Interpretation of Lunar Potential Fields

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Interpretation of lunar potential fields

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Understanding of the internal dynamics of the Moon must start from the interpretation of the gravitational and magnetic fields, both present and past.

It has been long known from the study of Cassini's laws and its librations that the Moon substantially departs from hydrostatic equilibrium. This is confirmed by the second harmonic of the gravitational field determined by the tracking of orbiting satellites which also reveals anomalies (the mascons) clearly associated with the processes by which the circular mare formed. The mascons must be retained by the finite strength of the lithosphere, although there is evidence that they may have subsided by about 1 km by slippage along cylindrical fault systems around these mare, and these processes may be important in discussing moonquakes and the lunar transient phenomena. The analyses of the present figure of the Moon by the geometrical librations and by the lunar laser altimeter of Apollo 15 and 16 and other space determinations now seem essentially in agreement. The data gives evidence of the figure of the Moon prior to the filling of the mare, i.e. before about 3300 Ma and it can be concluded that the present non-hydrostatic low harmonics of the gravity field were not then present. Comparison between the present figure of the Moon and its gravity field show that there is a low harmonic variation in density in the deep interior. Both these conclusions point to thermal convection described by second degree harmonics as being the cause of the present non-hydrostatic shape of the Moon.

The present lunar dipole magnetic field has been shown by successive analyses to be negligible, the most recent value being 0.05 nT at the surface. Yet magnetic anomalies near the surface of the Moon have been discovered: 1 nT at heights of 100 km and 10–30 nT with length scales of 10 km at the surface. These anomalies must arise from the magnetization of the crustal rocks as discovered in the returned samples. These various data conclusively show that the Moon between 4000 and 3200 Ma possessed a field of internal origin, probably dipolar, with an intensity which seemed to have diminished from over 1 G at 4000 Ma to a few thousand nT at 3.200 Ma. Whether this field arose by dynamo processes in a small iron core of about 300 km radius, which was inferred from the convection theory and is compatible with the now known value of the moment of inertia factor, or whether it was a permanent magnetization of the deep interior produced by a primeval solar system magnetic field must await further understanding of the early thermal history of the Moon. Thermal convection is seen as an essential basis for understanding the thermal history of the Moon, the traces of tectonic evidence in the lithospheric shell and the history of the magnetic field.

1. Introduction

Insight into the evolution and dynamics of terrestrial and planetary interiors must be sought from an understanding of their gravitational and magnetic fields. Planetary magnetic fields arise from electric current flow generated by motions in a fluid metallic core, analogous to a dynamo. But small scale magnetic field anomalies result from the permanent magnetization of those rocks at sufficiently shallow depths to be below the Curie point. Thus earlier magnetic fields to which the rocks were exposed at their origin or during subsequent metamorphism are recorded. Small scale terrestrial gravitational anomalies are caused by the complex rock formations of the Earth's crust, and similar gravitational anomalies arise in the lithospheres of the Moon and Mars: thus recording the geological evolution of these bodies as the finite strength of the lithospheres retains these anomalies. In particular, the lunar lithosphere must have been sufficiently rigid to support the positive gravitational anomalies coincident with the circular mare – the masons discovered by Muller & Sjogren (1968) – since the time the mare basins filled with lava between 3.8 and 3.2 Ga ago. The gravitational fields of the planets were originally supposed, following Newton, to correspond with their theoretical hydrostatic figures. However, the Moon has long been known to depart from hydrostatic equilibrium and the second degree harmonic terms are nearly twenty times those predicted on this theory. Runcorn (1962, 1967*a*) showed that convection provided a more satisfactory explanation of this phenomena, especially the discrepancy between the dynamical and geometrical ellipticities, than the theories based on the assumption of finite strength throughout the Moon. Runcorn (1967*b*) also proposed that the newly discovered non-hydrostatic, low harmonic terms in the Earth's gravitational field could be explained in terms of convection in the Earth's mantle. Thermal convection, occurring by solid state creep in the solid interiors of the Moon and the Earth was at that time almost universally disregarded by scientists, but it is now more generally agreed that the low harmonics of the geoid and selenoid are dynamically supported: these therefore reveal the pattern of internal convection if the inverse problem can be solved.

At first sight the Moon appears, of all planetary bodies, to be the least likely object for the application of such methods of inferring internal dynamical processes from external potential fields. Since the Luna 2 mission it has been known not to possess a general magnetic field and indeed a metallic core, essential for a dynamo process, had been generally assumed not to exist and still remains undetected. Similarly there is no plate tectonics on the Moon; no detectable horizontal displacements of one part of its lithosphere relative to any other. While the establishment of the reality of continental drift and sea floor spreading swept away reluctance among geophysicists and geologists to accept convection, or other similar dynamic processes, in the Earth's solid mantle, the lunar physicist has no such simple demonstration to which to appeal: he must proceed by less direct reasoning. But I will show that the existence of an ancient lunar general magnetic field may be inferred from its present palaeomagnetism: conditions must have been right for a lunar core dynamo – now defunct – in the period 4.0–3.2 Ga ago. I will also show that the palaeoshape and palaeo-gravity field of the Moon may be inferred from the present figure of the Moon and that solid state convection is present.

2. The lunar gravitational field

Tracking of the Orbiter and other satellites has provided data on the lunar gravitational field. The discovery of the large positive anomalies over the circular mare, the mascons, has caused an equally significant feature to be widely overlooked. While the lines of equal gravity form sets of ovals paralleling their edges, elsewhere there are no marked anomalies, neither over the mountain ranges nor over the highlands and irregular mare. Thus the Moon is in isostatic equilibrium except for the mascons and the second harmonics of its gravitational field, which are twenty times those corresponding to hydrostatic equilibrium under the present rotation rate and Earth–Moon distance. This latter fact, discovered by Laplace from consideration of Cassini's laws, has been confirmed from space data.

Clearly the mascons originated in the processes which created the mare basins and filled them with magma. About 4 Ga ago a final infall of large objects created the depressions, removing parts of the anorthositic highland shell which presumably completely covered the Moon. Since the mountain ranges seem to have been produced by the impacts, it is reasonable to suppose that the mare basins returned to isostatic equilibrium soon after their formation. Thus the lunar lithosphere was then too thin to support such loads. The lavas which filled these basins erupted some hundreds of million years later. If the anorthositic density is 2.7 and the thickness of this layer on the near-side is 60 km and the density of the underlying mantle about 3.0, then the floors of the depressions, after isostatic equilibrium had been attained, would have been about 6 km lower than the surrounding highlands. If, as a result of the partial melting of an asthenosphere-like shell within the Moon, basaltic magma rose to a height determined by the hydrostatic head, about 3 km of lava would have flowed into the basin, producing the gravitational anomaly now observed. But this explanation of the mascons requires that by 3.8 Ga ago the lithosphere had become much thicker through the isotherm at which creep is the dominant mechanical property over 10^8–10^9 a having moved to a greater depth, through the general cooling of the Moon. The mascons are now supported by the finite strength of the lithosphere and have not attained isostatic equilibrium, but I (1974) suggested that they have subsided, as these simple hydrostatic head arguments would suggest that the magma rose to the same height in the irregular and the circular maria basins, though, as the former were less deep depressions, they acquired only a negligible thickness of additional lava.

3. THE EXTERNAL SHAPE OF THE MOON AND ITS PALAEOGRAVITY

The external shape of the Moon has been studied for a century by Earth based methods and more recently by laser altimeter from Apollo 15, 16 and 17. An ellipsoidal shape is suggested by the second harmonic in its gravitational field, but spherical harmonic analyses of the heights of the surface showed that it departs from a sphere in a complex way: the fourth harmonic is as important as the second (Goudas 1965). It was concluded that the shape is simply a record of the early impacts which distorted it (Kopal 1967, 1974); consequent stresses have since been supported by finite strength. However it has been shown that it is physically more significant to analyse the heights of points on the highlands, the irregular and the circular maria separately. These surfaces are at different heights but to a first approximation they are fitted by ellipsoids of approximately the same ellipticity with their major axes pointing earthward. These surfaces, of different age and physiochemical characteristics, each have bulges towards the Earth of about 3 km. The polar axis is less than the third axis by about 1 km.

I will argue that the low harmonics of the shape of the Moon give information about its palaeogravitational field. The composition of mare basalts is such that the molten lava would have been nearly inviscid. Thus the surface of the magma flowing into the maria basins would have been that of an equi-selenopotential surface at that time between 3.2 and 3.8 Ga ago. This equipotential surface would have been determined by the mass distribution within the Moon, its rotation, and the Earth's gravitational field gradient (or tidal action) all of which could have been different from that of the present. The latter two factors are now negligible. Therefore the solidified surfaces of the mare basalts are fossil palaeogravity surfaces if allowance can be made for subsequent distortion. There is not sufficient data available at present to determine the 2nd degree surfaces fitted by the flows of different ages. It has been shown that the circular mare fit a surface lower than that of the irregular mare but of similar ellipticity: thus this difference has been attributed to later subsidence (Runcorn 1974). While it is true that such a bulge might be a fossil tidal bulge raised when the Earth–Moon distance was about 1/4 of its present value, arguments have been presented which show this explanation to be most unlikely (Jeffreys 1952; Runcorn 1967*a*). A further argument is that as the present 2nd harmonic term of the gravitational field arises from internal lunar mass variation and as this equipotential surface only has a bulge of 0.8 km, it follows that the present shape of the mare surface cannot have arisen from the present lunar gravitational field. Thus the present non-hydrostatic figure of the Moon must have been acquired in its later history and subsequent to the filling of the mare basins. Therefore I conclude that the non-hydrostatic shape of the Moon cannot be explained by events during accretion, by supposing that the Moon had inhomogeneities built into it at its origin or in the early great episodes of bombardment which created the mare basins. A further possibility arises that the bulge is due to a second harmonic variation in the thickness of the anorthositic highlands. Whether the highlands are isostatically compensated or not, this explanation fails for the same reason: this differentiation occurred and the shell formed over 4 Ga ago. It follows that the Moon must have been distorted by external or internal forces later than 3.2 Ga ago.

Of former possibilities only the tides are conceivable as Levin's (1967) theory of expansion from solar heating does not explain its triaxiality. Of the latter, one might postulate the existence of a second harmonic radioactive concentration which has gradually changed the internal temperature so as to give about 100 °C variation over horizontal surfaces, highest on the Earth–Moon line: it would be possible quantitatively to satisfy the values of the two ellipticities. A second degree harmonic convection system seems a more natural explanation (Runcorn 1967) than such a suggestion based on an artificial initial distribution, the genesis of which would involve an implausible accumulation hypothesis for the Moon. Convection being the result of instability seems a more natural explanation: the postulate which would be required is that the convection pattern changed its form to a second degree one subsequent to the filling of the mare basins, due to a gradual change in the physical or thermal boundary conditions. If as is reasonable the earlier convection pattern consisted of a single cell, i.e. one described by a first degree harmonic term, the similar values of the present ellipticites of the highland and mare surfaces would be explained (Runcorn 1975*d*).

From data on the free librations of the Moon obtained by laser ranging, Calame (1976) has determined third degree coefficients of the lunar gravitational fields, but these are very small except for those of first order. It is the large second degree terms which require explanation in terms of a second degree harmonic convection pattern. Table 1 compares the 2nd harmonic term in the shape of the Moon, obtained by the laser altimeter on the later Apollo missions and the ground based telescopic data. The agreement is fair considering the deficiency of coverage of the former and the inaccuracy of the latter determinations. Figure 1 exhibits the statistical treatment of the geometrical libration data. A discussion is given by Runcorn (1975*d*).

Were the Moon a uniform body, it would be a triaxial ellipsoid for $(C-A)/B = 631.25 \times 10^{-6}$ and $(B-A)/C = 227.37 \times 10^{-6}$. Thus we would expect $(a-b) = 0.4$ km and $(a-c) = 1.1$ km. The much larger ellipticities of the actual surfaces of the highlands, irregular maria and circular maria imply that the density distribution within the Moon varies with angle in the way expected for a two cell convection pattern. It is known from convection theory for marginal

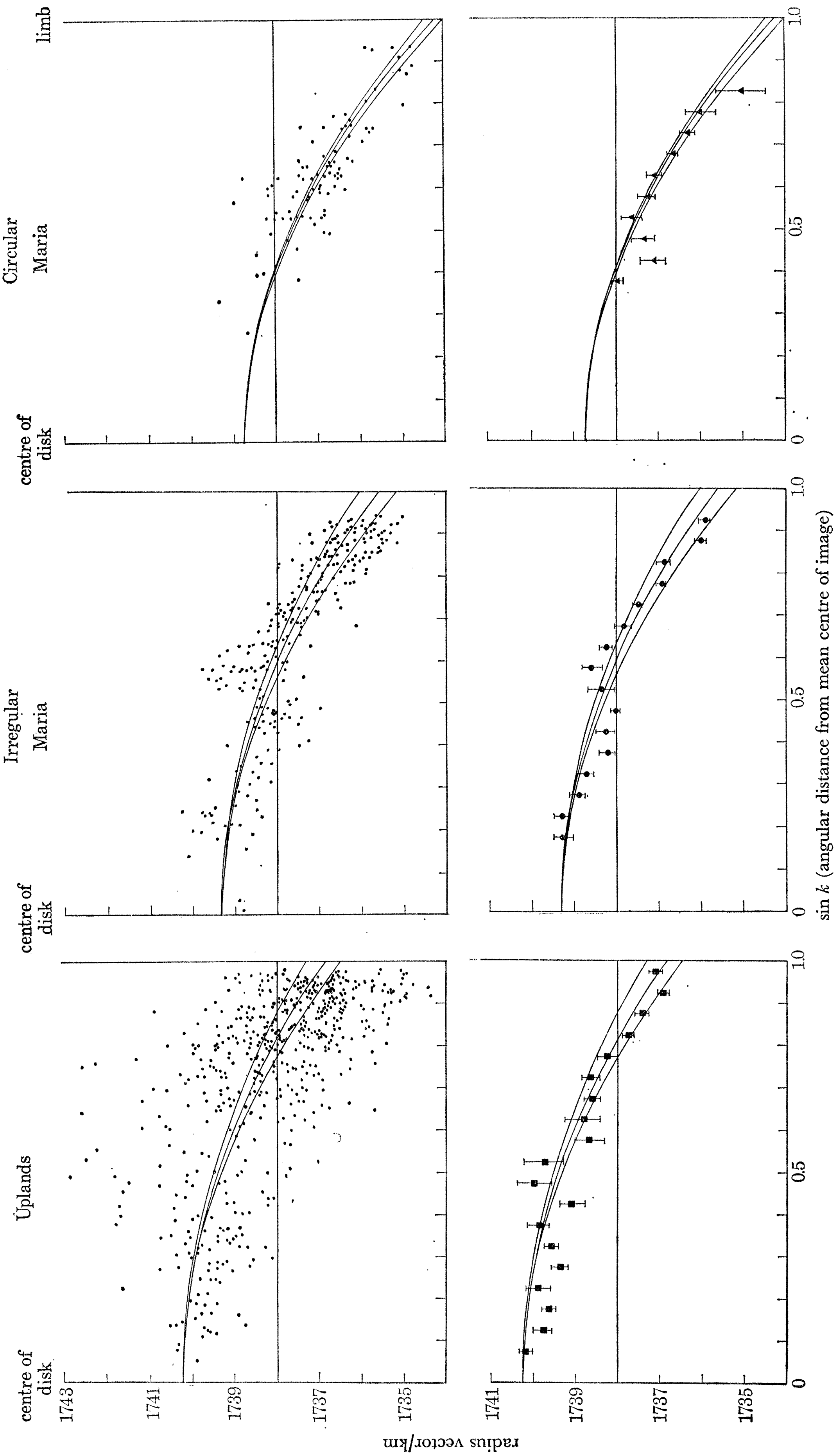

FIGURE 1. Geometrical libration data on the heights of the lunar surface; separately for the highlands, irregular maria, and the circular maria. The data are fitted by a second degree surface. The central curve in each case corresponds to a spheroid with its long axis towards the Earth: the other two are sections of the best fitting triaxial ellipsoid.

stability that the ratio of the dynamical ellipticity to the surface ellipticity should be 0.200 for a free boundary and 0.397 for a no-slip, rigid boundary. The observed ratios from Table 1, rejecting the anomalous value from the highlands (Apollo 14, 16, 17), the data of which were exceptionally scattered, give 0.25 from the value of $(a–c)$ and 0.13 for $(a–b)$.

TABLE 1

	a	b	c	$a–b$	$a–c$	offset of centre of figure from centre of gravity away from earth	and to west
irregular maria (Apollo 16)	1737.6	1735.5	—	2.1	—	2.1	1.2
irregular maria (geometric lib)	1739.3	1736.1	1735.2	3.2	4.1	—	—
circular maria (Apollo 15, 16, 17)	1737.3	1734.6	1733.8	2.7	3.5	1.72	1.23
circular maria (geometric lib.)	1738.7	1734.5	1734.0	4.2	4.7	—	—
highlands front side (Apollo 16)	1741.1	1737.1	—	4.0	—	2.1	1.2
highlands (Apollo 15, 16, 17)	1738.1	1738.2	1738.0	0.1	0.1	1.97	0.98
highlands (geometric lib.)	1740.2	1737.3	1736.5	2.9	3.7	—	—

Comparisons of ellipsoids fitted separately to all maria, circular maria and uplands by the laser altimeter and geometrical libration methods.

a, b, c are the semi-axes, towards the Earth, in the plane of the sky perpendicular to and along the polar axis respectively (in km).

4. THE LUNAR MAGNETIC FIELD

Understanding of the natural remanent magnetization of the rocks returned by the Apollo project and the magnetic fields presently observed near the Moon is based on two hypothesis:

(1) The magnetization was acquired on the cooling of the basaltic lavas or the high grade breccias by the process of thermoremanent magnetization (t.r.m.) in fields between about 1 μT and 1 G (10^{-4} T).

(2) Any field of internal or external origin capable of magnetizing the Moon rocks has now disappeared.

The processes by which terrestrial rocks of igneous and sedimentary origin became magnetized can be seen in operation today or in the immediate past; but although no such possibility exists in the case of the magnetization of the lunar rocks, Collinson *et al.* (1973) have shown (1) to be a reasonable hypotheses.

Surveys of the present lunar field show characteristics which suggest that it arises from the permanent magnetization of the outer shell.

(1) The dipole field is negligible, from the Apollo 15 subsatellite magnetometer its component in the plane of the orbit is less than 8×10^{15} e.m.u., i.e. less than 0.05 nT at its pole (Russell, Coleman & Schubert 1974).

(2) At heights of 100 km broad anomalies of up to 1 nT with a scale of 100 km, are observed especially on the far side (Coleman & Russell 1977).

(3) A similar pattern of local magnetic anomalies of the order of 10 nT strength and 10 km areal extent are inferred to exist near the lunar surface from (*a*) the deflexion of the solar wind by areas of the limb, detected as disturbances by the Explorer 35 magnetometer, (*b*) the electrons reflected from converging lines of force near the surface (Lin *et al.* 1976), (*c*) the magnetic

surveys conducted over the lunar surface during the Apollo 14 and 17 e.v.a. where anomalies up to 300 nT over 1 km were observed.

These observations are all mutually compatible with the laboratory measurements of the intensity of the magnetization of the Apollo samples (10^{-6}–10^{-4} e.m.u./g). Firstly it can be proved that if the magnetizing field is of internal origin and later disappears, the resulting field of the spherical shell is wholly internal and no field external to the outer surface exists. On the other hand if the magnetizing field is of external origin and later disappears, a field external to the shell does exist but no field exists in the cavity (Runcorn 1975*a*, *b*). An alternative proof of the former theorem, which is novel, will be given here.

Suppose a spherical shell of external radius b and internal radius a is magnetized by a field $\boldsymbol{H}$ of internal origin such that the intensity of magnetization $\boldsymbol{I}$ at any point (x, y, z) or (r, θ, ϕ) is given by

$$\boldsymbol{I} = c\boldsymbol{H} \quad \text{where } c \text{ is a constant.}$$

From a magnetic pole placed at (x', y', z') within the cavity, any field of internal origin can be generated by Maxwell's theory of multipoles so that the potential of the field V at (x, y, z) is

$$V = \frac{\partial^l}{\partial x^l}\frac{\partial^m}{\partial y^m}\frac{\partial^n}{\partial z^n}\left[\frac{1}{R}\right],$$

where $R^2 = (x-x')^2+(y-y')^2+(z-z')^2$.

As $\boldsymbol{I} = -c\nabla V$, $\nabla.\boldsymbol{I} = 0$. The magnetic field of the magnetized shell after the magnetizing field $\boldsymbol{H}$ has disappeared is therefore given by a distribution of north magnetic poles on the outer surface of areal density $(I_r)_{r=b}$ and of south magnetic poles of areal density $(I_r)_{r=a}$ on the inner surface.

If the potential outside the shell at (x'', y'', z'') is V'' then

$$V'' = -c\int_s \frac{1}{R_1}\frac{\partial \mathrm{V}}{\partial \mathrm{r}}\,\mathrm{ds},$$

where ds is a surface element $+^{\mathrm{ve}}$ on outer $-^{\mathrm{ve}}$ on inner surfaces and

$$R_1^2 = (x-x'')^2+(y-y'')^2+(z-z'')^2.$$

Thus
$$V'' = -c\,\frac{\partial^l}{\partial x'^l}\frac{\partial^m}{\partial y'^m}\frac{\partial^n}{\partial z'^n}\,(-1)^{l+m+n}\int_s \frac{1}{R_1}\frac{\partial}{\partial r}\left[\frac{1}{R}\right]\mathrm{ds}.$$

If (x', y', z') is the centre, there is no loss in generality and the integral becomes

$$\left[\int_0^{2\pi}\int_0^{\pi}\frac{1}{R_1}\frac{1}{r^2}\,r^2\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi\right]_a^b.$$

This is therefore the potential of a uniform distribution over two concentric spheres of an equal number of north and south poles. The potential and fields outside the shell vanish.

Within the shell itself and inside $r = a$, a field exists the distribution of which is described by spherical harmonics of the same degree as the magnetizing field. Runcorn (1975*b*) gives their values and figure 2 shows the lines of magnetic induction $\boldsymbol{B}$ and magnetic force $\boldsymbol{H}$ arising from a uniformly magnetized infinite plate, a uniformly magnetized spherical shell and a shell magnetized in the direction of a centred dipole.

This theorem is not exactly applicable for three reasons: (*a*) it neglects the induced magnetism of a shell by the field of those permanently magnetized shells outside it, (*b*) neglects that t.r.m. acquired by a shell from the field of those rocks external to it already magnetized from cooling through the Curie point and (*c*) it neglects the effect of susceptibility in modifying the field during the acquisition of t.r.m.

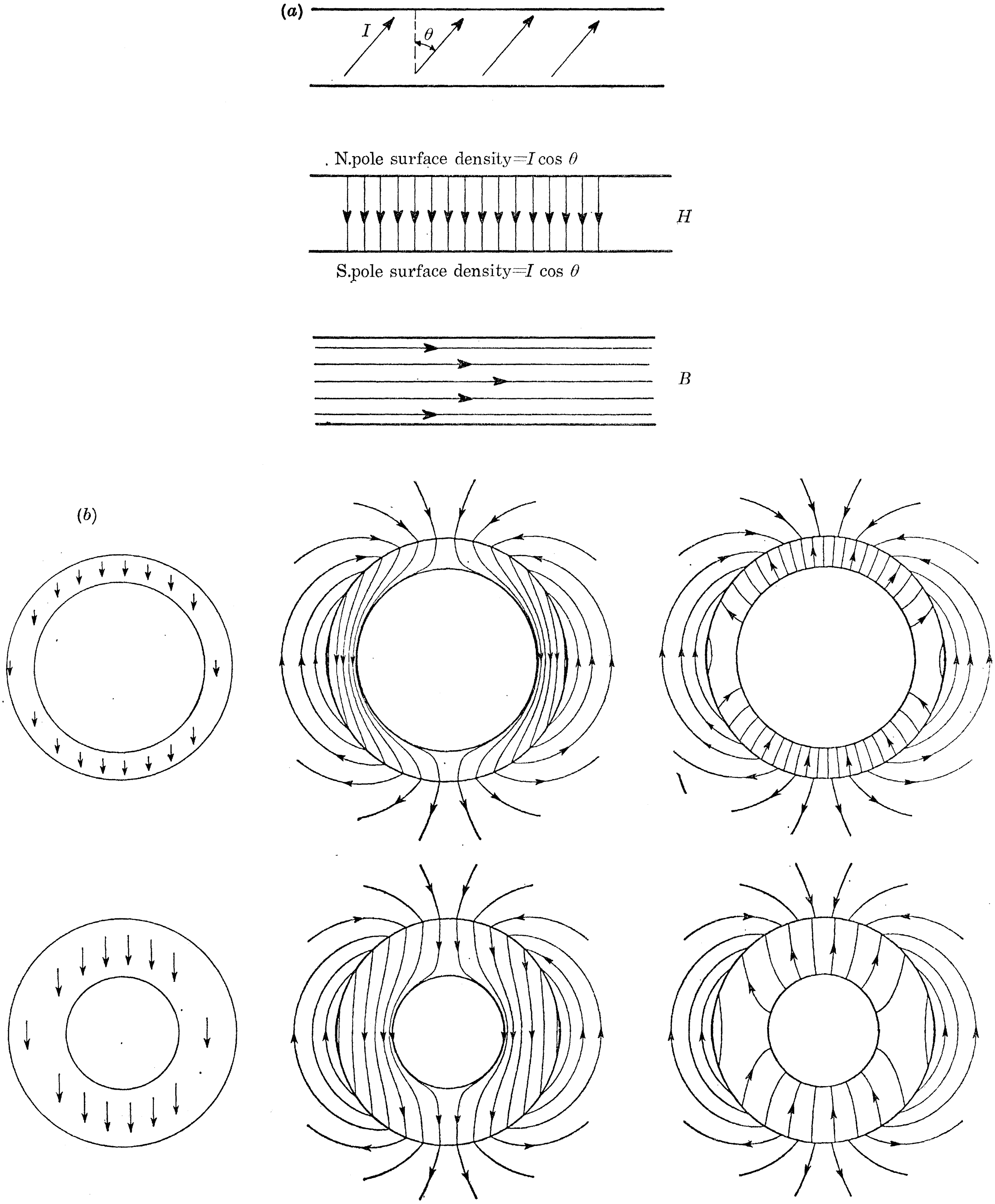

FIGURE 2(*a*) and (*b*). For description see opposite.

These questions have been dealt with by Goldstein (1975), Runcorn (1975*c*), Srnka (1975) and Stephenson (1975) but they seem negligible in this context and the conclusion remains that the negligible value of the present dipole field of the Moon is the strongest argument for the existence of a former lunar magnetic field from which the rocks acquired their magnetization.

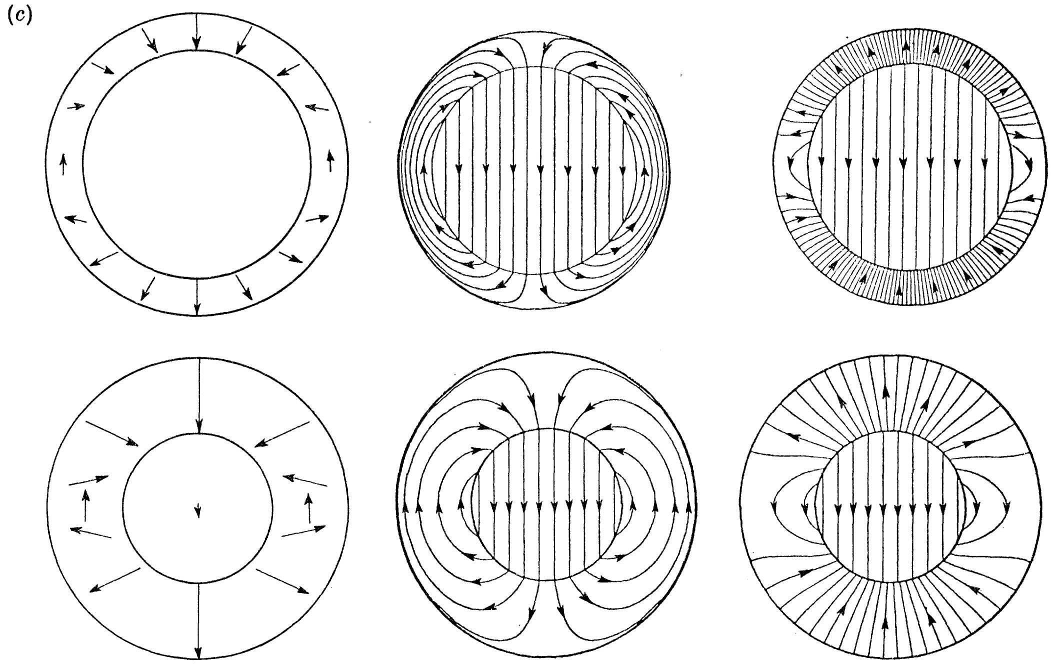

FIGURE 2. Magnetic induction (***B***) and magnetic force (***H***) lines arising from: (*a*) a uniformly magnetized infinite plate, (*b*) a uniformly magnetized spherical shell, (*c*) a shell magnetized in the direction of a centred dipole.

The magnetic anomalies referred to above can be understood with the aid of these theorems. It is clear from figure 2*a* that only at the edge of a uniformly magnetized rock layer is a field of the order of $2\pi I$ observed (with a scale of the order of its thickness): the new technique of surveying the Moon's surface field by the reflexion of low energy electrons observes fields of the right scale and magnitude. A particularly interesting case is the linear anomaly observed above Rima Sirsalis, which is explained if tension has parted an already magnetized rock layer to form a graben (Anderson *et al.* 1976). At the subsatellite orbit its field is just detectable and equivalent to a line of vertical dipoles at the surface. Anomalies above the large craters can be most simply interpreted in terms of the removal of a disk-shaped element from the magnetized shell: the observed field will be that of the removed volume magnetized in the opposite direction to the surrounding rock. Similarly over the circular mare a volume of highland presumably magnetized has been replaced by a disk-shaped layer of lavas magnetized with a different intensity and probably in a different direction. No clear case of an edge effect field has been seen and this may be due to the sloping sides of the basins. Additional phenomena may be involved: the impact may demagnetize or remagnetize a greater volume of highland than it removes, thus further complicating the identification of an edge effect. It can be shown that at heights (h) sampled by the subsatellites, the field of craters or circular mare should approximate to that of a dipole of moment Iv, when v is the volume discussed above, displaced a distance $h-\sqrt{(h^2+d^2)}$ below the centre of the crater or mare. The fitting of dipoles to the major magnetic anomalies does seem to improve if the dipoles are placed roughly about 50 km below the lunar surface.

The present magnetic maps only cover a small area of the Moon so that these concepts cannot be fully tested. When complete coverage of the Moon is available, it will be possible, on this hypothesis, to determine the directions of magnetization of the lunar crust at different places and at different times. It will then be possible to test whether the lunar field was dipolar or not and whether its axis changed with time.

The full implications of this cannot be explored here but the existence of an iron core first proposed by Runcorn (1962, 1967) seems the most likely explanation. It follows that the Moon was melted completely soon after its origin, as the magnetic anomalies over the highlands are here interpreted as implying that they are generally magnetized. The recent determination of the moment of inertia factor of the Moon by Gapcynski *et al.* (1975) as 0.392 ± 0.003 instead of earlier values more nearly equal to the value for a uniform sphere (0.4) suggests that an iron core in the Moon can possibly exist (Runcorn 1976).

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