POLYGONAL ARMS IN GRAND DESIGN SPIRALS

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ABSTRACT. The phenomenon of polygonal arms in grand design spiral galaxies is reviewed. The Whirlpool Nebula, Messier 51 (NGC 5194) in Canes Venatici, is taken as an archetypical example. Optical photographs, H_α, UV and far-UV images, CO, 21 cm, sinchrotron emission maps, K_s-band mosaic of M 51 are used to recognize the global spiral pattern in M 51 which contains multiple straight arm segments and is presented by two polygons almost entirely. The polygons are almost identical, and the pattern has approximate twofold symmetry. The length of the straight arm segments is about the distance from the center of the disk. The segments intersect one another at the angle which is in average $\approx 2\pi/3$. A brief list of galaxies with straight segments (M101 including) is given. The wave nature of the phenomenon is argued. A gasdynamical approach is discussed which implies that the formation of straight arm segments might be due to the generic stability of flat shock fronts and the tendency of a slightly curved shock front to get flat. A quantitative flattening criterion, based on this assumption, enables to explain the geometrical properties of the arm patterns found in M 51 and some other grand design spirals. Same considerations seem to be applicable to the ring structures that have a form of almost regular hexagons in a dozen disk galaxies.

Key words: Galaxies: spiral; Stars: formation.

1. Introduction: M51

The nearly face-on giant Sbc spiral Messier 51 (NGC 5194), one of most photogenic, constitutes a textbook example of a spiral structure. I do not know exactly who gave this galaxy its name The Whirlpool; may be it was Lord Rosse who was the first to detect the spiral nature of certain nebulae, now known to be galaxies. The Whirlpool Galaxy is one of the most symmetrical galaxies in the sky. Spirals exhibiting this high degree of symmetry and large-scale regularuty are often called grand design spirals. Presumably, they have been formed by some global process that involves the whole galaxy.

The geometry and physics of the spiral pattern of M51 is in the focus of my discussion here.

2. Polygonal pattern

Photographs of M51, like ones made by Zwicky in the 50s, are dominated by the blue light from luminous, young O and B stars and the regions of ionized hydrogen (HII). Since O and B stars live less than 10 Myr (compared to the age of the galaxy 10 Gyr), they can be seen only in the regions of recent star formation. Spiral arms are no doubt regions of rapid and effective star formation. The HII regions are also young objects; in Baade's apt phrase, they are "strung out like pearls along the arms".

There are dark strips on the inside of each arm which are well recognizable on the photograph in "The Hubble Atlas of Galaxies"; as Sandage noted there, "the entire spiral pattern of M 51 is dominated by the dust lanes". The dark strips are believed to be caused by absorbtion of the galaxy's starlight in dense clouds of gas and dust.

Looking at the photographs of M51 and following the shape of the arms as it is traced by the dust lanes, one can realize that the major spiral arms of the galaxy contain segments of different forms. The images demonstrate almost perfectly curved arm elements near the center of the disk. It is also obvious at a glance that out of the very central area, several arm segments are fairly straight. More careful analysis (Chernin 1999) has been done with the use of not only optical photographs, but also H_α, UV and far-UV images, CO, 21 cm, sinchrotron emission maps, K_s-band mosaic of M 51. The analysis shows that:

* the spiral pattern of M 51 contains 5 fairly straight arm segments in the EN arm and 4 in the WS one;

* the segments form two polygons which represent each arm almost entirely;

* the polygons are almost identical, and the pattern has approximate twofold symmetry.

* the length of a straight segment is about its distance from the center of the disk;

* the segments intersect one another at the angle which is in average $\approx 2\pi/3$.

At least a dozen other grand design spirals seen face-on demonstrate a similar geometry of arm patterns. For more than 50 straight segments recognized in the galaxies of this sample, the characteristic angle is mostly around $2\pi/3$ and the lengths of the segments is about their distances to the centers of galaxy disk (Chernin *et al.* 2000a).

It seems instructive that the polygonal pattern in M51 (and also in other galaxies) is traced by the youngest populations of the arms which are gas/dust clouds of the dust lanes, H II regions and bright blue stars. If to look at the galaxy M51 in red light dominated by older disk stars, one may see that the red stars exhibit a spiral pattern similar to the blue stars, but with smoother and broader arms. The old disk population participates in the spiral pattern, but its space distribution is remarkably differnt from the distribution of the O and B stars or HII regions. No straight forms are seen in red light.

3. Vorontsov-Velýaminov: rows in arms

The discussion of straight arm segments dates back to Vorontsov-Velýaminov (1951, 1964, 1978). He 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 are consisted of hot giants and open clusters".

Several spirals with straight arm segments (but not M51!) were listed in his book "Extragalactic Astronomy" . The nearest giant galaxy M 101 was pointed out a typical example. Two very large and bright rows can easily be recognized in the Eastern major arm of M 101. They are seen in both a blue photograph and the distribution of the column density of HI. Rows are not only large, but also bright forms. In M 101, they are among the brightest (and bluest) elements of the spiral arms. Huge superassociations and giant HII regions prefer to settle in them, like NGC 5461 and NGC 5462 in M 101.

The discovery of rows 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 images, *etc.*). Such misinterpretation may be due to the human eye's propensity to connect the dots in a regular manner and see patterns where none actually exist.

However, the 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 can be confirmed by comparing the features discovered in optical images with stellar and interstellar tracers at other wavelengths. The most impressive data on the spiral pattern of the galaxy M101 has recently been provided by the Shuttle-borne Ultraviolet Imaging Telescope. The deep FUV image has revealed that the spiral arm morphology consists of a dozen linear arm segments traced by a disk-wide system of bright knots (Waller *et al.* 1997). With the distance 7.4 Mpc and a radius 30 kpc, the largest outer straight segment in the Eastern arm is 23 kpc in length, being 2-3 kpc across. The other rows have the lengths in the interval of $5 - 13.6$ kpc. They intersect one another often at angle $\approx 2\pi/3$ (Waller *et al.* 1997). A polygon pattern may be recognized in two grand design arms of M 101 (Chernin 1998); a relatively small scale straight segments are found also in the irregular flocculent arms there (Waller *et al.* 1997).

More than 150 spirals with straight arm segments, including M 61, M 99, M 100, NGC 628, NGC 1232, NGC 1365, NGC 2997, NGC 3184, NGC 3631, NGC 4303, NGC 3310, NGC 3147, NGC 1179, NGC 1187, NGC 4535, NGC 5427, NGC 3938, NGC 6221, NGC 6946, NGC 7424, NGC 6744, NGC 7137, NGC 1313, are in the list which is now under preparation at Sternberg Institute (Arkhipova *et al.* 2000).

4. Polygonal pattern: tides or waves?

Do the polygonal pattern have material nature or wave nature? Waller *et al.* (1997) suggested that the straight segments in the arms of M101 had material nature and were due to tidal processes. On the contrary, I assumed (Chernin 1999) that these structures (at least in M51) were of wave nature.

Waller mention (in our personal exchange) that perhaps one of the best ways to determine whether tidal processes or wave processes are responsible for generating the straight-arm segments is to look for spatiotemporal evidence of propagating waves. For wave-dominated dynamics, there should be a spatial offset between tracers of the most recent star formation and tracers of more evolved stellar populations. If no offset is evident, then we are looking rather at material arms that have been drawn out by tidal action.

Waller did this sort of investigation in the center of M101, using CO emission and FUV emission as respective tracers of the current-epoch starbirth and the evolved blue supergiants $\simeq 3$ Myr downstream. In the inner galaxy, he found some spatial offsets (Waller *et al.* 1997). In the outer parts of M101 where the straight segments predominate, the image registration is trick, and so the work has not yet been completed. O'Connel has had some success comparing H_α and FUV in M51, finding some good offsets in the WS arm and inner EN arm (astro-ph/9706265), both of which show polygonal morphology.

The most impressive *prima facie* evidence for the offsets in M51 is given by the systematics in the positions of the dust lanes and bright stars along the polygonal arms there: the stars are regularily behind the dust lanes downstream. We can conclude that the wave nature of the polygonal grand design arms has all the grounds to be adopted.

However the nature of the small-scale straight segments in flocculent (not grand design) arms needs more studies.

5. Density waves and shock waves

The spiral structure in stellar disks is regarded as a density wave, a wave-like ascillation that propagates through the disk in much the same way that waves propagate through violin string or over the ocean surface. It was first recognized by C.C. Lin and F. Shu in the early 60s. As a wave parcel, the spiral structure rotates as a whole with a constant angular velocity, while the disks may rotate differentially. This is the basis of the current understanding of the phenomenon.

Propagating spiral waves should have their generator. In M 51, it is most probably the companion galaxy NGC 5195: it excites the wave pattern and supplies it with energy. In galaxies with bars, the spirals are most likely excited by the bars.

The profile of the density wave in M51 is directly seen in the distribution of the red old stars (Sec.2): the density wave ridges have a smooth round shape without any straight segments.

It has also long been recognized that the dust lanes are actually the fronts of spiral shocks seen edge-on when a galaxy is seen face-on. In the lanes, the interstellar gas is shocked into dense layers which obscure the starlight. This interpretation was suggested by W.W. Roberts and independently S.B. Pikelner in 1969. They argued that the fronts form when the gas of the galaxy disk passes through the gravitational potential of a density wave. The gravitational potential has minima along the spiral arms where the density of star distribution is higher. The gas falls into the potentiall well of a density wave and then leaves the well, but it loses its velocity partly in this process. The change of the velocity is rather sharp, and this means that the physics of the process is the same as in shock waves. It is this sharp decrease in the flow velocity that shocks the gas into the dense layers along the spiral arms. And just in these layers, new stars form.

When we look at the pattern of dust lanes (or the ridges of the synchrotron emission which practically coinside with the dust lanes) in M 51, we actually see adge-on two global shock fronts along the arms there. The shock fronts are curl in the central region of M51 and flat in the outer straight segmets. It means that the shock wave follows the lines of minima of the potential, but only in general. Withing the potential wells of the density wave, the shock fronts have their own spatial structure, and they may be flat where the potential well is round.

6. Why are they flat?

Why does a shock front get flat in the round potential wells of the spiral arms? I do not have an ultimate answer, and a conjecture can only be suggested. Perhaps this phenomenon is due to the generic propencity of any shock front for minimizing its surface. This tendency can be observed in a number of gasdynamical examples and may be perhaps formulated as a kind of theorem in the spirit of variation principles. From my discussions with V.M. Kontorovich and other experts in shocks, I learned that this may be probable, generally.

A more specific assumption about the flattening phenomenon implies that the formation of straight arm segments might be due to the gasdynamical effect of stability of flat shock fronts and the tendency of a slightly curved shock front to get flat. I suggest a quantitative flattening criterion, based on this assumption, which says that the size of the flattening shock front is near the local radius of curvature of the potential well of the arm where the shock forms (Chernin 1999). If so, one can explain why the length of a straight segment is about its distance from the center of the disk and why the segments intersect one another at the angle which is in average $\approx 2\pi/3$ (Sec.2). This follows simply from the shape of the gravitational potential well which may closely be described by a logarithmic (selfsimilar) spiral (with k ¡ 1).

Flattening is possible provided that the potential well of the arm is wide enough to contain a flat front of the size of the local radius of curvature of the well. Unfortunately, this is all I can now answer to the question why this galaxy has straight segments, but another one does not. The existence of the straight segments depends most probably on the width of the underlying gravitational potential wells. The width of the well may be related to such global physical characteristics of the disks as mean velocity dispersion in star distribution, etc. It would be interesting to try to find correlations between the existence of straight segments with these global properties of the disks.

7. Hexagonal rings

A considerable fraction of all disk galaxies reveal large-scale global structures which are described as rings, pseudorings or lenses (see Vorontsov-Vel'yaminov 1978, Buta and Combes 1996). In some of them, rings look rather like more or less regular hexagons with straight segments. This is, for instance, NGC 7020 (Buta and Combes 1996). A list of hexagons one may found is not too long; together with NGC 7020 or NGC 4429, it includes NGC 3081, NGC 3351, NGC 4429, NGC 6782, NGC 6935, PGC 31551, UGC 12646, ESO 325-28, ESO 565-11.

It is interesting that a pseudoring with "a characteristic hexagonal shape" (Buta and Combes 1996, p.104) is put in the central sketch of the de Vaucouleurs and de Vaucouleurs's three-dimensional classification in the cross section near Sb. The galaxy NGC 4303 is mentioned as a model for this sketch; but it proves to be rather a spiral with polygonal arms: one can clearly see this, for instance, in the Atlas by Sandage and Berdke.

Better images for some of the galaxies with hexagons we listed will perhaps lead to a similar re-examination of their morphology. Nevertheless, one may expect that at least the galaxies NGC 3081, NGC 3151, PGC 3351, and UGC 12646 will survive as closed hexagons.

What is the place of hexagonal structures in the general variety of galaxy morphologies? Why they are just hexagonal, and no closed pentagons or septagons are observed? What may be their physical nature? In a recent note (Chernin *et al.* 2000b), we try to approach these questions by examining a possible relation of hexagons to the polygonal arm patterns.

The major similarity between hexagons and polygons is that both structures are made of straight segments. Another property is more special: in both patterns, the angle between two straight segments is about $2\pi/3$, and the length of a segments is near the distance from the center of the disk. If these geometrical properties are generic or crucial for the phenomenon of straight segments, this may explain why we see hexagons, but not, for instance, pentagons or septagons.

The similarity in geometry suggests that both phenomena may have a common physical nature. Arguing along this line, one may assume that the hexagons are also made of flat segments of shock fronts. Hydrodynamical simulations by Guivarch and Athanassoula (1996) seem to support this view: regular hexagons made of flat layers of shocked gas may appear as a reaction of interstellar gas to a (strong) bar. On the other hand, the same simulations may be considered also as an argument for our general gas-dynamical approach to the phenomenon of straight segments and polygonal patterns.

8. Conclusions: back to M51

The galaxy M51 with its large angular diameter and prominent spiral pattern has been a favorite target of astronomers for more than 150 years since the first observations by Lord Rosse. The phenomenon of polygonal pattern found in M51 shows the morphology, dynamics and evolution of spiral (and also ring) galaxies in a new light. The phenomenon is closely related to basic physical processes that make galaxies look as they do. A complex interplay of density waves in the distribution of stars and shock waves in the disk gas is behind the phenomenon.

In conclusion, I would like to note that the physics of polygonal arms reveals also in systematics in the location of brightest OB/H II complexes in the arms of M51. It may be demonstrated that the objects occupy predominantly the areas around the corners of the polygonal arms of this galaxy (Chernin 2000). An interpretation of the phenomenon assumes that complex gas flows around the corners of the polygonal arms must include additional shock fronts and tangential discontinuities, as it follow from the general gasdynamical theory of shock-front intersections. These flows can enchance star formation because of extra compression of gas in the additional shocks and/or turbulization of gas via decay of the tangential discontinuities.

A similar assumption for hexagonal rings is definitely supported by the gasdynamical simulations by Guivarch and Athanassoula (1996); it is essential that these simulations describe also star formation process: the process is evidently enchanced in some of the the corners of the hexagons.

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