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CURRENT PROBLEMS IN RESEARCH

The Earth and Cosmology

The earth may be affected by the distant matter of the universe through a long-range interaction.

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Is the earth affected by its cosmological setting in the universe? It is to be presumed that the solar system was molded at its birth by galactic conditions which in turn reflected the primordial chaos of the primitive galaxy. However, we are not concerned here with questions of this type, interesting though they are, but rather with a problem of even grander proportions: Is there an effect upon the earth, here and now, of the distribution of matter in the universe? As the universe expands, as distant matter moves away from us, are there effects upon the earth of this changing distribution of matter?

This problem is a complicated one and can be approached from three orthogonal directions, from the viewpoints of astrophysicists, geophysicists, and physicists.

The traditional answer of the physicists is clear and unambiguous: "Distant matter of the universe, spherically distributed about the earth, is without a noticeable effect on the solar system. There are no locally induced consequences of the expansion of the universe."

A small minority of physicists, of which I happen to be one, have taken the contrary view, believing that this principle of independence is not established. P. A. M. Dirac (*1*) noting certain coincidences between dimensionless astrophysical constants and the dimensionless gravitational coupling constant, suggested a possible causal connection between the physical "constant" and the structure of the universe.

P. Jordan (*2*) and his students and associates (*3*) carried out an extensive theoretical development aimed at establishing a proper formal structure for Dirac's ideas. More recently my students and I have been concerned with the problem as it relates to Mach's principle (*4*).

Astrophysical and geophysical implications of the question have been discussed previously by P. Jordan (*2, 5*) and by me (*6, 7*). Certain aspects of the problem, as it relates to geophysics, are discussed in greater detail here. First, however, I present the question from the viewpoint of the physicist.

Physical Framework

While knowledge of significance to cosmology that is directly based upon experiment and observation is meager, the confidence of the physicist in the applicability and correctness of the basic tenets of relativity theory is considerable. This all-powerful theoretical tool imposes constraints so severe that relatively few cosmological theories in accord with these principles can be devised. It should be emphasized that although there are few significant direct observations on gravitation and cosmology, the host of high-energy experiments performed in the laboratory, interpretation of which requires the use of relativity, serve to establish the correctness of the basic relativistic foundations of physics and consequently, in a sense, represent indirect support of gravitational theory. This phalanx of observational evidence strengthens the hand of the physicist who must deal with a strange and dark physical situation.

It is paradoxical that the relativity principle, this strong instrument which can be applied to the cosmological problem, actually had its origin in cosmology. When the British philosopher Biship Berkeley (*8*) objected to Newton's concept of an absolute physical space (*9*), his objections were based on the impossibility of observing position or motion with respect to such an empty space. He emphasized that what is observed is position and motion of matter *relative* to other matter. He, and later Mach, emphasized that inertial effects should be associated with acceleration of matter relative to other matter, not relative to an absolute space.

Out of Mach's principle (perhaps better called Berkeley's principle) there eventually sprang the package of ideas which we call relativity. Actually, historically it took a number of laboratory experiments, by Michelson and Morley, Kennedy and Thorndike, Trouton and Noble, and others, to initiate the development of these ideas, and the classic ideas of Berkeley did not play a direct role. However, we can now see how these fundamental relativistic principles are rooted in Berkeley's philosophy and in a number of fundamental observations and experiments, of which the modern ones by Hughes and his associates and by Drever, the Eötvös experiment as recently repeated by the Princeton group, the long series of elementary-particle experiments at high energies, and the observed perihelion rotation of the planet Mercury constitute the chief bases.

This, however, is not the sole herit-

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age from Berkeley's philosophy. We have also the direct cosmological implication that the inertial stage upon which local physical phenomena occur is determined by, and anchored to, the distant matter of the universe. This means, not that distant stars serve as beacon lights to tell us where an absolute physical space lies, but rather that the distant matter in the universe is in some direct and prosaic way a source of the inertial properties of space. Thus, from Berkeley's point of view, inertial forces may be considered as interactions with distant matter in the universe.

The only relativistic means available to us for producing quasi-static interactions between bodies, widely separated, are the long-range fields. The prototype of such fields is electromagnetism. The electrostatic interactions between widely separated charged bodies is well known; so is the fact that electromagnetic waves exist, propagating with the velocity of light, and the fact that, associated with the waves, through quantum fluctuation effects, there are particles, the photons, having zero rest mass and a spin angular momentum of $\hbar$, where $\hbar = ½\pi$ (Planck's constant).

The principles of relativity and quantum mechanics provide us with a rigid classification for long-range fields. All such fields may be divided into two classes, boson and fermion, characterized respectively by particles with integral and half integral multiples of $\hbar$ for spin angular momentum. The necessity for interchanging pairs of fermions makes it unlikely that interesting and detectable long-range, quasi-static interactions will occur through a fermion field.

When we limit ourselves to boson fields there is a further classification provided by relativity. All such fields may be classified as scalar, vector, tensor, and higher-rank tensor. On the assumption that nature, although perhaps capricious, is not malicious, we shall assume that higher-rank tensors will not occur. The tensor field already provides such exquisitely beautiful mathematical difficulties that higher-rank tensors should be prohibited by fiat.

This classification, provided for us by the tensor calculus, is in itself a direct heritage from the ideas of Berkeley. If, as suggested by Berkeley, it is only the position of matter relative to other matter that is significant, an absolute coordinate system in space should be without significance. If all coordinate systems (including time as a fourth coordinate) are of equal validity, the mathematical tool appropriate for treating physical problems, including geometry, is the tensor calculus, for it is designed to treat geometry analytically but without reference to a specific coordinate system. In the tensor calculus a scalar is a field variable for which a single parameter is a function of position (and time). For a vector field, in a four-dimensional space, there are four position-dependent parameters, and for a general tensor field, 16.

A long-range vector field is known. It is that associated with electromagnetism. The four field quantities are the electromagnetic potentials. It can be shown that the requirements of relativity plus the assumption of charge conservation are sufficient to establish the essential features of the theory of electromagnetism.

A gauge-invariant vector theory, electromagnetism, or some similar vector field generated by a strongly conserved "charge" cannot play an important role, in the sense of introducing a quasi-static interaction, in the cosmology of a uniform isotropic universe. The reason for this is that, being vectors mirroring the symmetry of space, the electric and magnetic fields must average to zero over large volumes in a space which is isotropic (in large-volume averages). Thus, such vector fields are not a suitable source of long-range influence of distant matter on the laboratory.

Similarly, a long-range symmetric tensor field is believed to exist in the form of the gravitational field. This, Einstein's theory of gravitation, satisfies general relativistic requirements with the additional assumption of the equivalence principle. Thus, it too involves many experiments which, at first glance, seem to have nothing to do with gravitation.

It is in connection with the tensor field that a direct relation between inertial forces and the distribution of distant matter appears, a formal basis for some of the ideas of Berkeley and Mach thus being established. It is found that the interaction of a tensor field with a particle leads to two different types of forces. One is a force proportional to the acceleration. We recognize it as the inertial force. The other type of force is quadratic in the four-velocity of the particle (a vector) and is recognized as a gravitational force. Both types of forces may be called gravitational. Both are derived from the same term of an action principle, and a particle can be said to move in such a way as always to balance inertial forces against other applied forces. The arbitrariness in the choice of coordinate system is mirrowed in a similar arbitrariness in the force balance sheet. Through the use of coordinate transformations, inertial forces may be converted into gravitational forces, of opposite sign, as readily and arbitrarily as a clever bookkeeper can transfer funds from the liability to the asset side of a ledger.

Another heritage from Berkeley, Mach, and Einstein is the idea that gravitational and inertial forces are universal, applying in the same way to all matter. If the inertial and gravitational forces acting upon a particle are to be associated with the whole-mass distribution about the particle, the motion of the particle is determined by the mass distribution and should be substantially independent of the type of particle. Thus, the tensor field would be expected to interact in the same way with all matter.

It is a property of a universal tensor force field of this type that it affects matter in bulk, modifying the lengths of meter sticks and the rates of clocks. It is usually most convenient to define the meter sticks and clocks as unmodified and to ascribe the effects of these variations to a non-Euclidian geometry of space. From this point of view—the traditional and most convenient one—the symmetric tensor is the metric tensor of a Riemannian geometry, and gravitational effects are elevated from the mundane forces of the physicist to the ethereal geometry of the mathematician. It should be recognized that this interpretation of the role of the tensor interaction is convenient but not essential.

While this metric tensor field carries information about the matter distribution of the universe, it apparently is incapable of expressing completely the whole of Mach's principle. This can be seen by noting that, in a universe empty except for a localized mass distribution, it is possible to journey off, leaving the matter far behind. The geometry becomes flat, and the resulting metric tensor ascribes inertial properties to space, with no matter about. Furthermore, the space interior to a spherical mass distribution is flat, and nothing about the geometry of the space reflects either the total mass or the radius of this distribution. Thus, as noted earlier, it is usually believed that the spherically distributed distant matter is without effect on the solar system (except for the determination of intertial coordinate systems).

Only one more possible type of long-range field remains to be considered, the scalar. If there is any truth in the proposition that nature is simple, this field should exist and play an important role, for it is the simplest of the three massless, boson fields. Strangely enough, this primitive field is generally believed not to exist.

It is one of those strange twists, so queer that we almost miss it, that here is a field whose properties are much more certain than its existence. While the basic properties of a long-range scalar interaction are known to few physicists, they follow in such a direct way from general relativistic requirements that one can have considerable confidence in their correctness.

The scalar field is believed to be nonexistent because of the lack of a clear indication in laboratory experiments of effects due to its presence. However, I have shown (*10*) that this type of interaction must be very weak, of the same general strength as gravitation, and furthermore that the force masquerades as gravitation, being so similar to gravitation in its effects that it could be distinguished only with great difficulty. Five percent of the force we call gravitation could be due to the scalar field (the remainder being true gravitation associated with the tensor field) and we would have no way of knowing it.

Of course, the fact that a field is almost undetectable in the laboratory is not a sufficient reason for suspecting that it exists. On the contrary, there is every reason for divesting physics of useless encumbrances, of which an unobserved field would be a prime example. However, viewed in the larger arena of the cosmologist with the broad vista of the whole universe stretched before him, this scalar field, and the question of its existence, is of prime importance, for this is the only one of the three fields by means of which the matter distribution of the universe can affect the solar system and laboratory physics, apart from the trivial determination, by distant matter, of the orientation of inertial coordinate axes associated with the tensor field. The fact is that, if the scalar field exists and is correctly described by applying the standardized relativistic rituals, this scalar field provides a direct link between locally observed physical laws and the matter distribution of the universe. Furthermore, a particular form of scalar interaction serves to eliminate several deficiencies in general relativity theory with respect to Mach's principle and to bring the theory more nearly in accord with Mach's principle. Also, as is explained below, if the scalar field exists, it becomes possible to understand why the gravitational interaction is so weak.

The properties of the long-range scalar interaction have been derived from general relativistic principles elsewhere. Here I merely summarize the chief results.

1) While the quantum fluctuation effects are presumably not of importance for cosmology, I summarize them for completeness: There is associated with the scalar field an uncharged, spinless particle. It has zero rest mass, hence travels always with the velocity of light.

2) Treated as a classical field, the scalar interaction causes an attraction between bits of matter. As in the case of gravitation, this force falls off inversely as the square of the distance.

3) It has been shown (*10*) that the interaction, if it exists, would be expected to have a strength roughly within an order of magnitude of that of the gravitational interaction. The reason for this is the large contribution to the value of the scalar interaction of the enormous amounts of matter at great distance in the universe. In comparison, the contribution from some local body, such as the sun, is minuscule, and this leads to a weak interaction. One cannot obtain a strong interaction by introducing a strong coupling to matter because both contributions to the value of the scalar (from nearby and from distant matter) increase together.

4) One fundamental property of the scalar field, known to very few physicists, is that the mass of a particle interacting with a scalar field is a function of the scalar. This is such a fundamental property of the interaction that I attempt to find some simple way to illustrate its necessity. Let us consider a static scalar field acting on a particle. The force exerted is given by the gradient of the scalar φ. This force is equal to the rate of change with respect to proper time τ of momentum of the particle:

$$\frac{d}{d\tau} P_x = -\frac{\partial\varphi}{\partial x} \qquad (1)$$

This implies an acceleration of the particle in the X direction. On the other hand, the fourth component of the particle momentum is its energy, and we have:

$$\frac{d}{d\tau} P_4 = \frac{d}{d\tau} E = -\frac{\partial\varphi}{\partial t} = 0 \qquad (2)$$

since the scalar field is static. But this implies that the particle's energy is constant even though the particle is accelerating. This is possible if the particle loses rest energy mc^2 as it gains kinetic energy. A closer examination shows that the rest mass must be a linear function of φ if the particle is to interact with this scalar field. More generally, for any scalar field λ, the mass of an interacting particle must be a function of the scalar.

5) The functional form of the mass dependence must be substantially the same for all elementary properties. This is not a relativistic requirement but depends for its validity upon the great precision of the Eötvös experiment, which shows that all types of matter are accelerated gravitationally in the same way.

6) Because of this mass dependence, the magnitude of the scalar is in principle measurable by determining the ratio of the mass of some elementary particle, such as the proton, to the characteristic gravitational mass $(\hbar c/G)^{1/2}$. This ratio would vary if the scalar field variable at the location of the particle varied. This dimensionless ratio is roughly of the order of magnitude of

$$(Gm_p^2/\hbar c)^{1/2} \simeq 10^{-20} \qquad (3)$$

(G is the gravitational constant and m_p is the mass of a proton). The anomalously small value can be understood as the effect of the enormous amounts of matter in distant parts of the universe generating a large scalar field and a mass dependence of the form

$$m = m_0\,\lambda^{-1/2} \qquad (4)$$

with λ a dimensionless scalar field variable and m_0 constant (*11*).

7) The scalar field does not interact with light rays or with other particles moving with the velocity of light. Thus, the gravitational deflection of light

should be slightly less than the value expected from the gravitational weight of an object if a small part of the weight is due to the scalar interaction. In similar fashion the relativistic rotation rate of the perihelion of Mercury's orbit would be slightly less.

8) The scalar field satisfies a wave equation with the contracted energy-momentum tensor of matter serving as the source of the scalar field. For a slowly moving astronomical body, an integral of the contracted energy-momentum tensor over the body gives the total energy or mass of the body. Thus, for those cases where gravitational fields are detected and measured, the source of the scalar field is, as is the source of gravitation, the mass of the body.

9) When the masses of the elementary particles comprising a meter stick vary, the meter stick changes its length, the length being proportional inversely to the masses of the elementary particles. These length changes are in principle measurable, for they can be determined by making comparisons with the invariant length $(G\hbar/c^3)^{1/2} \simeq 10^{-33}$ centimeter. In similar fashion the rate of an atomic clock is proportional to the mass of its elementary particles.

10) For practical reasons the use of the invariant units of mass, length, and time given by the quantities $(\hbar c/G)^{1/2}$, $(G\hbar/c^3)^{1/2}$, and $(G\hbar/c^5)^{1/2}$ is inconvenient. If, instead, we prefer to use units of measure based on the particle, such as m, $\hbar/mc$, and $\hbar/mc^2$, this can be brought about by fiat, a transformation of units being introduced which results in particle mass being constant by definition. It is found that such a transformation of units leads to a dependence of the locally measured gravitational "constant" upon the field scalar, particle masses now being constant. It is obvious that, measured with these new units, the spatial geometry is now different. The metric tensor of the new geometry is conformably related to the old metric tensor. It should be noted that the gravitational coupling constant

$$(Gm^2/\hbar c) \simeq 10^{-40} \qquad (5)$$

was originally interpreted as variable, as a result of the scalar dependence of $m = m_0\lambda^{-1/2}$, the mass of an elementary particle. Expressed in new units of measure, this coupling constant varies because G varies, being $G = G_0\lambda^{-1}$, with G_0 a constant.

11) To preserve, formally, the validity of Einstein's general relativity theory, the scalar field was introduced above as an ordinary "matter field," Einstein's field equation for the metric tensor being satisfied. However, after the transformation of units, which results in the gravitational constant being variable, the scalar field loses its character as a "matter field" and becomes incorporated into the gravitational field, which may now be described as scalar plus tensor. In this form of the theory, the gravitational field equations were first given and discussed by Jordan (*2*) and his co-workers and later, in connection with Mach's principle, were discussed by Brans and me (*4*).

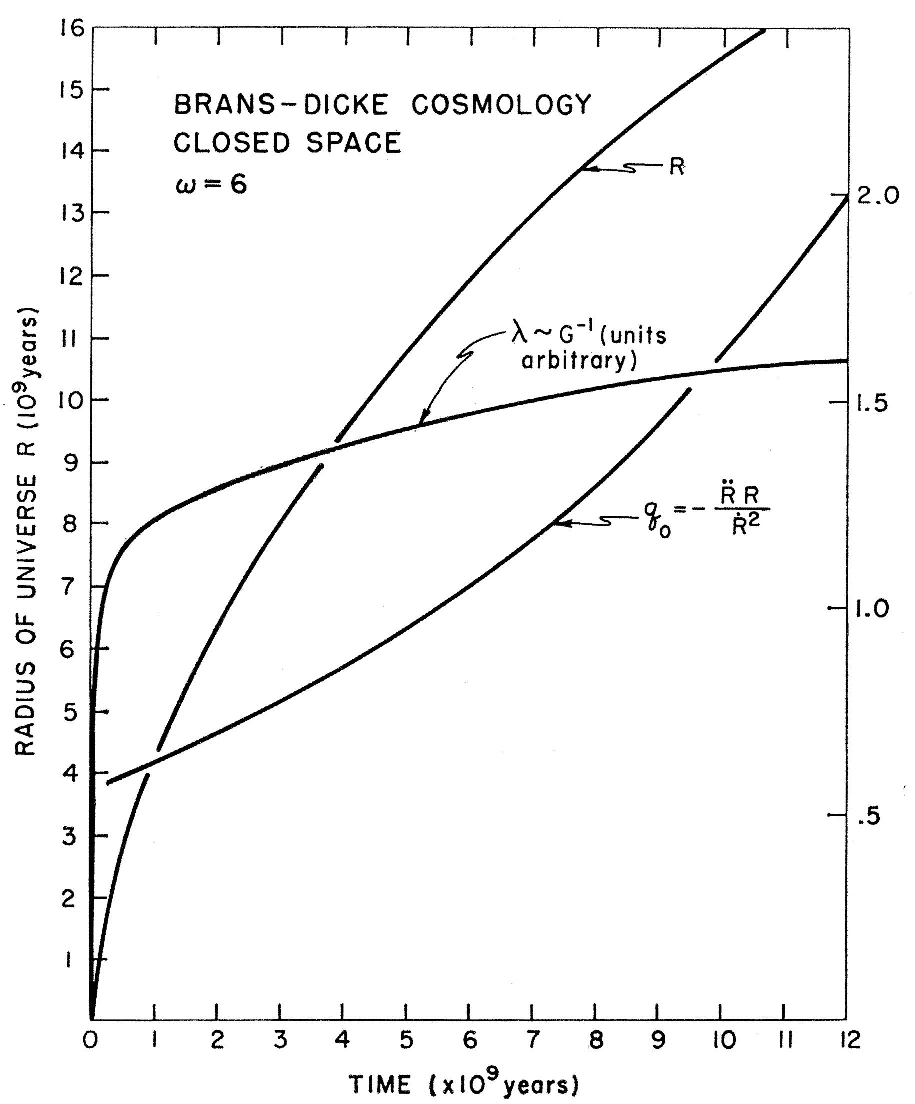

Fig. 1. A numerical integration by P. Roll and D. Curott of the cosmological equations of the Brans-Dicke theory for the case of a closed universe. R, The radius of the universe (in time units); q_0, the curvature parameter (for a flat space, $q_0 = 4/7$). The reciprocal of the gravitational constant is proportional to λ.

Cosmology and the Scalar Field

What, then, is the cosmological setting of the earth? The earth is surrounded by an essentially spherical distribution of galaxies. While departures from uniformity in the distribution of matter are great, the distribution is believed to be sufficiently uniform in large-volume averages to support the somewhat idealized picture of the isotropic universe.

This universe is observed to be expanding uniformly with a reciprocal fractional expansion rate (or Hubble age) of slightly over 10^{10} years. Again, in the expansion there are departures from uniformity in the velocities of the galaxies of about 200 to 300 kilometers per second.

We have seen that as a means by which the distribution of distant matter can influence the earth, only three fields merit serious attention—the scalar, the vector, and the tensor fields.

Let us consider first the tensor field of gravitation. As was mentioned previously, its local influence, having an origin in distant matter, seems to be limited to the association of local inertial coordinate axes with the distribution of distant matter. It appears to be quite precisely true that a local gyroscopic axis, such as the perpendicular to the invariant plane of the planetary orbits, continues to point at a fixed point with respect to the distribution of distant galaxies.

It might be thought that there could be more than one tensor field, and that consequently there could be additional effects of distant matter. However, it has been shown, through the very precise experiment of Hughes and Drever, that the existence of more than one tensor field is unlikely (*12*).

It was argued earlier that a gauge-invariant vector field, such as electromagnetism, could not be important for cosmology because of the isotropy of the universe.

The most interesting interaction, from the viewpoint of the cosmologist, is that induced by the scalar field, for if this field exists, the steady expansion of the universe should lead to interesting effects, locally observable. The reasons for this have already been given.

Briefly stated, the expansion of the universe results in a time variation of the basic part of the scalar, that contributed by distant matter. As has been discussed, this variable scalar can be considered to affect the masses of elementary particles, or alternatively, with the proper choice of units, the gravitational constant. In many ways this last interpretation is most convenient.

The choice of scalar which appears to be particularly significant for cosmology and Mach's principle is that given by Brans and me (*4*). With this theory, the gravitational constant is generated as the reciprocal of the scalar. The theory is such that, with the scalar satisfying outgoing wave boundary conditions, the time rate of change of the scalar λ is given by

$$\dot{\lambda} = - G_0\dot{G}/G^2 = 8\pi G_0 \rho t/(2\omega + 3) \qquad (6)$$

where ρ and t are the matter density and age of the universe, respectively, and ω is a dimensionless parameter, probably about equal to 6.

There are three types of geometry possible, for a uniform isotopic universe. These are closed, flat, and hyperbolic spaces. For a flat space, and the matter in the form of galaxies, the Hubble age of the universe is

$$T_h = [(4 + 3\omega)/(2 + 2\omega)]t \simeq (3/2)t \qquad (7)$$

The fractional time rate of change of the gravitational constant is

$$-(\dot{G}/G) = 2/(3\omega + 4)t \approx 1/10t \qquad (8)$$

Assuming that the Hubble age is 12×10^9 years one obtains 8×10^9 years for the age of the universe—a value in good agreement with a recent value (*13*) for the galactic age, 7.3×10^9 years, obtained from uranium decay. The resulting rate of decrease of the gravitational constant is 1 part in 10^{11} parts per year. With a closed universe this rate of decrease could be as great as 3 parts in 10^{11} per year. In Fig. 1, the reciprocal gravitational constant is given as a function of time for the best present choices of parameters.

This, then, is the chief new element which a long-range scalar field would introduce into cosmology, a steadily weakening gravitational constant. The geophysical problem to be considered, then, is the following: If we assume that the gravitational constant has been steadily decreasing with time, what effect would such a decrease have had upon the earth throughout its history?

The scalar field, causing the gravitational constant to decrease now at a rate of perhaps 3 parts in 10^{11} per year and more rapidly in the past, would have important effects upon the earth. However, the earth is such a complex system that it would be difficult to use it as a source of evidence for or against the existence of the scalar field. It is better to assume tentatively that the field does exist and to attempt to unravel the complex implications of such a decrease. The validity of the analysis would then depend upon some future demonstration of the existence of the field.

The effects upon the earth of weakening gravitation would be widespread and diverse. Among the direct effects is the general expansion of the earth which must accompany a decrease in gravitational interaction (an increase in radius of 0.2 centimeter per century accompanying a rate of decrease of the gravitational constant of 3 parts in 10^{11} per year). The expansion is almost certain, if we accept the basic premise, but the mode of expansion is somewhat uncertain. Also it should be said that, if mantle convection occurs, the required general expansion is so modest that its effects would probably be lost in the much more noticeable display of the effects of convection.

The thermal history of the earth would require rethinking. A secular decrease in the internal pressure, as a result of weakening gravitation, would result in an adiabatic decrease in the internal temperature of the earth. However, the melting point of the deep mantle would be expected to decrease even more rapidly. While there is not enough known about the thermal properties of the earth's interior to raise speculation about its thermal history much above the level of conjecture, it is interesting to consider the problem of the flow of heat from the earth's core, and from the earth's surface, with a specific model, on the assumption that gravitation has been decreasing.

Another type of thermal problem concerns the surface temperature of the earth. The luminosity of the sun would be expected to vary approximately as G^8 (*6, 7*). One would therefore conclude that the surface temperature of the earth had been higher in the past than it is now (*14*).

The Earth's Expansion

The effect upon the earth's radius of a change in G by an amount δG was determined by G. Hess (*15*) and C. Murphy (*16*), from calculations on earth models, to be approximately

$$\delta r/r = -0.1(\delta G/G) \qquad (9)$$

This is a decrease of 3 parts in 10^{12} per year for a fractional decrease in G of 3 parts in 10^{11}.

As it is the density of the earth's interior that must decrease, not the density of its surface, this expansion may take place in one or both of two ways. Tension cracks may open, to be filled with intrusions from the interior, or extensive magmatic extrusions from volcanos and surface fission could cause the interior of the earth to leak out through the crust, to form a new surface. This leakage might be at the rate necessary to bring about the needed expansion.

If this second mechanism dominates, the total lava flow from all volcanos and fissures must, on the average, total 9 cubic kilometers per year. There is no good estimate of the rate of extrusion of lava on the ocean floor, but a total flow rate for the whole earth of

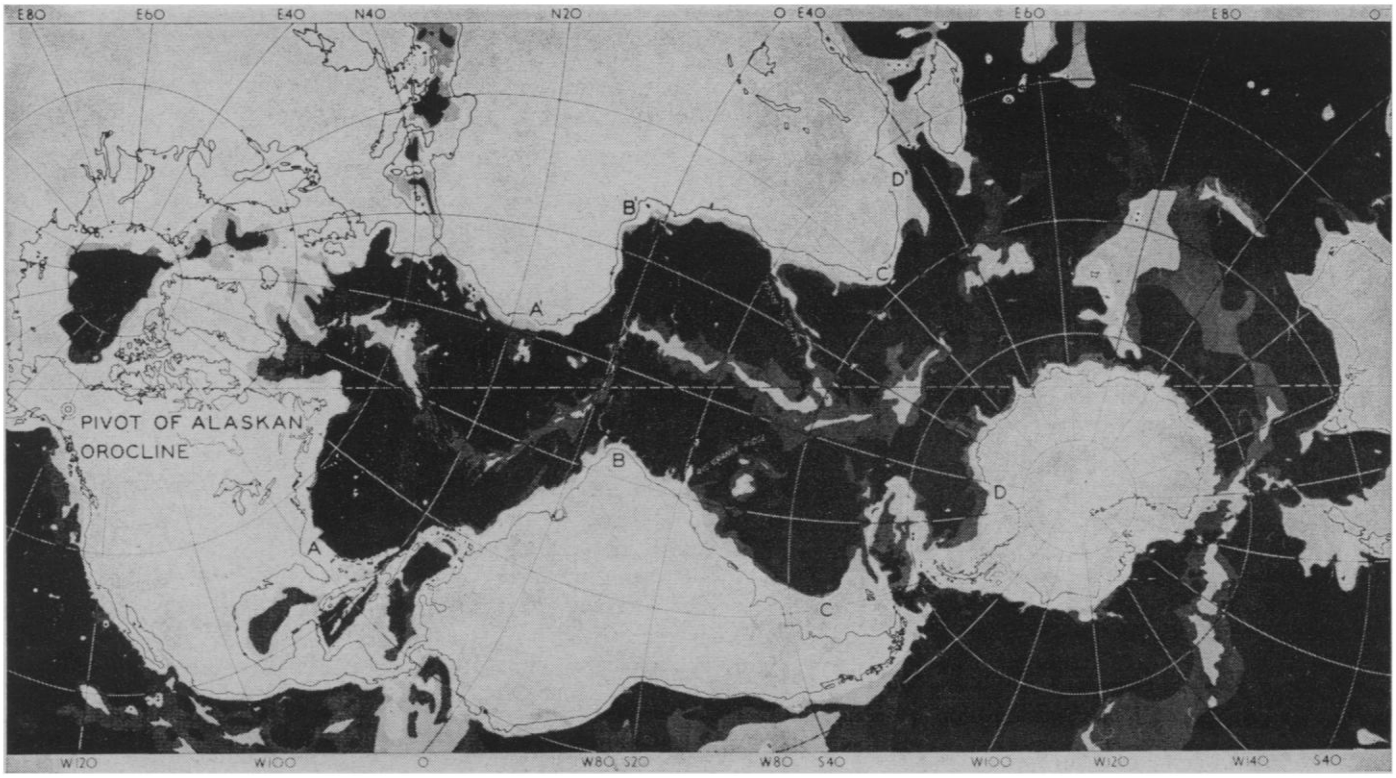

Fig. 2. The Atlantic Ocean, with the Mid-Atlantic Ridge dividing it down the middle. [After S. W. Carey (*19*)]

1 cubic kilometer per year has been suggested. Thus, the observed flow rate appears to be too small by an order of magnitude.

One way of estimating an upper limit for the average rate of extrusion is to assume that the total mass of the crust and water above the Mohorovičić discontinuity had its genesis in such extrusions. This total represents an average extrusion rate of 1.8 cubic kilometers per year, at a density of 3.3 grams per cubic centimeter. This is only one-fifth of what is needed.

The amount of material needed, in the form of magma intrusions, to fill tension cracks sufficiently to bring about the necessary expansion is much less. If we assume such cracks to be 10 kilometers deep, the amount of magma required is only 0.012 cubic kilometer per year.

On the ocean floor there is a global system of tension cracks which might be associated with a general expansion of the earth. However, what is needed is a sound reason for believing that they are associated with a gradual expansion of the earth. More probably they are caused by a slow convection of the earth's interior.

It is now well known, as a result of the work of the oceanographers, particularly of H. W. Menard of the Scripps Institution of Oceanography and of M. Ewing and his group, of the Lamont Geological Observatory, that there is a globe-girdling system of oceanic ridges of which the mid-Atlantic Ridge is a prime example. These ridges are characterized by large medial tension cracks running most of their length. Because of their global character, these could be cracks associated with a general expansion.

This mechanism for a general expansion was suggested some years ago by T. J. Wilson (*17*), B. C. Heezen (*18*), and me (*6*). However, the suggestion that the principal distributions of land masses could be accounted for by a gross expansion of an originally much smaller earth was made by S. W. Carey (*19*) and L. Egyed (*20*).

Carey pictures an earth that originally had a continental crust and only 40 percent of the present surface area. He visualizes the earth as having expanded to its present size during the past few hundred million years, the land masses having cracked apart, and the cracks having widened to form the ocean basins. This would account nicely for the presence of the mid-ocean ridges, but there are difficulties to which we shall come.

This picture of the formation of the continental land masses from the fragmentation of one or two supercontinents is actually much older; it goes back to the ideas of Richard Owen (1857), A. Wegener (1915), A. L. Du Toit (1937), and others. Wegener suggested that these continental fragments of an original "Pangaea" land moved to their present positions not as a result of the effects of an expanding earth but as "ships of sial floating upon a basaltic layer." The implied role of mariner was a bit too exotic for the American geologists, and these old ideas were largely ignored.

There is now a substantial body of knowledge which supports either or both of these ideas—the expanding earth and "continental drift." It was pointed out 47 years ago by Wegener that the continental margins of North and South America parallel those of Europe and Africa, giving the North and South Atlantic oceans an approximately constant width. This would not of itself suggest strongly that the Atlantic Ocean was formed as a gigantic rift valley. However, the fact that the Mid-Atlantic Ridge divides the Atlantic into an eastern and a western half by bisecting all arcs of constant latitude makes it likely that all three features are causally connected (see Figs. 2 and 3).

There are at least three possible explanations for this association.

1) The earth expanded by opening the Atlantic Ocean.

2) Convection of the interior of the young earth moved the crust about, producing, among other features, the Atlantic Ocean. Convection then ceased, leaving the continents in their present positions.

3) Convection of the earth's mantle is still continuing. The Atlantic Ocean is young, being only a few hundred million years old (*21*).

Of these three explanations, the most reasonable at the moment appears to be the last. The Atlantic Ocean appears to be young. This is supported somewhat by the apparent correspondence of some of the stratigraphic sequences on the two sides of the Atlantic; by the scanty sedimentary deposits on the ocean bottom; by the presence of wide, young, tension cracks along the Mid-Atlantic Ridge; by the high heat flow from the ridge, suggesting a rising column in the mantle; by the seismic activity along the ridge; and particularly by the paleomagnetic data, which suggest a close proximity of the Americas and Europe-Africa a couple of hundred million years ago.

The expanding earth is also a possible explanation, accounting in a reasonable way for the growth of the Atlantic. The big problem here is the magnitude of the expansion that would have been required to form the Atlantic in 200 million years. The expansion rate needed is 300 times as great as that given by Eq. 9. It has been suggested that a relatively small change in G could bring about a phase change and lead to a large change in the radius of the earth. Such a large change in radius, occurring at a rate of 1 part in 10^9 parts per year, can probably be excluded by evidence concerning the earth's rotation for the past 2000 years, for such a change in radius would decrease the earth's rotation rate by 2 parts in 10^9 per year. The observations suggest an uncompensated increase of less than 1 part in 10^{10} parts per year (*22*).

The problem posed by the Atlantic Ocean has been discussed in some detail. Actually there are many other features of the earth's surface which have a bearing on the problem of "continental drift" or "earth expansion," or both. Tension features such as the African rift valley, the Red Sea, and the Gulf of California are examples. The large lateral displacement along fault planes indicated by magnetic anomalies in the Pacific and the systems of island arcs and marginal trenches in the Pacific are indicative of the effects of mantle convection

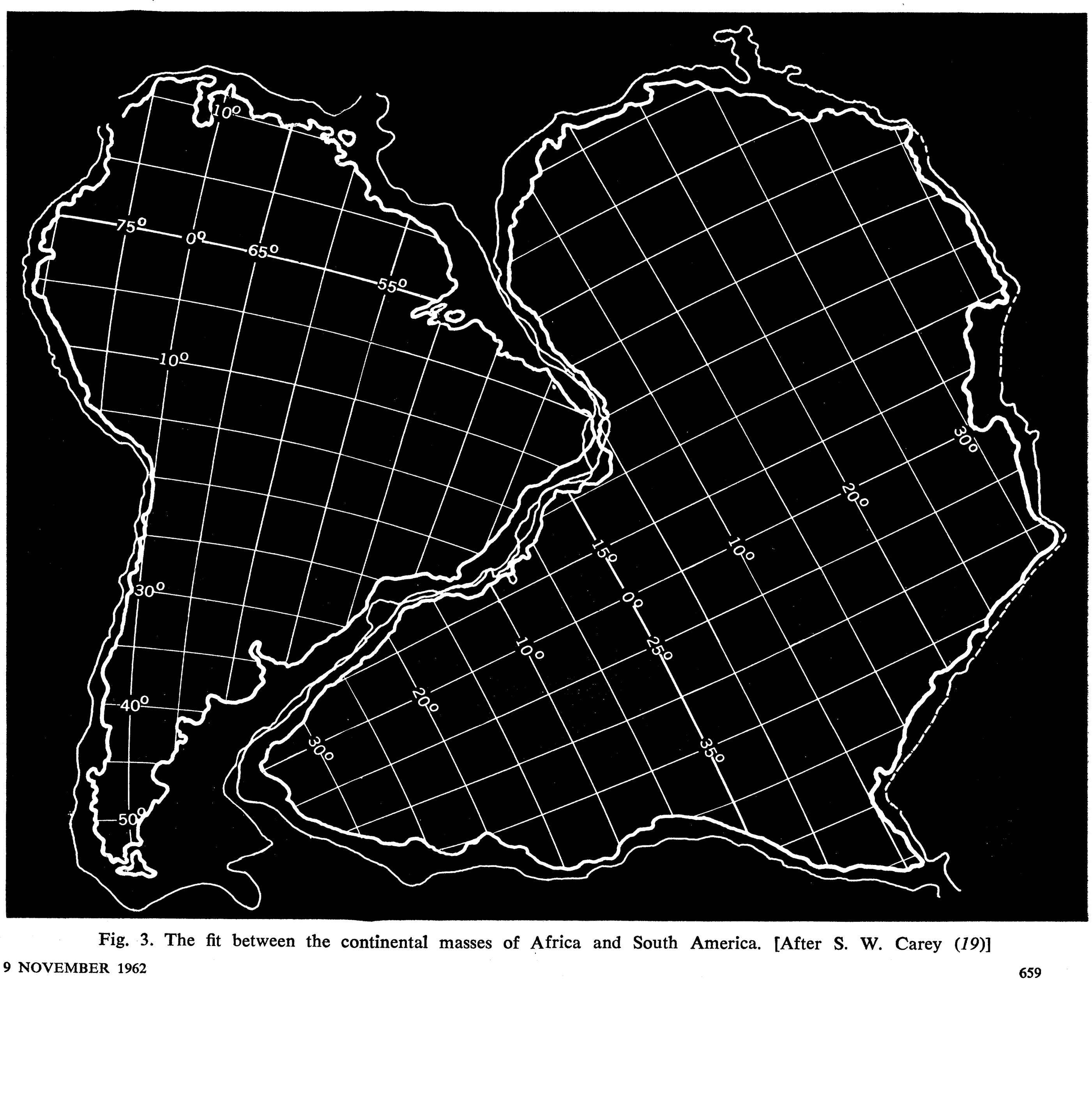

Fig. 3. The fit between the continental masses of Africa and South America. [After S. W. Carey (*19*)]

rather than of general expansion. Also, H. Hess (*23*) has suggested that the chains of guyots (discovered and investigated by him) are submerged islands which, with the atolls, mark old quiescent ridges which have subsided, suggesting convection rather than expansion.

While the evidence is not so strong as to present a clearly unambiguous story, the picture of an earth with a slowly convecting interior, gradually moving the continents, perhaps at a rate of 1 centimeter per year, is gradually unfolding. The resulting gross changes in the earth's surface are so great as to mask almost completely any effects of a slow expansion of the earth.

Let us consider briefly the expansion hypothesis as it relates to the moon. Here the expansion in radius to be expected as a result of a change in G of 10 percent in 4×10^9 years is only 0.15 kilometer. Such an expansion would presumably have taken place by the extrusion of magma, which might well cover 20 percent of the surface with basalt to a depth of 0.75 kilometer. It will be of interest to see some day if the maria are indeed basalt flows.

It has been suggested that the maria of the moon are seas of dust. There are two facts which make this unlikely. First, a number of craters without apparent cracks in the walls are filled inside and outside to the same level. Dust would not be expected to establish hydrostatic equilibrium under these conditions. Second, basins in the uplands are not filled with this "dust." Dust there probably is, but I would guess that it is only a thin layer.

It should be noted that there is no evidence of a "mantle convection" in the moon. Fault scraps are very rare on the moon, and there is no evidence of the large lateral displacements so common on the earth. Such a displacement of a fault plane cutting a crater would be very easily detected.

In summary, the evidence on the earth's surface favors "continental drift," with mantle convection as the driving mechanism. The miniscule effects of a modest expansion would be lost in the magnificent displays produced by convection. On the moon, however, the effects of a general expansion may be more readily apparent, for convection appears to be lacking. Expansion could lead to massive lava flows, perhaps in the form of fissure eruptions.

The Earth's Interior

The problem posed by the effects of decreasing gravitation on the earth's interior, particularly in relation to heat flow, have been discussed by C. T. Murphy and me (*16*). Here one is particularly hampered by lack of intimate knowledge of the earth's interior. Most of what we know is derived in an indirect, and often roundabout, way from observations at the earth's surface. The strength of the earth's magnetic field and its variations with time, variations in the earth's potential, gravity anomalies, and heat-flow measurements all help describe the interior, but the best source of information has been seismic waves. These have told us about the basic structure of the interior, about density distribution and pressure, about the liquid core and the solid inner core. Unfortunately, we know little about the temperature distribution in the interior.

Deep in the earth's interior there is a liquid core, of radius 3500 kilometers, probably containing a solid inner core of radius 1400 kilometers. Outside this is the earth's mantle, extending to the crust, which is only 5 kilometers thick under the oceans and about 35 kilometers thick under the continents. The mantle appears to be essentially uniform in character, with only slow changes in density (and sound velocity), associated with changes in pressure, and temperature changes, as a function of depth.

Since the mantle of the earth is assumed to be essentially homogeneous chemically, a sample would be of the greatest importance, for two-thirds of the earth is mantle. It has been pointed out by H. Hess (*24*) that there are several fairly obvious places to look for bits of the mantle and that at these sites an interesting and rather uncommon rock appears.

A volcano seems to have its roots deep in the earth. In particular, the oceanic crust is so thin that a volcano here would be expected to derive its lava below the Mohorovičić discontinuity. The lava of these volcanos, like that of most continental volcanos, is composed of basalt, a material which may be presumed to be a low-melting-point component of the mantle. It might be expected that the lava would occasionally carry to the surface blocks of the raw, unmodified mantle itself. Foreign bodies (xenoliths) are found in volcanic lava, and one of these, peridotite, is the prime suspect in the search for the true mantle. This dense, dark, basic rock occurs in basaltic lavas from all over the world, from both continental and oceanic volcanos. Continental volcanos show other types of xenoliths as well, but this would be expected in view of the enormous thickness of crust to be penetrated.

From the discussion of the significance of the Mid-Atlantic Ridge and the rapid heat flow found there, if the general picture of mantle convection is correct one would expect a predominance of basalt on the crest of the ridge, with the possibility of undifferentiated mantle protruding in places. It is notable, as Hess (*24*) pointed out, that St. Paul's Rock in the Atlantic is an enormous protrusion from the Mid-Atlantic Ridge of this same type of rock, essentially identical in composition, except for hydration, with samples yielded by volcanos from all over the world.

Finally, one would think that a steep escarpment on the ocean floor, where the crust is thin, might expose the mantle. This same type of rock has been dredged from the face of such an escarpment under the Atlantic. A hydrated form of this same rock, peridotite, has been found.

Peridotite is a relatively uncommon rock. Classified as igneous, it has a density and a sound velocity essentially the same as those of the mantle. It is the most likely candidate in the search for the true mantle.

For the purpose of this discussion, the most important property of the mantle is its radioactivity, primarily from potassium and traces of uranium and thorium. It is convenient to express these concentrations in terms of the equivalent concentration in chondritic meteorites, for there are reasons to believe that, except for hydrogen and the noble gases, chondritic meteorites pretty well reflect the primordial abundances of the elements.

If a sample of peridotite represents a piece of the mantle, as we are assuming, analysis of the sample for radioactive elements will give us important data. St. Paul's Rock may be more representative of the mantle than a xenolith would be, for the xenolith must have been in contact with hot magma for a considerable period of time. Relative to chondritic meteorites, a sample from St. Paul's Rock was found (*25*) to be deficient in potassium by a factor of 0.1. Peridotite in general is known to have a very low abundance of thorium and uranium, though the data are scanty. No thorium or uranium was obtained in the analysis of St. Paul's Rock.

Radioactive elements might be expected to occur in the core and crust of the earth as well as in the mantle. Direct observation of the core is impossible. If we assume that the core is composed of metallic iron and nickel, we would not expect it to contain the chemically active elements thorium and uranium—elements which would combine with the silicates of the mantle. This conclusion is supported by the virtual absence of these elements among the metallic components of meteorites.

MacDonald (*26*) has discussed carefully what is known about radioactivity in the earth's crust. It is of interest that the amounts of uranium and thorium in the crust appear to be from 40 to 80 percent of the amounts expected for the whole earth, if the earth is of chondritic composition. However, the potassium content of the crust is only 17 percent of the expected total for a chondritic earth. Apparently the earth is deficient in potassium, on the basis of the assumptions; the abundance is 0.3 that expected for a chondritic earth.

It is important to note that the uranium and thorium are concentrated mainly in the continental crust, the unit-area concentration being 10 times higher on the continents than under the seas. Similarly, the unit-area concentration of potassium is twice as high on the continents as under the seas.

These results concerning the distribution of heat-producing elements are given in Table 1.

On the basis of these assumed abundances, the present rates of heat production per unit of surface area can be calculated; they are given in Table 2 (row 5). It should be noted that, in the case of continental surfaces, the observed heat flow agrees well with the computed total.

While infrared transfer of heat is probably the dominant means of transfer in the lower mantle, apparently this is less important than thermal conductivity in the upper mantle. The depth of heat penetration is given by the expression $(K/\omega\rho c)^{1/2}$, which for a thermal conductivity of $K = 0.03$ joule per centimeter per second, specific heat of $c = 1.3$ joules per gram, and density of $\rho = 4$ grams per cubic centimeter, gives, for a period of $T = 2\pi/\omega = 4.10^9$ years, a heat diffusion distance of 100 kilometers. It is apparent that with a heat conductivity as low as this, or even with a conductivity greater by an order of magnitude, convection is needed to transfer heat from the interior of the earth to the surface. It may be noted that, by subtracting the contribution of the mantle, one obtains a calculated heat flow (Table 2) for the continents of 33 to 57 ergs per square centimeter per second.

Table 1. Mass of heat-producing elements.

Layer	Uranium (10^{19} g)	Thorium (10^{19} g)	Potassium (10^{23} g)
Oceanic crust	0.3–0.6	1.2– 3.1	3.5– 3.8
Continental crust	2.5–4.6	7.7–17	4.6
Mantle			5.3
Total	2.8–5.2	8.9–20.1	13.4–13.7
Expected total (chondritic)	6.6	26.0	48.0

Apparently, it is reasonable to assume, for the chondritic earth model, a distribution of the assumed total uranium and thorium as follows; in the continental crust, 65 percent; in the oceanic crust, 7 percent; in the mantle, or missing, 27 percent.

The continental crust is sufficiently thin for the heat produced there to reach the surface by conduction. However, the large value for heat flow through the ocean floor is something of a mystery. If the foregoing assumptions concerning the distribution of radioactivity are correct, this heat cannot arise in the oceanic crust but must have its origin deep in the mantle. However, convection is required to remove the heat from deep within the earth's interior.

Some of the evidence for mantle convection has already been discussed. It should be noted here that these observations suggest that there are rising mantle currents under the mid-ocean ridges and falling currents under the continents or continental margins. Thus, such currents would be transferring heat to the oceanic surfaces in areas where the observed values are substantially in excess of the computed flux from the crust.

Table 2. Heat production per unit surface area.

Source	Oceanic surface (erg/cm² sec)	Continental surface (erg/cm² sec)
Uranium in crust	1– 2	14–25
Thorium in crust	1– 2	11–24
Potassium in crust	4	8
Potassium in mantle	4	4
Total	10–12	37–61
Observed (average)	50	50

The source of this heat, transported by convection, is another question. Presumably either this heat must be produced in the mantle or core by radioactivity or the earth's interior must be cooling off, perhaps with the release of heat of crystallization. If, instead of being relatively steady, the convection should be impulsive, occurring periodically for relatively short periods, the heat from radioactive elements would be stored for perhaps many tens of millions of years before being transported to the surface. Since there is no evidence of a violent upheaval of the earth in the past, I will assume here that convection has been at a relatively steady rate.

The physical conditions to be satisfied in order for convection to occur in this manner are somewhat different from the usual conditions for convective transport in a fluid. Usually one expects to find an adiabatic temperature gradient if convection occurs, a slight excess gradient being sufficient to provide an adequate heat flux. In this case, however, the adiabatic temperature curve for the mantle lies well below the melting-point curve, and one is dealing with a solid rather than a liquid. While a solid can flow as a liquid at temperatures well below its melting point, its Newtonian viscosity would be expected to be too high for Newtonian flow to be important. Rather, the mantle would be expected to flow only if a finite yield stress is exceeded. This yield stress is a sensitive function of temperature, increasing as the difference between temperature and melting temperature increases. It is reasonable to assume, therefore, that the condition for a quasi-steady convective heat transport from the mantle is that the temperature curve should lie close enough to the melting-point curve to cause the mantle to be mechanically weak, permitting convection with small stress differences. If this condition were not satisfied, the resulting large yield stress would be expected to freeze convection until large stress differences developed, if they did. However, the relief of these large stresses after the yield stress is exceeded would result in the production of a large amount of heat along the flow surfaces, resulting in the reduction of the yield stress. It seems likely that the earth would be unstable under these conditions and that impulsive and catastrophic convection of the mantle would result. Large blocks of the mantle might be expected to turn over in a very short time (geologically speaking).

The condition that the mantle temperature be only slightly less than the melting point need not hold near the surface, where heat can be transported by conduction, nor need it hold at the bottom of the mantle, where radiation transport may suffice.

It is difficult to formulate the details of the convective process, particularly to find a model for which convection could occur without the basic instability of the system resulting in a rapid overturn of the whole mantle. However, for purposes of calculating heat flow we can by-pass the great complications of this complex problem by making use of a simpleminded, almost "thermodynamic" argument to calculate the rate of flow of heat, as follows: If it is assumed that the convective transport is steady and that the temperature of much of the mantle must therefore lie below, but near, the melting point, heat loss is at that rate which will keep the temperature near the melting point. This carries the following implications: If the melting-point curve is fixed because of a fixed gravitational constant, the rate of heat loss is equal to the present total generation of heat in the interior. If gravitation is growing weaker, and internal pressure is decreasing, there is an additional heat loss having its origin in a cooling of the interior because of a decreasing melting temperature.

If we assume that all the internally produced heat is carried by convection to the oceanic crust, the contribution from the mantle, per unit surface area, is given by the value in Table 2 increased by a factor of 5/3, the ratio of the surface area of the earth to that of the oceanic crust. This represents a contribution from the mantle of 7 ergs per square centimeter per second, or a total of 13 to 15 ergs per square centimeter per second. This is to be compared with an observed average flux of 50 ergs per square centimeter per second. The agreement is not particularly good.

The argument can be improved somewhat by adding the heat that has its origin in a cooling interior, as a result of weakening gravitation. The mechanism has just been discussed. As the gravitational "constant" decreases, the pressure and melting point of the lower mantle decrease. The temperature of the mantle follows the melting point, resulting in heat transport to the oceanic crust. Assuming 3 parts in 10^{11} per year as the rate of decrease of G, Murphy and I (*16*) have computed that this mechanism should yield 15 ergs per square centimeter per second, a value which should be added to that for heat having its origin in internal radioactivity. This gives a total of 28 to 30 ergs per square centimeter per second.

No allowance was made for heat due to uranium and thorium in the mantle. Assuming a content of uranium and thorium in the continental crust necessary (together with the potassium) to provide the observed heat flow and assuming the same abundances of these elements that are found in the chondritic meteorites, we find that the uranium and thorium in the mantle and oceanic crust would yield a heat flow through the oceanic crust of about 4½ ergs per square centimeter per second for uranium and for thorium, or a total of 9 ergs per square centimeter per second. Adding the mantle contribution to the total heat flow from the oceanic floor gives 37 to 39 ergs per square centimeter per second, a value which agrees fairly well with the observed values. It is doubtful that the heat-flow observations on the ocean floor represent a proper statistical sample, and the final discrepancy is probably not significant. If we assume the true mean heat flow from the ocean floor to be only 35 ergs per square centimeter per second, the effect of a decreasing gravitational constant represents almost half the total.

It must be emphasized that the foregoing discussion has a strong conjectural element; it cannot be otherwise until we know much more than we now do about the composition of the earth and its internal temperature distribution.

The Earth's Magnetic Field

While the details of the mechanism may not be completely clear, it is now generally agreed that the earth's magnetic field is generated in the earth's liquid core through a dynamo action driven by convection in the core (*29*). As an adiabatic temperature gradient is necessary for convection, the minimum necessary heat flow from the core is given by the thermal conduction with an adiabatic temperature gradient. This heat flow is computed at 1.5 to 4.0×10^{19} ergs per second, depending upon the thermal conductivity and adiabatic gradient assumed for the core (*16*). The heat required to drive the core as a heat engine to produce the magnetic field has been estimated by Verhoogen (*27*) as less than 8×10^{18} ergs per second. The total required heat flow may be taken to be 2 to 5×10^{19} ergs per second.

If the assumption of an iron-nickel core of meteoritic composition is correct, radioactivity can provide only about 5×10^{16} ergs per second—an amount completely negligible.

The densities of the inner and outer core derived from seismic observations suggest that the inner core is an iron-nickel solid phase obtained through the solidification of the outer core. Urey (*30*) has suggested that the heat of fusion released by the gradual growth of the inner core may be the source of heat required to drive the convection. The continuous release of heat from a growing core requires a gradual reduction in temperature. As a result, thermal heat is also released by the whole core. An analysis of the thermal and pressure balance indicates that these two contributions to the heat flow from the core are roughly equal and require a rate of temperature decrease, at the core boundary, of 0.7 to 1.9×10^{-15} degree Kelvin per second if 4×10^{19} ergs per second are to be released to the mantle by the core (*16*).

If the temperature at the base of the mantle is assumed to lie near the melting point, the rate of change of this temperature as a result of decrease in the "constant" of gravitation can be computed from Uffen's (*28*) melting-point curves. These give the result that the rate of change of temperature of the core boundary (when a fractional rate of decrease for G $3/10^{11}$ per year is assumed) lies in the range 2 to 4×10^{-15} degree Kelvin per second (*16*).

If radiative heat transfer is sufficiently effective at great depths in the mantle, the temperature may follow the variation of melting point at the intermediate depth of 1500 kilometers. In this case the rate of decrease of the temperature of the core boundary is 1.5 to 3×10^{-15} degree Kelvin per second.

This rate of decrease is slightly greater than is needed to maintain an adiabatic temperature gradient in the core. Thus, a decreasing gravitational constant would be expected to produce core convection, and the production of a magnetic field becomes a possibility.

Without a decreasing gravitational "constant," there are difficulties. Without the convective mechanism active in the mantle, the lower mantle, because of its radioactivity, would be expected to warm up rather than cool off. This is a common feature of all the conductive models computed by MacDonald (*26*). However, with a steadily convecting mantle, the temperature of most of the mantle should stabilize near the melting point, and this should produce an essentially constant temperature in the core.

One possible, but unlikely, mechanism for convection in the core is based on the assumption that the core was initially much hotter than the lower mantle. It could still be cooling off rapidly enough to provide the necessary heat transfer. In order for this to be feasible, it must be assumed that heat is transported by conduction in the lower mantle, for convective transport would quickly bleed off the excess heat until the temperature of the core fell to the value demanded by the previously stated condition for convection.

If transport of heat in the lower mantle is conductive, it is easy to compute an approximate value for the initial excess temperature of the core that would be needed to allow heat leakage at the right rate after 4×10^9 years.

The rate of flow of heat from the core, S, after a time t is given by the approximate expression

$$S \simeq 2\pi r_c^2 \, (K\rho c/t)^{1/2} \, \Delta T \qquad (10)$$

where K, ρ, and c are the heat conductivity, density, and specific heat, respectively, of the mantle, ΔT is the initial temperature difference between the core and the mantle, and r_c is the core radius. Assuming the high value of thermal conductivity $K = 0.5$ joule per centimeter per second per degree, $c = 1.3$ joules per gram per degree Celsius, $\rho = 5$ grams per cubic centimeter, $S = 4.10^{12}$ joules per second, and $t = 10^{17}$ seconds gives a temperature difference ΔT of 1000°K. For the more moderate thermal conductivity of 0.1 joule per centimeter per second, the required temperature difference is 2200°K. It should be emphasized that this expression neglects the warming effect of the radioactivity of the mantle. To include this effect these temperature differences must be increased.

There is no obvious reason for such a large initial temperature difference, and it is concluded that if the assumed compositions of the core and mantle are correct and convection of the lower mantle does not occur, or occurs in a continuous manner, none of the obvious ways of obtaining enough heat from the core are adequate. However, the heat flow accompanying decreasing internal pressure does appear to suffice.

Surface Temperature of the Earth

It is supposed that the luminosity of the sun varies with the value of the gravitational constant, very probably being proportional to its 7th or 8th power (*6, 7*); when the sun was hotter, in the past, the earth's surface must have been warmer, and it is interesting to investigate this time dependence (*14*).

The simplest assumption is that the mean temperature of the earth's surface is proportional to the 4th root of the solar radiation flux at the earth's surface. Thus, the absolute temperature should vary as $G^{2.5}$. There is an extra factor $G^{1/2}$, because the radius of the earth's orbit varies at G^{-1}. Using the variation of G with time that is given in Fig. 1 and assuming the present age of the universe to be 8.0×10^9 years, we obtain the simplified measure of the mean surface temperature of the earth that is plotted in Fig. 4.

Three effects were neglected in computing the curve of Fig. 4. Because of the effects of stellar evolution, the sun brightens as the hydrogen in its core is depleted. This effect was neglected. Also, the effect on the radiation balance of the earth of a varying water-vapor content was neglected. According to Opik (*31*), because of this variation the rate of heat transfer from the

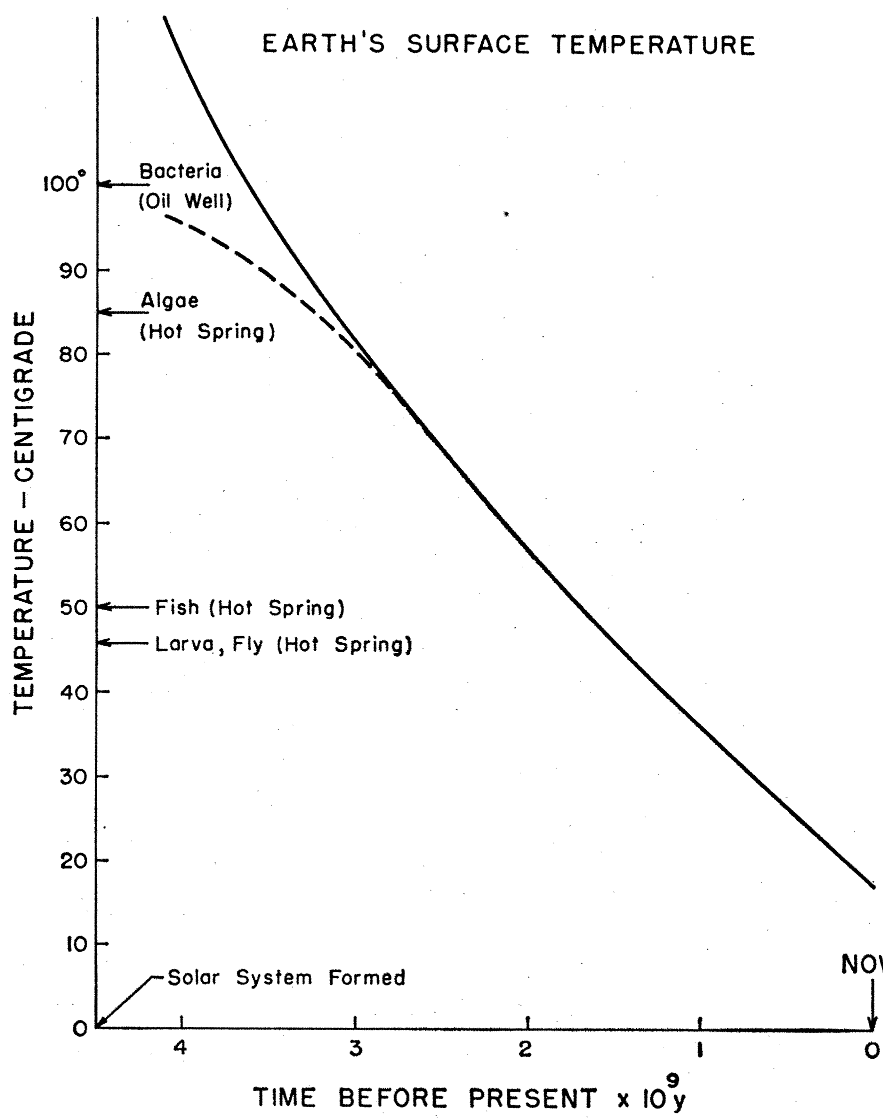

Fig. 4. The mean temperature of the earth in the past.

earth varies as the 3.65th power of the surface temperature rather than as the 4th power. These two effects tend to cancel each other, and the curve in Fig. 4 is still applicable.

The third effect is probably more important. Should the surface temperature of the earth rise so high that the atmosphere was mostly water vapor, the convective mechanism of the atmosphere would be expected to change in such a way as to increase the earth's albedo, decreasing its temperature.

With the present atmosphere one would expect, and there is observed, a cloud cover of roughly 50 percent associated with the 50 percent of the surface that is occupied by rising air currents. However, with a water-vapor atmosphere, the cloud cover could be nearly complete, for rising water vapor could occur on most of the sunlit side of the earth, the water returning to the earth's surface as rain. The dashed curve in Fig. 4 represents the temperature corrected for this effect. The correction is based on the assumption that the earth's albedo rises to 0.55 when the surface temperature of the earth is 100°C.

The biological conditions essential for life apparently can be satisfied at these elevated temperatures (*14*). The oldest extensive fossil evidence of life that we have is provided by the ancient algal reefs, some of which are over 10^9 years old. Apparently algae could have lived 3×10^9 years ago without violation of any conditions imposed by temperature requirements.

However, ancient glaciation may present a problem. Certainly it is difficult to believe that glaciation could have occurred 2.5×10^9 years ago with the mean temperature as high as 70°C. If completely reliable evidence for glaciation as long ago as this should be found—evidence that included glacial boulders and striated pavements as well as tillites—one would have to conclude that these high temperatures did not occur. The existence of an apparent tillite deposit by itself is probably not a positive indication of glaciation, as similar appearing conglomerates could be produced by other means.

The calculated temperature rise 6×10^8 years ago was so modest that glaciation at that time probably cannot be excluded.

It must be emphasized that the foregoing discussion cannot be marshaled as evidence for a gradual decrease in the gravitational constant. The earth is much too complex a system to be considered a reliable source of information to establish a physical theory. However, it is clear that the implications for the earth sciences of a gradually weakening gravitational interaction are far from trivial. The problems of the earth's magnetic field, heat flow, and expansion are all seriously affected. Even the biological sciences would be affected, for a high-temperature origin of life would be indicated under these conditions. What is badly needed to raise the discussion above the level of conjecture is a good demonstration that the gravitational constant has indeed been slowly decreasing (*32*).

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