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Stellar complexes in spiral arms of galaxies

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The history of the introduction and development of the star complexes conception is briefly described. These large groups of stars were picked out and named as such ones in our Galaxy with argumentation and evidence for their physical unity (using the Cepheid variables the distances and ages of which are easy determined from their periods); anyway earlier the complexes were noted along the spiral arms of the Andromeda galaxy, but were not recognized as a new kind of star group. The chains of complexes along the spiral arms are observed quite rarely; their origin is explained by magneto-gravitational or purely gravitational instability developing along the arm. It is not clear why these chains are quite a rare phenomenon – and more so why sometimes the regular chain of complexes are observed in one arm only. Probably intergalactic magnetic field participated in formation of such chains. Apart from the complexes located along the arms, there are isolated giant complexes known (up to 700 pc in diameter) which look like super-gigantic but rather rarefied globular clusters. Until now only two of these formations are studied, in NGC 6946 and M51.

Keywords: Galaxies, spiral structure, stellar complexes

1 Introduction

Initially the name *star complex* was suggested to designate star groups much larger than a cluster (up to 500–700 pc) but essentially older than an association. Such groups were first noted in our Galaxy as groups of Cepheids, periods of which indicated ages in 30–100 Myrs (Efremov, 1978). In this paper 35 complexes were picked out using the Cepheid variables; anyway the Local system (the Gould belt) is one of these. Even earlier star complexes were outlined in M31 – but under the name of OB associations. This was done by van den Bergh (1964), who found for them an average size of 480 pc, which is much larger than size of the local OB associations (80 pc). Efremov (1980) concluded that these superlarge M31 "associations" are the groups of the same nature as ones which were named "star complexes" in our Galaxy, and that star complexes generally contain OB associations as its sub-parts. Unfortunately earlier the paper by van den Bergh (1964) was missed.

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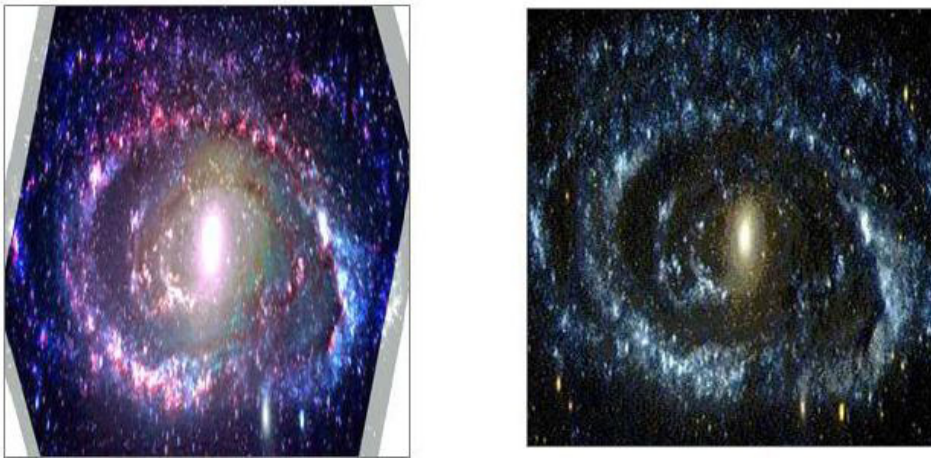


Figure 1 Left: The optical (red – HII regions) image of M31; Right: Far UV (GALEX) image of M31.

Later on striking regularities were found in the northwestern arm of the M31 galaxy (up in both parts of Fig. 1, as well as in the left part of Fig. 2). Star complexes located in this arm are spaced 1.2 kpc apart and have similar sizes of about 0.6 kpc. This pattern is observed within the arm region where Beck et al. (1989) detected a strong regular magnetic field with the wavelength twice as large as the spacing between the complexes. Moreover, these complexes are located mostly at the extremes of the wavy magnetic field. In this arm, groups of HII regions lie inside star complexes, which, in turn, are located inside the gas-dust lane. In contrast, the southwestern arm of M31 splits into a gas-dust lane upstream and a dense stellar arm downstream, with HII regions located mostly along the boundary between these components of the arm. The density of high-luminosity stars in the southwestern arm is much higher than in the northwestern arm, and the former is not fragmented into star complexes.

The explanation of this drastic difference in the structure of the segments of the same arm (Baade's arm S4) was suggested rather recently (Efremov, 2010). It probably is due mostly to the different pitch angles of these segments: the pitch angle is of about 0° for the northwestern part of the arm and about 30° in the southwestern segment. According to the classical spiral density wave theory, this might result in the lower star formation rate in the former and in the triggering of high SFR in the latter. Data on M31, M54, M74, and some other galaxies suggest that star complexes are mostly located in the arm segments that are not accompanied by a dust lane upstream – i.e., those that do not host spiral shock wave. The same is related as well to the tidal arms which often host a chain of complexes. The regularities in the distribution of complexes along a density wave spiral arm are most probably due to the development of the Parker–Jeans (magneto-gravitational) instability, which builds up star complexes if the magnetic field is regular along the given arm.

The large clouds of HI, outlined the spiral arms, are known in our Galaxy for many years, starting with the first HI observations of the Milky Way (McGee and Milton 1964). Regularity implies a characteristic scale, which is most likely the Jeans

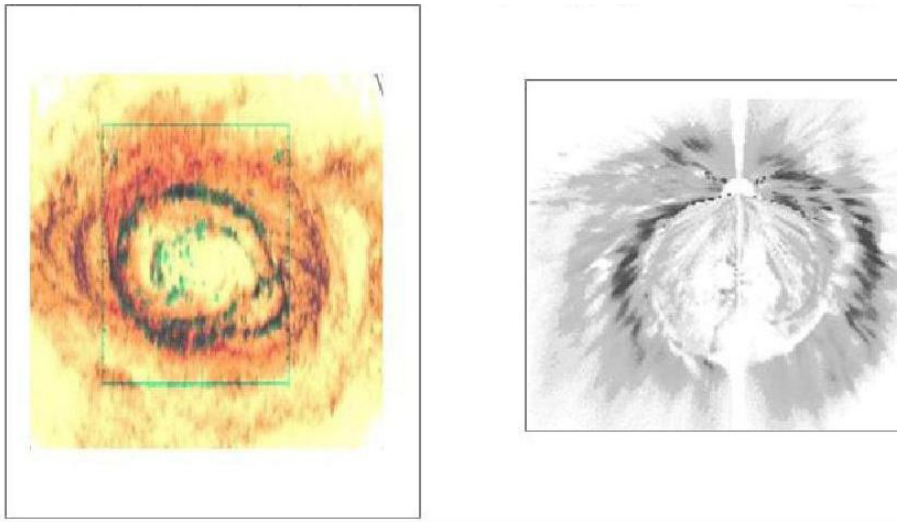


Figure 2 Left: the HI image of M31 (brown) with CO (green) overlaid. Right: HI arms of our Galaxy

length (Elmegreen and Elmegreen 1983). These observations demonstrate – like the situation which was later noted in M31 – that star complexes form in CO/HI cloud complexes. The stellar parts are hierarchically clumped, but still coherent up to 1 kpc in the main disks of galaxies, while the primary objects formed by galactic processes are 10^7 $M_\odot$ HI superclouds, while giant molecular clouds (GMCs) are inside them, at least in spiral arms (Fig. 3). This 10^7 $M_\odot$ mass is the Jeans mass in the ambient ISM, suggesting that the HI clouds and ultimately the star complexes form by gravitational instabilities. The formation of GMCs follows by a combination of self-gravitational contraction and turbulence compression inside the 10^7 $M_\odot$ clouds, but GMCs are not special, distinct objects (Elmegreen, 2004).

In our Galaxy, as well in M31 and probably in all grand design galaxies, the GMCs represent the most dense parts of superclouds, located within an arm. They are shaped as rather thin sheets inclined to a galaxy plane, which is easily seen in the part of the Carina arm which is about orthogonal to our line of view. The same is evident in the NW arm of M31. The well known inclination of the Gould belt to the galaxy plane may be of the same nature.

The regular spacing of HII regions/star complexes along an arm, a phenomenon studied first by Elmegreen and Elmegreen (1983), implies the magneto-gravitational instability developing along an arm as the most probable cause for the formation of such chains.

A spiral shock can probably prevent the fragmentation of the arm segment into superclouds (parental for star complexes), because it rapidly leads to a high gas density in the entire segment and, as a result, to star formation everywhere in it. Any process leading to fast formation of numerous small scale sites of star formation in an arm may probably prevents the formation of superclouds in the corresponding arm segment. In contrast, if there is no fast ubiquitous star formation, the conditions for

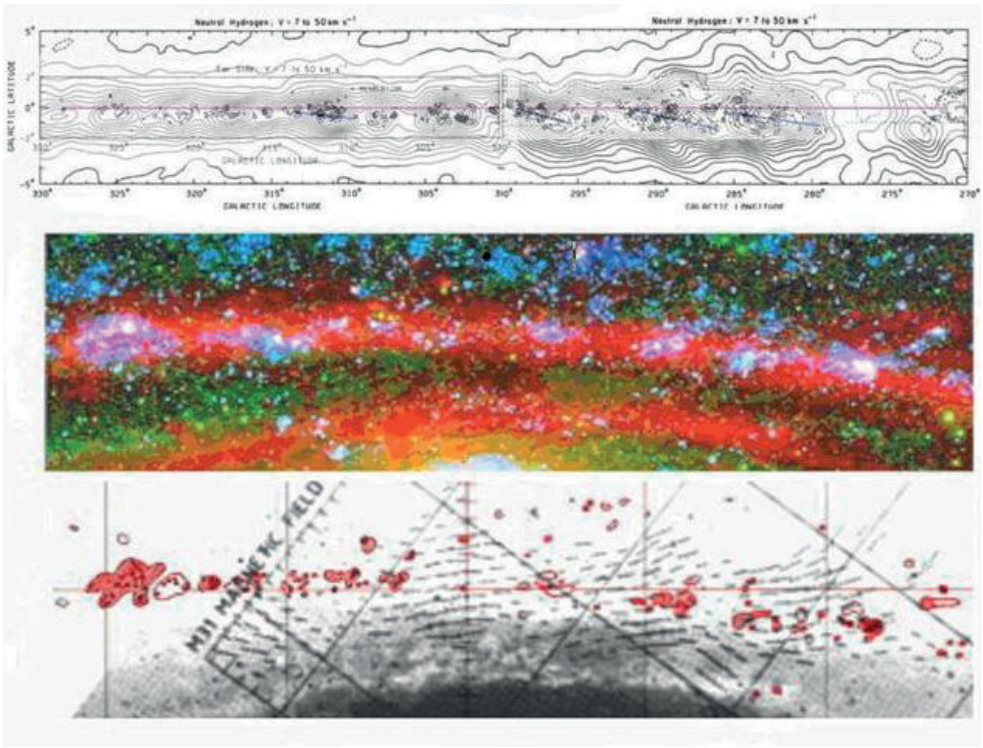


Figure 3 Top – isodenses of HI and GMCs (shown in black) along the Carina spiral arm of our Galaxy. Note the chain of GMCs, inclined to the galactic plane, which are inside superclouds of HI. Middle – part of the NW spiral arm of M31. Red – infrared emission of the warm dust (generally indicator of HI), blue – star complexes and associations of the young hot stars, mostly coinciding with the HII regions. Note the inclination of some of the latters, similar to observed in the Carina arm of the Milky Way. Bottom – orientation of the magnetic field (Beck et al., 1989) and the HII regions (red) in same part of the arm.

the development of a large-scale instability are retained along the gaseous arm and it fragments into superclouds, – only within which a gas density sufficient for star formation is initially reached – in such a way the star complexes may emerge.

There are the observations of the age gradients of the stars and clusters across an spiral arm, as well as many indirect evidences for its existence, such as the sequence of – dust/HII regions/high luminosity/fainter stars – downstream an arm, starting at its inner edge. However, this is observed within limited segments of arms only, – where the difference between the orbital velocities of the density wave pattern and stars is maximal, which implies the triggered star formation and especially where the pitch-angle of an arm segment is large and therefore is large too the component of the velocity difference (between the spiral pattern and the galaxy disk itself), orthogonal to the arm edge.

This situation was found in M31 SW arm S4 (Efremov 1985, 2010). He used the data on Cepheids, obtained long ago by Walter Baade with the 5-m reflector, and the period–age relation established (Efremov, 1972) with Cepheid members of open

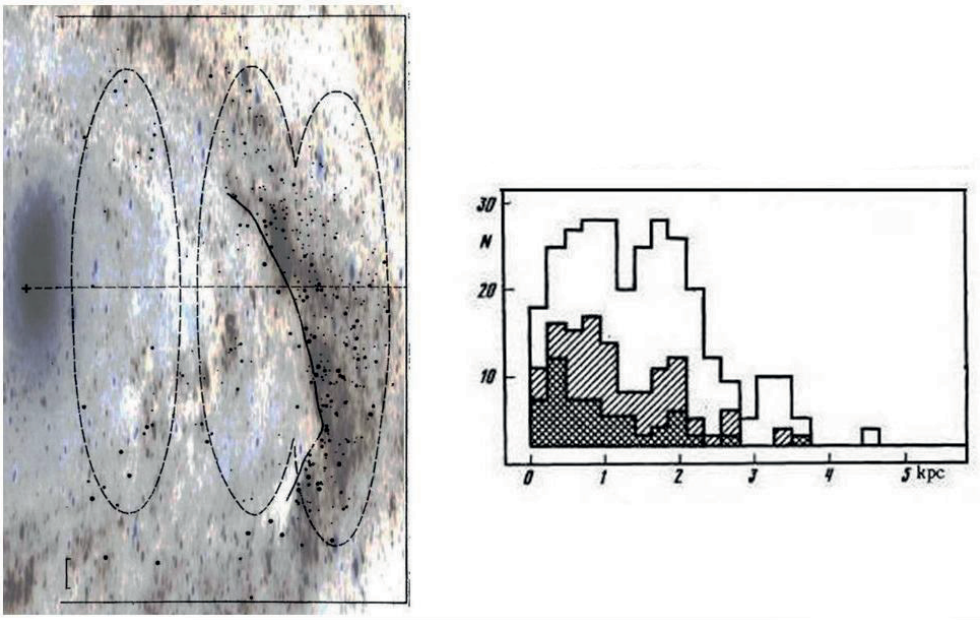


Figure 4 Left panel: Baade's field I, II and III where Cepheids (black points) were investigated overlaid onto the GALEX deprojected image. The inner edge of the S4 arm is shown. The vertical stretch in the lower left corner is equal to 1 kpc. Right panel: (white) distribution of Cepheids in the distance from the S4 arm edge. Upper histogram – all the periods, median – periods longer than 10 days, bottom (dark) histogram – periods longer than 15 days. According to the period–age relation, the longer the period, the younger the Cepheid (Efremov, 2003).

clusters. The increase of the minimal age of Cepheids with distance from the arm inner age was established (Fig. 4), which is evidence that the shock wave at the arm inner edge triggered the formation of more massive stars – and is also a confirmation of the theory, which explained the regular spiral pattern as the density waves.

The regular spacing of HII regions/star complexes along an arm, a phenomenon, first studied by Elmegreen and Elmegren (1983), implies that a gravitational or rather, in our opinion, a magneto-gravitational instability developing along an arm, is the most probable cause for the formation of complexes chains. However, there are still two problems (or better to say, two issues) which still await explanation. One is why the regular spacing of complexes along an arm is a rare phenomenon. The other difficult issue is the rather common occurrence of regular chains of complexes along one arm only – as it is observed in M31 (Fig. 1) and in M100 (Fig. 5). If the magnetic field (and not just the gravitation only) is essential for the formation of these chains, the regular spacing of complexes in one arm only (which is the case for 1/3 of all galaxies with these chains) may create a suspicion that in intergalactic space the regular magnetic field exists – and its interaction with a regular along the arm magnetic field of a galaxy – which may or may not have another polarization compared with that of the field along the arm – may result in the total field might be too faint as result?



Figure 5 Left – NGC 4321 (M100). Red color indicates the regions with HII emission, blue – the regions, rich in young stars. Right – Southern spiral arm of this galaxy. From up to down – the SPITZER far-IR image, the VLT color image, and the HST image, resolved into stars. Note that there is no warm dust around the round (and therefore plausibly gravitationally bound) complex at the Eastern tip of the arm. This complex should be the oldest one in this arm, as demonstrated by the absence of Hα emission in it and there is (only one in the arm) the rather small hole in the warm dust around it.

In Fig. 5, as well as in Fig. 1, one may suspect that the classical sequence of objects observed across a density wave arm (described in the beginning of this paper) is not observed if there is a chain of star complexes along an arm. It may be due to the faster formation of gas/star complexes along an arm under magneto-gravitational instability – compared with the formation of stars and star associations in the density wave at the upstream edge of an arm. Note that gas lane and young stars are never observed at the outer (downstream) edge of an arm.

The beautiful galaxy M51 contains a dozen of star complexes and hosts the regular magnetic field. All young star groups in its arms should be called associations, not complexes. The real complex, which even demonstrates concentration to the center, is a bit outside the Western inner arm, exactly to W of the galaxy center (Fig. 6). The diameter of the complex is about 500 pc and it is most probably bound – and may then be called a supergiant cluster of stars and clusters.

A rather similar (but even larger) object is known only in the NGC 6946 spiral galaxy. The galaxy itself is rather uncommon, it is known as the champion with the number of Supernovae observed in it (9 – and the possible number of young SNR is 15); its four spiral arms are wide and complexes cannot be picked out there – with one notable exception. This complex is at the very tip of a short arm (or, rather, a spur). It was noted first by P. Hodge long ago, and later on was investigated phometrically by Larsen et al. (2002) with the HST, and then several spectroscopic studies have been completed, the last one by Efremov et al. (2011) with the BTA. The complex



Figure 6 Left – the HST ACS image of the spiral galaxy M51. Right – the giant star and cluster complex, located at the position where the dust lane of M51 Western arm is ended. The concentration of the complex stars and clusters to the center may be explained by its gravitational boundness. It contains a few star clusters; the nearby group of 4 large unresolved clusters is seen to the complex NE.

is remarkable with its sharp Western edge, which is the perfect circular arc of 132 degrees long, and also by the giant young (about 30×10^7 years) cluster inside it.

This complex is shown in Fig. 7; the left plate shows an image obtained with the Gemini-North telescope and the right plate shows an image obtained with the HST; whereas its host, NGC 6946, is shown in Fig. 8 (the optical image – left, and the infrared one – right.)

Long ago Beck (1991) found that the regular magnetic field in this galaxy forms magnetic arms that are located between the gaseous-stellar arms and which have the same pitch angle, with the degree of field uniformity anticorrelating with the intensity of neutral and ionized gas lines. He explained this as the result of a high star formation rate in the stellar-gaseous arms of NGC 6946, which causes the magnetic field lines in them to be tangled. Note also the impossibility to divide the spiral arms of NGC 6946 into separate star complexes; they are entirely filled with sites of star formation and dispersed young stars. One might say that the Hodge complex is the only real complex in this galaxy.

The galaxy hosts a number of strange objects, apart from this supergiant unique complex. Among them are many Bok globules, extremely dark objects of unclear nature and some others... The galaxy also contains many holes in its HI disk, from

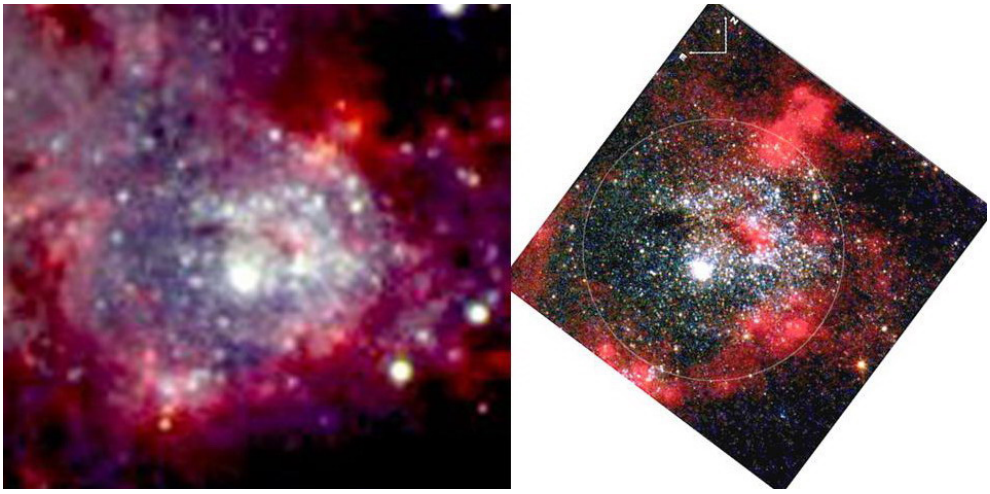


Figure 7 Images of the Hodge complex. Left – a Gemini-North image, right – an HST PC image.



Figure 8 NGC 6946, one of the most enigmatic galaxies near us. Left – a Subaru telescope BVR image, right – a near-IR image by the Spitzer orbital telescope.

the smallest to gigantic ones, including much larger then the thickness of the NGC 6946 gaseous disk (Boomsma et al., 2008) – and its origin is also enigmatic.

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