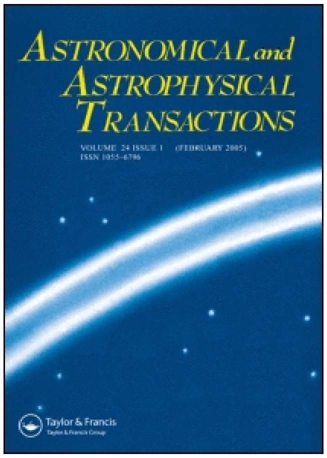

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A. D. Chernin [ab]; A. V. Zasov [a]; V. P. Arkhipova [a]; A. S. Kravtsova [a]
[a] Sternberg Astronomical Institute, Moscow, Russia
[b] Tuorla Observatory, University of Turku, Piikkiö, Finland

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POLYGONAL ARMS AND HEXAGONAL RINGS: MORPHOLOGY AND PHYSICAL INTERPRETATION

A. D. CHERNIN,[1,2] A. V. ZASOV,[1]
V. P. ARKHIPOVA,[1] and A. S. KRAVTSOVA[1]

[1]*Sternberg Astronomical Institute, 13, Universitetskij pr., Moscow 119899, Russia,*
E-mail chernin@sai.msu.ru
[2]*Tuorla Observatory, University of Turku, Piikkiö, 21 500, Finland*

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Straight arm segments and polygonal spiral patterns are studied on the basis of a sample of two hundred disc galaxies. Straight segments are also known in a ring of the galaxy NGC 4303 which is described by de Vaucouleurs (1970) as an almost regular hexagon. Several candidates for hexagonal rings are also found. The physical nature of the phenomenon is not completely understood. A gas-dynamical approach to the problem is suggested which assumes that straight segments in polygonal arms and hexagonal rings are formed in segments of the spiral or ring shock fronts that are locally flattened.

KEY WORDS Galaxies: individual (M51, M101, etc.) – galaxies: spiral – galaxies: rings

1 INTRODUCTION

In an elegant drawing of The Whirlpool Galaxy M51 made by Lord Rosse in the 1850s (reproduced in *ASTRONOMY* magazine, April 2000; see also a paper by Ross, 1850), one may recognize the perfect spiral grand design of the galaxy and also local arm segments of the spiral that look rather straight. A century later, straight arm segments were discovered in M101 by Vorontsov-Vel'yaminov (1951, 1964, 1978) who called these features **rows** and described them as 'straight-line segments of a spiral arm in the form of elongated star clouds or chains of knots that consist of hot giants and open clusters'. In M101, there are two very large – each about 20 kpc long – and bright rows noted in the Eastern major regular arm of the galaxy. The rows are seen in both a blue photograph and the distribution of the column density of HI in this galaxy (Vorontsov-Vel'yaminov, 1978, see p. 187 of the English edition of the book). Rows were also demonstrated in the galaxies NGC 2805, NGC 3124, NGC 309, NGC 509, NGC 1073, *etc.* (Vorontsov-Vel'yaminov, 1964, 1978). Independently, the straight rows of giant HII regions were found in M 81 by

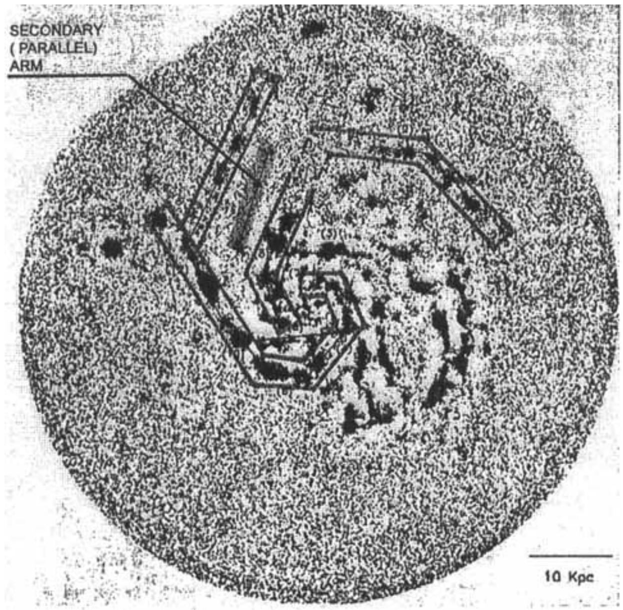

Figure 1 M101: FUV image by Waller *et al.* (1997) and two-arm polygonal pattern in the Eastern half of the galaxy; a secondary (parallel) arm is in between the two major arms.

Arp (1986), who considered these forms as puzzling and intriguing. Contopoulos and Grosbol (1986) discovered straight segments in NGC 5247 and suggested a stellar dynamics model for this galaxy. Recent observations of M 101 with the shuttle-borne Ultraviolet Imaging Telescope (Waller *et al.*, 1997) have revealed with impressive clarity that the spiral arm morphology of the galaxy consists of a dozen linear arm segments traced by a disc-wide system of bright knots. Chernin (1999) and Chernin *et al.* (2000) demonstrated that in M51, M101 and dozens of other galaxies, a polygonal spiral pattern can be recognized that is characterized by two geometrical properties: 1) the segments of the polygons intersect each other at an angle near $2\pi/3$, 2) the lengths of the segments increase with the distance from the center almost linearly.

The phenomenon of polygonal spiral arms and its physical nature are the focus of our discussion here.

2 ARCHETYPE GALAXY M101

Vorontsov-Vel'yaminov's discovery of straight arm segments has not attracted much attention for decades; perhaps this is partly because of some episodes in astronomy when geometrical interpretation of spatial patterns in the sky led to spurious conclusions (canals on Mars or ring configurations of stars on the Palomar Sky Survey

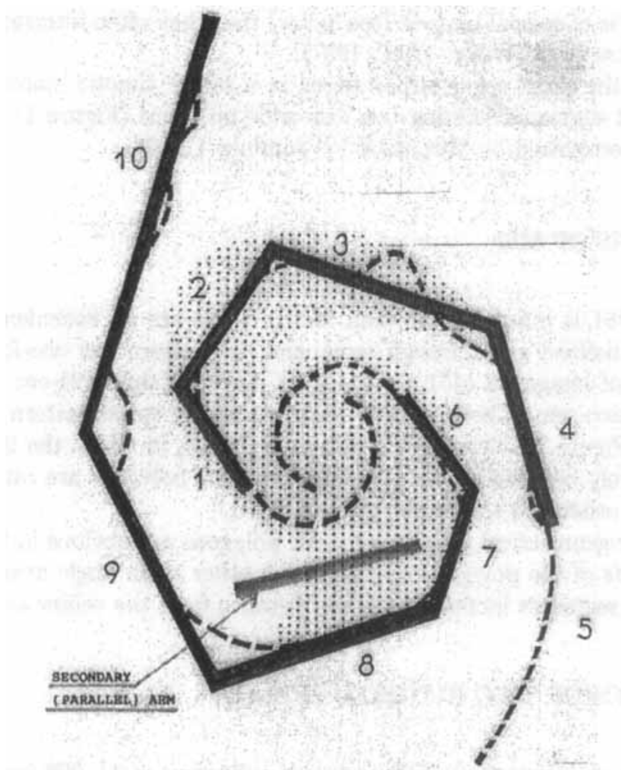

Figure 2 M51: Two-fold polygonal pattern, a schematic outline of the straight segments along the dust lanes cleaned from small-scale features. The dashed line is the line of maxima of the synchrotron emission (Mathewson *et al.*, 1972) which coincide almost perfectly with the dust lanes along the arms. Wide, smooth and round arms (dots) are traced by the old red population of the disk; the 'red' arms reveal the gravitational potential which does not contain any straight elements. A secondary (parallel) arm is in the south of the pattern.

images, etc.). Such misinterpretation may be due to the human eye's propensity to connect dots in a regular manner and see patterns where none actually exist. However, interpretive difficulties of this type can be avoided in the case of Vorontsov-Vel'yaminovs's rows. The reality of the straight segments in the spiral structure of the archetype galaxy M 101 has been confirmed by comparing the features discovered in optical images with stellar and interstellar tracers at other wavelengths.

Most impressive data on the spiral pattern of the galaxy M101 have recently been provided by the Shuttle-borne Ultraviolet Imaging Telescope (Waller *et al.*, 1997). The deep FUV image (Figure 1) has revealed that the spiral arm morphology consists of a dozen linear arm segments traced by a disc-wide system of bright knots. With the distance 7.4 Mpc, the largest outer straight segment in the Eastern arm is 22.6 kpc in length (Waller *et al.*, 1997). The other rows have lengths in the interval

5–13.6 kpc. It is of special interest (see below) that they often intersect one another at an angle of $\approx 2\pi/3$ (Waller *et al.*, 1997).

Alongside the short segments arranged in a rather chaotic manner are several longer straight segments forming two disk-wide polygons (Figure 1). The outer of them is that recognized by Vorontsov-Vel'yaminov (1987).

3 POLYGONS OF M51

The galaxy M51 is more regular than M101: there are no flocculent arms there, only two well defined grand design arms, and the pattern has two-fold symmetry. With the use of images of M51 in blue light, FUV, H-alpha, 21-cm, CO and synchrotron emission, etc., Chernin (1999) suggests for the spiral pattern of this galaxy a schematic (Figure 2), cleaned of small-scale details, in which the two-arm spiral is almost entirely represented by two polygons. The polygons are rather similar in shape to each other and to the polygons of M101.

Two major geometrical properties of the polygons are obvious in both galaxies: 1) the segments of the polygons intersect each other at an angle near $2\pi/3$, 2) the lengths of the segments increase with the distance from the center almost linearly.

4 STATISTICS OF TWO HUNDRED SPIRALS

We have inspected Vorontsov-Vel'yaminov's collection of 11 000 images of spiral galaxies at Sternberg (as well as other available data bases on galaxy images) and have found the polygonal patterns with a polygonal arm geometry or isolated straight segments in 209 galaxies. More than a half of the galaxies (121) are isolated non-interacting systems. A detailed catalogue containing basic observational data on these 209 galaxies is under preparation at Sternberg Institute.

A dozen face-on nearby spirals with polygonal arms have been studied most completely (Chernin *et al.*, 2000). For the whole sample of 209 galaxies, we have analyzed the distribution of the intersection angles; the peak near $2\pi/3 = 120°$ was obvious in the distribution (the median value of the distribution is 122°). For all these galaxies, the linear dependence of the segment length on the distance from the center of the disc has also been confirmed. With an accuracy of 10%, the length is simply equal to the distance.

5 THE ANDROMEDA NEBULA AND THE MILKY WAY

In the nearest giant spiral, The Andromeda Nebula, Yury Efremov (2000, see this issue of the Journal) has recently found two straight segments (one of more than 20 kpc long) intersecting at an angle of about $2\pi/3$ in the WS spiral of the galaxy. The distribution of about 800 blue stars, 300 Cepheids and 50 HII regions was used

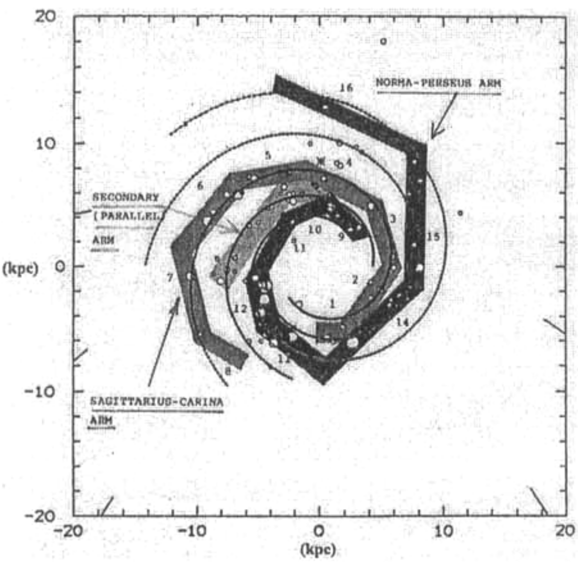

Figure 3 The Milky Way: Two polygonal arms of polygonal geometry and a secondary arm in the East superimposed on the space distribution of HII regions. The data on HII by Russeil *et al.* (1998). Black lines show one of the models of curved arms suggested by Russeil (Unpublished Thesis, 1998).

which trace the spiral arm very clearly in this part of the arm. The segments are located in the area where spiral shocks are expected to be especially strong because extremely intensive star formation is observed in this area. The pitch angle is rather large there – about 30 degrees on average compared to 7–8 degrees in other parts of the spiral.

For the Milky Way, the distribution of more than 2 000 Cepheids in the area around the Sun with a maximal distance of 7 kpc was obtained recently by Leonid Berdnikov, a Cepheid observer of Sternberg. The Saggitarius–Carina spiral arm, nearest to the Sun, is well traced by the Cepheids. Their distribution seems to give an indication (Berdnikov and Chernin, 1999) of the existence of two straight segments in the arm that intersect at an angle near $2\pi/3$. The global geometry of the Saggitarius–Carina arm can also be followed with the use of the Cepheids, HII regions (Russeil *et al.*, 1998) and superclouds (Efremov, 1998) along the arm. A polygon with the characteristic angle appears in a rather natural way there as a schematic representation of the tracer distribution.

The structure of the spiral arms in our Galaxy still remains very uncertain, generally. Nevertheless, a very tentative schematic (Figure 3) for the whole Galaxy may be suggested on the basis of the homogeneous data on HII distribution (Russeil *et al.*, 1998). With all the necessary reservations, we may say that this '2 1/2-arm' scheme does not contradict the data and may be considered as a competitive counterpart to the scheme of curved arms suggested by Russeil *et al.* (1998).

6 PHYSICS OF POLYGONS

In a search for the physical nature of the phenomenon of the polygonal arms, we may rely on the basic concepts of spiral structure; two basic ideas are especially important – the idea of density waves by C.C. Lin and Frank Shu and the idea of spiral shocks by W.W. Roberts and S.B. Pikelner. In the spirit of these ideas, Chernin (1999) assumes that the phenomenon of polygonal arms might be of a gas-dynamical nature.

In terms of morphology, straight arm segments might be formed by shock fronts that tend to get flattened on the spatial scale of the local radius of curvature of the curved spiral. If so, both geometrical properties of the polygons (the characteristic angle of $2\pi/3$ and the linear dependence of the length of a segment on its distance from the center) find an explanation – just a result of the geometry of the logarithmic spiral. A picture of the gas-dynamical simulations produced by C.C. Lin, W.W. Roberst and their colleagues for the galaxy M81 (Lowe *et al.*, 1994), where straight arm segments are clearly seen, seems to support this view.

In terms of physics, the phenomenon is assumed to be due to the global hydrodynamical stability of grand design shocks. The curved shock structure and the polygonal shock structure are considered as two quasi-stable states of the global hydrodynamical spiral. The states are similar to attractors in the phase space of a nonlinear dissipative system. The nonlinear shock structure transits spontaneously from one of the attracting states to the other, so that the states prove to be transient and alternate in a seemingly chaotic manner in the evolutionary history of the system.

One of the intrinsic mechanisms of this intermittent evolutionary behaviour of grand-design shocks may be related to the non-stationary gravitational potential of the underlying stellar component of the galaxy. It seems probable that even weak temporal changes of the potential (which can be seen in a number of computer simulations of the formation and evolution of the curved spiral structure in rotating stellar discs) can trigger a transition from one state of the global spiral shock to the other.

Each of the two states of the spiral shock structure is presented in accordance with its statistical weight in the history of an individual system, as well as in the observed ensemble of spiral galaxies. The data of Sec.4 suggest that the ratio of the weights of curved and polygonal states is approximately 50:1, in general.

7 HEXAGONS

Extending our search from spiral galaxies to ring galaxies, we have found in the literature that many years ago the galaxy NGC 4303 was recognized by de Vaucouleurs and de Vaucouleurs (1964) as a pseudo-ring with 'a characteristic hexagonal shape'. Buta and Combes (1996) describe two other ring galaxies in which the rings looked like more or less regular hexagons with straight segments; these are NGC 7020 and NGC 4429.

We add to these three galaxies a dozen candidates for hexagonal rings: NGC 3081, 3351, 4689, 6782, 6935, PGC 31551, UGC 12646, ESO 325-28, etc. Some of the hexagons are connected with spiral arms, and most have bars inside. Note that among the images of Vorontsov-Vel'yaminov's collection we inspected, there are no triangular nor quadrangular rings, neither are there pentagons or heptagons, – only six-side figures. This should seemingly mean something.

We consider hexagonal rings counterparts to polygonal arms in grand design spirals. The major similarity between these two structures is that both are made of straight segments. Two geometrical properties found in polygons (see above) have analogs in regular hexagons: the angle between two segments is $2\pi/3$, and the sizes are equal to each other, since they are equally distant from the center. This geometrical similarity suggests that both morphologies may have a common physical nature. If so, the gas-dynamical approach, assumed for polygonal arms, may indicate that the hexagons are also made of flat segments of shock fronts.

Hydrodynamical simulations produced by Guivarch and Athanassoula (1996) may be seen as an argument in favour of this view: regular hexagons made of shocked flat gas layers appear as a transient state (conf. Sec. 6) which appears as a reaction of interstellar gas to a (strong) bar.

Another direction we are trying to extend our studies is to the inner few hundred pc of disc galaxies where a nuclear spiral structure has recently been discovered with the use of the Hubble Space Telescope (Martini and Pogge, 1999). Three examples of polygons were recognized in a set of HST images. In addition, one nuclear hexagon (observed by Knapen, 1995) was also found (Chernin, 2000). The nuclear structures illustrated by these examples may be considered as small-scale counterparts to polygonal arms and hexagonal rings of disk-wide sizes.

Thus, the phenomenon of polygonal arms and hexagonal rings seems to be rather general and most probably has a common physical nature in disc-wide and nuclear grand design.

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