Stellar associations

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Some of the major problems of astronomy concern the ages of the various stars and the processes of star formation, including the question of whether stars are still coming into being. The discovery and study of the stellar associations have provided relevant evidence, and this evidence, together with that obtained by studying other groups, is discussed here.

Astronomers have recently paid considerable attention to the study of age differences between stars. Many of the results have been obtained by the discovery and study of a newly discovered kind of stellar system, the stellar association. Moreover, it can be said that such investigations first made possible a definite assertion that the formation of stars in our stellar system—the Galaxy—is still in progress. By comparing the numbers of stellar associations in various other galaxies of different types, we can draw conclusions concerning the relative amount of star formation in them.

Stellar associations form part of the structure of a galaxy and are akin to the open clusters of stars, groups which have long been known. Some information concerning the ages of the stars and the process of star formation can be obtained from the open clusters. We shall therefore discuss how such information may be obtained.

Observation shows that our Galaxy includes groups of stars in which the star density is higher than in the general star field surrounding them. Each such group as a whole executes a motion round the centre of the Galaxy, similar to that of the Sun and other single or multiple stars. These groups are called stellar clusters. Any star which is a member of such a cluster participates in the general motion of the cluster round the centre of the Galaxy and also executes some motion about the centre of gravity of the cluster. In this respect stellar clusters are analogous to double and multiple stars.

Stellar clusters are of two types. Some clusters contain upwards of tens of thousands of stars. These are the globular clusters. Their structure exhibits a fairly exact, though not always precisely spherical, symmetry. The globular clusters are found both near the galactic plane and at great distances from it.

Other clusters do not possess such a regular form and are much less rich in stars. They contain tens or hundreds, or occasionally thousands, of stars, and are found only near the plane of the Milky Way. Such clusters are called open clusters or galactic clusters. The Pleiades and the Hyades, which are visible to the naked eye, are examples. One of the most beautiful objects to be seen through a small telescope is the double cluster in Perseus, which is at a distance of about 6000 light-years.

The globular and open clusters differ also in the composition and nature of their stellar populations. The open clusters usually contain some blue giants, that is stars having both high luminosities and high temperatures. The globular clusters do not contain blue giants but always contain red giants, stars having low temperatures and very large radii.

Calculation shows that the members of a stellar cluster are retained in it by the forces of their mutual attraction according to the inverse square law. If each cluster were isolated, the processes occurring in it would be entirely determined by these forces. In 1934, however, B. J. Bok called attention to the following point. The stars of the Galaxy in general may pass through or near a cluster with velocities considerably greater than those of the cluster members relative to its centre of gravity. They will then lose some of their energy to the cluster. Consequently the energy of the cluster will increase, and so will its dimensions. After many such passages, the cluster stars will acquire velocities sufficient for them to move apart. The cluster is thus broken up.

It was found that this means of breaking up the cluster is unimportant for globular clusters, whose density is high and whose break-up therefore requires a large amount of externally supplied energy. However, the process indicated by Bok must be very effective as regards many open clusters, whose density is low, so that the gravitational interaction between their members is slight. The break-up of open clusters by this process is calculated to occur in a time of a few thousand

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million years, which is comparable with the lifetimes of the stars.

In 1937 the present author showed that there is another break-up mechanism, which in the majority of cases is the more effective. It operates even for those open clusters in which the star density is relatively high. It arises as follows. The motion of the stars in the cluster itself sometimes results in close encounters between them, and the stars which approach each other exchange energies. In some cases one of the stars acquires so much energy that it can overcome the gravitational field and leave the cluster. By the repetition of this process the number of stars in the cluster is reduced, and the cluster gradually becomes an ordinary multiple star.

This sequence of events leads to the break-up of some clusters after a time of the order of a thousand million years, or even less. The fact, therefore, that such clusters are still observed shows that their age cannot exceed one thousand million years. These clusters, therefore, are of an age considerably less than the mean age of the stars in the Galaxy.

It is very important in this connection that the reverse process, the formation of a cluster from stars previously independent, is practically impossible. In other words, the disintegration of clusters in the Galaxy is a one-way process.

If the cluster cannot have been formed from separate stars already existing, it is evident that the process of formation of the cluster was also that by which the stars in it were born. We thus conclude that stars may be formed in groups. It is also clear that different open clusters are of different ages. This means that many clusters were formed when the Galaxy was already in existence.

At the time when these conclusions were drawn it was still not realized that they are of profound importance in the general problem of the origin of the stars. It seemed then that the results obtained referred only to stars in clusters, which form only a small part of the total number of stars in the Galaxy.

At about the same time, however, statistical investigations were being conducted on double stars, which form a very large part of the total number of stars in the Galaxy. These investigations showed that the components of each double star have a common origin. That is, double stars cannot have arisen by the combination of previously independent single stars of the general galactic population.

The deep significance of all these results became clear only much later, soon after the Second World War, when the stellar associations were discovered.

STELLAR ASSOCIATIONS

As we have seen, the open clusters have a star density exceeding that in the surrounding space. Although the star density in the open clusters is much lower than in the globular clusters, they still represent marked concentrations of stars in comparison with the galactic star field around them. The stellar associations are groups of stars in which the star density is lower than that of the background of stars nearby. This does not mean that the stellar associations are rarefactions in the Galaxy. The surrounding stars which are not members of a given association penetrate freely into the volume occupied by it, and so the total star density in that volume is higher, not lower, than in the surrounding space. When we speak of the density of the association, however, we ignore the density due to stars which do not belong to the association and consider only the group of stars which do belong to it. This density is very low, and in this sense the stellar associations are extremely rarefied groups of stars.

The contrast in the density distribution must be reduced by projection on the celestial sphere. If the space density in the region of the association is only a little above that in the surrounding region, then, since we observe only the projection on the celestial sphere, the contrast in density between the association and its surroundings will be entirely negligible. Hence it would be almost impossible to discover associations by examining the apparent distribution of the stars as a whole, whereas ordinary star clusters are revealed on star maps and photographs in this way.

The chief feature of the stellar associations is that the large majority of the stars forming any one association have similar physical characteristics. Thus the members of the associations are mainly in certain definite physical states. This fact made possible the discovery of associations in our Galaxy.

The stellar associations may be assigned to one of the following two classes: the O associations, which consist of large numbers of hot giants, that is, stars of spectral classes O and B and relatively small numbers of other objects; and the T associations, which consist of relatively cool dwarf stars, many of which exhibit irregular variations in brightness.

If we draw a map of the sky which shows only the blue giants (O and B type stars), the O associations appear immediately as concentrations of stars. This must occur, because the O associations represent very dense regions in the density distribution of the blue giants taken alone.

Similarly, if we insert on the map the known irregular variables of low luminosity (called RW Aurigae type variables), we find that the great majority of them are concentrated in certain regions of the sky. Thus the T associations are very marked concentrations in the density distribution of these variable stars, taken alone.

Since, however, all the blue giants and all the irregular variables of the RW Aurigae type form only a small part of the total number of stars, the associations are almost unnoticeable on maps and direct photographs showing the distribution of all the stars.

Some O associations, nevertheless, which are remote from the galactic plane and relatively near to the Earth will be noticed as groups of stars of high apparent luminosity even against the general background of stars, since in those parts of the sky there are few giant stars in the general background. An example is the dense association in Orion. It includes the bright stars in Orion's Belt and some other bright stars.

The difficulty of directly discovering O associations is due to the fact that numerous other stars of low luminosity but relatively near at hand have about the same apparent brightness as the giants in the associations. The situation is entirely different when we observe other galaxies. All the stars of any other galaxy may be supposed to be at the same distance from us. Hence the bright stars, especially the supergiants and the giants, will stand out from the remainder on account of their high apparent luminosity. The O associations, which contain hot giants, will appear as extensive groups of bright stars. Many such groups are observed, for example, in the Greater Magellanic Cloud. They occur also in the Lesser Magellanic Cloud but are not quite so obvious there, since the luminosity of the brightest stars in associations is somewhat less in the Lesser than in the Greater Magellanic Cloud. O associations are also obvious in the galaxy M33 and the irregular galaxy IC1613.

In a remote galaxy, where the stellar associations cannot be resolved into separate stars, the O associations may appear as concentrations that can be distinguished by their colour, which is bluer than that of the rest of the galaxy.

The O associations are not found in galaxies of the elliptic type, and are relatively rarely found in those of type Sa, where they are not conspicuous. They are very frequently found in late-type spirals and irregular galaxies. These facts are of great interest. The associations are closely related to the spiral structure of the galaxies; in all the spiral galaxies they lie along the arms. It is certain that this relation between the O associations and the spiral arms is of profound significance in cosmogony. The T associations cannot be observed in other galaxies, since they consist of stars of very low luminosity. However, we can obtain some idea of the existence or otherwise of T associations in various types of galaxy from the fact that in most cases they are associated with clouds of cosmic dust. Hence, for example, we may conclude that they do not occur in the elliptic galaxies, since the latter do not contain any notable dark nebulae.

SIZE AND STRUCTURE OF STELLAR ASSOCIATIONS

As has already been mentioned, the mean density of O associations is much less than that of open clusters. Their dimensions, on the other hand, exceed those of open clusters by one or one and a half orders of magnitude. The largest diameters of open clusters lie between 2 and 8 parsecs,[1] while the dimensions of O associations are usually between 30 and 200 parsecs. Still larger associations are observed in other galaxies.

An O association usually contains one or more open clusters. For example, the Orion association contains an open cluster in the neighbourhood of the Trapezium. The association known as Perseus I contains the double cluster h and χ Persei already mentioned, and others. The clusters which are in associations usually contain, among other stars, hot stars of type O or B0. According to the classification devised at the Byurakan Observatory such clusters are called O clusters. The O associations contain, besides the clusters, other close groups of stars, mainly multiple systems of the type represented by the Trapezium in Orion. Such systems include three stars A, B, C such that all three distances AB, BC, and AC are of the same order of magnitude. Systems of this type are unstable, and must therefore be very young. It should be noticed that most (about 90 per cent) of the known multiple stars do not have this property. Hence the fact that Trapezium-type systems are found mainly in associations

[1] The parsec is a unit of distance used in astronomy, being the distance at which the radius of the Earth's orbit subtends an angle of one second of arc. The parsec is equal to 3·26 light-years, or about 25×10^{12} miles.

is of great importance. Another example is the multiple star σ Orionis in the Orion association. Its principal star is of type O9, while the other four components are of type B. The Trapezium itself is also a member of the Orion association. It is at the centre of the open cluster mentioned above. Another example of a star group found in associations is afforded by the star chains such as Orion's Belt, which consists of O9 and B0 supergiants.

The close groups occurring in associations, clusters, trapezia, and chains, are usually called the nuclei of the association. Thus each O association may have one or more nuclei.

Besides nuclei and individual stars, O associations usually contain gaseous nebulae, the radiation of which is due to hot stars belonging to the association. In some cases the gaseous nebulae are so situated in the association that there can be no doubt of their genetic relation to one of the nuclei. For example, the famous nebula in Orion NGC 1976, which is in the Orion association, is closely related to the Trapezium and the surrounding cluster. Another nebula surrounds the Trapezium-type system σ Orionis. Furthermore, according to Menon, the Orion association contains very large quantities of neutral hydrogen, which emit the 21 cm wavelength radio line. In only one case, that of the association Perseus 1, has no radiating nebula been observed, and radio observations of this show no radiation of neutral hydrogen.

The most striking feature of the T associations is their close connection with the dark nebulae. The members of these associations are embedded in such nebulae. This hampers the investigation of the star distribution in T associations, since the light of many of their members is absorbed by the nebulae. Nevertheless, the data available indicate that T associations contain separate concentrations of stars, similar to the nuclei of the O associations.

As has been said, the T associations contain irregular variables of the RW Aurigae type. Some of these variables have bright-line spectra. The prototype is the variable T Tauri. Many members of T associations were, in fact, discovered from the bright lines in their spectra, that is because they had spectra of the same type as T Tauri. However, not all RW Aurigae variables are stars of T Tauri type, although all T Tauri stars, apparently, are irregular variables of RW Aurigae type.

The question arises whether the T associations contain dwarfs of constant brightness as well as the RW Aurigae-type variables. Unfortunately this question is difficult to answer, since dwarfs of constant brightness belonging to T associations could not be distinguished from the multitude of similar dwarfs belonging to the general star population. This hampers the study of the structure of T associations. The dimensions of these associations lie between a few parsecs and 100 parsecs. In some cases they are quite dense groups, in others they are rarefied and less dense than the surrounding stars.

THE INSTABILITY OF ASSOCIATIONS

Every stellar system in the Galaxy, including clusters and associations, is subject to tidal forces due to the general gravitational field of the Galaxy. These forces tend to break up the system and to cause its members (in this case, stars) to move in independent orbits round the centre of the Galaxy. If the density of the system is high the gravitational interaction between its members is strong, and the tidal forces are unable to break up the system. It is found that the limiting density below which a system is rapidly broken up by the tidal forces is of the same order of magnitude as the mean density of the galactic star population.

Since the density of the open clusters considerably exceeds that of the galactic population, the tidal forces cannot rapidly break up a cluster. We have seen that the associations, on the other hand, have a density below this critical value, and so they must be broken up by tidal forces almost as soon as they are formed. The time necessary for this process is of the order of 10^7 years. Hence it follows that the age of the stellar associations is of the order of 10^6 years, and in some cases less still.

Since the mean age of the stars in the Galaxy is of the order of thousands of millions of years, and since the associations cannot be formed from previously existing independent stars, we must conclude that the formation of stars in the Galaxy is still in progress.

It can be shown that, if an association is broken up by tidal forces, its final disruption is preceded by the assumption of a very elongated form. Many associations of considerable size, however, are almost spherical. The association Perseus 1 is an example. The only possible explanation of this is that the stars in each such association were ejected from its central regions at the time of their formation, with speeds of the order of tens of kilometres per second. This value is derived theoretically from the sizes of the associations.

In 1952 the Dutch astronomer A. Blaauw, from a study of stellar motions in the association

Perseus II, found that the stars are moving away from the centre of the association at an average speed of about 12 km/sec. Thus the main conclusion of the theory of stellar associations was confirmed. Later the phenomenon of expansion in the O associations Cepheus II, Lacerta, and others was detected by investigating the motions of stars in them.

The proof of this expansion was in turn a direct proof that the members of the associations are young stars, and made possible a more precise determination of their ages. The age of the stars in the association Perseus II, for example, was found to be about 1·3 million years. Ages of a few million years were obtained for other associations.

However, the existence of several nuclei in dense O associations showed that it is not possible to reduce the motion of all the stars in associations to divergence from a single centre. It is natural to suppose that the various nuclei are different centres of star formation, so that the complete picture of stellar motions in the dense associations must be less simple.

The first indications of this were detected by Artyukhina, who showed that in the association Cepheus II there are two centres from which the stars are diverging. The Orion association is more complex. According to Blaauw and Morgan, two stars of early spectral type (AE Aurigae and μ Columbae) are moving very rapidly away from a point near the great nebula in Orion. The investigations of Strand have shown that the cluster around the Trapezium is expanding at about 5 km/sec. This means that the age of this cluster cannot exceed 3×10^5 years, in good agreement with the supposition that Trapezium-type systems are very young. Thus it may be regarded as established that the Orion association contains two expanding groups. It is also certain that this association contains other groups whose motion is different from either of these. For example, there is strong evidence that the three stars of Orion's Belt have a common origin. It has not yet been possible, however, to elucidate the law of motion in this group, on account of the smallness of the relative velocities.

The presence in dense O associations of separate groups formed at different times and expanding independently is an important fact, which must be taken into account in any attempt to reconstruct the origin of the O associations.

THE ORIGIN OF O ASSOCIATIONS

If we follow backwards in time the evolution of an association, we find that each expanding group must at one time have occupied a considerably smaller volume than it does at present. The main question, however, is what the volume of the expanding group was when its stars separated from some primitive body to form isolated objects. It must, of course, be assumed that the luminosity of these objects in the early stages may have been entirely different from that which resulted when each became a star in a more or less steady state.

The fact that systems of the Trapezium type are observed in the associations—systems which are unstable, yet have dimensions of only about 0·1 parsec—indicates that the original volume may have been very small. If we go further, and postulate that the Trapezia, in the early stages of their development, were still denser groups, we reach the conclusion that the pre-stellar body from which the expanding group was formed was of high density. It must also have been very massive, having some hundreds or thousands of times the Sun's mass. Neither observation nor theory indicates that equilibrium configurations of such large masses can exist with dimensions of the order of stellar radii or a few orders of magnitude greater. The present author therefore advanced the hypothesis that the pre-stellar body was 'superdense'. The density of this 'protostar' may have been of the same order as that of an atomic nucleus. It may be that protostars in this state have very low luminosities, and so we have not yet observed them.

It should be emphasized, however, that there is as yet no logical theory of the structure of such protostars such as would explain how the matter in them is subsequently transformed into ordinary stars moving apart at considerable speeds.

A less hypothetical way in which stellar associations might be formed has been suggested by J. H. Oort. According to him, an O-type star in a very massive nebula causes the inner parts of the nebula to become hot and expand. The result is that a compression of the gas occurs in a region at the boundary between the heated inner parts and the outer parts. Owing to the gravitational instability of the resulting condensations, stars are formed at the boundary of the nebula and move away from its centre. It seems to the present author that this theory contradicts the observed fact that Trapezium-type multiple systems, that is, groups of very young stars, are found in the very centres of nebulae.

It should be noticed that the idea that stars are formed from gaseous nebulae is in accordance with the traditional cosmogonical theories that all celestial objects are formed from nebulae. However, our supposition that groups of stars are formed from superdense protostars necessarily leads to the conclusion that the stars and nebulae were formed simultaneously from the protostar. On this theory, the expansion of the star group and that of the nebula are related phenomena caused by the break-up of the protostar. It should be noted that the idea of the formation of expanding nebulae from dense objects (supernovae, planetary nebulae) is already familiar in astronomy. Thus our viewpoint is to some extent in accord with a tendency known to exist in Nature.

NON-STEADY STARS

As we have seen, the members of T associations are variable stars of the RW Aurigae type. These stars exhibit extremely irregular variations in brightness. It is therefore certain that they are not in a steady state. This is natural, since the members of T associations are young stars.

However, the spectra of some of these objects have interesting features which compel the conclusion that they are emitting not only thermal radiation, i.e. radiation such as we receive from ordinary stars, but also non-thermal radiation, e.g. bremsstrahlung, solar radio waves, and so on. The non-thermal radiation is due to some unknown cause which operates from time to time in the atmospheres of non-steady stars. Whatever the actual mechanism of its emission, it is now clear that it contains energy liberated from powerful sources of some kind in the outermost layers of the star. Thus, in these stars, processes of energy liberation occur not only in the central regions but also in the atmosphere.

The Mexican astronomer Haro has shown that the non-steady stars in T associations include some which 'erupt', their luminosity increasing by several times in a few minutes. In such cases the energy released in the star's atmosphere from unknown sources is emitted during a very short time, and the process of energy release is explosive. How can these phenomena be explained?

Since the non-steady stars discussed here are young objects formed from superdense pre-stellar matter, we may suppose that some of this matter, still unconverted into ordinary stellar matter, remains in them. When the remaining islands of superdense matter in the star reach the outer layers of its atmosphere they are converted into ordinary matter, very large quantities of energy being released.

Thus we reach the idea of quasi-steady condensations of superdense matter (at nuclear density) which spontaneously break up in the outer layers and release energy in discrete quantities, as opposed to the continuous evolution by thermonuclear processes, as in all stars. These releases of energy are then observed as eruptions of non-steady stars.

HERBIG-HARO OBJECTS

We have seen that the O associations include Trapezium-type multiple systems, which are very close groups and, to all appearances, very young objects. The T associations include objects which to some extent correspond to the trapezia. These are the Herbig-Haro objects. They are small nebulae of diameter some 10^4 astronomical units (an astronomical unit is the mean radius of the Earth's orbit) and each contain several star-like condensations. These condensations are arranged similarly to the stars in Trapezium-type multiple systems.

The spectra of the nebulae which contain these condensations are similar to that of the small nebula round T Tauri. However, many of the spectral features which distinguish the latter nebula are more marked in the Herbig-Haro objects. The present author therefore put forward the suggestion that in this case we have star groups which are at the very beginning of their life as T Tauri stars.

This view received strong confirmation from the work of Herbig, who found that in 1954 two new star-like condensations, not previously visible in photographs, appeared in one of the Herbig-Haro objects. Whether we are here direct witnesses of the formation of new stars, or whether this observation indicates the strange and powerful processes occurring in the very early life of a star, is difficult to say. There is no doubt, however, that the study of these processes will lead us yet closer to understanding the way in which the stars are born.

CONCLUSION

We see that the results obtained by astrophysicists in the last ten or fifteen years, and especially the data on stellar associations, have brought nearer the solution of problems pertaining to the origin of the stars.

The most important results are that the process of the formation of stars is still in progress in our

Galaxy and other spiral galaxies, and that stars are formed in groups. It is certain also that the formation of expanding groups in the associations is related to the expansion of gaseous nebulae in them.

The stars formed in associations, however, have as a rule motions such that they do not go far from the galactic plane. The process here considered can therefore explain, at best, the origin of only that part of the stellar population which forms the 'plane sub-system'. By this we mean the galactic disk and the spiral arms.

There is, however, another sub-system, the 'spherical sub-system', or rather several such, whose members may pass far from the galactic plane. One of these spherical sub-systems includes the globular clusters. Another includes the short-period cepheids of the RR Lyrae type—variable stars whose period of variation in brightness is less than a day.

The question arises of the origin of these various objects. According to one theory (Baade, Schwarzschild, Spitzer), all the objects in spherical sub-systems are old, with ages exceeding 3×10^9 years. They were formed from objects in the plane sub-systems which acquired speeds enabling some of them to pass far from the galactic plane.

Another view (Kukarkin), which seems more likely to the present author, is that the great average age of the stars in the spherical sub-systems does not rule out the existence of young objects in them.

The hypothesis that star-group formation may have occurred among these objects also is supported by the presence of globular clusters there. Since the latter are never associated with conspicuous gaseous nebulae, it is evident that those who uphold the traditional view that stars are formed from nebulae must deny that young stars can exist among the members of the spherical sub-systems; but those who think it more probable that stars and nebulae are both formed from a third kind of object, the protostars, will see no reason against the continuing formation of stars even among the population of the spherical sub-systems.

We may hope that the coming years will bring the solution to this problem also. And then we shall be able to say whether or not the strange 'associations' occur even among the members of the spherical sub-systems.