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On the Evolution of Stellar Systems

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IN THIS lecture we shall consider some aspects of the problem of the evolution of stellar systems. We shall concentrate chiefly on *galaxies*. However, at the same time we shall treat here some questions connected with star *clusters* as component members of galaxies.

1. STELLAR SYSTEMS

An assembly of stars in which the motion of each member is determined chiefly by its interaction with other members of the assembly is called a *stellar system*. Not only galaxies but the star clusters and even the multiple stars fulfil the requirement of this definition, in the case when under the motions mentioned in it, the motions relative to the centre of gravity of the given assembly are understood.

The definition given above must be completed by the observation that a stellar system can contain considerable masses of diffuse matter, consisting of gas and dust as well as dense bodies of nonstellar nature, for example planets and comets. According to the information we possess, the total mass of the diffuse material and of minor bodies (planets and comets) represents usually only a small part of the whole mass of the stellar system. It may occur, however, that some stellar associations are exceptions in this respect. The mass of diffuse material in them may amount to a considerable part of the total mass.

2. THE GRAVITATING GAS

If we can assume that most of the mass of a system is concentrated in stars, the chief kind of the interaction between the members of the system should be the Newtonian gravitation. If we had no changes in the physical state of the stars and particularly if their masses were invariable, the problem of the evolution of a stellar system could be reduced to the problem of behaviour of a system of material particles, interacting according to Newton's law. On the other hand, if we assume that during the life of a stellar system the intrinsic nature of its stars changes considerably, but the masses remain invariable, the problem

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of the evolution of a stellar system can be divided into the following two independent parts:

(*a*) The description of the dynamic evolution of a gravitating gas, which consists of particles of invariant masses.

(*b*) The statistical description of the changes in the physical states of stars.

As the solution of this second part of the problem we could have, for example, the determination of the relative numbers of stars of each spectral type and of each luminosity class as functions of coordinates and of time. Actually we cannot consider the stars as having invariable masses. We know that they come into existence from some protostellar material of unknown nature and during their life they eject some part of their masses. The problem is complicated by the fact that the process of star formation in a stellar system can take a considerable part of its lifetime. This process of the formation of new young stars is proceeding simultaneously with the processes of evolution of already existing stars. The newly-formed young stars can have different masses and different physical states. It appears that the distribution of newly-formed stars in the volume of the system, as well as their initial physical states depend on the distribution and the physical state of protostellar material. This is the reason why the problem of the evolution of a stellar system in general cannot be simply reduced to the problem of stellar dynamics or of statistical mechanics.

Nevertheless, in some cases the characteristic time t_1 during which the number of newly formed stars reaches the same order of magnitude as the number of already existing stars

$$t_1 = N \Big/ \frac{dN}{dt}$$

may appear considerably longer than the interval of time necessary for some essential kinematical and dynamical processes. The change of the masses of the majority of stars during the same time t_1 may be negligible. In other words, during the intervals which are short compared with t_1, the stellar system may be considered as a simple system of a constant number of mutually attracting particles of constant masses (gravitating gas).

A system consisting of a large number of gravitating particles has some peculiarities which make impossible the application of some of the usual methods and of important deductions of statistical physics. Detailed consideration shows that the properties of such an assembly (gravitating gas) differ considerably from the behaviour of the usual

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physical bodies (solid bodies, liquids and gases). Those properties are caused by the peculiar form of the Newton's law. The most important is the slow decrease of the interaction energy with distance. As is well known, the forces acting between molecules of some electrically neutral body are important only at distances comparable with diameters of molecules. At greater distances they are completely negligible. This leads for example to the following difference in the macroscopic properties of the corresponding assemblies. The internal energy of an ordinary physical body, for example of a stone, can be represented as a sum of internal energies of the macroscopic parts composing this body, since the interaction between two such macroscopic parts is very small. In fact, this interaction essentially depends on the molecules which are situated on the border surface between them. Now the number of molecules on that surface is negligible compared with the total numbers of molecules in the corresponding volumes and therefore their interactions are also negligible. Thus the internal energy of a stone is almost exactly equal to the sum of the energies of its macroscopic parts.

The situation is quite different in the case of a stellar system. Here the total energy of the system is equal to the sum of the energies of its two halves *plus their interaction energy*, and this interaction energy is of the same order of magnitude as the total energy of each half.

This has farreaching consequences. In particular Gibbs's method is inapplicable, since this method assumes that the energies of macroscopic subsystems are additive. The statistical sums which play a fundamental part in the Gibbs's method are diverging. The physical meaning of this divergence consists in the fact that there is no state of statistical equilibrium for a gravitating gas. This means that there is no maximum for the probability of the possible distribution of particles in the phase space, if only the number of particles is limited, as it actually is in any stellar system.

Whatever state of a system of gravitating particles we choose, there are always some other states, more probable than that chosen. Therefore if the system is isolated from other systems the transition will occur into another, more probable state. Thus the state of the system will always change, the system evolving into more and more probable states, *without reaching the state of maximum probability*, since no such state exists.

We may ask now what will be the direction of the evolution of such a system. This question was analysed already in the thirties of this century and some of the results are described below. But it is worth while to remark here that a more rigorous treatment is necessary and more definitive conclusions are desirable.

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3. THE DIRECTION OF EVOLUTION OF A GRAVITATING GAS

Let us imagine an assembly of mutually attracting particles (a stellar system) without any external influence. A simple calculation shows that in such a system the mean free path is many times larger than the linear size of the system. The stars can cross the system from one edge to another without experiencing close passages which can essentially change their trajectories. Therefore, during an interval of time of the order of the period of revolution in the system or even during the intervals which are several times longer, each star is moving under the action of the gravitational force exerted by the system as a whole. The action of nearby random passages will be as a rule negligible.

As one of the consequences of this, all the stars which have kinetic energies sufficiently high to escape from the gravitational field of the system will leave the system immediately. Of course this will occur only in the case when such stars (members with positive energy) were present from the beginning.

The remaining stars, which do not have sufficiently high kinetic energy for immediate escape, will perform their motions around the centre of mass of the system for a long time. Owing to differences in initial positions and velocities we shall have increasing mixing of the stars and, as a result of this, some *steady state* will be established. This steady state cannot correspond to an equilibrium state in the sense of statistical mechanics, since a state of maximum probability is impossible. But it will be a steady state in the sense that during the motions of stars which will proceed under the action of the regular field of the whole system the distribution of stars in phase space will remain unchanged. Let us denote by t_2 the time necessary for the establishment of this steady state. This time t_2 will somewhat exceed in order of magnitude the mean period of revolution in the system.

The phase density f in such a steady state will satisfy the following equation:

$$\frac{\partial f}{\partial x}+\frac{\partial f}{\partial y}+\frac{\partial f}{\partial z}+\frac{\partial f}{\partial \xi}X+\frac{\partial f}{\partial \eta}Y+\frac{\partial f}{\partial \zeta}Z = 0$$

where

$$X = -\int\!\!\int\!\!\int\!\!\int\!\!\int\!\!\int \frac{Gf(x_1, y_1, z_1; \xi, \eta, \zeta)(x-x_1)}{[(x-x_1)^2+(y-y_1)^2+(z-z_1)^2]^{3/2}}\, dx_1 dy_1 dz_1 d\xi d\eta d\zeta,$$

$$Y = -\int\!\!\int\!\!\int\!\!\int\!\!\int\!\!\int \frac{Gf(x_1, y_1, z_1; \xi, \eta, \zeta)(y-y_1)}{[(x-x_1)^2+(y-y_1)^2+(z-z_1)^2]^{3/2}}\, dx_1 dy_1 dz_1 d\xi d\eta d\zeta,$$

$$Z = -\int\!\!\int\!\!\int\!\!\int\!\!\int\!\!\int \frac{Gf(x_1, y_1, z_1; \xi, \eta, \zeta)(z-z_1)}{[(x-x_1)^2+(y-y_1)^2+(z-z_1)^2]^{3/2}}\, dx_1 dy_1 dz_1 d\xi d\eta d\zeta.$$

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This equation is an equation for a stationary self-consistent phase function.

Let us put aside the question whether all the initial distributions in phase space will lead to some steady state of the given assembly of stars. It is quite possible that some of them do not lead to a solution of this type. But this is a matter for more rigorous treatment. As far as we know no such case has been investigated until now in any detail.

The statement made above about the very high value of the mean free path means that during the time t_2 the random nearby passages ("encounters") of other stars cannot lead to strong deflections of the given star from the regular orbit. However, during an interval of time many times exceeding t_2 such encounters will influence the motions, and the phase distribution will change. We shall have a transition from the given steady state of the system to some more probable state.

Let us follow in what direction this change will occur. Evidently, as a result of "encounters", we shall have in each volume a tendency towards the establishment of the Maxwell distribution of velocities. This will have the consequence that some percentage of stars will acquire the kinetic energy sufficient to escape from the system. As a result some members of the system will leave it. Then in each volume of the system some sort of truncated Maxwellian distribution of velocities will remain. But the nearby passages will occur again and as a result the system will lose more members. This process will lead to the total disintegration of the system. Only a multiple star (or perhaps some independent multiple stars) will remain (1). The time interval necessary for the disintegration of the system (let us denote it by t_3) exceeds the so-called relaxation time, e.g. the time of the establishment of Maxwell's distribution.

For the open clusters with the number of member stars of the order of 10^2 or 10^3 and with diameters equal to several parsecs the time of disintegration t_3 is of the order of several hundred million years, or of the order of a billion years. These intervals are shorter than the accepted ages of the majority of stars and galaxies. Therefore an open cluster, which is a member of a galaxy, will disintegrate during the lifetime of the galaxy and its members will enter into the general star field of that galaxy as independent members.

4. GALAXIES

The situation is quite different in the case of galaxies. The picture of statistical–mechanical evolution described above, which ends in the

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total disintegration of the stellar system, has no bearing on the evolution of real galaxies. The calculations show that for the giant galaxies, containing sometimes several tens of billions of stars, the time interval t_3 is measured by some hundred thousands of billions of years. But the ages of galaxies are measured by intervals of the order of 10^{10} years. During such intervals of time, very powerful processes of star formation, which bring important changes in the number of stars, occur in the galaxies. During intervals of the same length a considerable part of the stars almost completely exhaust their sources of energy. These are the most important facts which, together with kinematical mixing and the rotation of the system, determine the general trend of its evolution.

One of the best proofs of the fact that galaxies similar to our stellar systems have not proceeded in any considerable degree towards the Maxwellian distribution of velocities is the complete violation of equipartition of energies in the Galaxy (2).

It should be noted that the absence of equipartition is very favourable for the solution of the problems of evolution of stars and galaxies. In fact, if the equipartition were established more or less exactly, the distribution law in phase space for each physical type of stars should have been determined only by the value of the mass of a star of this type independent of the initial conditions of formation and of history of the evolution of stars of the given type. Actually we know that the majority of stars pass only through the first stage of the described picture of dynamical evolution—the mixing stage. In other words the age of the majority of physical types of the stars is greater than t_2 and smaller than t_3. Therefore the assembly of stars of such types reach a steady state. This means that the sub-system of stars of any such type is in a steady state. However the distribution laws for different sub-systems are different. These differences are caused not by differences in masses but by differences in the conditions of formation of the stars.

For example the distribution in phase space of F-G dwarfs is quite different from the distribution of RR Lyrae variables. But the values of the masses of these two physical types of stars may coincide closely. It is evident that the difference depends on the conditions in which the stars of both sub-systems have been formed. Apparently no immediate evolutionary connection may exist between these two groups of stars. Let us now compare the RR Lyrae stars with Humason's and Zwicky's blue objects. Incidentally we remark that a very large number of such blue stars were discovered during last years at the Tonantzintla Observatory (Mexico) and a considerable number were

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found at Burakan Observatory. The phase distribution of both types is apparently similar. How far this similarity extends will be checked by future investigations. But, if these two distributions are sufficiently close to each other, it will mean that the direct evolutionary connection between RR Lyrae stars and Humason–Zwicky's objects is not excluded.

Finally, it is necessary to say that for some physical types of stars the lifetime in the given state may be shorter than even the mixing time t_2. In the case when the stars in question evolve from stars of another type, which already form a sub-system in steady state, the phase distribution of both types will be the same. In the case where the stars of the type in question (the stars of short lifetime) originate immediately from protostellar material, the distribution law will be completely determined by the distribution of the prestellar material. The best example is the blue giants of O-B type. It is known that they are concentrated in the spiral arms of galaxies. Their lifetime is estimated to be of the order of 10^7 years. This interval is very short compared with t_2 which in the case of our Galaxy is of the order of 10^9 years. Therefore it is natural to assume that the distribution of these young stars in the spiral arms reproduces in some degree the distribution of protostellar material.

5. THE ORIGIN OF STELLAR GROUPS IN THE SPIRAL ARMS

The observations testify that the O stars as well as the stars of early sub-divisions of B type in spiral galaxies are not only concentrated in the spiral arms, but that within the arms they have the tendency to belong to stellar associations and O-clusters. Thus it is clear that the formation of young stars in the spiral arms proceeds in groups. Some of these groups have positive total energy and disintegrate very rapidly. But others may persist in the form of open clusters. It is essential, however, that during the intervals of time of the order of 10^7–10^8 years the O–B2 stars will change and enter into other spectral classes. This follows equally from the theory of the evolution of a star of constant mass (Schwarzschild, Hoyle) as well as from the theory of evolution accompanied by the ejection of matter (Fessenkov, Massevitch). Therefore, after the elapse of some period, we shall observe instead of O-clusters the clusters of B and A type (3).

In this connection the question arises as to the persistence of the position and of the form of a spiral arm in a spiral galaxy. Perhaps it is better to put the same question in the following form. Suppose that associations and O-clusters formed during an epoch between

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T_1 and $T_1 + dT$ are situated along some spiral arm. How will the location of associations and O-clusters which have been formed during some later interval between T_2 and $T_2 + dT$ differ? At the moment T_2, will the location of this new generation of stellar groups coincide with the positions of clusters of older generation at the same moment, calculated on the assumption that the dispersion of velocities for such clusters is zero?

Markarjan (4) has shown that, while the O-clusters closely follow the spiral arms in their distribution, the A-clusters (as well as later B's) show in their distribution some indifference to the spiral arms. At first sight it seems that we should expect this, because the dispersion of velocities in the direction perpendicular to the axis of an arm will cause considerable widening of the zone where the clusters are present.

However, it is clear that, if there occurs no progressive shift of the position of an arm, the width of the zone of old clusters will coincide with the width of the zone where the protostellar bodies, from which the clusters have been evolved, are situated. On the other hand, the last zone will coincide with the zone of the young generation. Thus both the young and old clusters will be distributed within identical zones, having identical widths.

The fact that the observations strongly contradict this conclusion may be interpreted in two possible ways:

(*a*) The axis of the arm systematically shifts relative to the stars. Owing to this, the clusters formed in the arm after some period of time appear distributed over the whole disk of galaxy.

(*b*) The dispersion of velocities of clusters is considerably higher than the dispersion of velocities of protobodies, from which they have been formed. In this case we should assume that at the epoch of their formation the clusters acquire complementary velocities relative to the axis of the arm.

It is difficult to see how any of these assumptions can conform with the usual concept of the formation of young stellar groups in spiral arms from an assembly of gaseous clouds. Thus there are difficulties connected either with the very nature of spiral arms or with the process of formation of stellar groups in them.

6. THE SPIRAL ARMS AND THE NUCLEI OF GALAXIES

One of the remarkable properties of supergiant stellar systems like our galaxy or M31 is the presence of very small (some parsecs in diameter) central nuclei in them. It is important that in M31 the spiral arms can be followed until they reach the nucleus.

This circumstance makes it clear that the mechanism responsible for *the formation* and long persistence of spiral arms is in some way connected with the nucleus and has some relation to the internal properties of the nucleus.

Walker, Lallemand and Duchesne have recently published the results of their spectrographic observations of the nucleus of M31 made with an electronic camera mounted on the new reflector of Lick Observatory (5). They have determined the velocity of rotation from the inclination of spectral lines. This has made it possible for them to determine the mass of the nucleus. They have found the mass to be of the order of some 13 millions of solar masses.

It seems now quite an enigma how a body of such a small mass may play the decisive part in the formation of spiral arms, which in the case of M31 must have masses of the order of 10^9 M.

Almost simultaneously, Guido Münch (6) published the results of his observation of continuous outflow of gases from the nucleus of M31. According to this estimate the mass ejected from the nucleus of M31 is about one solar mass per year. A similar estimate was made by Dutch astronomers for the mass continuously ejected from the nucleus of our Galaxy. These facts strongly confirm that the nuclei play a very important part in the formation of spiral arms. But at the same time it is difficult to understand how such outflow can persist during the time intervals of the order of 10^9 years, which follow from the estimates of ages of giant galaxies.

Nevertheless it seems that there is no escape from that conclusion that in the formation of the flat component of a stellar system the nuclei of the corresponding systems play a fundamental role.

7. THE EJECTIONS FROM THE NUCLEI

It is known that in the case of the famous radio galaxy NGC 4486 we observe a jet ejected from the centre of the galaxy. The fact that the jet has the form of a straight line leaves no doubt that here we observe the direct outflow of matter. The high luminosity of condensations observed within the jet (we have no exact data on these luminosities, but their absolute magnitude is of the order of -14^{m}) makes it probable that the total mass ejected is of the order of the mass of some dwarf galaxy. The polarization of the light shows that there are violent physical processes in different parts of the jet. It seems that this phenomenon is *another form of the cosmogonic activity of the nuclei of galaxies.*

The remarkable jet in NGC 4486 has stimulated the search for

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similar formations in other galaxies. The search for such objects made in Burakan Observatory has given the result that at least two galaxies, NGC 3561 and IC 1182, have jets and condensations of considerably greater magnitude. At the same time the condensations found in the jets present in these galaxies are intensely blue. These blue condensations themselves are galaxies of moderate sizes ($M = -16$). They are probably the bluest of all galaxies observed until now. This underlines the peculiarity of these objects.

You probably know well about the blue galaxies discovered by Professor Haro at Tonantzintla Observatory. They are doubtless of great interest. However, the objects under consideration are much bluer. Incidently, the above-mentioned galaxy, IC 1182, is a member galaxy of the Hercules cluster, which according to the Burbidges has a positive value of the total energy.

Apparently, we may consider the extremely blue colour of the above-mentioned condensations as a direct indication of their youth and as an indirect confirmation of the suggestion that they were ejected from the central regions (nuclei) of corresponding supergiant galaxies.

Later, some new blue dwarf galaxies were found around some elliptical giant systems on the maps of the Palomar Atlas. However, they are not connected by jets with the nuclei of corresponding galaxies. It is possible that these formations were also ejected.

Thus we may conclude that the central nuclei of giant galaxies along with "calm" activity, displaying itself in the formation of spiral arms, show also another form of "violent" activity, which is connected with the ejection of jets and condensations.

8. THE DIVISION OF NUCLEI

It is known that some years ago there was a wide-spread conviction that the majority of radio galaxies are pairs of galaxies in collision. In a series of papers we have strongly opposed this point of view. It seems that the existing data speak rather in favour of the opposite point of view.

In some of the radio galaxies (for example Cygnus A) we are dealing with the formation of two galaxies (two nuclei) from one. In other cases we encounter the processes of very intensive formation of spiral arms (radio galaxy Centaurus A). These problems were discussed in our Solvay Report and I shall not consider them in any detail. I shall point out only that the formation of multiple galaxies from original single bodies follows from a number of statistical data concerning the assembly of multiple galaxies.

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Here we underline the fact that not only in the case of Virgo A, but in all other radio galaxies we are witnessing different forms of violent cosmogonic activity of the nuclei.

9. THE GLOBULAR CLUSTERS

The investigations of Hoerner and Kinman have shown that the globular clusters as a rule are moving along very eccentric orbits penetrating into the central region of our Galaxy. It is very difficult to imagine the formation of such dense systems on the periphery of the Galaxy, where the general density of matter is very low. It is natural therefore to suppose that the origin of these clusters is in some way connected with the activity of the nucleus of our Galaxy.

Let us suppose that the globular clusters originate in the central parts of the Galaxy and are then ejected outward. We again meet here the case of formation of stars in groups, but in this case members of the spherical component of the galactic population are being formed.

Of course we must always have in mind that the assumption that the spiral arms and the sub-system of globular clusters originate directly from the nucleus of given galaxy meets difficulties connected with the conservation of mass and with the conservation of angular momentum. These difficulties perhaps indicate that the real connection between the nucleus and the processes of formation of arms and globular clusters is not a very simple one.

Let us now introduce the assumption that globular clusters formed in this way may have positive total energy. In this case it is possible to give an explanation of the origin of stars of the spherical component of the galaxy and of the globular clusters from one single point of view. If we take into account that the changes in the orbital elements of stars (owing to nearby passages) must occur very rarely, we may expect that the stars originating from such a group of positive energy should have during a long interval of time orbits which only slightly differ from the orbit of the centre of gravity of the original groups. Parts of such groups we can observe in the vicinity of the Sun as moving groups which consist of the subdwarfs, RR Lyrae stars and other representatives of the spherical population. It seems that the groups discovered recently by Eggen and Sandage are just of this nature (1830 Groombridge group, 61 Cygni group) (**7, 8**).

Perhaps this kind of cosmogonic activity plays the most important part in the evolution of elliptic galaxies of low luminosity (Sculptor-type systems). It is possible that this activity may cause the exhaustion and disappearance of the nuclei. It is interesting to consider from

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this point of view such member-galaxies of the local group as the systems in Fornax or NGC 147.

The population of each of these systems is by one or one and a half orders of magnitude larger than the population of a large globular cluster. At the same time, each of these systems contains a pair of globular clusters. Evidently we can suppose that from the initial nuclei of such galaxies some globular clusters of positive energy have originated as well as a pair of clusters of negative total energy. As a result the nuclei were exhausted and the galaxies are now devoid of nuclei. The globular clusters of positive energies have dissipated and have formed the general stellar field of the galaxies. At the same time the steady state clusters of negative energies persisting somewhere in the periphery of the corresponding galaxies remind us of the existence of the former nucleus. Otherwise it will be difficult to understand the presence of dense globular clusters within the very rarified population of the general fields of these galaxies.

In conclusion, may I tell you that, with increasing study of the problems of the evolution of galaxies, a very important circumstance emphasized many years ago by Kukarkin shows itself more and more clearly. This circumstance consists in the high degree of independence of ways of evolution of flat and spherical sub-systems of stars of our Galaxy. But now it appears that both ways will meet in the most remarkable feature of our Galaxy: in its nucleus.

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