On the Problem of the Mechanism of the Origin of Stars in Stellar Associations

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ALMOST ten years have passed since the idea of stellar associations as nonstable stellar systems was formulated.[1] The complex of observational data obtained during this time indicates that stars contained in the associations are young objects of some million years of age. We would like to stress here that this concerns both the O and T associations. It is also known that those O associations which could be sufficiently investigated in this respect, contain, as a rule, T Tauri type stars and are consequently T associations as well. There are, on the other hand, T associations which do not contain hot giants. But apparently the mechanisms of stellar formations must be similar in O and T associations. This means that any theory of stellar origin for a given type of association must permit variations, which will provide an explanation of the origin of stars in associations of other type.

Two hypotheses on the origin of stellar associations have been thus far discussed. One of them, suggested by the author at the initial stage of the idea about associations, supposes that each association has originated as a result of an expansion from a body or a system, the volume of which was initially very small. The dimensions of the latter was in any case less than one parsec. According to this point of view, these initial bodies (protostars) have either not been observed up to the present, or have not yet been identified with any known object. This point of view does not give any indication about a concrete mechanism of stellar origin, postponing its explanation to the time, when the earliest stages of the expansion of the association may be studied in detail.

On the other hand, Oort[2] and Oort and Spitzer[3] suggested a very interesting mechanism of the influence of radiation of O stars on large gaseous clouds in their surroundings. This mechanism leads to the possibility of transformation of a part of the radiative energy of the stars into kinetic energy of interstellar gaseous clouds. It seems to us that the role of the mentioned mechanism in the total balance of the kinetic energy of interstellar matter is very important. According to Oort, in the cold HI regions which surround the HII zone formed around an O star, a very high gas pressure can arise, which may lead as a result of condensation to the origin of stars when the limit of gravitational instability is passed. Oort's views were reported at the Second Symposium on gas dynamics of cosmical clouds so we shall not present them here in detail.

It is worthwhile, however, to check how much this hypothetical mechanism of the origin of stars is responsible for the formation of real associations. We shall investigate for this purpose data referring to large gaseous clouds, the structure of which is to a certain extent regular. It seems to us that a choice of such clouds of quasi-regular structure may be of interest from the point of view that the mutual relations between stars and the diffuse matter in them must be of greater simplicity and be more plausible, than in the cases of a quite irregular structure which does not permit an inference of the spatial geometrical configuration of the nebula. Let us consider for example the three following nebulae: the nebula around NGC 2244,[4] that around IC 1805,[5] and the large ring around λ Orionis.[6]

It is essential that in each of them a cluster of stars of early spectral classes is located. In the two first nebulae these clusters contain several O-type stars; in the latter case only one O star. The angular dimensions of the nebulae and of the central cluster are given in Table I.

The diameter of the central cluster is sufficiently small in all three cases, as compared with the diameter of the nebula. Therefore the possibility is excluded that the cluster stars could have originated at the periphery of the corresponding nebula. On the other hand, it is evident that all the stars of the cluster are genetically connected with the O stars of the cluster, which are causing excitation of the corresponding nebula. As the age of the O-type stars does not exceed several million years, there arises the question whether

TABLE I.

Nebula	Diameter of the nebula	Diameter of the association (central cluster)
NGC 2244	70′	25′
IC 1805	95′	12′
λ Ori	250′	30′

[1] V. A. Ambartsumian, *Stellar Evolution and Astrophysics* (Erevan, U.S.S.R., 1947).

[2] J. H. Oort, "Gas dynamics of cosmic clouds," *I. A. U. Symposium No. 2* (North-Holland Publishing Company, Amsterdam, The Netherlands, 1955), p. 147.

[3] J. H. Oort and L. Spitzer, Astrophys. J. **121**, 6 (1955).

[4] R. Minkowski, Publs. Astron. Soc. Pacific **61**, 151 (1949).

[5] G. A. Shajn and V. Th. Hase, *Atlas of Diffuse Nebulae* (Moscow, U.S.S.R., 1952).

[6] Morgan, Strömgren, and Johnson, Astrophys. **121**, 611 (1955).

an explanation of the origin of the cluster, the age of which is of this same order, can be given.

In other words, one must take into consideration that quite recently an intense process of stellar formation has taken place in the central region of each of the mentioned systems. This process is perhaps still continuing at present. I would like to draw attention to the fact, mentioned by Markarian,[7] concerning the presence of a multiple Trapezium-type system inside the central cluster of IC 1805 around the O star HD 15558. According to the data by Sharpless[8] this nucleus contains about 15 stars. As had been mentioned by us earlier,[9] the systems of the Orion Trapezium type must be very young formations. Their age must be of the order of one million years or even less. It may therefore be supposed that the process of stellar formation is still going on in IC 1805 at present, but that this process takes place in the center of the cluster. As regards star formation on the periphery of the above nebulae, there are no direct data to suggest it.

On the other hand cases are known to us, where open clusters containing O-type stars are not stable and must expand with time. Thus, direct signs of expansion were established by Markarian in IC 2602.[10] According to the last paper by Hopman the cluster IC 4996,[11] which is similar to the central part of the cluster IC 1805, is distinguished by large internal motions, which prove its instability. It is not excluded that O clusters located in the central parts of the mentioned nebulae can expand in the same way. In this case, after one or two million years these clusters will convert into expanding scattered groups, similar to the association around ζ Persei. Under these conditions the assumption about the origin of stars of expanding associations in the HI regions of symmetrical nebulae is superfluous.

Thus the data obtained from observations permit us to draw the following approximate picture: Each investigated formation represents a large diffuse nebula—or a complex of nebulae—which cannot remain in equilibrium. The assumption concerning an expansion of these nebulae is quite natural and their age must be evaluated as two-three million years. In the central part of such a nebula a cluster is present, the age of which is of the order of one to two million years. Also, in some cases, there exist in these clusters stars or stellar groups, the age of which must be less than one million years.

When considering this condition from the point of view of the cosmical time scale, we may say that the ages of the nebula and the cluster in the above systems are of the same order. Accordingly it is quite probable that the formation of the nebula and that of the cluster have occurred at the same time and as a result of a single cosmogonical process. The expansion of the nebulae forestalls somewhat the expansion of the cluster. This forestalling is caused by the fact that the stars of the central cluster are originating somewhat later. We do not exclude the possibility that some stars could originate with the nebula itself, possibly even before the formation of the nebula, and had therefore time enough to withdraw from its central regions. This possibility must be studied.

Of considerable interest is the discovery by Menon[12] of the expanding cloud of neutral hydrogen in the region of the star η Orionis. In the central part of this cloud hot stars are absent. They have either left this part of the nebula (in this case this must have been AE Aurigae, μ Columbae, and 30 Arietis, possessing the same center of expansion), or their formation may take place there at a future time. In both cases, our conclusion that the hot stars and the nebula do not originate strictly simultaneously is confirmed.

Thus, instead of the traditional formulation of the problem about the origin of stars or stellar groups from a nebula, we are led by observational facts to the problem about the joint (although not quite simultaneous) origin of stars and of nebulae out of some objects of unknown nature.

As concerns the mechanism of the formation of stars and nebulae there is, it seems to us, only one way to settle the point—it is the study and comparison of different groups of young stars. I should like in this connection to mention shortly some peculiar formations of this kind. I have in view stellar chains.

The observation that stellar chains are met in studying stellar distributions much more frequently than should be expected according to a random law, was raised many times by different investigators. The papers by Oberguggenberger,[13] Fessenkov,[14] and Martynov[15] can be mentioned in this connection. I consider here only the chains of stars in stellar associations and should like to draw attention to the indisputable reality of some of these chains. I shall give three examples, every one of which is striking and deserves special investigation.

1. Orion belt. This is an example of a stellar chain which has been known for the longest time. The exceptionally high luminosity of all three supergiants and the small differences between their spectral types, makes the hypothesis about the random grouping of these objects quite improbable. One may state with almost absolute certainty that this triple system of exceptional supergiants has a common origin. Their chain configuration is therefore of particular interest.

[7] B. E. Markarian, Communs. Burakan Obs. No. **5** (1950).
[8] S. Sharpless, Astrophys. J. **119**, 334 (1954).
[9] V. A. Ambartsumian, Communs. Burakan Obs. No. **15** (1954).
[10] B. E. Markarian, No. **11**, 19 (1953).
[11] J. Hopman and K. Heidrich, Mitt. Sternwarte Wien **9**, 57 (1956).
[12] T. K. Menon, 1956, "A 21-cm investigation of the Orion region," thesis, Harvard University.
[13] V. Oberguggenberger, Z. Astrophys. **16**, 323 (1938).
[14] V. G. Fessenkov and D. A. Rojkovsky, Astron. Zhur. **29**, 397 (1952).
[15] D. Ya. Martynov, Uchenye Zapiski Kazan. Gosudarst. Univ. im. V.I. Ul'yanova-Lenina **114**, 89 (1954).

2. Chain of O–BO type stars in the NGC 6823 cluster, first mentioned by Markarian.[16] According to Sharpless[8] this chain (BD+22°3782) consists of three multiple Trapezium-type systems of very compact stellar groups. The chain is located in the center of the cluster and the nebula NGC 6823, and its explanation by random grouping is out of the question. On the background of the nebula NGC 6823 numerous remarkable "veins" of dark matter of elephant trunk type are observed. According to Shajn the direction of the dark veins should coincide with the direction of the magnetic lines. It is of interest therefore whether the direction of the stellar chain BD+22°3782 coincides with the direction of these veins. This might give some indication about the mechanism of the origin of this star chain. However, these two directions are almost perpendicular. It must be underlined that the mentioned chain lies in the center of a large gaseous nebula, the diameter of which is of the order of 20 pc. Thus in this case again, we have a situation similar to that given at the beginning of the present communication. The length of the chain is less than one parsec.

3. The third example is not related to hot stars. We have in view the chain of Herbig-Haro objects in Orion. It seems probable at present that each of these objects contains a group of young dwarfs. Thus, we have in this case again a chain consisting of groups resembling the Trapezium-type systems. Contrary to the second example, we meet here cold dwarfs, but no hot stars.

The existence of a number of other chains of hot giants was established both in our galaxy and in M 33.

It seems to us that the fact of the probable appearance of chains of individual giants (or supergiants) and of chains of close stellar groups is of great cosmogonical importance, and indicates one of the directions which should be followed in the study of the real mechanism of stellar formation.

[16] B. E. Markarian, No. **9** (1951).

DISCUSSION

E. N. PARKER, *Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago Illinois:* Do I understand that you feel that, in a given cluster, when the stars are first formed from the gas, all the stars are not formed simultaneously? That is, do you suggest that, for instance, one or two stars are formed first and then a little later a few more are formed, and then a few more, until finally the entire cluster is formed?

V. A. AMBARTSUMIAN, *Burakan Astrophysical Observatory, Academy of Sciences of the Armenian S.S.R., Erevan, U.S.S.R.:* First, I do not consider it necessarily certain that the stars are being formed from the diffused matter. It seems to me that when we make speculations on the problem of the origin of stars, one of the first problems which must be examined is whether the only possible mechanism for the formation of stars is out of diffused matter, or if there is not some other way for stellar formation. Then, turning to your question proper, it seems to me that the data show that in these clusters, in some cases, we have formations of different age. The Trapezium-like systems are, it seems, younger than other stars in the clusters.

E. A. SPIEGEL, *University of Michigan Observatory, Ann Arbor, Michigan:* What are the relative motions of the three stars in the Orion Belt? Do they have a common motion which would indicate their being in a chain?

V. A. AMBARTSUMIAN: Yes. The relative motions of stars in the Belt are very small.

M. P. SAVEDOFF, *Department of Astronomy, University of Rochester, Rochester, New York:* Blaauw has called attention to the fact that the stars of high relative velocity in these associations are generally single stars, while those stars which lag behind and are at present in the center tend to be multiple systems. Does this fit into your picture, or have you any opinions on this observation?

V. A. AMBARTSUMIAN: I thank you for the information. But I propose no concrete theoretical mechanism for stellar formation. I cannot say what is the explanation of the fact mentioned by Blaauw. It is, of course, a very basic observation.

H. WEAVER, *Department of Astronomy, University of California, Berkeley, California:* Ambartsumian has cited λ Orionis as one of the clusters of particular interest. There have been some very interesting observations recently on the HI region surrounding λ Orionis. I would like to call on Campbell Wade for a short report on his observations of that association.

C. WADE, *Harvard College Observatory, Cambridge, Massachusetts:* The HII region excited by the 08 star λ′ Orionis has an apparent diameter of about 7°, which at the adopted distance of 300 pc corresponds to a linear diameter of 40 pc. λ′ Orionis is the brightest member of a small OB association which has been studied by Markarian.

Before describing the 21-cm observations, I should like to call attention to an interesting optical feature of the region. On Harvard patrol camera photographs of sufficiently long exposure (2 hr or more), the boundary of the nebula is clearly marked by a complete ring of dark nebulosity, although the emission nebulosity itself is not visible. The inner boundary of the dark ring follows the edge of the HII region so faithfully that there can be no doubt of a close physical connection between them. It is difficult to state the thickness of the ring with any degree of certainty since its outer edge is very poorly defined; however, it seems to have an angular thickness near one and a half degrees. The denser portions of the dark ring were listed by Barnard in his catalog of nebulae, although he did not perceive the ring structure.

A fact which may prove to be of importance is that a large number of faint *Hα* emission stars appear to be associated with at least part of the dark ring. Joy and Haro, Iriarte, and Chavira observed numerous stars of this type in and near Barnard 30, which is the densest part of the dark ring. Further observations covering the entire ring are needed before we can decide whether this fact is only a coincidence, or an actual physical property of the object. If the latter proves to be the case, the result should have importance for studies of the interrelationship between star, dust, and emission nebulae.

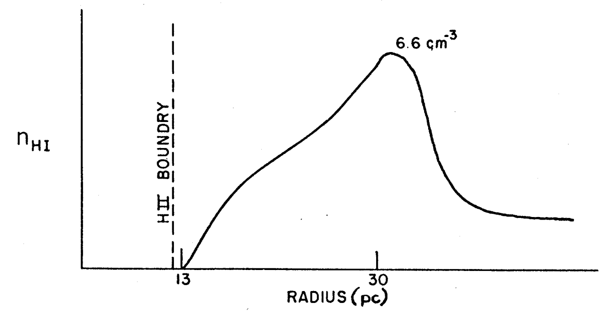

FIG. 2. Radial density distribution in the HI shell.

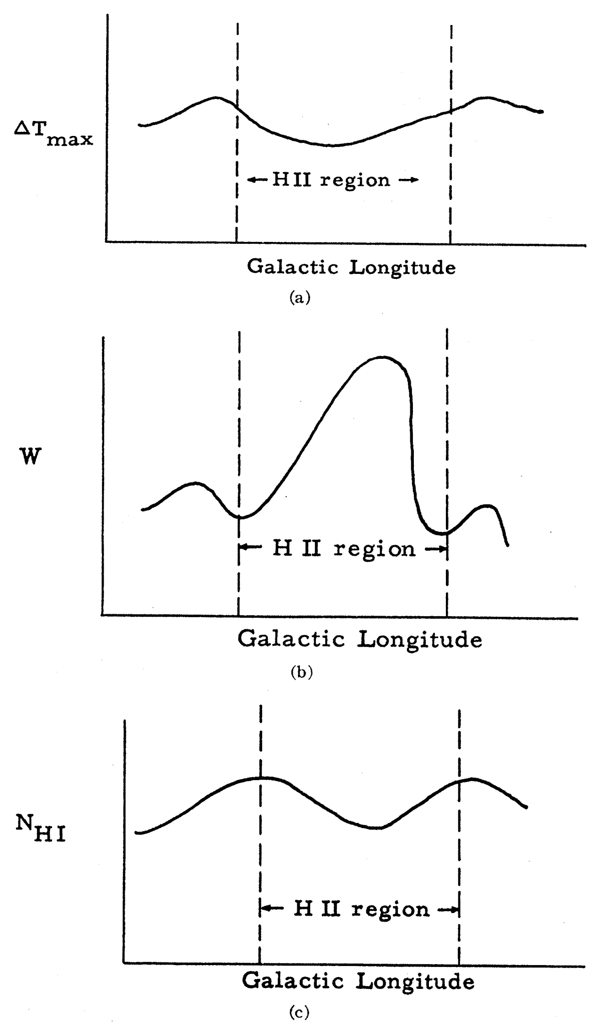

FIG. 1. (a) Peak line temperature as a function of galactic longitude. (b) Line width as a function of galactic longitude. (c) Number of neutral hydrogen atoms in the line of sight as a function of galactic longitude.

I have recently completed a 21-cm observing program on the λ Orionis region, using the 60-ft George R. Agassiz radio telescope of the Harvard Observatory. This instrument has a beam width of 49′ between half-power points at 21-cm wavelength; hence, the angular resolving power is sufficient to permit a detailed study of the region. Figures 1(a), 1(b), and 1(c) show how certain parameters of the hydrogen line vary along a diameter of the nebula lying at constant galactic latitude −10°.5. The main conclusions which can be derived from these observations are the following.

(a) *The nebula is surrounded by a thick, relatively dense shell of neutral hydrogen.*—The shell is very nearly spherical; its radial density distribution is shown in Fig. 2. In deriving the density model from the radio data, the location of the boundary of the nebula was not considered. Therefore the fact that the neutral hydrogen density goes to zero precisely at the known location of the edge of the ionized region provides some degree of confirmation of the model. The total mass of the HI shell is 45 000 solar masses, compared to 2000 solar masses for the ionized region.

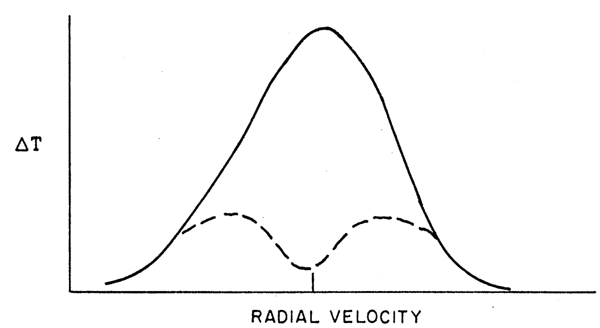

FIG. 3. The observed and corrected line profiles at the center of the HII region. The radial velocity which Courtès found for the nebula is indicated.

(b) *The HI shell is expanding at a velocity of about 8 km/sec.*—Figure 3 illustrates the derivation of this. The observed profile at the center of the nebula is shown together with the portion (corrected profile) remaining after subtraction of the contribution of the hydrogen in the line of sight. The two peaks of the corrected profile are interpreted as the contributions of the approaching and receding portions of the HI shell. The observed separation of the peaks is 17 km/sec; 1 km/sec of this is due to galactic rotation. Therefore the expansion velocity is 8 km/sec.

V. A. Ambartsumian: It is interesting to point out one other fact. On the periphery of the large nebula around λ Orionis there is an emission nebula which was observed by Shajn and by observers at the Tonantzintla Observatory. This nebula has the shape of an arc. In the central part of this small nebula, which is on the periphery of the larger one, we have a T Tauri star which has emission lines and is also a variable star. It is very interesting that this star is connected with a cometary nebula. The general impression is that when we have young groups of hot giants, they are connected with such large expanding diffuse nebulae. When we have young dwarfs, then we observe them in many cases in connection with cometary nebulae and here, perhaps, if it is not a random projection (this case is not excluded, of course) is an interesting case where such a complex of stars with T Tauri spectra are in the periphery of large nebular complexes.