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DOES THE GRAVITATIONAL CONSTANT VARY?

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Our former president, Georges Lemaitre, proposed a radical new idea as a cosmological theory. He supposed the universe started as a single highly radioactive atom, containing all the mass of the universe. Everything that we see consists of the products of its disintegration. Initially there was a tremendous explosion and various fragments were shot out with great speed, and we still see these fragments receding from us with velocities proportional to their distance from us. This over-all picture is now generally accepted and is known as the Big Bang cosmology.

It provides us with a natural origin in space-time, and gives an absolute time for any event, called the epoch. One usually assumes that the laws of nature hold the same throughout space and time. But this is not necessarily so. They might

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change with the epoch, the change being too slow to show up easily. One would then have an evolutionary cosmology.

I spoke about this at the Academy meeting three years ago. I would like now to discuss how the subject has progressed in the meantime.

I gave some arguments which make it seem plausible that the gravitational constant G varies with the epoch. Now G is a quantity having dimensions, so its value depends on what units one uses. There would not be much sense in using the standard units of physics, grms, cms and secs, because these units cannot be defined with sufficient accuracy. One should use atomic units, a unit of time provided by atomic clocks, a unit of distance equal to the distance traveled by light in a unit of time, and a unit of mass equal to that of the electron or the proton. Referred to such units, G becomes a dimensionless number and it has an absolute meaning to discuss whether it is constant or varies with the epoch.

The value of G in these units is extremely small. G^{-1} is approximately 10^{39}. Now the present epoch, according to recent values for Hubble's constant, is about 18×19^{9} years which, expressed in atomic units, is also about 10^{39}. It is natural to suppose that these two large numbers are connected. The second one increases as the universe gets older, so the first one should also increase in the same ratio. We are thus led to

$$G :: t^{-1}.$$

We get
$$\frac{\dot{G}}{G} = -\frac{1}{t} = 6 \times 10^{-11} \text{ per year.}$$

This value for G is very small, but it is within the reach of present-day technology to try to observe it.

Direct laboratory measurements of G are far too inaccurate to show an effect of this order. Dr. Jessie Beams is the expert on this subject and he is planning a vastly improved apparatus, which will work in a bath of liquid helium. He can measure

variations of G much more accurately than G itself and he hopes that his improved apparatus will be able to show the effect. It will need a few years work to get an answer.

One has better prospects if one uses astronomical observations. Einstein's law is extremely successful for describing the solar system. Just within the last few months it has scored a further success by giving correctly the deflection of radio waves passing close to the sun. But Einstein's law does not permit a variation of G. So we have a real difficulty here.

It seems to me that the best way out of this difficulty is to suppose that the equations of the Einstein theory are correct, but that they refer to units of time and distance that are not the same as the atomic units. The Einstein equations would then involve an interval ds_E that differs slightly from ds_A, the interval in atomic units. The successes of the Einstein theory can then all be preserved, because one retains the calculations with ds_E. The variation of G then shows up only when one brings in atomic measurements involving ds_A.

The development of these ideas in a reasonable manner suggests that one should consider all the large dimensionless numbers that are provided by atomic and cosmological constants to be connected with the epoch and to vary with the epoch so as to maintain the relationship. I call this the Large Numbers Hypothesis.

An application of this hypothesis requires one to postulate continuous creation of matter, by some new process not explained in terms of any of the standard physical theories, a new kind of radioactivity. The question arises, where is this new matter created? There are two alternative assumptions that are reasonable:

1) New matter is created uniformly throughout space, and hence mainly in intergalactic space. I call this assumption *additive creation*.

2) New matter is created close beside matter already existing, in proportion to the amount already existing there, and

probably of the same nature as the existing matter. I call this assumption *multiplicative creation.*

There is no obvious reason which assumption is preferable, so one should consider both and see which one better fits the observations.

By considering a simple example, such as the motion of the earth around the sun, one can show, as I did in my talk three years ago

$$ds_E = t^{-1}\ ds_A \quad \text{for additive creation}$$

$$ds_E = t\ ds_A \quad \text{for multiplicative creation.}$$

This means that for additive creation the whole solar system, measured in atomic units, is contracting. This is a cosmological effect, to be superposed on all other effects arising from the usual physical causes. Similarly, with multiplicative creation, there is a cosmological expansion superposed on all other physical effects.

Thus by making accurate observations of the solar system with atomic apparatus, we have a chance of checking whether G varies and also of distinguishing between the two kinds of creation.

Let us consider our nearest neighbor, the moon. Its distance from the earth should be changing by 2 cms a year. It is approaching with additive creation and receding with multiplicative creation. Now with the help of reflectors that have been placed on the moon by astronauts, the moon's distance can be measured with very great accuracy. The error has been reduced to a few cms. Unfortunately, this effect cannot be used to check the theory, because the moon's motion is strongly disturbed by the tides and the tidal effects are not known with sufficient accuracy.

Instead of the moon's distance, one could observe its motion in the sky. The angular velocity can be measured with very great accuracy by noting the times of occultations of stars.

One may observe these occultations by ephemeris time, that is to say by time marked out by the motion of the earth around the sun, and also by atomic time, and compare the two. Atomic clocks have been used for observing the moon since 1955. By comparing the time scales we get the relation between ds_E and ds_A and can check the theory. Tidal effects will disturb both time scales equally and will not affect their comparison.

Van Flandern has been working on this method and has obtained results indicating a difference of the two time scales corresponding to multiplicative creation, and a value for $\dot{G}/G$ somewhat larger than the theory would require. But the errors are rather large and the calculations should be studied in greater detail before one can have confidence in the results.

Another method is to make radar observations of the planets. One sends a radar pulse to a planet, say Mercury or Venus, and observes the reflected pulse. One then measures the time of the journey with an atomic clock and one gets the distance of the planet in atomic units.

I. I. Shapiro has been working on this method. He has not yet obtained a definite result for $\dot{G}$, but I heard recently that his observations tend to support additive creation. This is in contradiction to Van Flandern's results.

That is the situation to date concerning the variation of G. The question is not yet settled, but many people are interested and are working on it and we may hope to have a definite answer soon.

The Natural Microwave Radiation

I would like now to discuss another problem that is related to the variation of G.

A band of electromagnetic radiation with wave lengths extending from about 70 cm to about 1 cm is observed coming out of the night sky and falling on the earth. This radiation comes uniformly from all directions and steadily at all times. So it cannot have a local origin. Presumably it comes from beyond our galaxy.

Observations of the intensity of the radiation show that it agrees with Planck's formula for black-body radiation at a temperature of about 2.8°K.

The usual explanation for this radiation is that it forms the remnants of a primordial fireball that existed in the early stages of development of the universe. Originally this fireball was in temperature equilibrium with hot matter. The matter and radiation were all cooling together owing to the expansion of the universe. At a certain stage in the cooling the radiation and the matter became decoupled, and after that the radiation just cooled by itself, each spectral component getting redshifted according to the formula

$$\lambda :: t .$$

It is a property of black-body radiation that it remains black-body under this type of cooling, with its temperature varying according to

$$T :: t^{-1} .$$

The observed microwave radiation might then be explained as what is left of this primordial fireball, which has been cooling according to this law from the time it was decoupled.

This explanation does not fit in with the Large Numbers Hypothesis. The difficulties were referred to in my talk of three years ago but were then not adequately dealt with, and I would like now to give an amended discussion.

One sees the difficulty in its clearest form if one uses the microwave radiation to determine a dimensionless number. The microwave radiation, at a temperature $T = 2.8°K$, consists of photons whose average energy is roughly kT. Let us compare this with the rest-energy of an electron. We get

$$kT/mc^2 = 5 \times 10^{-10} .$$

This should be regarded as the reciprocal of a large number, to which the Large Numbers Hypothesis applies, so we get roughly

$$T :: t^{-1/4} .$$

We might have used the proton rest-energy instead of the electron's and then we would have got roughly

$$T :: t^{-1/3} .$$

With the present crude theory we cannot distinguish between these two possibilities, but in either case we have a big departure from the $T :: t^{-1}$ formula. The microwave radiation must be cooling more slowly than it does according to the primordial fireball theory.

To account for the slow cooling we must suppose the radiation is interacting with some intergalactic gas, say ionized hydrogen. It interacts with the free electrons by the Compton effect. The density of the free electrons must be sufficiently small so that they do not interfere with observations of the most distant things that are seen with optical and radio telescopes. But they must be sufficiently dense for a rough temperature equilibrium to be established between the free electrons and the microwaves. The temperature of the microwaves is then controlled by the temperature of the intergalactic gas, which has to cool according to the law $t^{-1/4}$ or $t^{-1/3}$.