COSMIC EVOLUTION

FIRST PART:

What is the Source of Stellar Energies?

It is becoming more generally and more clearly recognized that the source of the sun's heat does not lie in the gravitational contraction of the sun. It is true that if the sun had contracted from infinity to its present size the heat thus generated would be sufficient to supply the sun's present rate of radiation for about twenty millions of years. Not only is there no evidence that the sun was ever larger than it is at present, but, even, though we grant that it was larger, twenty millions of years is altogether inadequate to satisfy the geological requirements as to the age of the earth. The methods of determining the age of the earth from the thickness of the sedimentary rocks and from the amount of salt in the oceans agree in giving a minimum age of about three hundred millions of years, while the radioactive method determines the age of certain of the Archean rocks to be as high as sixteen hundred millions of years. It seems unlikely that even this figure represents the full age of the earth. Estimates recently made by Chamberlin and by Lord Rayleigh range from three to ten billions of years. Evidently the contraction hypothesis furnished less than one percent of the amount of heat that is necessary for the life history of the earth.

Turning from the study of the earth to a consideration of the dynamics of stellar systems it is seen that the difficulty is multiplied many fold. There are over eighty groups of stars which are known as globular star clusters. They contain many thousands of stars in what seems like a very minute region of space, although actually their size is very great, for the stars of which they are composed are doubtless, on the whole, comparable with the sun. Each star moves to and fro in the cluster under the gravitational attraction of all of the other stars of the cluster. This process of oscillating back and forth has gone on for so long a time that the clusters have arrived at a steady state in which the motions have become so uniformly distributed that the cluster has a spherical shape with a decreasing stellar density as one recedes from the center of the cluster. For every star that approaches the center of the cluster another recedes so that the general appearance of the cluster remains unaltered throughout the ages. If such a cluster has a radius of ten parsecs (thirty three light years) and contains one hundred thousand stars of the same mass as our sun, and these are conservative estimates, it would require ten millions of years for a single oscillation of the star, backwards and forward, across the cluster; and many thousands of such oscillations would have occurred before the exquisite symmetry of these clusters would have been attained. As we have no reason for supposing that they were all started upon their careers simultaneously, nor that they have just arrived at the state of equilibrium, it is hard to escape the conclusion that some of them, at least, are hundreds of billions of years old. Yet, notwithstanding this great age, none of them exhibits signs of decadence. They seem to be neither youthful nor senile; their state is one of vigorous maturity.

As for the galaxy as a whole, it has been remarked by Jeans that if the gravitation between the stars were suddenly annihilated, the effect of this annihilation upon the motion of the stars would be imperceptible even after the lapse of ten millions of years, so slowly does the gravitative attraction of the galaxy affect the motions of its individual members. Assuming that the radius of the galaxy is two thousand parsecs (6,600 light years) and that the average velocity of the stars is forty kilometers per second, and these are the ordinary assumptions of the astronomers; assuming furthermore that the galaxy is neither expanding nor contracting, and this is a pure assumption as we have no definite knowledge on the subject, then the total mass of the galaxy is slightly greater than nine hundred million times the mass of the sun. Assuming that there are this many stars within the boundaries of the galaxy (some of this matter, at least, is in the form of nebulae) then some other star will approach our sun as close as the orbit of the earth on an average of once in four millions of billions of years. These close encounters are fundamental events in the dynamics of the galaxy for they alter radically the distributions of the motions of the stars and bring about that particular type of chaotic distribution of motions that is necessary for a steady state. The studies of Charlier and of Jeans indicate that the steady state has not been attained in the galaxy, for in the steady state we should not have the phenomena of star clusters, star clouds, nor star streaming. But notwithstanding that the steady state has not been fully attained, their conclusions are that the galaxy is well advanced towards a steady state. It is not necessary, of course, that two stars should approach as close to one another as the earth is to the sun in order to affect their mutual motions, and more distant encounters are much more numerous. But Jeans has shown that it takes the more distant encounters forty thousand million years to produce a cross velocity of one kilometer per second, and he agrees with Charlier that a cross velocity equal to the velocity of the stars would require a million billion years.

These results are not sufficient to enable us to compute the age of the galaxy, but they are sufficient to indicate something of the order of magnitude of its age. It can hardly be less than thousands of billions of years, and it seems much more probable that it is of the order of millions of billions of years. These figures are startling, and would leave us in a somewhat skeptical frame of mind were it not for the fact that we have been somewhat prepared for their reception by the equally startling penetration of the astronomers into the depths of space. It has long been a commonplace among them that the galaxy is a physical unit so great that it takes light from fifteen to thirty thousand years to measure its diameter. Even though we bear in mind that light travels three hundred thousand kilometers per second and that there are over thirty one and a half millions of seconds in a year we appreciate but faintly the stupendous scale upon which the galaxy is built. It is roughly a billion times the size of the earth's annual orbit about the sun. It is certain that we cannot reflect upon such a magnificent organization without being prepared to grant that the time-scale required in its building is equally magnificent. The apparent motions of the stars in a million years as seen from the earth is less than the familiar terrestrial motions going on about us in a single second, and on such a scale it would require over two million billion years to correspond to a single life time of three score years and ten. Such an analogy, of course, is useful only in so far as it is helpful in maintaining our sense of proportion.

Although the geological evidences do not carry us as far back into the past as do the dynamical ones, nevertheless they are extremely valuable in that they assure us of the steadiness of the sun's light and heat throughout the geological record. The dynamics of the stellar systems deal only with the distributions of the stellar velocities under the action of gravitation, and it is quite immaterial in these studies whether the stars are hot or cold. If the contraction of the stars were the only source of stellar heat, in a few hundred million years the stars would all be dark and relatively cold bodies; but the distribution of the velocities under the action of gravitation would go on just the same. Eventually, that is to say after the lapse of a certain number of millions of billions of years, a steady state of motion will have been practically attained whether the stars continue to be incandescent or not; and if the masses remain unaltered, the galaxy has an almost indefinite future before it after it has attained the steady state. But the evidences of geology, so far as they go, indicate that the state of incandescence is one of permanence, and this is confirmed by the complete lack of evidence of the existence of cold, solid bodies of stellar mass.

The energy of the sun's radiation is about 3×10^{33} calories of heat per year. The radiation of the faintest known star is about one two hundredth of this, while the radiation of such brilliant stars as Rigel and Canopus must be a thousand or perhaps ten thousand times as great. How can such prodigious energies be maintained throughout the vast intervals of time which the dynamics of stellar systems seems to indicate; and furthermore, what becomes of this energy after it has assumed the form of radiation? Shall we think of it as spending an eternity upon a voyage which admits of no other incidents than a very rare reflection from or absorption by some physical object with a consequent increase in wave length? Or, shall we think of the radiant form of energy as but a phase in a grand cycle of existence? Obviously, such questions are fundamental ones in a rational cosmology. We cannot hope to answer them directly from experience. The best that we can do is to frame our answers in accordance with some chosen system of postulates and test them by their harmony or discord with our astronomical and our physical knowledge.

To most people it seems desirable to think of space as euclidian and infinite; the physical universe as infinite in extent, and such portions of it as come under our observations not essentially peculiar as compared with other portions; that our epoch of time has nothing essentially unique about it; and that, considered in a sufficiently large way, the physical universe is not tending towards some state which is inherently different from that with which we are familiar. Finally, we recognize that the physical universe is organized into units, such as atoms and molecules, crystals and cells, stars and galaxies, each of which is an organization of smaller units endowed with a certain amount of energy and possessing its own peculiar properties. We have no reason for supposing that the electron is the smallest physical unit, nor, indeed, that there is any smallest physical unit whatever: and similarly that there is no largest one. If we accept these postulates, then our cosmology, if it is rational, must be consistent with them, and at the same time in harmony with all of the known facts in every domain of physical science. As the hypotheses of physical science are rarely, if ever, in complete accord with all of the known facts, even when the field covered by the hypothesis is a relatively small one, it is hardly to be expected that the hypotheses of cosmology will be of a different character.

Consider for a moment a dilute solution of a chemical salt in water. If it were impossible to obtain concentrated solutions in the laboratory, and if our observations were limited to a modest range of dilution, we might conclude that the state of the salt in the solution was but little affected by a change in the dilution, for such would be the results of our experiments. Actually, we are able to carry the concentration to a point where a gradual change sets in and crystals appear. A similar error would result if our experiments in temperature were limited to but a few degrees. We would not recognize that a change occurs in the physical state when the temperature reaches a definite point.

These analogies should be useful to us in considering the effects of pressure. Such pressures as we can obtain in the laboratory affect the melting point, the rigidity and the density of a substance, but in general we think of a substance as being unaltered by pressure. One hundred thousand atmospheres is perhaps the upper limit of our experiment and this is a very modest range as compared with the tremendous pressures that are developed in the interiors of the astronomical bodies by the force of gravitation. The pressure at the center of the earth can scarcely be less than three million atmospheres. For astronomical bodies of the same densities the pressure at the centers varies directly as the square of the radius; so that a planet of twice the diameter of the earth and of the same density would be subject to twelve millions of atmospheres pressure at the center. But if such a planet were made of the same materials as the earth — an altogether reasonable assumption — then the extra amount of pressure would result in an increase of density and therefore a still further increase in the pressure at the center. As we do not know the law connecting pressure and density we cannot compute just what the pressure would be, but it is certain, at least, that in astronomical bodies in the same solid or liquid state and composed of the same materials, the pressure at the center increases faster than the square of the radius, provided the pressures are great enough to affect the densities, and the larger bodies will have greater densities than the smaller bodies.

From an astronomical point of view the earth is a small body, although it is the largest *solid* body with which we are acquainted. Planets and satellites smaller than the earth seem to be solid like the earth itself and of smaller density, while bodies larger than the earth are largely if not wholly gaseous and of much smaller density than the earth. Thus the earth seems to be near a maximum of density, and from the point of view of pressure this would seem to indicate that the pressure at the center of the earth is approaching a critical pressure beyond which a solid or liquid state cannot exist. In other words, a solid or liquid body much larger than the earth, and composed of the same substances, cannot exist on account of the great pressures developed in the interior. It is not reasonable to suppose that any organized structure, and the atom is known to be such, can withstand an unlimited amount of violence. We are not at liberty therefore to suppose that solid or liquid bodies can increase indefinitely in size, for the pressure at the center goes up faster that the square of the radius.

Just what the maximum size is we cannot tell from any laboratory experiments on matter, but we can examine the various astronomical bodies in the solar system, and this examination suggests that the earth is not far from the maximum size. The next larger body in the system is Uranus with a mass 14,4 times the mass of the earth, and then Neptune whose mass is 16,7 times the mass of the earth. If they were of the same density as the earth their diameters would be about 2,5 times the diameter of the earth and their central pressures would rise to about twenty millions of atmospheres. Actually they are not solid bodies, for their densities are 1,44 and 1,09 respectively, as compared with a density of 5,5 for the earth. It will be observed that Neptune is slightly more massive and slightly less dense than Uranus. These facts imply that the mass of Uranus is greater than the maximum solid mass, and consequently a large portion of its mass is in the gaseous state. Neptune is slightly farther from the maximum point, and a greater proportion of its mass is in the gaseous state since its density is smaller.

Saturn is the next larger body with a mass 94 times the mass of the earth. If it were as dense as the earth its diameter would be 4,5 times the diameter of the earth and its centrale pressure would be about seventy five millions of atmosphere. Its density, however, is only .63 that of water, and it is probably altogether gaseous.

This orderly relationship between the masses of the planets and their densities very strongly suggests that the pressure at the center of the earth is approaching a critical pressure at which the atoms begin to break down and their internal energies take the form of heat, a larger portion of the mass takes a gaseous form and the mean density of the planet diminishes. With a sufficiently large mass the heat generated would be sufficiently great to make to the entire mass gaseous, and this seems to be the case with Saturn.

It is evident that if all of the atoms at the center which are subjected to so great pressures should break down and yield up their internal energies simultaneously a violent explosion would ensue, and some such cataclysm may be the cause of temporary stars. But it is by no means necessary to suppose that this is the case. If we think of the atoms as in motion then the temperature and pressure at the center manifests itself to the individual atoms by the violence of their collisions. When we consider the very large number of atoms which enter into the problem and the great variety of their motions it is seen that the problem is a statistical one. The process begins when the pressure and temperature are what would be called « perfectly safe » by the collision of a pair of atoms which happen to be moving at speeds which are far above their normal speeds. The event is a very rare and unusual one, and the heat generated does not noticeably affect the general mass.

With increasing mass, and its accompanying higher pressures and temperatures, these extraordinary collisions become more frequent, though still excessively rare, and the temperature begins to rise. With rising temperatures the permanent gases hydrogen, helium, nitrogen, oxygen, etc., are driven from their chemical compounds, and the atmosphere is increased at the expense of the solid mass. Eventually, that is for sufficiently great mass, the solid part becomes hot throughout, and water exists only in the atmosphere. The importance of this will be appreciated by the fact that our own atmosphere would be increased three hundred times if the oceans were vaporized. The earth would be covered with a thick mantle of clouds; the diameter of the earth, as measured by an observer on some other planet would be noticeably increased, and the mean density consequently decreased. Rising temperatures with increasing masses would give exactly the reverse of the Laplacian condensation hypothesis, for the solid mass would gradually pass over into the gaseous state. No explosion would occur if the body under discussion were built up slowly so that the process of adjustment was gradual, and not, by the necessities of the case, a violent one.

While this change in the physical state is in progress there is a decline in the mean density since the conversion of a solid into a gas would result in a considerable increase of volume. But if a mass, already gaseous, should be still further increased, the resulting increase in pressure would result in a greater density, for there would be no increases of volume due to the conversion of solids into gases.

If the assumption that Saturn is wholly gaseous is correct then we should expect Jupiter, which is more than three times as massive as Saturn, to be more dense than Saturn; and this is actually the case, for the density of Jupiter is 1,25, or about twice that of Saturn.

If we had a planet three times as massive as Jupiter, we should expect it to be more dense than Jupiter for the same reason that Jupiter is more dense than Saturn. But the process of increasing density with increasing mass could not go on indefinitely with gaseous masses any more than it could with solid masses. The heat generated by the high temperatures and pressures in the interior would increase greatly with larger masses until the expansive tendencies, due to the heat generated, just balanced the compressive effects due to gravitation, and there would be a second maximum in the densities. For still greater masses the expansive forces of heat would exceed the compressive forces, and the density would again decline. We have no means of knowing for what mass this maximum density would occur: perhaps fifty times the mass of Jupiter. There is also some minimum gaseous mass which would become incandescent due to its generation of heat. It seems natural to identify this with the mass of maximum density, although in reality the two may be different. This point of maximum density would then separate large gaseous masses into two classes, the dark gaseous and the bright gaseous or stellar. The sun is one thousand times as massive as Jupiter, and it is in a state of intense incandescence, indicating that it is far beyond the point of maximum density. Its density is 1,4, or slightly greater than that of Jupiter.

We should now examine the consequences of this hypothesis that the energies of the stars are derived from a break down of the atoms due to the intensity of the gravitational stresses to which they are subjected in the interior of a star, and this is what we will do in the next second part of this article.

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