planetary models based on self-compression equations of state are invalid.
5. The now conclusive evidence favoring an iron-rich core rather than a silicate phase change.
6. The redetermination of the average radioactive abundances in the Earth, which suggest that the chondritic analogy is not appropriate for the Earth and, presumably, also not appropriate for the inner planets and the Moon.

Any one of the developments listed above would justify a re-examination of present conclusions regarding the structure and composition of the inner planets. By combining all of this new information into the discussion to follow we hope to update the study of planetary interiors to the present level of knowledge regarding the interior of the Earth.

The Moon is of particular interest because of the apparent paradox of its observed high mean moment of inertia. Surprisingly enough, however, if conditions within the Moon are comparable to those at the same pressure level within the Earth, then a density decreasing with depth is predicted for the lunar interior.

II. Equation of State

An equation of state for the Earth, which does not depend on the Adams-Williamson adiabatic and hydrostatic assumptions, has been determined from free oscillation and shock wave data. The equation implies that low densities are associated with low seismic velocities; this is also implicit in the velocity density relation of Birch. The study of the upper mantle of the Earth is particularly pertinent to the problem of planetary interiors since pressures at the center of the Moon and Mars correspond, respectively, to depths of only about 150 and 650 km within the Earth. This region of the Earth is anomalous on all counts, involving reversals of seismic velocities, densities, and probably the maximum departures from adiabaticity and hydrostaticity and the closest approach to the melting point. It is only at a depth below some 1000 km that the Earth starts to behave as a self-compressed ball.

The low-velocity, low-density zone is an important feature of the upper mantle of the Earth but its contribution to the overall mass and moment of inertia are slight. If conditions in the Moon are comparable to those at the same pressure level in the Earth, then the lunar low-density zone will dominate the properties of the Moon. In fact, a density *decreasing* with depth in the Moon is a feature that is difficult to avoid.

Figure 25 shows the free oscillation equation of state in terms of density vs pressure. For comparison we show the standard Bullen density models and the shock wave equation of state for iron. Below the curve for iron is a curve that shows the equation of state for the core, which represents a mixture of pure iron and mantle silicates. Note the discontinuities, which represent upper mantle phase changes. The arrows at the top of the figure are the minimum central pressures in the Moon, Mars, and Venus.

Figure 26 shows how the free oscillation equation of state is used with shock wave data to determine composition in the Earth. The curves are in terms of the seismic parameter, Φ, which is a measure of compressibility and density.

III. Application to the Moon

The simplest assumption regarding the Moon is that the physical properties are identical to those at corresponding pressure levels in the Earth. Figure 27 shows the equation of state variable Φ, which is directly measured for the Earth and its implied variation with depth in the Moon under the assumption above. Note that the pressure at the center of the Moon, about 52 kilobars, corresponds to a depth of about 150 km within the Earth. The seismic velocities in the Moon are related to the square root of Φ and the density is some fractional power of Φ. A low-velocity, low-density region is then immediately predicted for the interior of the Moon.

An alternate approach to the density structure of the Moon is to estimate the present temperature from thermal history calculations and allow for the effects of thermal expansion and compression. Figure 28 shows the condition for a constant density in the Moon. The change of density with depth is due to increasing pressure (first term, line 1) and increasing temperature (second term, line 1). Together this leads to an estimate of 0.8 C/km as the critical temperature gradient for constant density. Thermal history calculations suggest that this gradient is exceeded, at least to a depth near 400 km, where the melting curve is intersected. One can see that the melting point gradient itself is less than the critical gradient. Any partial melting and consequent upper migration of molten material will tend to smooth out the gradient and it is possible to exceed the critical gradient throughout the Moon, giving a decreasing density from the near surface to the center.

Table 10 gives the density gradients and the total change of density in the upper and lower Moon which result from thermal history calculations. The density decreases by about 4% in the upper 400 km and increases by about 3% from 400 km to the center, thus never recovering its initial value.

Table 10. Density gradients in the Moon[a]

	Upper Moon (0–400 km)	Lower Moon
$\frac{d\rho}{dh}$	−0.32 (g/cm³)/1000 km	+0.064 (g/cm³)/1000 km
$\Delta\rho$	−0.128 g/cm³	+0.086 g/cm³

[a] If partial melting occurs, the densities in the Moon will be lower than the values presented here.

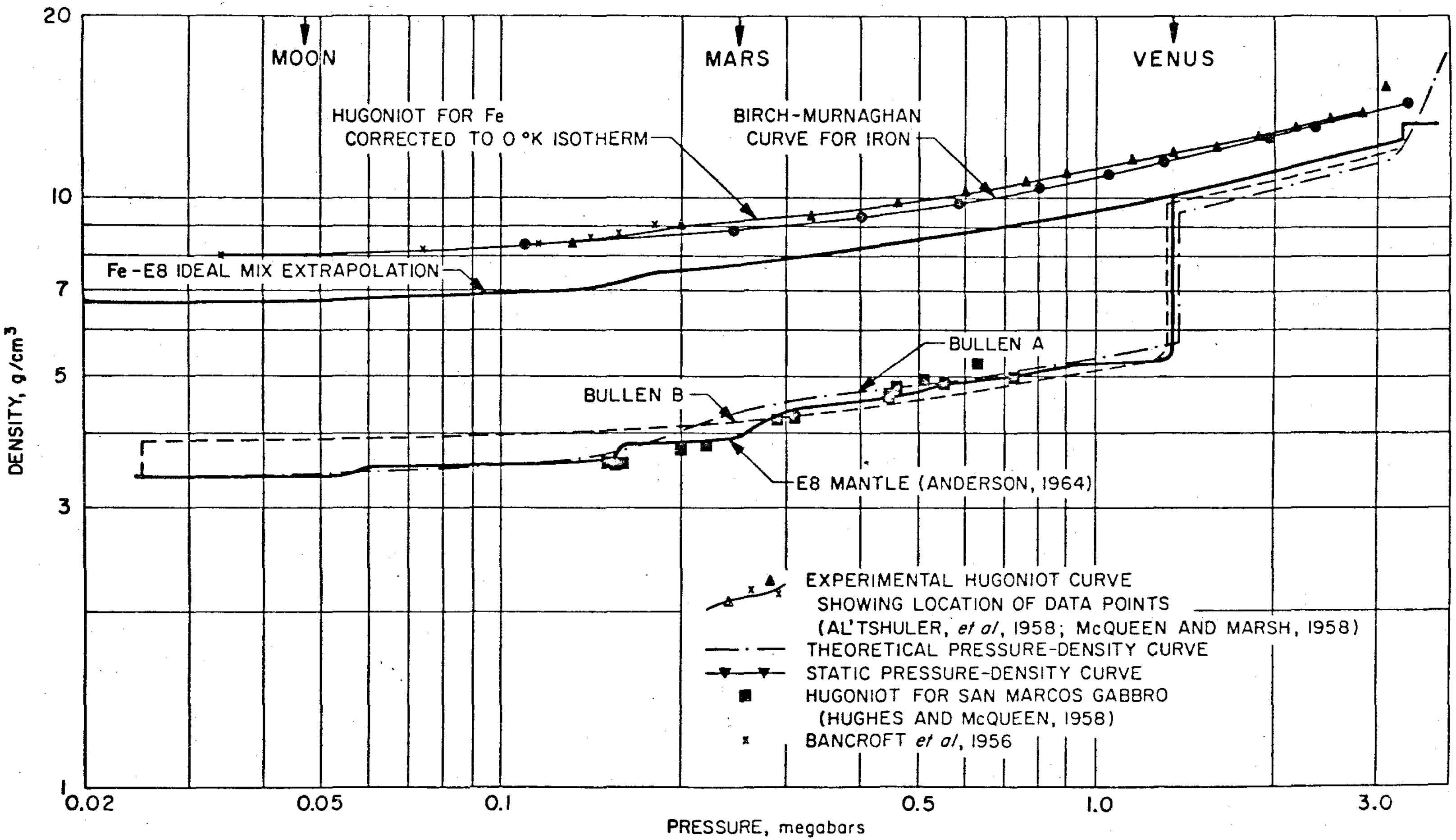

Fig. 25. Equations of state for the mantle and core of the Earth, as determined from seismic and shock wave data

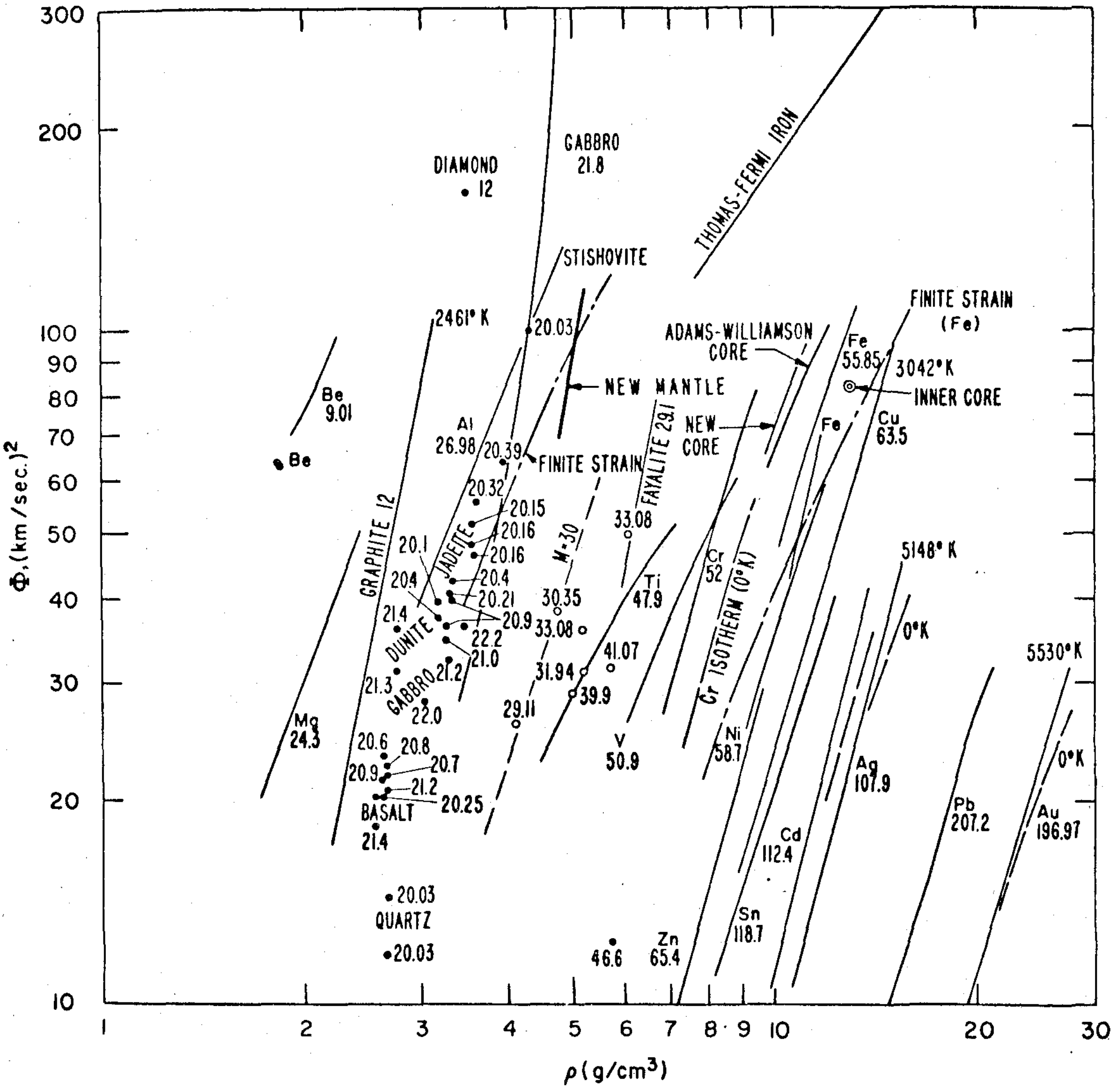

Fig. 26. Equations of state for metals and rocks as a function of mean atomic weight. Also shown are the free oscillation results for the mantle and the core

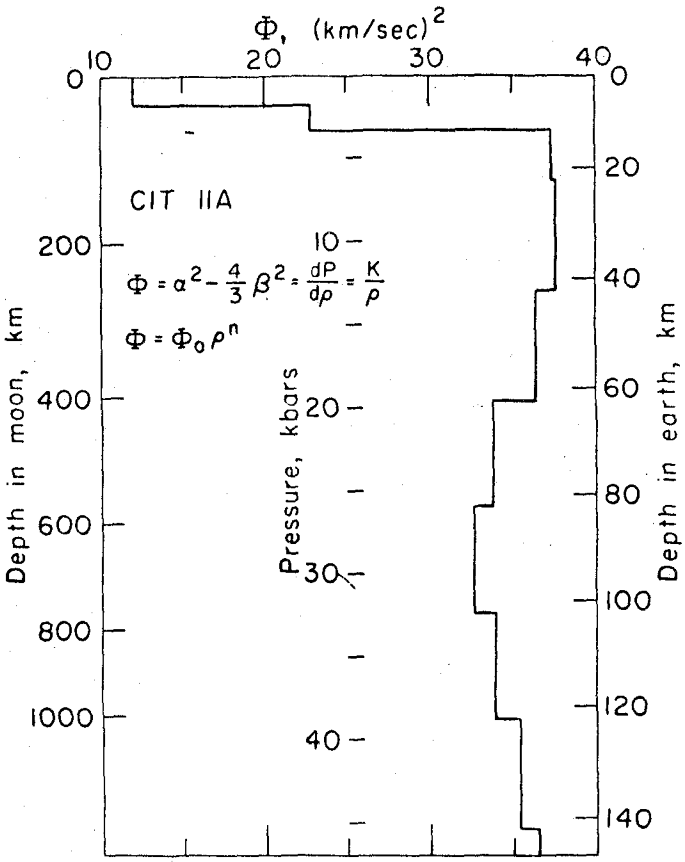

Fig. 27. The equation of state variable Φ in the Earth and in the Moon under the assumption that *dT/dP* is identical in these two bodies

Condition For Constant Density

$$\frac{d\rho}{dh} = -\frac{g\rho^2}{K_T} + \rho\alpha\frac{dT}{dh} = 0$$

$$\frac{dT}{dh} = \frac{g\rho}{\alpha K_T} = 0.8\ °C/km$$

Critical Gradient

If $\frac{dT}{dh} > 0.8°C/km$ *density will* *decrease* *with depth*

$\frac{dT}{dh} \sim 3°C/km\ (400 > h > 0 km)$ *Thermal history calculations*

$\frac{dT}{dh} \sim 0.1 - 0.2\ °C/km$ · *Melting point gradient*

Fig. 28. Condition for constant density in the Moon

The densities that result from the two approaches above are shown in Fig. 29. The solid curve represents basically a decompressed Earth and involves only an implicit effect of temperature, i.e., the assumption that the change of temperature with pressure is the same in the Moon as it is in the Earth. The dashed curve is the density estimated from an explicit allowance for the temperature from thermal history calculations. The results are similar and both require an extensive low-density region in the Moon and central densities that are less than the near surface densities.

Seismic experiments will supply the most direct evidence regarding the interior of the Moon. However, the decrease in velocities with depth that are predicted from the Earth-decompression analogy will make interpretation

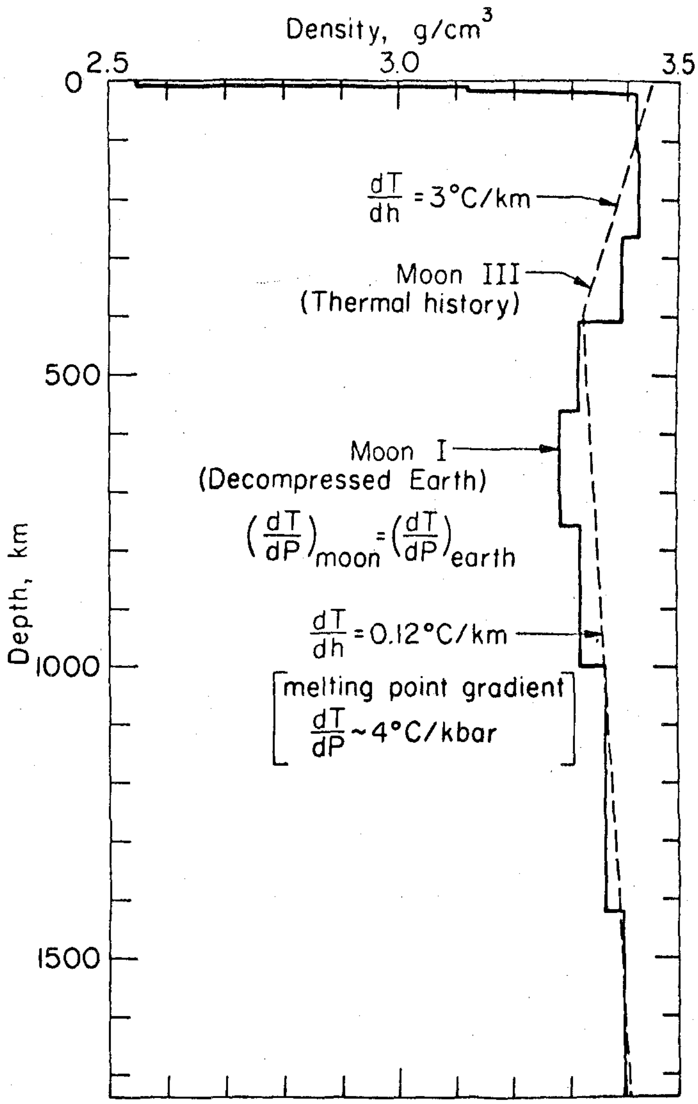

Fig. 29. Density vs depth in the Moon

of standard seismic body wave data less straightforward than for 'standard' Moon models that have previously been discussed. In regions where the velocity decreases inward, the seismic ray paths will be bent downward and defocused.

The theoretical periods of free oscillation of our new Moon model are important in the design of a lunar seismic experiment. These periods are shown in Table 11. These periods, when observed, will clearly differentiate between various models. Our new model has periods significantly longer than the others shown. A long-period lunar seismometer should, therefore, have a capability of detecting oscillations as long as about 16 min in period.

Table 11. Theoretical periods of free spheroidal oscillations of the Moon for several models

Order, n	Periods of spheroidal oscillations, minutes			
	Homogeneous	Self-compression	Density reversal	Heavy core
2	14.6	15.1	15.7	12.5
3	9.8	10.2	10.6	8.8
4	7.7	8.0	8.2	7.2
6	5.6	5.8	5.9	5.5

IV. Thermal History Calculations

Wasserburg et al. (1964) have recently shown that the radioactive abundances in the Earth are quite different from those in chondritic meteorites. Chondritic abundances have previously been used in thermal calculations for the other planets. However, the potassium-uranium ratio is eight times smaller and the uranium content is possibly four times larger in the Earth than in chondrites. To be consistent, therefore, with our general approach, we must redo the thermal history calculations. This has recently been done by Phinney and Anderson (1965) and the results are shown in Fig. 30, along with results for a chondritic Moon. Note that the Moon heats up more rapidly with the new abundances, intersecting the melting curve at a time 1.6×10^9 years after formation, assuming that it started at a constant temperature of 273°K throughout. These calculations are incomplete in the sense that the latent heat of melting and heat transferred by mass movement during the source of differentiation are ignored. For the present, however, we are simply comparing Moons of differing radioactivities. The conclusion is simply that a Wasserburg Moon will start to melt and differentiate earlier and more completely than a chondritic Moon. The surface features of the Moon are therefore probably older than would be assumed with the chondrite analogy. The effect of the latent heat of fusion would be to keep the temperatures at depth on the melting curve; the effect of heat transfer by mass movement would be to smooth out and lower the gradient in the upper part of the Moon.

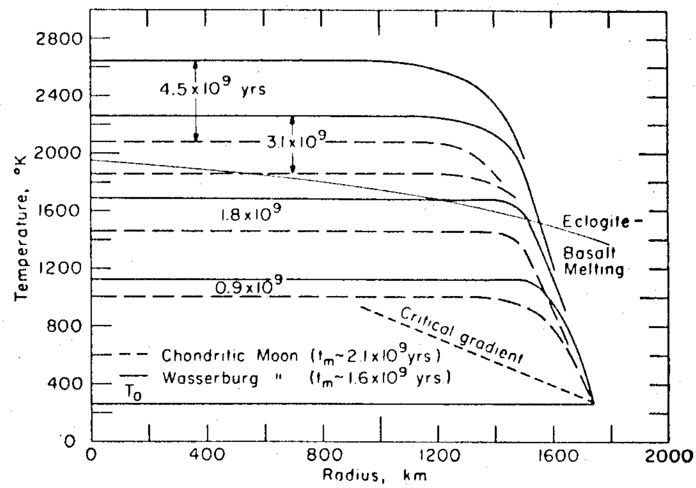

Fig. 30. Thermal history calculations for initially cold (273°K) chondritic and Wasserburg Moons. Extensive melting at depth is predicted for both models.

The calculations indicate that the Moon underwent severe radial differentiation some 3 billion years ago. Partial melting or differentiation does not imply homogenization of the lunar interior or large-scale regular convection cells. The Moon probably has an irregular sialic crust approximately 10 km thick in the highlands, overlying a more basic mantle. This estimate is based on the observed relief on the Moon's surface and is consistent with a degree of differentiation comparable to that having occurred on the Earth.

V. The Terrestrial Planets

It is commonly maintained that the differences in the mean densities of the inner planets imply that they all have different compositions.

Ramsey (1948), Bullen (1949, 1957), Lyttleton (1963), and Levin (1963) have maintained that the terrestrial planets have the same composition, but their conclusion requires that if any internal core is present it is composed of a high-density modification of the mantle silicates rather than an iron-rich alloy. On the other hand, Urey (1952), MacDonald (1962) and others have presented detailed calculations supporting the view that the Moon and the terrestrial planets differ markedly in composition. These calculations suppose that any planetary cores are chemically distinct from the mantle material.

Using the seismic equations of state for the Earth's mantle and core, it is possible to design undifferentiated protoplanets by mixing the iron core into the silicate mantle and suitably combining the individual equations of state. The resulting body, of course, has the same average composition as the Earth. It can be shown that the mean density and moment of inertia of Mars are satisfied by an Earth-like protoplanet that has undergone no differentiation.

Table 12 shows the ellipticities for Mars that result from various degrees of differentiation. Only the undifferentiated Mars gives the proper mean density and ellipticity.

Table 12. Properties of partially differentiated Mars models

Distribution of material	Radius, km	C/MR^2	η	e^{-1}
Differentiated	3309	.3449	.4568	231.2
80% core into mantle	3306	.3784	.1686	205.0
90% core into mantle	3305	.3828	.1332	201.7
80% mantle into core	3307	.3787	.1664	204.3
97% mantle into core	3309	.3836	.1289	200.3

*The "differentiated" model is geometrically similar to the Earth and represents a chemically differentiated model. The observed inverse ellipticity for Mars is 200, indicating that it is a chemically undifferentiated body; i.e., there is no core.

Thermal history calculations, Fig. 31, show that temperatures in the Earth will exceed the melting point of iron early in its history, thereby producing a heavy central core. The melting points of the silicates are exceeded later, thus giving a crust and a differentiated mantle. However, temperatures in Mars with the new radioactive abundances will never exceed the melting point of iron. Mars, therefore, will not be able to differentiate its iron into a central core. Since dynamo action in a molten iron core is believed responsible for the Earth's magnetic field, by analogy, Mars will have no magnetic field.

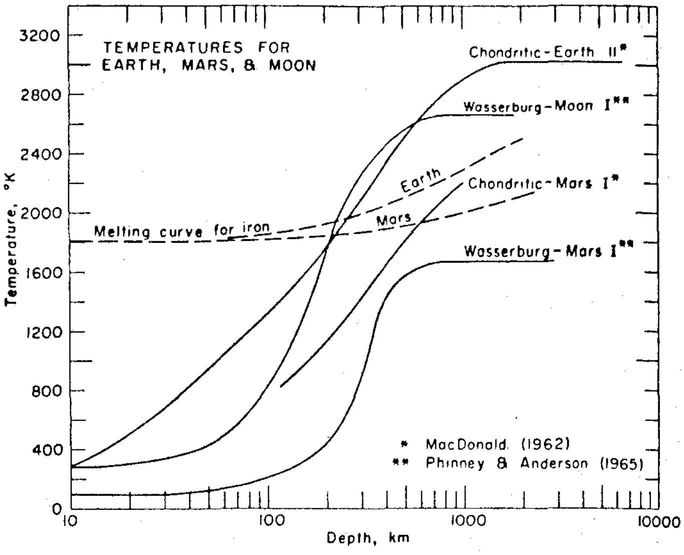

Fig. 31. Present-day temperatures from thermal history calculations for Mars, Moon, and Earth. Mars will not melt or differentiate a core downward nor continents upward. Both the Earth and the Moon go through a hot stage and will differentiate.

VI. The Strength of the Moon

It is often asserted that the irregular shape of the Moon requires great strength and therefore the Moon must be a cold body. Caputo (1965) has recently computed the strength required to support the lunar bulge under various assumptions regarding the size of a possibly liquid core. If the Moon is a solid body throughout, a strength of 18 bars will support the figure; if 75% of the Moon is molten, a strength of 28 bars is required in the remaining solid portion of the Moon. Similar calculations for the Earth show that the mantle is supporting stress differences on the order of 30–160 bars. If the Moon has the same strength as the Earth, it should be able to support stress differences at least 12 times larger than those existing on the Earth, or about 360–2000 bars. This is due to the lower gravity on the Moon. The fact that less than 30 bars is required to support the irregular shape of the Moon implies that it is a weaker, presumably hotter, body than the Earth.

VII. Summary

The differences in the mean densities of the terrestrial planets is usually taken as a compelling argument for the inhomogeneity of this part of the solar system. This conclusion is re-examined in the light of the latest information regarding the distribution of density in the interior of the Earth. Mars must have its iron more evenly distributed than the Earth but it is not necessary to conclude that Mars differs from the Earth in overall composition. It is possible to design models for Mars and Venus that have the same uncompressed density as the Earth and that satisfy the available data concerning these planets without assuming that the Earth's core is a phase change of the silicate mantle, as argued by Levin, Bullen and Ramsey. Thermal history calculations show that an undifferentiated protoplanet having the composition of the Earth and the dimensions of Mars will not heat up to the melting point of iron or silicates in 4.5×10^9 years and will, therefore, not differentiate an iron core or a crust. Mars will, therefore, have no magnetic field and no continents or mountains.

The pressure at the center of the Moon is about 52 kilobars, which corresponds to a depth of about 150 km in the Earth. Conditions down to this pressure level in the Earth are anomalous—namely, the seismic velocities and the density *decrease* with depth. Conditions in this region are not adiabatic nor hydrostatic and the viscosity is anomalously low. The low-velocity zone is an important feature of the upper mantle of the Earth but its contribution to the overall mass and moment of inertia is slight. If conditions in the Moon are comparable to those at the same pressure level in the Earth, then the low-velocity zone controls the overall properties and the Moon will appear to be a very anomalous body.

An equation of state that is appropriate for the Earth predicts a density decreasing with depth in the lunar interior, thereby giving a high moment of inertia. Thermal history calculations using the new Wasserburg radioactive abundances also predict a density decreasing with depth and, in addition, suggest that the Moon is a differentiated body.

Seismic travel-time curves and periods of free oscillation are computed for the new Moon model. The decreasing seismic velocities with depth make the standard seismic ray methods difficult to apply and interpret because of the defocusing effect. The periods of free oscillation will be the most important data to attempt to obtain in any seismic experiment designed to determine the internal structure of the Moon.

Acknowledgments

The thermal history models in this paper were computed by Dr. Robert A. Phinney. They form part of a more complete study of thermal history entitled "Internal Temperatures of the Moon" in preparation by R. A. Phinney and Don L. Anderson. We are grateful to Dr. Phinney for permission to use these calculations in advance of publication.