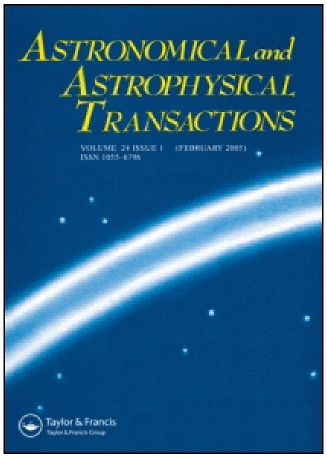

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

ON THE ORIGIN OF CIRCULAR AND HEXAGONAL FORMATIONS IN GALAXIES

Yu. N. Efremov [a]
[a] Sternberg Astronomical Institute, Moscow University, Moscow 119899, Russia.

Online Publication Date: 01 June 2003
To cite this Article: Efremov, Yu. N. (2003) 'ON THE ORIGIN OF CIRCULAR AND HEXAGONAL FORMATIONS IN GALAXIES', Astronomical & Astrophysical Transactions, 22:3, 245 - 262
To link to this article: DOI: 10.1080/1055679031000080339
URL: http://dx.doi.org/10.1080/1055679031000080339

Astronomical and Astrophysical Transactions,
Vol. 22, No. 3, June 2003, pp. 245–262

ON THE ORIGIN OF CIRCULAR AND HEXAGONAL FORMATIONS IN GALAXIES

YU. N. EFREMOV

Sternberg Astronomical Institute, Moscow University, Moscow 119899, Russia

(Received 24 June 2002)

Round and arc-shaped formations are known in some galaxies, the Bubble complex (the Hodge object) in NGC 6946 being the most remarkable. The rim of the complex has the form of a regular arc in which part of a hexagonal structure is embedded. A similar morphology is recognized in the NGC 7421 galaxy in the part of its rim which is leading in the galaxy motion through the intergalactic gas, as suggested by the bow-shock appearance of the H I halo of the galaxy. A hexagonal shape is also found in the NGC 4676A galaxy. The H II radial velocities across the Bubble complex are compatible with its retrograde rotation and drift, which are characteristic of solitary vortices known in nonlinear hydrodynamics. The drift motion may explain the location of the Bubble complex at the tip of the largest elliptical H I hole in NGC 6946. The hexagonal vortices in the atmospheres of Jupiter and Saturn are within the gas streams, which seems to be suggestive as well. It is conjectured that the hexagonal rims of stellar systems might be relicts of flat segments of the shock wave produced by the ram pressure. The giant stellar arcs in NGC 300 and M33 are associated with the high-energy X-ray sources P42 and X-4 respectively and these might be the relics of hypernovae.

Keywords: Galaxies; Individual (NGC 6946, M83. NGC 4449, NGC 7421, NGC 4676 and LMC); Stellar complexes; Large-scale star formation; Spiral arms; Vortices; Ram pressure and Hypernovae

1 INTRODUCTION

Most stellar systems are concentrated towards the centre of mass and have a more or less roundish overall shape, without sharp rims (except for the shell galaxies and some other products of galaxy interactions). This is natural, as their shape is mostly determined by the interplay of gravitation and rotation (internal motions). However, there are stellar complexes with sharp and very regular arc-shaped rims, which might have a peculiar origin (Efremov 2001a; 2002). Some galaxies are known also to have sharp circular rims or a polygonal shape. Here we give examples of such geometrically regular systems and discuss hypotheses on their origin.

2 THE PECULIAR STELLAR COMPLEX IN NGC 6946

The Bubble complex (the Hodge object) in NGC 6946 was discovered by Hodge (1967) and independently by Larsen and Richtler (1999). Its origin is a subject of discussion. The complex

E-mail: efremov@lnfm1.sai.msu.ru

ISSN 1055-6796 print; ISSN 1476-3540 online
DOI: 10.1080/1055679031000080339

is really unusual (Fig. 1), especially because its western rim is sharp and has the shape of the regular arc with radius 300 pc. The oldest stars are 30 Myears old and the rate of star formation there is one to two orders of magnitude higher than in the local complex (Gould Belt). Another peculiarity of the complex is the very massive young cluster near (but not at) the centre, quite similar to there known in the interacting galaxies (Larsen *et al.*, 2001; 2002).

The complex rim is sharp and circular only on the west side; this was the motivation for suggesting that the complex arises because of the impact of a cloud moving along the oblique trajectory from east to west (Efremov, 2002). The highest light absorption is also observed along this rim (Larsen *et al.*, 2002). Other suggested scenarios were the extreme case of the normal star formation (Elmegreen *et al.*, 2000a,b) and the triggering by a super-supernova (Hodge, 1967).

The kinematics of H II gas inside and near the complex were studied with a long slit at the 6 m telescope (Efremov *et al.*, 2002). The radial velocity curves along all three slit positions

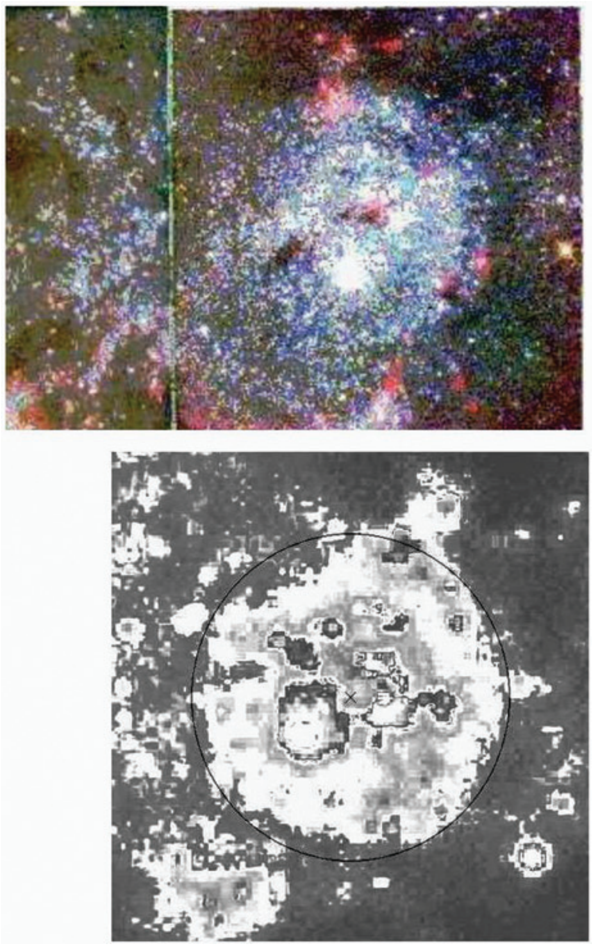

FIGURE 1 The images of the Hodge object in NGC 6946. At the top is the segment of the Hubble Space Telescope (HST) WF camera image. Note the symmetric arcs of clusters 'behind' (on the left) the complex (are the stellar relicts of the von Karman vortex street?). At the bottom is the edited NOT image, with the encompassing circle added. Note the slightly different orientation. North is up in the NOT image.

demonstrate many perturbations, some of which may be interpreted as the expanding shells or semishells. The most evident feature was considered to be a semishell with a velocity of expansion of about 120 km s^{-1} and size of about 300 pc; its center is 7$''$ east of the massive cluster. Apart from these disturbances, there is a wide positive bump encompassing all the complex, with an average velocity about 20 km s^{-1} higher than that of the surrounding field. It is worth noting that this velocity is quite close to the velocity of the young massive cluster, which was determined independently at the 10 m and 6 m telescopes and is 150 km s^{-1} (Larsen *et al.*, 2001; Efremov *et al.*, 2002).

We conjectured that the peculiarities of the velocity curves which are seen in Figures 4 and 5 and especially Figure 6 in the paper by Efremov *et al.* (2002) may be explained by the suggestion that the gas motions in the complex are mostly connected with vortices, whereas the positive bump might reflect the bulk drift motion of the complex in the plane of the galaxy. The velocity curve for PA -37° and the western (undisturbed) parts of the curves for PA 83° and PA 29° demonstrate the linear gradients which are different for different position angles in a way compatible with the solid-body rotation in the plane of NGC 6946, in the direction opposite to the rotation of the galaxy.

Retrograde rotation and drift are expected for the Rossby soliton in the galaxy disc (Korchagin and Petiashvili, 1985; Korchagin and Ryabtsev, 1991). Assuming the positive bump of H II velocity has the same value as the main cluster velocity and that both deviate from the rotation of the galaxy, prograde drift of the complex seems to be a possible interpretation. As the amplitude of the wide bump is about 20 km s^{-1} in radial velocity and the inclination of the galaxy plane to the sky is 32°, this translates to a velocity in the plane of the galaxy of about 40 km s^{-1}.

It is possible that the drift of the complex in relation to the stuff of the galaxy disc may explain the strange absence of the H I hole around it. Moreover, overlay of the Kamphuis (1993) map of the H I hole in NGC 6946 and the galaxy image from the Digital Sky Survey (DSS) (Fig. 2) demonstrates the position of the complex at the southern tip of the supergiant elliptical (6.5 × 2.9 kpc) H I hole (hole 13, surely) outside the latter. The geometry of the situation, the direction and the velocity of the suggested complex drift imply that 30 Myears ago (the age of the first burst of star formation in the complex) the complex was located well inside hole 13. One may suggest that formation of hole 13 and the complex were triggered by the same HVC impact. This hole is associated with the high-velocity gas region 12 (Kamphuis, 1993, Table 2) which has an energy of 8×10^{53} erg and a mass of $3.1 \times 10^{7} M_{\odot}$, whereas the missing mass in hole 13 is $22.3 \times 10^{7} M_{\odot}$ (Kamphuis, 1993, Table 1). The oval shape of hole 13 may reflect the path of the Bubble complex through the gaseous disc and the present-day location of the complex near the hole tip (yet outside it) may indicate its recent arrival at this point and the time needed to form the expanding H I hole around it.

Our hypothesis implies that under some conditions a cloud impact may trigger the gaseous vortices in the disc of the galaxy. There is no large-scale perturbation of the NGC 6946 galaxy rotation curve needed in the theory to trigger the solitary vortex (Rossby soliton). We suggest a special origin of the vortex, not connected with the bulk dynamics of the galaxy. The loop of the velocity field seen in the region of the Hodge object (Bonnarel *et al.*, 1988) may be result of the initial local perturbation. The vortices indeed formed in the tail of the impacting cloud in the Santillan *et al.* (1999) models of the HVC impact on the magnetized galactic gas disc. Can such gas motions then trigger star formation? At any rate, the star formation might be confined within the long-standing gas vortex.

The radial velocity curve for PA 83° (Efremov *et al.*, 2002; Figs. 4 and 6) contains the deep dip which was explained in that paper as an expanding semishell. The wide positive bump is centred on a massive cluster; yet the dip is in the centre of the additional narrower positive

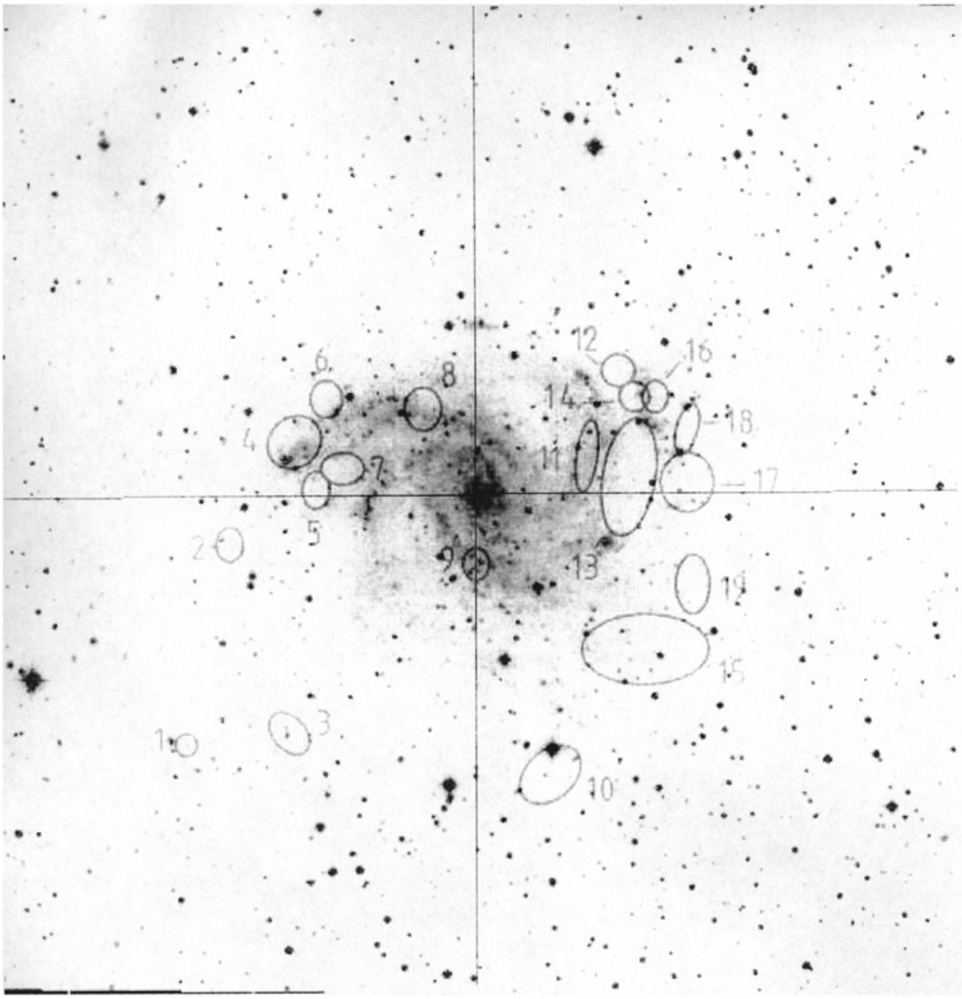

FIGURE 2 The map of H I holes in NGC 6946 (Kamphuis, 1993) overlayed by the galaxy image map from US Naval Observatory Image and Catalogue Archive Service. The Bubble complex is near hole 13, looking quite similar to the bright foreground star. North is up.

bump to the east of the complex centre. This configuration must be explained. It may be suggested that here we have not a semishell expanding towards us but two adjacent vortices with very fast and opposite rotation, the situation expected in cosmic hydrodynamics and known as the von Karman vortice street (Chernin, 1996).

The expanding semishell might be connected with the position of the pressure source outside the plane of symmetry of the galactic plane (which is compatible with the hypernova hypothesis for the origin of the semishell (Efremov *et al.*, 2002)). However, the plot of V_r for such a structure should be a sinusoid, whereas we see two straight lines. especially for the eastern side of the V_r dip. These two lines suggest the existence of two vortices, rotating in opposite directions. They might be parts of the 'von Karman vortice street' in the tail of the impacting cloud, such as those seen in the model suggested by Santillan *et al.* (1999). Such vortices are not the full rings and, apart from this, the rotation in the galactic plane easily explains why no line splitting is seen over the dip.

3 RAM PRESSURE AND STAR FORMATION

The best way to understanding a peculiar property is to find other examples of systems that share the property. So we have been looking for circular rims everywhere. Indeed, a arc 130° long of the western rim of the Bubble complex has analogies in the Quadrant and Sextant arcs in the LMC, and also in rims of a few galaxies.

Galaxies with circular rims are indeed known. One example is DDO 165 in the M81 group, the southern rim of which is sharp and arc shaped (Efremov, 2001a). In the same M81 group, the Ho II galaxy has the outer H I isolines of the characteristic comet-like shape (Bureau and Carignan, 2002), and the southeastern part of the H I halo of this galaxy is bordered by the perfect arc of a circle. These workers suggested the action of the ram pressure as the reason for this shape. Even earlier the same suggestion was proposed by Ryder *et al.* (1997) to explain the similar shape of the H I halo of the NGC 7421 galaxy and it is surely true for the NGC 2276 galaxy as well (Fig. 3).

The side of the stellar disc of NGC 7421 turned towards the direction of the movement is evidently enhanced and sharp bordered. This is even more evidence for NGC 2276, where the H II isolines (Gruendl *et al.*, 1993) and even the stellar discs are shaped in accordance

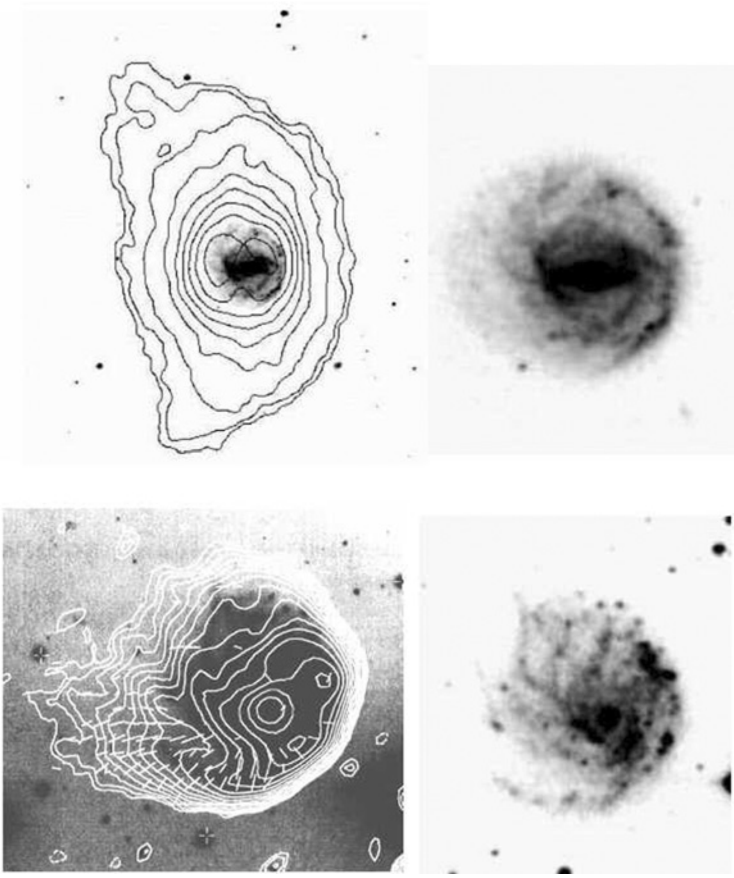

FIGURE 3 The ram-pressure-shaped NGC 7421 (top) and NGC 2276 (bottom) galaxies. On the left are the H I (NGC 7421) and 1.79 GHz (NGC 2276) isolines; on the right are the DSS images. North is up. See the text.

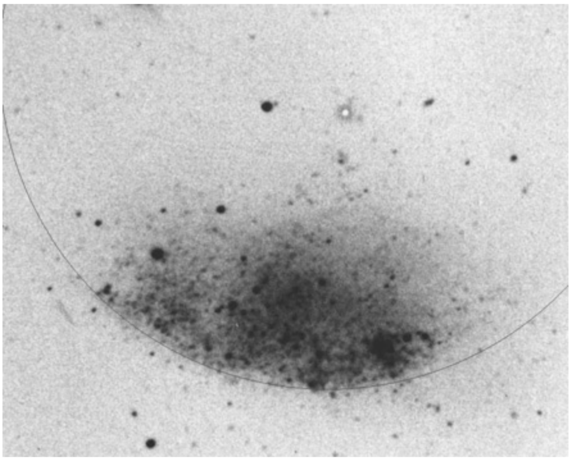

FIGURE 4 The DDO 165 galaxy images from the plate of the 6 m telescope. (Courtesy of I. Karachentsev.)

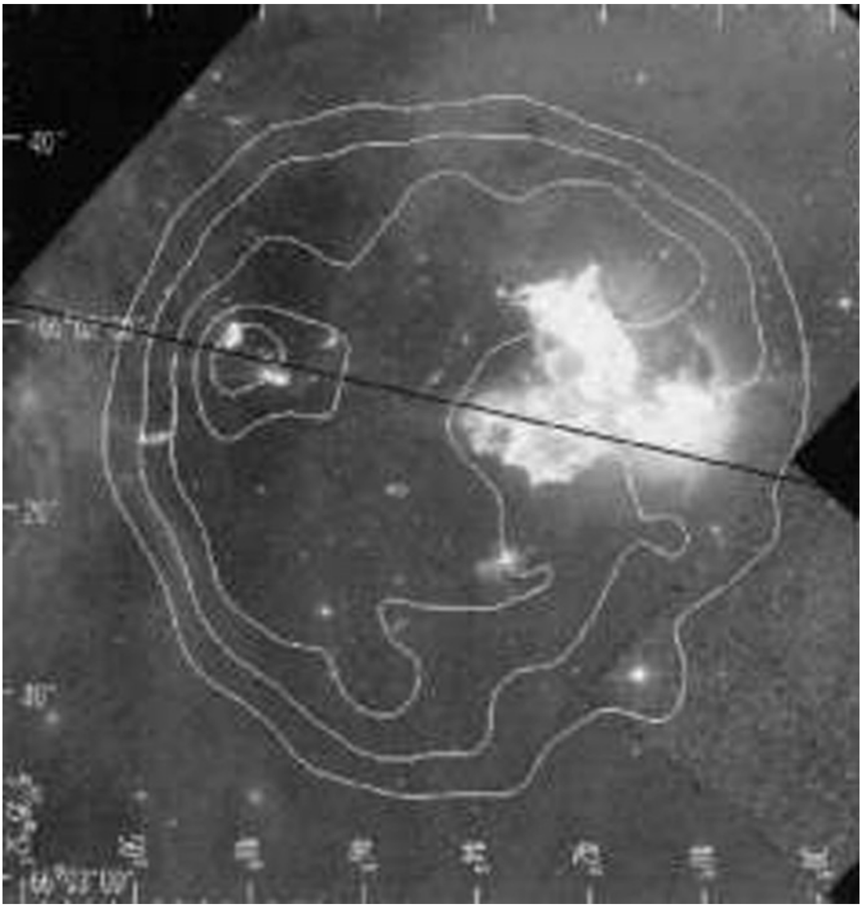

FIGURE 5 The SNR N63 in the LMC (Chu, 1999). The isolines of X-ray emission are shown with the direction of the LMC proper motion added. North is up.

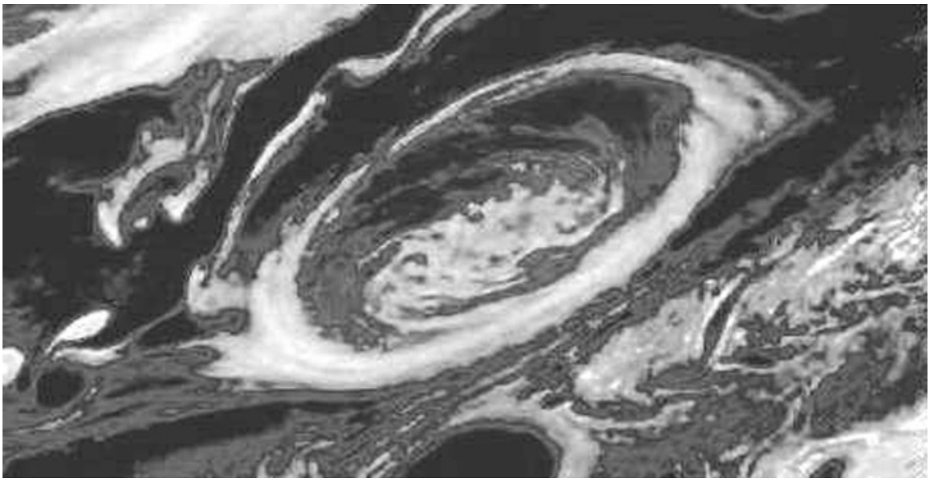

FIGURE 6 The Jovian Red Spot in 1979. See the text.

with the Mach-cone-like appearance (Fig. 3) of the galaxy at 1.49 GHz (Hummel and Beck, 1995).

These are clear places of evidence for star formation triggered by the ram pressure but still perserving the characteristic bow-shock shape. We may therefore suggest that the southern rim of DDO 165 (Fig. 4) is also a relict of the star formation triggered by the ram pressure in the bow-shock-shaped edge of the galaxy gas (Efremov, 2002).

The conclusion follows that the western arc 130° long of the Bubble complex rim in NGC 6946 may also be a relict of the star formation in the bow shock at the interface of the impacting cloud and NGC 6946 gas disc. The same explanation may be true also for the LMC arcs in the LMC 4 region, their occurrence in the same (northeastern) region of the galaxy being explained by the observation that the NEE edge of the LMC is leading in the LMC motion and is the first to meet the clouds of the galactic halo (Efremov, 2002).

We noted that this may be confirmed by the bow-shock appearance and orientation of the X-ray emission around SNR N63 (Chu, 1999) localized in the northeast of the LMC4 supershell, near the northeastern edge of the LMC gaseous disc (Fig. 5, see also Fig. 11 later); it may be shaped by the ram pressure owing to the LMC motion through the halo of the Galaxy. The line drawn through the X-ray maximum under the position angle of the LMC proper motion 79° (van den Marel *et al.*, 2002) is close to the axis of the symmetry of X-ray nebula (Fig. 5). The sharp northeastern edge of the distribution of H I in the LMC is in accordance with this.

4 HEXAGONAL RIMS CONNECTED WITH RAM PRESSURE?

The close examination of the Bubble complex rim under different image contrasts reveals that at least half of its rim is confined by segments of hexagon inscribable into a circle. This is seen for the ‘leading’ (western) part of the complex in the HST images, whereas in NOT images all the complex, after application of the non-monotonic characteristic curve, display the pentagon shape (Fig. 1).

There are also the examples of galaxies with hexagonal or pentagonal rims. It should be noted that the leading rim of NGC 7421 is also outlined by the segments of hexagon inscribable into the arc of the circle. Something like this is also seen in the NGC 2276 image that not so definitely (Fig. 3). The similarity of the leading-edge rims of these two galaxies and the western rim of the Bubble complex is evident. These galactic rims are certainly shaped (in the end) by the ram pressure and it is also plausible that the galactic rim of the Bubble complex is also shaped by the ram pressure. Anyway, a number of other galaxies (especially in the Virgo cluster) are known to have signatures of the ram pressure action and yet have no the hexagonal rims. This may be explained by the observation that the galaxy must be seen pole on, in order that the polygonal shape of its disc can be noted, as is the case for NGC 7421 and NGC 2276. Otherwise, the hexagonal shape may be a transient property of the ram-pressure-shaped gaseous cloud, which may not necessarily be preserved in the stellar distributions.

Other astronomical observations may be the clue to this issue. At the north pole of Saturn a hexagonal cloud feature was discovered in *Voyager* close-encounter images (Allison *et al.*, 1990). These workers interpreted the hexagonal cloud as a stationary Rossby wave. They also note that the wave is embedded within a sharply peaked eastward jet (of $100\,\mathrm{m\,s^{-1}}$) and appears to be perturbed by at least one anticyclonic oval vortex immediately to the south.

As a result of browsing through available images of the Jupiter Red Spot we have noted that sometimes a vortex bordered by segments of hexagon is developing inside the Red Spot, while the leading rim of the Red Spot has acquired the shape of two straight lines, as seen in the image obtained by *Voyager* in 1979 (Fig. 6). The turbulent vortices behind the Red Spot are also easily visible (see http://antwrp.gsfc.nasa.gov/apod/ap020205.html).

As a hexagonal cloud on Saturn, the Red Spot is known to be located in a stream of fast-moving gas in the Jupiter atmosphere; yet it is a persistent vortex that does not share the movement of the encompassing gas. The analogy with the ram pressure action to the galaxy moving through an intergalactic gas is evident.

Experiments with rotating shallow water demonstrated how the structure interpreted as the Rossby solitary vortex, which emerges because of the self-organization of dissipation system far from the equilibrium state, arose (Wang *et al.*, 2001). These workers concluded that the experiment is a model of the Jupiter Red Spot. In fact, similar experiments have been carried out by many researchers (see the references in the paper by Korchagin and Ryabtsev, 1991), and the suggestion that the Jovian Red Spot is a stationary nonlinear soliton-like vortex was advanced long ago by Maxworthy and Redekopp (1976). It is worth noting that, as was demonstrated by Korchagin and Ryabtsev (1991), the hydrodynamic theory of solitary vortices is applicable to a stellar galactic disc as well.

Hexagonal and asymmetrical galaxies are also seen in the Hubble Deep Fields. Some samples extracted from the ingenious site of S. Gwyn (http://astrowww.phys.uvic.ca/grads/gwyn/pz/hdfs/spindex.html) are given in Figure 7. These galaxies are mostly in small groups and the ram pressure origin of the hexagonal shape is plausible. It is worth noting that in some galaxies (293N and 222S) there are twin blue spots at the presumably rear (in motion) edge. These spots might be the result of the star formation in the vortex couple known to be located behind the fast-moving body (see also Fig. 1).

It is possible that the hexagonal shape might be the transient property of the persistent vortices, which are objects of the ram pressure. It is a result of self-organization, reminiscent in the resulting shape (but not in the physics of origin) of the cells of Benard. If star formation occurred in the shock wave while its front was flat, the part of the stellar system rim facing the stream would preserve the hexagonal shape.

Anyway, the Benard-cell-like appearance of the unique Honeycomb feature in the LMC, located 100 light years from the SN 1987A, should be noted. The structure consists of two dozen adjacent gaseous cells, most of similar size 3 pc (Noever, 1994; Meaburn *et al.*, 1995) and the high-velocity gas motions observed along the cell walls (in the direction perpendicular

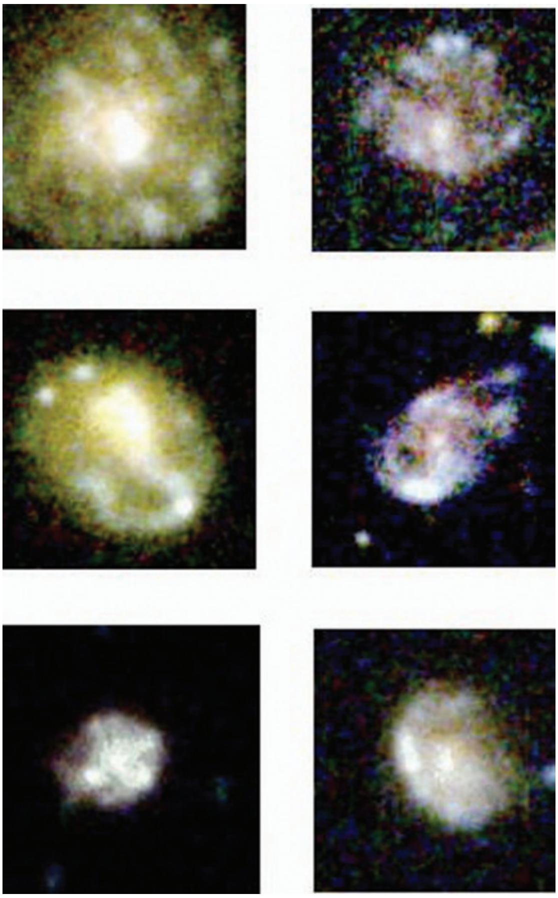

FIGURE 7 The samples of galaxies from the Hubble Deep Fields, probably shaped by the ram pressure: top row, 120S and 293N; middle row, 222S and 41N; bottom row, 255N and 96N. See the text.

to the cell planes) are reminiscent of the convective motions along the walls of the Benard cells. Redman *et al.* (1999) suggested that the cells were formed owing to the Rayleigh–Taylor instability in the shell of the old SNR, whereas Noever (1994) noted that regularities of the polygons of the honeycomb follow some laws of statistical crystallography.

Chernin (1996) noted an explanation of why the largest known eddies in the Universe are galaxies was necessary; one may wonder whether the whole galaxy might be considered as the Rossby soliton. A far reaching idea of this type was published by Dubrovsky (2000). In accordance with this suggestion, the rotational velocity of a galaxy is determined by the vortex instability rate and not by the central mass; so the hidden mass may not be necessary.

5 WHAT ARE THE DARK RINGS?

Dark rings surrounded by arcs of clusters are known in M83 (Efremov, 2001a) and NGC 4449 (Bothun, 1986), of about 500 pc diameters, like the Hodge complex (Fig. 8). They are seen in some other galaxies too (NGC 6946 and NGC 2207). At first glance, these rings might be considered to be examples of star formation triggered by the gravitational

FIGURE 8 The left-hand column shows the western (top) and southern (middle) (Efremov, 2001a) dark rings in M83 (the VLT ESO images) and the NGC 4449 ring (bottom). The right-hand column shows the dark rings in NGC 6946 (NOT image) (top), the dark ring in NGC 2207 (middle) and the peculiar complex, which includes the elliptical dark ring, in NGC 2207 (bottom). The last two HST images are from Elmegreen *et al.* (2000a).

instability in the swept-up gas shell, especially since the distances between clusters in the M83 western ring are extremely similar. However, a swept up expanding shell should leave the inner space of the ring empty from gas and dust, whereas there is dust; central clusters are not seen in the M83 rings (the bright object inside the southern ring should be the foreground star) but are present in NGC 2207 and NGC 6946 (Fig. 8). The visible darkness of the NGC 4449 complex inside the ring is confirmed by photometric data (Hitchock and Hodge, 1968). If this is so, the gas density inside such rings is higher than in the surroundings and the circular shape may suggest that these rings are gaseous (inward spiralling) vortices with an enhanced column gas density at least along their rims, where star formation was effective.

Multicolour observations could be used to determine the parameters of light absorption inside these rings. It would not be surprising to find that these are unusual, as is the case for the dark cone centred on the star cluster in the highly peculiar stellar complex in NGC 2207 (Elmegreen *et al.*, 2000a,b) (see Fig. 8). Very-high-resolution H I and CO observations could also solve the problem. To find the real absence of even old stars inside the dark rings would be a tremendous and yet surely improbable possibility. Features of this kind found in the cores of a few galaxies are much smaller (Lauer *et al.*, 2002).

Considering that inside the dark rings in NGC 6946 and NGC 2207 central objects (clusters?) are seen (and there is a suggestion of this in NGC 4449 (Fig. 8)), these rings may still be examples of swept-up shells, after some interactions of the shock waves. The smaller scallops on the inner side of both rings in M83 (the only images with good resolution) may also suggest this. Anyway the known tested examples of star formation in swept-up shells, such as in IC 2574, are quite different from these rings, as well as from other formations discussed here (Efremov, 2002).

6 OTHER HEXAGONAL GALAXIES

The hexagonal shape is well known for the rings surrounding some galaxies and also for bulges of some S0 galaxies. The list of such galaxies and discussion of their nature was recently given by Chernin *et al.* (2002). They noted that the galactic rings are intimately related to a spiral structure, as Buta and Combes (1996) demonstrated, and the origin of the hexagonal structure may be the same as that of the polygonal arms known in many grand design galaxies (Chernin, 1999; Chernin *et al.*, 2000).

As Chernin *et al.* (2002) noted, there is the major similarity between the hexagonal structures and the polygonal shape of the spiral arms; in both structures the angle between adjacent straight lines is about $2\pi/3$ and the lengths of the straight segments are equal to the radius of encompassing circle or to the local radius of curvature of the logarithmic spiral. Chernin (1999) suggested that the local flattening of the spiral front on the space scale of the local radius of curvature may be due to stability of a flat shock wave against any weak perturbations that disturb its front surfaces. On this basis, Chernin *et al.* (2002) concluded that the hexagons are also made of flat segments of shock fronts.

This suggestion may explain the hexagonally shaped rim of the Bubble complex and of galaxies which, like NGC 7421 and NGC 2476, are the objects of the ram pressure. The occurrence of the straight segments of rims of these galaxies on only the shocked side is especially indicative of this.

However, there are rare galaxies which are hardly objects of the ram pressure and yet whose discs have a hexagonal shape. The long-known example is NGC 6776 (Sansom *et al.*, 1988) which is considered to be an E galaxy but is certainly S0, being rotating. Another is NGC 1637, the three-armed well isolated spiral (Fig. 9). There are no other galaxies within 1° of it (Block *et al.*, 1999).

Another problem is the peanut shape of the bulges of some S0 galaxies, the best examples being NGC 7020 (Buta, 1990) and IC 4767 (Whitmore and Bell, 1988), These galaxies look like inclined hexagons. The proposed explanations were the interactions with other galaxies or the specific shapes of stellar orbits. The key issue here is the orientation; the visible prolate hexagons may be intrinsically prolate thick bulges seen edge on or they may be the hexagonal discs seen at an angle. The former possibility seems to be easier explanation of the orbit orientations for the NGC 7020 case (Buta, 1990). Also, Merrifield and Kuijen (1999) argued that the boxy and peanut-shaped bulges of some galaxies are galactic bars viewed from the side.

We found an example of the hexagon where the edge-on orientation is certain. It is the NGC 4676 (‘the Mice’) interacting galaxies case. The image obtained recently by the HST with the Advanced Survey Camera (ASC) (see http://oposite.stsci.edu/pubinfo/pr/

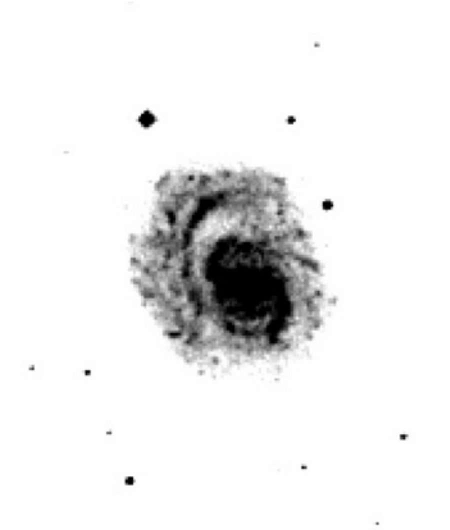

FIGURE 9 The hexagonal NGC 1637 galaxy (the edited DSS image).

2002/11/) after editing reveals the hexagonal shape of the northern (NGC 4676A) galaxy, whereas the existing kinematic data indicate that it is seen edge on (Yun and Hibbard, 2001). This inclination also follows from the thin and straight appearance of the long tail of NGC 4676A. The tidal tail should be intrinsically wide and planar; so, in the Mice system, it is seen edge on. The overlay of CO isolines from Yun and Hibbard (2001) and the HST ASC image (Fig. 10) demonstrates that not all dust clouds seen in NGC 4676A are connected with CO emission in the galaxy and vice versa. This might be partially explained by the localization of some dust clouds in front of the galaxy body.

These interacting galaxies are in the Coma cluster and may be objects of the ram pressure. We suggest that the curved cone-like plume in the north of NGC 4676B is just the manifestation of action of the ram pressure on to the leading edge of the galaxy. Overall structure of the system may display the orbital motion of the Mice. The blue colour of the turned cone tip of NGC 4676B is surely the result of star formation, triggered by the ram pressure. If so, one may still wonder whether the ram pressure participated in shaping the NGC 4676A galaxy as well.

7 STELLAR ARCS AND HYPERNOVAE

The best-known arc-shaped complexes are the LMC 4 group of arcs 200–300 pc in radii, noted first by Hodge (1967). The concentration of arcs near to each other (Fig. 11) was explained by their origin from objects ejected from the massive cluster NGC 1978 in the same area, which is 2 Gyears old. It was suggested that the progenitors of GRB–hypernovae are binaries of the compact objects formed owing to dynamic interaction of stars and/or their remnants within the dense cluster and then ejected from it. We argued that this is the main channel of formation of binaries with compact components (Efremov, 2001b).

The same idea is now accepted as explaining the concentration of X-ray binaries in the globular clusters (White *et al.*, 2002) According to Kundu (2002), 40% of the brightest

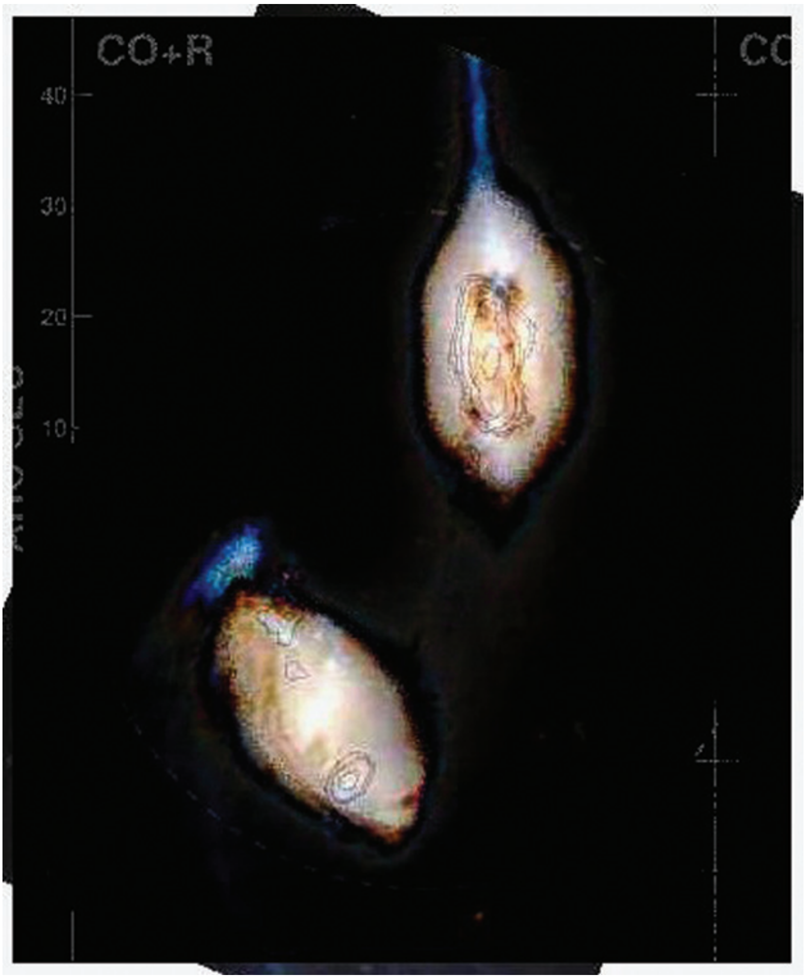

FIGURE 10 The Mice (NGC 4676AB) galaxies. This figure shows the overlay of the HST ASC image and CO isolines from Yun and Hibbard (2001). North is up.

LMXBs (which are suggested to be the black hole accretors) in the elliptical galaxy NGC 4472 are associated with globular clusters. We have noted the concentration of X-ray binaries in the region of the LMC 4 (see Efremov (2001b) and references therein) and may now conclude that the idea of the origin of progenitors of the LMC 4 arcs in the NGC 1978 cluster is still alive.

The origin of the LMC system of arcs due to the ram pressure on the surface of the impacting cloud was also considered (Efremov, 2002). The physically similar situation arises after interaction of a dense and sufficiently cold cloud with a blast wave from a powerful external explosion. The large increase in pressure leads to compression of the cloud, which is most rapid at the face, exposed to the blast wave, and the bow shock may appear along this side (McKee and Cowie, 1975). The observational data discussed above demonstrate that a triggered star formation may result, the bow shock appearance being preserved in the distribution of the young stars.

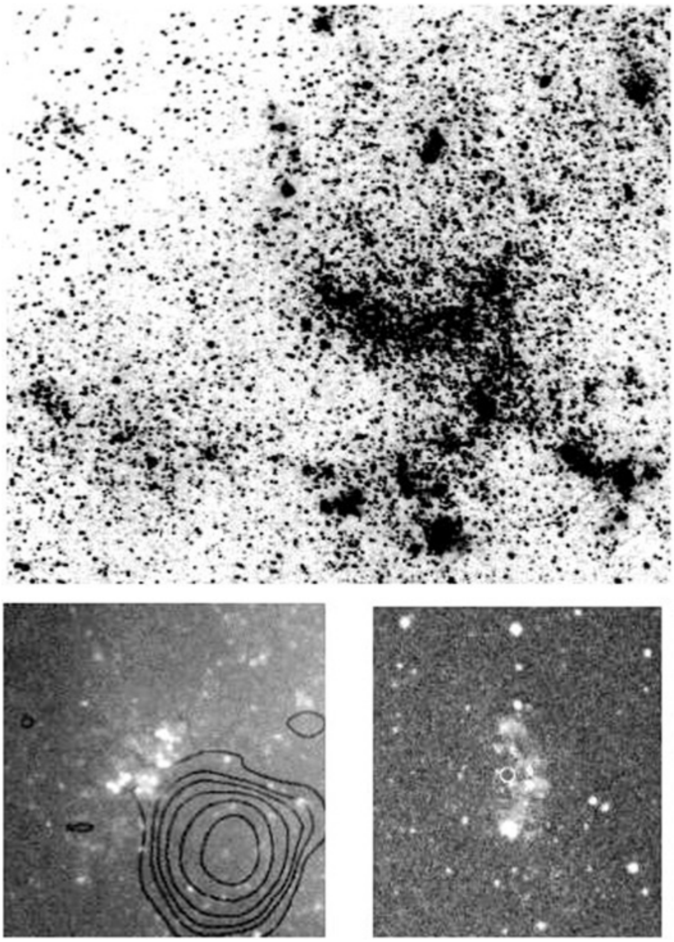

FIGURE 11 At the top there is the system of giant stellar arcs in the LMC 4 region (the edited image based on the Boyden Observatory photograph obtained by H. Shapley. (Courtesy of P. Hodge and K. Olsen.)) On the bottom left is the AS102 arc in NGC 300 with the position of the X-ray source P42 (X-ray isolines) overlayed (the NOT image was obtained by S. Larsen). On the bottom right is the IC133 complex in M33 (DSS), with the position of the M33 X-4 source shown as the yellow circle.

The arc of the bright stars 400 pc in size, noted by Efremov (2001a), and now known as the complex AS102, in the spiral arm of the NGC 300 galaxy may be result of such an event (Fig. 11). P42 = H13, which is the X-ray source that is brightest in the galaxy and which is classified as an X-ray accreting binary system including a black hole (Read and Pietsch, 2001), is near the complex on its convex side and exactly on the axis of symmetry of the stellar arc (Efremov, 2002). Considering the age of the complex (5 Myears (Kim *et al.*, 2002)) and its distance from P42, the energy needed to compress the paternal cloud to the AS102 stellar complex should be that of a hypernova.

The last example is the arc of the OB association HS137 in M33, noted by Efremov (2001a). It is also known as the H II region IC133 (Fig. 11). This arc encompasses the H I hole 31, the coordinates of which are the same as of these of the X-ray source M33 X-4 (Shulman and Bregman, 1995). This source was investigated recently by Okada *et al.* (2001) who found it to be a young SNR with energy considerably higher than those of

SNRs in the Milky Way. This X-ray source is the only source in M33 which is suggested to be physically associated with a H I hole (Shulman and Bregman, 1995).

The arc-like appearance of the AS 102 complex formed by the outer pressure to the paternal cloud is natural. However, for the IC133 complex we evidently deal with the classic model of the star formation in the swept-up shell, and the stellar arc was formed just on the side of the shell where the observed H I density is higher. It was just this assumption by Westerlund and Mathewson (1966) that was used to explain the 'arc of blue stars' in the LMC 4 region now known as the Quadrant arc. However, this suggestion cannot be used just to explain the LMC 4 arcs, for the new data demonstrated that the Quadrant is deep inside the LMC 4 H I hole. The rather similar complex in M83 was suggested as arising from the result of the HVC impact (Comeron, 2001), and this may be the case for the LMC arc complex as well (Efremov, 2002).

8 CONCLUDING REMARKS

By considering all the above facts, we hypothesize that the hexagonal appearance might be the transient property of persistent vortices (of wide size range), which have suffered from ram pressure. The straight segments of the rims might be the result of the local flattening of the shock front on the space scale of the local radius of curvature, which might, in turn, be due to the stability of a flat shock wave against any weak perturbations that disturb its front surfaces (Chernin, 1999). If star formation occurred in the shock wave while its front was flat, the respective part of the rim of the stellar system would preserve the hexagonal shape. The flattening of the shock wave fronts seen in galactic spiral arms (Chernin, 1999) and now in other formations are worth investigating. Maybe the Chandra data for clusters of galaxies will find something of this nature.

However. the origin of most round or arc-shaped complexes is still a problem. Considering that stellar arcs in both NGC 300 and M33 are the only such features in these galaxies and are associated with the most unusual galaxy X-ray sources, both well isolated, the chance coincidence seems to be improbable. We believe that these X-ray objects, P42 and X-4 (especially P42), will be proved to be the remnants of hypernovae. The estimated young age of the M33 X-4 SNR (Okada *et al.*, 2001) is somewhat incompatible with our suggestion; yet the source should be studied in more detail. Both these arcs are rather irregular, unlike the other arcs discussed here.

A similar origin is possible also for the LMC 4 arcs; yet there are no X-ray sources located at suitable positions with respect to the arcs. X-ray binaries are concentrated mostly to north of the LMC 4 supershell, near the NGC 1978 cluster. The origin of the LMC arcs as the result of ram pressure to the surface of impacting clouds seems to be more probable, considering also the similar opening angles of these one-sided arcs. The main problem is that there are at least two and probably five arcs close to each other; this is a difficulty for any hypothesis, as also are the different orientations and ages. The Hodge object is enigmatic also, with a couple of concentric semiarcs, suggesting the action of a central pressure but not having an evident source nor an age–space pattern (Larsen *et al.*, 2002; Figs. 1 and 9). Vortex motions might confine young stars within a round complex; however, the sharp arc of the western rim suggests one-sided ram pressure action. Note that the drift of the complex might explain the absence of the H I hole around it, which is very strange considering that the complex contains the cluster most suitable for forming a supershell. Maybe the understanding of these features will come from an unexpected topic, such as the presence of dark matter.

One may wonder how frequent the round peculiar formations are in galaxies. We were able to find only a dozen (Efremov, 2001). The Hodge object in NGC 6946 was the only result of the special searches for features similar to the giant arcs in the LMC 4 region (P. Hodge, private communication). The appearance of this complex under different resolutions and contrasts suggest that quite a number of similar features might be missed. Under low resolution, and in the distant galaxies they are almost star like (the best examples are the round complexes in M51 and especially in NGC 1232 (Fig. 12)), whereas under low contrast (such as in the Sandage–Bedke atlas), no encompassing circular rim is noted. This is also the case for stellar arcs, even those so large as in the LMC 4 region. The rather similarly sized complex in M83 (Comeron, 2001) also includes two giant arcs (Fig. 12), which are seen only in the highest resolution images (Efremov, 2001a).

At any rate, these peculiar entities are curious and elegant, and their interpretation may have far-reaching implications. Some were suggested in this paper.

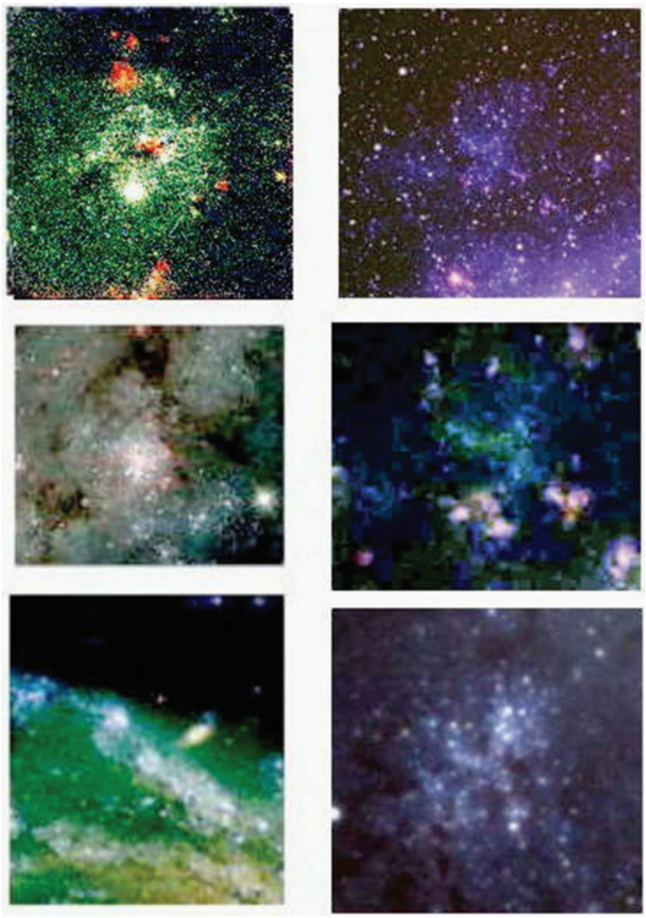

FIGURE 12 The left-hand column shows the Bubble complex in NGC 6946 (HST PC) (top), the round complex (300 pc in size, around the bright cluster), 1.5′ west of the centre of M51 (HST PC) (middle) and the round complex (the very centre of the image) inside the northern spiral arm of NGC 1232 (VLT) (bottom). The right-hand column shows the northeastern segment of the LMC, where the 30 Dor nebula is at the middle bottom (top), the LMC4 region (middle) and the southeastern complex in M83 with two arcs of clusters inside (VLT) (bottom).

Note added in proofs

A recent image of the NGC 6946 complex in K-band (S. Larsen, private communication) confirmed that the sharp western rim of the complex is due to the arc-shaped dust cloud. The object might be the blue compact dwarf galaxy, moving through the IGM of the NGC 6946 group (Yu. Efremov, in preparation). The radial velocity of the object is similar to that of three other dwarf galaxies in the group. As concerns the arc-shaped stellar complexes in the LMC, they might be products of the relativistic jets of microquasars. The latters are a stage of evolution of x-ray binaries, which do concentrate to the region (Efremov, Astron. Lett., submitted). The initial stage of the process is seemingly observed around SS 433.

Acknowledgements

I am very grateful to A. Chernin for comments on the draft of this paper and many useful discussions, and to P. Korchagin for comments on the theoretical motions of a solitary vortex in a galaxy. The use of the National Aeronautics and Space Administration Astrophysics Data Systems, the Los Alamos National Laboratory electronic preprint service, the DSS, the US Naval Observatory Flagstaff Station Integrated Image and Catalogue Archive Service, and also the HST and ESO Press Releases was necessary to carry out this work and is gratefully noted. Thanks are due also to S. Larsen and I. Karachentsev for the images obtained with the NOT and the BTA. The support from grants RFBR 00-02-17804 and 00-15-96627, RFFI 03-02-16288 and NS 389.2003.2 is appreciated.

References

Allison, M., Godfrey, D. A., and Beebe, R. F. (1990) *Science*, **247**, 1061.
Block, D. L., Puerari, I., Frogel, J. A., *et al.* (1999) *Astron. Space Sci.*, **269**, 5.
Bonnarel, F., Boulesteix, J., Georgelin, Y. P., *et al.* (1988) *Astron. Astrophys.*, **189**, 59.
Bothun, G. D. (1986) *Astron. J.*, **91**, 507.
Bureau, M., and Carignan, C. (2002) *Astron. J.*, **123**, 131.
Buta, R. (1990) *Astrophys. J.*, **356**, 87.
Buta, R., and Combes, F. (1996) *Fundamentals Cosmic Phys.*, **17**, 95.
Chernin, A. D. (1996) *Vistas Astron*, **40**, 257.
Chernin, A. D. (1999) *Mon. Not. R. Astron. Soc.*, **308**, 321.
Chernin, A. D. (2000) *Mon. Not. R. Astron. Soc.*, **318**, L7.
Chernin, A. D., Zasov, A. V., Archipova, V. P., and Kravtsova, A. S. (2000) In: J. G. Funes and E. M. Corsini (eds), *Galaxy Disks and Disk Galaxies, ASP Conference Series*, Vol. 230, p. 147.
Comeron, F. (2001) *Astron. Astrophys.*, **365**, 417.
Chu, Y.-H. (1999) *Astrophys. Space*, **269–270**, 441.
Dubrovsky, V. A. (2000) In: *New Cosmological Data and the Values of the Fundamental Parameters*, IAU Symposium, Vol. 201, Manchester, 2000, p. 52.
Efremov, Yu. N. (2001a) *Astron. Rep.*, **45**, 769.
Efremov, Yu. N. (2001b) astro-ph/0102161.
Efremov, Yu. N. (2002) *Astron. Rep.*, **46** (in press).
Efremov, Yu. N., Pustilnik, S. A., Kniazev, A. Y., *et al.* (2002) *Astron. Astrophys.* (in press).
Elmegreen, B. G., Efremov, Yu. N., and Larsen, S. S. (2000a) *Astrophys. J.*, **535**, 748.
Elmegreen, B. G., Kaufman, M., Struck, C., *et al.* (2000b) *Astron. J.*, **120**, 630.
Gruendl, R. A., Vogel, S. N., Davis, D. S., and Mulchev, J. S. (1993) *Astrophys. J.*, **413**, L81.
Hitchock, J. C., and Hodge, P. W. (1968) *Astrophys. J.*, **152**, 1067.
Hodge, P. W. (1967) *Publs Astron. Soc. Pacific*, **79**, 297.
Hummel, E., and Beck, R. (1995) *Astron. Astrophys.*, **303**, 691.
Kamphuis, J. J. (1993) PhD Thesis. University of Groningen, Groningen, The Netherlands.
Kim, S. C., Sung, H., and Lee, M. G. (2002) astro-ph/0203032.
Korchagin, V. I., and Petviashvili, V. I. (1985) *Soviet Astron. Lett.*, **11**, 121.
Korchagin, V. I., and Ryabtsev, A. D. (1991) *Astron. Astrophys.*, **246**, 368.
Kundu, A. (2002) astro-ph/0206221.
Larsen, S. S., and Richtler, T. (1999) *Astron. Astrophys.*, **345**, 59.
Larsen, S. S., Brodie, J. P., Elmegreen, B. G., *et al.* (2001) *Astrophys. J.*, **556**, 801.

Larsen, S. S., Efremov, Yu. N., Elmegreen, B. G., *et al.* (2002) *Astrophys. J.*, **567**, 896.
Lauer, T. R., Gebhardt, K., Richstone, D., *et al.* (2002) astro-ph/0206122.
McKee, C. F., and Cowie, L. L. (1975) *Astrophys. J.*, **195**, 715.
Maxworthy, T., and Redekopp, L. G. (1976) *Icarus*, **29**, 261.
Meaburn, J., Wang, L., and Bryce, M. (1995) *Astron. Astrophys.*, **293**, 532.
Merrifield, M. R., and Kuiken, K. (1999) *Astron. Astrophys.*, **345**, L47.
Noever, D. A. (1994) *Astrophys. Space Sci.*, **220**, 65.
Okada, Y., Takahashi, H., and Makishima, K. (2001) *Publas Astron. Soc. Japan*, **53**, 663.
Read, A. M., and Pietsch, W. (2001) *Astron. Astrophys.*, **373**, 473.
Redman, M. P., Al-Mostafa, Z. A., Meaburn, J., *et al.* (1999) *Astron. Astrophys.*, **345**, 943.
Ryder, S. D., Purcell, G., Davis, D., and Andersen, V. (1997) *Publ. Astron. Soc. Austr.*, **14**, 81.
Sansom, A. E., Reid, I. N., and Boisson, C. (1988) *Mon. Not. R. Astron. Soc.*, **234**, 247.
Santillan, A., Franco, J., Martos, M., and Kim, J. (1999) *Astrophys. J.*, **515**, 657.
Shulman, E., and Bregman, J. N. (1995) *Astrophys. J.*, **441**, 568.
van den Marel, B. P., Alves, D. R., Hardy, E., and Suntzev, N. P. (2002) astro-ph/0205161.
Wang, Z. P., Wang, L. Y., and Liu, S. S. (2001) *Acta Astron. Sinica*, **42**, 397.
Westerlund, B. E., and Mathewson, D. S. (1966) *Mon. Not. R. Astron. Soc.*, **131**, 371.
White, R. E., Sarazin, C. L., and Kulkarni, S. R. (2002) *Astrophys. J.*, **571**, L23.
Whitmore, B. C., and Bell, M. (1988) *Astrophys. J.*, **324**, 741.
Yun, M. S., and Hibbard, J. E. (2001) *Astrophys. J.*, **550**, 104.