STELLAR SYSTEMS OF POSITIVE TOTAL ENERGY

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At the beginning of my lectures I wish to express my sincere thanks to the Senate of the University of London for their very kind invitation to deliver these Lectures.

I intend to present some results on a new type of stellar system which we have been studying in recent years at the Burakan Observatory. One of the principal features of these systems is their instability and even rapid expansion in space. To this kind of system apparently belong (i) stellar associations, (ii) a number of classical open clusters and (iii) multiple stars of a particular kind—the Trapezium type. The expansion of these systems is possible only because the total kinetic energy of the system is much larger than the absolute value of the energy of gravitational interaction. This is a very important fact from the point of view of stellar dynamics.

One of the principal results of classical astronomy has been the proof that the components of every binary system interact according to Newton's law of gravitation. If the total energy of a binary is negative the orbit of the pair is an ellipse; if positive, a hyperbola. A large number of stars are known to be physical (not optical) pairs, and must have elliptical orbits. Thus, the total energies of an overwhelming majority of binaries must be negative. This is true of binaries in general, but there may be special cases where it would not hold. If we are told that, in addition to the binary nature of certain pairs of stars, the stars are also very young objects, then we cannot assert that the majority of pairs of this type have negative total energies. Relative motion of a satellite in a hyperbolic or linear orbit may be a characteristic of the initial short phase in the life of a star. An example of this is the γ Velorum binary, a Wolf-Rayet star with a B3 companion at a separation of 41″. Wolf-Rayet stars are believed to be young objects. It follows that we cannot assert that in this case the motion is elliptical. The results of measurements rather testify to a positive total energy.

These remarks on multiple stars also hold good for star clusters. The existence of many star clusters within the Galaxy has always been considered as evidence of the stability of these systems. A state of statistical equilibrium is impossible for a cluster containing a finite number of stars if the interactions between the stars is strictly taken into account. Hundreds of millions of years may elapse, however, before the cluster will begin to disintegrate by some stars acquiring velocities exceeding the escape velocity. The total energy of a cluster in a steady state is always negative, and of the same numerical magnitude as the kinetic energy. On the assumption of a steady state we can compute the mean square velocity of stars in the cluster, estimating their masses and mean separations. For some clusters, such as the Pleiades, Hyades, and others, the root mean square velocity thus computed lies in the neighbourhood of 1 km/sec. Observational data are very scant, but the observed velocities do not exceed 2 km/sec and many are about 1 km/sec. There is at least qualitative agreement between theory and observation, and we conclude that most star clusters are in a steady state.

For some classes of open clusters, however, the assumption of a steady state is untenable. Let us consider in detail O-type clusters as classified by Markarian, discussed in the *Communications of the Burakan Observatory* and illustrated in our Atlas of Clusters. The O-type clusters contain O or B0 stars as the earliest stellar type represented. Out of 171 open clusters whose types have been determined, 54 belong to the O type. Many of these clusters enter into O-associations. This proves the clusters to be young systems, because the O-associations are believed to have ages of less than 10^7 years. In any case, O-clusters must be regarded as systems which cannot continue long in this state, since the lifetime of an O or B0 star cannot exceed 10^7 years. O-clusters are poor objects, containing relatively few stars. B-clusters and A-clusters, which have B or A stars as the earliest type represented, are much richer in stars. If a cluster is stationary its members cannot increase in number. The O-clusters we observe at the present time will never turn into what we call B- or A-clusters. We have not been able to discover any clusters which could have evolved from O-clusters. This fact may be interpreted to mean that during the period in which an O or B0 star changes into some other spectral type, the cluster itself is dissolved. We must assume that most of the O-clusters have positive total energy. They will dissolve into space in the course of a few million years. Most O-clusters are so far away that we cannot determine their internal motions. However, the internal motions of the cluster IC 2602 in Carina have been measured and confirm the prediction of positive total energy. The stars are moving outwards from the centre of the cluster with velocities up to 7 km/sec. Notwithstanding these results on O-clusters, most B- and A-clusters (e.g. Pleiades, Hyades) have negative total energy.

Let us consider an O-cluster which is expanding at a rate of about 10 km/sec. The kinetic energy of such a cluster is many times higher than the absolute value of the potential energy. Under these conditions the interaction between the stars may be neglected. In about a million years the diameter of the cluster will exceed twenty parsecs. The majority of known clusters have diameters less than ten parsecs. This is because clusters with larger diameters are not easily recognized against the general stellar background. They can only be found by detailed studies of the distribution and motions of O and B stars. Recent work has shown that there are many concentrations of O and B stars in the Galaxy, and these have been called *stellar associations*. If an O or a B0 star is present in an association, the latter is called an O-association. It seems probable that in 10^6 years an O-cluster will turn into an O-association, although not all O-associations have necessarily arisen from O-clusters. Blaauw has investigated the proper motions in the association surrounding ζ Persei. He found decisive evidence of expansion, proving that stellar associations are systems with positive total energy. A million years ago the ζ Persei association was quite similar in size and form to IC 2602 at the present time. Many O-associations contain star clusters among their constituent parts. Thus, the ζ Persei association contains the cluster near IC 348. It seems probable that the development of an association involves both expansion and the formation of one or more open clusters.

In clusters and associations we have acting both the internal attractions and the disturbing tidal forces of the Galaxy. The latter deform and tend to destroy the stellar systems. In a cluster the stellar density is relatively high, so that the tidal forces are small compared with the internal attractions, even though the latter may be insufficient to prevent the expansion of the cluster. In an association the mutual attractions are small compared with the tidal forces. The latter increase as the association expands. After a certain interval of time the change in velocity due to tidal forces will become comparable to the initial velocity of expansion. A simple calculation shows that the interval of time required is independent of the initial velocity of expansion, and in the Galaxy near the Sun has a value of about 15 million years. An association which was initially spherical will become noticeably deformed in this time interval, and the deformation will continue to increase with time. A spherical association is young. An association which is elongated parallel to the galactic equator may have been deformed by tidal action. An alternative explanation is possible in some cases. Kopylov has shown that in the Scorpius association containing the cluster NGC 6231 the stars are moving radially away from two centres. After a considerable lapse of time this association will show an elongated form. If we observe an almost spherical association, estimate its distance and thence its diameter, and assume that it is less than 15 million years old, we can derive a lower limit to the expansion velocity of the association. For the Perseus association surrounding the Double Cluster we estimate a diameter of 180 parsecs, corresponding to an expansion velocity of at least 6 km/sec. Four expanding associations are definitely known from the analysis of proper motions:

Association	*Author*	*Expansion Velocity*
Perseus II	Blaauw (1951)	11 km/sec
Cepheus II	Markarian (1952)	8 ,,
Lacerta	Blaauw and Morgan (1952)	8 ,,
Scorpius	Kopylov (1933)	16 ,,

Further study of motions in O-associations can reveal new and interesting features. Consider the large Orion association, which includes the Orion nebula, early-type stars near the nebula, the Trapezium, the Orion Belt, and other stars. It is one of the nearest associations, about 500 parsecs away, but so far it has not been possible to derive general expansion velocities. This means that the expansion velocities do not exceed 5 km/sec. However, Blaauw and Morgan have shown that the two isolated stars AE Aurigae (O9) and μ Colombae (Bo), which are very remote from the Orion association, and are on opposite sides of the association, are moving away from it at great velocities. Both stars have large proper motions. If their paths are computed backwards for a period of 4×10^6 years we find that they meet inside the Orion association, near the Orion nebula. The number of high velocity early-type stars is so small that this coincidence of paths of motion could not have occurred by chance. We must assume that both stars started from the same region of space, and the opposite directions of the velocities of these stars are due to the law of the conservation of momentum. This also suggests that all the stars of an association do not arise simultaneously, but the process of formation of stars within an association proceeds in small groups.

The Cepheus II association extends from galactic longitude 66° to 73° and galactic latitude 2° to 8°, about one thousandth of the celestial sphere. This small region contains several O stars with apparent magnitudes brighter than 5·7, although only 20 such stars are known in the whole sky. This association of O stars is undoubtedly a real physical system. There is also a notable clustering of stars of types B0, B1 and B2 in the same region of Cepheus. For stars of later spectral types the contrast between the association and neighbouring regions diminishes. The association includes two open clusters, Tr. 37 and NGC 7160. The star HD 206267 (O6) is a member of the Tr. 37 cluster, which is therefore an O-cluster. The star is itself a quadruple system, ADS 15184. The earliest type star in NGC 7160 is HD 208392 (B1), which is also a component of a quadruple system ADS 15434. In addition to these quadruple systems, one octuple and three triple systems are found in the Cepheus II association, all these systems being in Aitken's Catalogue of Double Stars. The association also contains diffuse nebulae and hydrogen emission regions. The distribution of M-type supergiants is very irregular; almost all of them occur near stellar associations. Near Cepheus II we observe the stars μ Cephei and VV Cephei, the latter an eclipsing binary with an early-type companion. The multiple system ADS 15184 seems to be similar to the Orion trapezium type, and we shall consider this kind of system in greater detail.

In the great majority of multiple systems the distances between the components are not all of the same order of magnitude. Triple systems usually comprise a pair of stars whose separation is much smaller than its distance from the third component, while quadruple systems normally consist of two pairs in which the components of each are close together as compared with the distance apart of the pairs. Among the systems in the Cepheus II association the star ADS 15184 is of the rare type, similar to the Orion Trapezium, in which the distances between the components are all of the same order of magnitude. A system is defined as trapezium type if the ratio of the greatest to least space distances between the components is less than three. A study of such trapezium types in stellar associations was made at Burakan Observatory. It was found that, of multiple systems, the proportion of trapezium types is much higher in stellar associations than elsewhere. The proportion also varies greatly with spectral type. In the range O to B2 most multiple systems are of trapezium type, the proportion decreasing to about 10 per cent in A to K types where most multiple stars are found. The observed proportions will have to be corrected for the effects of projection since this can cause a system, which is physically of normal type, to appear as of trapezium type, and *vice versa*. These corrections can be made by assuming the systems to be randomly oriented in space, provided the relative frequencies of occurrence of the various configurations in normal type systems is known. I have made these corrections using a frequency law $N \propto dK/K$ where N is the relative number of systems for which the ratio K of the greatest to least distance apart of the components lies between K and $K + dK$. This law is not at variance with the observed properties of the nearest triple systems. It is found that the probability of a normal type system being transformed into an apparent trapezium is about 0·1. This strongly indicates that the 10 per cent trapezium systems observed among A to K types are not real trapeziums. It follows that real trapezium types occur mainly among the O and B stars, i.e., among young objects.

Calculations of the disintegration time of a trapezium system, using the formula for the relaxation time of an open cluster, support this conclusion. It is calculated that the lifetime could not exceed two million years with separations between the components of less than 10^4 A.U. The work of Sharpless on the occurrence of trapezium types among O stars in diffuse nebulosities also supports the conclusion.

The question arises as to whether the trapezium systems have positive or negative total energies. This cannot be determined directly from present observations. However, the fact that trapezium systems occur in stellar associations, where it is known that groups with positive total energy exist, gives some ground for supposing that they, too, have positive total energies. Furthermore, a star system of negative energy disintegrates by ejecting individual stars while the main configuration contracts, whereas the configuration of a positive energy system expands; the occurrence of several very wide trapezium systems in the Cygnus association therefore also supports the view that the trapeziums are systems of positive total energy. On the basis of micrometric measurements Parenago states that θ^1 Orionis has in fact much greater kinetic energy than the absolute value of the potential energy.

These considerations indicate strongly that an O-cluster develops from one or more trapezium type systems.

The views just elaborated lead to the following statement: "When a multiple system comes into being it may have either positive or negative energy. Systems with positive energy break up rapidly. Therefore at a given instant only a small number of such systems can be recorded by observation. Systems with negative energy live long and come to attain large numbers in the Galaxy." The possibility is not excluded that some normal type systems could arise from a disintegrating trapezium type, and also that some negative energy systems could be formed possessing a trapezium configuration.

The positive energy systems so far mentioned have been mainly of O and B type stars. Let us now examine the possibility of dwarf star systems with positive energy. It now appears certain that the T Tauri types form stellar associations, the so-called T-associations, the one in Taurus being a good example; this, like the others, is connected with a diffuse nebula. Dr. Kholopov of Moscow University has shown that this association comprises a group of relatively compact clusters with diameters of the same order of magnitude as classical open clusters. Herbig of the Lick Observatory has shown that the density in the clusters in S Monocerotis is much greater than in the general stellar field in the Galaxy.

From this it seems that the T Tauri stars have a common origin, rather than being formed by accidental encounters with diffuse nebulae, as in the view of some astronomers. Shajn and Gase of the Crimean Astrophysical Observatory have shown that some of the diffuse nebulae are expanding and must have very short lives. Thus the T Tauri associations must also be expanding and have short lives, otherwise there would be large numbers of them not connected with diffuse nebulae. Such occurrences, if they exist at all, are very rare.

It cannot be argued that, after the dissipation of the nebulae, the stars lose their T Tauri character and become ordinary dwarfs, because this would mean the existence of large numbers of ordinary dwarf-star clusters. But no such clusters have yet been discovered. Therefore, while there is as yet no direct evidence of expansion, it seems probable that the T Tauri clusters have positive total energy, and consist of newly-born stars.

We must now consider how these systems of positive energy come into existence. Professor Oort of Leiden Observatory suggests that they arise from one or more O-type stars within a gaseous cloud complex such as the Rosette nebula round the open cluster NGC 2244. The expanding *H* II regions formed round these stars compress the surrounding *H* I regions, thereby forming stars in them owing to the resulting gravitational instability. Owing to the outward movement of the gas as a whole, the star clusters so formed will move outwards from the central part of the cloud complex, thereby forming expanding O-associations. The work of Shajn and Pikelner showing that the Orion nebula is probably expanding supports the theory.

However, as Professor Oort realises, it is difficult to see how the parent O-stars could be formed within the cloud. Moreover, some of the stars of associations have observed escape velocities of the order of 100 km/sec, as for example in the case of AE Aurigae and μ Colombae. In the above theory the escape velocities could hardly exceed 30 km/sec.

My own view is that future observations will show that the stellar associations and the expanding nebulae are formed simultaneously.

Another suggestion, made by Öpik, is that they originate from supernovae. The expanding gas shells capture the surrounding interstellar gas and are decelerated, thereby forming high densities with consequent gravitational instability. Expanding groups of stars could then form as in Oort's theory.

A difficulty in both these theories is to explain why some clusters are found *within* diffuse nebulae.

I am not going to present to you any mechanism of the origin of stellar associations. However, I would like to point out that the expanding systems of relatively high density within associations, as concluded from the observations, strongly indicate a pre-stellar state of very high density. It seems natural to suggest, therefore, that the origin was a single body—a proto-star. This would divide, by some mechanism as yet unknown, to form a trapezium system. This, as I have mentioned, then gives rise to an expanding cluster, which in turn produces a stellar association.

The fact that such proto-stars are not observed means that they are under-luminous for their masses, but it is possible that matter at such high densities would behave quite differently from normal stellar material. It is tempting to propose densities of the order of nuclear density.

In short, I believe that we shall have to abandon the old ideas about the formation of stars from diffuse matter, and to suppose that both diffuse matter and stars are formed simultaneously from the division of proto-stars.

A possible approach in finding the nature of the division process is in a study of T Tauri stars. One might expect to find in these stars some phenomena arising from the transformation of matter from the pre-stellar to the normal stellar state. I have recently made an analysis of the T Tauri stars, the main results of which are, (i) the irregular variations in luminosity of a T Tauri star are connected with the process of liberation of discrete quantities of energy from some "potential sources" in different layers of the star. In many cases these processes proceed in the atmosphere or even outside it. (ii) When the liberation of some discrete quantity of energy occurs in the outer layer of the atmosphere or outside we directly observe the so-called "continuous emission" veiling the absorption lines. The non-thermal origin of this emission is obvious.

The UV Ceti stars are another example of continuous emission; in these cases the luminosity often rises in a few seconds. These phenomena are not consistent with the usual view that stellar energy is of thermo-nuclear origin. They resemble, rather, atomic disintegration on a very large scale, in which the usual modes of exchange of energy do not occur. It is reasonable to suppose that they are connected with the properties of matter which still exists in the pre-stellar state in these young stars.

Observational work is also being carried out in other directions which, I hope, will shortly throw more light on the problem.