On the Change of Physical Constants

EDWARD TELLER
The University of Chicago, Chicago, Illinois
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DIRAC* has proposed that the great numerical value of some pure numbers occurring in physics is due to a variation of some physical constants with time. In particular, he considers the ratio of electric forces to gravitational forces acting between elementary particles. He assumes that this ratio is proportional to the age of the universe. If we use e^2/mc^3 (m = mass of electron) as the unit of time, the age of the universe indeed is of similar magnitude as the ratio of electric and gravitational forces. Dirac further suggests that the number of particles in the world is equal to the square of the age of the universe measured in the same units.

In the following I should like to point out that hypotheses such as those quoted above may easily get into conflict with geological evidence. It will be shown that a reasonably steady temperature required for the existence of life on earth during the last 500 million years is most easily explained by assuming that the physical constants do not vary with time.

Dirac's hypothesis may be discussed either in terms of a change of the electronic charge or else in terms of a change in the gravitational constant, G. We shall choose the latter representation.

Of the smaller pure number $\hbar c/e^2$ we shall assume that it does not change with time. It has been suggested that this quantity is proportional to the logarithm of the age of the universe. If we consider a geological period at which the age of the universe was 0.9 of its present value (i.e., a time 200 or 300 million years ago), G would have been greater by 10 percent while $\hbar c/e^2$ would have changed by about 0.1 percent. The latter change is negligible, even if it should be real.

We shall consider two assumptions. First, we shall let G decrease with time but we shall assume that the number of particles in the sun and the earth are constant. Thus the sun and earth will have constant masses. This may be justified by dropping Dirac's second hypothesis and assuming instead that the number of particles in the universe does not change. Or else we may adopt a change in the number of particles but assume that new particles are generated in interstellar space.

As a second alternative, we shall assume that the number of particles in the sun and in the earth increases as the square of the age of the universe. The mass of the sun and earth will then increase in the same way.

This assumption implies that new particles are generated at the position where some particles are already present. It will be reasonable to assume that the new particles will share the average motion of the sun or earth, respectively. Thus, the linear momentum and angular momentum of these bodies will increase proportionally to their masses.

According to the virial theorem, the kinetic energy of the electrons and nuclei in the sun is proportional to the gravitational potential. Since the temperature T at the center of the sun is proportional to this kinetic energy, T will vary as

$$T \sim (GM/R), \tag{1}$$

where M is the mass of the sun and R is its radius.

The luminosity L of the sun is proportional to the product of the radiation-energy gradient T^4/R, of the mean free path of a light quantum λ and of the surface R^2 through which radiant energy may be propagated. This gives

$$L \sim RT^4\lambda. \tag{2}$$

Calculations on stellar opacities show that λ varies roughly as the third power of the temperature T^3 and as the inverse square of the density R^6/M^2. Thus, we get for L

$$L \sim R^7T^7M^{-2}. \tag{3}$$

* P. A. M. Dirac, "Cosmological constants," Nature **139**, 323 (1937); *Ibid.*, "New basis for cosmology," Proc. Roy. Soc. (A)**165**, 198 (1938); see also P. Jordan and C. Müller, "Field equations with a variable 'constant' of gravitation," Zeits. Naturforsch. **2a**, 1 (Jan. 1947).

Using (1) we may eliminate the radius and the temperature

$$L \sim G^7 M^5. \quad (4)$$

Equation (4) contains the well-known mass-luminosity relation. It should be pointed out that in deriving (4), the law of energy production by thermonuclear reactions was not used. This is due to the fact that in both (1) and (3) radius and temperature enter only in the form of the product RT. A different dependence of λ on the temperature and density would have made the simultaneous elimination of R and T impossible. It would then be necessary to consider the law of energy production. The final result, however, would not differ greatly from (4).

If the orbit of the earth is considered as a circle of radius r, we have

$$v^2/r = GM/r^2, \quad (5)$$

where v is the orbital velocity of the earth. If G (and perhaps M) should change, both v and r will be functions of time. The quantity

$$r^2v^2 = GMr \quad (6)$$

will, however, be constant. If the mass of the earth does not change, r^2v^2 is indeed proportional to the square of the angular momentum and must, therefore, retain its value. If the mass of the earth is changing, the angular momentum will change proportionally and r^2v^2 will still remain unchanged. Thus it follows from (6) that the radius of the earth's orbit varies as $1/GM$.

The temperature on the surface of the earth varies as the fourth root of the energy received, which is proportional to the luminosity divided by r^2.

$$\text{Temperature of earth} \sim (L/r^2)^{\frac{1}{4}} \sim G^{2.25} M^{1.75}. \quad (7)$$

Let us now consider M as a constant and let us assume that G is 10 percent greater than its present value. This corresponds to a time 200 or 300 million years ago. We have ample evidence of life on our planet at this time. According to (7) the surface temperature of the earth should have exceeded the present temperature by more than 20 percent. We are led to expect a temperature near the boiling point of water.

If, on the other hand, we assume that, at the time mentioned, G was 10 percent higher and M (varying as the square of time) was 21 percent lower, Eq. (7) would give a temperature about 12 percent lower than we now have. This would bring the average temperature on the earth below the freezing point.

It should be pointed out that changes in the opacity of the sun due to changing chemical composition may materially influence the results obtained. Such changes might occur if additional particles are generated in the course of time inside the sun. Thus our present discussion cannot disprove completely the suggestion of Dirac. This suggestion is, because of the nature of the subject matter, vague and difficult to disprove.

Further evidence on the change of constants may be obtained from the appearance of distant spiral nebulae. Light emitted from the farthest observed galaxies has originated about 500 million years before the present time. The total luminosity of such galaxies (assuming that no additional stars are formed) should change as G^7M^5 where M describes the variation of the mass of individual stars. The radius of galaxies should change as $1/GM$ where M in this formula is proportional to the mass of the galaxy.**

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** The change in galactic radius may be obtained from the virial theorem and from the statement that the volume occupied by an assembly of objects in phase space varies in direct proportion with the mass of the objects. It should be noted that the galactic radius and the radius of the earth's orbit vary according to similar laws.