STELLAR ASSOCIATIONS

Until recently only two types of "small" stellar systems were studied within our Galaxy: open and globular clusters. The orders of magnitude of gravitional interaction energy for open clusters and for many visual double stars are the same. This speaks for their kinship. However, the author recently established [1] that along with open and globular clusters, we have within our Galaxy still another type of stellar system: the *stellar associations.* They are of outstanding interest from the viewpoint of stellar evolution. In the present paper we consider some examples of stellar associations and discuss their types and properties. An association is a system of stars which have a common origin and are of much lower spatial concentration than that of the general stellar field of the Galaxy where the associations are imbedded. The most important examples of associations are the groups of variable dwarf stars of T Tauri type and the groups of supergiants of O and B types.

Associations consisting of supergiants often have in their center an ordinary star cluster, the associations nucleus.

By all indications, the giant clusters in the Large Magellanic Nebulae are stellar associations.

Examples of stellar associations.

1) A group of variable stars of T Tauri type and the associated stars in Taurus and Auriga.

It is well known that the stars of T Tauri type are restricted to certain parts of the sky. In particular, eight such stars form an isolated group in the constellations of Taurus and Auriga within a solid angle of $12^\circ \times 12^\circ$.

The distance order of 100 parsecs means that the diameter of the group is of the order of 25 parsecs. Joy has discovered within the same domain a series of dwarf stars whose spectra possess bright lines. This indicates their probable interrelation with the stars of T Tauri type. At this point we stress two important facts:

a) the compactness of this group of stars cannot be explained as accidental. Obviously we deal with a single system.

b) the density of this system of stars is so low that it could never be identified by direct observation as a cluster, even if it were situated several times nearer to us.

The discovery of this association became possible solely because its stars belong to a definite class of variable stars. An important characteristic of this system is its low spatial density.

Even if the system of 7–8 stars of T Tauri type is complemented by 40 dwarfs with bright lines, we obtain a spatial density which is much lower than that of the Galactic stellar field where the association is imbedded. This circumstance remains true even after we attach to the system some dwarfs lacking bright lines (they are several times greater in number than dwarfs possessing bright lines).

According to well-known dynamic criteria this means that the system we consider is unstable and will be destroyed under the tidal influence of the general gravitational field of the Galaxy. We are compelled to think that the system consists of stars diverging in space.

Possible relations between the stars of the system and both luminous and dark interstellar matter also deserve attention.

2) The Kukarkin and Parenago [2] catalogue of variable stars in a small region centered at $\alpha = 18^h40 : \delta = 9°0'$ indicates eight stars of T Tauri type (or by the catalogue terminology — of RW Auriga type). Three of them have a question mark, which refers to the type of variability. We present a list of these stars.

Name	α	δ	Stellar magnitude	Type
V637 Ophiuchus	$18^h31^m59^s$	$+9°51'.1$	$13^m.6 - 16^m.0$	T Taurus
V681 Ophiuchus	32 34	$+9°06'.1$	$14^m.2 - 15^m.4$	T Taurus ?
V643 Ophiuchus	32 34	$+6°16'.7$	$13^m.6 - 15^m.6$	T Taurus ?
V645 Ophiuchus	33 02	$+11°47'.1$	$14^m.6 - 15^m.6$	T Taurus ?
V476 Aquila	43 57	$+7°02'.3$	$13^m.3 - 14^m.2$	T Taurus
V480 Aquila	45 43	$+7°00'.7$	$14^m.0 - 16^m.0$	T Taurus
V489 Aquila	50 55	$+11°56'.3$	$13^m.1 - 14^m.8$	T Taurus
V490 Aquila	53 49	$+12°51'.1$	$14^m.1 - 15^m.5$	T Taurus

The stars are situated in a small, $6^\circ \times 7^\circ$ region, not far from the Galactic equator. Even if we neglect three stars, whose types need confirmation, the remaining five stars of T Tauri type still produce a concentration which cannot be accidental. We deal with members of a system of stars. Average maximal brightness of the variables for this system is $3 - 4^m$ less than that for the association in Taurus. Apparently, this is evidence of greater distance to the association in Aquila and Ophiuchus.

3) A group of stars of type O and B, as well as of red supergiants around the double open cluster χ and h of Perseus. This system was studied by Bidelman [3]. Observations leave no doubt about the existence of a group of supergiants of early and late types, which surrounds the χ and h Perseus clusters. The double cluster is the nucleus of this association.

The system diameter is 170 parsecs by order, while the diameter of both χ and h Perseus clusters is 10 parsecs by order (or 7 parsecs by Osterhoff). A characteristic feature of the system is the presence of a number of B-type stars with bright lines. In particular, there are at least five stars of P Cygni type (HD 12953, 13841, 14134, 14143 and 14818). Even if we accept that the association as a whole contains tens of thousands of stars, its mean density will still be less than that of the Galactic field. Doubtless, the stars of the association diverge in space. It should be noted, however, that the nuclei χ and h of Perseus, which are ordinary open clusters, are perhaps stable and their decay should necessarily follow the patterns common for open clusters.

4) The open cluster NGC 6231 is surrounded by a group of supergiants of O and B types. The study of radial velocities by Struve [4] shows that all these supergiants, together with the cluster, form a single stellar association. Its distance from us is about 1000 parsecs. The association's diameter exceeds the cluster's diameter by almost five times and is about 30 parsecs. Remarkably, the association includes two Wolf-Rayet stars and two stars of P Cygni type.

It is self-evident that the possibility of accidental concentration of these stars around the cluster is out of the question. In this case we again have to accept that the average density of the association is low in comparison with the density of the galactic field. The association is unstable, although the nucleus (NGC 6231 open cluster) probably is stable.

5) NGC 1910 system in the Large Magellanic Cloud is of peculiar interest. It is a large group of supergiants of early types where some stars are P Cygni-type, including the famous S Doradus. The diameter of this system is about 70 parsecs, i.e., many times larger than the sizes of common Galactic clusters.

6) The stellar association in Captein area SA 8 (around $\alpha = 1^h00^m, \delta = +60°10'$). The association is a group of weak stars of O and B type, occupying a region 2.5 degrees in diameter. The association includes a Wolf-Rayet star and two stars of B type with bright lines. Apparently at least 23 members of this association belong to the BO type. We note that the association is situated in a region poor in bright stars of B type (brighter than $8^m.0$). Judging from visible stellar magnitudes of stars of early types, this association is situated at a distance not less than 2000 parsecs. This suggests a diameter of about 100 parsecs. This extremely interesting distant association was discovered at the Byurakan Observatory in 1948 using the Bergedorf catalogue. The association's nucleus is the open cluster NGC 381, $7'$ or not less than 4 parsecs in diameter.

Basic characteristics of stellar associations. The above facts suggest the following general conclusions about stellar associations:

1) The associations are systems with small average densities compared with the density of the Galactic field. However, if we take partial concentrations of stars of separate spectral types, then associations are sharply distinguishable, owing to an abundance in them of stars of comparatively rare types. In some cases we deal with supergiants of O and B types, in others — with stars of T Tauri type. Because of their low density, the associations cannot be stationary in the sense of stellar dynamics. Unlike globular and open clusters, associations are nonsteady systems. Obviously members of associations diverge in space, and will eventually dissolve among the field stars.

2) Associations always contain stars which continuously emit matter. In three of the above six examples we find stars of P Cygni type. In examples 4) and 6) above, stars of Wolf-Rayet type are present. In the first two examples variable stars of T Tauri type are present, whose spectral bright lines possess absorption components on the violet side, i.e., they show the same peculiarity as the bright lines in the spectra of stars of P

Cygni type. A natural conclusion is that these stars also continuously emit matter.

3) In some cases the associations have nuclei looking like open stellar clusters.

Stellar associations in Large Magellanic Cloud. The Large Magellanic Cloud is very rich with open clusters. Remarkably, clusters of the Large Cloud in some cases have rather large sizes (several dozen parsecs) [5]. The most striking is the example of NGC 1910. The curve representing distribution of the open clusters in the Large Cloud according to their diameters has a minimum which divides all open clusters into two groups: a) clusters with diameters greater than twenty parsecs and b) clusters with diameters less than twenty parsecs. This alone makes us suspect that we are dealing with objects of two different types and scales. The presence of P Cygni stars in some clusters of the first group suggests that those are objects of the stellar associations type existing within our Galaxy, while the objects of another group are common open clusters.

The following consideration reduces this hypothesis to almost a certainty. Suppose we observe our Galaxy from some external system, e.g., from the Large Magellanic Cloud. Then the association around χ and h Perseus will contrast sharply with the surrounding background, due to the existence of a great number of supergiants in the association. Observing the same system from inside the Galaxy we face the fact that the stars of low luminosity, which are at far shorter distances than the association, are projected upon the latter. Both the members of the association and the projected stars will have a visible magnitude of the same order and, therefore, the former will be lost among the latter.

To an observer in the Large Magellanic Cloud the association would appear as a cluster of supergiants having a diameter of 170 parsecs. The χ and h Perseus clusters would appear to him as mere condensations in this magnificent system. On the other hand, the system NGC 1910 if transferred from the Large Cloud into the Galaxy and placed at the locus of χ and h Perseus would be observed as a typical association, i.e., it would not form a visible condensation of stars. Only a separate study of stars of early spectral types could betray its existence. Thus it seems that all giant systems in the Large Magellanic Cloud (about 15 in number) are in fact stellar associations, whose characteristics were described in the previous section.

Kinematics of stellar associations. The forces of interaction between the stars in an association are smaller than the tidal action of the general force field of the Galaxy. Therefore, at least for peripheral members of associations, the interaction forces can be neglected.

Considering the dynamics of stars of an association under the Galactic force field, it should be noted that the differential effect of Galactic rotation implies growth of distances between members of the association.

For a pair of stars distance r apart, the growth rate of r due to Galactic rotation is expressed via the well-known Oort coefficient A as follows:

$$\frac{dr}{dt} = Ar \sin 2(l - l_0).$$

Accordingly, for the radius R of the system at given galactic longitude l, we have

$$\frac{dR}{dt} = AR \sin 2(l - l_0).$$

For the radii R_1, R_2 at two epochs t_1, t_2 this implies

$$\ln R_2/R_1 = A(t_2 - t_1) \sin 2(l - l_0).$$

This formula says that for $l - l_0 = 45°$, the distance will be doubled after a period of $4 \cdot 10^7$ years.

Our derivation was based on the assumption that all stars in the association follow circular orbits around the Galactic center. Real orbits can of course be different. However, if we exclude too high relative speeds within an association, the radius duplication period will always have this order of magnitude.

Other possible causes of expansion can only support our conclusion that *each individual association came into existence rather recently and that it consists of stars which diverge from some primary volume where they have originated.*

However, the differential effect of Galactic rotation can produce expansion solely within the Galactic plane. If this were the only cause of expansion, then the associations would very soon acquire highly flattened shapes.

It should be stated that the rate of possible expansion of an association due to differences in the periods of oscillatory movements of its members along the Z axis should be much lower. The reason for this lies in the asymptotic independence of the oscillation periods and the amplitudes, for smaller values of amplitudes. Recall that for a star at the height z above the Galactic plane

$$\frac{d^2 z}{dt^2} = -2\pi G \int_{-z}^{z} \rho(z)\, dz,$$

where $\rho(u)$ is the Galactic density at height u.

For smaller values of z this reduces to

$$\frac{d^2 z}{dt^2} = -2\pi G \rho(0)\, z,$$

i.e., we have harmonic oscillations with period and amplitude mutually independent.

Since the associations which we observe are situated at low Galactic latitudes, their stars necessarily have almost equal oscillation periods in the z coordinate.

Therefore, the effect we consider is much less than the effect of differential rotation. Meanwhile observations do not show any considerable flatness in systems of the above examples. This compels us to think that there must be another cause of expansion, which prevails over Galactic rotation. We can suppose that the stars of the association left the initial volume where they formed, with certain velocities in different directions.

These initial velocities had to be no less than 1 km/sec. Otherwise, the effect of differential rotation should be evident for an association, whose sizes are several dozen parsecs. However, they should be less then 10 km/sec, for greater initial velocities would have been reflected in the distribution of radial velocities in the present epoch, for instance, in the association around NGC 6231.

If the distance from the center of an association increases at a rate of 5 km/sec, then the differential effect of Galactic rotation will fail to dominate until the sizes of the association reach several hundred parsecs. But such sizes would mean complete dissolution of the association among the field stars, i.e., the end of the association.

Consequently, flattening of the associations would not be observed. Therefore, the expansion velocities of 5 km/sec by order are most likely. We come to the conclusion that T Tauri-type stars in the association in Taurus-Auriga were expelled from a primary volume several million years ago, and the stars of the association around χ Perseus 10–20 million years ago, etc.

Expansion of an association begins without delay after the birth of its star members, since the assumption that the system spent considerable time in a stationary state before the expansion began contradicts stellar dynamics. This implies that the age of stars in the associations is measured by millions or at most by tens of millions of years.

This estimate is in good agreement with the fact that in associations we find stars of P Cygni, Wolf-Rayet or T Tauri type. A star cannot remain in P Cygni state more than one or two million years, as determined by the high emission rate of matter. On the other hand, P Cygni stars possess not only maximal luminosities among known stars, but probably maximal masses as well. If other states, which correspond to greater or equal masses, exist, then their lifespan should be rather short, for such masses are extremely rare. But P Cygni-type stars could not develop from stars possessing lesser masses. Consequently, they should be ranked among the youngest stars.

Number of stellar associations in the Galaxy. At present it is difficult to give a definite answer to the question concerning the number of stellar associations in the Galaxy. Associations containing supergiants of early type can be discovered at rather great distances (about 2000–3000 parsecs). Therefore, a considerable fraction of them can be observed. Such observable associations are probably several dozen in number. This means that the total number of such associations in the Galaxy is of the order of one hundred. As for associations consisting of T Tauri-type stars and other dwarfs with bright spectral lines, we know, at present, of only two.

However, both lie at rather short distances. In a ball of 100 parsecs radius there is one such association. This suggests that in the Galaxy they number in the thousands.

Assume that this number is 10,000. Also take into account that these associations remain detectable for a period of several million years. Then we have to conclude that in order to keep their present level, at least one association consisting of T Tauri-type stars should be generated in 1000 years on the average.

The question of formation of stars. Some astronomers have been putting forward a hypothesis that all stars in the Galaxy were born simultaneously or almost simultaneously several billion years ago, i.e., together with the formation of our Galaxy. The above facts cause this hypothesis to collapse. The birth of stellar associations and formation of stars within the latter from some other form of matter go on continuously almost before our eyes. The number of associations consisting of T Tauri-type stars which emerge during the lifetime of an association is of the order of ten thousand. For the time being, we do not know the mean number of stars born within an association, for we can identify only the brightest members. However, it seems reasonable that this number equals at least several hundred.

This means that at least a billion stars in our Galaxy were formed as a result of development of stellar associations from some other objects which remain unknown to us.

Other possible types of associations. It is highly probable that the system of B and O-type stars in Orion together with Trapezium make up a single giant association whose diameter exceeds 100 parsecs. The stars of Trapezium and the connected open star cluster apparently form the nucleus of this association. The presence of a giant diffuse nebula makes this system especially interesting and deserving of thorough study. The moving cluster of Ursus Major is a system of 32 members more than 200 parsecs in diameter.

The nucleus of this system is a subgroup of 11 stars nine parsecs in diameter. However, the system lacks direct indications of young age of the entering stars. This small system is probably a remnant of a formerly rich association. The Sun is situated in the interior of this system, but fails to be a member.

Conclusions. This article establishes the existence in the Galaxy of a great number of stellar associations, i.e., stellar systems of low density, unstable and dispersing in the Galactic space. The great role of stellar associations in the development of stars is evident. Therefore, they deserve the most thorough study.

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