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# 6-arm blue grand design of NGC 309

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The geometry and physics of the spiral structure of the giant Hubble type Sc galaxy NGC 309 is studied. A schematic of two patterns with three arms in each is suggested for the blue spiral. The red and blue patterns form together a grand design with two-fold symmetry. A possible gas-dynamics explanation of the phenomenon is suggested which shows how the two-arm red spiral may induce the formation of the six-arm coherent blue spiral.

*Keywords*: Galaxies: individual (NGC 309) – galaxies: spiral

## 1 Introduction

The NGC 309 galaxy is one of the largest and most luminous grand-design known spirals (Fig. 1). At a redshift distance of 83 Mpc ($H = 70$ km/s/Mpc), its diameter is $\simeq$70 kpc and its absolute blue magnitude is –22.52 which corresponds to the luminosity classification type I (van den Bergh 1960). In the images of the Hubble Atlas (Sandage 1961) and the Carnegie Atlas of Galaxies (Sandage and Bedke 1999), the spiral arms of NGC 309 spread over the whole galaxy disk. According to Sandage (1961), its Hubble type is Sc. Elmegreen and Elmegreen (1984) classify the galaxy as "extreme grand design".

Radically different morphologies are observed in optics and infrared wavelengths of NGC 309: instead of long, narrow, and clumpy multiple arm appearance seen in blue, only two principal arms and a prominent central bar are seen in red; the red arms are short, wide and smooth (Block and Wainscoat 1991). A similar difference between blue and red images was earlier found in the M51 galaxy by Zwicky (1957) who concluded that the morphology of the old red population of the disk need not mimic the morphology of the young blue population. The same point was also made by Vorontsov-Vel'yaminov (1978).

The morphology features of NGC 309 combined with an almost face-on orientation offers unique prospects for addressing important issues associated with the geometrical structure and physical nature of grand-design spirals. It is also important that the

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**Figure 1** SDSS image of the spiral galaxy NGC 309. From SDSS survey, compose *gri* image. Attribution for these images ought to be, at least, David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration.

galaxy does not have close companions; because of this its special features must be due completely to internal causes. What is the physical relation between the two-arm red spiral and the multi-arm blue spiral of NGC 309? An answer to this question proposed in this paper is based on the gas-dynamics approach to the spiral structure formation proposed by Roberts (1969) and Pikel'ner (1970). It is argued below that the blue multi-arm grand-design appears as a nonlinear response of the gaseous disk to the gravitational potential produced by the red arms.

In Sec. 2, a schematic for the blue and red spirals of NGC 309 is suggested based mainly on the images published by Block and Wainscoat (1991); in Sec. 3, the nonlinear gas-dynamics structure, the "Landau–Lifshitz configuration", is discussed as a possible physical mechanism of the blue arm formation; the results are summarized in Sec. 4.

## 2 Blue and red spirals

The optical image of NGC 309 presented by Block and Wainscoat (1991) was processed in a special way, so that faint features were printed at the same contrast as the bright ones. The processing enables us to recognize six long arms of different brightness, not to mention the small-scale spurs and branches, in the improved blue image inside

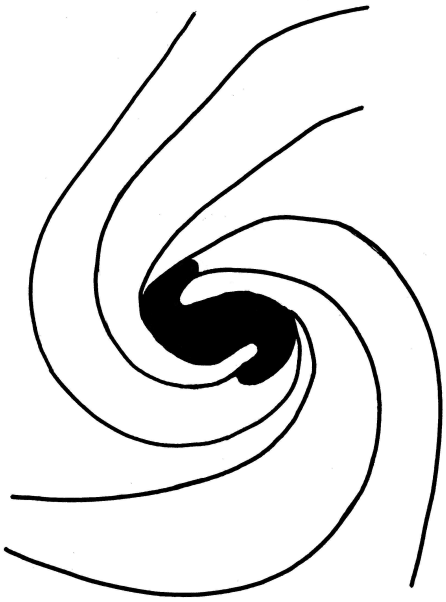


**Figure 2** A schematic of the six-arm blue spiral of the galaxy NGC 309: two coherent patterns with three arms in each. The two-arm red spiral is indicated by closed contour in the inner area of the disk.

35 kpc from the disk center ($H = 70$ km/s/Mpc). Block and Wainscoat (1991) mentioned a "three-arm appearance" of NGC 309 in blue light, and three of the arms are the brightest ones indeed; but three others can also be recognized in the image. In Fig. 2, the six-arm blue spiral is sketched in the manner of Zwicky's (1959) drawing for M51. The blue grand design of NGC 309 is shown cleaned of small-scale details and irregularities like spurs, bifurcations, branches, clumps, etc. The lines which represent the arms are given regardless of the brightness or the width of the arms, in Fig. 2.

Ignoring small-scale features as image noise, we find the six blue arms to be well regular and similar in shape to each other, in Fig. 2. It seems to be especially important that the blue arms are seen to be arranged into two wide coherent patterns with three arms in each. These patterns are not completely identical, but roughly similar in their shape. Each of the patterns goes from the central region outward, one to the NW direction (North to the top, East to the left in Fig. 2), and the other goes to SE direction. The length, width (which increases from the center outwards) and winding angle are practically the same in both patterns. The two patterns are located relative to each other in the way that their phase angles differ from each other in the angle of $\simeq 180°$. The patterns together form, therefore, a regular grand-design structure with two-fold symmetry.

The red (near-infrared, in fact) image of NGC 309 (Block and Wainscoat 1991) shows "only two short principal arms". The red spiral is of a "two-arm grand-design, with a prominent bar" which is "recognizable easily and unambiguously". It is characterized by 55–75% surface brightness enhancement compared with the underlying

disk. The red arms lie within a radius of 17 kpc from the galaxy center. They are smooth and round and "bear a striking resemblance to the red arms discovered by Zwicky on composite photographs of M51". Whereas the winding angles of the blue arms are large, the surface brightness of the red arms "decreases abruptly after a winding angle of only ∼180°". The inner two-arm structure is quite regular and has obvious two-fold symmetry, as represented in Fig. 2. Thus, both red morphology and blue morphology of the galaxy prove to have the same type of global symmetry. Moreover, the phases of both are nearly equal. The same symmetry and the same phase give clear evidence for a strong dynamical relation between the red and blue spirals of NGC 309.

It is hardly possible to recognize with certainty how the blue patterns are "connected" with the two-arm red spiral in the inner area of the galaxy where the blue patterns start winding. In a possible version of the connection given in Fig. 2, we use essentially a guidance from Zwicky's (1959) scheme for M51 and assume that each of the blue patterns starts to develop within the corresponding red arm.

Note that multi-arm spiral structures may also be found in the galaxies NGC 753, NGC 2997, NGC 5247, NGC 5584, NGC 5494, NGC 1566, NGC 3423, NGC 6878, NGC 6946, NGC 7125, NGC 7689, etc.

## 3 Landau–Lifshitz configuration

A possible approach to the physics which is behind the visible geometry of the NGC 309 can be developed on the basis of the classic theory of spiral shocks (Lin and Shu 1964, Roberts 1969, Pikel'ner 1970, Shu et al. 1973, Liverts and Mond 2003). According to the Roberts–Pikel'ner's spiral-shock paradigm, large-scale layers of compressed matter form in the interstellar gas when the gas flow crosses the gravitational potential wells of the spiral arms. The gravitational potential of the arms is considered to be mainly due to the density wave in the distribution of the old populations of red stars in the disk. Block and Wainscoat (1991) point out that the red image of NGC 309 enables us to see the underlying gravitational potential in the disk of the galaxy. Indeed, the potential has the two-arm structure and two-fold symmetry, as indicated by the red morphology of the galaxy (Fig. 1).

How can the two-arm gravitational potential drive six-arm grand design in the gaseous disk? This is the key question of the NGC 309 physics.

In a search for an answer to the question, a nonlinear supersonic gas-dynamical structure may be addressed which was described by Landau and Lifshitz (1979) as a "non-evolutionary jump". The jump appears, if, for instance, two gaseous masses come into contact collision with supersonic velocities. It forms on the surface of the first contact of the masses. Such a jump is called non-evolutionary because it is not a result of gradual nonlinear evolution of a supersonic flow, but produced by two independent flow masses that did not "know" about each other before the collision. In the simplest way, one may consider two plane flows that move towards each other from opposite directions. Generally, the physical parameters of one of the flows are completely independent from that of the other. Because of this, there is no "standard" correspondence between the densities, velocities, pressure, etc. on the opposite sides of the jump surface, and so the gas-dynamics laws of continuity are not

met at this surface. The non-evolutionary jump is completely unstable, and it must rapidly transform into a structure in which the continuity laws are satisfied (Landau and Lifshitz 1979). As a result, the non-evolutionary jump transforms into a set of "standard" jumps. The new structure – the Landau–Lifshitz (LL) configuration – includes three basic elements: a contact jump at the surface of the first contact of the flows and two shock fronts on the opposite sides of the contact jump. The normal (to the plane of the contact) component of the flow velocity is continuous at the contact jump. The flow densities are, generally, different on the sides of its plane. The matter inflows into the area between the shock fronts from the opposite sides, and the normal component of the matter flows has a jump at the surfaces of the chocks. This configuration is hydrodynamically stable, and a quasi steady-state can develop at which the configuration may evolve only on the time scale that is much larger than the time scale of the instability that leads to formation of the configuration itself. All the three jumps of the LL-configuration are the surfaces (actually layers) where gas is compressed.

If the flow is not one-dimensional, an additional dynamical feature may appear in the LL-configuration: the tangential (to the contact jump) velocity component may have a jump (tangential discontinuity) at the contact jump surface. This kind of discontinuity is known to be unstable, and a turbulence layer develops usually along the contact jump.

It may be assumed that the LL-configuration can appear in the gaseous disks of galaxies as the gas-dynamics response to the gravitational potential produced by over-densities in the red stellar population of the disk. In NGC 309, the massive two-arm over-density in the disk central area produces a two-arm spiral gravitational potential well which extends over the whole rotating disk (Lin and Shu 1964, Roberts 1969, Pikel'ner 1970, Shu et al. 1973, Liverts and Mond 2003). Moving in this potential, the gas of the rotating disk crosses the potential well and forms the LL-configuration along each of the two arms of the gravitational potential. The compression of the gas in the three jumps of the configuration leads to star formation there. As a result, the jumps become loci of star formation, and the sites of young blue stars trace the underlying gas-dynamics configuration. In this way, two-arm red spiral can induce six-arm blue spiral in the galaxy disk.

## 4 Conclusions

The image analysis of Sec. 2 suggests a rather regular model for the spiral structure of the galaxy NGC 309. This model is represented schematically by Fig. 2. As one can see:

1. The blue spiral grand design has six arms which are similar to each other in shape, if they are considered regardless of their brightness.
2. The blue arms are arranged into two coherent patterns with three arms in each.
3. The difference in phase angle between the two blue patterns is $\simeq 180^\circ$, and so they form together grand design of two-fold symmetry. The red spiral has the same symmetry.

The physical interpretation of the phenomenon of the six-arm grand design in NGC 309 may be searched in the context of the Roberts–Pikel'ner's spiral shock and the Landau–Lifshitz configuration. On this basis, a conjecture is suggested according to which:

1. The two-pattern blue grand design with two-fold symmetry is driven by the gravitational potential produced by the inner two-arm red spiral.
2. Each of the blue patterns consists of three arms formed by the Landau–Lifshitz nonlinear gas-dynamics configuration of the three standard jumps.
3. Gas compression in the standard jumps triggers star formation which reveals to us the six-arm underlying nonlinear gas-dynamics structure.
4. First attempts to find the Landau–Lifshitz configuration in computer simulations of the spiral structure seem to be promising (Filistov 2013).

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