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EVOLUTIONARY COSMOLOGY

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SVMMARIVM — Cosmologiam evolutionistica primum proposuit Lemaître. Auctor ulteriorem progressum notionum a Lemaître conceptarum proponit.

The Fundamental Hypothesis.

Evolutionary cosmology implies a universe which started at a definite time and is always changing and departing more from its early state. It is to be contrasted with steady state cosmology, which implies that the universe has always existed, much the same as it is now, and no very drastic change ever occurs. The former is the one now generally preferred.

An extreme version of evolutionary cosmology was put forward by G. LEMAÎTRE [1]. He proposed that one should consider the universe to have started with a single highly radioactive atom. All that we see now, the galaxies and stars, are merely products of its disintegration. The universe is thus always diverging more from its original state and there is no possibility of its ever returning to anything like what it previously was. This is the essential idea of evolution.

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The evolutionary concept is in agreement with a hypothesis I have made concerning the large natural numbers [2]. One can determine approximately the age of the universe from the observed recession of the galaxies, by calculating the time when they were all very close together. If one then expresses the age in terms of a unit of time provided by atomic clocks, one gets a dimensionless number t. It is somewhere around 10^{39}. It characterizes the present epoch in a natural way, independent of man-made apparatus.

Working from data provided by astronomy and atomic physics one can obtain other large dimensionless numbers. Any such number which turns out to be of the order 10^{39} is then assumed to be connected with the epoch t. Thus it will not be constant with the passage of time, but will increase proportionally to t. We have here a general hypothesis connecting all the large dimensionless numbers provided by nature, so that they all increase together.

One such number is the ratio of the electric to the gravitational force between electron and proton in the hydrogen atom. The electric force is e^2/r^2. The gravitational force is $\gamma\, m_1 m_2/r^2$, with γ as the gravitational constant. Their ratio is about 10^{39}. According to our general hypothesis it cannot be constant. It must be proportional to the epoch t. One can infer that the gravitational constant, referred to atomic units, is decreasing proportionally to t^{-1}.

Our fundamental hypothesis demands an evolutionary cosmology. The gravitational constant will continue to decrease forever, and physical conditions will always depart more and more from what they were like close to the time of creation.

2. *The Law of Expansion.*

Let the distance between two neighboring galaxies, expressed in terms of atomic units, be $kf(t)$. The number k depends on the pair of galaxies chosen. The function $f(t)$ is the same for all pairs, if we assume the universe is essentially uniform. This function gives the law of expansion of the universe.

If one assumes Einstein's equations with no cosmological constant, then, as shown by Friedman and Lemaître, one finds the universe expands to a maximum size and then contracts again. Such behavior would not agree with our fundamental assumption. The maximum radius of the universe, expressed in atomic units, would provide a large number which is constant and not connected with the present epoch. It is just such numbers that are excluded by our fundamental assumption.

The function $f(t)$ cannot contain any parameters that are large numbers of the order 10^{39}. Any parameters that it does contain must be of the order unity. If we are not concerned with the very early stages of the universe, then we are interested only in the asymptotic form of $f(t)$ for large t. This must be t^n, with some $n > 0$, or possibly log t. The velocity of recession of a neighboring galaxy is then

$$knt^{n-1} \text{ or } kt^{-1} .$$

The case $n = 1$ corresponds to uniform expansion, $n > 1$ corresponds to an accelerating expansion, while $n < 1$ or the log case corresponds to a decelerating expansion. It is important to decide between these cases for any theory of cosmology.

For a galaxy close to our own, the velocity of recession is about 10^{-3}, if we take the velocity of light to be 1. For $n > 1$ this velocity increases steadily and eventually becomes greater than 1, which cannot be allowed. If $n < 1$ the velocity has been steadily decreasing and we can calculate a time in the past, t_1 say, when it was equal to unity. Thus for $n = 3/4$, we get $t_1 = 10^{27}$. Obviously our model cannot be valid earlier than t_1. If t_1 is large, such as 10^{27}, the existence of such a number playing an important role in the theory contradicts our fundamental assumption. A much smaller value for t_1 would be admissible.

We can conclude that $n = 1$, corresponding to uniform expansion, or else is slightly less than 1, corresponding to a slow deceleration.

In our future work we shall take the simplest case $n = 1$, as there would be no point in bringing in fine details with the present preliminary theory. We shall therefore have the distance of a neighboring galaxy equal to kt and its velocity of recession is constant.

Continuous Creation of Matter.

One can estimate the total amount of matter in the universe by taking into account all the visible matter and then making an allowance for invisible matter, assuming its contribution is not so very much greater than that of the visible matter. The result, expressed in terms of the nucleon mass, is a large number which is somewhat near 10^{78}. From our fundamental hypothesis this number would have to be proportional to t^2. We can conclude that the amount of matter in the universe is continually increasing. We are forced to a cosmology with continuous creation of matter.

We have to decide where the new matter is created. There are two reasonable postulates one might make. A: Matter is created uniformly throughout space, and hence mainly in intergalactic space. B: Matter is created where it already exists, in proportion to the amount existing. In either case one is postulating a new physical process which has not been observed, and which is hard to understand in terms of accepted physical ideas.

With postulate A one must have a sort of radioactivity of empty space. It would be remote from observation and there is no basis from which one could build up a theory about it.

Postulate B would not be so remote from observation and allows one to make some assertions in order not to have obvious disagreement with known facts. One must suppose that the new atoms that get created are of the same kind as those already existing. Each atom must have a probability of reproducing one of its own kind, amounting to about 10^{-10} per year, the new atom appearing somewhat near the original one. The effect is too small to show itself directly in the laboratory, but it would require that old rocks grow during the course of geological ages. We must imagine this growth to take place in some way that does not disrupt the rocks and preserves any crystalline structure they may have. Thus each crystal must steadily increase in size. It is rather hard to understand how this growth takes place, as it is a volume effect and not a surface one. The new atoms spontaneously appearing must somehow get transferred to the surface of the crystal. They have, of course, plenty of time to do so, as the rate of growth is excessively slow.

It would be desirable to have our theory conforming to Einstein's general relativity. Now Einstein's theory demands conservation of mass. There is no way of fitting it in with postulate A. However, it can be fitted in with postulate B if we refer it to a unit of mass which increases with respect to the nucleon mass in proportion to t^2. With respect to this new unit, the mass of a piece of matter is constant.

I believe postulate B is to be preferred, in spite of its difficulty in explaining crystal growth, because of its agreement with Einstein's theory. It allows one to develop a reasonable cosmology, whose main ideas we shall now examine.

The Two Metrics.

With the new unit of mass we require new units of distance and time, differing from the atomic units. We shall take the velocity of light referred to the new units to be still 1, so the units of distance and time are both changed in the same ratio. We then have a new metric ds_E required for the Einstein equations, differing from the metric ds_A provided by atomic measurements.

To obtain the ratio of the two metrics, let us discuss the motion of the earth in its orbit round the sun, neglecting the eccentricity. From Newton's laws

$$\gamma M = v^2 r ,$$

where M is the sum's mass and v and r are the velocity of the earth and radius of the orbit. The formula must apply both in atomic units and in Einstein units. With Einstein units $\gamma = 1$ and M, v and r are constants. With atomic units v has the same value as with Einstein units, so it is still a constant. But $\gamma : t^{-1}$ and $M : t^2$, owing to the continuous creation of matter. Thus r is proportional to t in atomic units, while it is constant in Einstein units. So $r_A = t r_E$.

The same ratio must apply to all measurements of distance and time with the two sets of units, so we have

$$ds_A = t\, ds_E . \tag{1}$$

The epoch may be expressed either in Einstein units or in atomic units. The t in formula (1) is the epoch referred to atomic units. If we use τ to denote the epoch referred to Einstein units, we have

$$dt = t d\tau ,$$

so

$$\tau = \log t , \qquad (2)$$

ignoring a possible constant of integration.

One must use the Einstein units and the time τ when one is applying the laws of classical mechanics, either the Einstein theory or its Newtonian approximation. One must use the atomic units and the time t when one is applying the laws of quantum mechanics. There is thus a cosmical limitation on Bohr's Correspondence Principle which expresses the similarity of the quantum and classical laws.

Referred to the Einstein units all the atomic "constants" will be varying. The radius of a Bohr orbit $a : t^{-1}$. The mass of the electron $m : t^{-2}$. The velocity u of the electron in its orbit is the same in Einstein as in atomic units, so it is constant. The acceleration of the electron in a Bohr orbit is

$$e^2 / m a^2 = v^2 / a ,$$

so $e^2 = m\, a\, v^2 : t^{-3}$. It has sometimes been supposed that the reciprocal fine-structure constant h / e^2 might be varying in proportion to log t, but there is observational evidence that it does not vary. Taking it to be constant, we find $h : t^{-3}$.

The idea of having two times connected by (2), one for classical mechanics and one for atomic events, was first proposed by E. A. MILNE [3]. He set up a general theory of world structure, but he did not make the fundamental hypothesis of the present paper and the details of his work are not in agreement with those of the present theory. For example he has $h : t$. (See p. 120 of Milne's book).

The Einstein Model.

The distance of a neighboring galaxy in atomic units is kt. In Einstein units it is, according to (1), just k, a constant. Referred to Einstein units the galaxies are not receding, but keep approximately at a constant distance. So referred to Einstein units we have Einstein's static universe as a first approximation.

If we work in terms of this Einstein picture we must suppose that an atomic clock, marking out units $\Delta t = 1$, will mark out units $\Delta\tau = t^{-1}$. With increasing t these units continually get smaller, so the atomic clock is continually speeding up.

The time of creation $t = 0$ corresponds to $\tau = -\infty$. So in the Einstein picture the universe has always existed. But this does not mean unlimited time available for evolution, since as τ goes back to $-\infty$ all physical processes get slowed up with the atomic clocks. The situation is similar to that discussed by LEMAÎTRE [4] for his model in which the time of creation was pushed back to the infinite past.

To understand how the red shift of the galaxies arises in the Einstein model where they are not receding, one must take into account that their light was emitted in the past when atomic clocks were slower. The wave length of the emitted light was referred to these slow atomic clocks. The wave length remains constant, in Einstein units, as the light travels to us. When it arrives here it is referred to the present atomic clocks and appears longer. The increase is in the proportion t/t_e, where t_e is the time of emission. Thus the red shift is $z = (t - t_e)/t_e$.

With the Einstein static model we have a natural unit for the time τ provided by the radius of the universe. Let this radius, referred to the Einstein metric, be R_E. We may take $R_E = 1$. We then have a definite unit for τ.

With definite units for τ and t, the formula (2) should be amended to

$$\varkappa\tau = \log\ (\mathrm{K}t)\ ,$$

where $\varkappa$ and K are constants of the order of magnitude 1. We see at once that K has no physical significance. It merely changes the origin of τ. So we take $\mathrm{K} = 1$ and get

(3) $$\varkappa\tau = \log t\ .$$

The $\varkappa$ that survives here does have physical significance.

To express its physical significance explicitly, take a second time t' corresponding to τ'. We get

$$\varkappa\ (\tau - \tau') = \log\ (t/t')\ .$$

Taking $t/t' = e$, we get $\varkappa\ (\tau - \tau') = 1$. So $\varkappa$ is the Einstein time interval required for light to travel the radius of the universe divided by the Einstein time interval during which atomic clocks speed up by a factor e.

The formula (3) leads to

$$\varkappa\ d\tau = t^{-1}\ dt\ .$$

Thus the formula (1) connecting the two metrics must be amended to

(4) $$ds_{\mathrm{A}} = \varkappa t\ ds_{\mathrm{E}}\ .$$

The factor $\varkappa$ must be of the order 1, but there is no theoretical way of deciding what it should be with our present knowledge. It could only be calculated from a specific theory giving a connection between the universe and the atom, and we are far from having such a theory. We can get some information about $\varkappa$ from observation, connecting the average density of matter with the Hubble constant.

Let R_A be the radius of the universe in atomic units. From (4)

$$R_A = \varkappa t \, R_E = \varkappa t$$

since we are taking $R_E = 1$. We thus get another physical meaning for $\varkappa$, namely, the radius of the universe in atomic units divided by the present epoch in atomic units.

With Einstein's static universe the density of matter, referred to the natural unit of mass, is

$$\rho = (4\pi R^2)^{-1}$$

The average density of matter in the actual universe is not known very accurately, because one does not know how much non-luminous matter there is, in the form of black holes or intergalactic gas. But their contributions are probably not much greater than that of luminous matter. Using reasonable estimates, one gets for R about 80×10^9 years. The now-accepted value for the Hubble constant gives for the present epoch 20×10^9 years. So we find $\varkappa$ is about 4.

The usual cosmological theories require the radius and the epoch to be closely equal and this factor 4 is very disturbing to cosmologists. They usually assume that there must exist a large amount of unobservable matter, but it would be necessary to increase the density by a factor 16 to resolve the discrepancy. With the present theory there is no discrepancy, because there is no theoretical value for $\varkappa$.

Consequences.

The foregoing theory all follows from two basic assumptions, the fundamental hypothesis at the beginning and the postulate B governing the continuous creation of matter. These assumptions appear plausible in the light of our present knowledge, but still they are conjectures and can only be proved by a comparison of their consequences with observation. Let us examine the consequences in regions where a clash with observation might show up.

One may consider the earth's temperature changes during geological times. There is evidence that primitive life existed on earth 3×10^9 years ago, so the temperature then should not have been too widely different from what it is now. TELLER [5] has shown that the luminosity L of a star like the sun is proportional to $\gamma^7 M^5$. With $\gamma : t^{-1}$ and $M : t^2$, we get $L : t^3$. The rate at which the earth receives heat from the sun is $L/r^2 : t$. So it was somewhat less in the past. This may have been partly compensated by increased radioactivity inside the earth. In any case the theory would not require big temperature changes which would be inconsistent with the paleontological evidence.

According to the present theory the earth must have been expanding during geological times, owing to the continual creation of new matter inside it. The observed drifting apart of the continents supports this view; also the occurrence of rifts, in the continents and oceans. P. Jordan has written a great deal on this subject [6].

The conservation of energy in Einstein units requires that the number of atoms in a particular piece of matter shall increase proportionally to t^2. It requires similarly that the number of photons in a particular beam of light shall increase. The energy of a photon is $h\nu$ and we have $h : t^{-3}$ in Einstein units while ν is constant. (The constancy of ν in Einstein units and its decrease proportionally to t^{-1} in atomic units is what leads to the red shift). Thus the energy of a photon decreases proportionally to t^{-3}. So the number of photons in the beam must increase proportionally to t^3.

This effect will cause the apparent brightness of a distant galaxy or quasar to be increased. For a galaxy or quasar with red-shift z, the apparent brightness will be increased by a factor $(1 + z)^3$. If we know the absolute brightness, we would have a strong way of testing the theory. But of course we do not know it. We might assume that the average absolute brightness of the distant objects is statistically the same as that of the near ones. There is then some evidence of an enhancement of apparent brightness of the distant objects such as the theory requires. But the assumption is not a reliable one, because the distant objects are being observed at an earlier stage in their history and are not therefore in the same condition.

For extremely distant objects there will be a further enhancement effect arising from the curvature of space. If the $\varkappa$ of equation (3) really has about the value 4, this effect will not be appreciable except for objects considerably farther away than any yet observed.

The increase in the number of photons must apply also to the microwave radiation that is observed falling continuously on the earth and is believed to come from a primordial fireball. With conservation of the number of photons, if this radiation is black-body at a certain time, it remains black-body at later times and just gets transformed to a lower temperature corresponding to the red shift. With the number of photons increasing, as required by the present theory, the black-body character is not preserved. If initially grey, the radiation approaches black with the passage of time, and eventually passes through the black stage and becomes super-black.

It would be against the present theory if the radiation was observed to be black at the present time, as that would involve an unjustifiable coincidence. Fortunately for the theory it is not observed to be black. Observations made on the earth's surface of microwaves that penetrate the atmosphere agree with Planck's formula for a black body, but they can be made only for a range of wave lengths where they would fit equally well the formula for a grey body at a higher temperature. Observations for shorter wave lengths made by instruments in rockets above the earth's atmosphere support the grey-body formula.

The most definite test of the present theory will probably be provided by radar observations of the planets. The discussion we made of the earth's orbit shows that, in atomic units, the combined influence of the weakening gravitational constant and the increasing mass of the sun causes an increase in the radius of the earth's orbit, amounting to about 5×10^{-11} per year. All planetary distances should increase in the same ratio. This would be a cosmological effect, to be superposed on other planetary disturbances. Radar observations of planetary distances can now be made with extremely high accuracy. SHAPIRO [7] asserts that the cosmological effect, if it exists, should show up in a few years time.

Summary

Evolutionary cosmology was first proposed by Lemaître. He imagined the universe to have started at a definite time with a single highly radioactive atom. All that we see now, the galaxies and stars, are products of its disintegration. The universe is thus always diverging more from its original state.

If we use an atomic clock to measure time, we get a definite number t for the present time, of the order 10^{39}. A reasonable development of Lemaître's ideas follows if we assume that all fundamental large numbers of this order that can be constructed from the data of astronomy and atomic physics are connected with t and increase proportionally with it.

In order to fit in this theory with Einstein's, one must assume that the Einstein metric ds_E is not the same as the metric ds_A given by atomic clocks. Their ratio must vary with time, according to $ds_A = t\ ds_E$. Thus atomic clocks are continually speeding up relative to the Einstein metric.

REFERENCES

[1] LEMAÎTRE, G., *British Association Report,* p. 605 (1931).

[2] DIRAC, P.A.M., *Proc. Roy. Soc. A, 165,* 199 (1938).

[3] MILNE, E.A., *Kinematic Relativity,* Oxford, p. 36 (1947).

[4] LEMAÎTRE, G., *Ann. Soc. Scient.* Bruxelles 47A, 40 (1927) or Monthly Notices of R. A. S., *91,* 483 (1931).

[5] TELLER, E., *Phys. Rev., 73,* 801 (1948).

[6] JORDAN, P., *Cahier de Physique, 194,* 357 (1966). Also the book, The Expanding Earth, Pergamon Press (1971).

[7] SHAPIRO, I.I., *Scientific American, 219,* 32 (1968).