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Does gravity change with time?

Highly regarded theories hold that the gravitational "constant" should decrease with time. To date no observations have refuted this prediction and some offer positive evidence supporting it.

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The Newtonian gravitational parameter G is a constant in both Newton's law of gravitation (force $= -GM_1M_2/r^2_{12}$) and Einstein's general theory of relativity. However, over the last fifty years there have been numerous suggestions that G might in fact change with time. The detailed grounds for these suggestions have differed, but most variable-G theories account for gravitation on a cosmological basis. As such, they usually involve a time-dependent G: $G = G(t)$, where t is a parameter that can, loosely speaking, be interpreted as the "age" of the Universe. A value of G that depends on time is a drastic departure from the established physics of gravitation (based on Newton's and Einstein's theories). Before looking at G-variability in detail it is therefore logical to ask first: Why should G vary?

The cosmological coincidence. As regards theory, the main reason for expecting that G might vary with time is a cosmological coincidence between two enormous numbers. Several unexplained coincidences between numbers crop up in cosmology.[1] The most discussed such coincidence has been assumed by P. A. M. Dirac, among others, to be not just a chance effect but a result of some underlying law of physics.

Dirac[2] noticed that the ratio of electrical ($e^2/4\pi\epsilon_0 r^2$) to gravitational ($Gm_p m_e/r^2$) force between the proton (mass m_p) and electron (mass m_e) in a hydrogen atom is a large number of order 10^{10}: $e^2/4\pi\epsilon_0 Gm_p m_e \approx 10^{40}$ (e is the electron charge and ϵ_0 is the permittivity of free space). Similarly, the ratio of the present age of the Universe $t \cong 2\times10^{10}$ yr to the atomic unit of time ($e^2/4\pi\epsilon_0 m_e c^3$) is of roughly the same size. Dirac suggested [in what is known as his large-numbers hypothesis (LNH)] that the two numbers are in fact equal:

$$\frac{e^2}{4\pi\epsilon_0 Gm_p m_e} \approx 10^{40} \approx \frac{4\pi\epsilon_0 m_e c^3 t}{e^2} \quad (1)$$

Assuming that the atomic parameters do not vary with time, the last equation says that

$$G \propto \frac{1}{t} \quad (2)$$

which leads one to expect that $\dot{G}/G \cong -6\times10^{-11}\ \mathrm{yr}^{-1}$ in the present epoch. This derivation of a changing G as judged by clocks keeping (atomic) t-time is a direct result of the LNH, which says that the two numbers in equation 1 should be equal, and (in generalized form) that dimensionless numbers of size 10^{40n} should vary with the epoch of the Universe t as t^n.

The simple line of reasoning that leads to equation 2 is still the most compelling theoretical reason for believing that G should vary with time. As noted, it predicts $\dot{G}/G \cong -6\times10^{-11}\ \mathrm{yr}^{-1}$.

Observations. As regards observation, the main areas of physics from which information on G-variability can be obtained are astrophysics and geophysics (because gravity dominates over other forces of physics on the large scale). It should be stated right off the bat that these subjects provide us in most cases with only *limits* on $\dot{G}/G$. That is, there is no direct *proof* as yet from these disciplines that G varies.

Predictions of how fast G varies and what effects this has in astrophysics and geophysics depend on which of the variable-G theories one uses. We will review the three main variable-G theories, and examine in detail how these theories affect astrophysics and geophysics. No observations available at this time rule out the possibility that one of the theories we will discuss below is correct.

Astrophysics provides us with examples of systems that must be seriously affected if G varies, simply because they are gravitationally bound. Systems which are of interest are stars like the Sun (figure 1); star clusters like Messier 67 (figure 2); galaxies like the Milky Way and the Whirlpool Nebula (figure 3); clusters of galaxies like the one in the constellation Hercules; and perhaps superclusters. The physics involved in testing variable-G theories with systems like these is discussed below. But we can state now that data from all such astrophysical systems yield only the limit $[\dot{G}/G] \lesssim 10^{-11} - 10^{-10}\ \mathrm{yr}^{-1}$. The rate predicted by Dirac's theory falls at the center of this range.

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The Sun. It is a sphere of burning hydrogen held together by its own gravity. If G varies, the Sun's size, internal properties and luminosity will also vary. Figure 1

Star cluster Massier 67. The stars group together because of their mutual gravitational attraction. If G varies, the compactness of the cluster will also vary. Figure 2

The Whirlpool Nebula (Messier 51 or NGC 5194) is a spiral galaxy consisting of stars and gas bound by gravity in the form of a disk. If G varies, the galaxy's form will also vary. Figure 3

Geophysics is a rather more complicated subject than astrophysics for the purpose of testing whether G varies, but here again, one finds that only limits of order $[\dot{G}/G] \lesssim 10^{-11} - 10^{-10}$ yr^{-1} can be set. However, we shall see that geophysics provides us with a unique positive indication of a changing G and also hints that other processes predicted by variable-G theories may be active in the Earth.

We can now answer the question "Why should G vary?" Theoretically, we expect it to vary because of the cosmological coincidence. Observationally, there is no evidence that rules out variability. Thus we are justified in taking variable-G gravitation seriously.

Variable-G theories

Numerous theories have been proposed in which the Newtonian gravitational parameter G varies, but progress in astrophysics and geophysics has winnowed out the field somewhat, so that today there remain only three main competitors: (a) Dirac's theory[2,3]; (b) the theory of Fred Hoyle and Jayant V. Narlikar[4]; and (c) the scale-covariant theory of Vittorio Canuto *et al.*[5] In former years, much effort was expended on testing the consequences of the Brans–Dicke scalar–tensor theory,[1] but research in solar physics has shown that even if the theory is correct, it does not differ significantly from Einstein's general relativity in its consequences. This leaves the three theories (a), (b) and (c) as the main contenders for a possible new theory of gravitation that might replace Einstein's theory.

Dirac's theory has as its basis the Large Numbers Hypothesis outlined in simple form above. The simple account of G-variability expressed in equation 1 has been considerably extended by Dirac[2] and others using a reformulation of a theory originally due to Hermann Weyl. This is a theory of the background structure of the Universe that describes its geometrical properties mainly in terms of a gauge function β (fixes the ratio of gravitational units and electromagnetic units). Weyl's theory as applied to Dirac's idea shows that β is closely connected with the question of whether the cosmological constant Λ is zero or non-zero. The cosmological constant, which is familiar from Einstein's theory, describes a force that pushes matter apart if Λ is positive and draws it together (like gravity) if Λ is negative. Observations of the effects of the Λ-force only show that Λ is small in the actual Universe, but not that it is zero, although it may be.

The Dirac theory as it is based on the LNH is characterized by two natural gauges, one in which $\Lambda = 0$, while in the other, Λ is finite. The LNH and the field equations of the theory in both gauges imply continuous creation of matter—additive creation (zero-Λ gauge) or multiplicative creation (finite-Λ gauge). In the first instance, continuous creation occurs at the same rate everywhere in the Universe. In the second, matter is created where matter is already most dense, which means that all dense bodies (such as planets and stars) increase in mass with time.

Most astrophysical tests of Dirac's theory have shown more or less conflict with the additive-creation model and agreement (or at least lack of conflict) with the multiplicative-creation model.[1,6] Physically, the main consequence of the additive model is that $G \propto t^{-1}$; the continuous-creation process does not significantly affect the masses of astronomical bodies, because most of the new matter is created in interstellar space. Many astrophysical systems would be seriously and noticeably affected by such a decrease in G with time uncompensated by increased masses. In the multiplicative model the increase in masses due to continuous creation tends to compensate for the decrease in G and the effects of this version of Dirac's theory in the processes involved on the Earth, stars and star clusters, galaxies and clusters of galaxies do not, in general, contradict observation. There exist, in fact, only two problems that have prevented this theory from being in complete agreement with observation. The first involves the Sun's luminosity and the temperature of the Earth in the past. The other has to do with the relic radiation from the big-bang fireball.

The first problem is a knotty one, and is connected with the question of whether G *and/or* masses change with time. If M_* is the mass of a body like a star, then an examination of the physics of gravitating systems shows that G

and M_* always occur together, as long as we are talking only about gravitational phenomena. Thus GM_* is the important parameter. Canuto and his coworkers have shown that in astrophysical problems such as those to do with the Sun's structure, for example, there is an important constraint—$GM_* = \text{constant}$.[7] Many researchers have overlooked this. Among other things, it means that a famous result of Edward Teller, that the luminosity of a star varies like $L \propto G^7 M_*{}^5$ is wrong. This relation implies a very strong variation of the Sun's luminosity both with G and M_*, and has long acted as a damper on theories with variable G and variable masses: the Earth's temperature would have been either too high or too low in the past to be compatible with geological data for most dependences of G and M_* on time. The constraint $GM_* = \text{constant}$ leads to the new result $L \cong \text{constant}$. There is still another factor to be taken into account before the Earth's temperature in the past can be worked out, and that is the change in the Earth–Sun distance with time due to changes in G and/or the masses. When this factor is included, calculations of the past temperature of the Earth agree with geological data. Thus a problem that has long plagued variable-G cosmology seems to have been solved.

The second problem that has troubled Dirac theory involves the big-bang relic or 3K microwave background radiation. The 3K background is a very uniform radiation field with a black-body spectrum that appears to pervade all of space. It is conventionally believed to be the cooled-down remnant of the big-bang origin of the Universe. Cosmologists have worried for some years that Dirac's theory does not appear to have a natural explanation for the black-body form of this field that is compatible with what is known about the distances of very remote astronomical sources such as quasars. The most serious aspect of this problem is that in Dirac's theory the continuous creation process (of whatever form) is expected to add photons to the 3K-microwave background as well as produce massive particles (like protons). Some calculations[6] appeared to show that the continuous-creation process would not lead to or preserve the black-body spectrum of the cosmological radiation field, as observed in the actual Universe. However, these calculations were later found to be inapplicable; Canuto and his co-workers[8] have since shown that the 3K-radiation field poses no obstacle to Dirac's theory.

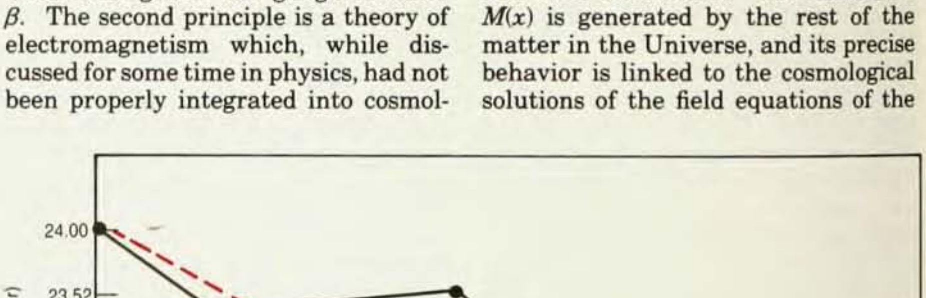
Thus the two major stumbling blocks for the Dirac theory can be circumvented. We conclude that the theory by and large agrees with observation.

Hoyle and Narlikar's theory[4] is based on different principles than Dirac's, although the two theories have important technical aspects in common. A similar situation holds for the theory of Canuto *et al.* (to be examined below). Hence we will restrict our discussion of these two theories to those aspects that differ significantly from Dirac's theory.

The two main principles on which the Hoyle–Narlikar theory is based are conformal invariance and the absorber theory of radiation. The first leads to a technical similarity with Dirac's theory: the laws of Nature are invariant under changes in the gauge function β. The second principle is a theory of electromagnetism which, while discussed for some time in physics, had not been properly integrated into cosmology prior to the formulation of the Hoyle–Narlikar theory.

The two main principles underlying the Hoyle–Narlikar theory have profound implications for astrophysics and geophysics.[1] The most notable consequence concerns the variations in the masses of elementary particles, and in particular of the electron mass m_e, predicted by the theory. The behavior of the mass is assumed to be given in terms of mass field $M(x)$, so that $m_e = \epsilon M(x)$ where ϵ is a dimensionless parameter and x represents the space and time coordinates. The mass field $M(x)$ is generated by the rest of the matter in the Universe, and its precise behavior is linked to the cosmological solutions of the field equations of the

Phobos, one of the moons of Mars. If G varies, the orbit of Phobos around Mars will also vary. By landing an accurate clock on Phobos and monitoring the clock in conjunction with data on the distance of Phobos from Mars, it might be possible to detect the change of G. Figure 4



Change in the length of the day over the last 360 million years from observations of growth lines in coral fossils. Figure 5 theory. *Spatial* fluctuations in the mass field cause anomalous, gravitational redshifts, and in fact the evidence that had been adduced for the presence of non-Doppler redshifts in astronomical sources such as quasars represented the original motivation for proposing the Hoyle–Narlikar theory. However, the case for non-Doppler redshifts is now much weaker than it was at the time the mass-field theory was proposed in 1971.[6]

In other directions, the Hoyle–Narlikar theory has recently gained ground; one of the old objections to the theory has been shown to be incorrect. The main reason many cosmologists had tended to discard the theory was that it appeared to conflict with data on the luminosities of stars and galaxies.[9] Like the Dirac theory, the Hoyle–Narlikar theory predicts a decrease in G with time and continuous creation of matter (although the physical reason for these processes in the latter theory is not as readily understandable as in the former). The form of the Hoyle–Narlikar theory in which $G \propto t^{-1}$ predicts that $\dot{G}/G \cong \times 10^{-10}$ yr^{-1}. With such a high rate of change in G, the Teller relation $L \propto G^7 M_*$[5] leads to the inference that stars and the galaxies composed of them would have been considerably brighter in the past. Studies of galaxies so remote that we are now viewing their early stages in history show that galaxies were *not* considerably brighter in the past. This conflict long appeared as a serious drawback to the Hoyle–Narlikar theory. But recent research[10] that uses the constraint $GM_* =$ constant mentioned above has shown that this old objection to the Hoyle–Narlikar theory falls away.

The theory is in agreement with other astrophysical data also.[10] But we recall that the case for the existence of non-Doppler redshifts in astronomical sources, which really motivated the theory, is weak.[6] Thus the Hoyle–Narlikar theory is based on two good foundation stones and is in acceptable agreement with observation, but is lacking a bit in motivation.

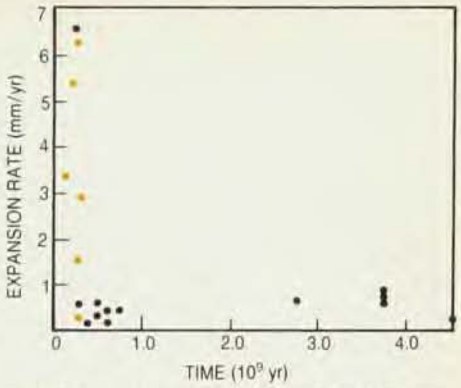
The theory of Canuto et al[5] is the most recent of the major variable-G theories. It has been developed in recent years in considerable detail, and it clearly represents a viable account of gravitation in which G is time-dependent.

The theory is scale covariant (or scale invariant), meaning that the laws of physics as they relate for example, to gravitation are not affected by the choice of a gauge function β which fixes the ratio of the gravitational and electromagnetic units in the Universe. In comparing gravitational physics and atomic physics, the form of β defines how the time scale typical of the one set of laws compares with the time scale typical of the other set. In general, there is no reason why the time used in describing gravitational phenomena should be the same as the time used in describing atomic phenomena. Indeed, Dirac has presented a good reason in the form of the Large Numbers Hypothesis for believing that the two are not the same (see above): the difference manifests itself as a decrease of G measured in atomic time ($G \propto t^{-1}$). The LNH can thus be employed to fix the gauge function β in the scale covariant theory, and in this form the theory of Canuto *et al.* represents an alternative way of interpreting Dirac's ideas.

Like Dirac's theory, the scale-covariant theory can be expressed in a form in which it is in overall agreement with observation. If the LNH is employed as a gauge-fixing condition, then $\dot{G}/G \cong -6 \times 10^{-11}$ yr^{-1} as in the Dirac theory. There may or may not be continuous creation in the scale-covariant theory, depending on the choice of gauge. Astrophysical tests[8] have not yet indicated with certainty the correct gauge for the real Universe; but data on the motion of the Moon are in best agreement with the form of the theory that has no creation.[11] While the relevant choice of gauge is still undecided, extensive work by Canuto and his co-workers has shown that the theory yields as good (or better) agreement with all of the standard cosmological tests as does Einstein's general relativity.[8,11] Clearly the scale-covariant theory is a strong contender for a new theory of gravitation.

Astrophysics

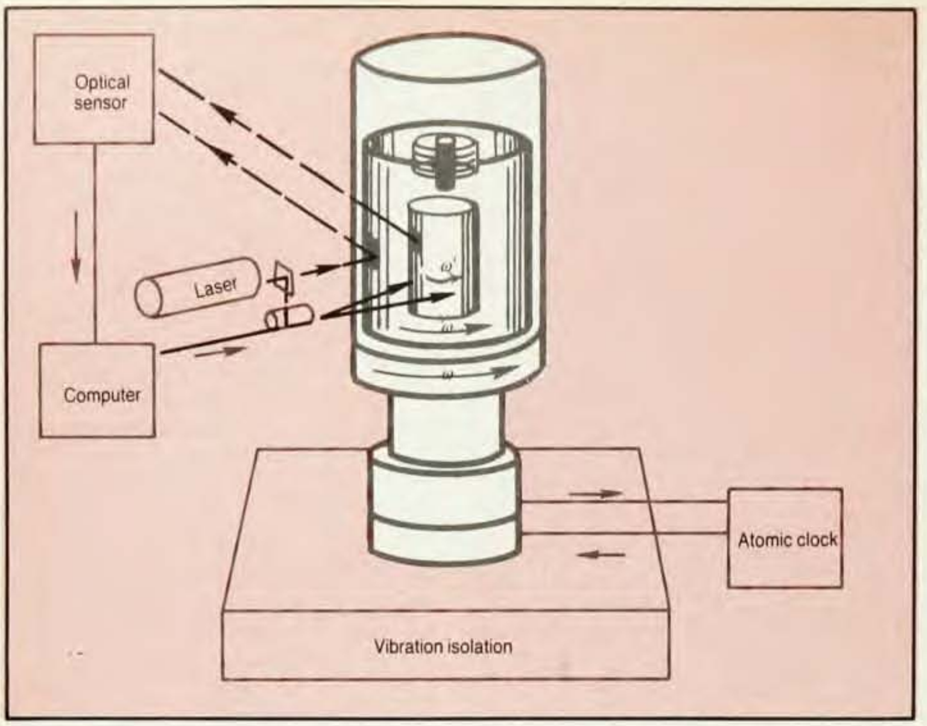
Astrophysical systems are affected by a decrease in G in numerous ways, some of which we have already discussed. The main consequences of a simple decrease in G as measured in atomic time are the following: (1) the distance from the Earth to the Sun changes; (2) the Sun and other stars become less luminous; (3) likewise, the Milky Way and galaxies in general become less luminous, due mainly to the dimming of the component stars; (4) the orbits of stars around the center of the Galaxy become less tightly bound to the nucleus, and the same is true of stellar objects in galaxies in general; (5) the dynamics of clusters of stars and clusters of galaxies (on an atomic time scale) are altered compared to ordinary Newtonian theory, so that the clusters become less strongly bound; (6) cosmological parameters such as those describing the cosmological history and dynamical future of the Universe are altered with respect to those calculated on the basis of conventional ($G =$ constant) theory.



Rate of increase in the Earth's radius with time.[1,6] The horizontal axis gives the time measured from the present back to the origin of the Earth (4.5×10^9 yr). The points are plotted with the ages of the data used to estimate the past radius of the Earth. The open circles represent estimates based on paleomagnetism; the closed circles represent estimates based on all other methods. Figure 6

If continuous creation of matter operates in conjunction with changing G, some of the above processes are modified. In particular, the Earth and the other planets can now either recede from or approach the Sun, depending on what type of creation is involved and which theory is used to describe the process (thus in the Dirac theory multiplicative creation causes a recession, while additive creation causes an approach). Also, the masses of dense bodies like planets and stars increase with time for multiplicative creation (the mass is proportional to t^2 on atomic time). The effects of multiplicative creation often offset the consequences of the decrease in G, whereas the effects of additive creation leave the consequences of decreasing G dominant.

Information on pure G-variability has been obtained from studies of meteorites, stellar evolution, pulsars, white dwarfs, star clusters, galactic evolution and cosmology.[1,6] Meteorites would have been warmer or cooler in the past if the Sun's luminosity has been affected by a varying G. This would have affected the outgassing of gaseous isotopes and resulted in discordances between radioactive decay ages deduced using gaseous and non-gaseous isotopes. Stellar evolution is perhaps the most important way of testing varying G. The rate at which a star like the Sun burns hydrogen and other elements depends on the internal temperature. This is in turn governed by the hydrostatic balance of gravity and pressure inside the star. This balance depends on the value of G. The condition that the Sun (for example) should have evolved to the state in which it is observed today can be used as a condition to limit changes in G throughout its past history. Pulsars represent astronomical clocks, which go slower as the neutron stars giving rise to the pulses undergo spin-down on a time



Experiment to detect the continuous creation of matter being carried out by R. C. Ritter *et al*[13] at the University of Virginia. Instrumentation detects deceleration of inner of two rotating cylinders due to spontaneous creation of matter in that cylinder. Figure 7

scale of order 10^9 yr. Changes in G would affect the spin-down of a given pulsar and affect also the expected number of long-period pulsars. White dwarfs (and neutron stars) have extremely high densities, but are able to resist collapse to black holes. The most important parameter influencing whether or not a dense star will collapse to a black hole is the Chandrasekhar limiting mass, and this depends on G. Star clusters, individual galaxies and the large-scale distribution of the galaxies in general (that is, cosmology) are all affected by a changing G in a similar fashion. They are all systems of (roughly) point masses interacting through gravity. The effectiveness of their gravitational self-binding depends on the strength of the gravitational interaction and so on G.

The methods of gaining information on varying G discussed in the preceding paragraph are indirect ones. Most of these indirect methods imply that $[\dot{G}/G] \lesssim 2\times10^{-11}$ yr^{-1} or thereabouts. More stringent limits on both $\dot{G}/G$ and time variation of other physical "constants" (especially Planck's constant, h) can be inferred from processes that were active in the early history of the Universe. In particular, the process of nucleosynthesis (the building up of heavy elements from light ones) has been used to limit $\dot{G}/G$ and $\dot{h}/h$. The argument involved[6] is that the abundances of the elements depend on the values of G and h as they were at the origin of the Universe about 2×10^{10} yrs ago. However, it is not clear if this method as it has been used hitherto is consistent, because the law of conservation of matter when G is time-variable is not the same as it is in general relativity. In view of this doubt the limits on $\dot{G}/G$ that the nucleosynthesis method leads to do not yet merit confidence. This leaves the result noted above, $[\dot{G}/G] \lesssim 2\times10^{-11}$ yr^{-1}, as the best available limit on the time variation of G. It must be emphasized, however, that this limit is based on indirect methods. A more direct method of measuring $\dot{G}/G$ involves landing on accurate clock on Phobos, one of the moons of Mars (see figure 4). But experiments of this type lie in the future; for the time being we must be content with the just-quoted limit for G-variability.

Many of the indirect methods that have been used to limit $\dot{G}/G$ do not take into account a possible time-variation of the masses of astronomical bodies of the type involved in the multiplicative-creation form of Dirac's theory. If one allows the possibility of mass variations, limits on $\dot{G}/G$ are relaxed somewhat from the value noted above. The inference from astrophysics is that G may vary at a rate of up to $[\dot{G}/G] \cong 10^{-11} - 10^{-10}$ yr^{-1}.

Geophysics

The Earth, by virtue of its rotation, represents a kind of cosmic clock that has been running for about 4.5×10^9 yr. During that time it has been gradually slowing down at a rate of about 2 millisec a century. By estimating the various processes that contribute to this spin-down it is possible, in theory, to gain information on long-term cosmological effects such as changes in G and continuous creation.[1,6] In practice, this is a complicated problem, because there are various purely geophysical effects that contribute to the spin-down. Most of the deceleration is believed to be due to ocean tides, which are raised on the Earth by the gravitational attraction of the Moon, and which dissipate energy and so lead to a decrease in the angular velocity of rotation. The energy so lost by the Earth is transferred to the Moon, which therefore recedes, and measurements of the acceleration of the Moon in its orbit provide one method of estimating the spin-down rate of the Earth. Cosmological effects, such as a decrease in G and continuous creation of matter, must be evaluated in conjunction with the tidal effect and other geophysical processes that can alter the planet's rate of spin.

Data that involve the Moon as a way of estimating the rotational history of the Earth are available from lunar occultations of stars monitored directly against atomic time (for the last few decades), telescope observations (for the last few centuries), records of eclipses (for the last few thousand years) and records of growth lines in some types of fossil that reflect the ancient sequence of days and months (for the last few 10^8 yr) (see figure 5). The interpretation and intercomparison of these sets of data is not completely free of ambiguity. But the consensus is that they are *compatible* with the limit on the rate of change in G obtained from astrophysics—$[\dot{G}/G] = 10^{-11} - 10^{-10}$ yr^{-1}. More positive evidence than compatibility for a change in G has been found recently from studies of the rotation of the Earth and the motion of the Moon in combination. The first result indicating that G really may be variable is due to Thomas Van Flandern.[12] He used data on the times of occultations of stars by the Moon (as seen from the Earth). Van Flandern found $\dot{G}/G \cong -8\text{x}10^{-11}$yr^{-1}. This result caused considerable controversy, since the reduction of the data is a tricky matter. However, several other studies of a similar type have been made, and they tend to confirm Van Flandern's result. Thus the situation at the moment is that data on the motion of the Moon and the Earth's rotation indicate that G is indeed changing with time.

Apart from long-term changes in rotation, the major predicted effect of changing G and/or continuous creation in geophysics is an expansion of the Earth.[1] This effect follows directly from the decrease with time of the gravitational force that binds together the material of which the Earth is composed and is augmented if there is creation of new material. The Hoyle–Narlikar theory[4] predicts an expansion rate of about 0.1 mm yr^{-1}. The scale-covariant theory,[5] using Dirac's Large Numbers Hypothesis as a basis, predicts a rate of 0.02–0.03 mm yr^{-1} if there is no matter creation, and 0.2–0.3 mm yr^{-1} if there is matter creation. Dirac's theory[2,3] itself has consequences for geophysics similar to those of the scale-covariant theory. In testing these theories, the question is whether geophysical evidence indicates expansion and, if so, at what rate the expansion is taking place.

There are many pros and cons to the expanding-Earth hypothesis.[1] To summarize data from a wide range of geophysical studies, one can say that there is indeed evidence of expansion, and that the rate appears to be about 0.5 mm yr^{-1}. Figure 6 shows estimates of the rate of increase of the Earth's radius with time that were obtained from palaeomagnetic studies and other methods. The palaeomagnetic data scatter widely, some giving considerably lower limits; there are reasons to believe this method gives spurious results, especially for small amounts of expansion.[1] Similarly, the extreme non-palaeomagnetic point (6.6 mm yr^{-1}, 0.25×10^9 yr) can be ruled out.[6] The remaining twelve non-palaeomagnetic data points define a reasonable coherent group, indicating a mean rate of expansion over the history of the Earth of about 0.45 mm yr^{-1}. If the Earth is expanding, the measured rate of approximately 0.5 mm yr^{-1} is noticeably higher than the rates predicted by variable-G cosmologies, even with continuous creation. (The highest rate for the scale-covariant theory with reasonable values of the cosmological parameters is about 0.3 mm yr^{-1}.) However, a rate of about 0.5 mm yr^{-1} *is* of cosmological order (the radius of the Earth divided by 1×10^{10} yr defines a rate of 0.64 mm yr^{-1} and gives a rough measure of cosmological expansion on the geophysical scale). This indicates that the expansion has a cosmological origin, even though the mechanism cannot be identified yet.

Future research

There are three viable theories in which the strength of gravity becomes weaker with time, and these theories have serious implications for astrophysics and geophysics. Data from these two fields can be used to test G-variability, and such data are compatible with a value for $[\dot{G}/G]$ of order 10^{-11}–10^{-10} yr^{-1}. There is positive evidence that G is changing at a rate $\dot{G}/G \cong -8\times10^{-11}$ 10 yr^{-1}, which may be compared to the theoretical prediction $\dot{G}/G = -6\times10^{-11}$ yr^{-1} of Dirac's theory. An overall comparison of data from astrophysics and geophysics shows that all three of the major G-variable theories (Dirac, Hoyle–Narlikar, Canuto *et al*) are in agreement with observation.

The question may now be posed: Which directions should research take in the quest to decide on a new theory of gravity? The following are some specific problems that need to be examined further:

▶ Is G varying with time, and if so, how fast? So far, there is only one set of data that positively indicate a changing G (the set of data to do with the Moon's motion, as analyzed by Van Flandern[12] and others). Very sensitive laboratory experiments to measure the possible rate of change in G and masses are under development at the University of Virginia.[13] Figure 7 shows the apparatus consisting of two cylinders of temperature-stable ceramic (Zerodur) rotating concentrically in an evacuated region inside an acoustic and magnetic shield. The inner cylinder is magnetically suspended from the outer one, which rotates with precise angular velocity ω. Mass created in the inner cylinder tends to slow it down. A feedback system employing laser pulse sensing and photon driving keeps the inner velocity ω' very near to ω. The forward–backward asymmetry needed in these feedback-driving pulses to keep $\omega' = \omega$ constitutes the signal. With the two cylinders running synchronously, viscous, magnetic hysteresis and other damping effects are kept near zero. The development of other methods of measuring these effects would be valuable.

▶ If masses vary as well as G, what kind of cosmology should one employ as a model of the Universe? The uniform, big-bang cosmology underlies most modern research in astrophysics, but it is by no means obvious that the uniformity and big-bang concepts are compatible with a theory of gravity in which G and the masses of astrophysical systems vary.

▶ Is the Earth really expanding at a rate of 0.5 mm yr^{-1}, as indicated by some geophysical data? New methods of detecting a growth in size of the Earth are needed. It would be interesting to study the evolution of a model planet subject to the influences of a change in G, a change in mass and a change in radius with time.

These three questions represent the main problems facing variable-G theory at the present time. Answers to them will probably be found only through *multidisciplinary* research.

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