GEORGES LEMAITRE:

The Primeval Atom

Introduction

THE PRIMEVAL ATOM hypothesis is a cosmogonic hypothesis which pictures the present universe as the result of the radioactive disintegration of an atom.

I was led to formulate this hypothesis, some fifteen years ago, from thermodynamic considerations while trying to interpret the law of degradation of energy in the frame of quantum theory. Since then, the discovery of the universality of radioactivity shown by artificially provoked disintegrations, as well as the establishment of the corpuscular nature of cosmic rays, manifested by the force which the Earth's magnetic field exercises on these rays, made more plausible an hypothesis which assigned a radioactive origin to these rays, as well as to all existing matter.

Therefore, I think that the moment has come to present the theory in deductive form. I shall first show how easily it avoids several major objections which would tend to disqualify it from the start. Then I shall strive to deduce its results far enough to account, not only for cosmic rays, but also for the present structure of the universe, formed of stars and gaseous clouds, organized into spiral or elliptical nebulae, sometimes grouped in large clusters of several thousand nebulae which, more often, are composed of isolated nebulae, receding from one another according to the mechanism known by the name of the expanding universe.

For the exposition of my subject, it is indispensable that I recall several elementary geometric conceptions, such as that of the closed space of Riemann, which led to that of space with a variable radius, as well as certain aspects of the theory of relativity, particularly the introduction of the cosmological constant and of the cosmic repulsion which is the result of it.

Closed Space

All partial space is open space. It is comprised in the interior of a surface, its boundary, beyond which there is an exterior region. Our habit of thought about such open regions impels us to think that this is necessarily so, however large the regions being considered may be. It is to Riemann that we are indebted for having demonstrated that total space can be closed. To explain this concept of closed space, the most simple method is to make a small-scale model of it in an open space. Let us imagine, in such a space, a sphere in the interior of which we are going to represent the whole of closed space. On the rim surface of the sphere, each point of closed space will be supposed to be represented twice, by two points, A and A', which, for example, will be two antipodal points, that is, two extremities of the same diameter. If we join these two points A and A' by a line located in the interior of the sphere, this line must be considered as a closed line, since the two extremities A and A' are two distinct representations of the same, single point. The situation is altogether analogous to that which occurs with the Mercator projection, where the points on the 180th meridian are represented twice, at the eastern and western edges of the map. One can thus circulate indefinitely in this space without ever having to leave it.

It is important to notice that the points represented by the outer surface of the sphere, in the interior of which we have represented all space, are not distinguished by any properties of the other points of space, any more than is the 180th meridian for the geographic map. In order to account for that, let us imagine that we displaced the sphere in such a manner that point A is super-posed on B, and the antipodal point A' on B'. We shall then suppose that the entire segment AB and the entire segment A'B' are two representations of a similar segment in closed space. Thus we shall have a portion of space which has already been represented in the interior of the initial sphere which is now represented a second time at the exterior of this sphere. Let us disregard the interior representation as useless; a complete representation of the space in the interior of the new sphere will remain. In this representation, the closed contours will be soldered into a point which is twice represented, namely, by the points B and B', mentioned above, instead of being welded, as they were formerly, to point A and A'. Therefore, these latter are not distinguished by an essential property.

Let us notice that when we modify the exterior sphere, it can happen that a closed contour which intersects the first sphere no longer intersects the second, or, more generally, that a contour no longer intersects the finite sphere at the same number of points. Nevertheless, it is evident that the number of points of intersection can only vary by an even number. Therefore, there are two kinds of closed contours which cannot be continuously distorted within one another. Those of the first kind can be reduced to a point. They do not intersect the

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outer sphere or they intersect it at an even number of points. The others cannot be reduced to one point, we call them the *odd contours* since they intersect the sphere at an odd number of points.

If, in a closed space, we leave a surface which we can suppose to be horizontal, in going toward the top we can, by going along an odd contour, return to our point of departure from the opposite direction without having deviated to the right or left, backward or forward, without having traversed the horizontal plane passing through the point of departure.

Elliptical Space

That is the essential of the topology of closed space. It is possible to complete these topological ideas by introducing, as is done in a geographical map, scales which vary from one point to another and from one direction to another. That can be done in such a manner that all the points of space and all the directions in it may be perfectly equivalent. Thus, Riemann's homogeneous space, or elliptical space, is obtained. The straight line is an odd contour of minimum length. Any two points divide it into two segments, the sum of which has a length which is the same for all straight lines and which is called the tour of space.

All elliptical spaces are similar to one another. They can be described by comparison with one among them. The one in which the tour of the straight line is equal to $\pi = 3.1416$ is chosen as the standard elliptical space. In every elliptical space, the distances between two points are equal to the corresponding distances in standard space, multiplied by the number R which is called the radius of elliptical space under consideration. The distances in standard space, called space of unit radius, are termed angular distances. Therefore, the true distances, or linear distances, are the product of the radius of space times the angular distances.

Space of Variable Radius

When the radius of space varies with time, space of variable radius is obtained. One can imagine that material points are distributed evenly in it, and that spatio-temporal observations are made on these points. The angular distance of the various observers remains invariant, therefore the linear distances vary proportionally to the radius of space. All the points in space are perfectly equivalent. A displacement can bring any point into the center of the representation. The measurements made by the observers are thus also equivalent, each one of them makes the same map of the universe.

If the radius increases with time, each observer see all points which surround him receding from him, and that occurs at velocities which become greater as they recede further. It is this which has been observed for the extra-galactic

nebulae that surround us. The constant ratio between distance and velocity has been determined by Hubble and Humason. It is equal to $T_H = 2 \times 10^9$ years.

If one makes a graph, plotting as abscissa the values of time and as ordinate the value of radius, one obtains a curve, the sub-tangent of which at the point representing the present instant is precisely equal to T_H.

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These are the geometric concepts that are indispensable to us. We are now going to imagine that the entire universe existed in the form of an atomic nucleus which filled elliptical space of convenient radius in a uniform manner.

Anticipating that which is to follow, we shall admit that, when the universe had a density of 10^{-27} gram per cubic centimeter, the radius of space was about a billion light-years, that is, 10^{27} centimeters. Thus the mass of the universe is 10^{54} grams. If the universe formerly had a density equal to that of water, its radius was then reduced to 10^{18} centimeters, say, one light-year. In it, each proton occupied a sphere of one angstrom, say, 10^{-8} centimeter. In an atomic nucleus, the protons are contiguous and their radius is 10^{-13}, thus about 100,000 times smaller. Therefore, the radius of the corresponding universe is 10^{13} centimeters, that is to say, an astronomical unit.

Naturally, too much importance must not be attached to this description of the primeval atom, a description which will have to be modified, perhaps, when our knowledge of atomic nuclei is more perfect.

Cosmogonic theories propose to seek out initial conditions which are ideally simple, from which the present world, in all its complexity, might have resulted, through the natural interplay of known forces. It seems difficult to conceive of conditions which are simpler than those which obtained when all matter was unified in an atomic nucleus. The future of atomic theories will perhaps tell us, some day, how far the atomic nucleus must be considered as a system in which associated particles still retain some individuality of their own. The fact that particles can issue from a nucleus, during radioactive transformations, certainly does not prove that these particles pre-existed as such. Photons issue from an atom of which they were not constituent parts, electrons appear there, where they were not previously, and the theoreticians deny them an individual existence in the nucleus. Still more protons or alpha particles exist there, without doubt. When they issue forth, their existence becomes more independent, nevertheless, and their degrees of freedom more numerous. Also, their existence, in the course of radioactive transformations, is a typical example of the degradation of energy, with an increase in the number of independent quanta or increase in entropy.

That entropy increases with the number of quanta is evident in the case of electromagnetic radiation in thermodynamic equilibrium. In fact, in black body radiation, the entropy and the total number of photons are both proportional to the third power of the temperature. Therefore, when one mixes radiations of

different temperatures and one allows a new statistical equilibrium to be established, the total number of photons has increased. The degradation of energy is manifested as a pulverization of energy. The total quantity of energy is maintained, but it is distributed in an ever larger number of quanta, it becomes broken into fragments which are ever more numerous.

If, therefore, by means of thought, one wishes to attempt to retrace the course of time, one must search in the past for energy concentrated in a lesser number of quanta. The initial condition must be a state of maximum concentration. It was in trying to formulate this condition that the idea of the primeval atom was germinated. Who knows if the evolution of theories of the nucleus will not, some day, permit the consideration of the primeval atom as a single quantum?

Formation of Clouds

We picture the primeval atom as filling space which has a very small radius (astronomically speaking). Therefore, there is no place for superficial electrons, the primeval atom being nearly an *isotope of a neutron*. This atom is conceived as having existed for an instant only, in fact, it was unstable and, as soon as it came into being, it was broken into pieces which were again broken, in their turn; among these pieces electrons, protons, alpha particles, etc., rushed out. An increase in volume resulted, the disintegration of the atom was thus accompanied by a rapid increase in the radius of space which the fragments of the primeval atom filled, always uniformly. When these pieces became too small, they ceased to break up; certain ones, like uranium, are slowly disintegrating now, with an average life of four billion years, leaving us a meager sample of the universal disintegration of the past.

In this first phase of the expansion of space, starting asymptotically with a radius practically zero, we have particles of enormous velocities (as a result of recoil at the time of the emission of rays) which are immersed in radiation, the total energy of which is, without doubt, a notable fraction of the mass energy of the atoms.

The effect of the rapid expansion of space is the attenuation of this radiation and also the diminution of the relative velocities of the atoms. This latter point requires some explanation. Let us imagine that an atom has, along the radius of the sphere in which we are representing closed space, a radial velocity which is greater than the velocity normal to the region in which it is found. Then this atom will depart faster from the center than the ideal material particle which has normal velocity. Thus the atom will reach, progressively, regions where its velocity is less abnormal, and its proper velocity, that is, its excess over normal velocity, will diminish. Calculation shows that proper velocity varies in this way in inverse ratio to the radius of space. We must therefore look for a notable attenuation of the relative velocities of atoms in the first period of expansion. From time to time, at least, it will happen that, as a result of favorable chances,

the collisions between atoms will become sufficiently moderate so as not to give rise to atomic transformations or emissions of radiation, but that these collisions will be elastic collisions, controlled by superficial electrons, so considered in the theory of gases. Thus we shall obtain, at least locally, a beginning of statistical equilibrium, that is, the formation of gaseous clouds. These gaseous clouds will still have considerable velocities, in relation to one another, and they will be mixed with radiations that are themselves attenuated by expansion.

It is these radiations which will endure until our time in the form of cosmic rays, while the gaseous clouds will have given place to stars and to nebulae by a process which remains to be explained.

Cosmic Repulsion

For that explanation, we must say a few words about the theory of relativity. When Einstein established his theory of gravitation, or generalized theory, he admitted, under the name of the principle of equivalence, that the ideas of special relativity were approximately valid in a sufficiently small domain. In the special theory, the differential element of space-time measurements had for its square a quadratic form with four coordinates, the coefficients of which had special constant values. In the generalization, this element will still be the square root of a quadratic form, but the coefficients, designated collectively by the name of *metric tensors,* will vary from place to place. The geometry of space-time is then the general geometry of Riemann at three plus one dimensions. The spaces with variable radii are a particular case in this general geometry, since the theory of spatial homogeneity or of the equivalence of observers is introduced here.

It can be that this geometry differs only apparently from that of special relativity. This is what happens when the quadratic form can be transformed, by a simple change of coordinates, into a form having constant coefficients. Then one says with Riemann that the corresponding variety (that is, space-time) is flat or Euclidian. For that, it is necessary that certain expressions, expressed by components of a tensor with four indices called Riemann's tensor, vanish completely at all points. When it is not so, the tensor of Riemann expresses the departure from flatness. Riemann's tensor is calculated by the average of second derivatives of the metric tensor. Starting with Riemann's tensor with four indices, it is easy to obtain a tensor which has only two indices like the metric tensor; it is called the contracted Riemannian tensor. One can also obtain a scalar, the totally contracted Riemannian tensor.

In special relativity, a free point describes a straight line with uniform motion, that is the principle of inertia. One can also say that, in an equivalent manner, it describes a geodesic of space-time. In the generalization, it is again presumed that a free point describes a geodesic. These geodesics are no longer representable by a uniform, rectilinear motion, they now represent a motion of a point

under the action of the forces of gravitation. Since the field of gravitation is caused by the presence of matter, it is necessary that there be a relation between the density of the distribution of matter and Riemann's tensor which expresses the departure from flatness. The density is, in itself, considered as the principal component of a tensor with two indices called the *material tensor;* thus one obtains as a possible expression of the material tensor $T\mu\nu$ as a function of the metric tensor $g\mu\nu$ and of the two tensors of Riemann, contracted to $R\mu\nu$ and totally contracted to R,

$$T_{\mu\nu} = aR_{\mu\nu} + bRg_{\mu\nu} + cg_{\mu\nu}$$

where a, b, and c are three constants.

But this is not all; certain identities must exist between the components of the material tensor and its derivatives. These identities can be interpreted, for a convenient choice of coordinates, a choice which corresponds, moreover, to the practical conditions of observations, as expressing the principles of conservation, that of energy and that of momentum. In order that such identities may be satisfied, it is no longer possible to choose arbitrarily the values of the three constants. b must be taken as equal to—$a/2$. Theory cannot predict either their magnitude or their sign. It is only observation which can determine them.

The constant a is linked to the constant of gravitation. In fact, when theory is applied to conditions which are met in the applications (in particular, the fact that astronomical velocities are small in comparison to the speed of light) and when one profits from these conditions by introducing coordinates which facilitate comparison with experiment, one finds that the geodesics differ from rectilinear motion by an acceleration which can be interpreted as an attraction in inverse ratio to the square of the distances, and which is exercised by the masses represented by the material tensor. This is simply the principal effect foreseen by the theory; this theory predicts small departures which, in favorable cases, have been confirmed by observation.

A good agreement with planetary observations is obtained by leaving out the term in c. That does not prove that this term may not have experimental consequence. In fact, in the conditions which were employed to obtain Newton's law as an approximation of the theory, the term in c would furnish a force varying, not in the inverse square ratio of the distance, but proportionally to this distance. This force could therefore have a marked action at very great distances although, for the distances of the planets, its action would be negligible. Also, the relation c/a, designated customarily by the letter *lambda,* is called the cosmological constant. When λ is positive, the additional force proportional to the distance is called *cosmic repulsion.*

The theory of relativity has thus unified the theory of Newton. In Newton's theory, there were two principles posed independently of one another: universal attraction and the conservation of mass. In the theory of relativity, these principles take a slightly modified form, while being practically identical to those of

Newton in the case where these have been confronted with the facts. But universal attraction is now a result of the conservation of mass. The size of the force, the constant of gravitation, is determined experimentally.

The theory again indicates that the constancy of mass has, as a result, besides the Newtonian force of gravitation, a repulsion proportional to the distance of which the size and even the sign can only be determined by observation and by observation requiring great distances.

Cosmic repulsion is not a special hypothesis, introduced to avoid the difficulties which are presented in the study of the universe. If Einstein has re-introduced it in his work on cosmology, it is because he remembered having arbitrarily dropped it when he had established the equations of gravitation. To suppress it amounts to determining it arbitrarily by giving it a particular value: zero.

The Universe of Friedmann

The theory of relativity allows us to complete our description of space with a variable radius by introducing here some dynamic considerations. As before, we shall represent it as being in the interior of a sphere, the center of which is a point which we can choose arbitrarily. This sphere is not the boundary of the system, it is the edge of the map or of the diagram which we have made of it. It is the place at which the two opposite, half-straight lines are soldered into a closed straight line. Cosmic repulsion is manifested as a force proportional to the distance to the center of the diagram. As for the gravitational attraction, it is known that, in the case of distribution involving spherical symmetry around a point, and that is certainly the case here, the regions farther away from the center than the point being considered have no influence upon its motion; as for the interior points, they act as though they were concentrated at the center. By virtue of the homogeneity of the distribution of matter, the density is constant, the force of attraction which results is thus proportional to the distance, just as is cosmic repulsion.

Therefore, a certain density exists, which we shall call the density of equilibrium or the *cosmic density,* for which the two forces will be in equilibrium.

These elementary considerations permit recognition, in a certain measure, of the result which calculation gives and which is contained in Friedmann's equation:

$$\left(\frac{d\mathrm{R}}{dt}\right)^{2}=-1+\frac{2\mathrm{M}}{\mathrm{R}}+\frac{\mathrm{R}^{2}}{\mathrm{T}^{2}}$$

The last term represents cosmic repulsion (it is double the function of the forces of this repulsion). T is a constant depending on the value of the cosmological constant and being able to replace this. The next-to-last term is double

the potential of attraction due to the interior mass. The radius of space R is the distance from the origin of a point of angular distance $\sigma = 1$. If one multiplied the equation by σ^2, one would have the corresponding equation for a point at any distance.

That which is remarkable in Friedmann's equation is the first term -1. The elementary considerations which we have just advanced would allow us to assign it a value which is more or less constant; it is the constant of energy in the motion which takes place under the action of two forces. The complete theory determines this constant and thus links the geometric properties to the dynamic properties.

Einstein's Equilibrium

Since, by virtue of equations, the radius R remains constant, the state of the universe in equilibrium, or Einstein's universe, is reached. The conditions of the universe in equilibrium are easily deduced from Friedmann's equation:

$$R_E = \frac{T}{\sqrt{3}}; \; \rho_E = \frac{3}{4\pi} \frac{1}{T^2}; \; M = \frac{T}{\sqrt{3}}.$$

In these formulas, the distances are calculated in light-time, which amounts to taking the velocity of light c as equal to unity, but, in addition, the unit of mass is chosen in such a way that the constant of gravitation may also be equal to unity. It is easy to pass on to the numerical values in C.G.S. by re-establishing in the formulas the constants c and G in such a manner as to satisfy the equations of dimension. In particular, if one takes T as being equal to 2×10^9 years, as we shall suppose in a moment, one finds that the density ρ_E is equal to 10^{-27} gram per cubic centimeter.

These considerations can be extended to a region in which distribution is no longer homogeneous and where even the spherical symmetry is no longer verified, provided that the region under consideration be of small dimension. In fact, it is known that, in a small region, Newtonian mechanics is always a good approximation. Naturally, it is necessary, in applying Newtonian mechanics, to take account of cosmic repulsion but, aside from this easy modification, it is perfectly legitimate to utilize the intuition acquired by the practice of classic mechanics and its application to systems which are more or less complicated. Among other things, it can be noted that the equilibrium of which we have just spoken is unstable and that the equilibrium can even be disturbed in one sense, in one place, and in the opposite sense in another region.

Perhaps it is necessary to mention here that Friedmann's equation is only rigorously exact if the mass M remains constant. While one takes account of the radiation which circulates in space and also of the characteristic velocities of the particles which cross one another in the manner of molecules in a gas and, as

in a gas, give rise to pressure, it is necessary to consider the work of this pressure during the expansion of space, in the evaluation of the mass or the energy. But it is apparent that such an effect is generally negligible, as detailed researches elsewhere have shown.

The Significance of Clusters of Nebulae

We are now in a position to take up again the description which we had begun of the expansion of space, following the disintegration of the primeval atom. We had shown how, in a first period of rapid expansion, gaseous clouds must have been formed, animated by great, characteristic velocities. We are now going to suppose that the mass M is slightly larger than $\dfrac{T}{\sqrt{3}}$.

The second member of Friedmann's equation will thus be able to become smaller, but it will not be able to vanish. Thus, we may distinguish three phases in the expansion of space. The first rapid expansion will be followed by a period of deceleration, during the course of which attraction and repulsion will virtually bring themselves into equilibrium. Finally, repulsion will definitely prevail over attraction, and the universe will enter into the third phase, that of the resumption of expansion under the dominant action of cosmic repulsion.

Let us consider the phase of slow expansion in more detail. The gaseous clouds are undoubtedly not distributed in a perfectly uniform manner. Let us consider in a region sufficiently small, and that only from the point of view of classic mechanics, the conflict between the forces of repulsion and attraction which almost produces equilibrium. We easily see that as a result of local fluctuations of density, there will be regions where attraction will finally prevail over repulsion, in spite of the fact that we have supposed that, for the universe in its entirety, it is the contrary which takes place. These regions in which attraction has prevailed will thus fall back upon themselves, while the universe will be entering upon a period of renewed expansion. We shall obtain a universe formed of regions of condensations which are separated from one another. Will not these regions of condensations be elliptical or spiral nebulae? We shall come back to this question in a moment.

Let us note that, although it is of rare occurrence, it will be possible for large regions where the density or the speed of expansion differ slightly from the average to hesitate between expansion and contraction, and remain in equilibrium, while the universe has resumed expansion. Could these regions not be identified with the clusters of nebulae, which are made up of several hundred nebulae located at relative distances from one another, which are a dozen times smaller than those of isolated nebulae? According to this interpretation, these clusters are made up of nebulae which are retarded in the phase of equilib-

rium; they represent a sample of the distribution of matter, as it existed every-where, when the radius of space was a dozen times smaller than it is at present, when the universe was passing through equilibrium.

The Findings of De Sitter

This interpretation gives the explanation for a remarkable coincidence upon which De Sitter insisted strongly, in the past. Calculating the radius of the universe in the hypothesis which bears his name, that is, ignoring the presence of matter and introducing into the formulas the value T_H given by the observation of the expansion, he obtained a result which scarcely differs from that which is obtained, in Einstein's totally different hypothesis of the universe, by introducing into the formulas the observed value of the density of matter. The explanation of this coincidence is, according to our interpretation of the clusters of nebulae, that, for a value of the radius which is a dozen times the radius of equilibrium, the last term in Friedmann's formula greatly prevails over the others. The constant T which figures in it is therefore practically equal to the observed value T_H: but since, in addition, the clusters are a fragment of Einstein's universe, it is legitimate to use the relationship existing between the density and the constant T for them. For $T = T_H$ one finds, as we have seen, that the density in the clusters must be 10^{-27} gram per cubic centimeter, which is the value given by observation. This observation is based on counts of nebulae and on the estimate of their mass indicated by their spectroscopic velocity of rotation.

In addition to this argument of a quantitative variety, the proposed interpretation also takes account of important facts of a qualitative order. It explains why the clusters do not show any marked central condensations and have vague forms, with irregular extensions, all things which it would be difficult to explain if they formed dynamic structures controlled by dominant forces, as is manifestly the case for the starclusters or the elliptical and spiral nebulae. It also takes into account a manifest fact which is the existence of large fluctuations of density in the distribution of the nebulae, even outside the clusters. This must be so, in fact, if the universe has just passed through a state of unstable equilibrium, a whole gamut of transition between the properly-termed clusters which are still in equilibrium, while passing through regions where the expansion, without being arrested, has nevertheless been retarded, in such a manner that these regions have a density which is greater than the average.

This interpretation permits the value of the radius at the moment of equilibrium to be determined at a billion light-years, and thus 10^{10} light-years for the present value of the radius. Since American telescopes prospect the universe as far as half a billion light-years, one sees that this observed region already constitutes a sample of a size which is not at all negligible compared to entire

space; hence, it is legitimate to hope that the values of the coefficient of expansion T_H and of the density, obtained for this restricted domain, are representative of the whole.

The only indeterminate which exists is that which is relative to the degree of approximation with which the situation of equilibrium has been approached. It is on this value which the estimate of the duration of expansion depends. Perhaps it will be possible to estimate this value by means of statistical considerations regarding the relative frequency of the clusters, compared to the isolated nebulae.

The Proper Motion of Nebulae

Now we must come back to the question of the formation of nebulae from the regions of condensation. We have seen that the characteristic velocities, or the relative velocities of gaseous clouds, which cross one another in the same place, must have been very large. Since certain of them, because of a density which is a little too large, form a nucleus of condensation, they will be able to retain the clouds which have about the same velocity as this nucleus. The proper velocity of the cloud so formed will hence be determined by the velocity of the nucleus of condensation. The nebulae formed by such a mechanism must have large relative velocities. In fact, that is what is observed in the clusters of nebulae. In the one which has been best studied, that of *Virgo*, the dispersion of the velocities about the mean velocity is 650 kilometers per second. The proper velocity must have been the proper velocity of all the nebulae at the moment of passage through equilibrium. For isolated nebulae, this velocity has been reduced to about one-twelfth, as a result of expansion, by the same mechanism which we have explained with reference to the formation of gaseous clouds.

The Formation of Stars

The density of the clouds is, on the average, the density of equilibrium 10^{-27}. For this density of distribution, a mass such as the Sun would occupy a sphere of one hundred light-years in radius. These clouds have no tendency to contract. In order that a contraction due to gravitation can be initiated, their density must be notably increased. This is what can occur if two clouds happen to collide with great velocities. Then the collision will be an inelastic collision, giving rise to ionization and emission of radiation. The two clouds will flatten one another out, while remaining in contact, the density will be easily doubled and condensation will be definitely initiated. It is clear that a solar system or a simple or multiple star may arise from such a condensation, through known mechanisms. That which characterizes the mechanism to

which we are led is the greatness of the dimensions of the gaseous clouds, the condensation of which will form a star. This circumstance takes account of the magnitude of the angular momentum, which is conserved during the condensation and whose value could only be nil or negligible if the initial circumstances were adjusted in a wholly improbable manner. The least initial rotation must give rise to an energetic rotation in a concentrated system, a rotation incompatible with the presence of a single body but assuming either multiple stars turning around one another or, simply, one star with one or several large planets turning in the same direction.

The Distribution of Densities in Nebulae

Here is the manner in which we can picture for ourselves the evolution of the regions of condensation. The clouds begin by falling toward the center, and by describing a motion of oscillation following a diameter from one part and another of the center. In the course of these oscillations, they will encounter one another with velocities of several hundreds of kilometers per second and will give rise to stars. At the same time, the loss of energy due to these inelastic collisions will modify the distribution of the clouds and stars already formed in such a manner that the system will be further condensed. It seems likely that this phenomenon could be submitted to mathematical analysis. Certain hypotheses will naturally have to be introduced, in such a way as to simplify the model, so as to render the calculation possible and also so as artificially to eliminate secondary phenomena. There is scarcely any doubt that there is a way of thus obtaining the law of final distribution of the stars formed by the mechanism described above. Since the distribution of brilliance is known for the elliptical nebulae and from that one can deduce the densities in these nebulae, one sees that such a calculation is susceptible of leading to a decisive verification of the theory.

One of the complications to which I alluded, a moment ago, is the eventual presence of a considerable angular momentum. In excluding it, we have restricted the theory to condensations respecting spherical symmetry, that is, nebulae which are spherical or slightly elliptical. It is easy to see what modification will bring about the presence of considerable angular momentum. It is evident that one will obtain, in addition to a central region analogous to the elliptical nebulae, a flat system analogous to the ring of Saturn or the planetary systems, in other words, something resembling the spiral nebulae. In this theory, the spiral or elliptical character of the nebula is a matter of chance; it depends on the fortuitous value of the angular momentum in the region of condensation. It can no longer be a question of the evolution of one type into another. Moreover, the same thing obtains for stars where the type of the star is determined by the accidental value of its mass, that is, of the sum of the masses of the clouds whose encounter produced the star.

Distribution of Supergiant Stars

If the spirals have this origin, it must follow that the stars are formed by an encounter of clouds in two very distinct processes. In the first place, and especially in the central region, the clouds encounter one another in their radial movement, and this is the phenomenon which we have invoked for the elliptical nebulae. Kapteyn's preferential motion may be an indication of it. But besides this relatively rapid process, there must be a slower process of star formation, beginning with the clouds which escaped from the central region as a result of their angular momentum. These will encounter one another in a to-and-fro motion, from one side to another of the plane of the spiral. The existence of these two processes, with different ages, is perhaps the explanation of the fact that supergiant stars are not found in the elliptical nebulae or in the nucleus of spirals, but that one observes them only in the exterior region of the spirals. In fact, it is known that the stars radiate energy which comes from the transformation of their hydrogen into helium. The supergiant stars radiate so much energy that they could only maintain this output during a hundred million years. It should be understood, thus, that, for the oldest stars, the supergiants may be extinct for lack of fuel, whereas they still shine where they have been recently formed.

The Uniform Abundance of the Elements

But it is doubtless not worthwhile to allow ourselves to be prematurely led to the attempted pursuit of the theory in such detail, but rather to restrict ourselves, for the moment, to the more general consequences of the hypothesis of the primeval atom. We have seen that the theory takes account of the formations of stars in the nebulae. It also explains a very remarkable circumstance which could be demonstrated by the analysis of stellar spectra. It concerns the quantitative composition of matter, or the relative abundance of the various chemical elements, which is the same in the Sun, in the stars, on the Earth and in the meteorites. This fact is a necessary consequence of the hypothesis of the primeval atom. Products of the disintegration of an atom are naturally found in very definite proportions, determined by the laws of radioactive transformations.

Cosmic Rays

Finally, we said in the beginning that the radiations produced during the disintegrations, during the first period of expansion, could explain cosmic rays.

These rays are endowed with an energy of several billion electron-volts. We know no other phenomenon currently taking place which may be capable of such effects. That which these rays resemble most is the radiation produced during present radioactive disintegrations, but the individual energies brought into play are enormously greater. All that agrees with rays of superradioactive origin. But it is not only by their quality that these rays are remarkable, it is also by their total quantity. In fact, it is easy, from their observed density which is given in ergs per centimeter, to deduce their density of energy by dividing by c, then their density in grams per cubic centimeter by dividing by c^2. Thus one finds 10^{-34} grams per cubic centimeter, about one ten-thousandth the present density of the matter existing in the form of stars. It seems impossible to explain such an energy which represents one part in ten thousand of all existing energy, if these rays had not been produced by a process which brought into play all existing matter. In fact, this energy, at the moment of its formation, must have been at least ten times greater, since a part of it was able to be absorbed and the remainder has been reduced as a result of the expansion of space. The total intensity observed for cosmic rays is therefore just about that which might be expected.

Conclusion

The purpose of any cosmogonic theory is to seek out ideally simple conditions which could have initiated the world and from which, by the play of recognized physical forces, that world, in all its complexity, may have resulted.

I believe that I have shown that the hypothesis of the primeval atom satisfies the rules of the game. It does not appeal to any force which is not already known. It accounts for the actual world in all its complexity. By a single hypothesis it explains stars arranged in galaxies within an expanding universe as well as those local exceptions, the clusters of nebulae. Finally, it accounts for that mighty phenomenon, the ultrapenetrating rays. They are truly cosmic, they testify to the primeval activity of the cosmos. In their course through wonderfully empty space, during billions of years, they have brought us evidence of the superradioactive age, indeed they are a sort of fossil rays which tell us what happened when the stars first appeared.

I shall certainly not pretend that this hypothesis of the primeval atom is yet proved, and I would be very happy if it has not appeared to you to be either absurd or unlikely. When the consequences which result from it, especially that which concerns the law of the distribution of densities in the nebulae, are available in sufficient detail, it will doubtless be possible to declare oneself definitely for or against.