STELLAR ASSOCIATIONS AND THE REGIONS OF ACTIVE STAR FORMATION IN THEM

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1. INTRODUCTION

The recognition of stellar associations as regions of star formation, i.e. regions containing groups of recently formed stars (Ambartsumian 1947), had an important significance for our understanding of the origin and evolution of stars.

Among the first arguments in favour of a recent formation of the OB-associations observed in our Galaxy, the idea of their dynamical instability took a special place. In fact the analysis of the situation in stellar associations gave strong reasons to predict the expansion phenomenon of stellar associations (Ambartsumian 1949).

The first confirmation of this prediction was obtained by Adriaan Blaauw (1952), the hero of today's anniversary, over 30 years ago. On the basis of an analysis of proper motions of stars, he showed that one of the nearest groups of stars of early spectral type is expanding with an average velocity equal to 12 km/sec. The "kinematic age" of this group observed around ζ Per (Per OB2) was estimated to be only 1.3×10^6 years.

Blaauw's result was important from two points of view. First, it contained direct observational evidence in favour of the idea of expansion and hence of the dynamical instability of young OB-star groups. And this fact confirmed the conclusion that stellar associations represent the centres of star formation in our Galaxy, where the formation of stars in groups is still continuing at present. Secondly, his paper showed that a new type of stellar motions, away from the region of their formation, takes place in stellar associations. This type of motions differs greatly from the star motions previously known in stellar dynamics, both in character and in the causes giving rise to them (see, for example, Ambartsumian 1954a).

The present paper gives a brief survey of some results obtained on non-stable motions of stars in stellar associations, induced by Blaauw's original (1952) paper.

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2. EXPANSION PHENOMENA IN STELLAR ASSOCIATIONS DETERMINED FROM PROPER MOTIONS

Blaauw's 1952 paper on the Per OB2 system as well as the next investigations of the local motions of OB-stars in associations were based on proper motions. The expanding motions in the Per OB2 association were confirmed by Delhaye and Blaauw (1953) on the basis of richer observational data. Results in favour of expanding motions in some of the nearest OB-associations have been obtained by other authors (see, for example, Mirzoyan 1981).

In contrast to these results there are some investigations of this period which cast doubt on some of the results. For example, the conclusion on the expansion of the association Lac OB1 drawn by Blaauw and Morgan (1953a) was called in question in a paper by Woolley and Eggen (1958). These disagreements apparently were caused by large errors in the stellar proper motions used for the study of internal motions in associations.

In this respect Blaauw's more recent paper (Blaauw 1978) on the Upper Scorpio group is of exceptional interest. On the basis of an analysis of proper motions of stars in this group he has shown that this part of the more extended system of B-type stars in Scorpio-Centaurus is expanding at present with an average velocity corresponding to a "kinematic age" of 5×10^6 years. It must be emphasized that here also the regularity refers only to part of the stars of this association, a group of stars having nearly the same age.

This result is quite important for the problem under consideration, as it was based on a study of stellar proper motions determined with higher accuracy.

3. MOTIONS OF STARS IN STELLAR ASSOCIATIONS DETERMINED FROM RADIAL VELOCITIES

In the absence of precise proper motions for the study of local motions of stars in stellar associations, radial velocities may be used. In contrast to proper motions they are not so greatly influenced by errors of measurement, whose effect increases with the distances of stars.

The method of using the radial velocities proceeds from the observational fact that the dispersion of space velocities of stars formed in associations is considerable. For example, while in the first papers on the motions of stars in associations it was considered that these velocities are of the order of 5-10 km/sec (see, for example, Ambartsumian 1949, 1954a), subsequent investigations showed that they can be much larger. Thus, as it turned out, in the association Per OB1 they reach up to 40 km/sec (Ambartsumian 1958). Moreover, Blaauw and Morgan (1953b, 1954; Blaauw 1956) showed that among OB-stars there are so called run-away stars, having space velocities of the order of 100 km/sec.

It can be shown that, at sufficiently large distances from the maternal nuclei (centres of star formation), owing to the presence of the dispersion of velocities, the average space velocity of stars moving away from the nuclei must increase monotonously with their distances from the nuclei.

Taking into account the limited number of OB-stars with measured radial velocities in individual associations, this question was studied statistically for the totality of all OB-associations. At the same time, the fact was taken into consideration that some associations have more than one nucleus.

For this purpose a united "synthetic" assocation has been composed around one common centre, by means of superposition of the subsystems of OB-stars around separate nuclei in observed associations. It is evident that in this synthetic association one can assume spherical symmetry for the distribution of stars around its centre. In this case the space velocities of stars can be determined from their radial velocities and therefore can be replaced by them.

The application of this method to the radial velocities of about 300 O-B1-stars and the data on known OB-associations showed (see, for example, Mirzoyan 1961, 1966) that in the synthetic association the mean space velocity of OB-stars indeed increases with the distance from the centre of the system, as is to be expected in the case of expansion. This is a natural consequence of the phenomenon that OB-stars having small velocities away from the nuclei can not reach large distances during their stay in the spectral interval O-B1.

Later on, this method was developed mathematicaly and applied to the synthetic association (Mirzoyan and Mnatsakanian 1970b), as well as to the Per OB1 association where there are about 40 OB-stars with known radial velocities (Mirzoyan and Mnatsakanian 1970a). In both cases the results confirmed their expansion.

4. THE REGIONS OF ACTIVE STAR FORMATION IN STELLAR ASSOCIATIONS

In the paper by Blaauw (1952) on the expanding motions of stars in the Per OB2 association, the "kinematic age" of this group was estimated. Naturally this age concerns only the group of bright stars under study. About the motions of other, fainter stars of the Per OB2 association we do not know enough. Therefore it would be prudent to say that the association contains an expanding group of stars having an age of the order of 1.3×10^6 years.

Before Blaauw's 1952 paper, the conclusion that in associations several nuclei or centres of star formation can exist was contained in the paper by Ambartsumian and Markarian (1949) on the Cyg OB1 association. Later on, morphological studies of the nearest OB-associations confirmed that in some associations several centres of this type exist.

From this point of view the ζ Per group or the Upper Scorpio group as well as the run-away OB-stars from the Orion association can be considered as parts (subsystems) of more extended systems where the processes of star formation are going on. This circumstance especially was taken into account when the synthetic assocation was composed by superposition of subsystems of OB-stars around maternal nuclei for the study of local motions of stars in stellar associations on the basis of radial velocities (Mirzoyan 1961; Mirzoyan and Mnatsakanian 1970a).

The discovery of run-away OB-stars by Blaauw and Morgan (1953b, 1954; Blaauw 1956) gave the first indication that the star-formation processes in stellar associations were lasting for a long time. The space motions of the OB-stars AE Aur, μ Col and 53 Ari allowed them to assume that these stars were expelled from the Orion association a few millions years ago, but not simultaneously. Probably AE Aur and μ Col originated in one group about 2.6×10^6 years ago, and 53 Ari was formed earlier, in an other group, about 4.8×10^6 years ago. Although we know nothing about the other members of these groups, the existing data may be considered as evidence in favour of the idea that in the Orion association some small groups of stars which formed earlier and others still forming at present are expanding now with different velocities.

Let us consider this question on the basis of contemporary observational data concerning the Orion association.

It has been already noted that the results of Blaauw and Morgan (1953b, 1954, Blaauw 1956) on run-away stars showed that in the Orion association in the region near the Orion Trapezium the process of star formation took place several million years ago. Further, taking into account that the Orion Trapezium is a group belonging by its structure to the disintegrating mechanical systems (see next section), and assuming an estimate $< 10^6$ years for its age, we can say that the Orion Trapezium region was a region of star formation about 5×10^5 years ago.

Finally, on the basis of recent data concerning the infrared sources, motions of the CO gas and H_2O masers, we can speak about a region of contemporary star formation in Orion, the region constituting only a small part of the volume of the stellar association. In particular, at present in the Orion association we undoubtedly observe regions of active star formation near the infrared object IRC-2 (see, for example, Scoville 1980).

Thus, the observational data testify that in stellar associations stars are formed in small groups, in various places and at different times. As a consequence of this in a given association we observe, in general, stars of several generations.

5. TRAPEZIUM-TYPE MULTIPLE SYSTEMS

The existence of Trapezium-type systems in stellar associations is one of the most important testimonies in favour of the formation in groups of stars in them (Ambartsumian 1954b).

As is well known, the structural peculiarity of Trapezium-type multiple systems is the presence in them of at least three components whose mutual distances are of the same order of magnitude (the ratio of the largest distance to the smallest one does not exceed several units, for example 3).

In contrast to the multiple systems of ordinary (or hierarchical) type (for example, triplets consisting of one close pair and one component located much farther, quartets of the ε Lyr type etc.), where star motions are Keplerian or almost Keplerian, in Trapezium-type multiple systems star motions should be non-Keplerian and, as a rule, non-periodic. We refer, of course, to real Trapezia, and not to pseudo-trapezia, which are observed as Trapezia only owing to the suitable projection of a hierarchical system on the sky (Ambartsumian 1954b).

Observations show that real Trapezia are found frequently among multiple stars having as their brightest component a star of spectral class O-B2, and comparatively rarely among multiple stars with a brightest component of later spectral types (Ambartsumian 1954b; Mirzoyan and Salukvadze 1984).

According to their structure, and hence to the character of motions of their components, the Trapezium-type multiple systems are similar to typical galactic star clusters, differing from them only by a much smaller number of stars. Moreover, sometimes they represent in fact a dense configuration of bright stars, in a more extended cluster consisting of faint stars surrounding this configuration. In particular, the prototype of these systems, Θ^1 Ori, is surrounded by such a cluster.

Like the open star clusters, the Trapezium-type multiple systems must disintegrate owing to close encounters of components occurring from time to time. According to the general formula established for clusters (see, for example, Chandrasekhar 1942), the disintegration time of the observed Trapezia must be of the order of 2×10^6 years, although considerable deviations from this figure are possible. In this estimate we assumed that the Trapezium-type multiple system has negative total energy. If we assume that, unlike the majority of clusters, the total energy of our system is positive, then for the disintegration time we obtain only 10^5 years. During this time at least part of the stars will leave the system (Ambartsumian 1954b). This means that in either case the system can disintegrate during a time comparable with the duration of stay of O-B2 stars in the corresponding spectral subclasses.

Many statistical data and also the results of computer modelling of the dynamical evolution of Trapezium-type systems are in agreement with these conclusions (for details, see Mirzoyan and Salukvadze 1984).

It is important to note that for all assumptions the lifetime of the Trapezium-type systems is less than the age of associations which is of the order of 10^7 years (Ambartsumian 1947, 1954a). Consequently the Trapezia in the observed associations are a result of processes taking place, in each case, in a region with a diameter from 0.1 to 0.4 pc over the last 10^6 years. In other words we are dealing with a process of star formation in a volume which is more than one million times smaller than the volume of a typical association.

The age of the order of 10^6 years concerns the Trapezia as multiple systems. It must not be confused with the duration of the interval of time when the formation of stars as luminous objects took place. The latter interval of time, if we judge by what is going on not far from the Orion Trapezium in the Kleinman-Low (KL) Nebula (see, for example, Scoville 1980), must be significantly shorter.

The processes of intense ejection of matter, which are typical for this earlier stage of star formation, last not more than 10^5 years. Therefore, if the object KL can be called the region of contemporary star formation, then the Orion Trapezium, which probably already passed this stage, must be considered as a region of recent star formation.

Let us dwell briefly on the fate of the Trapezium-type systems. We have seen that after about 2×10^6 years, as estimated in the first papers on Trapezium systems (see, for example, Ambartsumian 1954b) the Trapezia stop to be such systems. A number of numerical experiments carried out later have confirmed that the interaction of members in Trapezia leads to their disintegration, in the majority of cases.

A quite detailed description of such numerical experiments we find in a paper by Allen and Poveda (1974). Unfortunately, the authors have described their results in such a way that the impression may arise that the results of experiments contradict the conclusion of an (almost) inevitable destruction of the initial system. In fact, the results of these experiments confirm this conclusion completely (see Mirzoyan and Mnatsakanian 1975).

To be precise, in the paper by Allen and Poveda (1974) 30 sextets have been considered. During one million years 16 of these disintegrated. In 3 cases the disintegration reached completion (that is, after one million years only three double systems and 12 single stars remained), and in 13 other cases one or two stars from each sextet were thrown out. But these systems remained Trapezia and, obviously, their disintegration will continue. From statistical considerations one can expect that, after losing one member, further disintegration of a system must on average go faster. This was indeed observed experimentally. Among the 13 cases of partial disintegration mentioned above, in 6 cases one star and in 7 cases two stars were thrown out. This means that, after ejection of one star, the further disintegration is accelerated.

Among the remaining 14 initial sextets, six have retained a configuration of Trapezium type, and there is no doubt that the majority of these will disintegrate during the next one or two million years.

A somewhat unexpected result of the numerical experiment by Allen and Poveda is that after one million years 8 systems were transformed into systems of ordinary (hierarchical) type, without losing any of their members.

In order to clarify what can be expected in this case, let us remember that, because of the invariance of the laws of motion with respect to time reversal, inverse transformation of ordinary systems into Trapezia is also possible. Considering for a moment the case of triplets, one can verify that the probability of such inverse transformations must not be too small. What, in fact, does the transformation of a triplet of Trapezium type into an ordinary triplet mean? It means that one of the stars is thrown out from the system to a large distance. A close pair results, and the star ejected goes away in an elongated orbit. But then this star must return to the close pair along the same elongated orbit. In this case a triple strong interaction may occur again; in particular, the star thrown out earlier may lose part of its kinetic energy, and as a result we may have restoration of a Trapezium-type system. Of course, this qualitative reasoning must be confirmed by quantitative calculations.

Thus, it is evident that if one assumes that all stars originate as members of Trapezium-type systems, then mathematical experiments of the type discussed can lead to interesting results, which may be compared with observations. In particular, the following conclusions already suggest themselves.

1. As a result of the distintegration of each former Trapezium, at least one pair of negative energy or one multiple system of ordinary type is left. This pair or system originates from three or four of the most massive stars.

2. The process of ejection of single stars from Trapezia occurs very frequently. The impression arises that at least one third of all stars contained in Trapezia must be transformed into single stars.

Let us note that the observed percentage of single stars in the vicinity of the Sun (Van de Kamp 1969) is of the order of 35%. If one considers that besides the Trapezia some other, independent source of replenishment of field stars plays a considerable role, then obviously this source must also yield about one third, or a smaller number, in single stars.

As an example of an other possible way of enrichment of the general star field of the Galaxy, the system Per OB2 studied by Blaauw (1952) should be mentioned. This is the possible origin of groups of stars with positive total energy, which are comparatively larger than Trapezia. However, the question arises here whether the origin of the expanding group Per OB2 cannot be reduced to the dissolution of several Trapezia. It is difficult to answer this question at present.

Thus, one may trust that further, more realistic calculations will bring a definite answer to the question: What percentage of all stars formed in Trapezia will appear in the general field as single stars or as members of double, triple etc. systems? The comparison of such results with the observed distribution will allow some conclusions on the star formation processes. In particular it may allow an answer to the question what role could be played by processes of division or fission which are different from that leading to the formation of Trapezia.

It must be noted that in the paper by Allen and Poveda (1974), as well as in other investigations on computer models of stellar motions in Trapezium-type systems for the study of their dynamical evolution, the assumption is made that the total energy of these systems is negative. Concerning this assumption it can be said that the observations give some (though not very strong) evidence in favour of positive total energy in a number of Trapezia. Discussion of this kind of observations is continuing now, and we shall not give here arguments for or against the assumption. Let us note only that observations of the highest possible accuracy for the Trapezium-type multiple systems listed in the papers by Salukvadze (see, for example, Mirzoyan and Salukvadze 1984) can give a solution to this problem already in the next ten years. This solution can be expected, in particular, after successful service of the astrometric satellite "HIPPARCOS".

The idea of picking out the Trapezia as stellar groups formed recently in associations should urge us to search for Trapezia in those parts of associations which are occupied by molecular clouds and therefore are inaccessible to observations in the visible parts of the spectrum. Only in the last few years has attention been paid to the fact that the infrared stars of high luminosity found in such regions often form groups with configurations similar to Trapezia.

Statistical comparison of groups of infrared objects with Trapezia consisting of OB-stars has been carried out by Beichman (see Wynn-Williams 1982). The source GL 437, located in a molecular cloud, is an example of an infrared Trapezium.

6. MANIFESTATIONS OF DYNAMICAL AND PHYSICAL INSTABILITY IN OTHER YOUNG OBJECTS

Non-stable (expanding) motions are observed also in other systems of young objects.

First of all it must be noted that Trapezium-type multiple systems have been found in T-associations, among the T Tau-type stars (see, for example, Mirzoyan and Salukvadze 1984; Salukvadze 1980). Important indications on expanding motions were obtained from the proper motions of several Herbig-Haro objects (Herbig and Jones 1981; Mundt et al. 1983). Further evidence for expanding motions in star-formation regions is contained in the results of recent radio-astronomical observations of diffuse matter and of cosmic masers (see, for example, Ambartsumian 1982).

Manifestations of instability caused by non-stable physical phenomena in young stars are of special interest. It has been known since long that a quiet outflow of matter is taking place from some young stars (P Cyg, WR, Be, T Tau and other types), owing to which emission lines are observed in their spectra. Recent observations of OB-stars show that outflow of gas takes place even from stars having no emission lines in the visual part of the spectrum (see, for example, Lozinskaya 1982), and thus is a general property of young stars.

Hence, dynamical instability of groups of newly formed stars and outflow of matter from young stars caused by their physical instability are typical properties of the star-formation process.

7. CONCLUSION

The studies of motions of stars in stellar associations begun with the historical paper by Blaauw (1952) testify that expanding motions (the escape of stars from their formation regions) are taking place in small groups, and can lead to the disintegration of the association as a whole. These studies, as well as studies of the structure of stellar associations, have revealed some important peculiarities of star-formation processes, which previously could be only suspected.

In particular, they definitely indicate that in stellar associations stars are formed in individual expanding groups, which initially have very small sizes compared with the sizes of associations themselves. Besides, the groups of newly formed stars in a given association, in general, have various "kinematic ages"; that is: the star-formation process in the association as a whole continues over a substantial period. In consequence of this, the age of an association is as a rule larger than the ages of individual disintegrating groups within it. In other words, in an association several generations of stars usually exist. However, the age of the association as a whole is much smaller (by several orders of magnitude) than the age of our Galaxy.

Thus, at present, the observational data completely confirm the idea that the stellar associations are the centres of star formation where the formation of stars in groups is continuing nowadays. At the same time these data show that the stars in associations are formed at various epochs.

It should be added that the non-stable phenomena of dynamical and physical nature, which are typical for the early stages of stellar evolution (Ambartsumian 1954a, Mirzoyan 1981, Ambartsumian 1982), indicate, in all probability, the general direction of processes connected with star formation and evolution in the Galaxy: disintegration and dissipation of matter.

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DISCUSSION

ELMEGREEN: A Trapezium cluster with a small number of stars will disintegrate, as you indicate. But if the high-mass stars are in the centre of a cluster of lower-mass stars, as appears to be the case in Orion, then the evaporation process may be very different. The low-mass stars may evaporate first, taking away binding energy from the high-mass stars, which migrate toward the core. Thus the high-mass component may contract first, becoming more and more tightly bound with time, while the low-mass stars are lost. Then the few stars remaining can desintegrate by the stochastic processes discussed in former Trapezium models. All of this implies that some Trapezium systems may be relatively long-lived.

MIRZOYAN: The existing observational, statistical and theoretical information about Trapezium-type multiple systems indicates that these systems have to be very young and are disintegrating. For example, such systems usually have an O-B2 type star as the main (brightest) component. This means that the life-time of these systems is less than the life-time of O-B2 stars. Salukvadze (1980) from Abastumani Astrophysical Observatory in Georgia has studied the proper motions of 15 Trapezium-type multiple systems with O-B2 stars as brightest component over a period of about 100 years and shown that 12 of them are expanding.

VAN WOERDEN: What is the maximum duration of star-formation activity in an association?

MIRZOYAN: About 10^8 years.

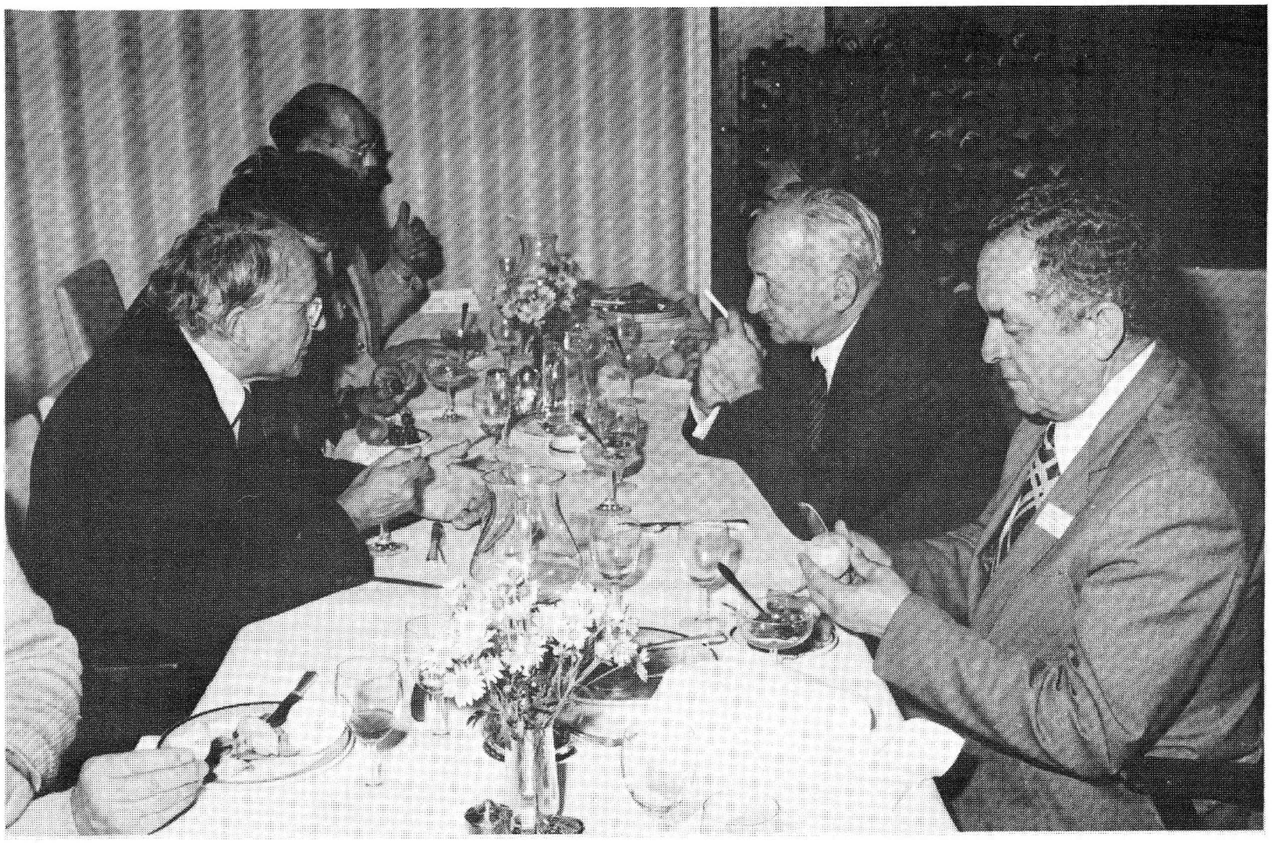
BLAAUW: Would you kindly specify what exactly is the controversy in view points that you referred to at the end of your talk?

MIRZOYAN: I made the statement that dynamical and physical instability is a fundamental property of the early stages of stellar evolution. All phenomena of instability (expanding motions in young stellar groups, outflow of matter, etc.) are connected with transformation of matter from denser states to less dense ones. Therefore it is natural to think that the initial stage of star formation might be a very dense or even a superdense stage of matter. This idea is in contradiction with the traditional point of view.

TRIMBLE: Are there any observational data that can be explained within your picture of a superdense state, and that don't make sense within the conventional picture?

MIRZOYAN: The answer to that question can be divided into two parts:
1. In stellar associations with regions of star formation we definitely observe expanding motions of young groups of stars, outflow and explosion of matter from young stars. This means that we observe

processes of disintegration and dissipation of matter connected with star formation. On the other hand we don't observe direct evidence of condensation and collapse. At the same time the interpretations of some phenomena connected with young stars by means of collapse were not successful. For example, Herbig has tried many years ago to interpret the FU Ori phenomenon as a result of collapse after the star has become a T Tau-type object. He made the statement that it would be strong evidence in favour of the collapse theory if a second FU Ori-type object would be found. But in 1911 Welin has found such a star - V1057 Cyg -, which was already a T Tau-type star before its brightening.
2. According to Ambartsumian's hypothesis the initial stage of matter before the formation of expanding stellar groups had to be a superdense stage. This is a hypothesis, maybe a probable one. It requires further theoretical development and some observational confirmation. Of course a theoretical study of hypothetical protostellar matter is quite difficult, because the properties of this matter are yet unknown.



Mirzoyan (right) at dinner; at his side: Ledoux, opposite: Golay. HM