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The Peculiar Complexes of Star Clusters in Galaxies

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Abstract. Existence of complexes of clusters and complexes of isolated stars is the key to understand the cluster and isolated modes of star formation. Examples of such complexes in the LMC are considered. New kind of complexes with the circular shape or including arc-like structures is described, first of all in the LMC and NGC 6946. They may be of other origin than most HI supershells. The system of the giant stellar arcs (partiall spheres seen in projection) in the NE region of the LMC might be formed by GRB events, progenitors of which might be ejected from the massive nearby cluster NGC 1978. Otherwise the arcs might be results of cloud impacts, being concentrate at the NE side of the LMC because this side is leading in the orbital motion of the LMC. The strong arguments are given for the NE (and not Eastward) direction of the LMC movement. Also, the shock wave from a superexplosion might give the shape of the partial sphere to the facing surface of a nearby dense cloud.

1. Complexes of stars and complexes of star clusters

Star complexes are the highest level groupings in the hierarchy of the young stellar groups. Some 90% of the associations and the young clusters united into vast groupings 600 - 1000 pc in size, which include also older isolated stars, such as Cepheids (Efremov 1979, 1989, 1995). In the spiral galaxies the complexes are mostly in chains along the arms, and they form the chaotic appearance of the irregular galaxies. The star complexes are stellar counterparts of the largest HI clouds - superclouds, which formed first in the result of the large scale gravitational instability of the gaseous disk of a galaxy (Elmegreen and Elmegreen, 1983) and their maximal sizes in a galaxy depend on the galaxy mass and thickness of its gaseous disk (Elmegreen et al. 1996). In a sense, the star complexes are the fundamental units of star formation.

The range of ages within complexes is usually quite large. Most complexes include the associations with still active star formation and also Cepheids and clusters with ages up to 100 Myr or so. Some rare complexes, however, composed of only young stars and associations and these are known as superassociations (Efremov, 1994). Most likely such synchronised over all the complex star formation is triggered, though the source of triggering is often unknown. Complexes - superassociations represent the local starbursts.

The great deal of the star complexes includes isolated stars (which are mostly the oldest members of a complex), clusters and associations in the same

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proportion as it is in the general field of a galaxy. However, there are a few examples where this is not a case and they are of the great significance.

Lynga (1987) has noted that the complexes (or their parts) in our Galaxy often composed either mostly of clusters or mostly of Cepheids. Much more extreme examples of such a situation are known in the LMC (Efremov, 1979, 1989, 1997).

The most prominent complex of clusters in the LMC consists of ten young clusters in the region 500 x 800 pc across. Four of these clusters (NGC 2156, 2159, 2164 and 2172) are very rich. All the clusters in the whole complex are about coeval (50 - 70 Myr), the age being well within the age range of Cepheids. However, only a few Cepheids are known within the complex.

The 'normal' situation exists in the dense complex of 7 coeval clusters, including the young massive clusters NGC 2058 and NGC 2065, at the Eastern end of the LMC bar. The numerous Cepheids are known in these clusters and also in the field of the complex. But at the distance of only 200 pc toward the SE, there is another dense complex of 300 pc across, and it composed of only the Cepheids and not the clusters (Efremov 1997). Recourse to the recent OGLE data showed up that no new clusters was discovered in this complex, yet a number of new Cepheids was, most of these being again within the quite narrow period (age) range. These data imply the column density of Cepheids in this complex being 850 stars per square kpc, what is 100 times higher than the density of Cepheids around Sun! The numerous late B-stars, the progenitors of the shorter period Cepheids, are to be found in this region. This very dense group of about coeval stars is a relict of the local starburst, and this was indeed the star-burst, not cluster-burst!

The correspondance between positions of Cepheids (the well sampled stars of the known ages) and the clusters within the Cepheid age range (around 30 - 100 Myr) in the LMC was investigated by Battinelli and Efremov (1999) with an objective method. We found that only one clump, out of four groups of clusters coeval with Cepheids, coincides with a region of the high density of Cepheids; it is just the above mentioned NGC 2058/2065 complex.

I have to conclude that within the limited space and time extensions within a galaxy, the high rate of isolated star formation mostly did not accompany the high rate of (massive) cluster formation. This could be explained by the preferential formation of small quickly dissolved clusters and/or unbond associations within clusterless (at the present) complexes (Efremov 1989). Anyway, it is saying nothing on the possible reasons for this. Clustered or isolated mode of star formation may be determined by the parameters of turbulence in respective regions (MacLow, 2000). Note also the position of this dense Cepheid complex near the end of the LMC bar, at the site opposite to the acting starburst 30 Dor.

It looks like the local situation contradicts to Larsen and Richtler (2000) conclusion that the number of young massive clusters in a galaxy continuosly increases with the SFR, normalized per unit area. Anyway, only the most rich young clusters in the LMC are similar to the young massive clusters found by these authors in other galaxies.

Larsen and Richtler (2000) found with data on 21 spiral galaxies that the luminosity of the brightest young cluster in a galaxy increases with the total

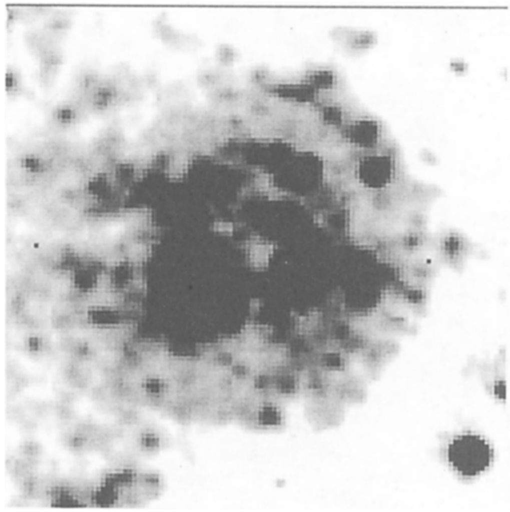

Figure 1. The Hodge complex in NGC 6946, independently rediscovered by Larsen and Richtler (1999). I-band image obtained by S.Larsen with NOT

number of young clusters there, and Whitmore (2000) found that the clusters in star-burst galaxies continue this relation at the bright end. These authors concluded that there exists the universal luminosity function for the young clusters and presence of the young massive clusters in a galaxy is nothing but a sampling effect. Anyway Whitmore (2000) noted the important exclusion: the brightest clusters in NGC 1569 and NGC 1705 are 2 - 3 magnitudes brighter than the second brightest cluster in the galaxy.

These two galaxies are known as starburst ones, yet the supercluster brighter by two magnitudes than the next one in the galaxy was found recently in the quite normal spiral galaxy NGC 6946 (Larsen and Richtler, 1999). Anyway, this cluster is within the semiround complex of two dozen small clusters and a few hundreds stars of the high luminosity, 600 pc across, which may be called the local starburst (Fig. 1).

2. Arc-shaped star complexes

This structure in NGC 6946 was found first by Hodge (1967) as the only result of the searches for the formations similar to the system of the giant stellar arcs he noted in the LMC (Fig. 2).

The most evident of these arcs was first described by Westerlund and Mathewson (1964) under the (wrong) title the Shapley Constellation III. The whole system of the arcs was studied first quite recently (Efremov and Elmegreen 1998). The arcs are in the region of the HI/HII superbubble LMC4, the best arc (Quadrant) being inside the HI void. This arc (Quadrant) has radius of

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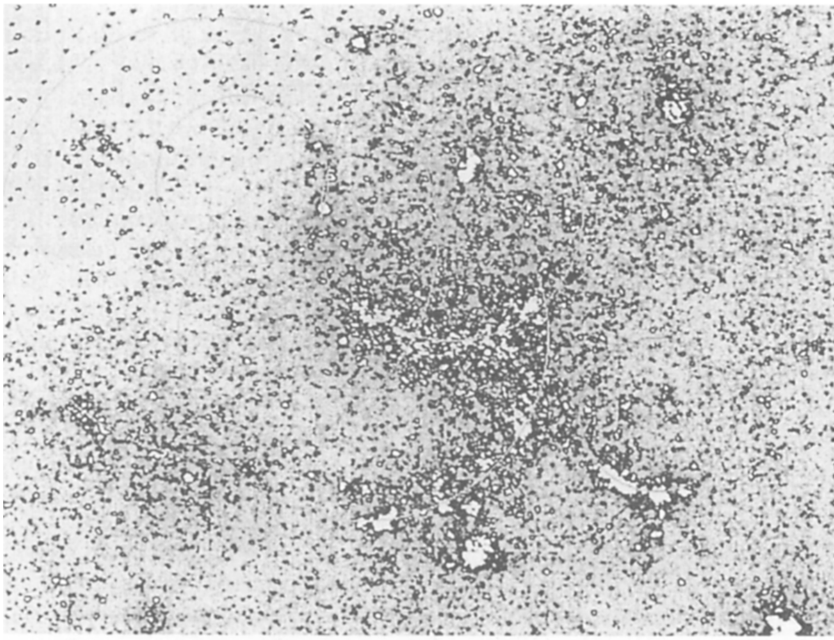

Figure 2. The system of the giant stellar arcs in the LMC. The highest densities are white. The Quadrant arc is in the center, the Fifth arc is above its Eastern end, the Third arc is below the Quadrant, the Sextant arc is at SW, and the Fourth arc is at SE. All arcs are part of circles and therefore are partiall spheres. Here and everywhere N is upward, E is leftward.

about 300 pc and the average age of clusters there is about 15 Myr, the radius of the smaller arc (Sextant) is 200 pc and the age about 5 Myr. The Third arc southward Quadrant might be the case superposition of unconnected clusters, the range of their ages seems to be too large. Apart from these arcs there exist plausibly two more (Efremov, 2001). The Fourth arcs, at SE of the region, may not be real, it is well dispersed. Anyway, this may be just connected with its older age, some 100 Myr - the arcs surely cannot be gravitationally bound structures. There exists seemingly the young Fifth arc above the Eastern end of Quadrant, it is in the Hodge (1967) sketch.

Hodge (1967) has sketched the feature he found in NGC 6946 as consisting of a few arcs. The largest of these arcs is the sharp and strictly circular Western edge of this complex (Figs. 1 and 5). It cannot be explained by the dust cleaning from the giant young cluster which is inside the complex. There is no evidence for the much higher light absorption outside the complex. This sharp edge is the real Western borderline of the Hodge complex. Its Eastern edge is rather uncertain and the whole structure has some similarity to a comet with the very short tail. About 20 much smaller clusters are inside the complex and their ages

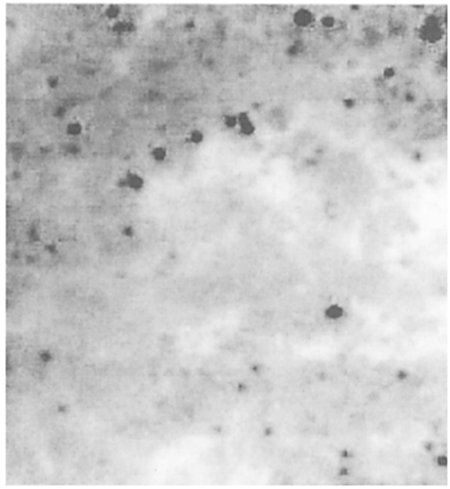

Figure 3. The arc of five clusters (one is triple) around dark arc-shaped region on the W outskirts of M83. The detail of the M83 image, obtained with the VLT; from the ESO press-release.

from the integral UBV photometry are about the same as for the giant cluster (Elmegreen et al. 2000). The age of this cluster is some 15 Myr, as follows from photometric (Elmegreen et al. 2000; Larsen et al. 2001) and spectral (Efremov et al. 2001) data. Anyway, the variable through the field light absorption makes the photometric ages rather uncertain.

The light distribution and the total luminosity of the brightest cluster (from the HST images) and velocity dispersion (from the Keck spectra) give for its mass the value of two millions suns, and assumption of the normal IMF leads to the conclusion that the cluster will rest bound, being thus the *bona fide* young globular cluster (Larsen et al. 2001). Note that the mass of this cluster is amongst the largest known, only a few young clusters in the NGC 4038/4039 interacting galaxies are a bit more massive. Yet the NGC 6946 cluster is at outskirts of otherwise normal galaxy - though within a quite unusual region.

There are other examples of the giant arcs of clusters (Efremov 2001). The 500 pc across arc of a few groups of young clusters, still surrounded by HII gas, is known in NGC 300. Two arcs of clusters around the dark regions are found in M83 (Fig. 3).

There is also in SE outskirts of this galaxy the isolated complex of clusters, inside which two small arcs may be outlined. This complex was independently noted by Comeron (2001) and Efremov (1999, 2001), the latter author stressing the similarity between it and the system of arcs in the LMC4 region (Fig. 4).

These arc-shaped and round complexes might be rather numerous, yet not easy recognisable.

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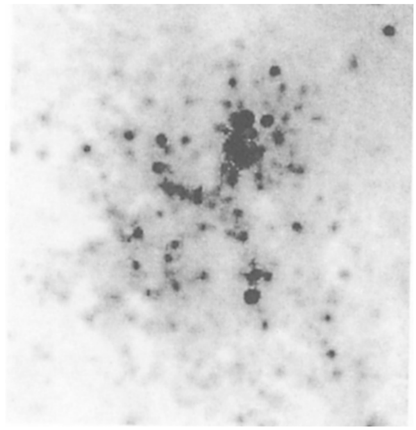

Figure 4. The isolated star complex on the SE outskirts of M83. Note two small arcs inside the complex, resembling the Quadrant and Sextant arcs. The detail of the M83 image, obtained with the VLA.

3. The origin of the arc-shaped complexes

Most of such complexes are on a galaxy outskirts and looks like the extraneous bodies there. Their shapes provide a key to their origin. The most natural assumption is they are results of star formation in the swept up gas shell, as Efremov and Elmegreen (1998) suggested for the LMC arcs. The energy needed for formation of such shells is equivalent to a few dozen SNe and these authors considered the multiple SNe in the central clusters as the sources of the central pressure. However the very existence of these clusters is doubtful (Braun et al. 2000). At any rate, they are quite small and the question arise why there is no similar structures around a lot of more suitable clusters. It is also surprising that all the arcs are near each other in the only region of the LMC.

There is no such difficulty in the idea that the central sources were the GRB-connected superexplosions, the progenitors of GRB being ejected from the nearby massive cluster NGC 1978 (Efremov, 1999; Efremov and Elmegreen 1999). This hypothesis ressurected Hodge's (1967) initial idea on Super-supernovae as the cause of the structures he described in the LMC and NGC 6946. The common origin in a dense cluster seems to be the only logic possibility for the progenitors of the multiple superexplosions found in the same region, and if so, certain conclusions on the nature of GRB follow (Efremov, 2000).

Another possibility is the arcs in the LMC were formed by the infalling clouds which must be in more or less the same orbit, giving all the arcs are within the region 1.5 kpc across. The similar orientation of Quadrant and Sextant arcs then reflects the direction of the cloud movement, and the opening angles of the

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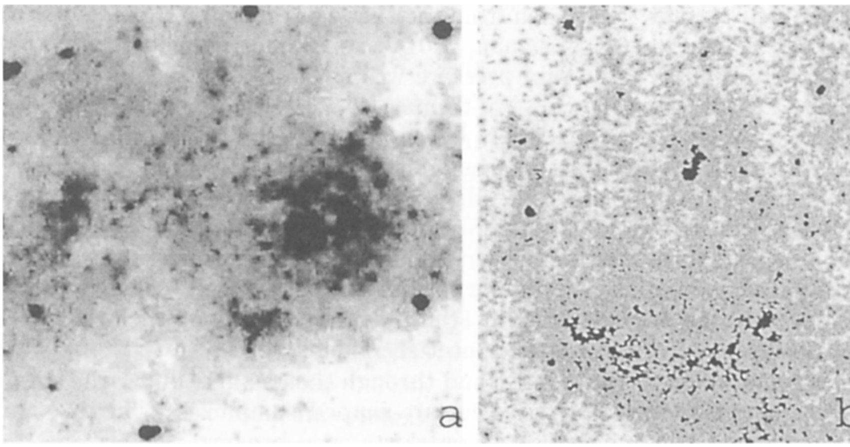

Figure 5. The Hodge complex (a) and the Quadrant arc (b) both have the sharp semiround edge and the diffuse opposite site, what is compatible with the origin under the ram pressure or the shock wave, acting on the isolated dense cloud.

arcs are then determined by the angle under which the clouds impact the plane of the LMC.

There are some data which may indicate that just in this region of the LMC the cloud infalls are more probable. It is worth noting the recent determination of the proper motion of the LMC, which was found to be directed to PA = 31° (Anguita, 1999), and it is important to note that this is close to the PA of the line connecting the LMC and the SMC. Also, Demers and Kunkel (1999) noted that the carbon stars in the LMC extend to the NE up to distance 20 kpc from the center, mentioning this may be connected with the tidal interaction. At last, the HI distribution in the LMC has the most sharp edge just in the NE direction (see Putman et al. 1999, Fig. 1).

In our opinion, all these facts taking together imply that the LMC is moving to the NNE (or, after averaging all three existing determinations of the proper motions, to NE) as the head of the Magellanic Stream, or, at least, the LMC-SMC system. Then the NE part of the LMC first meets the intergalactic gas clouds and this may explain why all the stellar arcs and the LMC4 HI void are here. This is compatible also with the orientation of Quadrant and Sextant arcs.

The multiple SNe, a hypernova, or the infalling cloud being the source of the central pressure, the stars along the giant arcs are suggested to be formed owing to the gravitational instability in the swept up gas shells. If so, the origin of the arc-shaped star complexes is nothing but the controvesial issue of the formation of the gas supershells. Note, however, the very irregular appearance of complex of clusters around the HI hole in IC 2574, considered the best example of star formation in a shell swept up from the central cluster, which is well seen

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there (Stewart and Walter, 2000). It is still possible that the arc-shaped star complexes, so regular in appearance, were formed by other processes.

The facing surface of a gas cloud acquires the semispherical shape under action of the ram pressure, as it seen from the shape of the outer HI isodenses of the Ho II galaxy (Bureau and Carignan, 2001), the HI density inside the galaxy being quite non-uniform. The ram pressure was suggested by Braun, de Boer and Altmann (2000) to be the cause of formation of LMC4 supershell, whereas concerning the arc origin these authors have only noted that "four cluster arcs are rather due to cloud structure long before star formation than being directly connected to the formation process". However, the giant stellar arcs might be results of star formation from the ram pressure at the interface of a galaxy disk gas and the leading surface of the denser clouds which have crossed the gas disk with the high relative velocity and under the quite small angles. This hypothesis is compatible with the orientation of most arcs in the LMC along with the NNE or NE-ward movement of the LMC to meet the clouds.

The fast movement of the dense cloud through the gas disk under the small angle to its plane may explain also other arc-shaped complexes. This is compatible with their occurence on galaxy outskirts, also because the gas density is low there. The opening angle of the resulting arc should be always large yet smaller than 180°, as it is observed. The distrubution of stars and clusters in the Quadrant arc and in the Hodge complex in NGC 6946 have some similarity to the outer HI isodenses of Ho II (Bureau and Carignan, 2001), looking like comets with the very short tails (Fig. 5). The outer pressure may be also the reason for formation the very massive bound cluster within the Hodge complex, considering the high pressure in the ISM has been suggested as the condition for formation of such clusters (Elmegreen and Efremov, 1997).

The shock wave from the external superexplosion could probably also result in the transformation of the facing surface of the nearby dense and large cloud into the partiall sphere, which may have then any orientation - because the superexplosions (if connected with a GRB from the merging in the pair of compact objects) may occur everywhere, even outside a galaxy. Might the density of the IGM near a galaxy be high enough for the shock wave from a superexplosion? The perfect semicircular boundary of the HI gas in the Ho II galaxy was explained by the ram pressure from the IGM (Block and Carignan, 2001), yet how to explain the sharp semicircular stellar edges of the DDO 165 (Efremov, 2001) and NGC 922 (Block et al. 2001) galaxies?

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