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GALACTIC EVIDENCES FOR THE TIME-SCALE OF THE UNIVERSE[1]

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AN important phase of modern astronomical research is concerned with the time scale of the universe, *i.e.*, with the specification of a natural unit of time in which it would be most convenient to describe the changing aspects of the astronomical universe. Stated in this manner, it is apparent that the solution to the problem of the time scale will not permit us (not at any rate in the first instance) either to "date" the present epoch in a "fundamental" calendar or to forecast with definiteness the "end." What it would allow us, however, is to specify an interval of time in which various aspects of the astronomical universe may be expected to change appreciably. Conversely, the solution to the problem of the time scale will ultimately depend on the study of a variety of different aspects of the universe and the establishment in each case of a time interval during which the aspect studied might change to an appreciable extent. And if such studies should lead us in most instances to time intervals which are of the same order of magnitude, it would not be unreasonable to attribute to a unit of time of this order of magnitude a fundamental significance. It would appear that this is the only manner in which a rational approach to the problem of the time scale can be made. However, in formulating the problem in this manner it is evident that a certain element of arbitrariness has been introduced into the discussion. But this is unavoidable and inherent in a problem in which the emphasis is on an order of magnitude and not on an absolute measure.

During the past twenty years many attempts have been made to establish a time scale in the sense de-

[1] Address given before the Philosophical Society of Washington on December 4, 1943.

scribed above.[2] But several of the arguments were inconclusive and in some cases even left room for violent disagreements. However, more recently, through the study of the dynamics of star clusters and the statistics of binary stars, some fresh evidences have come to light which bear on the question of the time scale. And it is the object of this report to describe the nature of these newer evidences.

To consider first the problem presented by galactic star clusters we shall take a concrete example and consider the case of the Pleiades. This star cluster includes some 200 stars in a spherical volume of radius about 3 parsecs (*i.e.,* approximately 10 light years). Moreover, a study of the internal motions in this cluster (made possible by some photographic plates of this cluster taken by Rutherford as early as 1870) has revealed that relative to the center of gravity the cluster members have a random motion with a root mean square velocity in the neighborhood of 500 meters per second. Since the average space density of stars in the general neighborhood of the sun is only about one star per ten cubic parsecs, it follows that in the Pleiades the star density is about twenty times that of the background "field" stars. Further, these field stars have motions relative to the center of gravity of the cluster of the order of 25 to 30 kilometers per second. Accordingly, it would appear that the Pleiades can be considered as an "isolated" stellar system, *i.e.,* practically uninfluenced by the field stars. And the question arises as to the permanence of such stellar aggregations. In order to answer this question we need to go into the dynamics of star clusters, and as this theory appears to have some general interest we may be allowed to elaborate on it a little.

First of all, it is evident that the gravitational force acting on a star is subject to fluctuations. The fluctuations arise simply as a consequence of the relative motions between the stars and the consequent changing complexion of the distribution of stars around any given one. In a general way it is clear that there will be practically no correlation in the forces (due to the near neighbors) acting on a star at two instants separated by an interval of the order required for an average star to traverse a distance equal to the average distance between the stars. For in this interval of time the complexion of stars around any given one may be expected to change radically. Now we may ask as to the effect of this fluctuating force on the motion of a star. In order to answer this question consider an interval of time of the order of a million years. During such an interval a star would have experienced some hundred elementary fluctuations, and a theoretical analysis shows[3] that the cumulative effect of such a large number of fluctuations has a two-fold consequence. First, it systematically decelerates the star in the direction of its motion and, second, superposes on this a random acceleration. More precisely, if we consider a time interval Δt long compared with the elementary fluctuations (but not so long that the increment in the velocity which the star may be expected to suffer is comparable with its initial velocity) then in the direction of its motion it will experience, on the average, a deceleration proportional to Δt. And the constant of proportionality, which may very well and, in fact, does depend on the magnitude of the initial velocity, may properly be called the *coefficient of dynamical friction:* it is dynamical because it operates only on stars in motion and it is friction because it acts as a brake on the motion of the star. Regarding the random part, it may be said that in consequence of this the mean *square* acceleration which the star may be expected to experience during a time Δt will also be proportional to Δt: the constant of proportionality which occurs here is sometimes called (for reasons which we shall not go into) the *coefficient of diffusion* in the velocity space.[4] The existence of these two terms in the acceleration experienced by a star may sound somewhat paradoxical. But it can be readily shown that these two terms (together with the relation which exists between them) are both necessary and sufficient for the maintenance of statistical equilibrium.

It will be noticed that the foregoing description of the effect of the fluctuating gravitational field on the motion of a star is very similar to the influence of the molecules of the surrounding liquid on the motion of suspended colloidal particles in the theory of the Brownian movement. Thus, in the latter theory, it is assumed that the colloidal particles experience both a dynamical friction (now given by Stokes's law) and a random acceleration (related in fact with Stokes's frictional coefficient in a definite manner). There is, however, one important difference: in the stellar case stars influence each other, while in Brownian motion the colloidal particles are influenced only by the molecules of the surrounding fluid. But physically, the close analogy that exists between the motion of a star in the fluctuating gravitational field of its neighbors and the motion of a colloidal particle describing Brownian motion results from the following circumstance: Even as the collision with a single molecule of the surrounding liquid hardly affects the motion of a colloidal particle, so also does an elementary fluctuation in the force due to the neighbors hardly affect

[2] For a comprehensive account of these attempts see H. N. Russell, SCIENCE, 92: 19, 1940.

[3] The interested reader may refer to S. Chandrasekhar, *Astrophysical Journal,* 97: 255–262, 1943.

[4] It can further be shown that the ratio of the diffusion coefficient to the frictional coefficient is a constant of the system.

the motion of a star; and in both cases what is of importance is the cumulative effect of a large number of separate events, each having only a very minute effect.

Having described the manner in which the motion of a star is influenced by a fluctuating force acting on it, it is evident that we should, in principle, be able to calculate the probability with which a star initially having a given velocity will acquire (for the *first time*) some other preassigned velocity at some specified later time. And if a star should acquire in this manner a velocity sufficient to escape from the entire gravitational attraction of the cluster altogether, then we should have calculated the probability that the star would escape from the cluster at the specified later time. In other words, we have here a rational means for estimating the rate at which stars may be expected to escape from a cluster and thus an estimate of the rate at which clusters tend to disintegrate. On carrying through the necessary calculations[5] it is found that we can express the probability that a star would have escaped from the cluster during a time t in the form

$$1 - e^{-t/t_0} \qquad (1)$$

where t_0 is a certain time related in a definite way to the physical parameters of the cluster (*e.g.,* its radius, star density, etc.). According to the foregoing formula, in a time equal to t_0 the probability that a star would have escaped from the cluster amounts to as much as 0.63. Accordingly, t_0 may be taken as a measure of the average life of the cluster. For the Pleiades it is found that t_0 is about 3×10^9 years. Since, however, the Pleiades are in no way exceptional as a galactic cluster it may be concluded that galactic clusters in general have mean lives of this order. On the other hand, galactic clusters appear to be an essential feature of the Milky Way system. It would, therefore, appear that the existence of galactic clusters like the Pleiades would point to a time scale for the galaxy of the order of 3×10^9 years. This is the first of the two major galactic evidences to which we referred at the outset. We now turn our attention to the second evidence.

As is well known, a very substantial fraction of all the stars occur as components of multiple stars. And by far the most important among these multiple stars are the binaries. We shall now indicate how from a study of the statistics of binary stars,[6] *i.e.,* from a study of the frequencies of occurrence of the various parameters of the binary such as its period, eccentricity, the semi-major axis of the relative orbit, etc., we can draw some conclusions bearing on the question of the time scale. As in the case of galactic clusters the basis for the discussion is again provided by considerations relating to stability. However, while the "instability" of the clusters arose from the possibility of its members accidentally acquiring under the influence of the other cluster members velocities sufficient to escape from the cluster, in the case of binaries the tendency towards disruption is caused by the tidal effects of the nearby stars. For, the distances of the neighboring stars from the two components of the binary, respectively, will be different; consequently, the net forces acting on the two components will also differ. For the separations between the components normally encountered, and which are of practical interest, this difference in the forces acting on the two components will in general be only very slight. But it is precisely this difference operating over sufficient lengths of time that will cause the eventual dissolution of a binary. Without going into the details of the calculation[7] it may be stated that under the conditions prevailing in the general neighborhood of the sun in the Milky Way, the time of dissolution of a binary can be expressed as

$$\tau = 2.2 \times 10^{15}\, a^{-3/2} \text{ years} \qquad (2)$$

where a denotes the semi-major axis of the relative orbit in astronomical units ($= 1.5 \times 10^8$ km). The meaning of the foregoing formula is simply that in a time τ the tidal effect of the neighboring stars is sufficient to accelerate one component of the binary relative to the other by an amount which will make the kinetic energy of relative motion of the two components exceed the gravitational binding energy between them. And now, according to formula (2), binaries with separations between 1,000 and 10,000 astronomical units will be "dissociated" in times ranging from 7×10^{10} to 2×10^9 years. This result can be reinterpreted as follows: Suppose we consider an interval of time of 10^{10} years. Then during such an interval the dynamical elements of binary orbits with semi-major axes between 1,000 and 10,000 astronomical units will have suffered substantial changes. In other words, for these binaries the distribution over the different parameters must (in course of 10^{10} years) tend towards what should be expected under conditions of statistical equilibrium. But it has been shown by V. A. Ambarzumian[8] that the observed distribution of the separations among the binaries, in the range 1000–10,000 astronomical units, is such that those with the larger separations occur with far less frequency than should be expected under conditions approximating those of equilibrium. Accordingly, we should

[5] For the details see S. Chandrasekhar, *Astrophysical Journal,* 98: 54–60, 1943.

[6] The most recent of such statistical studies is that due to G. P. Kuiper, *Astrophysical Journal,* 95: 201, 1942.

[7] For these see a forthcoming paper in the *Astrophysical Journal.*

[8] *Russian Astronomical Journal,* 14: 207, 1937; also *Nature,* 137: 537, 1936.

conclude that sufficient time has not elapsed for the tidal forces of the neighboring stars to appreciably modify the elements of binary orbits with separations in the range stated. This implies that 10^{10} years represents a true upper limit to the time scale, and would suggest a time scale of the order of, say, 5×10^9 years.

The discussion of the mean lives of galactic clusters and the statistics of binary stars agree therefore in pointing to a time scale of the order of a few billion years. We may now briefly summarize the other evidences which also point to a similar time scale. First, we have the geochemical evidence derived principally from the lead content of minerals containing uranium salts and leading to the ages of the igneous rocks containing these minerals. In our present context most interest is naturally attached to those determinations which lead to the greatest ages. Thus, the analysis of a pegmatite in Manitoba containing uranite, monozite and mica leads to three independent determinations of age ranging from 1,600 to 1,900 millions of years. We may say then that a billion and a half years represents a true lower limit to the age of the earth. An upper limit can also be found (as was first indicated by H. N. Russell) from the entire lead content of the earth's crust on the assumption that all of it has been derived as the end products of radioactive disintegrations. In this manner an upper limit of three and a half billion years has been estimated. In other words, the age of the earth has been bracketed between one and a half and three and a half billions of years. Similar ages have also been found for the meteorites from their helium content.

Still another evidence for the time scale comes from the velocity interpretation of the "red shift" shown by the extra-galactic nebulae and the velocity-distance relationship of Hubble. As is well known, this relationship can be interpreted as meaning that some two billion years ago all the nebulae were confined to a relatively very small volume and that they were projected with their present speeds in their present directions. It is, of course, possible that the velocities of the nebulae were different at earlier epochs, but the interpretation given is probably adequate for drawing inferences concerning the time scale.

Finally, we may also draw attention to the information that can be derived from clusters of extragalactic nebulae such as the Coma and the Virgo clusters. The Virgo cluster, for example, includes some 400 nebulae in a spherical volume of about 200,000 parsecs radius. It is not certain that the Newtonian laws of gravitation can be applied to objects of this size. But we can probably apply the theory which we have described for the galactic star clusters to the clusters of nebulae to obtain very rough estimates. In this manner Miss Tuberg[9] has recently estimated for the Virgo cluster a mean life of the order of 10^{11} years.

To conclude, then, we see that the geochemical evidence bearing on the age of the earth and meteorites, the galactic star clusters, the statistics of binary stars, the clusters of extragalactic nebulae and finally the system of the nebulae, all agree in pointing to a time scale of the order of a few billion years. It does not seem that this can be accidental.

[9] *Astrophysical Journal*, 98: 501, 1943.

SOVIET STUDIES ON VIRUSES[1]

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ON February 12 in 1892 a young man, Dmitrii Iwanowski, appeared before the Academy of Science at St. Petersburg and presented his second scientific contribution, a short four-page paper entitled "On the Mosaic Disease of the Tobacco Plant."[2] Most of this short paper was devoted to an innocuous discussion of the symptomatology of the disease as he had observed it in the Crimea, and it is only near the end that there was given a one-sentence description of an experiment which has come to be recognized as a landmark in medical history. This sentence goes as follows: "Yet I have found that the sap of leaves attacked by the mosaic disease retains its infectious qualities even after filtration through Chamberland filter-candles." This filtration experiment by Iwanowski led to the discovery of viruses, which we now recognize as a large group of infectious agents, smaller than ordinary living organisms, that may cause disease in man, animals, plants and bacteria. To this group belong the agents responsible for such diseases as smallpox, yellow fever, poliomyelitis, influenza, the virus pneumonias of man, horse encephalomyelitis, foot-and-mouth disease of cattle, hog cholera, rabies, dog distemper, fowl pox, certain types of tumorous growths in fowls and other animals, jaundice of silk-worms, various yellows and mosaic diseases of plants and

[1] Address at the Science Panel of the Congress of American-Soviet Friendship, New York, November 7, 1943. The complete proceedings of the Science Congress including the Medical Session will be published at a later date by the National Council of American-Soviet Friendship.

[2] D. Iwanowski, *Bull. Acad. Imp. Sci. St. Petersburg*, 3: 67, 1892.