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NEW IDEAS ABOUT GRAVITATION AND COSMOLOGY

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Creation

It is observed that all the distant galaxies are receding from us, with velocities roughly proportional to their distances. This suggests that, at a certain time in the past, all the matter in the universe was very close together and was suddenly shot apart in a gigantic explosion. We are led to the idea of the creation of the universe occurring as a Big Bang.

The former president of our Academy, G. Lemaître, studied this question extensively, and was a pioneer on the subject. He put forward the idea that the universe started as a single atom. All the matter of the universe was then concentrated in a single atom, of course with a very high atomic weight and extremely radioactive. The disintegration of this atom started off our universe, and successive disintegrations led to all the processes that we now observe. The radioactivity that we

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now observe is the remnants of this primitive disintegration. We then had a picturesque view of the Creation, but it was not sufficiently definite to provide a basis for a detailed theory.

In any case, it seems certain that there was a definite time of creation. This is called $t = 0$ in our theory. The course of development of the physical universe is concerned with values of $t > 0$.

People sometimes ask, what was there before the Creation? The answer is that it is quite unobservable to Science and it is not a proper question to ask. We never have $t < 0$ in our equations. The whole of science is concerned with $t > 0$.

To find out how long ago the Creation occurred one must find the coefficient of proportionality between the distance of a galaxy and the velocity of its recession. This was first done by Hubble and the coefficient is known as Hubble's constant. It is not an easy coefficient to determine, because there are great inaccuracies involved in the attempt at measurement of the distances of very distant objects. According to the best estimates now available the age of the universe is about 18×10^9 years. According to Hubble's original estimate, which he put forward about 1930, it was very much less, only about 2×10^9 years.

The Large Numbers Hypothesis

If one compares the electric to the gravitational force between the electron and the proton in the hydrogen atom one gets a large dimensionless number. It has the value

$$\frac{e^2}{G\, m_e\, m_p} = 7 \times 10^{39}. \qquad (1)$$

If one expresses the age of the universe in terms of an atomic unit, say $e^2/m_e c^3$, instead of years, one gets the number 2×10^{39}. This is quite close to the previous number.

You might say, this is a remarkable coincidence. But I do not believe it is a coincidence. I think there must be some explanation for it, which will become evident when we know more about both cosmology and atomic theory. Assuming that there is such an explanation, the number (1) will be connected with the age of the universe, and as the age increases the number (1) will increase in proportion. If we use atomic units, then we shall have

$$G : : t^{-1}. \tag{2}$$

One may set up the general assumption that all the large dimensionless numbers that one can construct from atomic and cosmological data are connected in a similar way with the epoch t. Such an assumption is needed if one is to avoid inexplicable coincidences. I call it the Large Numbers Hypothesis (LNH).

With this assumption one can immediately draw some conclusions about cosmology. People have often wondered whether the universe will not expand to a maximum size, then stop and contract again. We can now see that this is impossible. The age of the universe at the time of maximum expansion, expressed in atomic units, would give us a large number that is a constant, which is not allowed. There can be no maximum expansion.

A steady state model for the universe can also be ruled out. The relation (2), implying a continual change in G, makes a steady state impossible. The universe had a definite beginning but will have no end. It will continue to evolve forever, dominated by the formula (2), which ensures perpetual change.

Another large number is provided by the total amount of matter in that part of the universe that is receding from us with a velocity $< \frac{1}{2}$ c. I take this part of the universe, rather than the total universe, because the total universe might very well be infinite and this part will in any case give us something definite. Expressing the mass in terms of the proton mass as unit, one gets a dimensionless number N say, which is rather uncertain because we do not know how much dark matter there is, but which is somewhere in the neighbourhood of 10^{78}. From the LNH we should thus expect

$$N :: t^2 \tag{3}$$

Thus there is a continual increase in the amount of matter in this part of the universe. Various people, including myself, have often supposed that this requires continuous creation of matter, in violation of one of the most fundamental of physical laws, conservation of mass. The violation would only be a small one and would not show up in laboratory experiments, but there are grave difficulties in reconciling it with the precise knowledge available nowadays. So I now believe one should avoid continuous creation and go back to the old idea of strict conservation of mass.

One can reconcile (3) with conservation of mass by supposing that the velocity of recession of a galaxy is continually slowing down, so that more and more galaxies are continually appearing with velocity $< \frac{1}{2}c$.

When I first introduced the LNH in 1938, I tried to develop it using this basis of conservation of mass and the slowing down of the galaxies. But it was quite impossible with the value of the Hubble constant that was then accepted. So I gave up this line of work and later went over to continuous creation. But with the revised value of the Hubble constant one can return to conservation of mass and build up a satisfactory theory.

The Two Metrics

The Einstein theory of gravitation has had enormous success and one must believe that it is substantially correct. But the Einstein theory requires G to be constant. How can one reconcile it with (2)?

One must suppose that it applies to a metric ds which is different from that provided by atomic apparatus governed by quantum laws. The Einstein metric ds_E is to be used in Einstein equations to determine the motion of classical bodies. The atomic metric ds_A is different. The relation between them can be worked out just from dimensional arguments.

We shall use the suffixes E and A generally to refer to quantities measured in Einstein and atomic units, and keep t to denote the epoch in atomic units. Thus (2) should be written

$$G_A :: t^{-1}$$

and should be supplemented by

$$G_E = \text{constant}.$$

We have conservation of mass in both Einstein and atomic units, so

$$m_E = m_A. \tag{4}$$

The velocity of light c we take to be unity in both Einstein and atomic units, so that units of time and of distance are changed in the same ratio when one goes from the Einstein to the atomic units. From the dimensions of G as $(\text{mass})^{-1}$ $(\text{distance})^3$ $(\text{time})^{-2}$ we now find

$$ds_E = t\, ds_A. \tag{5}$$

The relations (4) and (5) are fundamental for the reconciliation of the LNH and the Einstein theory.

Let τ denote the epoch in Einstein units. Then

$$d\tau = t\, dt \tag{6}$$

or

$$\tau = \tfrac{1}{2} t^2.$$

The Law of Expansion

In the present theory the universe at a particular time turns out to be infinite, so we cannot talk about the radius of the universe. But we can introduce a variable R which gives the distance of a particular galaxy and discuss how R varies with the epoch. This will provide the law of expansion of the universe. We may take any not too distant galaxy, so that we are not disturbed by questions of the curvature of space.

The variation of R can be worked out from the condition (3). We use atomic units, so R becomes R_A. The average density in atomic units is, with conservation of mass,

$$\rho_A :: R_A^{-3}. \tag{7}$$

Let us take a general law of expansion

$$R_A :: t^n. \tag{8}$$

Then the velocity of recession of the particular galaxy we are concerned with is

$$dR_A/dt = n\, R_A/t.$$

The distance of a galaxy whose velocity of recession equals 1/2 c is now t/2n. The total mass within this distance is :: $\rho_A t^3$. According to (3) this must be :: t^2. So

$$\rho_A :: t^{-1}, \tag{9}$$

and (7) gives

$$R_A :: t^{1/3}. \tag{10}$$

This is a much slower rate of expansion than in the usually accepted picture, for which R_A :: t rather closely.

With the new law of expansion we must revise our estimate of the age of the universe. For the general law of expansion (8) the Hubble constant is

$$H = R_A^{-1}\, dR_A/dt = n/t.$$

With the usual value $n=1$ we get $H=t^{-1}$. With the present theory $n=1/3$ and $H=1/3\, t^{-1}$. Thus with the same value for H, the age of the universe is reduced by a factor 3.

The value of the Hubble constant is still not known with great accuracy, but is believed to correspond to an age of the universe of about 18×10^9 years with the law of expansion $R_A :: t$. It thus corresponds to an age of about 6×10^9 years with the new law of expansion. This is rather less than the age of the universe that one usually believes, but still it is greater than the age of the Solar System, namely 4.5×10^9 years, so it is not impossible.

The Model of the Universe

The LNH requires that *every* large dimensionless number that appears in fundamental theory shall vary according to a certain power of the epoch, depending on the value of the number. Thus there must not be any large dimensionless number that is constant.

We consider the universe with local irregularities smoothed out. There are several possible models conforming to the Einstein field equations. They have been worked out by various authors, some by our former president G. Lemaître. Of all these models one can see by elementary arguments that there is only one that does not contradict the LNH. This was a model that was introduced in a joint paper by Einstein and de Sitter. We shall refer to it as the E. S. model.

It involves the line-element, in Einstein units,

$$ds_E^2 = d\tau^2 - \tau^{4/3}\ (dx^2 + dy^2 + dz^2). \qquad (11)$$

Any model of this type involves a universe with a uniform density and a uniform pressure. The pressure is zero with the coefficient $\tau^{4/3}$ in front $dx^2 + dy^2 + dz^2$, which is appropriate for the actual universe where the radiation is negligible compared with the matter density. The coefficient agrees with (10), which gives

$$R_E :: tR_A :: t^{4/3} :: \tau^{2/3}.$$

With the ES model (11), the three-dimensional space at a particular epoch is flat. Thus it is of infinite extent, not closed as in Einstein's static model.

The Natural Microwave Radiation

Is there any confirmation for the law of expansion (10)? There is very good confirmation, provided by the observation of the natural microwave radiation.

The microwave radiation is believed to be of cosmological origin because of its uniformity and isotropy. So far as it can be observed it appears to be black-body radiation, satisfying Planck's law. Now black-body radiation in an expanding universe remains black-body radiation (provided there is no creation of photons, such as might occur in a theory with continuous creation of matter). Each spectral component of the radiation gets redshifted according to the same law as the distance of a galaxy, thus from (10)

$$\lambda :: t^{1/3}.$$

The temperature T of the radiation decreases according to the same law as the frequency of one of its components, thus

$$T :: \nu :: \lambda^{-1} :: t^{-1/3}. \qquad (12)$$

The rate of cooling is much slower than in the usual theory, according to which the distance of a galaxy is roughly :: t, so that $\lambda :: t$. This would make

$$T :: \lambda^{-1} :: t^{-1}. \tag{13}$$

The observed value of T is about 2.8°K. This gives an energy kT, which may be compared to the rest-energy of a proton to give a dimensionless number

$$kT/m_pc^2 = 2.5 \times 10^{-13}.$$

According to the LNH we should expect this to vary with the epoch according to the law

$$kT/m_pc^2 :: t^{-1/3}.$$

Thus $T :: t^{-1/3}$, in agreement with (12) above, but disagreeing strongly with (13).

The microwave radiation thus provides confirmation of our present picture. The radiation has been cooling according to the $t^{-1/3}$ law since a time close to the Big Bang. According to the usual views it has been cooling according to the t^{-1} law since a certain decoupling time, when it became decoupled from matter. This decoupling time must have been around $t = 10^{26}$, when T was 10^{13}, times greater than now, so that kT was approximately m_pc^2. The existence of such a decoupling time, playing a fundamental role in cosmology, would contradict the LNH.

I have spoken about this problem at a previous meeting of the Academy. (Commentarii, Vol. III, N. 7). I realized then the need for the $t^{-1/3}$ cooling law, but could not set it up without artificial assumptions about intergalactic gas. The difficulties disappear with the new theory.

Consequencens of the New Theory

In applying the Einstein theory to the Solar System one works with the Schwarzschild solution of the Einstein field equations. This solution now has to be modified to fit in with the E. S. model for large values of r. The modification can be worked out, and then one can calculate the motion of the planets in the new theory.

These calculations lead to two results for which the new theory differs from the standard Einstein theory.

(1) Ephemeris time, the time marked out by the motion of the planets around the sun, differs from atomic time, the time marked out by atomic clocks. Atomic clocks should be slowing down with respect to ephemeris time. (2) With distances measured in atomic units, the planets should all be spiralling inward toward the sun. This is a cosmological effect, superposed on the motion of the planet due to all other physical causes.

Observations have been made by various people to check on these effects. There is some evidence in favour of them, but in each case the probable error is about as large as the effect being sought for, so there is no real confirmation yet.