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The Evolution of Stars and Astrophysics

V.A. Ambartsumian

Byurakan Astrophysical Observatory, Armenia

Abstract

Ambartsumian published this article in Russian 75 years ago. In this work, he showed for the first time that star formation was not interrupted in the past, but continues in our cosmological time. His conclusion was that at the same time as the old stars, such as the Sun, there are also much younger ones, which are only a few tens of millions of years old. Another important conclusion was that stars are born in groups. The author called the groups of young stars stellar associations. Actually, by publishing this article, Ambartsumian established a new, so-called "Byurakan concept" of the formation of space objects.

Keywords: *Stellar associations, young stars, star formation*

Explanation of the origin and evolution of celestial bodies, including such as the Earth and the Sun, is one of the main tasks not only of astronomy but also of all natural science. The field of astronomy that deals with this question is called cosmogony. In the 19th century and at the beginning of the 20th century, cosmogonic information was reduced mainly to the construction of so-called cosmogonic hypotheses. Usually, each cosmogonic hypothesis sought to explain the origin of the present state of that part of the Universe that was known at the time the hypothesis appeared. Thus, after the current state of the solar system was clarified, Laplace raised the question of how it happened. In the recent past, Jeans has already raised the question of the origin of not only the solar system but also the stellar system (Galaxy), where the Sun is one of the members. The same can be said about numerous other cosmogonic hypotheses. However, the authors of the hypotheses were faced with the following difficulty: the planetary system has so far been known only in one example. No other planetary systems have been studied that, being in other stages of development, could give an idea of the possible past or future stages of evolution of our planetary system. Jeans, however, when raising the question of our star system, knew about other star systems, but he was completely possessed by the strange idea that elliptical nebulae and spiral cores do not consist of stars, but their dust and gas. As you know, it turned out that these formations consist of stars. He had a correct idea about the structure of only our star system, and even then in a limited volume around the Sun.

Having no significant observational data on the possible past states of the considered systems of celestial bodies, the authors of the cosmogonic hypotheses were guided by some preconceived notions about the initial state of the system.

Most often, it was assumed that the initial state was a rarefied nebula.

Naturally, this path of research led to speculative constructions, often very fruitless. Only a few of the cosmogonic hypotheses (I mean just the hypotheses of Laplace and Jeans) have played a known positive role in the history of astronomy.

However, over the past thirty years, there has been a radical change in the state of affairs in this area of science. The development of modern astrophysics has led to the accumulation of colossal factual material about stars and stellar systems of the most varied types and at different stages of development. The physical properties of stars in these states have been studied. It is shown that the totality of various states of stars in nature is amazingly diverse. Some are characterized by a high rate of running, i.e., abrupt stages in the evolution of stars, such as the outbursts of novae and supernovae, are observed by us directly and are subjected to careful study. The application of modern statistical-mechanical methods to stellar systems consisting of a large number of members has led to very significant conclusions about the nature of secular changes in these systems.

As a result, the formulation of the cosmogonic problem must be completely changed and has really changed. It should not concern only the current state of an individual system out of a hypothetical initial state. It should already be about the derivation of the general laws of the evolution of celestial bodies and

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their systems. In particular, the origin of the Sun and the solar system must be understood within the framework of the general theory of stellar evolution.

This does not mean that the task of cosmogony now seems easier than it used to be. On the contrary, the richness of observational data on stars has led to the posing in the cosmogony of a whole series of new and, moreover, very deep questions about which we had no idea before. However, at the same time, it became possible to start solving the problem, starting with a consideration of a simpler problem about which of the observed states of the stars and how are genetically related to each other. By going this way, carefully studying the factual material and introducing at the necessary moments the corresponding physical hypotheses and theories (one cannot deny the usefulness of hypotheses where they are really needed), it will be possible to solve the entire cosmogonic problem.

However, even to this day, some authors continue to follow the path of speculative constructions, such as old cosmogonic hypotheses, which have already become unusable, leaving aside the entire arsenal of modern knowledge about the physical states of stars, neglecting the conclusions of the statistical mechanics of stellar systems and theoretical physics in general, and thereby piling up errors on errors. In this report, I did not consider it possible to dwell on these fruitless constructions.

Those facts and astrophysical data of cosmogonic significance, which I cite below, were obtained largely thanks to the works of Soviet astrophysicists, who, despite some weakness of our observational base, correctly direct their works toward solving the fundamental, fundamental problems of stellar physics associated with the problem development of stars, and achieve success in this field. Therefore, it is appropriate to cite them here, when summing up the results of Soviet science over 30 years.

We will first give data on individual stars and then move on to stellar systems.

Individual stars. The state of each star is characterized by the values of three basic quantities: its mass, radius, and luminosity, i.e., the power of the emitted radiation. However, not all conceivable combinations of values of mass, radius, and luminosity are found in nature. In order to make this clear, let us focus on two quantities: let's say the radius and the luminosity. In the diagram showing the dependence of luminosity on the radius, each star will be represented by one point. It turns out that the points representing the totality of stars that make up our Galaxy are concentrated around some specific lines in this diagram. According to the data we know, the overwhelming majority of stars (tens of billions in our Galaxy) are concentrated around one such line on the radius–luminosity diagram. These stars are called main sequence stars. The so-called white dwarfs, located in another area of this diagram, are the second most abundant. This is the second sequence in the diagram. The absolute number of white dwarfs should be in the hundreds of millions. By the way, this abundance of white dwarfs was first established by Soviet astronomers (Ambartsumian & Shain, 1936). In third place in terms of number is a group or sequence of giant stars. Their number in the Galaxy is, at best, several million. Indications of the existence of another, new sequence - the sequence of subdwarfs, were obtained by prof. Parenago (Parenago, 1944). We do not yet have data on the number of this sequence, and it is difficult to make a judgment about its evolutionary significance.

When the state of the star changes, the values of mass, luminosity, and radius should change. Therefore, in its evolution, the star must move along our diagram. The question is what are the possible routes of this movement.

The very examination of the various sequences we observe in the radius-luminosity diagram allows us to draw interesting conclusions. Namely, it turns out that of all the conceivable paths of evolution, only a few do not contradict this diagram. The rest contradict it and therefore must be discarded.

Obviously, the vast majority of stars are on the main sequence almost all the time. Therefore, almost all the time, their changes should be expressed in moving along the main sequence. However, stars located at different points in the main sequence have different masses. Therefore, any significant movement of a star along the main sequence must be accompanied by a significant change in mass.

This leads to the following conclusion:

Either the star of the main sequence, while remaining in it, hardly changes its state or the mass of the star changes.

It must be mentioned that so far, no possible method for increasing the mass of stars has been observed and has not been proposed theoretically. The increase due to interstellar matter is negligible. As for the decrease in mass, a similar mechanism was proposed by Eddington and Jeans and consists of the loss of mass due to radiation. The data arising from the statistical mechanics of stellar systems leads, as I have shown elsewhere, in a completely unambiguous way to such intervals of the existence of stellar systems in which the mass spent on radiation is negligible in comparison with the total mass of the star.

However, the investigations carried out in recent years (Ambartsumian, 1939b) on the direct emission of matter from stars have made it possible to find out that the loss of stellar mass that occurs in this way is many times greater than the loss due to radiation and may have an important evolutionary significance.

Below we will touch on several important examples of such direct mass emission, in which the mass of a star will be significantly reduced. It should be noted here, however, that most of the observed cases of intense ejection of matter refer to hot stars.

As for the giant branch, masses of the same order correspond to different states of this branch. Therefore, possible movements along this branch can occur without a significant change in the mass of the star. In the case of white dwarfs, for most of the known objects of this kind, we do not know the mass value. In this regard, it is still very difficult to talk about what changes in mass are possible for the advancement of white dwarfs along their branches. Finally, we must take into account the possibility of jumping transition from one branch to another.

At the same time, if we take jump-like transitions with a change in mass, then those can be of the most diverse nature and directions (branch of giants - branch of giants, but at a different point, branch of giants - main sequence, white dwarf - main sequence, white dwarf - giant, etc.). The jumps without a significant change in mass do not contradict the radius-luminosity diagram as well, for example, from the main sequence to white dwarfs and back, presumably from white dwarfs to giants or vice versa.

We see that just a simple consideration of this diagram shows, which paths of evolution on this diagram contradict it and which do not contradict it.

It may be asked whether a gradual evolutionary movement between these branches is also possible. We answer: it is possible, but the observed low frequency of stars between the branches indicates either that this happens with only a small percentage of stars, or that the residence time between the branches is very short, i.e., the transition is nevertheless made in leaps and bounds.

In order to choose from the paths of development and evolution allowed by the diagram under consideration, those that are true, i.e. to make a further selection among all conceivable changes in the state of stars, we must turn to a number of facts related to the study, so to speak, of small stellar systems, i.e. double stars and star clusters.

Binary stars converge and diverge from other stars in our Galaxy during their lifetime. At such approaches, the systems are perturbed and the elements of their orbits change. In the course of time, a certain equilibrium distribution of the orbital elements should be established. Analyzing the data on the eccentricities of binary stars, Jeans (1935) came to the conclusion that such a uniform distribution has already occurred. However, on the basis of the data relating to a more significant characteristic for the question under consideration, to the semi-major axes of the orbits, we (Ambartsumian, 1937) found that this conclusion was incorrect. It turned out that the distribution of the elements of the orbits of stellar pairs is completely different from the equilibrium one. This led to the conclusion that the time required for the establishment of an equilibrium distribution (relaxation time) had not yet expired. Thus, it was possible to calculate that the age of the overwhelming majority of stellar pairs does not exceed several billion years.

This is the first, extremely important cosmogonic conclusion from modern astrophysics. However, the approach of a pair with a third star can lead, in other cases, to the breakup of the pair. Theoretically and opposite processes of pairing are conceivable in the case of a random approach of three stars.

In statistical equilibrium, both processes occur equally often, dissociative equilibrium takes place. However, the observed ratio of the number of pairs to the number of single stars is millions of times greater than it should have been at dissociative equilibrium (Ambartsumian, 1937) Since the probabilities of the formation and decay of pairs do not significantly depend on the presence or absence of this equilibrium, it follows that now in the stellar system decay processes occur millions of times more often than the processes of pair formation (see Appendix 1). In addition, we come to the conclusion that the totality of star pairs existing in the Galaxy cannot be the product of random encounters. The components of each pair have a common origin.

This is the second extremely important cosmogonic conclusion from the data of modern astrophysics.

Open star clusters. Open clusters usually consist of several tens or hundreds of stars. In some cases, the number of members of the cluster is measured in thousands. They are systems in which all members are connected to each other by gravitational forces. Typical open clusters are the Pleiades and Hyades. Each star cluster moves as a whole around the center of the Galaxy. However, in addition to this, each star entering the cluster makes some movement within the cluster, under the combined action of the rest of its stars. In stellar dynamics, it is proved that as a result of the random mutual close encounters of individual stars, a certain fraction of the stars will receive kinetic energy sufficient to leave the cluster. So, over time, a complete disintegration of the cluster may occur (Ambartsumian, 1938). The calculation shows that the time required for such decay is measured in several billion years, and in the case of clusters of poor stars - several hundred million years. In this case, dwarfs, i.e. low-mass stars leave the cluster faster, and already at the first stages of its existence, the cluster becomes relatively poor dwarf stars.

Some open clusters, such as and of Perseus, Messier 11, are comparatively rich in dwarfs. One might think that such systems are younger than other ones.

Among the features of these and similar clusters is their richness in B- and O-type stars, i.e., hot stars of high luminosity. Among other things, they also contain hot stars with bright lines and P Cyg stars. Both are distinguished by the fact that from them there is a continuous outflow of matter, which in any case cannot continue in each star for more than several hundred thousand years, otherwise, all the matter of the star will be exhausted. Therefore, such a state, when in the cluster there is continuously one or several P Cyg or Be stars, cannot last more than several tens of millions of years. This confirms the youth of this kind of star clusters. In turn, the presence in such clusters of a large number of hot stars of high luminosity proves that these stars are young.

Star associations. Even stronger evidence in favor of this is the presence of scattered groups of hot stars around some clusters, for example, the double cluster χ and h Persei, the NGC 6231 cluster, and others. These scattered groups, which are associations of loosely connected members, are unstable and, for dynamic reasons, must disintegrate over several tens of millions of years. I would suggest calling them star associations. In such a stellar association around NGC6231, there are, among only twenty high luminosity stars, for example, two Wolf-Rayet stars and two P Cyg stars. According to Kozyrev's theory of extended photospheres (Kozyrev, 1934), stars of these types emit one hundred thousandths of the mass of the Sun every year. Therefore, such an outflow cannot continue for one star without change for more than a million or two million years. Therefore, it is not difficult to see that such a state of these stellar associations, which undoubtedly have a common origin, can last generally at most on the order of tens of millions of years.

Especially remarkable is the stellar association around the double cluster χ and h Persei. In a circle with a radius of 2.5 degrees centered in this cluster, there are several dozen type B and M supergiants. It is possible that this association also contains many stars of other physical types. Taking a distance of two thousand parsecs for this system, we find that its diameter is about two hundred parsecs. The double cluster forms the core of this association. This core itself may have the same degree of stability as other open clusters, but the entire association as a whole is certainly unstable and should disintegrate under the disturbing influence of the galactic center unless the mass of this system is estimated at millions of solar masses. However, there is no evidence in favor of such a large mass.

Groups of T Tauri variable stars are another striking example of young stellar associations.

The facts show that almost all the variable stars of this type known to us, characterized by extremely irregular changes in brightness and certain other physical characteristics, are concentrated in two or three specific parts of the sky. Such an extremely pronounced tendency towards crowding cannot in any way be connected with the accident in their discovery. There is no doubt that we are dealing here with members of certain physical groups of stars. However, the linear dimensions of each of these groups are so large that there can be no question of their proximity in space to be supported by the forces of mutual attraction. The tidal action emanating from the center of the Galaxy should destroy them very quickly. Most likely, one should assume that these stars are already slowly diverging. So, one of these groups of 7 T Tauri stars, according to Joy (1945), has a center at a point in the sky with a galactic longitude of 140° and a latitude of $-14°$. Joy's data (Joy, 1945) suggest that the linear dimensions of this system reach 10–20 parsecs. Even if we assume that the number of members of this system is more than a thousand, this stellar association, cannot be held for a long time under the influence of internal forces of attraction. The conclusion is that if we now observe these stars together, it is because they have recently formed and have not yet had time to disperse. This stellar association cannot be older than one hundred million years. This period is short compared to the age of the Galaxy, which we estimate at several billion years. Consequently, *even now, in our era, the formation of stars in the Galaxy continues.* This is also an extremely important conclusion from the data of modern astrophysics.

In the case of T Tau stars, we are already dealing with dwarfs. By the way, they are closely related to small comet-like nebulae, showing bright lines in the spectrum, and, undoubtedly, will bring new important data for cosmogony in the future. Sanford's just-published study on the structure of the T Tauri spectrum confirms that there is a continuous outflow of matter from this star. By the way, almost half of the T Tau stars turned out to be visually binary. In those cases when it was possible to obtain the spectrum of the companion, it turned out to be the spectrum of an M-type dwarf with bright lines. Since there is no doubt about the common origin of the companion and the main star (see above on binary stars), we conclude that

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at least these bright-line M-type dwarfs are as young as T Tauri stars.

If we add here that about 40 late-type dwarf stars with bright lines, mainly M-type dwarfs, were discovered in the region of the considered stellar association in Taurus, it becomes clear that they can be attributed to a common origin with the T Tau type variables, and therefore they are also very young stars.

Since most of the stars in the Galaxy are type M dwarfs, further study of this issue will be of great importance for cosmogony.

It is also necessary to pay attention to the fact that due to the low absolute brightness of stars of the T Tauri type, the associations of stars, consisting of them, can still be detected by us only at small distances from the Sun. This is also facilitated by the low density in these associations. This can explain that until now we know only two associations of these variables and, moreover, both at distances of the order of one hundred parsecs. Therefore, there is no doubt that the number of such associations in the Galaxy is measured in at least thousands. If their age is on average about one hundred million years, then one can expect that among them there are also younger ones with an age of the order of, say, ten million years. After all, there is no reason to believe that over the past two hundred million years there was such a special moment in the life of the Galaxy, when such associations immediately, at a time, were formed, after which they ceased to arise.

So, we can say that, although the age of the Galaxy according to all stellar dynamics data is of the order of several billion years, the formation of all star clusters did not occur simultaneously and continues to this day. In any case, in the Galaxy and the Magellanic Clouds, we have very young star clusters and associations that could not exist in their present form for more than several tens of millions of years. The process of formation of open clusters and associations in the Galaxy is now continuing.

On the other hand, the formation of stellar associations and star clusters could not occur by combining into one group of previously independent stars. The proofs of the impossibility of such a mechanical emergence of a cluster (or association) of single stars are of the same nature as the argument about double stars that we gave above. The only difference is that in this case all the arguments become even stronger since the ratio of the probability of destruction of a cluster to the probability of formation of a cluster as a result of star encounters under conditions existing in the Galaxy is expressed by a number containing hundreds of significant digits.

Thus, we come to the result: stellar associations (and some clusters) as systems of stars are young, and somehow arise in our Galaxy, but they do not arise by combining previously independent stars. The stars belonging to associations and clusters, therefore, did not exist before the corresponding associations and clusters emerged. On the other hand, these systems themselves, by definition, are composed of stars.

We come to the inevitable conclusion that stars in open clusters (associations) are formed during the formation of this cluster (associations).

Comparing this with the fact that in the Galaxy we have very young stellar associations with an age of about ten million years, we conclude that the stars contained in these associations have the same age.

If so, then by studying stars in these stellar systems, we should get an idea of the states of stars in the period immediately after their formation.

We see here a rather large variety of states: Wolf-Rayet stars, P Cygnus stars, O and B stars with and without bright lines, variable T Tauri dwarfs, and yellow and red dwarfs with bright lines.

On the radius-luminosity diagram, all these states are depicted by points of the main sequence. In this case, the pure occurrence of bright lines of the P Cygnus type in the spectra of these young stars is evidence that a continuous outflow of matter occurs from them, i.e., they are not yet in stationary states. It is possible that in the future they turn into ordinary stars of the main sequence.

Thus, it should be assumed that newly formed stars enter the radius-luminosity diagram not only from one end of the main sequence but along the entire front of this sequence.

Origin of open star clusters. The question is, from what and how does the formation of stellar associations and open star clusters come about? How do appear the stars that make up these systems, namely, the Wolf-Rayet stars, P Cyg, and T Tau type stars, from which there is a continuous ejection of matter and which, perhaps, subsequently turn into ordinary stars of the main sequence. We do not know of luminous stars of such a large mass, from which, through some fission processes, open star clusters could arise. Obviously, star clusters and associations must arise from some kind of dark or faintly luminous objects of enormous mass.

In this case, there are two possibilities:

a) The original body occupied the same large volume as the stellar system that originated from it (cluster, association). Then it is possible to identify this original body with a dark nebula. At present, the presence in the Galaxy of a large number of dark diffuse nebulae consisting of cosmic dust can be considered proven. In this case, we must attribute to these nebulae masses of up to several hundred solar masses, which is much higher than the previously estimated masses of dark nebulae.

b) The formation of stellar systems of the type under consideration occurred by the division and mutual removal of the formed parts of a certain body of small dimensions in comparison with the diameters of these systems. For example, it could be a body with a diameter on the order of the diameters of ordinary stars. However, in order to overcome the force of mutual attraction and disperse over large distances, these parts should have received significant kinetic energies at the time of fission. Then the question is why these kinetic energies turned out to be almost exactly equal to the one needed to overcome the attraction field, and there are no cases at all when, after overcoming this field, the star retains a significant fraction of the kinetic energy, and thus the initial velocity.

Such stars, however, would leave the cluster but would remain in the Galaxy in the form of fast-flying stars. But we do not observe fast-flying P Cyg or even B stars in the Galaxy.

At present, no way is seen to overcome this difficulty associated with the hypothesis of an initial body of small linear dimensions.

Therefore, leaving open the question of other properties of the bodies from which the clusters and associations were formed, we must consider the low luminosity of these objects to be reliable.

This idea that star clusters and associations before their formation were some kinds of very weakly luminous objects, perhaps of a very small radius, must be connected with data on the integral emissivity in stellar systems. By the integral emissivity in a stellar system, I mean the amount of energy emitted per unit time by a unit of mass of the stellar system. It is a “macroscopic” quantity that characterizes every point in the system. It turns out that this emissivity (according to Oort) for some elliptical nebulae is, in round numbers, a hundred times less than for the vicinity of the Sun in the Galaxy (Oort 1940). When deriving the value of this coefficient, Oort used data on the rotation rates of these systems. Oort suggested that such a low emissivity value indicates a large amount of diffuse matter (cosmic dust) in them. Now that we know something about the population of elliptical systems (Baade), it is clear that these systems are much poorer in the diffuse matter than the Galaxy, they are almost devoid of it (see Appendix 2). It remains to assume the presence of a large number of clouds of low luminosity and relatively large mass.

And now it is difficult to give a clear answer to this question. However, it is worth paying attention to the close relationship of hot stars with cool supergiants and variable stars of late types. A large number of objects are already known that show in the spectrum, on the one hand, characteristics of O or B type star, on the other, characteristics of cool M star. Suffice it to name the famous star P Aqu, in which not only a set of lines, but even a continuous spectrum seems to be the superposition of continuous spectra of two stars - hot and cold.

Now, after the works of the Leningrad astrophysicist Sobolev, it is clear that in fact, we are not dealing here with the addition of the spectrum of two stars, but we are talking about the addition of the spectrum of the hot core and the outer relatively cold shell.

Even a small increase in the optical thickness of the envelope leads to a complete attenuation of the direct radiation of the hot nucleus, and the energy distribution becomes entirely corresponding to type M. The presence of a nucleus is detected only due to the emission lines. With an even thicker shell, the emission lines should also disappear. We will have an ordinary cold supergiant.

It is also known that the masses of type M supergiants are equal to the masses of stars B and O. Also, the luminosities of both categories of stars are equal.

If the internal structure of yellow and red supergiants and giants would differ significantly from the internal structure of main sequence stars with the same mass, then it would be natural to expect a different performance of energy sources in them. Meanwhile, they obey the same ratio between mass and luminosity, which is established for the stars of the main sequence. This also makes one think that there is no significant difference in the internal structure of the stars of the giant branch and the main sequence. Only the structure of the outer layers is different.

Thus, it turns out that stars of type B and O, i.e. hot stars of high luminosity, surrounding themselves with rarefied shells of a sufficiently large radius, can appear as such cold supergiants.

From the point of view of the spatial distribution, which, as we will see below, is a well-known criterion for the genetic relationship of objects of two types, the situation is good here. The spatial distributions of type B stars and late-type supergiant stars are very similar.

From this point of view, the facts about the rotation of stars, established over the past two decades by Academician Shain and American astrophysicist Struve, are of great importance. They indicate that a very

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significant part of the stars of types B and A have fast rotation. If the evolution of these stars proceeded along the main sequence towards dwarfs, then among the latter we would have to observe, by virtue of the law of conservation of rotational moment, even higher rotation rates. Meanwhile, observations indicate the opposite. True, part of the torque could be carried away by the ejected substance. But we would have to assume that the overwhelming part of the rotational moment leaves with the ejected matter. Such a mechanism has not yet been proposed. Meanwhile, during the formation of late-type supergiants from a type B star, the linear rotation velocity, due to the same law of conservation of momentum, should decrease, which is actually observed.

However, I must make a reservation here that the requirement to fulfill the law of conservation of the rotational moment regardless of the above question leads to difficulties in a number of other questions of cosmogony. Here I mean not only the problem of the origin of the solar system but also the whole complex of questions related to the origin of multiple stars.

By the way, it is precisely these difficulties associated with the rotational moment that have recently forced many authors, who are following the path of drawing up abstract cosmogonic hypotheses, to again turn to the hypothesis of capture (ready-made satellites or initial matter - it's all the same). Meanwhile, all the factual data convincingly indicate that the formation and evolution of systems of celestial bodies occur due to internal reasons, according to the laws of internal development, and serious difficulties associated with rotational moments indicate only the existence of some, we have not yet clarified, effects, the introduction of which will eliminate these difficulties.

The presence of these difficulties shows that, in theoretical terms, cosmogonic phenomena turn out to be much deeper than we thought until now. Here, in this old problem, apparently, we must still encounter a whole series of qualitatively new, original phenomena that represent a fundamental novelty for science.

However, the formulation of these questions is still moving forward very slowly due to the absence of a correct theory of the internal structure of stars.

The data of modern astrophysics on some extremely proceeding stages in the development of stars are of great importance for cosmogony. While the lifespan of most stars is measured in billions of years, i.e., for most stages of evolution, such periods are required, in comparison with which human life and even the duration of the entire history of human astrophysical observations seem to be an instant, we, along with this, are witnesses to the fact when changes in the structure of a star are directly observed within a few days, and sometimes hours. The outbursts of new stars can serve as an example of such processes.

Novae. The outbursts of Novae are cosmic phenomena that are absolutely amazing in scale and speed. Within a few tens of hours, the star increases its brightness by several tens of thousands of times. It throws out into the surrounding space a shell of gas (at a speed of about a thousand kilometers per second), which previously constituted part of its mass. Apparently, we are dealing here with a giant explosion associated with the almost instantaneous release of large amounts of intra-atomic energy. Milne suggested that the outburst of a Nova is a process of rapid transition from the state of an "ordinary" star to the state of a white dwarf.

However, statistical data on the frequency of Novae outbreaks in stellar systems convince us that, at least with part of the stars included in stellar systems, a flare occurs not once, but many times in life.

In this regard, mention should be made of the excellent study of the Moscow astronomers (Kukarkin & Parenago, 1937) concerning Nova-like variables.

The point is that, along with Nova stars, the so-called Nova-like variables have long been known, i.e., those stars that experience flares at regular, albeit inconsistent, intervals. These outbreaks are usually on a smaller scale than the flares of the Novae. Despite the difference in the time interval between two successive flares, i.e., volatility of the cycle, for each Nova variable we have some average cycle length between two successive flares.

It turned out that there is a simple functional relationship between the average cycle length and the average brightness change amplitude. The greater the amplitude, the longer the average cycle. If this dependence is extrapolated to the amplitudes of ordinary Novae, then it turns out that the outbursts of each Nova should repeat once every several thousand years. In other words, the idea arose that Novae differ from Nova-like variables only in the length of the cycle.

The assumptions of Parenago and Kukarkin were brilliantly confirmed when last year the second outburst of the star T Coronae Borealis took place before our very eyes, the first outburst of which took place in 1866. Since until 1946 only one outburst of this star was observed, it was considered an ordinary Nova. The time interval between two flashes was in full agreement with the indicated relationship between the amplitude and the cycle length.

Thus, there is no doubt now that all ordinary Novae are recurrent.

As a result of calculations carried out by my colleagues, many methods have been used to determine the masses of the shells ejected during the outbursts of Novae (Ambartsumian, 1939a). It turned out that with each flare, a mass of the order of 10-5 solar masses is ejected. It is natural from this to conclude that with each separate outburst, the structure of the Nova changes little (since the mass also changes little), but a number of successive outbursts lead to a radical change in the structure of the star.

The question arises: the transition between which two states corresponds to this sequence of outbreaks of the Nova, accompanied by a significant change in mass?

The same question can be asked with respect to Nova-like variables.

Finally, Supernovae are of great importance: during such explosions of stars, the stars for several days become a hundred million times brighter than the Sun. The calculation shows that in the case of supernova explosions, a mass is immediately ejected, which in any case constitutes a noticeable fraction of the mass of the star. Therefore, one outburst of such a supernova already means a change in the entire structure of the star, which occurs abruptly.

Again, the question arises, what were the supernovae before the outburst and what do they turn into after the outburst?

Similar examples, when an intermediate state or transient is given, but the initial and final states are unknown, could be multiplied.

Modern astrophysics, along with Nova stars, Supernovae, and Nova-like variables, knows a whole string of types of stars that can be summed up under one general category of nonstationary stars (type Be stars, type Z Andromeda, planetary nebulae, etc.). All these non-stationary states are transient states and have a limited duration. They relate in each case two different stages of a star's life, and the question of which preceding and subsequent states correspond to these unsteady states is extremely important.

I will give one more example here in order to point out later on a possible way of solving such problems.

Short-period Cepheids. Short-period Cepheids form a sharply delineated group of stars that stand out in a number of their features. Changes in their brightness are accompanied by changes in the radius, i.e., pulsations. What state were they in before the onset of pulsations, into what state do they pass after the end of the pulsations, and how long is the stage of variability?

Let us denote the state before entering the stage of a short-period Cepheid by X, and after exiting it - by Y. The question is, what are X and Y?

The following method can provide an indication of which physical types of stars to look for X and Y stars.

The point is that the distribution of stellar velocities cannot change sensitively over a period that is small compared to the duration of a star's entire life. Therefore, the distribution of the velocities of short-period Cepheids in the case under consideration should be similar to the distribution of the velocities of both X-stars and Y-stars.

Since the velocity distribution determines the spatial distribution of stars, the same can be said for the corresponding spatial distributions. But the spatial distribution of short-period Cepheids has the very important feature that these stars meet at very large distances from the Galactic plane. Therefore, X- and Y-stars should also occur in the corresponding parts of space. The shorter the duration of the variability stage in comparison with the X - Y stages, the greater the number of X - Y stars should be compared to short-period Cepheids. From this point of view, the paper published this year by Humason and Zwicky (1947) on the presence of a known number of blue stars at high galactic latitudes is interesting, showing that in the considered regions of space, along with short-period Cepheids and globular clusters, there are also noticeable numbers of other stars. Data on their numbers are very scarce, but they force us to conclude that the duration of the stage of the short-period Cepheid cannot be very short in comparison with the entire duration of the star's life. It is measured for at least tens of millions of years, if not more. However, for conclusions, it is still necessary to obtain data on the number of dwarfs in these regions of space.

What we said about short-period Cepheids is also applicable to other transitional stages (Novae, Supernovae, planetary nebulae, etc.). We must look for other stages in the development of these objects among stars with similar spatial distributions. Unfortunately, we still do not know very well the galactic spatial distributions for individual physical types, since the transition from the visible distribution over the sky to the spatial one is extremely difficult. But, for example, we can already say that there is a similarity between the distribution of planetary nebulae and the distribution of ordinary dwarfs. A whole series of other interesting examples from this area could be cited, but it would be more expedient to wait until more

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complete data on the spatial distribution and the distribution laws of the velocities of stars of different physical nature are accumulated.

Planetary nebulae. Until recently it seemed that we were close to solving the problem of the origin of planetary nebulae. The fact is that the gaseous envelopes ejected during the outbursts of Nova stars have a certain similarity with planetary nebulae. However, it was found that the masses of planetary nebulae are measured at least hundredths (if not tenths) of the solar mass and therefore are thousands of times larger than the masses of the shells ejected by the novae. On the other hand, it was found that the brightness of the Nova at the maximum is the higher, the more mass is ejected. Consequently, if only planetary nebulae were formed as a result of explosions similar to the outbreak of Nova, then the scale of such explosions should have been much larger and the brightness of the flared star at its maximum was thousands of times higher than that of Nova. It was natural to assume that such explosions leading to the formation of planetary nebulae are supernova explosions.

Note that the assumption that planetary nebulae are formed as a result of the ejection of an envelope by central stars, in itself, can hardly raise any doubts. Observations indicate that the planetary nebulae we observe are in the process of expanding. On the other hand, it has been theoretically proven that a planetary nebula cannot be in a state of statistical equilibrium. The observed expansion rates of planetary nebulae make it possible to calculate that their age cannot exceed ten thousand years in order of magnitude. During this period they must scatter in space and become invisible. On the other hand, according to the calculations made by (Parenago, 1947), the number of all planetary nebulae in our Galaxy should be about 15000. Under these conditions, to maintain the number of planetary nebulae at this level, it is necessary that on average more than one planetary nebula arise annually. Meanwhile, according to the available data, in one Galaxy, on average, one Supernova flares out in five hundred years. Therefore, supernova explosions cannot be identified with the processes of the formation of planetary nebulae. Consequently, the question of the origin of planetary nebulae requires further study. As for the Supernovae, one should pay attention to the recent suggestion by Rusakov (1947) that diffuse nebulae arise as a result of supernova explosions.

Evolutionary connection between stars and interstellar matter. This connection is one of the most exciting problems in astrophysics. The authors of the so-called cosmogonic hypotheses very often sought to prove that stars and other celestial bodies arose from nebulae. Interstellar matter is a collection of nebulae. We have already seen that modern astrophysics knows many cases when the rarefied matter in a gaseous state is ejected from stars. There are also very strong reasons to believe that particles of interstellar dust can concentrate from interstellar gas.

The presence of reverse processes - the transformation of diffuse matter into stars, has not yet been proven. Their theoretical possibility is not properly substantiated and needs to be studied. However, it should be noted that diffuse nebulae are found in the same galaxies and in the same regions of galaxies where open clusters, type O and B stars, and other young formations are often found. Diffuse nebulae, according to Baade's terminology, belong to the first type of population in the Galaxy. Therefore, their evolutionary role deserves careful study.

Two types of populations of stellar systems. The establishment of two types of populations of stellar systems is a fundamental fact that cannot be ignored when studying the problems of stellar evolution. Since the spatial distribution of the stars that make up the population of these two types differs sharply from each other, it must be assumed that constant transitions from states belonging to one of these types to states belonging to the other type do not occur. Therefore, short-period Cepheids and another type II objects are not directly related evolutionarily to type B, O, Wolf-Rayet stars, and others. However, a deeper evolutionary connection, rooted in the formation of our Galaxy, is by no means excluded. The facts established regarding various types of galactic populations have already forced many to abandon previous misconceptions (for example, the idea that elliptical nebulae are the initial stage in the development of galaxies).

Here we want to draw attention only to the following circumstance. In galaxies such as the Magellanic Clouds, we have a large abundance of supergiants, P Cyg stars, and open clusters. All these are undoubtedly young formations. In particular, in the Large Magellanic Cloud, attention is drawn to a large number of open clusters, which include a significant number of supergiants and which have unusually large linear dimensions. Thus, the NGC 1910 cluster, which includes the brightest of the known supergiants, has a diameter of about 70 parsecs.

On the other hand, it is known that open clusters observed in the Galaxy have diameters on the order of two or three parsecs. It seems that the Large Magellanic Cloud is much richer in open clusters of large diameter.

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In fact, the difference is apparent. It is easy to see that the above stellar associations in the Galaxy, containing a large number of supergiants, when observed from outer galaxies, should stand out entirely against the galactic stellar background since supergiants are very rare among background stars. For an observer located inside our Galaxy, these supergiants have the same apparent brightness as stars of low absolute brightness, which are close to the observer, and are lost among the latter. Such an observer is struck by only the nuclei of associations, which are ordinary galactic clusters.

So, when observed from the Magellanic Clouds, the association of stars around and Perseus should stand out as a giant star cluster with a diameter of two hundred parsecs with a double core. Obviously, there is no such size association in the Large Magellanic Cloud.

The full significance of the facts relating to different types of population of galaxies will become clear in the coming years. They can quickly generalize the factual material that relates to our Galaxy.

We have given here only a few examples showing the fundamental cosmogonic significance of many facts established by modern astrophysics. These examples provide fair answers to many questions, but it is still impossible to merge them into a unified theory of stellar evolution. In particular, as you can see, we have not yet made any conclusions about the process of star formation.

But it becomes obvious that in the future cosmogony will increasingly rely on a solid and broad base, consisting of the facts established by modern astrophysics, and increasingly lose the character of a speculative discipline, which was inherent in it even in the recent past.

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Appendices

Appendix A On the question of the absence of dissociative equilibrium in a stellar system

In a stellar system, from a mechanical point of view, both processes of destruction of stellar pairs and processes leading to the creation of a pair of two single stars are possible. The destruction of a pair can occur when a third disturbing star passes by the pair. The reverse process, when three stars meet and when, under the influence of one of the stars, the other two form a pair, giving the energy of relative motion to the first star, leads to the formation of a double star. In the course of time, a dissociative equilibrium should be established in the stellar system, in which these opposite processes compensate for each other.

Let us set ourselves the task of finding out whether there is a dissociative equilibrium in the Galaxy at the present time.

In this case, for definiteness, we consider pairs made up of two types of stars: stars of the type α with masses m_α and stars of the type β with massesm_β. Let's assume that $m_\alpha > m_\beta$.

The number of single stars α and β per unit volume is denoted by n_α and n_β respectively. Let us now select from the volume unit all pairs $\alpha\beta$ for which the distance between the components lies between r_1 and r_2. Let the number of such pairs be $n_{\alpha\beta}(r_1, r_2)$. For the number of such pairs, the dissociation formula gives

$$\frac{n_{\alpha\beta}\left(r_1, r_2\right)}{n_\beta} = \frac{\Gamma\left(r_1, r_2\right)}{\left(2\pi m_\beta \Theta\right)^{3/2}} n_\alpha, \tag{1}$$

where $\Gamma\left(r_1, r_2\right)$ is the sum over the states corresponding to all possible states of the satellite β around one star α for which the distance is between r_1 and r_2.

Here $\frac{3}{2}\Theta$ is the average kinetic energy of single stars. We have

$$\Gamma\left(r_1, r_2\right) = \int e^{-\frac{\varepsilon}{\Theta}} d\Gamma_\beta,$$

where the integration is extended to the region of phase space in which the distance to the main star lies within the considered limits.

Let us now take these limits such that $\varepsilon \ll \Theta$ is everywhere in this part of the phase space. This requirement, for example, will be satisfied if we take $r_1 = 100AU$, $r_2 = 1000AU$

Then $e^{-\frac{\varepsilon}{\Theta}}$ under the integral sign can be replaced by unity and

$$\Gamma\left(r_1, r_2\right) = \int d\Gamma = \iiint \iiiint dxdydzdp_xdp_ydp_z = 16\pi^2 \int\limits_{r_1}^{r_2} dr \int\limits_{0}^{P_0} r^2p^2dp,$$

where p is the value of the momentum vector. At a given distance r from the central star, in an elliptical motion, p cannot exceed the limit P_0 , given by the formula

$$\frac{P_0^2}{2m_\beta} = \frac{Gm_\alpha m_\beta}{r},$$

otherwise the satellite will be hyperbolic. That's why

$$\int\limits_0^{P_0} p^2dp = \frac{P_0^3}{3} = \ frac13m_\beta^3\left(\frac{2Gm_\alpha}{r}\right)^{3/2},$$

whence it follows that

$$\Gamma\left(r_1, r_2\right) = \frac{16}{3}\pi^2 m_\beta^3 (2Gm_\alpha)^{3/2} \int\limits_{r_1}^{r_2} r^{1/2}\, dr = \frac{32}{9}\pi^2 m_\beta^3 (2Gm_\alpha)^{3/2} \left(r_2^{3/2} - r_1^{3/2}\right)$$

or as in this example, $r_2^3 \gg r_1^3$

$$\Gamma\left(r_1, r_2\right) = \frac{32}{9}\pi^2 m_\beta^3 (2Gm_\alpha r_2)^{3/2} .$$

Substituting this result into (1), we find

$$\frac{n_{\alpha\beta}\left(r_1, r_2\right)}{n_\beta} = \frac{32}{9}\pi^{1/2}\left(\frac{Gm_\beta m_\alpha}{r_2\Theta}\right)^{3/2} n_\alpha r_2^3.$$

The two dimensionless factors included in the right-hand side

$$n_\alpha r_2^3 and \left(\frac{Gm_\beta m_\alpha}{r_2\Theta}\right)^{3/2}$$

have a very simple physical meaning. The first one means the number of α stars per sphere with radius $r_2 = 1000AU$. The number of all stars in such a volume is less than 10^{-7}. The smaller this number is for each separate type of stars α. The second factor is two thirds of the ratio of the potential energy of a pair with a distance of $1000AU$ to the average kinetic energy of a single star raised to the power of $3/2$. Its numerical value is in any case less than 10^{-4} , unless m_α is many tens of times greater than the mass of the Sun.

Therefore, we get

$$\frac{n_{\alpha\beta}\left(r_1, r_2\right)}{n_\beta} < 10^{-10}.$$

Meanwhile, observations show that pairs with component distances from $100AU$ to $1000AU$ make up a significant fraction of all pairs. A significant proportion of visual doubles have just such distances. If we take the main stars of all types α, then in any case

$$\frac{n_{\alpha\beta}\left(r_1, r_2\right)}{n_\beta} > 10^{-2}.$$

Thus, the observed percentage of binaries with the considered distances with respect to single ones is 10^8 times greater than the number of cases of pair formation as a result of triple encounters. In conclusion, we note that above we limited ourselves to pairs with certain distances in order to give more definiteness to the dissociative formula. If we talk about all pairs in general, then it would be necessary to introduce an upper and lower limit for distances (the upper limit is due to the fact that the distance in a pair cannot be greater than the average interstellar distances, the lower limit is due to the presence of the physical radius of the star). Their determination would require additional calculations, in addition, the lower bound would turn out to depend on the type of stars. This would, however, lead to similar conclusions.

Appendix B On the amount of absorbing matter in elliptical galaxies

From a macroscopic point of view, we can characterize each stellar system by specifying in it the volume emissivity η and the absorption coefficient α as functions of a point. Then the intensity of the light leaving the system will be determined by the formula:

$$I = \int\limits_0^\infty e^{-\tau} \eta ds, \tag{1}$$

where ds is an element of the ray path, and the optical depth τ is a function of the point with abscissa s on the ray.

$$\tau = \int\limits_0^s \alpha ds.$$

Since $d\tau = \alpha ds$, equation (1) can be rewritten as:

$$I = \int\limits_0^{\tau_1} e^{-\tau} B d\tau,$$

where

$$B = \frac{\eta}{\alpha},$$

and τ_1 is the total optical depth of the entire system in the considered direction.

Taking the average value of B out of the integral sign, we get:

$$I = \overline{B}\left(1 - e^{-\tau_1}\right), \tag{2}$$

where

$$\overline{B} > I. \tag{3}$$

Observing the brightness of the Milky Way in any direction in the galactic equator, we can consider the optical thickness in this direction to be very large. Therefore, for the intensity in the Milky Way, according to (2), we will have:

$$I_M = \overline{B}_{Gal}. \tag{4}$$

On the other hand, when observing the central regions of elliptical nebulae, we encounter intensities almost a hundred times greater than the brightness of the Milky Way:

$$I_{El} = 100 I_M = 100 \overline{B}_{Gal}.$$

Comparing with (3), we obtain

$$\overline{B}_{El} > 100 \overline{B}_{Gal}.$$

Or

$$\left(\frac{\eta}{\alpha}\right)_{El} > 100 \left(\frac{\eta}{\alpha}\right)_{Gal},$$

in other words, the ratio of the emissivity to the absorption coefficient, i.e., the amount of light matter to the amount of dark matter in elliptical nebulae, is more than a hundred times greater than this ratio in the part of the Galaxy surrounding the Sun. Thus, the mere fact of the high surface brightness of elliptical nebulae leads to the conclusion that there is practically no absorbing matter in them, at least in a continuously distributed form. Observations also do not establish the presence of separate dark clouds in them.

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