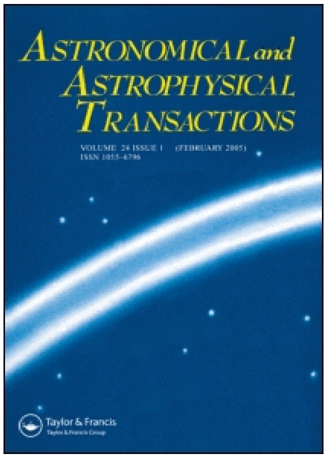

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 October 1999
To cite this Article: Chernin, A. D. (1999) 'Rows of star complexes in giant spiral galaxies', Astronomical & Astrophysical Transactions, 18:2, 393 - 405
To link to this article: DOI: 10.1080/10556799908229776
URL: http://dx.doi.org/10.1080/10556799908229776

Astronomical and Astrophysical Transactions, 1999,
Vol. 18, pp. 393-405
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ROWS OF STAR COMPLEXES IN GIANT SPIRAL GALAXIES

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(Received April 9, 1998)

The straight geometrical forms observed as bright rows of star complexes in spiral arms of giant galaxies are discussed. The nearby spirals M 51 and M 101 seen almost face-on reveal a polygonal two-arm pattern. Some other examples of spirals with straight arm segments are demonstrated. A gas-dynamical approach to the physical nature of the phenomenon is suggested. It is argued that the formation of the straight segments in spiral arms can lie due to the stability of flat shock fronts and the tendency of a slightly curved shock front to become flat. The flattening criterion enables us to expect that the length of a straight segment depends on its location in the global spiral structure and increases with the distance from the centre. This is generally confirmed by observational data. The same considerations show that the opening angle between two straight segments is typically $\simeq 120°$, which also agrees with the observed geometry of polygonal arm patterns.

KEY WORDS Star complexes, spiral structure, galaxies

1 INTRODUCTION

More than two decades ago, Vorontsov–Vel'yaminov (1989) (Russian original book of 1978; hereafter VV), discovered and described the large-scale straight segments in spiral arms of M 101 and some other galaxies. The features are commonly seen as line chains of bright star-forming regions. We know now that these regions are star complexes, the building blocks of the structure of galactic disks (Efremov, 1989; 1995).

According to VV (p. 194), "Row structures are encountered rather often, either as separate straight parts of spiral arms or as isolated trains of features. ... The forms are not at all unique, and their abundant variety suggests these structures have some fundamental significance, rather than an abnormal or peculiar character."

The giant galaxy M 101 was pointed out as the archetype of spirals with straight geometrical forms. VV (p. 187) found rows in a blue photograph of M 101 and in the distribution of the surface density of H I in this galaxy. Straight segments have lengths of several kiloparsecs, some of them up to 10–15 kpc, being 2–3 kpc across.

The rows are among the bluest segments of spiral arms; huge gas-star complexes, superassociations and giant H II regions prefer to settle in them (like NGC 5461 and NGC 5462 in M 101).

The straight rows of giant H II regions were observed in M 81 by Arp (1986), who found these forms puzzling and intriguing.

The discovery of rows has not attracted much attention (the only known reference is in the book by Efremov, 1989); 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, ring configurations of stars, etc.). Such (mis) interpretation may be due to the human eye's propensity to see patterns where none actually exist.

However, such interpretive difficulties can be overcome in the case of Vorontsov–Vel'yaminovs's rows. A strong recent argument in favour of this has been given by Waller *et al.* (1997) for M 101. The deep FUV image has revealed with impressive clarity bright rows of star complexes in this galaxy. It has also been demonstrated that the spiral arm morphology consists of such linear arm segments that intersect one another often at an angle $\sim 120°$ having the lengths in the interval of 5–20 kpc. Waller *et. al.* (1997) have confirmed the reality of the straight segments in the spiral structure of the archetype galaxy M 101 by comparing the features discovered by them in FUV with stellar and interstellar tracers at other wavelengths.

In this paper, I re-examine the pattern analysis of M 101 combining VV data with the new data by Waller *et al.* (1997) and also H_α, H I and CO data. This enables me to select the features in a more reliable way and also to recognize a global polygonal geometry of the major spiral arms in M 101. I show that another nearby giant spiral M 51 reveals a similar geometry of its spiral arms. Both bright rows and dark linear segments are seen in the arms of M 51. The dark lineaments are fairly sharp and thin; because of this, their straight linearity is even more obvious than that of rows. Finally, I make an attempt at a physical interpretation of the phenomenon of straight arm segments assuming that the problem of the geometrical interpretation of these features has now been clarified. I base this on the idea that non-linear gas-dynamics with shock waves can be responsible for the phenomenon of bright rows and dark lineaments. The gas-dynamical effects develop on the underlying gravitational grand-design which may not contain straight-line elements. It is not my aim here to develop a complete quantitative theory of the origin and evolution of the spiral structure in all its complexity; I will rather present and discuss some qualitative physical arguments which may suggest new insights into the complex non-linear interplay of gravity and gas-dynamical effects in the disks of giant spirals.

2 THE ARCHETYPE GALAXY M 101

The imaging of the far-ultraviolet emission from the galaxy M101 by the Shuttle-borne Ultraviolet Imaging Telescope (Waller *et al.*, 1997) demonstrates a disk-wide system of bright star-forming knots. The knots present star-gas complexes which

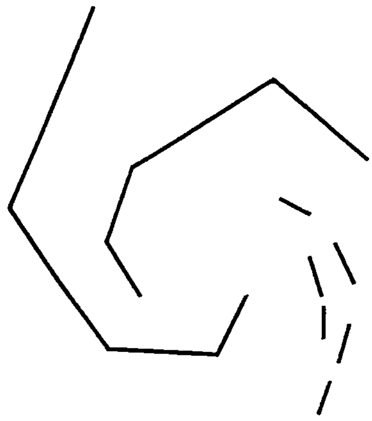

Figure 1 Bright rows in M 101: Schematic of the spiral pattern traced by star-gas complexes and H I. The data on the rows from Vorontsov–Vel'yaminov (1989) and Waller *et al.* (1997), as well as the data on H I column density (Kamphuis and Sancisi, 1993) are used. Dashed lines are for the flocculent arms.

are known as huge aggregates of bright stars and gas clouds, with masses of about a million solar masses and sizes about a kpc where active massive star formation proceeds (Efremov, 1989; 1996; Efremov and Chernin, 1994).

The spatial distribution of complexes in FUV (Waller *et al.*, 1997) confirms strongly the early known picture given by blue photographs described by VV (p. 242) and reveals new important details. These data, together with the contours of the H I surface density (VV p. 187) and the total H I column density distribution (Kamphuis and Sancisi, 1993), H_α and CO data (see Knapen *et at.*, 1996 and references therein) provides grounds for a new detailed pattern analysis.

The result is presented in Figure 1. There are eight rows recognized in the major spiral arms of M 101. No prominent rows are found in the flocculent arms. In both major arms, straight segments comprise more than 90% of the arm length. In the central area of the disk with the radius of 3–5 kpc, the FUV data (Waller *et al.*, 1997) do not allow us to draw a definite conclusion about the geometry of the arms.

The lengths of the segments 1–8 are 0.30, 0.30, 0.65, 0.85, 0.30, 0.30, 0.50, 0.50, normalized to the largest distance from the centre. The number of complexes in a row ranges from five in the inner parts of the arms to 15 in the outer ones.

The segments 1, 2, 3, 4, 6, 8 of Figure 1 are identical with Waller's *et al.* (1997) segments 4, 6, 10+12, 11, 8, 1, correspondingly. Segments 5 and 7 in Figure 1 are additionally recognized in the pattern. Five segments (from the total number of 12) identified by Waller *et al.* (1997) are not confirmed by the new analysis; the global quasiregular two-arm geometry of the pattern has not been revealed in their work.

Thus, we may see that (1) the global spiral pattern in M 101 is represented by two polygonal lines; (2) the polygons are almost identical; (3) the phase angles of the arms differ by $\pi/2$.

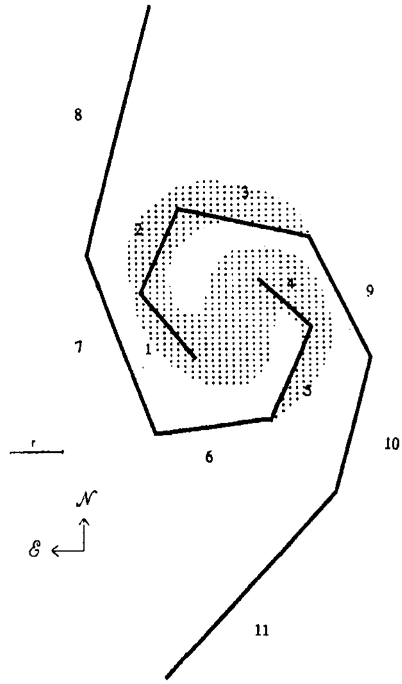

Figure 2 Schematic outline of the straight segments in the spiral pattern of M 51. The data on the emission of the interstellar gas used for this figure seem to be especially instructive. The emission is strongly peaked in the major spiral arms of the galaxy and mainly organized into coherent structures that follow rather closely the "optical" straight arm segments (see references in the text). The CO density is strongly concentrated in the stripes that are completely coincident with the dark dust lanes along the inner edges of the major spiral arms. The narrow and sharp dust lanes are especially contrasted in the polychromatic images of the galaxy given by photographs in blue, yellow, and red as well as by combinations of the photographs (VV, pp. 37, 79, 584). The polygons traced by dark lanes and CO emission are overlaid here on the wide and smooth arms traced by the old red stellar population in the disk (González and Graham, 1996).

3 ANOTHER EXAMPLE: M 51

The nearby face-on giant spiral M 51, one of most photogenic, can be analysed in a similar way. The geometry of this galaxy is well traced not only by bright chains of complexes, but also by the dark lanes. A polychromatic view of the galaxy is provided by the photographs in blue, yellow, and red with masked and unmasked images (VV pp. 37, 79, 464, 484). The data on ionized, atomic and molecular gas in M 51 (Tully, 1974; Visser, 1980; Rydbeck *et al.*, 1985; Vogel *et al.*, 1988; Petit *et al.*, 1996; Hippelein *et al.*, 1996; Beckman *et al.*, 1996) are also used in the analysis.

Figure 2 presents the "dark" two-arm spiral pattern of M 51 traced by dust lanes. Here 11 major straight segments are recognized. The dark lineaments are identified with even better reliability than the bright rows in the case of M 101

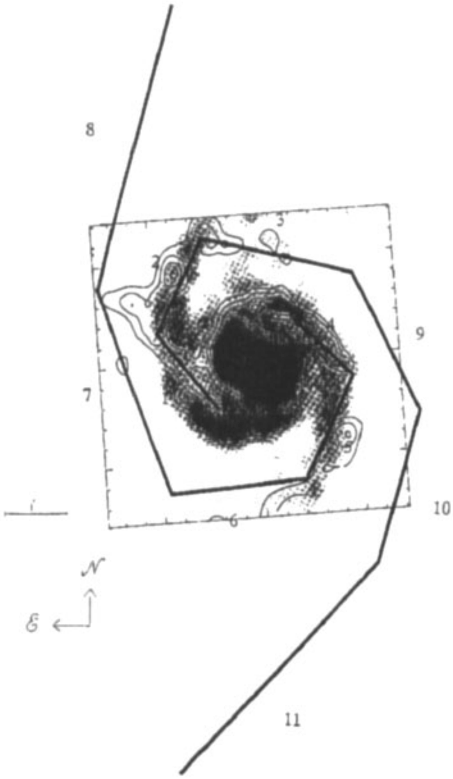

Figure 3 The dust lane pattern overlaid on the CO map of M 51 (Garcia–Burillo *et al.*, 1993).

because the dark lanes are fairly sharp and thin, in the photographs I used. The Eastern arm is presented as a broken line with five segments, and the Western one with six. In both arms, straight segments comprise more than 90% of the arm length. The lengths of the segments 1–11 are 0.35, 0.30, 0.60, 0.80, 0.85, 0.30, 0.45, 0.50, 0.60, 0.8, 0.85, as normalized to the largest distance from the centre.

The dark and bright features are evident related to one another; the brightest rows of M 51 are associated with the dark lineaments 1, 2, 3, 5, in Figure 2. The two-arm polygonal pattern of Figure 2 is well confirmed by the interstellar tracers, as demonstrated by Figures 3, 4.

We may see from Figures 2–4 that: (1) the global spiral pattern in M 51 is represented by two polygonal lines; (2) the polygons are almost identical; (3) the phase angles of the arms differ by π; (4) the dark lineaments are located along the inner edges of the spiral arms; the bright rows are behind dark lanes.

A comparison of two patterns shows that there is a remarkable similarity in the geometry of the polygons in the spiral patterns of M 51 and M 101. The polygons form the patterns of two types of symmetry: one corresponds to the phase rotation on the angle π (M 51) and the other on the angle $\pi/2$ (M 101).

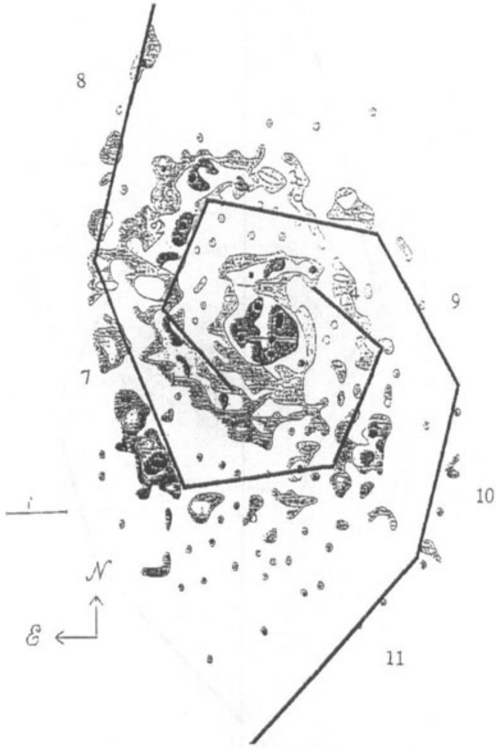

Figure 4 The dust lane pattern overlaid on the H_{α} map of M 51 (Tully, 1974).

4 THREE MORE EXAMPLES

Following VV, we have recently compiled a list of spirals with straight arm segments (Arkhipova *et al.*, 1999). Figure 5 shows three spiral patterns with straight segments identified in optical photographs. One of them, NGC 2997, have two polygonal arms shifted by an angle $\pi/2$ in phase; it is very similar to M 101. Two other galaxies, NGC 6954 and MGC 5457, exhibit four-arm structure with the phase shift angle $\pi/4$.

We see again that the polygonal geometry of the arms is more or less similar; in five patterns of Figures 1–5 the length of a segment increases generally with the distance from the centre and the open angle between two segments is near 120°.

VV (pp. 200–202) mentioned that the longest dark lanes are usually observed in the outer parts of the disks where the lanes become straighter as the distance from the centre increases, especially in barred spirals (see also Chernin, 1997). Examples of these structures can be found in NGC 5383, NGC 1300, NGC 6951, NGC 1097, NGC 3504, NGC 1530. Dark lanes are a good tracer of the spiral structure as bright chains of star-gas complexes, in many galaxies.

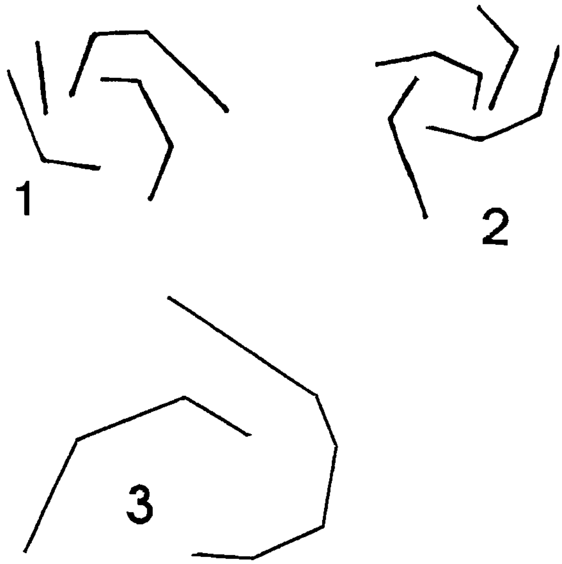

Figure 5 Outlines of spiral patterns with straight segments in three galaxies: (1) NGC 6946, (2) NGC 5457, (3) NGC 2997.

5 ON THE NATURE OF STRAIGHT SEGMENTS: FLATTENING SHOCKS

The physical nature of the phenomenon of straight arm segments has not yet actually been discussed. In the work by Waller *et al.* (1997), it was only mentioned that the origin of the rows cannot be explained by the gravitational potential of the grand design spiral or/and tidal torques from a satellite galaxy, because the equipotential contours do not contain finite straight-line segments (cf. Elmegreen *et al.*, 1992; Howard *et al.*, 1993). Waller *et al.* (1997) mention briefly that internal perturbations by massive disturbers orbiting within the disc "seem to do the best job"; they argue that simulations with such disturbers (Byrd, 1983) yield spiral arm patterns with linear arm segments and with opening angles of $\sim 120°$.

However this is hardly the only opportunity. It seems reasonable to assume that non-linear gas-dynamics with shock waves can also be a key player here. The gas-dynamical approach is suggested by the fact that the observed dark dust lanes in the spiral structure are definitely associated with the shock fronts: these are the dense shocked gas layers (see the book by Kaplan and Pikel'ner, 1979, for detailed discussion and references). Therefore, looking at the "dark" pattern of Figure 2, we see directly the geometry of the large-scale shocks in the disk of the galaxy.

Gas-dynamics of the giant galactic disk develop in the gravitational potential which is mainly due to the distribution of the old populations of red stars of the disk. The latter seems to be typical for grand-design disks; the old-star population is directly detected in the spiral arms of our Galaxy (Efremov, 1989, 1997). I suppose that the old-star equipotential profile is of "standard" density-wave type, without any local disturbances, in the galaxies like M 51 and M 101.

The latter is supported by the IR surface photometry of M 51. In IR images, spiral arms, though broader and indeed smoother than in the optical, turn out to he more regular and well defined (see Gonzalez and Graham, 1996, and references therein). The IR images reveal directly the underlying distribution of the old red stellar populations of the disk. There are no straight segments in the IR spiral pattern (Figure 2).

The following considerations seem to be useful in the search of the relation of rows and lineaments to each other and to shocks:

(1) Global spiral shocks compress gas and dust into thin dense layers along the spiral arms (Kaplan and Pikel'ner, 1970; Elmegreen, 1979; Efremov, 1989; Elmegreen *et al.*, 1992). Therefore, if we see a straight segment in a given area of the dust lane, it means that the shock front is flat in this local area.

(2) Star-formation proceeds behind the spiral shock fronts in such a way that huge gas clouds, or superclouds (Efremov, 1989, 1995; Elmegreen, 1990, 1994; Elmegreen and Elmegreen, 1983; Elmegreen and Efremov, 1996) form out of the material of the shocked layers via gravitational instability and fragmentation. They transform eventually into star-gas complexes. This was discussed for the curved segments of the spiral arms, but it is clear that the curvature itself does not affect the process, because the star-gas complexes and giant H II regions with their sizes about 1 kpc cannot be sensitive to the curvature with the radius of curvature of 10–20 kpc and more. So one can think that the same process of star-formation proceeds behind flat local areas of the shock fronts and form rows there in exactly the same way.

(3) Large-scale chains of gas-star complexes formed behind spiral shock fronts keep the regular spiral geometry of the parent gas layer for at least $\approx$ 20–30 Myr against shear flow distortions in the rotating disks. This is a reason to believe that the rows of complexes formed in flat layers can also preserve the regular c flat geometry of the parent gas layer for some time. In the galaxies seen face-on, they should look like straight local segments of the spiral pattern.

Thus, the major question of the discussion is: How can local flat areas form in the global spiral shock fronts?

Large-scale spiral shocks in galaxies have been widely studied since the pioneering works by Lin and Shu (1964), Roberts (1969), Pikel'ner (1970), Shu *et al.* (1973), Elmegreen (1979). They form in the interstellar gas flow when it crosses the gravitational potential wells of spiral arms. Both gravity and gas-dynamics control this process. The potential well acts as a "piston" which tries to slow-down the flow. Gas reaction to this gives rise to large-scale shock formation.

It is well known in gas-dynamics that the geometry of the pistons is not necessarily copied by the surfaces of the shock fronts that are formed by them. The front geometry depends also on complex and dynamically rich non-linear effects like generation of high-frequency harmonics, their propagation behind the front, reflection from the front and the piston, etc. Because of this, for instance, a concave or convex piston can form a flat front, in a shock tube. The same is possible – under certain conditions – in the grand-design gravitational potential; its contours are concave to the up-flow.

Indeed, soon after the formation of a shock by the potential well of the arm (and actually during the very process), the structure and evolution of the shock is controlled by non-linear gas-dynamical effects which are as strong as gravity, at the front. One of these effects can make local areas of the global spiral shocks become flat in the course of this evolution. The time-scale of flattening is the same as that for the formation of the shock.

Basically, local flattening of the front has the same physical nature as the universal stability of a flat shock against any weak perturbations that disturb its front surfaces. This stability has been long recognized in both experimental and theoretical studies (see Landau and Lifshitz, 1986 – original Russian book of 1954; Kontorovich, 1959; Zel'dovich and Raizer, 1967; Whitham, 1974).

It might be noted, however, that the stability of a flat shock was studied for the case of a uniform medium, while the interstellar medium in galactic disks is not uniform. The question of stability of large-scale flat shocks in galaxies against weak distortions of their front surfaces was especially studied in some works. In the most recent one (Dwarkadas and Balbus, 1996), the stability has been tested and completely confirmed in a "semiglobal" analysis of the oblique galactic shocks: a slightly curved initially front surface rapidly becomes flat. (See also the important papers by Kovalenko and Levi, 1992; Jenkins and Binney, 1994; and books by Rohlfs, 1977; and Marochnik and Suchkov, 1996, for the references to earlier results.)

The stability of a flat shock takes place in the case when the surface of the front is curved not strongly, but slightly in a local area. This indicates the conditions under which the process of local flattening can develop in global spiral shocks. Consider a local area of the global shock front and assume that the shock front surface follows initially the local spiral geometry of the spiral potential well. This curved surface can be considered as a weak deviation from an imaginary flat surface here, if the size of the area is less than the local curvature radius (Figure 6).

More accurately, the condition can be formulated as $s \leq \langle R \rangle$, where s is the length of the chord S_i in Figure 6, and $\langle R \rangle$ is the average radius of curvature of the corresponding arc segment S_i. The effective amplitude of the perturbation, δ (see Figure 6), is definitely small in this case: $\delta/R \ll 1$.

As an illustrative example, one may use a logarithmic spiral to describe the criterion in some more quantitative detail. As VV (p. 189) mentioned, like many other spiral patterns in nature, the spiral arms of galaxies are mostly logarithmic spirals. The spiral is given by the equation $r = r_0 \exp(k\phi)$, where r, ϕ are the polar coordinates, r_0 and k are constants. The curvature of the spiral decreases with the distance from the center, and its local radius of curvature, $R = (1 + k^2)^{1/2} r$, increases linearly with the distance.

The flattening criterion shows that the size of an area that can become flat increases linearly with the radial distance: $R \propto r$. This means, in particular, that the process of flattening indeed has a local character: it cannot make the global

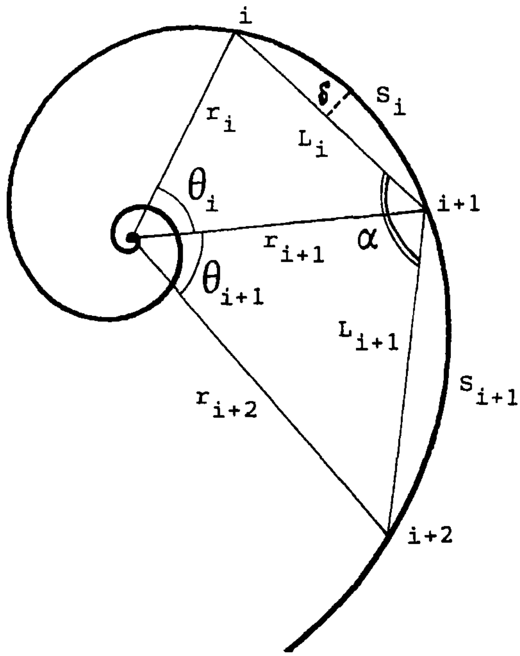

Figure 6 The flattening criterion and the characteristic angle. A logarithmic spiral $r = r_0 e^{k\varphi}$, is chosen as an example. If $k \ll 1$, the length L_i of each segment equals to the radius of curvature R_{i+1} of the spiral at point $i+1$, then each two neighboring segments intersect at angle $\approx 2\pi/3$, and also $L_i \propto r_{i+1}$.

spiral geometry totally flat, but it can be effective in local areas of the global spiral shock front. If an arc segment of a size s meets the criterion, every part meets the criterion as well; thus the final size of the segment in the process of flattening will be equal to the critical length R. In this sense, the process does not lead to any kind of self-similar fractal structure of flat segments.

A systematic increase of the lengths of the rows and/or dark lineaments with the distance from the centre is more or less obvious in M 51, M 101 and three other galaxies discussed above; the same can generally be seen in other galaxies with straight structures.

One may use the grand-design pattern to calculate the angle α between two chords (Figure 6) which meet the criterion above; the angle may also be followed as a function of the distance from the centre. Simple arguments (Figure 6) show that $\alpha \simeq 120°$. This is roughly confirmed by the observed geometry of M 101, M 51 and other galaxies under consideration.

Looking finally again at Figure 2, where both shock fronts and contour of the spiral-arm potential wells are outlined, one can find that the process of the spiral shock formation starts most probably at the bottom of the potential wells and the fronts do not leave the wells when they become flat.

6 CONCLUSION

The polygonal geometry of spiral arms discussed above can be recognized in many galaxies. The list we compiled includes M 87, M 100, NGC 309, NGC 1232, NGC 2805, NGC 2997, NGC 3134, NGC 4254, NGC 4303, NGC 3310, NGC 3147, NGC 1179, NCC 1187, NGC 4535, NGC 5427, NGC 5457, NGC 6221, NGC 6946, NGC 7424, NGC 6744, NGC 7137, NGC 1313 and a number of other galaxies (Arkhipova *et al.*, 1999).

The straight geometrical forms in the galaxies of this type provide a new insight into the complex and robust interplay of gravity and gas-dynamical effects in giant, galactic disks. The physical interpretation of the phenomenon given above (a brief account is in Chernin, 1997) assumes that the straight features, bright rows and dark lineaments, manifest the structure of the shocked gas and youngest stellar populations formed out of the shocked gas. Gas-dynamics with large-scale shocks develop on the background of the underlying grand-design gravitational potential. This potential is mainly due to the distribution of the old stars of the disk.

The key point of my discussion is the process of local flattening in the global spiral shock fronts. The universal stability of flat shocks reveals this direction here. The physics gives a simple and natural explanation of the phenomenon. It also provides grounds for the discussion of some more specific questions: (1) In M 101 and M 51, rows look like the brightest and bluest parts of the spiral pattern; can it be due to their specific orientation relative to the streamlines of the up-flow? (2) Galaxies with both regular and so-called chaotic (Elmegreen, 1979) spiral patterns contain rows mostly in the regular component. Does this mean that star-formation in the chaotic component is not associated with large-scale shocks? (3) Observed spiral structures exhibit a diverse morphology, with spurs, bands obliquely joining arms, rays extending radially, feathers, and miniature arms often present (VV pp. 193, 194; Elmegreen, 1990). How do they form and what is their relation to rows, lineaments and other larger structures?

The role of "internal massive disturbers" mentioned by Waller *et al.* (1997) to be responsible for the linear structures needs more discussion as well. Can disturbers explain the linear increase of the sizes of rows and dust lineaments with the distance from the centre? Or the existence of dust spirals turning into straight lines as the distance from the centre increases? The fact that straight structures are not at all unique and demonstrate abundant variety suggests rather more general physical causes than internal orbiting disturbers, for the phenomenon. The process of shock flattening seems to be general enough, in this sense.

But if the polygonal pattern is due to such a universal physical cause as stability of flat shocks, why do straight arm segments appear in many, but not in all spiral galaxies? Examples are known of almost completely regular spirals, and an extreme case is NGC 4622. The thin tightly wound arms wind round almost twice; their regularity and sharpness is exceptional. This galaxy is characterized by a bulge which is larger in relation to the disk. One can assume that the large bulge and, perhaps, some other peculiarities in the structure and dynamics of this galaxy, determine very narrow, sharp and steep spiral-arm potential wells which confine the spiral shocks strictly within them. The galaxies of Figures 1–5 demonstrate the other extreme with wide and smooth potential wells, while most spiral galaxies seemingly constitute a common case with various combinations of the features of both extremes.

Acknowledgements

I thank Yuri Efremov and Anatoly Zasov for discussions and cooperation. The work was partly supported by the Russian Foundation for Basic Research and the Program "Universities of Russia: Fundamental Science".

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