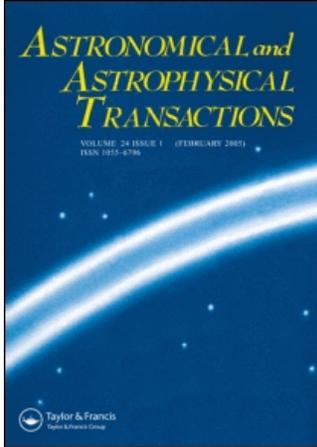


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## A PECULIAR STELLAR COMPLEX IN NGC 6946 OR THE BLUE COMPACT GALAXY IN FRONT OF THIS GALAXY?

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The origin of the peculiar stellar complex in the outskirts of the spiral galaxy NGC 6946 is discussed. The complex hosts a superstar cluster, two dozen smaller bright clusters and many high-luminosity stars 5–30 Myears old. In spite of this, no features in H I or CO are associated with the complex. The most simple explanation is that the complex is a foreground blue compact galaxy, a member of the NGC 6946 group. The arc of high light absorption along the complex rim could then be the result of the ram pressure of the intergalactic medium gas. The existing velocity data cannot prove or disprove this hypothesis.

*Keywords:* Stellar complexes, Blue compact galaxies, Young massive clusters, Star formation, NGC 6946 galaxy

### 1 INTRODUCTION

A bright roundish stellar complex is known in the outskirts of the spiral galaxy NGC 6946. It was discovered by Hodge (1967), who identified it as an arc-shaped object, somewhat similar to the system of giant stellar arcs found in the Large Magellanic Cloud. The object was independently rediscovered with the Nordic Optical Telescope (NOT) by Larsen and Richtler (1999), who described it as the bubble-like complex 600 pc in size. It includes a number of stellar clusters one of which is outstanding in its size and luminosity. In addition to its high surface brightness and the occurrence of the very large young cluster, the Hodge–Larsen–Richtler (HLR) object is unusual in having a sharp arc-like western rim (Fig. 1).

The properties of the complex were studied first with NOT data by Elmegreen *et al.* (2000) who obtained *UBV* photometry for the clusters and discussed the complex's origin. Later the complex was studied in more detail with Hubble Space Telescope (HST) and Keck-I data (Larsen *et al.*, 2001, 2002). Based on the velocity dispersion inside the large young populous cluster, its age (13 Myears) and luminosity ( $M_V = -13$ ), values for both the photometric mass and the dynamic mass of the cluster were obtained. Both were found to be approximately equal ( $10^6$  solar masses), which suggests that the cluster is bound and that it will look like a classical

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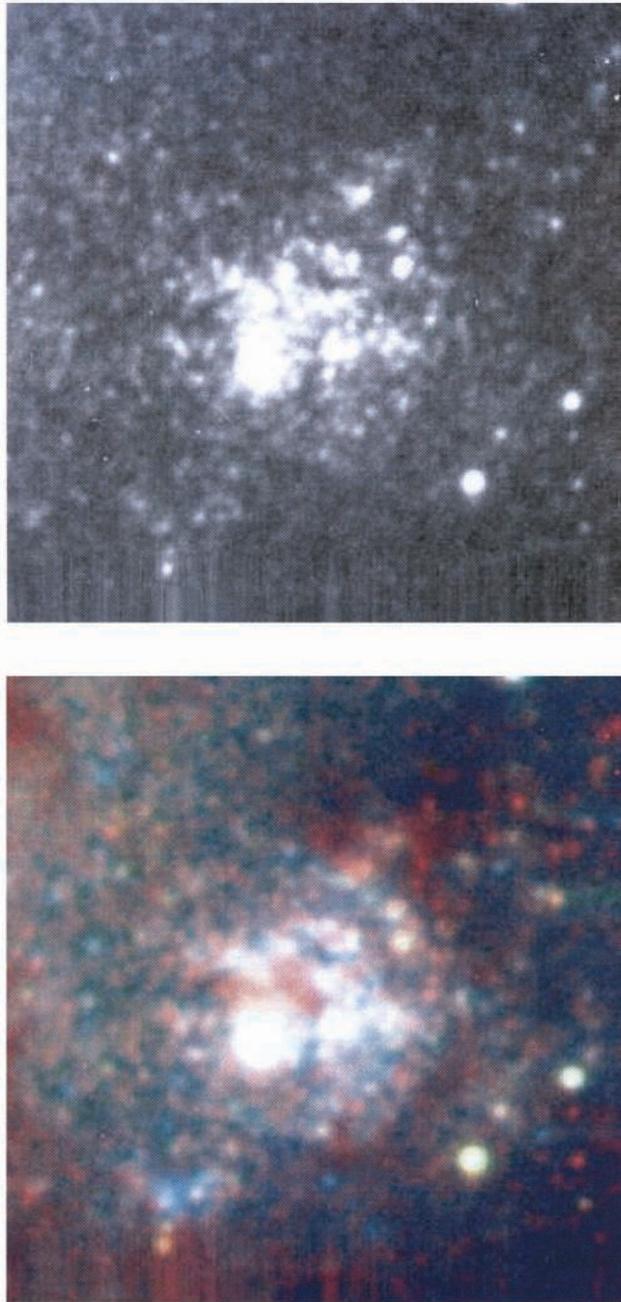


FIGURE 1 The HLR object: (a) image obtained in the K band with the Keck telescope; (b) overlay of K-band and BVI images obtained with NOT. Both images were obtained by S. Larsen.

globular cluster after a few gigayears. The current parameters of this cluster are quite similar to those of stellar superclusters, which are found to be numerous in interacting and star-burst galaxies. The whole complex hosts at least 18 bright clusters.

The star formation there was most active 30–5 Myears ago (Larsen *et al.*, 2002). Long-slit spectroscopy of the complex was obtained with the 6-m telescope and Keck-I telescopes in 2000

(Efremov *et al.*, 2002). Three cross-sections of the complex were obtained with the BTA and a shorter cross-section with Keck-I. The curves of the radial velocities demonstrated many disturbances, including a dip which might be the sign of a rapidly expanding semishell with nothing in its centre. The radial velocity of the supercluster and the bulk of the complex's H II gas is  $150 \text{ km s}^{-1}$ , about  $20 \text{ km s}^{-1}$  higher than the local velocity of the galaxy's rotation, based on H II data outside the complex. Some features of the radial velocity curves across the complex might be suspected as demonstrating a gradient compatible with a slow rotation of the complex. The presence of gas vortices inside the complex is also not excluded (Efremov, 2002a).

One more strange property of the complex is its sharp western edge (in visible light) which forms a regular arc with an opening angle (at the centre of the complex) of about  $130^\circ$ . Along this edge a wide arc of a high extinction was found. The K-band image obtained with the Keck telescope (obtained by S. Larsen (Fig. 1) demonstrated the absence of the sharp western rim at that wavelength and found that there is a large colour excess of the clusters located west of the complex, thus confirming that its appearance in visible light is due to an arc-shaped dust cloud along the western edge of the complex. The absence of H I or CO features connected with the complex is also unusual. There is no H I hole or superbubble around the complex, in spite of the fact that the supercluster inside it is the most suitable with respect to its age and luminosity to form such a supershell. Numerous H I voids are known in NGC 6946; yet the complex is outside all of these, although it is near the southern tip of the largest elliptical hole (Efremov, 2002a). Also, there are no CO features at the complex location (Walsh *et al.*, 2002).

## 2 THE HYPOTHESES ON THE COMPLEX ORIGIN

Two suggestions about the origin of the object have been discussed recently. One is the natural suggestion that the object in question is simply a peculiar stellar complex inside the galaxy. The position of the complex at the tip of a short piece of a spiral arm (or a spur) is favourable to the formation of the large regions of star formation. Provided that this is the case, the dust arc on the west of the complex must be due to the pressure from the supercluster (Elmegreen *et al.*, 2000). Complexes with a high star formation rate (superassociations), although not having peculiarities similar to those observed in the NGC 6946 complex, are known indeed at the tip of spiral arms in a few other galaxies. However, it is unclear why such complexes are generally very rare, and why in the NGC 6946 complex the pressure from the supercluster was so anisotropic. It is strange that the dust arc there was formed on only one side, and it is especially peculiar that it is opposite to the direction of the centre of the galaxy. The feature considered as the spur might be, in fact, the eastern continuation of the complex itself, which then may be considered as quite isolated and somewhat comet shaped.

Another hypothesis is that the complex might be the result of the oblique infall of high velocity clouds (HVC), from east to west, to the gas disc of NGC 6946. The star formation in the complex and the regular gas-dust arc along its western edge then might be the result of the cloud impact (Efremov *et al.*, 2002). The regular magnetic field known to exist in NGC 6946 might then prevent the formation of a supershell after such an impact, according to the theory given by Santillan *et al.* (1999). The high pressure arising as a result of the collision of the shock waves after impact is favourable to the formation of the massive bound cluster, according the general theory (see for example Elmegreen and Efremov (1997)). A similar explanation was suggested by Comeron (2000) to explain the isolated stellar complex in NGC 5236 (see also Efremov (2001)).

However, there are strong objections to this scenario. The radial velocities of the complex and supercluster are only 20–30 km s<sup>-1</sup> larger than the local velocity of the NGC 6946 rotation from H II data (Efremov *et al.*, 2002). If this difference is the immediate relic of the impact, it implies plausibly quite a small inclination of the impacting cloud trajectory with respect to the NGC 6946 plane. The western dust arc is then also a relic of the impact, indicating that the movement of the cloud was from east to west. Considering the location of the complex in the western outskirts of the galaxy, it is strange that the cloud has not impacted closer to its centre. This could suggest that the velocity of the impacted HVC was very high.

### 3 THE HODGE–LARSEN–RICHTLER OBJECT AS A FOREGROUND COMPACT STAR-FORMING GALAXY

There is also a third possibility. The HLR object might be, in fact, a blue dwarf compact galaxy (BCDG) that moves west through the gas halo of NGC 6946 or, more plausibly, through the intergalactic medium (IGM) of the NGC 6946 group. The sharp semiregular western rim of the object images is then the result of a bow shock that forms the dust-gas partial sphere at the object's leading surface. The object might be a member of the group of seven dwarf irregular galaxies which was discovered recently by Karachentsev *et al.* (2000). Moreover, according to their results, the three dwarf galaxies closest to NGC 6946 in the sky, have velocities (126, 127 and 132 km s<sup>-1</sup>) rather similar to the velocity of the object in question (150 km s<sup>-1</sup>). However, this velocity is also close to the H II gas velocity around the object; so the radial velocity data alone cannot either prove or disprove the hypothesis that the complex is a BCDG. (The velocity of the dynamical centre of NGC 6946 is 47 km s<sup>-1</sup>). Anyway it is worth noting that all these three galaxies are star-forming dwarf irregulars, rather similar in size to the HLR object (and some of them in appearance as well (Karachentsev *et al.*, 2000)).

Also, superstar clusters are common in the BCDGs and some of these galaxies have a cometary shape, connected plausibly with the fast movement through the IGM. In the M81 group, two small galaxies are known to be shaped by the ram pressure of the IGM. It is evident in the appearance of the outer isodensities of H I in the galaxy Ho II (Bureau and Carignan, 2002) and probably in the stellar edge of the galaxy DDO 165 (Efremov, 2001, 2002b). In the same group there is the BCDG UGC 4483, which has the cometary shape. Its young massive cluster is in its head (Izotov and Thuan, 2002). The striking similarity of the Hodge object to the famous post-starburst BCDG NGC 1705 should be noted; this is evident in Figure 2, the linear sizes of both objects being about the same. Both images in Figure 2 were obtained with the HST, although that of NGC 1705 does not include the H $\alpha$  band (see Larsen *et al.* (2002) and the HST Heritage).

Another recent finding is the superstar cluster with an age of 3–4 Myears and a mass of 10<sup>5</sup> solar masses in the centre of the isolated BCDG POX 186 (Corbin and Vacca, 2002). It is the only bright cluster in this galaxy, which also has a comet-like appearance. Its diameter is only 300 pc, half the size of the HLR object and the stellar mass is about the same, 10<sup>7</sup> solar masses.

The hypothesis that the HLR object is a foreground dwarf galaxy in the post-starburst state is a quite natural explanation of why almost no features in the NGC 6946 interstellar medium (ISM) are seen in its position. BCDGs with a low gas mass are often observed and this could be explained by the ejection of the ISM by stellar winds during the burst of star formation. In particular, inside the low-mass galaxy hosting the massive starburst (see Fig. 3 of the paper by Silich and Tenorio-Tagle (2001)), tidal stripping is a mechanism that can also be responsible for gas removal. The high-density environment defined by the NGC 6946 group is also favourable for this. The normal O-to-H abundance ratio (Efremov *et al.*, 2002) might



FIGURE 2 (a) The HLR object image obtained with the HST (Larsen *et al.*, (2002). (b) The NGC 1705 blue compact galaxy, hosting the superstar cluster (the HST Heritage image).

be considered an objection against the dwarf galaxy hypothesis, because most dwarf galaxies are known to have low abundance ratio. However, chemical abundances in dwarf galaxies of a tidal origin vary within a wide range, including solar values, as is the case in some dwarfs in the Virgo cluster (Vilchez and Iglesias-Paramo, 2003). The dwarfs nearest to NGC 6946 might be of the same origin. Also, the normal metallicity might be connected with the supply

of metals to the ISM as a result of superbubble evolution; the hot gas from the latter may enrich the ISM with metals (Kunth *et al.*, 2002). Finally, gas in the direction of the HLR object observed as having the normal O-to-H ratio might belong to NGC 6946 background, the velocity difference being very small, as discussed above. This may be the most probable explanation.

It is possible to suspect the signature of rotation in the H II velocity profiles of the HLR object in Figure 6 of the paper by Efremov *et al.* (2002). Considering that the right (eastern) part of the H II radial velocity curve for a position angle of  $83^\circ$  (and partly for the position angle of  $29^\circ$ ) is disturbed by the expanding semishell, that the centre of the complex is not at the point  $X = 0$  and that its size is smaller than the length of the slit, the gradient of  $V_R$  is certainly seen in the left-hand parts of the curves. This gradient is compatible with the solid-body rotation of the complex, the velocity (orthogonal to the sky plane) being  $30\text{--}40\text{ km s}^{-1}$  at its outskirts and the position angle of the kinematic major axis being about  $70^\circ$ . Note once more the giant cluster (which is at  $X = 0$ ) is shifted to the southeast of the centre of the complex. The rotation velocity seems to have the normal value for the inner parts of the blue compact galaxies. Anyway, non-rotating BCDGs are also known (such as VII Zw 403 (Silich *et al.*, 2002)).

A complete velocity field and high-resolution H I and CO maps are necessary to establish the nature of this curious object. However, the fact that it belongs to the BCDGs class now seems to be the most reasonable explanation of the object's appearance and content. Although the gas left after the last starburst may have disappeared via winds and/or by tidal stripping, the presence of an older (gigayears) underlying galaxy is now considered a common feature in BCDGs. Deep broad-band visible–near-infrared images could be used to detect the underlying host galaxy which should have resisted the tidal stripping.

#### 4 CONCLUDING REMARKS

Apart from the peculiarities described above, the object hosts some others. The presumed dust-gas western arc is on the side of the lower density of molecular hydrogen (see Figs. 2 and 9 in the paper by Walsh *et al.*, (2002)); so it hardly might be formed under superstar cluster pressure. There is also the arc of younger blue stars which is approximately concentric to the western arc-like rim of the complex and is on the same side of the complex. This arc is centred; however, this is not at the superstar cluster but at the centre of the large clump of older stars, which is close to the centre of the western rim's curvature (Larsen *et al.*, 2002). The superstar cluster itself is at the eastern edge of this clump, its age being somewhat intermediate. Between the superstar cluster and the western rim there are two small dark comet-shaped clouds, their common apex being near the centre of the complex. The clouds are rather similar to the cone dark cloud in the peculiar complex known in NGC 2207, whose apex is a bright star cluster, the latter being a strong radiocontinuum source. The law of light extinction was found to be peculiar inside this dark cone (Elmegreen *et al.*, 2001), and this might be the case also for the comet-shaped clouds in the HLR object.

A high content of dark cold matter is known in the dwarf compact galaxies and there are also ideas that part of it might exist in some condensed state. If the HLR object is indeed one of the BCDGs of the NGC 6946 group, the issue of the occurrence of a superstar cluster in it is simply a part of the general problem of why the BCDGs so often host superclusters, even when the galaxy in question is well isolated, such as POX 186. The high content of the cold dark matter in BCDGs might be connected in some way with the high occurrence of superstar clusters there. The origin of the latter is connected to the issue of the origin of the classic old globular clusters, which are at least as old as their host galaxies. The issue has therefore deep cosmological implications.

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We are grateful to Bruce Elmegreen and Simon Pustyl'nik for useful criticism of the idea of the foreground object. Yu.E. appreciates the support from the Russian Foundation for Basic Researches (project 03-02-16288) and the Scientific School Program (project SSP 389.2003.2). This paper has widely used the Astrophysics Data System.

### Note added in the proof

Recent observations of the velocity field of emission lines in complex with 6-m and 4-m telescopes (with the authors participation) proved the existence of the deep  $V_R$  dip 7'' eastward of the supercluster. According to the private communication by R. Boomsma, at this position is also the small H I hole and the break in the H I velocity curve, accompanied by the HVCs. The probability that this hole is near the complex only by chance is low, and the HVC impact might be indeed involved in the complex and supercluster formation. However, any scenario of the origin of the complex meets objections. Considerations on the possible rotation of the complex (in the end of Section 3) seem now to be doubtful.

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