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Large-scale star formation in galaxies

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Contents

Abstract. A brief review is given of the history of modern ideas on the ongoing star formation process in the gaseous disks of galaxies. Recent studies demonstrate the key role of the interplay between the gas self-gravitation and its turbulent motions. The large scale supersonic gas flows create structures of enhanced density which then give rise to the gravitational condensation of gas into stars and star clusters. Formation of star clusters, associations and complexes is considered, as well as the possibility of isolated star formation. Special emphasis is placed on star formation under the action of ram pressure.

1. Introduction

Astronomy is an evolutionary science; all its branches ask questions on the nature of the corresponding objects. The understanding of the energy sources and evolutionary laws of stars in the 1940-1960s was one of the greatest triumphs in natural sciences. During the same years it became clear that stars form by condensation of a rarefied gas but the motive forces of this process are still under discussion. The evolution of galaxies is determined by the star formation history therein and the most prominent details of their structure are extended regions where star formation continues at the present time. The understanding of galactic evolution is a necessary premise to solve the question of their origin, which is deeply connected with the cosmological problem which remains the greatest aim of the science.

The gas serving as the original material for star formation constitutes a complex multiphase medium with regions of different density, temperature, and ionization degree. In particular, there are cold (with a temperature of about 100 K) and dense clouds embedded in a warm (near 10^4 K) or even hot (up to 10^6 K) rarefied medium. This gas undergoes large-scale chaotic motions which are excited by supernova explosions inside it and intense stellar wind from young massive stars. Most frequently, the velocities of the gas motions exceed the sound speed; for this reason such complex supersonic motions of the interstellar medium are termed 'supersonic turbulence' for brevity. A distinctive feature of such turbulence is the presence of shock waves of different scales and strengths propagating in the medium. In addition, the interstellar medium is also magnetized, with the energy of the magnetic field being sometimes comparable with that of the chaotic motions.

In the gas inside galactic discs, spontaneous star formation occurs which is ultimately caused by gravitational collapse — the gas cloud contraction and transformation into stars. Density fluctuations of the interstellar medium are produced by the supersonic turbulence; those of them with masses and densities exceeding critical values give rise to stars.

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The turbulence and gravity are always present and one can even say that there is no spontaneous star formation at all, at least in the sense in which the process of radioactive decay of nuclei is spontaneous. However, the star formation induced by processes (and, in particular, by instabilities of different kinds) that are not related to specific phenomena but constitute the intrinsic property of the interstellar medium can well be considered spontaneous.

An increasing number of scientists are coming to a conclusion that star clusters form in those parts of molecular hydrogen clouds (the most dense structures in the interstellar medium) where the turbulence proves to be too weak to resist gravity. The processes increasing density and pressure in the interstellar medium (stellar wind from hot stars, supernova shocks, galactic spiral density waves, collisions of gas clouds and shocks, etc.) and triggering mechanisms of (stimulated, induced) star formation can overcome the turbulence opposing gravity.

Our review is devoted to large-scale star formation processes in the interstellar medium and to the structures they produce. Special attention is given to discussion of the role of turbulence in forming star groups of different scales, as well as to structures resulting from the impact of shock waves on the interstellar medium, especially due to ram pressure. The motion of gas clouds and whole galaxies through a less dense medium leads to stimulated star formation and the appearance of characteristic, almost unstudied phenomena.

2. Stars form at the present time, too

Stars form at the present time too — this fact was recognized about half a century ago, and first we shall briefly narrate how this conclusion was arrived at. At the beginning of the 1930s, all stars were thought to have originated simultaneously and at time immemorial. By 1950 almost everybody came to the agreement that the difference in star ages amounts to billions of years and that star formation continues up to the present day.

The scientific setting of the problem of the origin of stars was put forward by W Hershel who was the first to have started systematical studies of star clusters and nebulae with sufficiently big telescopes. He came to the conclusion that different objects can be at different evolutionary stages, and as changes in the world of stars proceed very slowly and we can not notice them directly, the purpose is to correctly place the object on the evolutionary sequence. "In order to prove the development of a plant, would not it be one and the same to consecutively observe the germination, fluorescence, leaves, fruiting, fading, and death of one specimen of a given plant, or to simultaneously observe a huge number of specimens demonstrating all stages this plant passes during its existence?", Hershel wrote in 1789. Hershel thought he observed directly the formation of stars by looking at planetary nebulae, and it appeared to him that in some of them this process had already been completed — a star was shining in the center! Now we know that precisely these nebulae are shells that the stars eject shortly before death. The problem of determining the evolutionary stage of a star, posed by Hershel, was correctly solved only in the middle of the 20th century.

By the end of the 19th century, sufficiently reliable data as to luminosities, temperatures and masses of stars had been obtained and the first attempts trying to relate these data to a physical theory and to give them an evolutionary interpretation appeared. Of special importance for the observational approach to stellar evolution was the appearance of a spectrum – luminosity diagram introduced by E Hertzsprung and H Russell (1905 – 1913). In 1913, based on the idea by Lockier, Russell assumed that stars originate as cold huge giants which then contract, get warm and arrive at the main sequence on this diagram. After that they gradually cool down and 'roll down' along this sequence. The gravitational contraction was considered to be the source of the star energy. However, already by 1926, mainly due to works by A Eddington, it became clear that this evolutionary scheme fails. In this hypothesis, the lifetime of the Sun appeared to be two orders of magnitude shorter that the age of the terrestrial rocks and the predicted rapid decrease of the Cepheid period pulsations (due to the assumed contraction) was not observed. A Eddington pointed to nuclear synthesis as a plausible source of stellar energy and J Jeans considered the transformation of the stellar matter into radiation more probable, meaning the coalescence of protons with electrons. This annihilation provided a lifetime of the Sun of about 10^{13} years. For the whole population of stars in the Galaxy, Jeans obtained the same estimate of their ages from dynamical considerations using the decay time of star clusters and the statistics of binary star orbits.

It might appear that the problem of star formation moves into the deep past converging with the problem of galaxy formation. In fact, as early as in the mid-1930s B Bock and V A Ambartsumian estimated the dynamical evaporation time scale of star clusters to be significantly shorter than the age of the Galaxy according to the Jeans estimate. Shortly after astrophysical data on the short life time of at least massive stars appeared. At the beginning of the 1930s some papers appeared which proposed nuclear reactions as the source of stellar energy. This idea became widely recognized after the famous paper by H Bethe (1938), who is still alive, in which he showed that the transformation of hydrogen to helium could be such a source. The theory of nuclear reactions allowed estimation of the time for nuclear fueling a star. The ages of stars can be assessed from the estimates of the nuclear fuel store (i.e. the mass of a star) and its expenditure rate (i.e. the luminosity), and since the luminosity is proportional to the mass cube, it became clear that the higher is the luminosity of a star, the shorter is its lifetime.

One of the first who understood that highly luminous stars formed quite recently was F Whipple. In the paper presented in January 1942 at the Inter-American Astrophysical Congress, Whipple (1946) noted that none of the known physical mechanisms of energy generation can sustain the radiation of supergiant stars for three billion years, the minimally allowed age of the Galaxy, and so some process of contemporary star formation must exist. "The interstellar medium provides the only clear source of material to construct stars", Whipple concluded. Using the paper by L Spitzer on the dynamics of the interstellar medium, F Whipple found that in a time interval of about 10^9 years the presently observed gas-dust clouds can evolve into star clusters, which explains the similarity between the spatial-kinematical characteristics of the clusters and the tendency of young stars to associate with light absorbing dust clouds. Essentially, these were the grounds of the modern concepts of star formation.

In 1944, Unsold calculated the time for highly luminous stars to expend their thermonuclear energy. For example, he found that the lifetime of an O7 star is as short as

1.3×10^7 years. The publication of Unsold's paper was also delayed and appeared only in 1947. By noticing that high luminosity stars are usually found in the vicinity of light absorbing clouds, Russell concluded in 1948 that this is explained by the ongoing condensation of stars from the pre-stellar substance, the gas-dust matter. In 1946, Bock considered all possible means of estimation of star ages and concluded that "we almost have to allow the probability that all stars are still 'being born' or that at least some supergiants originated less than 5×10^8 years ago". In 1952, B Stromgren also stated that 'the consideration of ages of massive O and B stars leads to the conclusion that such stars are continuously forming from the interstellar matter'.

In the same years, however, F Hoyle (1915 – 2001) tried to explain the existence of hot high luminosity stars by their rejuvenation by accretion of interstellar matter — exactly aimed to bring in agreement their age with the age of the Galaxy. The positions of adherents of the formation of all stars in the deep past were far from being surrendered.

Works by V A Ambartsumian (1908 – 1996) on stellar associations started in 1947 played an important role in recognizing the ongoing star formation. The associations in our Galaxy are usually not visible in photographs. They are discernible against the background stars only as condensations of stars of a certain spectral class (Fig. 1). As early as in 1910 – 1914, after first catalogs of stellar spectra and radial velocities appeared, J Kapteyn, W Boss and A Eddington discovered large groups of hot stars (of spectral classes O and B) and, in particular, the presently known as OB-associations in Orion, Scorpio, and Centaurus. In 1929, A Pannekoek published the list of 37 condensations of OB-stars which contained very large groups in addition to clusters.

H Shapley in 1927 concluded that star clusters in some cases represent concentrated parts of big systems. A similar conclusion was reached by W Bidelman who published in 1943 the results of studies of supergiants in the region of the binary open cluster h and χ Persei. Their physical connection with the cluster is unquestionable, but the size of the whole group is about 200 pc (ordinary open clusters are smaller than 5 pc). W Bidelman thought that these supergiants could not have originated in the binary cluster, since each of the components is capable of retaining its members, and that the problem of the dynamics of star clouds is far from being solved. In 1945 O Struve studied the similar group of supergiants around the open cluster NGC 6231 (in Scorpio) and noted that the tendency of a cluster to be surrounded by extended groups of supergiants is one of their most important structural features.

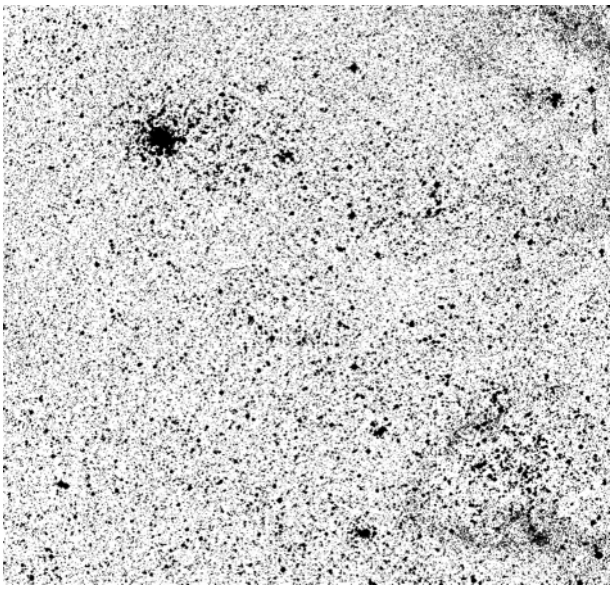

Figure 1. Part of the nearest galaxy — the Large Magellanic Cloud. To the upper left — young massive cluster NGC 2100, to the right bottom — OB-association LH 104 = NGC 2081.

It was these two groups that were used by V A Ambartsumian in 1947 as examples of rarefied groups of OB-stars; he proposed to call them 'stellar associations'. Of course, the matter was not in the new name for already known groups. V A Ambartsumian evaluated their density and concluded it to be insufficient for the stability of the group subjected to the action of tidal forces of the Galaxy. Neither W Bidelman, nor O Struve dared to make this conclusion, although Ambartsumian initially operated only with their data. He found that in a time of about 10^7 years the associations should have disintegrated. The dynamical instability of the associations implied a young age for their stars, so these estimates of the age of associations drew great attention. They were confirmed in 1952 when W Blaauw discovered that the proper motions of stars of a small O-association near ζ Persei suggest its expansion at a rate of about 10 km s^{-1}. The conclusion on the young age of high luminosity stars became widely recognized.

Soviet cosmogonical meetings in 1951 – 1954 reported in their resolutions the 'discovery of new types of stellar systems' and the 'victory of Soviet materialistic cosmogony' that arrived at the conclusion of group star formation. O Struve, the heir of the Struve astronomical dynasty and white emigrant, who closely watched Russian astronomy, in 1949 published in *Sky and Telescope* a sympathetic paper on stellar associations with due acknowledgment of V A Ambartsumian's conclusion on their dynamical instability. But in 1952, in the full swing of the campaign of 'fighting for the priority of Russian science', in a paper entitled 'Astronomy in the spirit of '1984'', Struve wrote in a different way. "Ambartsumian did not 'discover' the presence of 'stellar associations', although he owns the outstanding merit of putting forward remarkable stimulating ideas concerning their properties and origin. Did the memory about Kapteyn 'evaporate' in the Soviet Union and did the great Dutch astronomer become a 'non-personality'?", he wrote.

In fact, most star groups named 'stellar associations' by V A Ambartsumian were known before his studies and he himself (in contrast to his followers) did not speak of the 'discovery' of the associations. The term 'association' was also used before, but it was Ambartsumian who introduced the notion of the 'associations' as large rarefied groups of young stars, which proved to be very useful. However V A Ambartsumian did not stop at the conclusion of the dynamical instability of the associations. According to his estimate, on a time scale of the order of 10^7 years the associations must noticeably extend in direction parallel to the galactic plane, however observational data at that time did not reveal this. Then V A Ambartsumian concluded that stars of the associations acquired a velocity of at least 1 km s^{-1} at birth (otherwise the influence of the galactic differential rotation, i.e. the galactic tidal forces, would affect the shape of the associations) but less than 10 km s^{-1} (such high velocities would be easily noticed). As the condensation of diffusive matter (keeping the initial mass constant) can give rise to only

a gravitationally bound system, Ambartsumian had to assume that stars form due to an explosive disintegration of compact unobservable massive bodies. This conclusion leads to both physical and purely logical problems, which causes many astronomers to come out against it. The idea of the very existence of stellar associations, their expansion and explosive star formation from unobservable superdense bodies was frequently considered as a unified 'doctrine', which made the opponents of V A Ambartsumian come out against the very reality of stellar associations, too. A battle flared up at the Second Meeting on Problems of Cosmogony in May 1952 and ended in the victory of V A Ambartsumian. He and his adherents secured the leading heights in Russian astronomy.

Note that the very possibility of criticising the 'doctrine on stellar associations' (in spite of it being awarded the Stalin Prize in 1950) shows that the moral climate in Soviet astronomy was very different to that, say, in biology... Nevertheless, the decision of this meeting with respect to A I Lebedinskiĭ and L É Gurevich contains the advice to 'take into account the criticism and to make more complete use of rich factual data'. In theoretical studies, it was recommended to 'more fully unmask the idealistic essence and scientific failure of physical idealists Hoyle, Weizsecker, Jordan, etc.'. At this meeting, B A Vorontsov-Vel'yaminov, A I Lebedinskiĭ, L É Gurevich especially actively opposed the mysteriously originated pre-stellar 'superdense bodies' which eject individual stars or give birth to gravitationally bound clusters and gas clouds (which are always related to young star groups) and, while being a collisionless system, nevertheless concentrate for some reason (as gas and young stars) in the galactic plane. None of them became members of the Academy of Sciences of the USSR. Later on, S B Pikel'ner, one of the founders of the modern theory of star formation, who was many times voted down in elections to membership of the USSR Academy of Science (see Ref. [1]), in the fall of 1975 said that the impossibility of scientific discussions with the adherents of the 'Burakan concept' is a shame for our science. In the beginning of the 1970s, the paper of P N Kholopov who argued against this concept was refused for publication in the *Astronomicheskiĭ Zhurnal*.

The critics of the 'doctrine on the associations' (which was later named the Burakan concept) argued against both the reality of stellar associations and their expansion. In a strange way, the role of the internal stellar energy supply into the ambient medium (in the form of stellar winds and expanding HII zones around O-stars), as well as due to supernova explosions, was underestimated. In 1956, Lebedinskiĭ and Khorosheva argued definitely against the gas loss by the protocluster as a reason for the expansion of associations. In fact, to correctly estimate this effect, modern knowledge of the very low efficiency of star formation in most protoclusters was needed. If a lot of gas leaves the protocluster rapidly enough, the newborn stellar group becomes gravitationally unbound and fairly soon must get rarefied and extended to be classified as an association. Perhaps, the severe discussions that shook Soviet astronomy at the beginning of the 1950s and renewed in the 1970s, would not have occurred, if this simple mechanism for expansion and disintegration of associations was then recognized as it is now. It was known long ago, but data on the low efficiency of star formation, on molecular clouds were accumulated only in the 1980s. Now the problem is how to explain in general the formation of massive gravitationally bound clusters, since they necessarily should have O-stars and supernovae. The usual 'magic wand', the assumption of a different initial stellar mass function, fails here because in many cases old massive clusters contain neutron stars, the remnants of massive stars.

To conclude the historical introduction, we note that in some sense the protoclusters indeed prove to be dense (but not superdense) unobservable (until around 1975) bodies. In the obsolete 'Burakan concept', being wise after the event, one can find a rational kernel. The density of molecular clouds, whose studies started at the middle of the 1970s, is much higher than that of the associations generated by them. However, as late as in 1986, V A Ambartsumian argued that both stars and nebulae originate from something else (and since then he has never discussed this problem in public). This persistence in upholding the deliberately hopeless concept seems strange; it is difficult to imagine that he himself did not understand its being hopeless. I S Shklovskiĭ in a conversation (that was fated to become the last one) with one of the authors in December 1984 named this concept 'Lysenko-like' and added that the social roots are the same... However, there is information that in private talks V A Ambartsumian admitted that the 'concept' became something like a trade mark of the Burakan Observatory, which should not be abandoned...

Notice that the Burakan concept later included also notions on the disintegration of galaxy clusters and on a special role of galactic nuclei. In both cases, the origin of galaxies from unobservable superdense matter was assumed. Similar ideas on the appearance of new matter in galactic nuclei were expressed earlier by J Jeans and then by F Hoyle and H Arp. Up to now, there are a lot of unclear points in the galactic origin, however there is much observational evidence that 'ordinary' black holes host galactic nuclei, and the 'virial paradox' for galaxy clusters is explained by the existence of dark matter. V A Ambartsumian objected to both these explanations, but as in the case of stellar associations, he attracted attention to really important problems. The points considered in this section are discussed in more detail in books [1 – 3].

3. Hierarchical stellar groups

From the end of the 1950s, progressively more data indicated that alike hot young stars appear not individually but in associations, the OB-associations themselves form groups (Fig. 2). It was discovered later that significantly older stars — cepheids, regularly pulsating massive stars, also tend to concentrate in extended groups. The period – luminosity dependence for cepheids allows their reliable distance determination, as well as the distance to the open clusters. For cepheids, the period – age relation was also found. The higher the mass of the star, the larger its radius and smaller the density, and the latter determines the period of pulsations. Cepheids with the longest and shortest periods have an age of about 20 and 200 mln years, respectively [4], whereas the age of O-stars is less than several million years. The groups singled out by cepheids also contained younger objects, including stellar associations, and have a mean size of about 600 pc. These groups were termed stellar complexes [5].

Further studies revealed that nearly 90% of associations in our Galaxy and nearby galaxies enter stellar complexes [3, 6]. Realizing the fact that OB-associations are embedded as a rule into star groups of a much larger size comprised of older low-luminosity stars helped to understand the contradictory results which were obtained in studies of stellar associations in other galaxies. In 1964, S van den Bergh [7]

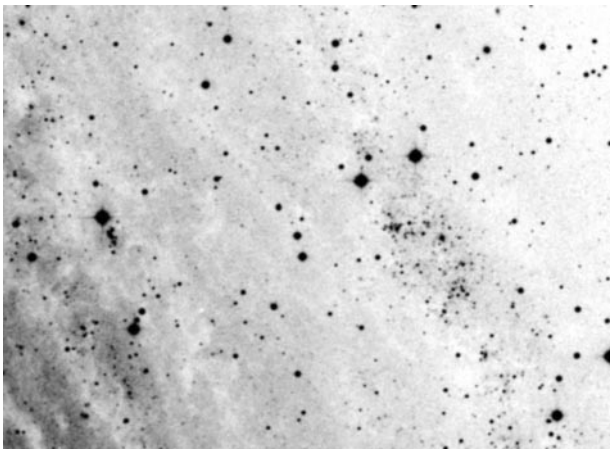

Figure 2. Part of the nearest spiral galaxy — the Andromeda galaxy (M31). To the right — stellar complex OB 122, to the left (below the bright front background star) — stellar association OB 132. It looks like a chain of several stars due to the inclination of the M31 plane to the line of sight. The OB 132 diameter is about 100 kpc. This is a rare example of an isolated OB-association.

singled out about 200 groups of blue stars in the Andromeda galaxy with a mean size of about 500 pc. He considered these groups as OB-associations and explained their sizes, which were ten times larger, than in our Galaxy, by outer parts of associations in our Galaxy being lost against a denser star background than in M31. However, later on cepheids were discovered also to concentrate in the extended groups of blue stars in M31. After stellar complexes in our Galaxy have been selected, it became clear that in M31 they would appear exactly as groups described by van den Bergh as OB-associations.

The larger age and size of stellar complexes compared to OB-associations enabled the astronomers to explain the large dispersion in sizes of the 'associations' selected in some other galaxies (many of them should have been classified as stellar complexes). True OB-associations were singled out inside the van den Berg groups in M31 in searches for the most blue and bright (and hence the youngest) stars, the mean diameter of these 'true' OB-associations being around 80 pc. Approximately the same size was found for the associations studied in all other galaxies, if only the brightest stars were selected [6]. This conclusion was confirmed many times, including when objective methods for combination of stars in groups were used and with the high angular resolution provided by the Hubble Space Telescope [8].

The 80 pc size might appear characteristic for OB-associations, and we assumed it could be related to the mean size (around 40 pc) of giant molecular clouds which are progenitors of the OB-associations. At the usually low star formation efficiency and the all-around small probability of formation of O-stars, it was a giant molecular cloud with mass of the order of 100 000 solar masses that was needed for O-stars to arise in a stellar group produced inside which should have been named an O-association [6].

However, new data cast doubts on the existence of a distinctive size for gas clouds, and the distributions of sizes and masses for gas clouds demonstrate a large, generic similarity with stellar groups. The series started from multiple stars and further from clusters, associations and group of associations towards stellar complexes, corresponds to the sequence of gas clouds from condensations in the molecular cloud nuclei with fractions of a parsec in size to super-clouds with a mass of 10^7 solar masses and a size up to 1 kpc. Apparently, only these super-clouds can be considered as independent, separately existing structural units, and they occur as a rule in spiral arms of galaxies; we shall return later to this point. Smaller structures are apparently artifacts of the limited angular resolution of radio telescopes; speaking more precisely, they are conditionally separated elements of the continuum.

Increasingly more data are accumulating that, excluding comparatively rare cases where regular forces (like gravity in spiral density waves) act on the gas, the cloudy structure of the interstellar gas mainly represents an extended net of turbulent gas with supersonic motions and a hierarchical, fractal density distribution. The clouds in this net have a hierarchical, self-similar, fractal structure whose the volume fractal dimension was found to be $D \simeq 2.3$ [8]. (We recall that the mass is proportional the radius cube for a homogeneous density distribution and the fractal dimension in this limiting case is 3. The smaller the fractal dimension, the smaller is the volume occupied by objects of the fractal nature in a given sphere).

This value is close to that observed in the laboratory in turbulence-related processes, which may suggest the significant role of turbulence in the formation of interstellar gas clouds [9]. The star formation in gas clouds of different sizes also must be hierarchical giving rise to groups of different scales embedded into each other, the largest of them being stellar complexes [10]. But a fractal distribution possesses no characteristic scale or distinctive mass. The recent high-resolution observations of the Large Magellanic Cloud (LMC) in the neutral hydrogen line (Fig. 3) confirm that essentially there are no individual clouds; this is an idealiza-

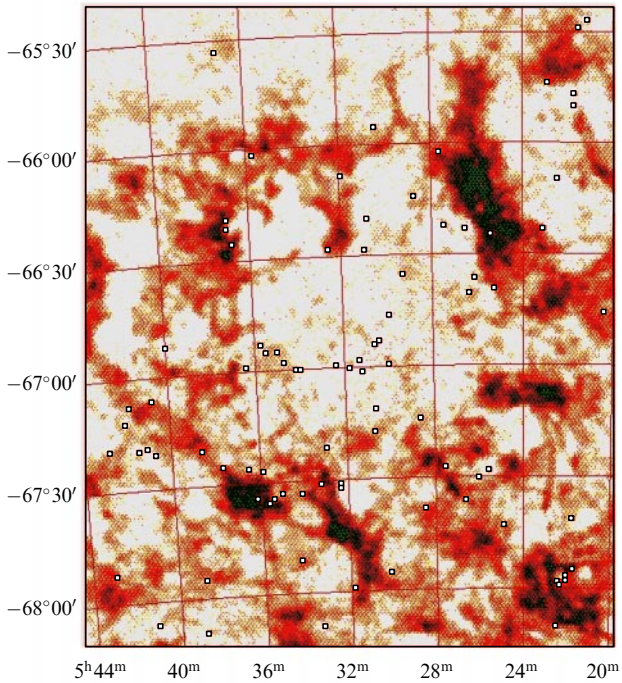

Figure 3. Neutral hydrogen (HI) surface density map in the north-east part of the LMC (according to [11]) and stellar clusters (quadrangles) therein. The extended bubble/supershell LMC4 is in the middle. 1° = 900 pc. The coordinates are of the 2000.0 epoch.

tion of the reality. In fact, there is an inhomogeneous density distribution with filaments, condensations, rarefications, and numerous cavities which we discuss below [11]. The fractality means that the gas density decreases as the volume considered increases, and turbulence means the presence of irregular motions in the gas which are characterized by the velocity dispersion inside a given volume. The turbulent crossing time of a cloud equals to the ratio of the cloud size λ to the Gaussian velocity dispersion v. According to observations, for molecular clouds, which are the most dense regions of the interstellar gas, this time is approximately proportional to the square root of the size λ (see [11] and references therein).

The latter result is in remarkable agreement with the theory developed by S A Kaplan [12] for quasi-isotropic acoustic turbulence with discontinuities and shocks. The spectrum of such turbulence, i.e. the dependence of velocity on the scale of motion, has the form $v \propto \lambda^{1/2}$, so that the size divided by the corresponding velocity is indeed proportional to the square root of size. As mentioned above, turbulence in star forming regions is mainly due to energy release by supernova explosions, as well as to gas fluxes generated by stellar winds from young massive stars. Then large-scale shells (up to hundreds of parsecs in diameter) moving with supersonic velocities appear in the medium, which can collide with each other by generating motions of smaller scales. These secondary short-wave motions have a complex spatial structure, include both acoustic and vortical components and can be supersonic, too. Here at all scales, from the smallest to that of large shells, there are shock waves that form significant condensations in the interstellar gas.

The supersonic cascade of turbulent motions thus generated and described by the Kaplan spectrum is similar to the Kolmogorov cascades in vortical turbulence of an uncompressed medium. The similarity is strengthened also by the universality of fractal spectra of chaotic motions, the power-law exponents of these spectra being close to each other. However, there is a distinctive difference that no energy dissipation occurs in the Kolmogorov cascade (it occurs only in the smallest scale due to viscosity), while in the supersonic cascade the energy dissipation occurs in every act of the shock front interactions. That is why, in particular, in the acoustic turbulence the velocities decreases faster with the scale than in the incompressible medium turbulence case. The supersonic cascade generates (exactly due to its energy dissipation) the corresponding hierarchical system of condensations in the gas, which only in the most crude approximation resembles the ensemble of clouds. But even in the rough terms of clouds a reasonable interpretation of observational facts becomes possible that confirms the existence of the very cascade of motions and even gives the correct fractal dimension reflecting the spectrum of original supersonic chaotic motions.

The duration of star formation inside a given region turns out to increase according to the law $Dt \simeq 3.3\lambda S^{0.38}$, where Dt is the difference of cluster ages in million years, S is the relative distance in parsecs, which was established when matching the relative distances S and the difference of ages Dt of star clusters in the Large Magellanic Cloud [13]. The power-law exponent in this empirical law is close to $1/2$.

These data clearly indicate that it is the supersonic turbulence that is responsible for the formation of condensations in the gaseous medium that start collapsing into protostars. Besides, the star formation ends very rapidly, over one-and-a-half – three turbulent crossing times. The formation of stars can begin when the turbulent energy in the original cloud has dissipated away, with the dissipation time being small, on the order of one-two crossing times, as follows from estimates based on numerical modeling of magnetohydrodynamic supersonic turbulence (see [10] and references therein).

The assumption of the rapid star formation is confirmed by estimates of the dispersion of stellar ages in clusters [14] and means that we observe young stars practically where they arose as protostars, so their distribution conserves the fractal structure of the initial gas defined by turbulence which also determines the initial stellar mass function. Here there is no problem of energy support of molecular clouds against rapid collapse, because the star formation indeed proceeds very rapidly. However, only a small fraction of the mass of these clouds participates in this process at each time, so the rapid collapse of this fraction does not lead to rapid disappearance of the clouds. Star formation is ineffective at large scales and the problem of explaining the large lifetime of the whole fractal network of molecular clouds does not arise [15]. The fractal structure of stellar groups embedded into each other, reflecting the interstellar gas structure, is firmly established [16].

The dependence of the star forming region size on its age (i.e. on the age of the oldest stars inside it) allows us to consider the problem of expansion of stellar associations and their having a definite mean size in a different way. More aged associations have a larger size in accordance with the formula given above and not because they have expanded and aged over this time. The expansion out from a common center, which was assumed by the Burakan concept of the ejection of stars from 'superdense bodies', would imply a linear dependence of the age on the size. This does not refute the dynamical instability of associations but casts doubt on this instability being responsible for the age – size relation. The recent studies show that the motion of stars in a gravitationally bound group depends on too many factors (for example, the presence of nearby gas clouds) and the starting moment of the association's expansion start and hence its age can not be reliably determined from motions of stars.

As mentioned above, the fractal hierarchical structure possesses no distinctive scale, which contradicts the observed preferential scale. Possibly, this characteristic scale is due to OB-associations being selected by stars of certain ages — O- and early B-stars. This question requires further investigation. It is not excluded that associations do not exist as a separate class of stellar groups, they represent just one scale from the continuum of these group scales corresponding to an age around 10 mln years. The sizes of stellar groups are compared with their ages in paper [17] which revealed the signs of large groups having large ages. However, the ages of groups unresolved into stars considered in Ref. [17] were determined ignoring data in the U-band and so are very ambiguous. The problem remains actual.

4. The nature of stellar complexes

Physically determined sizes appear when we approach scales corresponding to the thickness of spiral arms or gaseous disks of galaxies. The sizes of the largest oval, not rotationally stretched stellar complexes make the case. They depend on dynamical and morphological parameters of the host galaxies and increase with the galactic diameter [18, 19].

The regions with even larger sizes can not be categorized as complexes. When their diameters approach the galactic disk thickness (several hundred parsecs), they become stretched by galactic differential rotation into short scraps of spiral arms. In this sense, the hierarchical sequence of increasingly large star formation regions can be supplemented by the class of objects next the complexes, the flocculent spiral arms [20].

However, not all the star forming regions are turbulent and not all structures are fractal. Expanding gas shells, spiral density waves, post-relaxation star clusters and in general all structures whose morphology is defined by the external pressure or directly by gravity are not fractal [21].

Most star-gas complexes are apparently remnants of supergiant gas clouds isolated due to large-scale gravitational instability inside the galactic disk [22, 23]. It is these superclouds with a mass of around 10^7 solar masses that must originate first according to the Jeans criterion at densities and velocity dispersions usually observed in galactic gaseous disks. The value of the critical density in galactic disks below which star formation stops corresponds to exactly 10^7 solar masses and a Jeans wavelength of 1 kpc [24]. Such massive clouds and stellar complexes emerging from them are density fluctuations sufficiently large for a spiral structure to appear in marginally stable galactic disks [25]. However, spiral arms also exist in galaxies where the density is below the critical one, for example in M33. The necessity of reaching the threshold gas density for triggering the large-scale star formation has been studied in Ref. [26].

Images of very distant and hence young galaxies in the deep Hubble telescope fields frequently show the presence of several very bright stellar complexes — superassociations, usually located in spiral arms [27]. In regular two-arm spiral galaxies, whose arms are density waves, numerous star-gas complexes concentrate in spiral arms (Fig. 4) and frequently are evenly spaced along the arm [23]. The last fact indicates that these (so to say, secondary) complexes were formed due to gravitational instability [28] or magnetogravitational instability [29] developing along the arm. In the latter case the magnetic field along the arm must be regular, and this is indeed observed for the part of the western arm of M31 where stellar complexes are evenly spaced. At the same time, this sort of regularity is fully absent in the arms of the spiral galaxy NGC 6946 with irregular magnetic field (the regular magnetic field in this galaxy is present between the optically visible arms). Thus we conclude that the magnetogravitational instability is the dominant formation mechanism of star-gas complexes along density wave spiral arms, which are characteristic of the grand design galaxies.

So at present two points of view on the origin of the largest structural units of young stars coexist. In the context of star formation in a fractally structured gas, it is difficult to speak of the physically common origin of stars of the complex, and the problem of the origin of stellar complexes simply does not arise. These are the regions of the interstellar gas with ongoing star formation. However, the reasons for the persistent appearance of the selected size of O-associations remains unclear and observational tests of the age-size relation for stellar associations are still required. Many data point to the existence of isolated superclouds, inside which the stellar population of a complex appears with time. At least inside long spiral arms in grand design galaxies, stellar complexes undoubtedly form from originally isolated superclouds. The same fractal density distribution is established inside them.

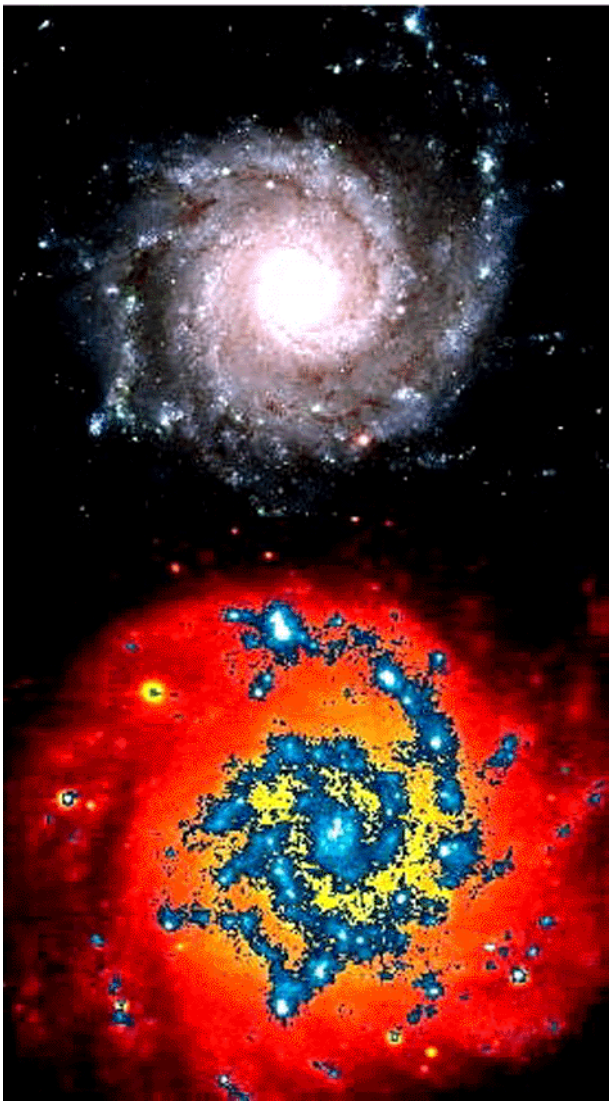

Figure 4. Spiral galaxy NGC 628 = M74. Upper panel: image taken by the 8-m Gemini telescope; bottom panel: UIT (ultraviolet telescope onboard Shuttle) image. Stellar complexes appear as bright spots on spiral arms.

5. The formation of star clusters

Until recently, stars were thought to originate in groups, and the presence of isolated young stars was explained by rapid disintegration of groups where they were born. The low efficiency of star formation raises the question as to how in general gravitationally bound clusters containing massive stars could be preserved. These stars at the stage of O-stars and supernova explosions strongly affect the interstellar gas by pushing it out from the cluster. This problem also relates to classical (old) globular clusters, which for sure contained massive stars, as follows from the large content of neutron stars in them (and in general from the natural and largely confirmed conclusion of the universality of the initial stellar mass function in the clusters, in addition to the large (up to 10^6 solar masses) mass of these clusters).

One may also speak about the universal mass function for star clusters themselves, ranging from low-mass open clusters to globular clusters, and the form of this function is similar to the mass distribution of gas clouds. The hierarchical self-similar structure, including that of gas clouds, at any fractal

dimension must have the mass distribution of the form $n(M)\,\mathrm{d}M \propto M^{-2}\,\mathrm{d}M$, which is confirmed by observations (see [21] and references therein). The same law is characteristic for the mass distribution of all star clusters (after the correction for escape of stars from old clusters), which is evidence for their origin from fractally structured turbulent gas clouds [30]. Massive globular clusters form inside regions with a high pressure stabilizing the initial gas cloud against the destructive action of radiation of O-stars and supernova explosions. Dense gravitationally bound clusters must form inside such clouds [30, 31].

The common origin of open and globular clusters, suggested in paper [30], agrees with Larsen's conclusion [32] that the traditional difference between open, massive, and globular clusters is conditional and is essentially caused by the present low formation rate of stars and clusters in the Galaxy. Similar ideas were formulated by P N Kholopov long ago [2]. The classical old globular clusters in the halo of our and other galaxies formed in the conditions of high pressure in the primordial star formation burst, which explains their nearly equal ages.

Under normal conditions, as inside the present-day disk of the Galaxy, the effect of O-stars and supernovae on the gas leads to its loss and the appearance of a gravitationally unbound association. So our Galaxy contains almost no massive compact clusters — more massive groups, whose formation continues in the disk, are rarefied associations. Only NGC 3603 and Cyg OB2 can be classified as young globular clusters.

There are, however, plenty of gravitationally bound young clusters in the Magellanic Clouds, and in the last years numerous young stellar clusters have been discovered in interacting galaxies [33 – 35]. The hypothesis that such clusters originate in high-pressure regions naturally explains this fact. Such a pressure arises in the gas when galaxies approach each other thus provoking the collision of clouds inside them. Both the Magellanic Clouds periodically approach each other, which evidently explains the great amount of rich stellar clusters in them.

The mass distribution of old globular clusters in our Galaxy, however, has not a power-law shape but a Gaussian form, most clusters having a mass of the order of 10^5 solar masses. This fact has usually been considered as the indication that the formation mechanism of open clusters (for which many authors have obtained a power-law distribution with an exponent of around 2 for a long time) is quite different than for globular clusters. However, the absence of old low-mass globular clusters is explained by the fact that over the 12×10^9 years since their formation such clusters have already disintegrated due to close approaches with the Galactic center and giant molecular clouds, as well as due to the evaporation of stars, as many authors conclude following Surdin [36].

Young compact clusters similar to rich young clusters in the LMC have recently been discovered in many irregular and spiral galaxies, mainly due to systematic searches in the latter case carried out by Larsen and Richtler [20] in 21 spiral galaxies. The number of young massive clusters normalised by the host galaxy luminosity was found to vary over a wide range but at the same time it correlates with the star formation rate in the galaxy. These authors note that the high star formation rate and the resulting large density of hot stars supplying energy into the interstellar medium can be sufficient for the high turbulent pressure to be established and gravitationally bound clusters to form. They conclude that a lot of massive young clusters are present where there are a great number of young stars in general and the formation of numerous massive compact clusters in interacting and star-forming galaxies is explained by the same mechanisms as in normal galaxies but operating under extreme conditions [34]. This conclusion was confirmed by Whitmore [22] who found that the relation between the star formation rate and the number of young massive clusters determined in Ref. [34] can also be extended to interacting galaxies which contain many young rich clusters.

6. Two modes of star formation

However, the formation of a massive star cluster does not always simply follow from the general high star formation rate. In our Galaxy and the LMC some star complexes are known to contain unusually large or small numbers of clusters with respect to the number of isolated stars of the same age [3]. The most striking example is provided by the group of stars with the same age around NGC 2164 (Fig. 5), in which only three cepheids (and additionally a few inside clusters) are known, although the age of this complex is optimal for cepheids to be present there.

The objective comparison of the cepheid and cluster distributions in the LMC yielded three additional cluster groups; it turned out that only one of four cluster groups coincides with the cepheid concentration [37]. This group is located at the eastern edge of the galactic bar, where two tens of smaller clusters and nearly 150 cepheids, of which more than 20 are cluster members, were found around massive clusters NGC 2058 and NGC 2065. Immediately to the south-east of this complex a dense group of nearly the same size (around 200×300 pc) comprising 180 cepheids but having no somehow evident star clusters is found (Fig. 6). In the middle of this group, inside an area of about 0.1 kpc^2, no clusters are visible and the cepheid number density is about 900 per square kiloparsec, i.e. two orders of magnitude larger than in the solar surroundings. The periods and hence ages of these cepheids fall within narrow limits. This implies that this

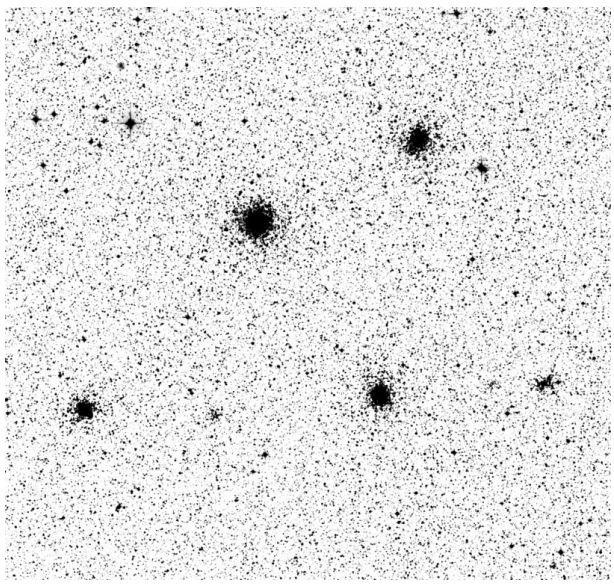

Figure 5. Group of young massive clusters near NGC 2164 in the LMC.

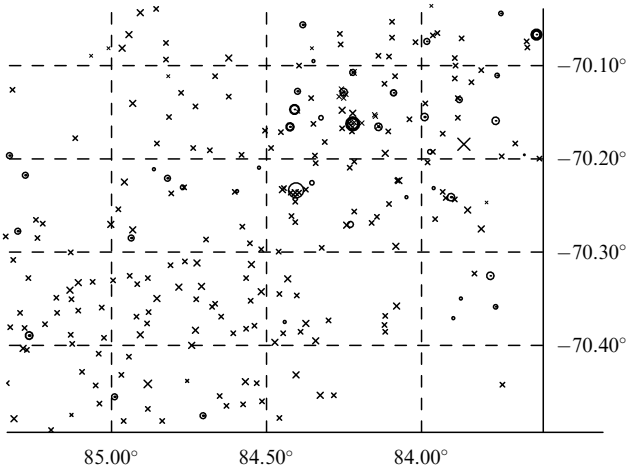

Figure 6. Cepheids (crosses) and clusters (circles) near the east end of the LMC bar.

complex to the southeast of NGC 2058 is a relic of an unusual star formation burst which did not give rise to gravitationally bound clusters or generated isolated stars only. Detailed investigation of this entire region of the LMC is critically important to understand the reasons for the appearance of both clusters and isolated stars or only the latter. It should be noted that the region of the present star formation 30 Dor lies almost symmetrically to this group of cepheids with respect to the bar axis. Such a localization is apparently favorable for intensive star formation.

There are more significant discrepancies between the appearance of clusters and isolated stars both in space and time. For example, the cluster formation rate in the irregular galaxy of the Local group IC 1613 normalised to the LMC star formation rate is 600 times lower than in the LMC, which is the same type of galaxy [38]. Such a discrepancy arises both at different locations and at different times in a given galaxy. The interruption in the cluster formation (at least, for massive clusters), which occurred 4 – 14 bln year ago in the LMC, had not been accompanied by a decrease in the star formation rate.

Apparently, the situation could be again understood from the viewpoint of the theory of star formation in a turbulent medium. According to this theory, it is turbulence, not magnetic field, that retains molecular clouds from freely collapsing. Either clusters or isolated stars form preferentially depending on the physical characteristics of the turbulence (intensity, spatial scale).

A rapid formation of clusters occurs if only gravity is present; it is also possible for decaying turbulence or turbulence with a large wavelength, whereas at shorter wavelengths only isolated field stars form [40, 41].

The last fact is very important since it can serve as the best explanation for both the existence of a star complex without clusters (however, without providing any reason for its high density) and the existence of isolated young massive stars in general. It is undoubtedly proved in the papers by Massey et al. [42, 43] who studied high luminosity stars in the LMC and showed these stars to occur equally in the field and associations. Considering the young age of these stars, this fact cannot be explained by the presently isolated stars having migrated to such large distances from their possible birth sites in the associations. Apparently, these stars are too numerous for the assumption that they have been ejected due to dynamical stellar interactions in dense cores of young clusters. Here it is important that the stellar mass function in the field goes much more steeply (indicating a larger fraction of less massive stars) than for stars in associations [43]. The steep shape of this function for stars of higher mass is obtained exactly for the case of short-wavelength turbulence, which corresponds exactly to the isolated star formation [44].

The conclusion that in the absence of turbulence or for the decaying turbulence case (and insignificant role of magnetic field in supporting clouds against the gravitational collapse, as advocated by adherents of this theory) clusters and not isolated stars are produced clearly means that the star formation in the cluster proceeds very rapidly, because in the absence of the turbulent support (and general rotation) the collapse of the gas protocluster occurs very rapidly. Klessen et al. [41] found that at larger densities gas collapses into dense cores over short free-fall times and the star formation efficiency exceeds 50%. These authors also concluded that the difference in the strength and character of the turbulence could be quite sufficient to explain the formation of isolated stars and stars in clusters.

It is quite possible that the presently observed old classic globular clusters were formed in the absence of the turbulent support of the original cloud. As Phinney [45] concluded, a great number of neutron stars and massive white dwarfs (i.e. the remnants of massive stars) in globular clusters is evidence that most gas in the protoclusters should have formed all massive stars very rapidly, over a time scale of the order of the crossing time, before at least 1% of massive stars started to affect the ambient gas as supernovae or O-stars do. This suggests the formation time for massive compact clusters to be really small and close to the free-fall time that for the half radius of a globular cluster is about 1 mln years, which is shorter than the lifetime of massive stars.

Therefore, it is possible that both the external high pressure and very rapid collapse of the protocluster in the absence of turbulence are favorable for the formation of massive gravitationally bound clusters. Then we should admit that sometimes turbulence is absent inside sufficiently extended regions, like 300×300 pc for the group of clusters around NGC 2164. The theory of turbulence-controlled rapid star formation has no need for admitting turbulence regeneration to prevent the collapse of molecular clouds, they indeed can be short lived formations [46].

Apparently, there is no need to look for special reasons for the existence of regions without strong turbulence; the spatial (and temporal) intermittency of cells with laminar and turbulent flows is well known in hydrodynamics and this stochastic phenomenon may quite possibly occur in the interstellar medium, too. It would be important to find other indications of its reality and to understand its spatial and temporal scales in galactic disks. The presence of only cluster complexes or stellar complexes can mean that outside the spiral arms stellar complexes correspond to maximal cells of the interstellar gas turbulence of the same character [47].

7. The origin of HI supershells

As we have seen above, normal stellar complexes appear due to processes which are obligatorily occurring in gaseous galactic disks. However, sometimes complexes have an arc-

like shape or are bounded by circle segments which clearly should be formed in some special way; they are described in Refs [48, 49].

The characteristic form of such complexes suggested the presence of some central source of pressure that shaped the expanding shell of swept-up gas which then disintegrated into stars. The problem of formation of arc-like complexes thus appeared to be a particular case of the old problem of formation of giant shells of neutral hydrogen known to be present in some galaxies. The energy of the central pressure source capable of forming the 1 kpc supershell of swept-up gas is tens to hundreds times the energy of one supernova explosion (ordinarily taken to be 10^{51} erg), so successive supernova explosions in a sufficiently rich cluster together with stellar wind from its hot stars are thought to be the energy source for these supershells. This possibility was considered by Vader and Chaboyer [50] for the giant arc of clusters in NGC 1620 and by Efremov and Elmegreen [51] for two arcs at the North-East of the LMC. Clusters in the swept-up gas shell are assumed to form due to gravitational instability which develops at some critical gas density in the shell.

In the absence of the central cluster, expanding supershells are hypothesized to form due to the fall of a fast gas cloud on the galactic plane. This idea was originally proposed to explain the origin of stellar 'superrings' [52]. However, in many cases it was proved that such clouds do not exist near galaxies with HI supershells.

Sometimes the invisibility of a central cluster can be explained by the supershell being inside a region with small differential galactic rotation and/or by a large thickness of the gas disk. Then this supershell can persist for such a long time that the central parent cluster is sufficiently old and thus invisible [36, 41]. However, the age and size of the supershell can be used to estimate the parameters of the progenitor cluster and thereby to check the 'standard model' of the supershell origin.

Strange as it may seem, such a test has been done only recently. Rhode and her colleagues [53] carried out careful searches for clusters within the HI supershells in the irregular galaxy Ho II. But only inside 6 of 44 supershells did they find clusters for which the number of stars and the age are consistent with the assumption that in the past they contained a sufficient number of massive stars to create these supershells. In Ho II, there are no clusters inside the largest supershells as well, which additionally (as supershells in our Galaxy) occur in the galactic periphery where there are no or very few young massive stars.

It is possible that only in very massive (of the order of 10^6 solar masses) clusters supernova explosions are frequent enough to create supershells. The authors [54] note that a mean energy supply rate even from 1000 supernovae over 2×10^7 years implies a heating rate of the interstellar medium close to its cooling rate at the normal pressure, and it seems possible that in order to create a supershell very massive clusters indeed are needed. The distribution of many HI envelopes in the LMC shows a very weak relation with clusters (see Fig. 3).

There are also other, poorly studied possibilities. A supershell initiating the subsequent star formation may appear around the crossing place of the galactic plane by a sufficiently massive (globular) and fast moving cluster [55]. The hypothesis on the origin of giant cavities in the turbulent interstellar medium due to non-linear development of the combined gravitational and thermal instabilities without energy supply from stars seems to be inadequate [56].

If the galaxy moves in a sufficiently dense intergalactic medium, the initially small cavities in its gaseous disk could get larger under the action of the ram pressure [57]. This hypothesis was proposed (but not justified) in [57] to explain numerous cavities in the Ho II galaxy. The external HI isodenses in this galaxy are bounded from one side by a perfect circular arc, which is evidence for the galaxy moving through the interstellar gas of the M87 group [57] (see below).

The problem of the supershell origin has a long history. Heiles [58], who first discovered a dozen supershells in our Galaxy, noted that though they could have been produced by a large number of type II supernovae exploding in OB-associations, 'the absence of their [supershell] associations with extremal population I objects is a strong argument against such a possibility'. He even assumed that the 'agent responsible for the existence of supershells has never been observed directly. This agent could be by itself a new unknown type of astronomical object' [58, p. 544]. Perhaps, Heiles was right. Gamma-ray bursts were proposed to be such objects supplying sufficient energy into the interstellar medium to create supershells (see Refs [54, 59]).

If supershells form under the action of multiple supernovae and hot O-stars on the interstellar medium, then why have no supershells been found around many clusters in which these objects (judging by the amount of presently observed stars therein and their ages) were undoubtedly present? The explanation could be that around such clusters the density of neutral and/or molecular hydrogen is very high. Morphological relations between shells of ionized hydrogen around hot stars and the ambient gas are actually very complex and ambiguous [60].

It would be interesting to solve the inverse problem — not to search for clusters inside supershells but supershells around massive clusters, and using the mass and age of the cluster and parameters of the surrounding medium, to explain the cases of the absence of HI cavities.

At present, only two clear cases are known (in galaxies NGC 1620 and IC 2574) when an older cluster is found near the center of the cluster complex or the HI supershell which could be responsible for the formation of the entire structure. Here it is important that young clusters in the IC 2574 complex are located irregularly within an ellipse circumventing a cavity in HI (Fig. 7). Its form corresponds to a circle that looks like an ellipse due to the inclination of the galactic plane to the line of sight [61].

The giant arc in NGC 1620 also has an irregular shape [50], which, however, judging by the galactic images could be a usual fragment of a spiral arm. Both these formations bear little resemblance to regular stellar arcs in the LMC or to the western boundary of the Hodge complex in NGC 6946, which are segments of a perfect circle.

8. Stellar arcs in the LMC and gamma-ray bursts

The very existence of a multiple system of giant stellar arcs in the LMC means that they can not have originated in a supershell swept-up by supernovae and O-stars that existed in the central clusters. One can admit that these specific clusters are already indiscernible, but still why are all the arcs located close to each other? The hypothesis was put forward that these arcs could result from individual super-

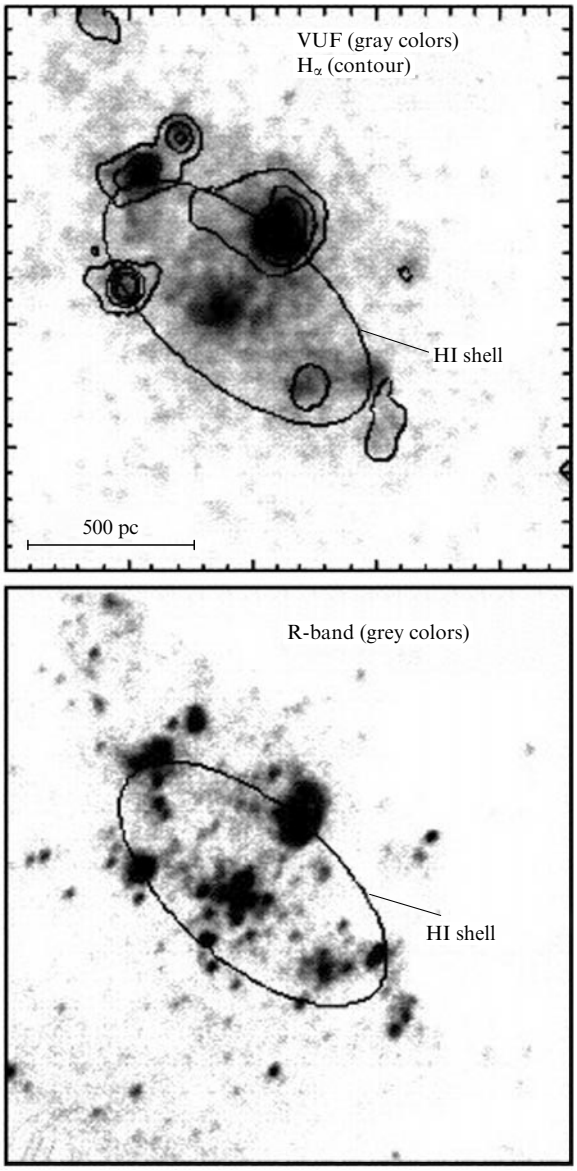

Figure 7. Stellar complex in the IC 2574 galaxy formed by the swept-up HI shell (taken from paper [61]).

strong explosions related to gamma-ray bursts (GRB), whose progenitors were ejected from the massive cluster NGC 1978 located inside the same region of the LMC (Fig. 8). This hypothesis utilizes the assumption that GRBs emerge due to the coalescence of binary compact objects forming due to dynamical interactions of compact objects with stars in the dense stellar cluster core ([62] and references therein).

The form and sizes of stellar arcs in the LMC in that case could reflect the central angle of the GRB jets, but more probably they could result from a long-term effect on the interstellar medium of a narrow multi-precessing jet similar to that which created the observed HI shell around SS433 [48, 63].

Should giant stellar arcs really be generated by energy release from gamma-ray bursts, important implications for the nature of GRB follow. The data indicating that these bursts occur in star forming regions are thought to be inconsistent with the hypothesis that systems of compact objects are the GRB progenitors because it takes such a long

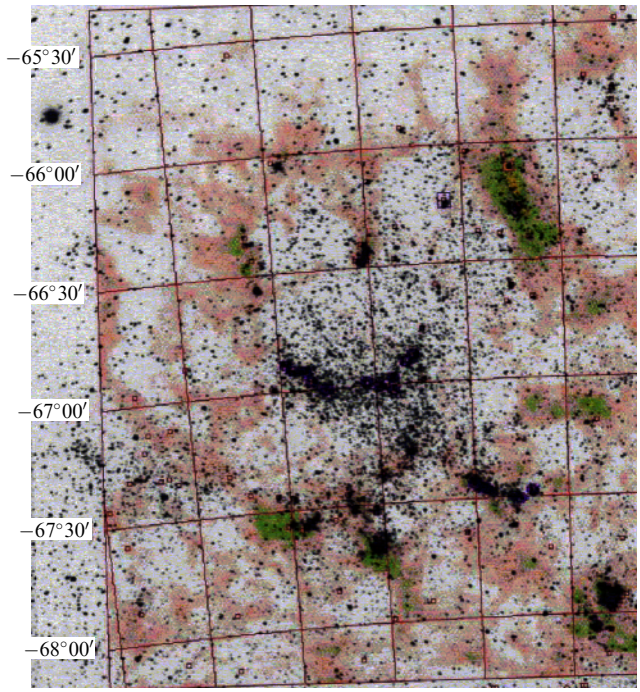

Figure 8. Stellar arcs in the region of the LMC4 supershell in the LMC (against the neutral hydrogen background). The Quadrant is in the middle, the Sextant is on the bottom. The large quadrangle marks cluster NGC 1978.

time for the initial binary system to coalesce that it escapes far away from the place of birth [64]. However, these difficulties do not arise if these binaries form inside dense cores of stellar clusters. Multiple gamma-ray bursts are possible close to the parent cluster and they are capable of creating star forming regions near which subsequent bursts occur.

Recently, some observational indications supporting such a scenario have appeared. GRB 980425, which is the closest to us, occurred in a stellar cluster inside a star formation region, and an arc-like structure is present nearby with the curvature center located in the region of the cluster [65]. It is important to note that this is the only GRB sufficiently close for these facts to be observed. Tsvetkov et al. [66] found that contrary to the conclusion of paper [64], the distribution of GRBs over distances to the host galaxy centers is similar to neither star formation regions, nor supernova remnants. In our opinion, it resembles the distribution of classical old globular clusters and demonstrates a clear concentration towards the center of the composite galaxy [63].

It is very intriguing that the GRB distribution over redshifts indicates that most of the observed GRBs occurred about 8 – 12 bln years ago, i.e. when classical globular clusters had an age similar to that of NGC 1978, about 2 bln years. Perhaps, massive clusters of exactly such an age serve as an effective source of objects creating gamma-ray bursts [63]. This stage, however, does not last a very long time since today classical globular clusters (whose age is about 12 – 14 bln years) evidently have no relation to gamma-ray bursts.

9. Peculiar stellar complex in NGC 6946

The peculiar stellar complex in NGC 6946 discovered by P Hodge in 1967 is unique in having a perfect semi-circular boundary and a high density of stars and clusters (Fig. 9). The

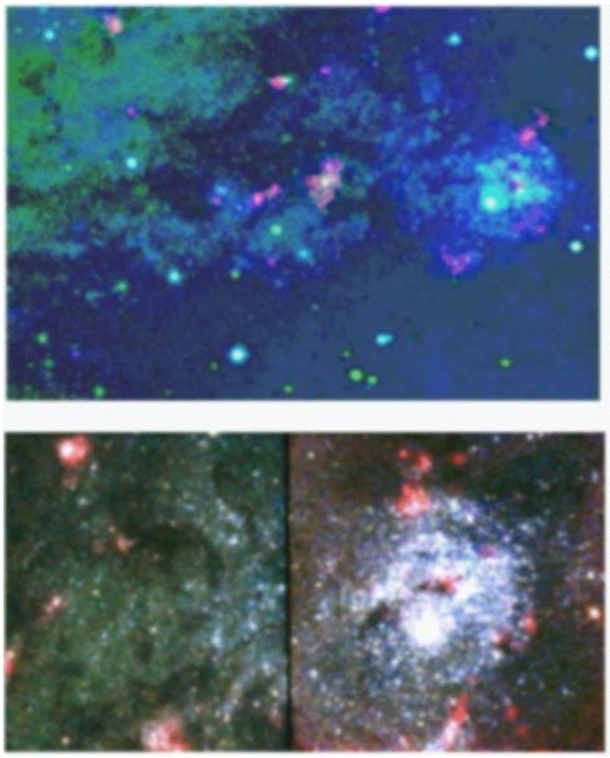

Figure 9. Peculiar stellar complex in spiral galaxy NGC 6946. The top image is obtained by the NOT (Nordic Optical Telescope), the bottom image is taken by the HST (Hubble Space Telescope).

history of its discovery and studies is described in Ref. [49]. The HST observations of this complex revealed the presence of nearly 20 rich young clusters, in addition to the previously known giant cluster with an age of about 15 mln years which has a mass of 10^6 solar masses and is (assuming the normal luminosity function) gravitationally bound [67, 68]. In the galaxy, especially in its western half, there are many high-velocity clouds and HI voids; they are also present near the Hodge complex, but strikingly they do not coincide with any of the HI holes. The absence of at least large a HI cavity around the giant and sufficiently young cluster seems very strange.

A group comprising eight dwarf late-type galaxies has been discovered around NGC 6946. Almost all of them are registered in the HI line [69] so that they could supply the gas clouds due to the tidal interaction with the main galaxy. This enables us to consider the fall of a gas cloud onto the galactic plane to be a plausible reason for the complex formation [47].

The spectroscopy of the complex in the H_α line of ionized hydrogen on the BTA and Keck-I telescopes showed that the radial velocity of the main cluster is 150 km s^{-1}, which exceeds the local rotational velocity of the galaxy as measured by HII by 20 – 30 km s^{-1} [70]. This small deviation indicates that if the cloud infall hypothesis is correct, its trajectory is strongly inclined towards the galactic plane. There are significant perturbations of the velocity field, especially to the east of the complex; some of them can be interpreted as rapidly expanding ionized gas shells.

However, another interpretation of the radial velocity curve features is possible that assumes the presence of vortical gas motions within the complex. The entire complex could be connected with a solitary giant vortex [71].

Galaxy NGC 6946 is known to have a strong magnetic field which is regular outside bright spiral arms (see [72] and references therein). The collision of a high-velocity cloud with a galaxy having such a magnetic field was modeled under different assumptions about the cloud trajectory in Ref. [73]. According to this paper, at certain angles of the trajectory to the galactic plane and the magnetic field force lines, the field impedes the cloud penetration into the galactic disk, and one may assume that this causes the absence of at least a large HI cavity around the complex. For the slanting fall, a complex picture of magnetohydrodynamic waves emerges, and one may suppose that the shock wave collisions lead to the creation of the peculiar complex structure. This process, which is possibly the most effective star formation trigger, will be considered at the end of this review.

The slanting fall variants calculated in Ref. [73] predict the formation of a forward shock wave, the appearance of vortical motions in the oscillating tail of the cloud and then the appearance of the Parker instability. Judging by the sharp arc-like western edge of the complex, the cloud moved along the slanting trajectory from east to west, and possibly this is why the most prominent radial velocity perturbations are observed eastward of the complex [70]. The Parker instability could be responsible for the creation of the giant young gravitationally bound cluster. However, it could also be just one more result of the collision of shocks.

10. Ram pressure and star formation

A striking feature of arc-like stellar complexes in the LMC and NGC 6946 is that large pieces of their boundaries very closely resembles segments of perfect circles (Fig. 10). Such an almost ideal geometry can probably hint on answer to the question as to their origin. The planes of the LMC and NGC 6946 are inclined to the sky plane (by an angle about 30 – 40°), so arcs of circles lying inside the galactic plane would appear as ellipses significantly different from what is observed. The only explanation to the perfect circular form is the assumption that such structures are segments of spherical layers (in the case of the Quadrant and Sextant arcs in the LMC) or a segment of a filled sphere (in the case of the Hodge complex in NGC 6946) seen from one side [49]. The plowed gas envelope represents a circle in the galactic plane and remains as such only when we observe the galaxy exactly face-on.

In the world of galaxies, however, almost perfect hemispheres are known. The gas corona of a galaxy moving in a sufficiently dense intergalactic medium acquires the characteristic comet-like shape with a sharp semi-circular boundary along the motion direction under the ram pressure's action. For example, external HI isodenses of the irregular galaxy Ho II [57] and spiral galaxy NGC 7421 [74] have from one side a perfect circular form (Figs 11, 12), which is considered to be a manifestation of the bow shock emerging during the galactic motion through the intergalactic gas inside the group of galaxies these two galaxies belong to.

The perfect circular arc bounding the stellar disk of the dwarf galaxy DDO 165 (see Fig. 11) in the M81 group is hard to explain other than as a consequence of the star formation in this galaxy being significantly determined by the intergalactic gas ram pressure [49, 47]. There are no data on the gas in this galaxy, so this interpretation is just a hypothesis for this galaxy. However, it is almost undeniable for some other galaxies.

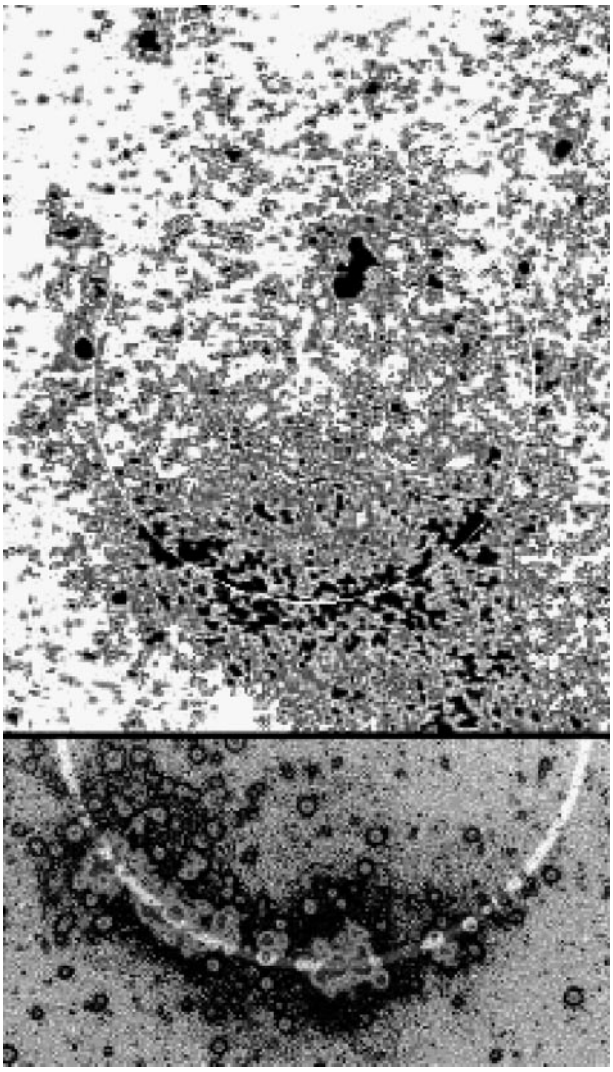

Figure 10. Quadrant (top) and Sextant (bottom) arcs are segments of a perfect circle.

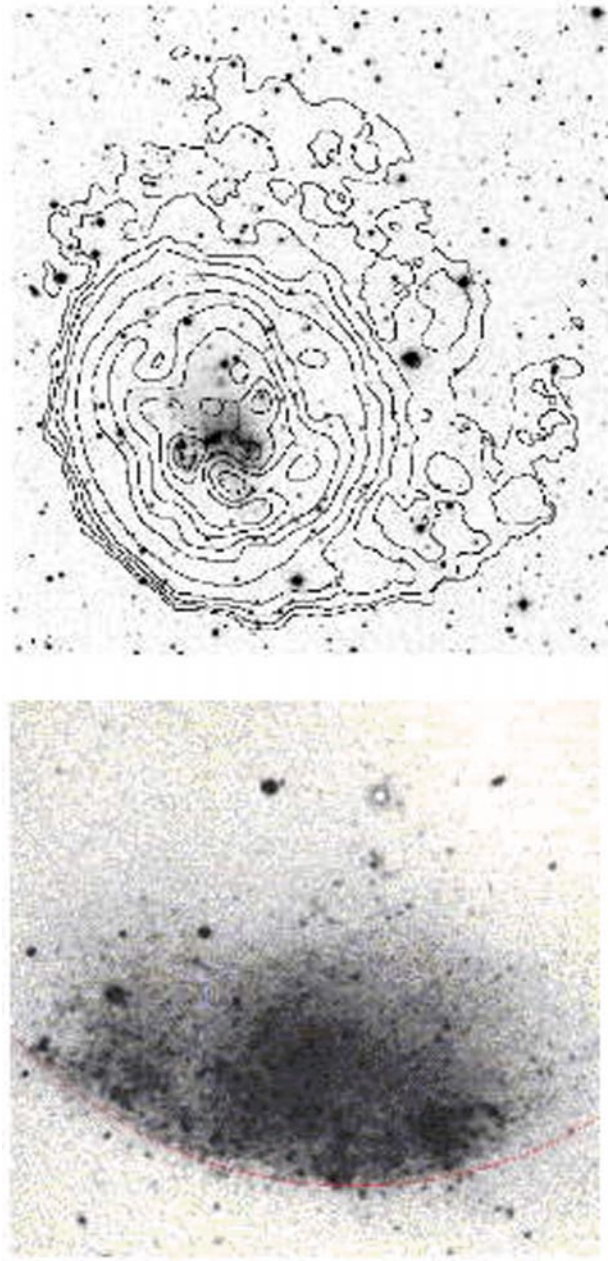

Figure 11. External HI isodenses of galaxy Ho II (top) and the edge of the star distribution in galaxy DDO 165 (bottom). Over a large range both isodenses and stellar edges are described by arcs of perfect circles.

For example, the unusual form of the spiral galaxy NGC 2276, the member of the NGC 2300 group, was noted long ago. It is bounded from the west by a perfect circular arc that is also repeated in the form of the ionized hydrogen isolines, which are most dense exactly along this semi-circular boundary [75]. It is along this arc where the brightest X-ray sources of this galaxy occur [76], which must outline the bow shock theoretically.

The galaxy NGC 7421 mentioned above is prominent not only by having a semi-circular western boundary of its hydrogen corona (see Fig. 12). The western boundary of the galactic star distribution is brighter and sharper than all other periphery and is semi-circular in the first approximation too. A closer inspection reveals this boundary to be outlined by three straight segments with an angle of around 120° between them (Fig. 13). Also there are other morphological signatures of the motion of galaxies in clusters in a resisting medium. Because of the flat form of their gas disks and the corresponding orientation, a 'lifting force' analogous to that arising in air flowing around a wing must emerge, which is possibly observed in the bent form of their gaseous tails [77].

The bow shock with flat front segments strikingly resembles the polygonal (elbow) structure of spiral arms of many galaxies discovered and described in Ref. [78]. In the spirit of this analogy, the size of the forward front flat segments can be expected to be nearly equal to the local curvature radius of the 'unperturbed' oval front. If so, the angles between segments must be close to 120° where the 'unperturbed' front line is close to a circle, which indeed is observed on the sharp western edge of NGC 7421 progressing along the galactic motion (see Fig. 12).

Probably, the flat (broken) geometry is a transient, short-term state of the front and changes from time to time into the state with smooth geometry. These states apparently represent two attractors in the space of states of the system, and the system spontaneously transits from one state to another. Using the analogy with the phenomenon of polygonal spiral arms [78], the duration of the state

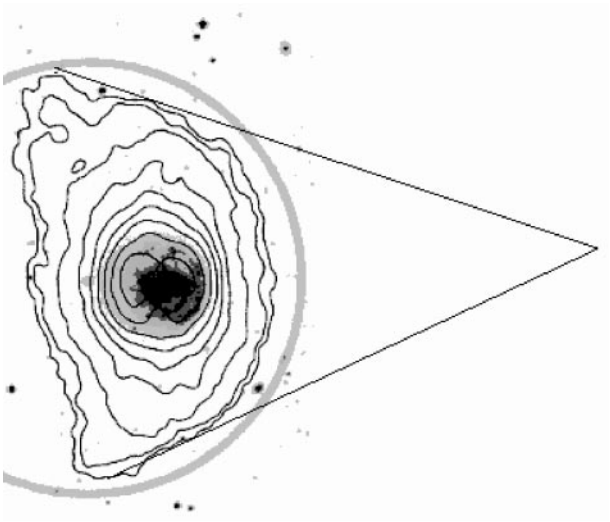

Figure 12. Neutral hydrogen isodenses in NGC 7421 (according to Ref. [74]). The outer isodenses at the west rim (west to the right) are well described by a circular arc; an auxiliary circular arc is drawn outside the isodenses for convenience. Also shown is the Mach angle as calculated by those external isodenses where the direction of transition to the asymptote of the bow shock front is visible. The value of the angle corresponds to a Mach number of between 1.5 and 2.

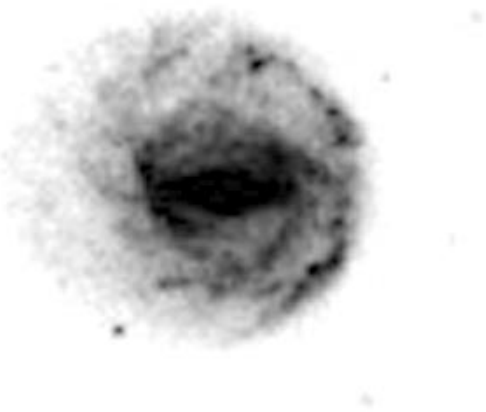

Figure 13. Spiral galaxy NGC 7421 in blue light. The bow shock at the west edge of the galaxy shows three flat segments with an angle of (slightly larger) 120° between them.

with flat segments is 8 – 10 times shorter than with smooth geometry.

Now it is necessary to note that the western boundary of the peculiar complex in NGC 6946 looks circular only in the first approximation. Images taken by the HST allow us to consider it to be more exactly described by three straight segments, which resemble the western boundary of NGC 7421 (see Fig. 9). We think this to be a strong argument in favor of the assumption that the peculiar complex in NGC 6946 also suffered from ram pressure. This supports the hypothesis that it can be created (and acquire its visible form) as a result of a slanting fall of a fast dense cloud that moved for sufficiently long time through the galactic gas disk [47]. We should also add that the perfect arc-like form of the western boundary is due to large local absorption of light, i.e. by a gas-dust cloud seen arc-like in the projection.

The star formation on the galaxy periphery, stimulated by its motion through the surrounding medium, is almost unstudied, however some signatures of the ram pressure effect on the galaxy morphology are worth much attention. They allow estimates of the velocity and the motion direction of the galaxy, as well as of the ambient matter density, etc. Applying this to the relative motion of galactic clusters, even the possibility of obtaining in this way some restrictions on the interaction cross section of hypothetical dark matter particles with ordinary matter has been discussed [79].

The high fraction of galaxies with peculiar form in the HST deep field observations noted by van den Bergh [80] may be evidence for the dynamical pressure effect on the form of galactic disks. He considers such galaxies to be an early stage of development of spiral galaxies. The authors [81] find that the spiral galaxy NGC 922 has a form somewhat resembling that of the remote galaxies van den Bergh discusses, but explain its peculiar form by the influence of a large dust matter content absorbing light. However, the asymmetric form with a perfect semi-circular boundary is fully similar to the picture arising due to the ram pressure action. Indeed, in the HST deep fields one can find some galaxies with asymmetric forms or with semi-circular boundaries which may be due to the ram pressure [77]. For example, galaxy #293 in the North Hubble deep field (redshift $Z = 0.95$) [82] shows on the one side an arc-like sharp boundary, and from the opposite side — two blue condensations, which apparently result from star formation in vortices in the gas tail forming when a body moves through a sufficiently dense medium. The contours of galaxy #293 looks very similar to those of NGC 922 (Fig. 14), as well as to the more dense part of the complex in NGC 6946 (see Fig. 9), in the eastern ('tail') part of which some traces of vortical structures are possibly observed.

Many galaxies in the HST deep fields enter small groups, inside which it is natural to expect the ram pressure. However, testing the possibility of a systematical increase of the fraction of the ram-pressure shaped galaxies with redshift, and especially of those outside groups and clusters, would lead to important cosmological conclusions on the physical conditions in the Universe at the time of formation of the first galaxies (and, perhaps, on the nature of the invisible matter, too).

11. The origin of arc-like stellar complexes

Turning back to stellar complexes, we conclude that direct observational data lead to the conclusion that arc-like or circular arc-bounded complexes may be products of star formation initiated by the action of one-sided external pressure action on a dense gas cloud moving through the gas disk of the galaxy.

For the Quadrant arc in the LMC the central radius-vector of the spherical fragment is inclined by about 10° to the sky plane, which follows from modeling this arc as the projection of a spherical layer segment (see Fig. 3 in Ref. [49]). The radial velocities of stars in the Quadrant are on average 10 km s^{-1} larger than those in the neighboring regions, as well as the mean velocity of neutral hydrogen, indicating the structure's motion (and hence the parent cloud's) toward us. Considering the direction of motion of the initial cloud (which is determined, evidently, by the arc

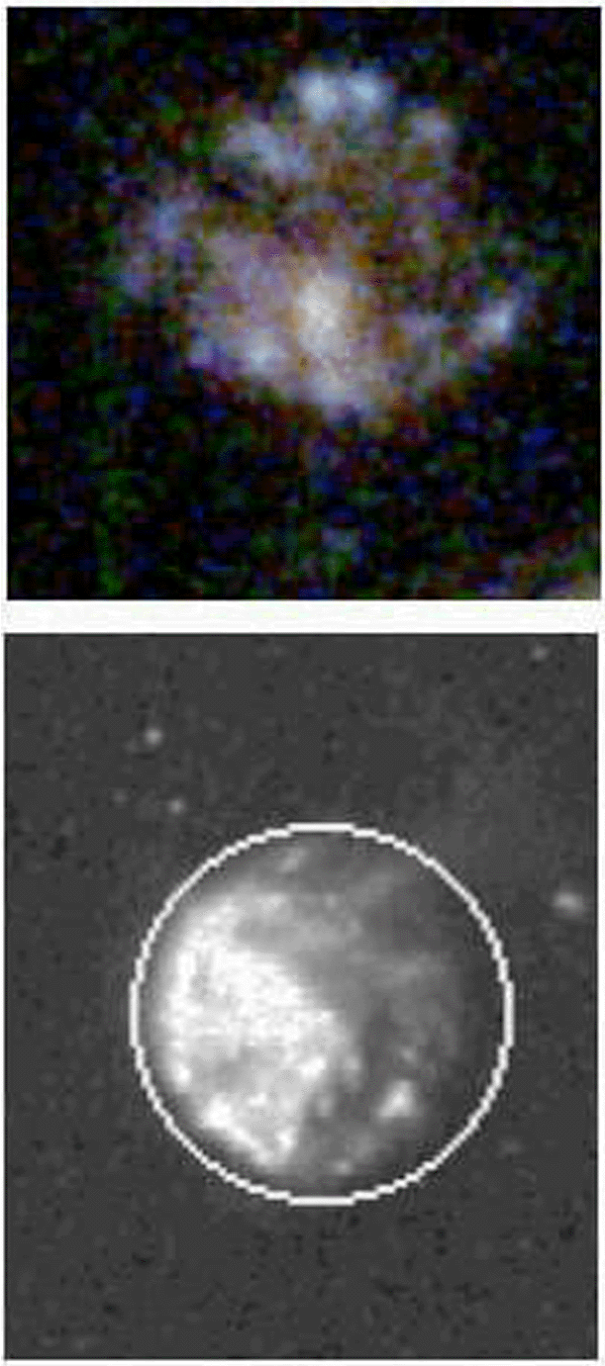

Figure 14. Galaxy #293 in the North Deep Hubble Field (top) and galaxy NGC 922 (bottom).

symmetry axis) and the existing extremal estimates of the LMC plane spatial orientation, the cloud trajectory inclination to the plane of this galaxy can be inferred to be from 10 to 40 degrees. The most probable value is close to 20°, then the cloud velocity relative to the galaxy was 30 km s^{-1}. But this is only a lower limit, since the presently observed velocities of stars reflect the cloud velocity at the moment of star formation at the end of the braking path.

Plausibly, it is a sufficiently long path of a slantingly moving cloud inside the gas galactic disk that leads to the possibility of star formation in the bow shock. If this hypothesis is correct, the concentration of arcs close to each other at the north-east of the LMC may be due to exactly this edge of the galaxy progressing in the LMC orbital motion. The orientation of arcs of Quadrant and Sextant is almost the same and is close to the direction of the LMC motion to NNE, as argued in Ref. [83]. Note that the north and east outer boundaries of the HI distribution in the LMC are straight lines, which possibly indicates supersonic motion of the LMC through the gas corona of the Milky Way galaxy.

Apparently, only the assumption on the origin due to the external pressure effect on the dense cloud allows one to explain why all such complexes show approximately the same (around 100 – 150°) opening angle, as is observed in the picture of the front shock for galaxies. This assumption is further supported by a weak northward continuation of the Quadrant arc resembling a broad comet tail, which is clearly seen in Fig. 1 in Ref. [49].

The existing theoretical data indicate that the range of conditions leading to the initiated star formation in cloud collisions is rather narrow [84], especially by requiring the conservation of the bow shock form for the resulting stellar complex, which clearly explains the scantiness of arc-like stellar complexes. One such condition could be the presence of a magnetic field [85], which apparently is applicable to the case of the NGC 6946 complex.

12. Arc-like stellar complexes and hypernovae

A physically similar situation arises when a shock wave from a comparatively nearby and powerful external explosion propagating in less dense gas of the galactic disk impacts a sufficiently dense cloud. Clearly, the convex part of the shock-cloud interaction front must be turned to the explosion and the resulting arc-like complex must be symmetric with respect to the direction to the shock wave source. A case is known suggesting such an interpretation. We discovered [47] that in the spiral galaxy NGC 300, the arc composed of bright stars and clusters subtended an arc of about 45″ ($\simeq$ 400 pc) lies close to the most intensive point-like X-ray source of this galaxy and is turned to it by the convex part (Fig. 15). This is

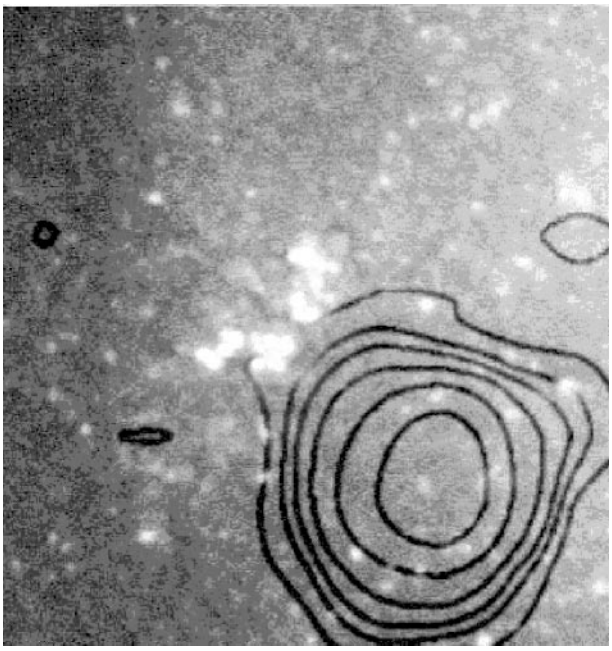

Figure 15. Arc-like stellar complex AS 102 in the spiral galaxy NGC 300 and the position of X-ray source P42.

the object P42 = H13, which is classified as an X-ray binary system containing a black hole (with a mass of about five solar masses) and is unique in the galaxy NGC 300 [86]. It may well represent the stellar remnant of a hypernova. The arc of clusters under consideration enters the list of OB-associations and complexes in NGC 300 as AS 102 with a size of 360 pc [87]. It is classified as a stellar complex because, as seen in Fig. 15, it includes four subgroups. The estimate of the complex age inferred from the color – luminosity diagram is about 5 mln years [88]; this is consistent with the complex being embedded into a bright HII region, as the Sextant arc is. Over this time, supernova gas remnant seen in the optical or radio bands disappears, but the stellar remnant, the black hole, accreting matter from the binary system companion, can be detected as an X-ray source under certain conditions.

Figure 15, constructed by superposing the image obtained by S Larsen on NOT and the map of X-ray sources from Ref. [86], shows that the unique for NGC 300 X-ray source lies not only nearby the complex, but exactly on the symmetry axis. Unfortunately, existing data on neutral hydrogen in NGC 300 have been obtained with a resolution insufficient for possible peculiarities to be detected in this region. If the above hypothesis is correct, no gas between the AS 102 complex and the P42 source should be present. Should this be confirmed, there will be all grounds to consider this X-ray binary with a black hole as a remnant of a hypernova.

This conclusion is apparently also applicable to the case of X-ray source X-4 in the Triangle galaxy (M33). It is inside the arc-like complex HS137 = IC133 at the center of an HI superbubble, and possibly the classical picture of star formation in the plowed gas shell [71] is valid in this case.

No similar X-ray sources are known near stellar arcs in the LMC. Although the age of the Quadrant arc seems to exceed the possible lifetime of X-ray emission in a stellar supernova remnant, the very presence of two (and, not excluded, five, see Ref. [49]) arcs close to each other makes the above mechanism of their formation highly unlikely. As mentioned above, the existence of several nearby arc-like stellar complexes can be explained either by the origin of their progenitors not far away in the same cluster, or by the north-east rim of the LMC where they occur first coming across more dense clouds in the halo of our Galaxy.

13. Superassociations

Starbursting galaxies are one of the most popular fields of recent studies. Almost always they are interacting or have suffered a close fly-by with other galaxies in the recent past. The active star formation inside them is due to an enhanced gas density and collisions of molecular clouds. In many normal galaxies, however, local starbursts are observed whose nature is unclear, except for active star formation in the central parts with high gas density.

Isolated regions of violent star formation have long been known as superassociations. This term was proposed by W Baade in the well known Harvard lectures [89] on the basis of studies of the object 30 Doradus in the LMC and similar stellar groups in other galaxies, i.e. groups of OB-stars significantly exceeding the ordinary associations in size. "Shapley noted them some years ago and called them constellations; I think that by analogy with the term 'associations' we can call them superassociations...", Baade said.

The comparison with associations was essential for Baade; he noted that superassociations are not merely very large associations with sizes tens times exceeding those of normal associations, but a quite specific new class of objects. "I believe it is very important to realize that star formation proceeds on two scales — in associations, as they were defined by Ambartsumian, with a diameter of the order of 10 or 100 pc, and in extended regions 500 or even 600 pc across" [89].

Superassociations are quite rare objects; in normal galaxies, they constitute less than 1% of the stellar complexes of the same size and mass. For example, in the Local Group there are at least three hundred 'standard' complexes and only three superassociations. These are the already mentioned 30 Doradus in the LMC and the object NGC 206 = OB78 in M31, as well as NGC 604 in M33 [90].

Burakan astronomers [91] found 150 superassociations in 57 giant spiral galaxies outside the Local Group. Superassociations are found relatively often in irregular galaxies like the LMC and especially in the so-called 'clumpy' irregular galaxies which essentially simply consist of several (sometimes up to ten) superassociations [3 (§ 12.1), 92, 93].

Some arguments suggest the superassociations are not a sort of initial short evolutionary stage in the history of each standard complex [3, 90]. Their formation is rather due to the appearance of some especially favorable physical conditions for a large-scale collective star formation burst in a given site of the interstellar medium. The very existence of intensive star formation process within a 1 kpc region is a violation of the age – size relation which we discussed earlier in this paper. To tell the truth, superassociations can always be subdivided into one-two tens of normal associations [3], but the concentration of the latter in one region needs to be explained. Superassociations cannot be the product of spontaneous star formation in turbulent gas. At the same time, they are also found in normal galaxies, so that interaction between galaxies is far from being a necessary condition for their formation. The infall of a rapidly moving cloud, as we have seen above, can produce a local starburst, and 10 – 20 mln years ago the Hodge complex in NGC 6946 looked like a bright superassociation, though of an unusual form.

The bright stellar cloud NGC 206 = OB78 in the spiral arm of the Andromeda galaxy is a typical superassociation (Fig. 16). In this cloud one can clearly distinguish two sharply separated stellar groups of comparable sizes each including approximately a hundred OB-stars. The age of these stars is less than 10 mln years. HII regions are located at the outer rim of one of the superassociation components. In the other component, cepheids with an age of about 50 mln years are observed together with OB-stars. A dust band extends between the components. It can be said that this association reveals the presence of both binary spatial and temporal structures. Obviously, at least two events of collective star formation occurred in its history, one around 50 mln years ago, another less than 10 mln years ago. Apparently, it is this second event that transformed the system into the superassociation: the violent star formation virtually simultaneously embraced the entire two regions of the two-component structure.

The classical superassociation 30 Doradus demonstrates a very complex spatial structure; there, however, two dominating components of approximately the same size can be definitely singled out — the western and eastern ones. It is worth specifying that the superassociation is thought to

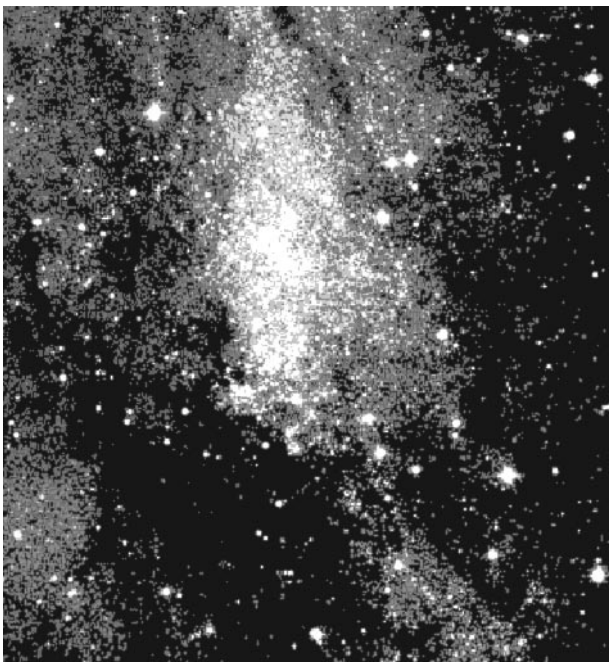

Figure 16. Superassociation NGC 206 = OB78 in a spiral arm of the Andromeda galaxy.

encompass the whole so-called region IV, including 30 Dor East and 30 Dor West, with the latter consisting of fainter stars (see [3]). These two components lie within the HII supershells discovered by Meaburn [94, 95]. The boundaries of the components almost exactly coincide with these shells. Their boundaries are almost perfect circles with virtually equal radii of 450 – 500 pc. There is a dust band between the components, and the Tarantula Nebula, the brightest object of the superassociation, joins this band from the east. This nebula represents an extended HII region ionized by many young OB-stars of the central cluster NGC 2070.

The OB21 complex in M31 provides one more interesting example of the binary spatial-temporal structure. The luminosity of this complex being insufficiently high, it is not a 'classical' superassociation, but it is not excluded that it may correspond to a superassociation at its earliest formation stage [95]. Young HII regions in this complex occur on both sides of the dust band. Two populations of stars are clearly distinguished in both subregions of the system — the comparatively old population of cepheids and the very young generation of OB-stars and HII regions.

In fact, it should be borne in mind that the dust bands crossing NGC 206 (OB78) and OB21 may be details of the Andromeda galaxy spiral structure; both bands can be traced far outside the stellar complexes. However, the binary structure is definitely characteristic for most large-scale regions of violent star formation. A large number of such objects have been found by the HST observations (see, for example, the talks at conference [96]). More complex three-component or even four-component structures are frequently observed [96].

The peculiar stellar complex NGC 6946 considered above may be related to such structures. Two elongated dust clouds cross the complex; there are two generations of stars with ages differing by 20 – 30 mln years. They are spatially separated — older stars concentrate near a giant cluster, while the younger ones are in a wide arc west of it, on the other side from the dust clouds. The age of the oldest stars in the complex is about 30 mln years, but in some regions star formation is still underway. About 10 – 20 mln years ago the region looked like a bright superassociation, but now its high surface brightness is explained by the high density of B-stars.

The complex in NGC 6946 lies far away from the galaxy center and the thickness of the gas disk here may also be sufficiently high. The star formation rate there was irregular, with maxima at about 30 and 5 mln years ago, and between these epochs of the formation of isolated stars and usual stellar clusters a giant star cluster was created [67]. A slanting infall of an intergalactic gas cloud probably played the role of the initial event in the chain leading to this complex formation, and the strong magnetic field of this galaxy, regular outside the optical spiral arms [47], had an essential effect.

What are the facts that turn a stellar complex into a large-scale region of extremely effective star formation? We shall discuss some ideas that basically use the gas-dynamic approach to this problem.

14. Collision of shocks: a gas-dynamic scenario for the local star formation burst

We start with an example of a possible sequence of events which is capable of ultimately leading to the appearance of the superassociation phenomenon. This is the scenario which basically uses shock waves and their interactions [95]. In the simplest version, it could look as follows.

(1) In isolated but neighboring regions of the interstellar medium an almost simultaneous formation of two starbursting regions occurs (for example, in the spiral arm behind the spiral shock front). The energy release due to powerful stellar winds from massive stars as well as due to multiple supernova explosions generates a spherical shock in each of these regions which rapidly propagates and collects gas into a dense shell. When a certain density is reached, the gravitational instability initiates the formation of star clusters inside each shell [96], but when the neighboring shell is present this is not the end.

(2) At some moment, two expanding spherical fronts touch each other in the region between the centers of the initial star formation sites and interact nonlinearly. One of the results of the interaction is the formation of reverse shocks moving backward to the centers of the initial spherical shock fronts.

(3) The reflected fronts involve substantial masses of gas in motion; this gas turns out to be sufficiently dense: it is shock-compressed twice, first by the initial and then by reverse shocks. This dense gas is thus injected into almost empty spherical volumes, which causes the break-out (as it is termed in the theory of a strong explosion in an inhomogeneous medium) or, which is the same, the champagne effect (as it is usually called in astrophysics). The gas propagation within these volumes is accompanied by its turbulisation and fragmentation, which ultimately creates the conditions for effective and violent star formation simultaneously in both volumes.

The first stage of this evolutionary scheme is based on the well studied gas dynamics of the formation of expanding spherical shells — or, as is said more often, supershells, considering their kiloparsec scales — around the star formation regions, as described, for example, in review [97].

The second stage involves the non-linear physics of shock collisions. The basic example for such an analysis is the theory

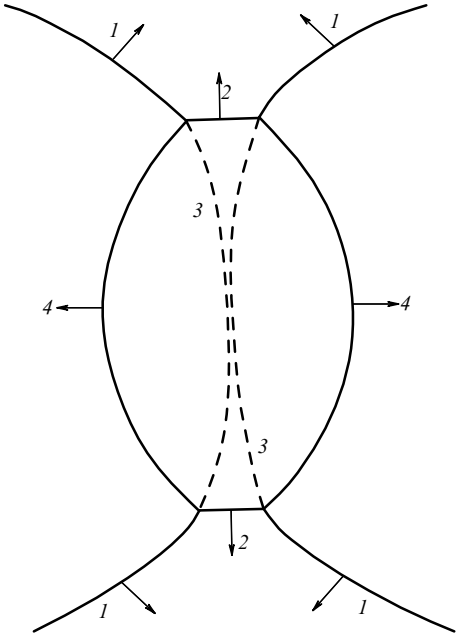

Figure 17. Collision of expanding shock fronts: the Courant – Friedrichs configuration [98]: *1* — initial fronts, *2* — the Mach front, *3* — tangential discontinuities, *4* — reflected fronts.

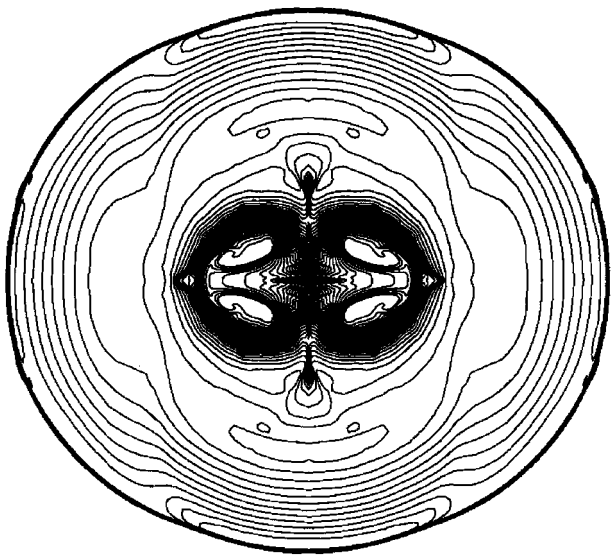

Figure 18. Collision of expanding shock fronts: computer modeling [102, 103]. The Courant – Friedrichs configurations at late stages of evolution; the isodenses indicate the common expanding envelope formed by the initial front parts and the circular Mach front, as well as the inner structure of whirled supersonic flows.

by Courant and Friedrichs [98] (Fig. 17) complemented by modern computer modeling [99 – 103] (Fig. 18).

Most interestingly, both the whole picture and its most important details have been fully confirmed in a dedicated laboratory experiment specially carried out on our initiative [104].

The third stage in the above scenario is based on both the results of the theory of shock collisions and the results related to the break-out effect [97, 105, 106].

The high efficiency of massive star formation in high-density turbulent gas, as assumed on the third stage of the process, is beyond doubt; some arguments have already been given above (see also Refs [21, 90, 107, 108]).

The scenario under discussion deals with two neighboring star forming regions that appeared nearly simultaneously. Such a situation must indeed often occur. For example, the star formation behind the spiral shock proceeds in such a way that separate star formation regions emerge more or less simultaneously and form chains along the spiral arms. This is a reliable observational fact (see, for example, Ref. [3]). But then the condition of 'unity of place and time' implies the possibility of 'unity of action' — the collision of fronts leads to the secondary, possibly brighter star formation burst simultaneously in both regions due to the injection of matter into these regions by reflected fronts.

It seems that such a scenario enables us to to answer some essential questions related to structural features of superassociations and their origin. Here are just several of them. Why do the interaction of adjacent and simultaneously created star formation regions occur so rarely in normal spiral galaxies? What determines the possibility of such an interaction, and when does it really occur? Why do superassociations appear more frequently as a rule in irregular (especially clumpy) galaxies than in regular disk galaxies?

Possibly, the point is that the shock wave interaction in this scenario represents an essentially three-dimensional effect. For expanding spherical fronts to collide, the neighboring supershells in a disk galaxy are required as a minimum to come in contact. This is not that easy, for the front expansion in a thin disk occurs extremely anisotropically; the front moves most rapidly in the vertical direction perpendicular to the disk plane, while the opposite horizontal motions rapidly brake and stop. When the radius of a supershell reaches the semi-thickness of the gas disk of the galaxy, the hot gas escapes out of the disk and the supershell stops expanding. The fronts can collide only where the gas layer thickness is sufficiently large, i.e. is comparable to or exceeds the distance between the expanding front centers; then the opposite horizontal front motions can be sufficiently rapid and long.

If so, then superassociations in spiral galaxies must populate disk edges where the gas layer thickness is maximal but the gas density is still sufficiently high for the effective star formation to occur. The tendency of superassociations to occur at the periphery of galaxies and spiral arms was noted already by Vorontsov – Vel'yaminov [109]. Superassociations are frequently observed in irregular galaxies possibly due to their thick gas disks.

It is also not excluded that the relatively small number of superassociations — the local starbursts — is due to not every young cluster being capable of creating an expanding HI/HII supershell. Especially prominent in this respect is the absence of the HI bubble around a giant (with a mass of millions solar masses) cluster in the peculiar complex in NGC 6946. Its age (around 15 mln years) is optimal to blow out a large supershell, and no other suitable clusters are known in this galaxy. Nonetheless, although two tens of HI supershells/bubbles are found in NGC 6946, none of them encompasses a peculiar stellar complex. However, as mentioned above, this can be due to special formation conditions for this complex.

The scenario considered here describes the interaction of two initial pressure centers. But the emergence of several such centers over the suitable spatial-time interval could be more

frequent, and it is generally not easy to identify the observed picture as arising due to the shock front interaction described here. However, this interaction is necessarily present and can give rise to a high gas density and the subsequent local starburst which is not connected with the general structure of the galaxy or its interaction with other galaxies.

15. Conclusions

The study of large-scale characteristics of star formation is the field where the progress is made by joint efforts of specialists on the physics of the interstellar medium and the physics and morphology of galaxies. The general picture of the phenomenon emerging here is complex, diverse and still far from being completed. Only now are we starting to understand the reason for local star formation bursts in galaxies and the strange morphology of some of them. The star formation problem does not enter the list of V L Ginzburg [110], and we tried to show that its study can lead to conclusions which are important for understanding the most actual problems of physics and astrophysics.

Undoubtedly, stars emerge from gas condensations, and during the process of condensation of the interstellar medium into stars and their groups the self-gravity of gas plays the crucial role, at least at the final stages of the process. It is becoming more and more clear that the hydrodynamics of the gas plays an equally important role, especially at the very beginning of the condensation process. It seems that it is the large-scale gas motions that generate initial condensations which give rise to stellar groups and individual stars. Here the motions must be predominantly supersonic. This motive unites those observations and theoretical concepts, uncoordinated at first glance, which are described in the present review.

Shocks appear in supersonic gas motions which create strong condensations in the protostellar gas. Moreover, shocks propagate in diverse directions and so can strongly interact in front collisions. The shock collisions result in even more dense gas condensations and also give rise to new shocks. In favorable conditions, multi-scale cascades of shocks can appear that spend the energy stored in the most large-scale motions. The astronomers utilize here the term 'supersonic turbulence' which we also use in this text.

What are the energy sources generating supersonic hydrodynamics of the protostellar gas? First of all, these are stars themselves, more precisely, the most massive of them. Such stars produce stellar wind flows emanating from their surface layers. At large evolutionary stages stars can explode as supernovae thus injecting a huge portions of energy into their surroundings. But in addition to these old-known generators of supersonic motions, other effective sources exciting large-scale motions inside galaxies are possible. These include the collision of galaxies where gas motions are generated due to both tidal forces and the liberation of the kinetic energy of the initial relative motion of the interacting galaxies. The latter appears due to the fall of galaxies in the gravitational field of galactic groups and clusters, so the ultimate source of this energy is the self-gravity of these systems. Gas motions borrowing their energy from the differential rotation of galactic disks have a similar gravitational origin.

The complex supersonic hydrodynamics with bow shock fronts, contact discontinuities, turbulent layers, large-scale vortex cores, etc., is produced by orbital motions of galaxies in the intergalactic medium of the galactic clusters. The external gas flowing round galaxies is directly observed by optical, X-ray and radio telescopes. Star formation bursts stimulated by this process sometimes outline the bright and sharp leading rim of the galaxy. We believe that such a mechanism of violent star formation can operate on the subgalactic scale as well, which results in the appearance of arc-like stellar complexes which are probably created by the motion of an external gas cloud in the galactic gas disk. The leading boundaries of such objects, which are sometimes delineated by straight line intervals, give evidence for the presence of a ram-pressure shock wave stimulating the star formation.

Apparently, all the diversity of young stellar groups of various scales is due to a complex interplay between the nonlinear supersonic gas dynamics and the self-gravity of the galactic gas. Thorough studies of this processes started only recently by both observational and theoretical means.

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