proportional to distance. The final end here is a universe in which all matter has shrunk to nothing.

On the other hand, if the universe is expanding, the stars are merely pouring out their radiation into a bottomless pit, since the space to be filled with radiation is for ever increasing in amount. The total energy of the universe is for ever decreasing in amount, because radiation does work in pressing out the boundaries of the universe—just as a gas loses energy and so cools, when it expands and presses back the boundaries of its 'universe'. Thus the mass of the stars is continually changing into energy, while this energy in turn changes into mere additions to the size of the universe. There is conservation neither of mass nor of energy. Nor, if the evidence of the cosmic radiation is to be trusted, is there any conservation of matter. Matter turns into energy and energy into mere bigness of space.

Suppose some infallible oracle offered to give a 'Yes' or 'No' answer to two scientific questions for each of us. Personally, I think I might choose as my two questions:

1. Does the main energy of stellar radiation come from the annihilation of matter?

2. Is the universe expanding at about the rate indicated by the spectra of the nebulæ?

By Abbé G. Lemaître, Observatory, Louvain.

I PROPOSE to give some answer to the two questions raised by Sir James Jeans, which so clearly summarise the present state of the problem of the evolution of the universe. I will begin with the second question, because I think that its solution may throw some light on the first one: "Is the universe expanding at about the rate indicated by the spectra of the nebulæ", the atomic constants not being modified by some artificial change of gauge? I add these words, because it is clear that any artificial expansion could be provided by arbitrarily varying the units of length, time, and mass. Expansion of the universe is in some sense relative: it is relative to the whole set of essential properties of matter being assumed to be constant.

The expansion of the universe is a matter of astronomical facts interpreted by the theory of relativity, with the help of assumptions as to the homogeneity of space, without which any theory seems to be impossible. I shall not discuss the legitimacy of this interpretation, as I do not know any definite objection made against it and this is not the place; and it is not necessary to give a new popular version of the leading principles of the theory of relativity. I shall rather try to show that the universe must be expanding, or rather that the most necessary processes of evolution are contradictory to the view that space is and has always been static.

It has been pointed out by Sir Arthur Eddington that a static universe is unstable, and he proposed the problem of finding the possible causes of its expansion. He suggested that such a cause might be the formation of condensations. I obtained recently a solution of this problem, and the main results are as follows:

When the expansion is already started, the effect of kinetic energy or pressure of radiation is quite negligible. On the contrary, pressure is the chief factor in the question of instability of a static universe. If the pressure were rigorously zero, the expansion could never appear. But, if the pressure (or kinetic energy) is not zero, any diminution of pressure must start the expansion. For example, a world full of radiation starts expanding as soon as the radiation can transform itself into matter.

When condensations exist or are formed, the problem is complicated by gravitational effects; but it can be shown that the general expansion of the universe depends entirely on the density of kinetic energy or of pressure at the places where the gravitational influences of the condensations cancel one another. I call these places (for brevity) 'neutral zones'. Condensation in itself has no direct effect whatever on the stability of the universe: but condensations would necessarily induce a rarefaction at the neutral zone and so a diminution of the density of kinetic energy at the neutral zone; and this must induce expansion.

We can conclude that any general process of condensation, occurring in a world where the kinetic energy does not vanish, must induce expansion. Therefore, practically, the expectation of Sir Arthur Eddington is fully confirmed. For example, formation of stars out of a primeval gas starts the expansion; formation of extra-galactic nebulæ out of a uniform mass of gas or of stars starts the expansion. I think that these results add much weight to the fact that the actual velocity of expansion fixes a limit to the time scale of the evolution, as we must rule out of our speculations every process which would start a premature expansion of space.

Even if we had no experimental evidence of the expansion of space, considerations of stability would fix a limit to the time-scale of evolution. The reason is that, if the universe has existed for too long a time, any general process of condensation would be contradictory to the actual value of the density of matter. Although this quantity is not known with great accuracy, its value may give some idea of the maximum scale of evolution. I find that any general process of condensation, even of very moderate intensity, cannot have happened earlier than a few hundred thousand million years ago.

As stated by Sir James Jeans, this brings almost complete chaos into the already chaotic problem of stellar evolution. A complete revision of our cosmological hypothesis is necessary, the primary condition being the test of rapidity. We want a 'fireworks' theory of evolution. The last two thousand million years are slow evolution: they are ashes and smoke of bright but very rapid fireworks.

I think that the key of the problem is afforded by the discovery of the cosmic rays. Cosmic rays are of enormous energy. Their intensity is estimated to be about one-tenth of that of the light coming to us from the stars. If these rays are really cosmic, their energy is much bigger than that of the light of the stars, because it must be of equal intensity all over space. Simple computation shows that the energy of cosmic rays is comparable in amount to the whole energy of matter, being possibly one thousandth, and at least one hundred thousandth, of the total energy of matter.

If the cosmic rays originated chiefly before the actual expansion of space, their original energy was even bigger, and it has been reduced by the expansion in the ratio of the change of the radius of the universe during the time of their transmission through free space. We get photographs of nebulæ at a distance of about one hundred million light years; light from these nebulæ travelled through space during about one hundredth of the time of expansion. It does not seem improbable that the cosmic rays have travelled around one hundred times longer and were really produced by the process of the formation of the stars. This may give the solution of the puzzle. The only energy we know which is comparable to the energy of the cosmic rays is the matter of the stars. Therefore it seems that the cosmic rays must have originated from the stars.

Now the stars are surrounded by an atmosphere, and an atmosphere would altogether prevent any escape of cosmic rays from the inside of a star. The explanation seems to be that the cosmic rays went off from the stars at a time when the stars had no atmosphere. The stars are born without atmosphere; the atmosphere evolved after the escape of the cosmic rays.

We are thus led to the conclusion that the stars were born some ten thousand million years ago without atmospheres, and that the cosmic rays are outstanding features of the formation of a star.

How could we explain such a phenomenon as that? Sir James Jeans has given strong reasons for admitting the existence of atoms of considerably higher atomic weight than our actual dead atoms. Cosmogony is atomic physics on a large scale—large scale of space and time—why not large scale of atomic weight? Radioactive disintegration is a physical fact, cosmic rays are like the rays from radium. Have they not escaped from a big scale super-radioactive disintegration, the disintegration of an atomic star, the disintegration of an atom of weight comparable to the weight of a star.

The birth of a star would be an atom of weight somewhat greater than the actual weight of the star, and the star would be formed by the super-radioactive disintegration of its original atom. It is conceivable that the greater part of the products of disintegration would be kept back together by the gravitational attraction of such a massive atom, although a considerable part, say one thousandth, should be able to escape into free space at the beginning of the evolution, before the products of disintegration are numerous enough to form an atmosphere. Cosmic rays would be glimpses of the primeval fireworks of the formation of a star from an atom, coming to us after their long journey through free space.

The frequency of cosmic rays is, of course, very high; nevertheless, it may be thought to be too low to be the by-product of such a tremendous disintegration of matter. However, it must be realised that the observed frequency of the cosmic rays is not the original frequency. The original frequency has been reduced in the ratio of the expansion of space, and was at least twenty times greater than the observed frequency.

I think that a possible test of the theory is that, if I am right, cosmic rays cannot be formed uniquely of photons, but must contain, like the radioactive rays, fast beta rays and alpha particles, and even new rays of greater masses and charges. I have shown that the momenta of such rays must be reduced by the expansion in about the same ratio as that of the photons.

The mass of a star should be determined by the weight of its original atom, and it is conceivable that stars might be born with different masses. If the mass of the original atom is too big, the star must be finally broken up by radiation pressure, and the original atom must give birth to a cluster of stars, chiefly formed by stars of maximum mass. If the star comes from an atom, both masses and luminosity are determined by the weight of the original atom. Thus this theory accounts for a mass-luminosity relation.

The actual theory does not completely bring order into the chaotic state of cosmogony imposed by the fact of the expansion of space. Explanation of the approximate equipartition of energy between the stars, or evolution with loss of mass along the Russell diagram, might be dismissed with regret. But I do not see any way to retain these processes of evolution, because they are altogether too slow.

If I had to ask a question of the infallible oracle alluded to by Sir James Jeans, I think I should choose this: "Has the universe ever been at rest, or did the expansion start from the beginning?" But, I think, I would ask the oracle not to give the answer, in order that a subsequent generation would not be deprived of the pleasure of searching for and of finding the solution.

If the total time of evolution did not exceed, say, ten times the age of the earth, it is quite possible to have a variation of the radius of the universe going on, expanding from zero to the actual value. I would picture the evolution as follows: At the origin, all the mass of the universe would exist in the form of a unique atom; the radius of the universe, although not strictly zero, being relatively very small. The whole universe would be produced by the disintegration of this primeval atom. It can be shown that the radius of space must increase. Some fragments retain their products of disintegration and form clusters of stars or individual stars of any mass. When the stars are formed, the process of formation of the extra-galactic nebulæ out of a gaseous material, proposed by Sir James Jeans, could be retained for the star-gas filling the space. The numerical test works out equally well for this case.

Whether this is wild imagination or physical hypothesis cannot be said at present, but we may hope that the question will not wait too long to be solved.

We want two things. First, a theory of nuclear structure sufficient to be applied to atoms of extreme weights. For these atoms, the problem cannot be separated into a nuclear problem and a problem of surrounding electrons; because it is easily seen that the K ring would merge into the nucleus. We must wait, but we may trust the physicists that we do not have to wait too long. The second thing we want is a better knowledge of the nature of the cosmic rays. The correlation of the theory of nuclear structure with further observations on the cosmic rays must answer yes or no to our question; and we shall prefer this answer, however incomplete it may be, to any answer of any infallible oracle.

By Prof. W. de Sitter, Observatory, Leyden.

I HAVE been asked to make a short contribution to this discussion about the evolution of the universe. I hope you will find it short, although its length will, I fear, exceed the diameter of the earth's orbit round the sun. This way of expressing a time in a unit of length is perhaps somewhat unusual. To have a distance expressed in a unit of time is, of course, very familiar. A light-year has become an accepted unit of distance.

I have purposely used the inverse method to direct attention to the fact that the corresponding units of time and of space are so very widely different in relation to actual phenomena. The diameter of the earth's orbit enormously exceeds all lengths that we ever come across in our daily life, whilst a quarter of an hour is considered a short interval. Similarly, a thousand million light-years is a long distance, in fact many times greater than any actual distance of which we have certain cognisance, but a thousand million years is a short time in the evolution of the universe. It is only a third or a quarter of the accepted age of the earth, and I do not think geophysicists will be ready to take off even one single zero. We believe, and so far as I can see on good grounds, that the ages of the sun and the majority of the stars are at least a thousand times longer. The time needed for the development of a double star, or even a quadruple or sextuple system, and that required for the evolution of a stellar system or spiral nebula are at least of the same order.

In the farthest galaxies that we can observe things appear to be very much the same as in our immediate neighbourhood. There seems to be no indication that these far-away systems are in an appreciably earlier state of evolution than our own.