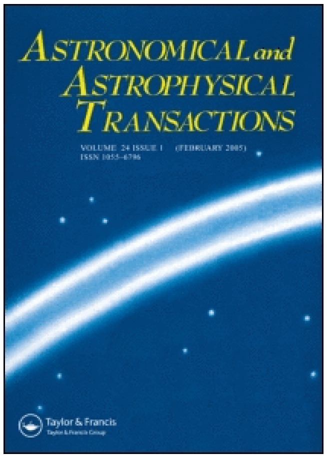

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INVESTIGATING THE EVOLUTION OF STARS IN GALAXIES

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The paper presents some recollections, mainly on studying Cepheids, star complexes, spiral arms and the distance scale since 1960. Recent results concerning spontaneous and triggered star formation in galaxies are described in more details.

KEY WORDS Cepheids, spiral arms, star clusters, associations and complexes, the large-scale star formation

1 INTRODUCTION

These notes are a rather unusual kind, being mixture of recollections, and expositions of some results considered to be more important as well as new ones. Most of them are connected with attempts to understand certain issues in the evolution of stars and the history of star formation in galaxies. However, a few others are what is called serendipity–results of lucky events – and also my belief that in the heavens occasional things are rarer than regular ones.

2 GOOD LUCK

One of my finding was the discovery that the SN1987A in the LMC is at the outskirts of the small cluster KMK80. I noted the small double cluster near the progenitor immediately after identification of Sk-69 202 on the Pulkovo–Chile plates, which was possible owing to careful determination of coordinates by colleague astrometrists. This identification was certainly obtained independently by many people elsewhere, yet the existence of a "cluster" was noted by Walker and Suntzeff later. They seemingly did not believe the small clumping to be a real cluster, putting the "cluster" in "..." and giving no CMD. Yet from their photometry I constructed the CMD, which has been proved normal for a young cluster and found the position of Sk-69

202 there to be quite compatible with its membership in the cluster, which I identified with KMK80 in the list of small clusters in the LMC, recently published by a team of Greek astronomers. They paid no attention to the SN, whereas Walker and Suntzeff did not identify the cluster. Was this serendipity, or just a consequence of my love of putting things together – and interest in the LMC as well? Indeed, it is the best location in the Universe to study the spatial relationship between different kinds of objects.

Recently Suntzeff (1997) confirmed the strong concentration of bright blue stars at SN1987A and concluded that "it is extremely likely that Sk-69 202 was part of a loose association including KMK80 with an age of 15 Myrs". He mentioned only my determination of the cluster age though it would be correct to say explicitly that arguments for the physical connection of the small cluster near SN1987A with the star were given first by me, as well as the identification of the cluster with KMK80 (Efremov, 1991). Membership of the SN in a cluster is indeed important, the radial velocities and abundances being able to give the data for the progenitor itself.

I could consider as serendipities too my participation in studying the variability of optical counterparts of 3C273 and HZ Her. Anybody at my position in room 60 of the SAI would do the same, I guess. Anyway, I am proud that I was the first to suggest that the optical variability of HZ Her is triggered by X-ray heating, after N. E. Kurochkin found the period to be exactly the same as for the X-ray variations.

However, serendipity only cannot explain the successful use of Cepheids to study large-scale star-formation in galaxies. The close similarities of periods and radial velocities of a number of Cepheids, which are also quite – or rather – close to each other in space has a significance which I noted first, though it was again N. E. Kurochkin who often turned my attention to such cases.

3 EVOLUTION OF CEPHEIDS

The star which has led me to the present days was SZ Cas, a Cepheid with a 13 d period and sinusoidal light curve. I was estimating it during 1954 in the SAI circle of young investigators of variables stars, and it was Igor Novikov who advised me to come there. Later on, in 1958, being at a 3 d course of the Astronomical Department of the MSU, I was invited to speak to Prof. P. P. Parenago, who said that he never saw such fast variations of periods – he had found a card with my results in the catalogue of variable stars; and he insisted I prompltly publish a note on SZ Gas.

It soon appeared in the *Variable Stars* bulletin. Instead of getting photos of the Moon with the Solar tower telescope, as I intended, I began in observations of two other Cepheids.

The same SZ Gas was later noted as one of four Cepheids connected with the double cluster h and χ Per. In fact, the association of Cepheids and clusters was my main topic during these years. I realized, working beside P. N. Kholpov, that Cepheids should also be members of cluster halos, which he intensively studied, and

I started in 1963 to search for Cepheids in wide fields around clusters. The case of SZ Tau, with the same radial velocity as NGC 1647 at $B = 18$ deg and at 1 deg from the cluster was especially reliable. Anyway, some of these Cepheids in halos of clusters should rather be considered as members of the same star complexes as the cluster.

Soon I joined P. N. Kholopov in observations of CE Cas, double Cepheids within NGC 7790 and we resolved the stars at $2.''3$ distance and published the results obtained at the Lenin Mountains with the 0.7 m telescope two years earlier than was done with the 5-m telescope. Later on we two were the first to decipher the nature of V367 Set in NGC 6649, which has proved to be the only bimodal Cepheid in a cluster. Altogether half of the total number of Cepheids in open clusters of the Galaxy were studied (or linked to clusters) at the SAI.

Certainly during all these years, from 1960 to 1973, my main occupation was the participation, under the leadership of B. V. Kukarkin, in the compilation of the General Catalogue of Variable Stars. I may note that a new type of variable star, rotating ones, was introduced after my suggestion, as well as the class of Cepheids with small amplitudes and sinusoidal light curves.

Studies of Cepheids in clusters naturally led to the issue of their luminosity and evolution. By using Kholopov's ZAMS and the best studied Cepheids and clusters, we obtained with L. N. Berdnikov in 1985 the period–luminosity relation which implied a shorter distance scale. Many confirmations of this scale have been obtained recently (see below). I am happy that investigations of Cepheids have been carring out by Dr. Sci. L. N. Berdnikov with great success during the last two decades. Another astronomer, where topics of study I was able to influence successfully, is Prof. G. R. Ivanov in Sofia University, who investigated the Cepheids, as well as complexes and associations in nearby galaxies.

The history of the important period–age relation is described completely in my book (Efremov, 1989). It was in fact the basis for studying the structure of spiral arms and stellar complexes. Here I would like only to note that the revision of the relation is in progress now, using many new ages of the LMC cluster connected with Cepheids, mainly from the large set of integral UBV colours by Bica *et al.* (1996). The ages were obtained by using the Girardi *et al.* (1995) data, based on the evolutional tracks of massive stars with mild overshootings. The increase in these ages transforms the ages of Cepheids to about three-fold older than before.

4 THE FAILED PAPERS

During my work I had a few papers which never were published. It is difficult to believe that two of them were popular ones. The title of one paper was "Large telescopes are necessary" and it was ready for publication in *Priroda* in the beginning of 1973. The paper followed the paper of Acad. Artzimovich "The future belongs to astrophysics". He understood very well that it is astronomy that is able to give the necessary data to the advance of physics. L. A. Artzimovich headed the new

United Council on Astronomy and plans for the building of a large observatory in Middle Asia were elaborated. His sudden death in 1973 stopped everything, and my paper was extracted from the issue, as well.

This may be understood by assuming that most physicist are afraid that astronomy will take money from physics. Around the same time I was introduced to the Editorial Board of *Kvant*, and decided to give a paper to "my" journal. I wrote on the distance scale determination and stressed that the Hubble constant is a physical constant of the same importance as, say, the mass of the electron. Imagine, I wrote, that over the world only two devices existed good enough to determine the mass of the electron – yet this is just the situation with the possibility of the determination of the Hubble constant. Only two telscopes large enough existed then. The paper by me, the Editorial board member, was refereed by another member, a famous physicist. He rejected the paper and I did not insist further, leaving the journal: in the report the referee confuzed galaxies and quasars.

One paper was rejected in 1996 by *Priroda* too. This was against Fomenko's crazy chronology. They said that they had already published my paper on this in 1991. The same was the fate of another recent paper on the same topic and to the same magazine, with the late Yuly Avraamovich Zavenyagin.

Two scientific papers also failed. The first one was on "The star complexes as groups of clusters and associations", rejected by *Pisma v AZh* as it was considered to be a review, in 1986. Its conclusions were however published soon elsewhere and its abstract was given in my 1989 book as well.

5 THE CEPHEIDS OF Cs TYPE

One of the rejected papers was devoted to Cs Cepheids. It was written in 1991 and was never published elsewhere, having received a bad report from the *ApATrans* referee. I considered the report to be unjust and did not bother much, because the same conclusions were in a note sent to a conference in Japan. Yet they decided not to publish a paper if the author had not participated. The paper developed the idea (Efremov, 1970) that Cs Cepheids may be at the stage of the first crossing of the instability strip.

Let us consider first the arguments for the first overtone nature of the Cs stars.

(1) The Cs stars in the Magellanic Clouds fit the period (P_0) – luminosity relation if their period is P_1 and equal to $0.7P_0$. Indeed, for all 14 galactic bimodal Cepheids we have $P_1/P_0 = 0.69$–0.71.

(2) The same relation of periods is roughly satisfied when a Cs star is in the same cluster with normal Cepheids, Cs always (exept one case in NGC 1866) having the smallest period.

(3) The Cs stars are usually bluer than normal Cepheids of the same period, as theory predicts for the first overtone oscillators. Also they have a different relation between light amplitude and colours.

The following arguments may be advanced for the proposition that Cs stars are at the first crossing of the instability strip after leaving the main sequence.

(1) The period – amplitude diagram leads one to the conclusion that all stars with period smaller than 3 days are either Cs or CW stars; and stars with masses lower than about 4 solar masses have no blue loops of evolutionary tracks entering the instability strip; their periods are smaller than about 3 days. The recent data on the C-M diagram and the Cepheids of the populous cluster NCC 1866 in the LMC confirm this conclusion. The bluest tip of the cluster giant branch (masses about 4 solar masses) enters the red border of the instability strip and this tip is inhabited by Cepheids whose periods are 2.6–3.5 days. Therefore the Cepheids with periods smaller than about 3 days must be at the first crossing – and they are the Cs stars!

(2) The majority of the Cs stars have rather quickly increasing periods and therefore go quickly to the right at the CMC. The case of Polaris shows that it may well be the rule for all Cs stars because the investigations of the period variations are difficult for these small amplitude stars. The very fast increasing of the period of SZ Cas found by me many years ago, is explained by this. It was a pleasure for me to note that the new Cs type Cepheid discovered resently by S. Antipov with the SAI plate collection, also has an increasing period.

It is quite possible that Cs stars are the first overtone oscillators at the first crossing of the instability strip. The decrease of the light amplitude of Polaris is then consistent with its location away from the red border of the instability strip, this border being shifted to the blue side for overtone pulsations. There should exist some reason for Cepheids to be or not to be overtone oscillators. Maybe only after the red supergiant stage does a star acquire the potential to pulsate with large amplitude and fundamental period (Efremov, 1970). At the moment it seems probable that the Cs stars are at the first crossing of the instability strip and the first overtone pulsators at the same time. The latter property may be connected or may even be a reason for the former. Now after discovering a lot Cs stars in the LMC by MACHO collaborations, it looks as it the percentage of Cs stars is too large if they are at the first quick crossing of the instability strip. However new determinations of the rate of period changes (Berdnikov *et al.*, 1997) seems to be compatible with the first crossing hypothesis. The matter is still unsettled. Probably all stars at the first crossing are Cs stars yet not all Cs stars are at the first crossing. Recently the MACHO team declared the existing of the sequence in the P–L relation, which could represent the Cepheids at the first crossing; however, they noted that during four years of observations these stars did not demonstrate a variation of periods (Alcoc *et al.*, 1998).

6 SPIRAL ARMS

Another area where new results were first obtained is the issue of the spiral structure of galaxies. I approached this again mainly with the Cepheid data, in M 31 and the Galaxy. Within one segment of a spiral arm S4 in M 31, the concentration of the largest periods was found in 1980 along the inner borderline of the arm. As described in detail in my book, this may be considered as strong confirmation of the density wave theory of spiral arms, though the quantitative evidence is still not very certain. The occurrence of the pronounced age gradient across just this one segment of an arm was explined by its pitch-angle, the largest in M 31. The age gradient suggests corotation in M 31 at 15–20 kpc from the centre, in drastic contradiction with the predictions of the hydrodynamic models of the spiral structure, elaborated by A. M. Fridman and his co-authors, according to which the corotation should be close to the galactic centre. This was the main reason of my reluctance to accept this theory, which was claimed to replace the Lin–Shu gravitational theory of the spiral density wave.

It seems that the author of the hydrodynamic theory no large insists on this, also because he now studies the whirlwinds of gas and stars in galaxies which are in positions consisting of just the gravitational nature of the arms. These spiral waves are really strong as suggested by recent IR-data for a number of grand design galaxies. The density of old stars within such arms is twice that in the inter-arm space and this is also the case for our own Galaxy. The old suggestion that only young objects concentrate within arms was proved to be true only for the local Cyg–Ori arm, which is a pure star-formation arm (Elmegreen and Efremov, 1996), yet not for the Car–Sgr arm which is surely a part of the Galaxy grand design, as follows also from the regular spacing of the H I/CO superclouds along this arm (Efremov, 1997a, 1998) in the way similar to found by Elmegreen and Elmegreen (1983) in a number of galaxies. Such strong arms surely demands the improvement of the theory.

7 THE DISTANCE SCALE

I was the first to suggest in 1971 (see Efremov, 1989) that the difference of the ZAMS positions as given by Kopylov and Johnson is explained by the high metal abundance in the Hyades. The correction to the distance moduli as a function of the difference of abundances (or ultraphiolet excess) relative to the Hyades was suggested and later a similar suggestion was independently advanced by others. Recently I compiled evidence for a shorter distance scale (Efremov, 1997b), which follows from the luminosity of Cepheids and the distance to the centre of the Galaxy, obtained in our department by Berdnikov, Rastorguev, Dambis *et al.*. This scale gives the distance module 18.35 for the LMC and about 7.5 kpc for the distance to the centre of the Galaxy, contrary to the IAU value 8.2 kpc. The issue is still controversial, as it has been so during all the history of astronomy.

8 STELLAR ASSOCIATIONS AND COMPLEXES

There is no a strict definition of what is an association, though everybody agrees that they are larger, younger and looser groupings than clusters and are plausibly unbound groups. There were suggestions to name as associations just all unbound star groupings. However to determine the dynamical status of a group is not easy; strictly speaking, one should have for this goal data on velocities of stars there and independent of them, data on the total mass. The usual way to determine the cluster mass is just the opposite: from the velocity dispersion and size, the mass is determined, assuming the system to be in virial equilibrium. So most people - and everybody who studied stars of other galaxies - implied that OB-associations are stellar groupings which are larger and scarcer than a cluster, which are often inside associations. The composite, hierarchical inner structure - subgroups embedded in each other - is always observed in associations.

As the very name shows, associations usually are detected from the distributions in the sky of O and early B (till B2) stars. However in other galaxies the spectral types are seldom available and one is forced to use ones own judgement as to which star groupings might be considered as associations. So the results may be different for the same galaxy. In 1978 P. Hodge and P. Lucke published the catalogue of 122 OB-associations in the LMC, the sizes being 15–150 pc (the average is 80 pc): they noted however that "it is often a matter of judgement as to how many separate nuclei should be considered as separate associations" and that there are many more entries in the unpublished listing of the LMC associations by Bengt Westerlund.

Some of Lucke–Hodge associations are much larger, up to 350 pc, and these were called "star clouds". Somewhat similar to large structured associations were groupings detected in the LMC by Harlow Shapley long ago. In 1931 Shapley noted there 15 subclouds or "small irregular star clouds", and stresseed that "nearly all of which appear to be distinct physical organizations". Sizes of these "subclouds" are in the range 150–400 pc and they include up to four clusters of the NGC.

In 1951 Shapley noted that only the smallest of groups of supergiants in the LMC are comparable in dimensions with what are called galactic clusters: "Many of them have ten times the diameters and luminosities of such galactic clusters as M 11 and Pleiades. Should such widespread assemblies be called subclouds or superclusters, or would it not be better to designate them constellations? They are doubtless comparable to the Orion, Scorpio and Vela aggregations of bright galactic stars". Thus "constellations" in the LMC appear.

Even larger, about 500 pc, were dimensions of 200 groups of blue stars, which S. van den Bergh detected in 1964 in M 31 under the name OB-associations. He believed that these sizes are so large, about 10-times as may associations in the Milky Way, because the denser background in the latter prevents us noting the outer, presumably rarefied parts of the associations. In comparing results of searches for associations in a number of galaxies, Hodge (1986) concluded that their sizes depend on resolution. With resolution lower than there used by van den Bergh, he found in M 31 only 42 associations with a size of 300 pc. Evidently he was able to find only the brighter parts of van den Bergh' associations, who noted the existence of bright, cores in many of them.

In 1986 together with Bulgarian colleagues, Georgi Ivanov and Nikola Nikolov, we used the large-scale plates of the 2-m telescope at Rozhen Observatory for independent searches of stellar associations in M 31. We were able to find 203 large groups of blue stars with 650 pc average size, most of which were more or less identical to associations which were found earlier by van den Bergh. Yet looking only for the brightest blue stars in U plates we found 210 smaller groups with average size 80 pc; these groups are genuine, classical associations, similar to those known in the MW galaxy.

However the appearance of the large groups seems to be not the result of only smaller background density in M 31. They were mostly older (except for their cores, genuine OB-associations), as followed from the concentration of the Cepheid variable stars, which are ten times older than O-stars. Whenever a large association of van den Bergh was in a field of M 31 investigated for variable stars, Cepheids with ages of up to 50 Myrs concentrated there.

This was just the property of stellar complexes, the name suggested for the largest groupings of young stars and clusters, which I had detected in the MW galaxy by 1975–1978 mainly by using the Cepheids (Efremov, 1978). The large associations of van den Bergh in M 31 were similar to star complexes in the Galaxy in every way, by age, dimensions, stellar content and tendency to lie along the spiral arms.

I recognized that at least larger complexes rich in stars and detected by Cepheids in the Galaxy are just star clouds, bright knots well known in spiral arms of other galaxies. Indeed, long ago Scares believed that these knots are similar to the Local system (the Gould Belt) of rather young stars inside which the Sun lies and many parameters of this System were quite similar to those observed for more distant complexes. I argued that the complexes are omnipresent in spiral and irregular galaxies, being the largest grouping of rather young stars, inside which associations formed and dissolved a few times during the life of the complex (Efremov, 1979). Then Efremov and Sitnik (1988) confirmed that as much as 90 per cents of the OB-associations and young clusters of the Galaxy may be united into vast complexes. The largest complexes detected with Cepheids (Efremov, 1978; Berdnikov and Efremov, 1993) coincide with complexes detected with young clusters and associations. Peculiarities of distributions of complexes in the Galaxy were then studied by Alfaro and Efremov (1996).

Long ago, in 1958, in his Harvard lectures Baade (1963) stressed that star formation in the LMC occurs on two scales – in associations with dimensions of the order of 10–100 pc, and over huge areas with diameters of 500 pc. The latter scale is that of superassociations, the groups of OB-associations and H II regions, the first example of which is the 30 Dor region in the LMC. However, the superassociations are rare, exotic objects; in the giant spiral M 31 only one group was deemed worthy to be dignified with this name: NGC 206, the bright star cloud in the southern spiral arm S4 (Baade, 1963). The origin of superassociations as the result of collisions of two density waves was suggested by Chernin *et al.* (1995).

A superassociation seems to be a complex within which all star formation goes simultaneously over all its area. The hierarchical inner structure is seen there very well because bright OB-stars are numerous in a superassociation – inside it there is never a uniform field of stars yet always a number of clusters and associations with embedded subgroups.

A similar hierarchy is seen in the distribution of gas clouds. This should be so, because these clouds are parental to stellar groups. After finding star complexes I was searching for data on gas clouds large enough to produce the whole complex, and at the same time Bruce Elmegreen, having found that gravitational instability in gaseous galactic disks formed the supergiant clouds most quickly (1979), was searching for data on the largest stellar assemblages. So we found papers by each other, some fifteen years ago. Yet we met only at the Elba conference in 1992.

9 UNIVERSAL MECHANISM OF FORMATION OF STELLAR CLUSTERING

Many observations have been made during the last four decades of the hierarchical structure of the ISM and star-forming regions. The embedded sequence of stellar clusterings extends smoothly from multiple stars to clusters, to associations, to groups of associations, to stellar complexes, and possibly even to short blue spiral arms, such as the Orion arm. Along this sequence the age range of the oldest members usually increases, implying a longer duration of star formation inside larger groups.

A similar hierarchical sequence has been observed for the distribution of gas clouds, from unresolved clumps at the excitation density of the gas, to tiny resolved clumps, to small molecular cores ($M < 10^3 M_\odot$), GMCs ($10^5 M_\odot$), and giant spiral arm clouds or "superclouds" ($10^7 M_\odot$) in which whole star complexes form (i.e., the "beads on a string" of star formation in spiral arms). Both stellar and gaseous structures in these sequences appear to be self-similar, or fractal over a wide range of scales.

The considerations of the turbulent and fractal nature of the ISM were the basis for elaboration of the unified mechanism of cluster formation. As Bruce Elmegreen noted, "Even though astronomers have recognized the fractal nature of interstellar clouds for 10 years, they have not, considered all of the implications yet. What is new here is that this fractal structure apparently solves three important problems that have been with us for over 30 years: the relative proportions of clouds, clusters and individual stars of various masses".

The fractal dimension of interstellar gas has been determined to be $D = 2.3$ from the size distribution of molecular clouds (Elmegreen and Falgarone, 1996). This is about the same as the fractal dimension of structures seen in laboratory turbulence and is therefore a strong indication that most interstellar clouds form by processes related to turbulence. The mass spectrum of interstellar clouds and the mass–size correlation also follow from this fractal structure. Fractal clouds have a mass distribution close to M^{-2}, and can therefore account for the common formation of young stars in clusters, which have the same mass distribution.

Young stellar clusters, such as open clusters, associations, and young globulars in starburst regions, have such a wide range of masses and sizes, and such a diversity in their state of gravitational binding, that different specific formation mechanisms have always been envisioned for each type. The same is true for old globular clusters in the halos of galaxies, whose formation has often been assumed to be intimately connected with conditions in protogalaxies. Yet in spite of all their apparent diversity, these clusters have important common properties, and the protocluster gas must have had important common properties too.

In a joint paper (Elmegreen and Efremov, 1997) a universal mechanism for cluster formation in all epochs and environments was suggested. We found it to be consistent with the properties and locations of young and old globular clusters, open clusters and unbound associations, and interstellar clouds. The primary structural differences between various cluster types result from differences in pressure at the time of formation, combined with different ages for subsequent evolution. We found that it is quite possible that all clusters begin with a mass distribution similar to that for interstellar clouds. Comparison of the exponent mass function for open clusters and associations with the normal law for the mass distribution of globular clusters has long been considered evidence of different mechanism of formation. However we argued (as first suggested by Surdin, 1979) that old halo globulars have a current mass distribution that falls off at low mass because of the Hubble time of cluster destruction. Young globulars have not yet had time for a similar loss, and some old open clusters have survived because of their low densities. The peak globular cluster mass is therefore not a characteristic or Jeans mass in the primordial galaxy, as previously suggested.

The uniform data on ages of about 600 star clusters in the LMC, were the basis for the conclusion that the initial mass distribution functions for young and old globular clusters, open clusters and associations, and interstellar clouds are all power laws with a slope of ~ -2. As stated above, this distribution could be the result of fractal structure in turbulent gas. The slope is so steep that it implies that significant fraction of star formation occurs in small clusters. Numerous halo field stars should come from the evaporation of small halo clusters, and a high fraction of disk field stars should arise in small unbound disk clusters. This differs significantly from previous suggestions that most disk stars form in large OB associations.

Another important conclusion concerns the long-standing problem of the formation of globular – i.e. massive and dense – clusters. We suggested that globular clusters of all ages preferentially form in high pressure regions. High pressures at the time of globular cluster formation are either the result of a high background virial density in that part of the galaxy (as in dwarf galaxies or galactic nuclei and nuclear rings), turbulence compression (in halo globulars), or large-scale shocks (in interacting galaxies). The present day young globulars are indeed observed mostly within such environments as was observed recently with the HST. The young massive clusters in M31 are mostly within just that one small fragment of a spiral arm for which the strong spiral density wave is suspected to exist.

Massive clusters that form in such high pressure environments are more likely to be bound than low mass clusters or clusters of equal mass in low pressure regions.

This is because virialized clouds are more tightly bound at high pressure. The extremely high pressure prevents hot, young stars from dispersing the gas and preventing other stars from forming. A massive bound cluster results.

10 THE HIERARCHY OF YOUNG STAR CLUSTERING

In recent papers (Elmegreen and Falgarone, 1996; Elmegreen and Efremov, 1996, 1998) it was emphasized that the hierarchical structure of gas clouds suggests that the gas is organized by turbulence and self-gravity and this involves well-known scaling laws between distance and velocity, or between distance and time. These scaling laws are expected to be essentially the same for the gas and stars because the stars get their clustering properties from the gas. Recently (Efremov and Elmegreen, 1998a) we confirmed the existence of the relation between the duration of star formation in a region and its size using the star clusters of the LMC.

At this point it is worth noting that the Large Magellanic Cloud is the best site in the Universe to investigate star formation processes not connected with spiral arms. This is because the galaxy is near enough, is seen about pole-on and has no large depth (contrary to the SMC case). The relative visible positions of objects in the LMC are as close to their spatial relationships as it is possible to be. Concerning the stars and clusters that are young enough, this give the best opportunity to study the larger-scale properties of star formation, as far as their space distribution reflects the distribution of the paternal gas clouds and the basic mechanisms of star formation.

Spontaneous star formation in the turbulent gas implies the hierarchical structure of distributions of young stars. This is indeed observed as a sequence of embedded young star groups, from mini-clusters to clusters to associations to aggregates to complexes (Efremov, 1995). Qualitative evidence is also obtained. The time – size relation for regions of star formation must be observed if this mechanism is in action, similar to the relation between crossing times and sizes in the gas cloud hierarchy (Elmegreen and Efremov, 1996). Such a relation was found for ensembles of young clusters in the LMC – the mutual distances, taken as sizes of star-formation regions, were found to be increasing with the maximal age difference, taken as the duration of star formation in a region (Efremov and Elmegreen, 1998a). The time–size relation implies that the duration of star-formation in a region is about three crossing times for parental gas velocity dispersion there.

This size–age relation for the SFR is of great importance. In the fractal distribution of masses and sizes there are no prefered scales, there is a normal (Gaussian) distribution, and this relation may explain the impression of the prefered size, 80 pc, for the OB-associations in nearby galaxies, evidence of which was given by Efremov (1995). The answer is already just in the term, OB-association. In searching for these groups, one looks to O and early B-stars, this implies blue and bright ones. The age of O-B2 stars is about 10 Myrs and the velocity dispersion in star-forming ISM is generally 5–10 km/s. Thus the size–age relation gives for groups which are called OB-associations sizes within 50–100 pc, which is indeed observed. We may explain this with the suggestion that while searching for OB-associations in near by galaxies, people were looking for stars no fainter than about B2. This seems to be true, the angular resolutions and limiting magnitudes in such investigations being different for different galaxies – yet considering the different distances of the galaxies in questions, they mostly correspond to the same spatial resolution and absolute magnitudes. If this was not the case, then large variations and controversy concerning association sizes in galaxies would appeared. It is quite understandable now.

OB-associations are not a fundamental unit of star formation, but only part of a large hierarchy of structures. They have their observed sizes and masses only because O stars typically last for 10 Myr. All regions of star formation follow common relationships between size, velocity dispersion, time of star formation, brightness, and so on. This relationship is seen in all galaxies and in all regions of star formation.

So stellar associations are not well-determined entities. Taking stars of different ages (this means different luminosities and magnitudes – for early stars) one obtains different borderlines and even different groupings. This explains the controversial results often obtained for associations.

Larger star-forming regions have both larger velocity dispersions and larger average ages than smaller regions. This trend is similar to that found for OB-subgroups and whole OB-associations and may contribute to the impression that OB-subgroups expand into OB-associations. There may not be that much expansion, however. Instead, there could be a difference in the sizes and velocity dispersions of the two types of regions from birth. OB-subgroups are born small and they may stay moderately small during the formation time of the other subgroups. All of the subgroups together define the association, which is a composite of clumpy subparts.

The identification of OB-associations is based entirely on the presence of O-stars, and is therefore only a selection of one particular scale out of a continuum of scales for the star-formation process. This was implicitly the case in Efremov *et al.* (1987) and Battinelli *et al.* (1996), where stars in M 31 were selected to be brightest in U or B to detect the O-associations. However, OB-associations are not representative of the star formation process in general; they are only one level in a continuous hierarchy of self-similar processes that extends from parsec to kiloparsec scales.

The largest obvious scale for star formation, which is that of a star complex, is usually comparable to the disk thickness. This is also about the Jeans length in the ambient medium. In spiral galaxies, the selection of complexes as the largest clearly defined (roundish!) objects implies their ages are not so large that shear has significantly distorted them. Gas and star formation structures larger than a disk thickness certainly exist, but because of their long dynamical time scales, they get sheared into independent spiral arms before their star formation stops (Elmegreen and Efremov, 1996).

The unified approach to spontaneous large-scale star formation processes, which is based on the interplay of gravitation and turbulence in the fractal ISM, seems to be really promising. At any rate, the fractal – turbulence approach implies a drastic change of the existing conception of stellar associations and complexes. This approach is valid unless we deal with regular forces. It must be changed while considering the spiral density waves or star formation triggered by SNs/O-stars clusterings or by collissions of clouds. The regular spacing of superclouds–star complexes along the arm, which was found also for our Galaxy (Efremov, 1998) strongly suggests the large-scale gravitational instability as the main mechanism of their origin (Elmegreen, 1994).

At present density waves or young stars concentrate there just because most of the gas is there (Elmegreen, 1987). It seems that triggering did occur in the strong arms, such as the arms of M 51. However, the LMC provides the clearest evidence of triggered star formation in certain regions.

11 TRIGGERED STAR FORMATION

There is a region where triggered star formation was suggested by many investigators – this is the constellation III/LMC4. There was no agreement, however, on the concrete mechanism of triggering and no reliable age gradient found.

We considered the origin of a regular, 500 pc-long arc of young stars and clusters in this region, named Quadrant by us (Efremov and Elmegreen, 1998b). The circular form of this arc suggests that the prestellar gas was uniformly swept up by a central source of pressure. In the centre of the arc we found a concentation of rather old A-type supergiant stars and a Cepheid variable, which may be the source of this pressure. The expansion of a bubble around such old stars was calculated and it was shown that it could have triggered the formation of the arc at the right time and place. Surrounding the centralized old stars and extending well outside the young arc is the LMC4 superbubble and giant H I shell. We show how this superbubble and shell could have formed by the continued expansion of the initial cavity, following star formation in the arc and the associated new pressures.

However, some puzzles of this region remain. There are two more arcs of stars and clusters there besides Quadrant. Why are all of these arcs within the LMC within the same rather small region? The origin of the large arc was suggested long ago to be a Super-SN explosion and this idea is now quite attractive, after the identification of GRBs with super-explosions in far galaxies (Efremov *et al.*, 1998; Efremov, 1999).

All in all, spontaneous and triggered star formation usually operates jointly. As Elmegreen (1998) wrote, "Spontaneous processes probably dominate the onset of star formation on a galactic scale, bul triggered star formation sustains, amplifies and disperses what large-scale instabilities begin". The simultaneous actions of many different forces make star formation processes so various, so picturesque and so interesting to study.

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