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Principle of Equivalence and the Weak Interactions

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AFTER 40 years the Einstein theory of gravitation still rests on little more than the experimental and observational evidence available when the theory was first constructed. This consists of the very precise astronomical observations on planetary motion, including the small departures from the results of Newtonian theory in the case of the orbit of Mercury, and the experiments on the equivalence of gravitational and inertial masses.

Shortly after the introduction of general relativity, the gravitational deflection of light was found to be in agreement with predictions with an accuracy of about 10%. More recent observations have tended to give deflections too large by about 10% with about the same probable error.[1]

The gravitational red shift could be expected from elementary considerations of energy conservation involving photons, and hence does not represent a crucial test of General Relativity. The red shift observed for the white dwarf stars is in rough agreement with expectations. For the light from the sun, there is a strange anomaly that has not yet been satisfactorily explained.[2]

After the advent of general relativity, fundamental experimental work on gravity essentially ceased. Only one significant new result needs to be mentioned.[2a] In connection with the practical problem of locating oil, sensitive gravimeters were devised. These have been improved to the point where they show tidal variations in the gravitational acceleration.[3] This work is of fundamental significance as the agreement with expected tidal variations is sufficiently good to rule out an ether drift effect such that the acceleration of gravity would vary with angle of acceleration relative to the direction of motion of the earth relative to galactic matter. An effect of the order of $(v/c)^2$ can be pretty well excluded, although observations have not yet been extended over a whole year.

Newtonian mechanics is even adequate for the construction of a cosmology in agreement with the observations.[4] Hence, no strong support for general relativity can be obtained from the present state of galactic observations. This conceivably could improve greatly in the next few years.

EÖTVÖS EXPERIMENT AND THE PRINCIPLE OF EQUIVALENCE

The Eötvös experiment[5] shows that, with an accuracy of about $1/10^8$, the inertial and gravitational measures of mass are equivalent, independent of material, at least for the exotic materials tested by Eötvös which included tallow and snakewood. It would be a serious mistake to assume, as is sometimes done, that this proves that the principle of equivalence is exact or even that all deductions from the principle of equivalence should have an accuracy of $1/10^8$.

Actually, the great accuracy of this experiment allows far reaching conclusions to be drawn. For example, with an accuracy of about $1{:}10^7$ we can conclude that the ratio of weight to mass for the electron plus proton is the same as that of the neutron. With an accuracy of about $1{:}10^5$ we can conclude that the reduction in the mass of a nucleus resulting from nuclear binding forces is accompanied by a like reduction in weight. In similar manner with an accuracy of $1{:}10^5$ we conclude that the electrostatic reduction of the nuclear binding energy is accompanied by a like increase in weight. With an accuracy of about $5{:}10^{+3}$ the same conclusion can be drawn concerning the binding energy of the orbital electrons.[6]

From these facts we conclude that the strong interaction constants are at least approximately position independent. If the strong interactions were to vary with position, the ratio of binding energy to particle rest energy would depend upon position and there would be an anomalous contribution to the weight associated with this variation. This can be seen by considering a small displacement of an atom. If this were accompanied by a small change in the fine structure constant or the interaction constant associated with nuclear forces, work would be required to produce the resulting change in binding energy. This added work would imply an anomalous weight of the body if energy were to be conserved.

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[1] Whittaker, *History of the Theories of Ether and Electricity* (Nelson, London, 1953) Vol. 2, p. 180.

[2] E. Finlay-Freundlich, Phil. Mag. **45**, 303 (1954).

[2a] Although not a new result, it should be mentioned that the very careful observational work of G. M. Clemence [Revs. Modern Phys. **19**, 361 (1947)] has resulted in considerable improvement in the accuracy of our knowledge of the perihelion rotation effect.

[3] B. Baars, Geophys. Prospecting **1**, 82 (1953).

[4] H. Bondi, *Cosmology* (Cambridge University Press, Cambridge, England, 1952).

[5] R. v. Eötvös, Ann. Physik **68**, 11 (1922).

[6] See A. H. Wapson and G. J. Nijgh, Physica **21**, 796 (1955), for a similar analysis.

TABLE I. Fundamental constants written as dimensionless numbers. Physical and astrophysical constants (units of $\hbar$, c, m).

10^0	10^{20}	10^{40}	10^{80}
Masses elementary particles	Reciprocal "weak" coupling const^2 β decay, μ decay, $\pi\rightarrow\mu$ decay, etc., etc., etc.	Reciprocal gravitational coupling const^2	
$e^2=\alpha\hbar c$		$\left(\text{Ratio } \frac{\text{electrical force}}{\text{gravitational}}\right)$	Number of particles in universe to Hubble radius
		Age of universe	
Other "strong" Coupling const^{+2}		Hubble radius of universe	

The weak interactions (Fermi interactions and gravitation) do not contribute sufficiently to the binding energy of a small complex system to allow any conclusion to be drawn regarding their constancy. Consequently, the Eötvös experiment in itself does not preclude variation of the weak interaction constants with position.

Normally it would seen reasonable to assume that constancy of strong interactions could be inferred to hold as well for weak interactions. Stated in other words lack of experimental information concerning constancy of weak interactions should not be taken as evidence that the interactions are not constant.

On the other hand, there are independent reasons for believing that there is something unusual about the weak interactions and that, in fact, these interaction constants vary with position and time. The line of reasoning is a bit tortuous and starts with a consideration of the sizes of the physical and astrophysical constants.

In Table I is tabulated a few representative examples of the fundamental constants of physics and astrophysics. They have been expressed as dimensionless numbers by introducing c, $\hbar$, and m, the mass of the electron, as units. By very great stretching of the meaning of "order of magnitude" the numbers can be said to all have the order of magnitude given in the first row of Table I.

Expressed in this way these constants have two remarkable properties. First, the large size of the reciprocal of the square of the weak interaction constants is unexpected. For, if nature is not capricious, such dimensionless numbers would be expected to result some day from theory, and the solutions of equations. Surely it is unreasonable to expect such a large number to result as a function of e, π, etc.

The second remarkable property of this table of numbers is the apparent interrelation between numbers, with the Fermi interaction constant seemingly related to the gravitational interaction constant and these weak interaction constants apparently related to the astrophysical constants.

Now what sense can be made of these systematics? There are three classes of explanations which have been offered in the past. The first is probably the one most commonly believed. According to this explanation, the apparent interrelations are not very close and there are only a few constants significantly different. Also, it is claimed that nature is somewhat capricious. A weak interaction is weak, and that is all there is to it.

The second type of explanation is of the type put forward by Eddington. This type of explanation seeks to obtain all of these dimensionless numbers, physical and astrophysical, as solutions to very involved equations whose origin is not always crystal clear.

A third class of explanations is associated with the names of Dirac[7] and Jordan.[7a] The apparent regularities between numbers are taken to indicate interconnections not presently understood. The age of the universe clearly varies with time. It is assumed that all numbers of the order of 10^{40} vary together and are, hence, proportional to the age of the universe. The number 10^{80} should vary as the square of the age of the universe.

The problem of the large size of these numbers now has a ready explanation. There is one large capricious or random number. The epoch of man would be expected to be a time which on an atomic scale is large and random. Man with all his complexity could not have evolved in a characteristic atomic time. Because of the interconnections, occurrence of a single large number of capricious origin is now sufficient to account for all the large numbers.

The characteristic features of this third class of explanations is the assumption of interrelations between constants and the occurrence of a single large number, statistical in origin.

This third type of explanation is very satisfactory in many ways, but appears to be incompatible with the strong version of the principle of equivalence usually assumed. According to Dirac the gravitational interaction constant should be getting weaker with cosmic time. In a frame of reference moving relative to the cosmological co-moving coordinate system, the cosmic time axis is tilted, and the gravitational interaction is a function of both time and position. As was discussed previously a space variation in the weak interaction constant would lead to a violation of the usual strong version of the principle of equivalence. The local gravitational acceleration now depends upon the pro-

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[7] P. A. M. Dirac, Proc. Roy. Soc. (London) **A165**, 199 (1938).

[7a] P. Jordan, *Schwerkraft und Weltall, Grundlagen der Theor. Kosmologie. Braunschweig* (Vieweg and Sohn, 1952).

portion of weak interaction energy in the total binding energy. Thus, all bodies do not fall with the same acceleration and the principle of equivalence is satisfied only as an approximate relation.

To summarize, Dirac's explanation of the regularities in Table I is incompatible with the usual strong version of the principle of equivalence. On the other hand, if one is to believe that nature is not capricious, Dirac's explanation, or one of this general type, seems to be the best available.

As this represents all the direct experimental evidence concerning the constancy of the weak coupling constants, one must turn to indirect evidence, evidence concerning the distant past and available from geology, biology and astronomy.[7b] This is a very difficult task. There are enormous numbers of degrees of freedom in the earth and solar system. Projections into the past are heavily dependent upon what one assumes for physical laws in carrying out the projection. Consequently, it is often difficult to disentangle the actual observations from the interpretation, based as it is upon preconceived notions. This is particularly true of the qualitative aspects of the earth science, which is the main source of information concerning the past.

It seems very unlikely, in view of the complexities, that such indirect information can ever be used to prove that the weak interactions constants vary with time. For any effect that is observed there are a number of possible explanations.

On the other hand, the converse is not true. If the expected variation in the weak interaction constants were to lead to results incompatible with present observations, the hypothesis could be eliminated. It becomes important, therefore, to explore the implication of the assumptions that these constants vary with time.

In the interest of conciseness the conventional viewpoint is not presented here. It can be read in many of the references cited. Thus the interpretation presented here is to be viewed as a possible one but by no means the only one.

EARTH'S TEMPERATURE

Under the assumption that the gravitational constant were to vary with time, the earth's temperature would vary with time. This was first pointed out by Teller[8] who showed that the sun's radiation rate would vary as G^7 where G is the gravitational constant. Assuming conservation of angular momentum, the temperature of the earth was computed by Teller to vary as $G^{2.25}$. From this he concluded that if G varied inversely as the age of the universe, dinosaurs would have found it uncomfortably warm.

Since Teller's paper the galactic red shift data has given an age for the universe roughly 3 times that assumed by Teller and the effect is now not nearly as serious. Also, Teller did not take into account the marked atmospheric changes which would accompany a general increase in the solar constant.

The heat balance of the earth's atmosphere is very complicated and is affected by many factors; circulatory patterns, carbon dioxide content, water vapor content, and a host of others. Any extrapolation several billion years into the past is of necessity unreliable.

Ignoring the finer details, the most important effect of increased temperature upon the earth's atmosphere is the resulting increase in water vapor content. With a very moderate increase in the earth's mean temperature, the amount of atmospheric water vapor would increase greatly.

An increase in water vapor content would be expected to affect the radiation balance of the earth and to lead to either a lower or higher mean temperature for the surface of the earth. Thus the great temperature sensitivity of the water vapor pressure serves either to stabilize the earth's temperature or to make it unstable.

In order to decide between these two alternatives it is helpful to consider a simplified atmosphere consisting mostly of water vapor. A lower bound on the temperature of the atmosphere at any height can be obtained from the vapor pressure curve for water. The cloud cover of such an atmosphere would be essentially 100% as any hole in the cloud cover would lead to convection with resulting cloud formation. Convection is not of the usual type as the down-flow is almost completely liquid water with a water vapor up-flow.

It would appear that there are two effects tending to reduce the surface temperature of the earth. First, with 100% cloud cover the albedo of the earth is very high. Second, because of the small temperature gradient of a saturated vapor atmosphere, the temperature of the surface of the earth is only slightly greater than the temperature of the emitting layer of the atmosphere.

Assuming an age of the universe of 6.5×10^9 years and a solar energy flux at the earth varying as t^9, the solar flux at the earth 1.7 billion years ago would have been almost 15 times the present value. On the other hand, assuming a visual albedo for a cloud banked earth of 0.8, the surface temperature would have increased to 100°C only.

For an incident energy flux much greater than the above value, the regulatory mechanism fails to operate. This comes about in the following way: The temperature of the emitting layer is ultimately raised so high that the whole of the outer part of the atmosphere is at a temperature above the dew point. The cloud cover disappears and the convective mechanism becomes the normal type with vapor being heated by compression as it falls. Without precipitation the temperature gradient becomes that of adiabatic equilibrium. This leads to a greatly increased temperature at the earth's surface with more evaporation of water resulting. But the increased atmospheric pressure leads to a still greater

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[7b] P. Jordan (reference 7a) has also discussed some of the geological implications of a varying gravitational interaction.

[8] E. Teller, Phys. Rev. **73**, 801 (1948).

surface temperature with more evaporation. The atmosphere has become unstable and the whole content of the oceans evaporates producing an atmospheric pressure of about 3×10^8 dynes/cm^2 and a temperature greater than 1000°C at the earth's surface.

This high-temperature form of a water vapor atmosphere is opaque to the sun's radiation. However, the heat flow from the earth at a rate of 10^{-6} cal cm^{-2} sec^{-1} is sufficient to maintain convective equilibrium.

A temperature curve for the earth based upon the above model is plotted in Fig. 1 as curve A. It may be noted that for times in the past greater than 1.9 billion years the atmosphere has the high temperature form. This part of the curve is obtained by assuming an albedo of 0.6 and an emitting layer in the top 0.006 of the atmosphere. Also, because of the very small heat transfer in the lower part of the atmosphere, the temperature distribution is assumed to be adiabatic with the temperature at the "top" of the atmosphere being the lowest encountered over the whole of the earth's surface. This is assumed to be 100° below the average emitting temperature.

The low temperature curve is obtained by assuming that at the time -1.9 billion years the albedo of the earth is 0.8. The temperature distribution in the lower part of the atmosphere is assumed to be given by the vapor pressure curve. A smooth extrapolation is made to present mean surface temperatures. The change from the high temperature to low-temperature form takes place in a time short compared with geological time. The curve B is based upon a time dependence of G obtained from the following paper with $\epsilon_0 = 0.5$. (See Fig. 1 of the following paper.)

Referring to Fig. 1, there is no particular difficulty in accounting for life over a period of the past billion years. Hot springs algae survive at a temperature of 90°C.[9] The high temperature could conceivably be the reason that no life is observed prior to one billion years ago. Also, it has been suggested that the conditions for spontaneous origin of life in a condensed organic goo would be improved at a somewhat elevated temperature of about 100°C.[10]

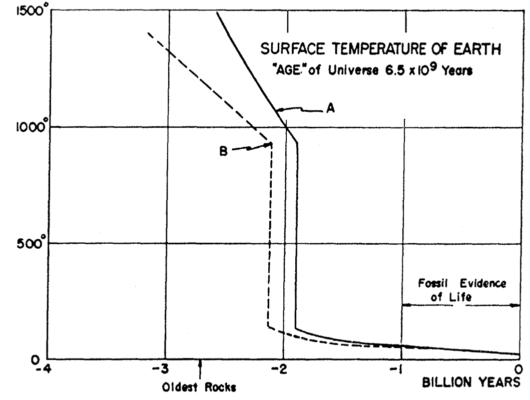

FIG. 1. Temperature curve of earth assuming Dirac's hypothesis.

It is known from radioactive dating that the oldest rocks are not found at a single spot of the earth but are located in such widely separated regions as the Canadian and African shields. These carefully dated rocks all have ages of about 2.7 billion years. This apparent upper limit on the age of terrestrial rocks is much lower than the age of 4.5 billion years found for meteorites. It may be significant that according to Fig. 1, temperatures of the order of the melting point of surface rocks are obtained at about this time.

Finally, there is some geological evidence that the earth was formerly very hot. The separation of the earth into a light crust, heavier mantle and very heavy fluid core lends support to the picture of an originally liquid earth. This is also supported by the fact that the light silicic rocks are found localized as continental masses. The existence of an originally hot sun is also supported by the evidence that the inner planets lost much of their lighter components and that the uncompressed densities of the inner planets range in a regular sequence from 5.2 to 3.8, with Mercury being the heaviest. The hypothesis of an originally hot sun is also supported by the essential absence of the noble gases from the earth's atmosphere. This is usually taken to mean that the earth lost its first atmosphere. Argon is an exception and is believed to have resulted almost wholly from the decay of K_{40}.

FORMATION OF THE MOON

The very interesting problem of the origin of the moon deserves some mention, not because it says anything very conclusive for or against the proposition that the weak interactions were stronger in the past, but because it illustrates the drastic and subtle changes that can be induced in a physical picture by a relatively minor change in an underlying physical law.

The picture of the formation of the earth-moon system which seems to be fairly generally adhered to at present has these two bodies formed apart,[11] and there seems to be a considerable body of opinion which alleges that earth and moon were formed cold.[12] With the assumption that the sun was much hotter in the past, it is much more likely that these bodies were molten at the time of formation and that the moon was derived from the earth by fission.

The diameter of the moon is 0.273 times that of the earth and its mean density is 3.34 against a mean density for the earth of 5.52. It is rigid and its surface departs rather greatly from an equilibrium figure.

Expressed in terms of principal moments of inertia

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[9] F. H. Johnson, Sci. American **191**, 65 (1954).

[10] H. F. Blum (private communication).

[11] H. Jeffreys, *The Earth* (Cambridge University Press, Cambridge, England, 1952), third edition.

[12] H. C. Urey, *The Planets* (Yale University Press, New Haven, 1952).

A, B, and C about the axis toward the earth, in the orbit plane and perpendicular to the orbit plane of the moon respectively, the ellipticities are[13]

$$(C-A)/C=(62\pm3)\times10^{-5}$$
$$(B-A)/C=(11.8\pm6)\times10^{-5}.$$

For an equilibrium surface including the effect of tidal forces the ellipticities would be

$$(C-A)/C=3.75\times10^{-5}$$
$$(B-A)/C=2.81\times10^{-5}.$$

The earth is divided into two parts, of which the inner liquid core is believed to be largely iron and roughly half the diameter of the earth. The outer mantle is solid but is moderately plastic and has an uncompressed density of approximately 3.4. It is difficult to explain the low mean density of the moon without assuming that its composition is drastically different from the earth's (uncompressed density $\sim$4.4). The moon would have roughly the right density if it were assumed to have a composition similar to the mantle of the earth. If it were assumed to have been thrown out of the earth in the manner suggested in 1878 by George Darwin, this composition difference would be understandable.

From ancient eclipse observations, it is known that the earth is presently slowing down because of tidal forces and that the moon is receding from the earth to conserve angular momentum. If this be projected into the past it is found that some 3 to 4 billion years ago the moon was very close to the earth (one earth diameter away) and had a period equal to the rotation period of the earth of about 4 hours. It is difficult to carry out this projection with any great confidence as a knowledge of solar-tide angular momentum transfer is required.

Darwin suggested a tidal wave resonance[11] as the mechanism for the fission of a primordial earth. The longest oscillation period of a rigid earth is about 1 hour, but for a liquid earth the longest period would be roughly 2 hours and would be resonant with a 4-hour day on the earth.

If it be assumed that the gravitational constant was twice its present value at the time of the fission of the earth, the period of the liquid earth vibration would be roughly 1.5 hours and the distance of the moon's center from the earth's would be just the diameter of the earth for a period of rotation of 3 hours.

A liquid earth of the present radius radiating as a blackbody would freeze from the bottom up in a few hundred years. On the other hand, it would require at least two orders of magnitude more time to build up a resonant tidal wave in the earth.[11] This much time is required on resonance to produce the requisite energy transfer. Also E. W. Brown[11] has pointed out that the detuning of the resonance produced by nonlinear terms is a source of difficulty. These terms produce a tilted resonance curve which can be climbed only when approached from the right direction. This generally requires a slow variation of the resonance frequency relative to the driving frequency, hence much more time than the minimum discussed above. It would appear that at least 10^5 years would be required to build up the necessary tidal resonance in the earth.

On the other hand, if the temperature of the earth varied in the manner described in the previous section, its temperature would be above the melting point of olivine 3–4 billion years ago. The gravitational energy of formation is easily sufficient to melt the earth at the time of formation. It is clear, therefore, that an abnormally hot sun could have served to keep the earth fluid during the long period required for a tidal resonance to build up.

A possible explanation for the ellipticities of the moon is the assumption that the moon possesses a fossil tidal wave, frozen in when the moon was 70 000 km from the earth.[14] By assuming that the moon was in rotation at the time of solidification and that the rotation was damped out by tidal friction near the end of the solidification process, the observed ellipticities may be accounted for.

Seventy-thousand kilometers is about $\frac{1}{6}$ of the present radius of the moon's orbit, and a very long time would be required for the moon to move that far away from the earth. Radiating as a blackbody, and assuming an adiabatic temperature gradient, the moon would freeze from the bottom up in about 100 years. It is clear that the fossil wave theory of the moon's shape can be made compatible by assuming a hot sun or some other way of keeping the moon warm for a long period of time.

Many years ago Jeffreys showed that turbulent damping would keep a tidal resonance from building up in a primordial earth. However, it has been pointed out by J. A. Wheeler[15] that the earth's magnetic field could suppress turbulence so that only the small viscous damping would be encountered.

The surface of the moon is a most valuable source of information concerning early times. Being devoid of atmosphere there has been little weathering to erase the records of the past. The surface is divided into light and dark colored upland and maria regions.

The uplands are very irregular and contain most of the craters. These craters can be easily ordered in their age. This can be done not only from the way they overlap but also from their form. The very old craters present the appearance of having been formed in a very viscous liquid which flowed after the formation (e.g., the Crater Maginus is old and seems to have flowed).

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[13] H. Jeffreys in *The Earth as a Planet*, edited by G. P. Kuiper (University of Chicago Press, Chicago, 1953), p. 49.

[14] R. B. Baldwin, *The Face of the Moon* (University of Chicago Press, Chicago, 1949).

[15] J. A. Wheeler (private communication). The author is grateful for several helpful conversations with Professor Wheeler on the question of the moon's formation.

For the oldest craters there are only vestigial remains in the form of a very shallow circular depression to indicate their presence. There appears to be a correlation between crater size and age with the largest craters being old. This correlation may not be significant, however, as the old small craters could have disappeared from view.

The maria present a very different appearance. Craters here are not nearly so numerous and are usually new in their apearance with little evidence of flow. The maria regions were clearly fluid after the uplands were solid as indicated by the invasion of this dark colored rock into the interiors of some upland craters and the appearance of the boundaries between the two regions.

With the assumption of a hot sun and the present albedo and emissivity, the surface temperature of the moon without an atmosphere would have been near the melting point 3–4 billion years ago. The apparent flow of the old upland craters is believed to be significant. It can be accounted for if the surface were at a temperature only slightly below the melting point of upland rocks for very long periods of time. The surface would be expected to flow under these conditions.

The fact that there are relatively few craters in the maria indicates either a very long interval of time between the formation of the uplands and the solidification of the maria or a very rapid decrease of the rate of meteoric incidence with time. The first possibility would be accounted for with a slowly cooling sun. This would lead to a very slowly cooling moon and a long time interval between the solidification of the uplands and the maria. The second possibility would seem to require a large number of impacts right after the time of formation. It is conceivable that in the fission of the earth-moon system, many small fragments were also formed. These could have been the chief source of the moon's craters.

Because of the rigidity of the moon it would be expected to show numerous small surface cracks produced by the general expansion accompanying a weakening of gravity after the time of solidification. If solidification occurred about 3.25 billion years ago the surface area would be expected to increase about 1% in the intervening period as a result of the halving of the gravitational constant. Silicates are very weak under tension and should produce many small cracks. Many large cracks, called rills, appear in good photographs of the moon.[16]

Cracks appear also in the ocean floors of the earth, and are believed by some geologists to be of relatively recent origin. If the ocean bottoms slowly creep as is claimed by some geologists, it is unlikely that the very slow expansion produced by gravity would produce permanent cracks.

The amount of expansion expected for the earth is very much greater than for the moon. From the known compressibility curves of the mantle and core, one computes an increase in volume of about 15% in the past 3.25 billion years. This corresponds to a change of 4.5% in circumference, or 1100 miles. This would amount to some 50 cracks 20 miles wide distributed over the ocean bottom. If such cracks were permanent, once formed, they would be a prominent feature of the ocean floor. Alternatively, the expansion could have occurred through very small cracks filled with sediment or intrusions, or through "creep" of the ocean bottom.

EARTH'S ROTATION

With a time variation in the gravitational constant there are two ways of defining a time scale. If an atomic measure of time is employed, the moon and planets will be found to be moving more slowly with lapse of time. The ratio of a gravitational to an atomic frequency should vary inversely as the square root of the age of the universe. Atomic clocks are now just being developed that will enable a significant comparison of atomic and gravitational time to be made in an interval of 5–10 years.

Meanwhile, it is possible to make use of an atomic clock provided for us. It is a relatively poor one, but it has been operating for the past 2500 years, and short period irregularities should have somewhat averaged out.

The atomic clock under discussion is the earth and its rotation. The dimensions of the earth are largely determined by nongravitational forces, and its rotation rate should be relatively constant on an atomic time scale. Observations of eclipses of the sun made by Babylonian and Egyptian priests 2500 years ago can be compared with modern observations to give a comparison of atomic and gravitational time.[17]

As was discussed previously, these eclipse measurements show that the earth has been slowing down in its rotation and this change in rotation rate can be traced to a tidal effect. On the other hand, the observations also give the changes in the moon's period. On the assumption that angular momentum lost by the earth in its rotation is transferred to the earth-moon system, it should be possible to predict the motion of the moon.

In order to carry out this calculation it is necessary to know the ratio of solar to lunar induced tidal dissipation. This cannot be properly calculated but was estimated by Jeffreys. The final result is this: the observations are consistent only if it is assumed that the earth is speeding up in an anomalous way at a relative rate of 9×10^{-11}/year, or equivalently that the moon is slowing down relative to the earth.

Assuming a time varying gravity and an age of the Universe of 6.5×10^{9} years, the expected rate of increase of the moon's period is 7.7×10^{-11}/year. This agrees very well with the above observed value.

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[16] Reference 12, p. 55, also reference 14.

[17] H. S. Jones, *The Earth as a Planet*, edited by G. P. Kuiper (University of Chicago Press, Chicago, 1954).

There are, of course, other possible explanations, including a change in the moment of inertia of the earth due to a rain of iron into the core,[12] the melting or growth of ice caps,[17] or the effect of atmospheric tides.[18]

FLOW OF HEAT FROM THE EARTH

It is remarkable that the rate of heat flow from the earth should present a crucial test for a physical hypothesis, but such appears to be the case. This comes about in the following way: It is known that the temperature of the mantle is quite high, believed by many geophysicists to be near the melting point of the mantle. Under these conditions a gradual release of pressure, because of a decreasing gravitational interaction, would lead to a lower melting point. Would the mantle remelt? If it did not, heat would flow from the earth at such a rate as to keep the mantle from melting. If this calculated heat flow greatly exceeded the observed rate of heat flow, the physical hypothesis could be discarded.[19]

Assuming an originally liquid earth, the adiabatic temperature gradient of the upper part of the mantle would be about 1.1°/km (Adams, 1924), and the melting point gradient would be 2.5°–5°/km. Because the melting point gradient exceeds the adiabatic gradient present in the convective mantle, it should freeze from the bottom up.

Uffen (1952) has computed the melting point in the mantle and obtains 4700°C for the bottom of the mantle, assuming 1350°C for 100 km depth.

After the mantle has solidified, the melting point temperature is essentially frozen in. For depths greater than 500 km heat conduction to the surface is of negligible importance.

The outer 100 kms would be cooled by conduction. Its measured temperature gradient is on the average about 20°/km.

Although heat conduction is of negligible importance, convection in the solid mantle is probably of considerable importance in transferring heat to the surface. If convective equilibrium existed in the solid mantle, the temperature gradient would be quite small, leading to a temperature at the core boundary of only 1400°–2500°C depending upon assumptions (Birch, Verhoogen). In view of the observed rigidity of the moon, it is unlikely that the viscosity of the mantle would be sufficiently low for convection to be very important at temperatures this far from the melting point. Also, there would be difficulty in accounting for a liquid iron core (Verhoogen).

After the mantle has solidified, its temperature is at the melting point, and its temperature gradient greatly exceeds the adiabatic convective gradient of the solid mantle. The mantle would have a relatively low viscosity ($\ll 10^{22}$) at the melting point and convection would occur.

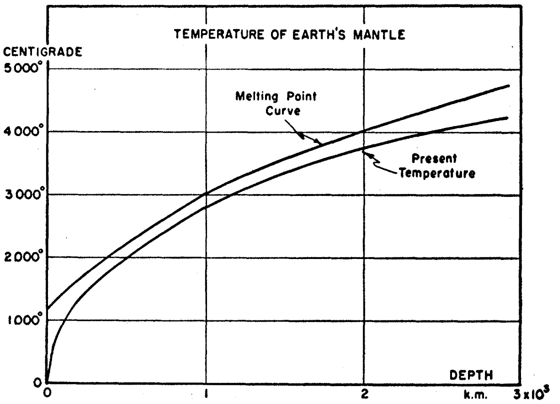

FIG. 2. Temperature distribution in the earth's mantle assuming limiting of convection, by viscosity.

The convective cooling of the mantle would occur until the temperature fell some hundreds of degrees below the melting point after which the viscosity would be too high for convection to continue.

If there were a source of heat in the interior of the earth, the temperature of the mantle would adjust itself at each depth to allow convection to occur at such a rate as to carry the necessary amount of heat away. Hence, the temperature curve below the 100-km level should be such that viscosity would be roughly constant and lie some hundreds of degrees below the melting point curve.

This convection mechanism would occur for depths greater than 100 km, with conduction being the dominant heat transfer mechanism in the first 100 km. An estimated temperature curve is plotted in Fig. 2.

With this heat transfer mechanism in mind, it is easy to discuss the effect of a gradual decrease in the gravitational constant. At any given depth the melting point would decrease with decreasing pressure and this would result in a decrease in the viscosity of the mantle. This would result in increased convection, with a transfer of heat to the surface to keep the viscosity at the proper value.

A knowledge of the melting point curve, pressure curve, and the specific heat of the mantle and core is sufficient to enable a calculation of the rate of heat flow from the earth. Assuming that the gravitational constant, hence pressure, varies inversely as the age of the Universe (6.5×10^9 years) and taking the average specific heat of the mantle and core to be 0.2 and 0.15, respectively, this contribution to the rate of flow of heat from the earth is found by numerical integration to be 1×10^{-6} cal/cm^2 sec. This agrees with the total of 1×10^{-6} cal/cm^2 sec actually observed.

In view of the uncertainty regarding the temperature curve and the specific heats, the effect of the variation

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[18] Holmberg, Monthly Notices Geo. Suppl. **6**, 325 (1952).

[19] The references for the following discussion are to be found in an excellent survey of the literature by J. Verhoozen, *Physics and Chemistry of the Earth,* Ahrens *et al.*, editors (McGraw-Hill Book Company, Inc., New York, 1956).

of gravity in releasing the earth's heat should be regarded as uncertain by a factor of 2.

Estimates of the amount of radioactive heating of the earth have steadily decreased with time. According to the latest estimate[20] radioactivity accounts for 2/3 of the total observed heat flow. Unfortunately, the radioactivity of the earth's mantle is so poorly known that this number is at best a rough estimate.

The release of heat through weakening of gravity could explain one very puzzling fact. The rate of heat flow under the oceans is observed to be essentially the same as that in the continents. But on chemical grounds it would be expected that the bulk of the radioactive materials would be found in the continents. If the bulk of the heat had its origin in the gravity effect, the uniformity of distribution is obvious.

The gravitational release of heat by the mantle is accompanied by a gradual lowering of the temperature of the core. This contribution to the outward heat flow was included in the foregoing number.

Because of the varying gravitational constant, heat flows out of the core itself at a rate of about 10^{12} cal/sec. In order to maintain sufficient convection in the core to account for the earth's magnetism, a heat flow out of the core of at least 3×10^{11} cal/sec[21] is required. That there should be enough radioactivity in the core to account for such heat release is unlikely in view of the great chemical activity of the radioactive materials.

To summarize, it appears that the heat flow from the earth that would accompany a varying gravitational constant is not excessive and furthermore could be the chief source of the observed flow. This could account for the heat flow under the oceans. It could also account for the convection in the earth's core which is needed to explain the earth's magnetism.

BETA DECAY AND GEOLOGICAL DATING

The second column of Fig. 1 contains the square of the reciprocal of the Fermi interaction constants. Following Dirac's rule this would imply that β decay rates would vary inversely as the square root of the age of the Universe. For 2 billion year-old rocks there should be a 10% discrepancy between rubidium-strontium dates and those obtained from uranium or thorium. The strontium dating method should give ages 10% greater than those obtained from α decay measurements.

It is doubtful that present geological dating methods are sufficiently reliable to detect an absolute difference of 5–10% between two quite different dating methods.[22]

To summarize, none of the evidence reviewed here can be used to give strong support to Dirac's hypothesis. On the other hand, it would appear that a variable gravitational interaction cannot be easily excluded by evidence reviewed here.

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[20] H. C. Urey, Proc. Natl. Acad. Sci. **42**, 889 (1956).

[21] W. Elsasser, Revs. Modern Phys. **22**, 29 (1950).

[22] See L. H. Ahrens, *Physics and Chemistry of the Earth*, for a recent survey article on this subject.