

On the Spiral Structure of the Milky Way Galaxy

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Abstract—We consider a possible scheme of the overall spiral structure of the Galaxy using data on the distribution of neutral (atomic), molecular, and ionized hydrogen. Our analysis assumes that the spiral structure is symmetric, i.e., that the spiral arms are translated into each other via a rotation about the Galactic center by 180° (a two-arm pattern) or 90° (a four-arm pattern). In the inner region, the observations are best represented with a four-arm spiral pattern, associated with all-Galaxy spiral density waves. The initial position is that of the Carina arm, reliably determined from distances to HII regions and from HI and H₂ radial velocities. This pattern continues in quadrants III and IV with weak outer HI arms; from their morphology, the Galaxy should be considered an asymmetric multi-arm spiral. The knee-like shape of the outer arms, which consist of straight segments, may indicate that these arms are transient formations that appeared due to gravitational instability in the gaseous disk. The distances between HI superclouds in the two arms that are brightest in neutral hydrogen, the Carina and Cygnus (Outer) arms, are concentrated near two values, suggesting the presence of a regular magnetic field in these arms.

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1. INTRODUCTION

That the Milky Way system is a spiral galaxy has long been beyond doubt, but the positions and number of the spiral arms remain a matter of debate. Spiral-arm tracers are well known: the arms concentrate the most massive gas clouds and young stars and clusters. Distances to these latter objects can currently be determined very precisely, but only for those within three to four kpc from the Sun. Direct data have recently begun to accumulate on larger distances to sources of maser emission associated with young stars, obtained using VLBI. Only a dozen such distances are known so far, but even they can be helpful for refining distance estimates to fragments of spiral arms whose existence and location were established from other data.

It is currently possible to make quite specific conclusions on the positions of spiral arms, at least for the outer part of the Galaxy (i.e., for distances exceeding the solar distance from the Galactic center) based on data on clouds of neutral and ionized hydrogen, their velocities, and the Galaxy's rotation curve. For the inner Galaxy, it is sometimes possible to distinguish between small and large distances for clouds of atomic, molecular, and ionized hydrogen (determined from their radial velocities and the rotation curve) and also to get an impression concerning the spiral-arm locations.

Three principal types of spiral galaxies can be distinguished. A spiral structure that is symmetric with

respect to rotation about the galactic center, known as a grand design (GD) spiral, is related to quasi-stationary spiral-density waves due to deviations of the galaxy's gravitational potential axial symmetry, possibly due to the presence of a bar [1] or satellites; the best-studied examples are the galaxies M51 and M81. A multi-arm, or knee-like, structure (M101, NGC 1232) is probably transient and could be due to gravitational instability of the galactic disk [2, 3]; it is sometimes considered a variety of a GD spiral, because the inner parts of such galaxies may contain regular spiral arms. In contrast to the first two types, flocculent (patchy) spiral galaxies (NGC7793, NGC2841) consist of many short arm fragments that can be considered star complexes twisted by differential galactic rotation [4].

Data on other galaxies demonstrate that HI superclouds, giant molecular clouds (GMCs) and genetically related young stars, and HII regions are all located along spiral arms, and are often concentrated in giant star and gas complexes [5, 6]. The complexes in the spiral arms related to an all-galaxy density wave are probably formed by magnetic and gravitational instability due to the regular magnetic field directed along the arm. Observational evidence for this was recently found in the northwestern fragment of the S4 spiral arm in the Andromeda Galaxy, along which a regular wave-shaped magnetic field was detected long ago [7, 8].

We will try to draw some conclusions on the all-Galaxy spiral pattern initially assuming it to be sym-

metric; i.e., that the arms translate into each other for a rotation around the Galactic center by 180° (a two-arm pattern) or 90° (a four-arm pattern). Such symmetry is known in many galaxies with GD spiral patterns (for example, in M51). Evidence for the presence of this symmetry in our Galaxy has been presented in many studies (e.g., [9]).

Many years ago, de Vaucouleurs [10] classified the Milky Way as an SB(rs) galaxy. This classification is generally confirmed by modern data on the distribution of atomic, ionized, and molecular hydrogen; we will demonstrate that these data indicate a four-arm spiral pattern within the solar circle. The two strongest gas arms are subdivided into HI superclouds, and we found them to be located at quasi-regular distances along the arms, which is a possible indication of a regular magnetic field in these arms.

Data on the locations of rich young clusters and the regions of strongest star formation agree with this idea. The arms traced by HI assume a knee-like character in the outer part of the Galaxy, but generally continue the flow of the inner arms as they are represented by a four-arm scheme for the Galaxy.

2. CARINA–SAGITTARIUS ARM

A concentration of young clusters and OB associations in the solar neighborhood was detected long ago in three fragments of spiral arms, known as the Carina–Sagittarius, Perseus, and Cygnus–Orion arms (on the history of this problem, see, for example, [5]). There is no doubt that the first two of these fragments are parts of the all-Galaxy spiral pattern, while the Cygnus–Orion arm appears to be a bridge between the first two arms, probably beginning as a spur originating at the Sagittarius arm.

The key issue is the position of the Carina–Sagittarius arm, which has been reliably determined from data on the distribution and velocities of giant clouds of molecular hydrogen (GMCs). These indicate the presence of a single Sagittarius–Carina (Sgr–Car) arm with a length of about 40 kpc and a pitch angle of about 10° [11]. As a rule, these clouds are located in the cores of giant clouds, or superclouds, of atomic hydrogen; this was noted in [11] and is especially evident when overlaying Figs. 7 and 15 from [12], as is shown in Fig. 1 (top). The regularity of the distances between the superclouds is striking; it was first noted by Efremov [13] and later confirmed in other studies [7, 8, 14].

A large part of the Carina arm is outside the solar circle, so that the kinematic distances to the gas clouds tracing the arm are unambiguous. These distances are also free of considerable random errors. The distances to closer HII regions are determined from their exciting hot stars rather than kinematically

(from radial velocities and the rotation curve). These regions are consistent with the general smooth shape of the arm, and thus can be used to “anchor” the position of the arm as a whole. In addition, the line of sight for longitudes $\sim 280^\circ$ – 300° is directed along the arm, so that distance uncertainties for objects in this longitude range do not change the position of the arm.

Based on the data of Grabelsky et al. [11, 12] for quadrant IV (which correspond to a limited range of velocities, from 7 to 50 km/s, and thus a limited range of distances) and of B. Elmegreen and D. Elmegreen [15] for the whole of longitude quadrant I, we derived the distribution of superclouds in the Car–Sgr arm displayed in Fig. 1 (bottom left) [13, 14]. We read the longitudes of supercloud centers for quadrant IV from Fig. 15 in [12]; we assumed their distances to be the same as those to the largest GMCs and HII regions located within the superclouds in the plane of the sky (Fig. 1, top). The data for quadrant I were taken directly from [15].

3. FOUR-ARM SCHEME FOR THE GALAXY

Figure 1 (bottom left) shows that the position of the Carina–Sagittarius arm defined by HI superclouds is in good agreement with the Galaxy’s spiral pattern plotted by Weaver [16] based on HI data.

The spiral pattern in GD galaxies is strictly symmetrical with respect to rotation about the galactic center by 180° (this is especially evident for M51 [17]), and, if a second pair of arms is present, these arms are located between the two arms of the first pair. Thus, it is possible to restore the entire spiral pattern knowing the position of a single arm, like a paleontologist is able to restore the entire image of a fossil animal from a single bone. Admittedly, significant deviations of the pattern from regularity, gaps, and additional arms are observed in most cases, but the presence of a bar in our Galaxy (cf. [18]) means that the dominant pattern should be a more or less regular two-arm or four-arm structure.

If our Galaxy is indeed a GD spiral, the Carina–Sagittarius arm should be overlaid on the other arms if rotated about the Galactic center. Figure 1 (bottom right) shows four logarithmic spiral arms with a pitch angle of 12° . The positions of all the arms in this spiral pattern are uniquely determined by the location of the Carina–Sagittarius arm, rotated three times by 90° about the Galactic center. Note that most studies based on the distribution of HI clouds and HII regions in the Galaxy as a whole result in a four-arm spiral structure.

Figure 2 (left) demonstrates that this scheme for the spiral pattern, based solely on the shape of the Carina–Sagittarius arm and the assumption that the

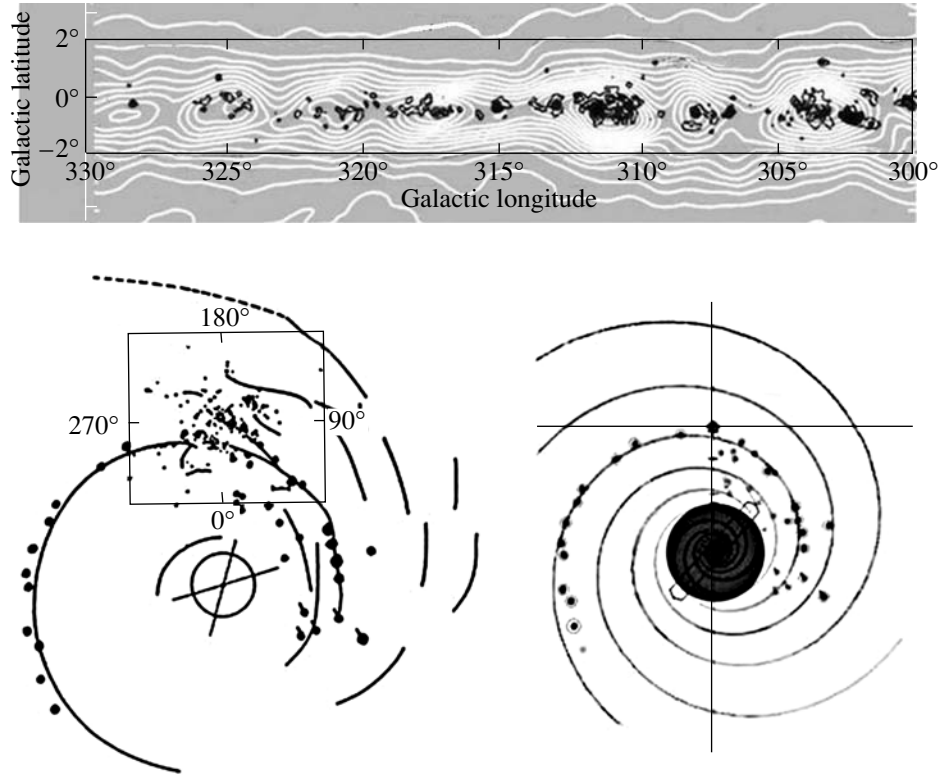


Fig. 1. Top: HI superclouds (light density contours) and molecular clouds (dark curves) in a part of the Carina arm. Bottom: scheme for the HI arms from Weaver [16] and the HI superclouds in the Carina arm and in quadrant II (left); the Carina–Sagittarius arm and its image repeated three times after rotation by 90° (right).

Galaxy's spiral pattern is symmetrical, fits perfectly that derived by Vallée [9], who summarized numerous studies devoted to this problem.

The right side of Fig. 2 plots the longitude dependences of the radial velocity for each of the arms in longitude quadrants I and IV derived by Vallée [9] based on his scheme and the assumption that the Galactic rotational velocity is constant (220 km/s). We overlaid the curves of [9] with the observed radial velocity curves for neutral hydrogen (Fig. 2, top right; data from [19]) and for CO (Fig. 2, bottom right; data from [20]). The agreement is good; the data for the Carina arm agree especially well. Figure 2 suggests that the Outer arm in quadrant IV in [21] should be considered a continuation of the Cygnus arm.

The positions of the tangents to the arms shown in the scheme of [9] (Fig. 2, left) generally agree with the longitudes where the kinematic arms change direction, visible in the data for the HI and CO velocities (Fig. 2, right). Note that, according to Fig. 7 of Luna et al. [22], the arm tangent-point longitudes in quadrant IV are located just inside the distances to the Galactic center where the rotation curve is closer to that of a rigid body (i.e., corresponds to a constant angular velocity). According to Elmegreen [23], such

a reduction in the amount of shear, i.e., with the rotation becoming closer to rigid-body rather than differential, should be observed within the spiral density waves. Similar fragments of rigid-body rotation were also detected in the rotation curve based on northern data.

Figure 3 displays the distribution of HI in the Galaxy based on essentially the same observations and the same rotation curve for the studies of Nakanishi and Sofue [24] (top left) and Levine et al. [25] (bottom left). The two studies indicate similar, very well-defined Carina and Cygnus arms, but their results differ strongly for the outer parts of the Galaxy. These regions of the spiral structure in quadrants II and IV, with low density and strongly deviating from the Galactic plane, are absent from the results of Nakanishi and Sofue [24]. Levine et al. [25, 26] were able to trace them using unsharp masking, which emphasizes density contrasts at intermediate and low levels.

Figure 3 (bottom right) demonstrates that the agreement between the two studies is actually excellent. Closer to the Galactic center, the positions of the Carina and Cygnus arms coincide, and the shapes of the Cygnus arm and of regions of enhanced HI density (superclouds) in this arm are virtually

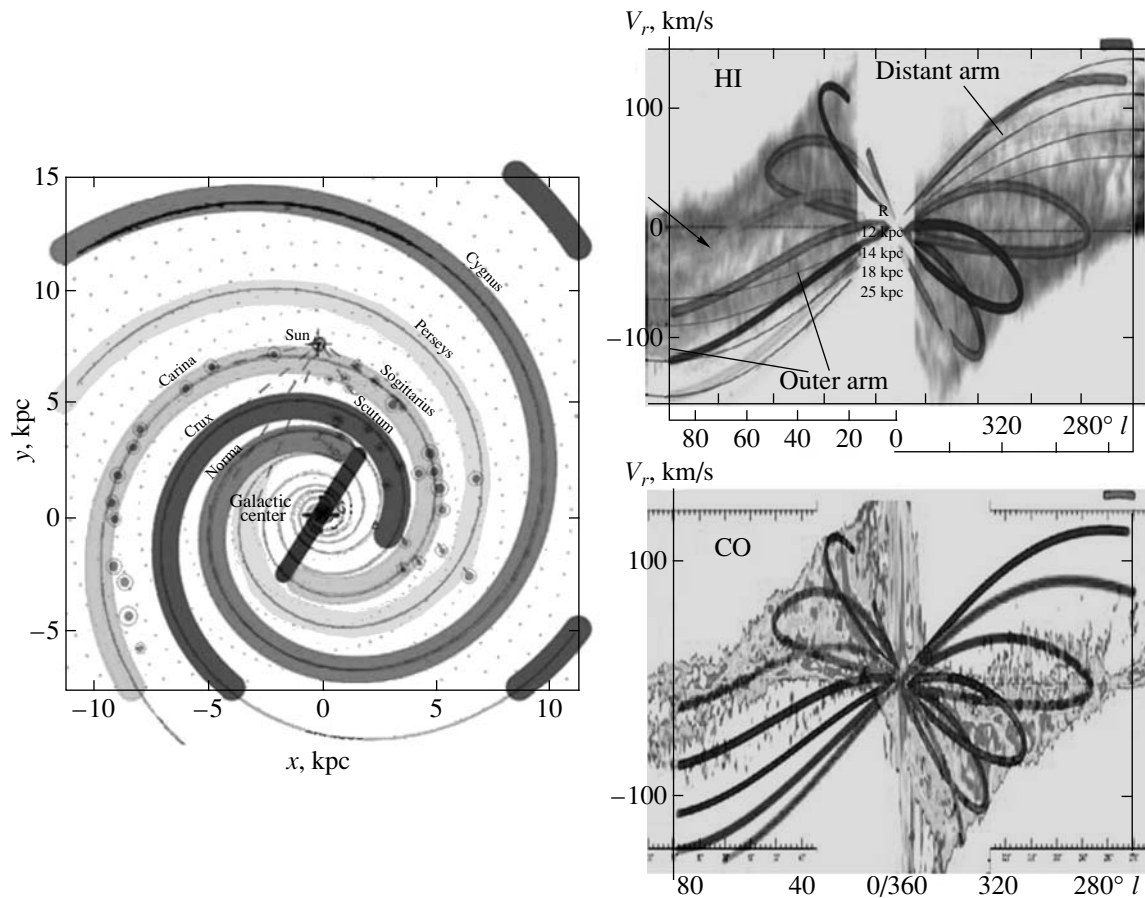


Fig. 2. Left: four-arm scheme for the spiral structure [9]. Right: observed HI (top) and CO (bottom) radial velocities (data are from [19, 20]) with overlaid computations by Vallée [8, 9, 14].

identical. The reason for this is probably that the two studies used approximately the same Galactic-rotation velocities (220 km/s) for their distance determinations (for 7–15 kpc from the center). Note that the Carina arm and Cygnus arm are equally strong within quadrants I and IV.

Figure 4 shows that overlaying the four-arm scheme of Vallée [9] with the HI distributions derived by Nakanishi and Sofue [24] (left) and Levine et al. [25, 26] (right) provides an excellent agreement for the Carina arm and a satisfactory agreement for the Cygnus arm. As was noted above, this scheme has arm positions corresponding to three rotations of the Carina–Sagittarius arm by 90° about the Galactic center. The four-arm scheme is in good agreement with the distributions of GMCs (Fig. 4, left) and HII regions (Fig. 4, right), taken from the currently most complete data of Hou et al. [27].

Figure 5 shows that the distribution of young rich clusters and giant star-forming regions are in excellent agreement with the four-arm scheme of Vallée and Efremov. The four-arm scheme also successfully

reproduces the positions of a dozen young rich clusters recently discovered from IR observations [28]; the scheme likewise agrees with the distances to maser sources (related to young high-mass stars) determined from their annual parallaxes using VLBI [29]. This scheme also agrees better with the positions of giant star-forming regions (presented in [30] based on Spitzer GLIMPSE Survey data) than the four-arm model suggested by Nakanishi and Sofue [31], based on their data on the distribution of molecular hydrogen. Note, however, that the scheme of [31] differs from our scheme only in the position of those parts of the Carina–Sagittarius arm that are most distant from the center (Fig. 5).

4. FOUR OR TWO ARMS?

We now consider data on Cepheids and open star clusters, which have reliable distances and should be concentrated in spiral arms, as follows from their distributions in other galaxies. Unfortunately, these data are complete only within about 3 kpc. Figure 6 shows that Cepheids (with ages mostly between 50 and 100 million years) are concentrated toward the Carina arm

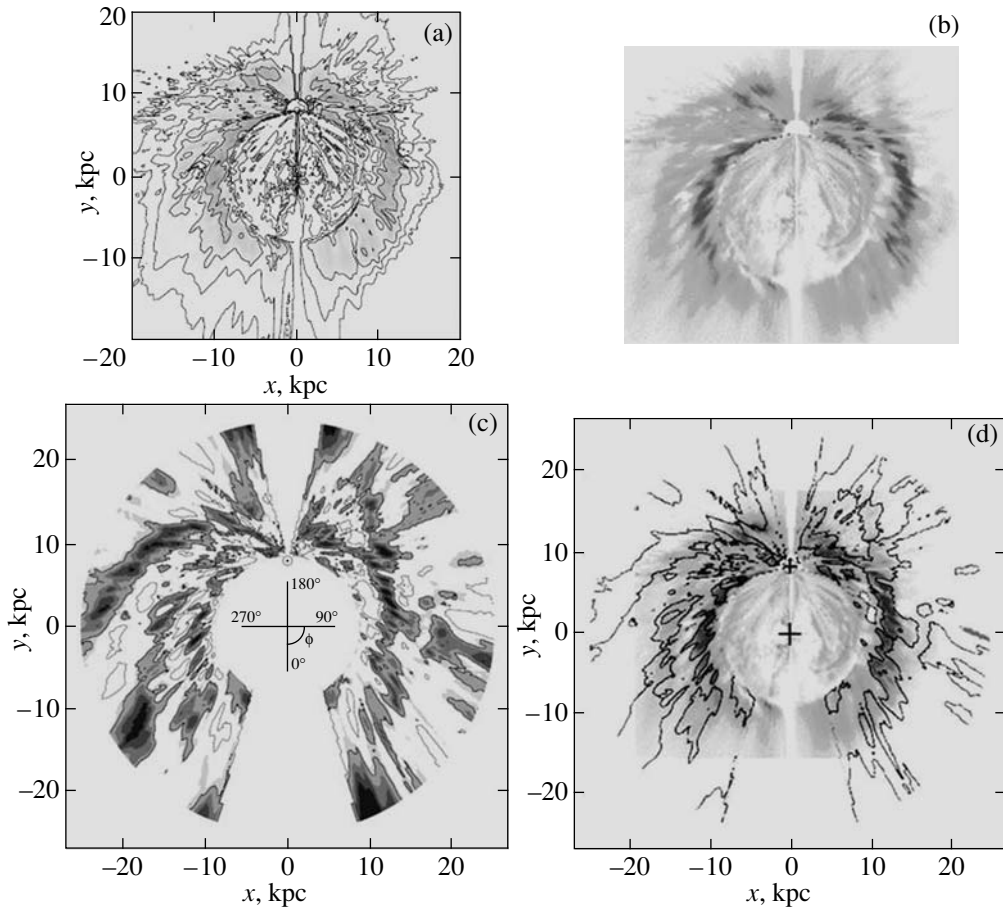


Fig. 3. Top: distribution of HI in the Galaxy [24] (left) and a raster image of the same map extracted from the pdf file using the Adobe Photoshop image editor (right). Bottom left: the distribution of HI in the outer regions of the Galaxy [26]. Bottom right: the top right map overlaid with boundaries of enhanced hydrogen density (compared to the mean local density), determined using data from [25, 26].

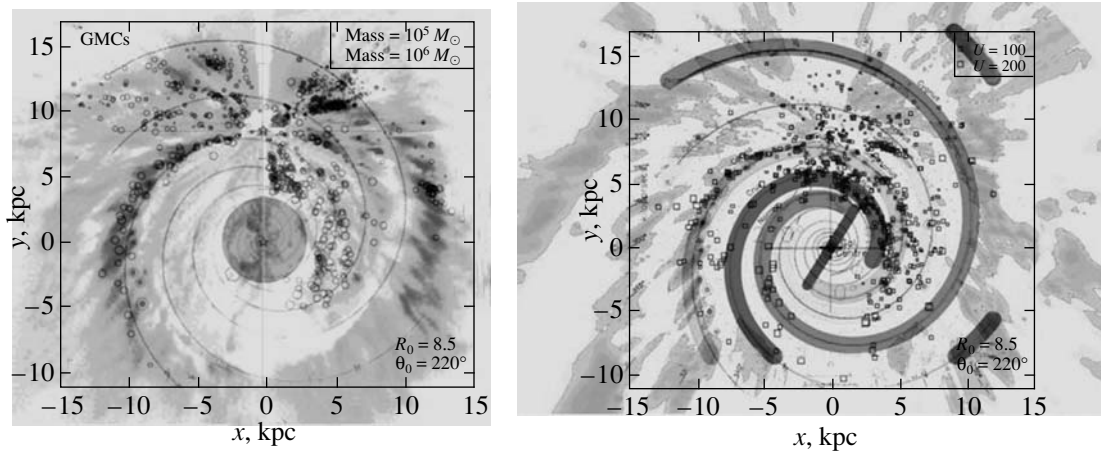


Fig. 4. Left: four-arm scheme overlaid on the positions of GMCs [27] and the HI distribution [24]. Right: scheme for the outer HI arms [26], overlaid on the positions of HII regions [27].

and, to a lesser extent, the Perseus arm, and are also present in the bridge connecting the Sagittarius

and Perseus arms (earlier often called the Cygnus–Orion arm). Younger clusters and O associations

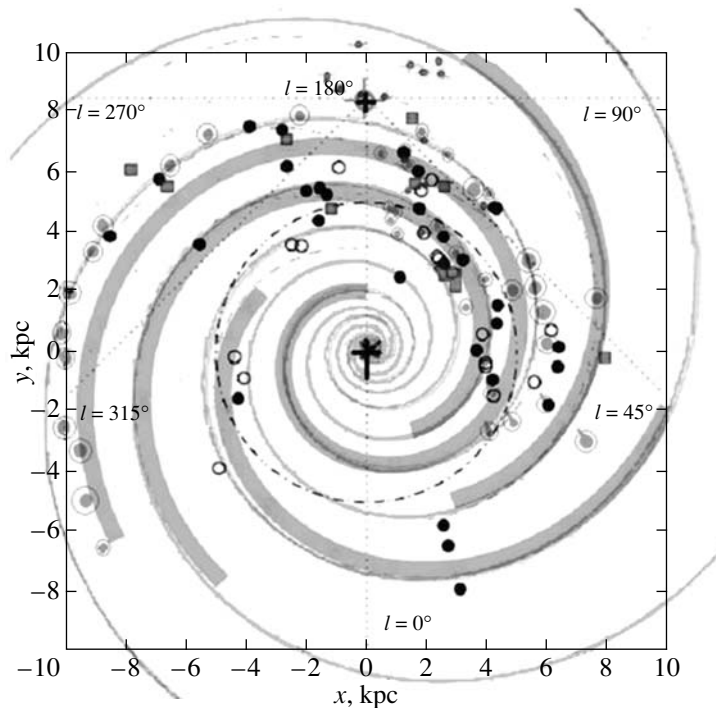


Fig. 5. Four-arm scheme overlaid on the distributions of rich young clusters from [28] (squares), star-forming regions with maser sources (dots), whose distances were derived from VLBA data [29], the largest star-forming regions (circles), whose distances were derived from IR data [30], and the spiral structure obtained in [31] from CO data.

reliably trace these three long-known arm fragments. Cepheid data based on extensive series of observations by L.N. Berdnikov were taken from [32], data on young clusters from [33], and data on OB associations from [34]. The bottom left panel of Fig. 6, taken from [35], presents the distribution of open clusters overlaid on fragments of spiral arms with a pitch angle of 6° .

In general, Fig. 6 demonstrates that the clusters and Cepheids (observable only in the solar vicinity) cannot be used to distinguish between the four-arm scheme (with a pitch angle of 12°) and the two-armed scheme (with a pitch angle of 6°). For both options, the position of the spiral pattern is uniquely fixed by the condition that the Sun is about 0.7–1.0 kpc from the axis of the Carina–Sagittarius arm.

However, the distribution of gas seems to provide evidence for the four-arm scheme, especially in the outer parts of the Galaxy. Figure 7 displays the Galactic distributions of HI (top) and CO (i.e., molecular hydrogen; bottom) with the two-arm (left) and four-arm (right) spiral patterns overlaid. The pattern in the left half of Fig. 7 strongly contradicts the direction of the HI spiral arms in the outer parts of the Galaxy, while the four-arm pattern satisfactorily agrees with the regions of enhanced density for both HI and CO.

Thus, the scheme with four almost symmetric arms with a pitch angle of about 10° – 12° meets no contradictions with available data at distances from the Galactic center to 9–10 kpc. Note that the pitch angle of about 6° that follows from the two-arm scheme is close to the lowest observed for other galaxies (4°), while 12° is close to the value implied by the correlation between the level of development of the bulge (i.e., the Hubble spiral subtype) and the pitch angle found by Kennicutt [36]. According to this correlation, the pitch angle of 6° needed for the two-arm model is possible only for Sa galaxies, while there is no doubt that the Milky Way galaxy has a later type (Sbc). Note, however, that GD galaxies display two arms more often than four arms.

According to the scheme of Vallée, like the Carina–Sagittarius arm, the Cygnus (Outer) arm originates at the ends of the bar, whose most probable direction and size are indicated in Fig. 6 [18]. The Cygnus arm is as prominent in neutral hydrogen as the Carina arm, but it is much weaker in molecular hydrogen (CO), corresponding to the decrease of the fraction of molecular hydrogen relative to neutral hydrogen with distance from the center observed for all galaxies. Thus, the star-forming intensity is much lower in the Cygnus arm. Figure 4 indicates that only a few star-forming regions are contained within this arm, concentrated toward the highest-density HI

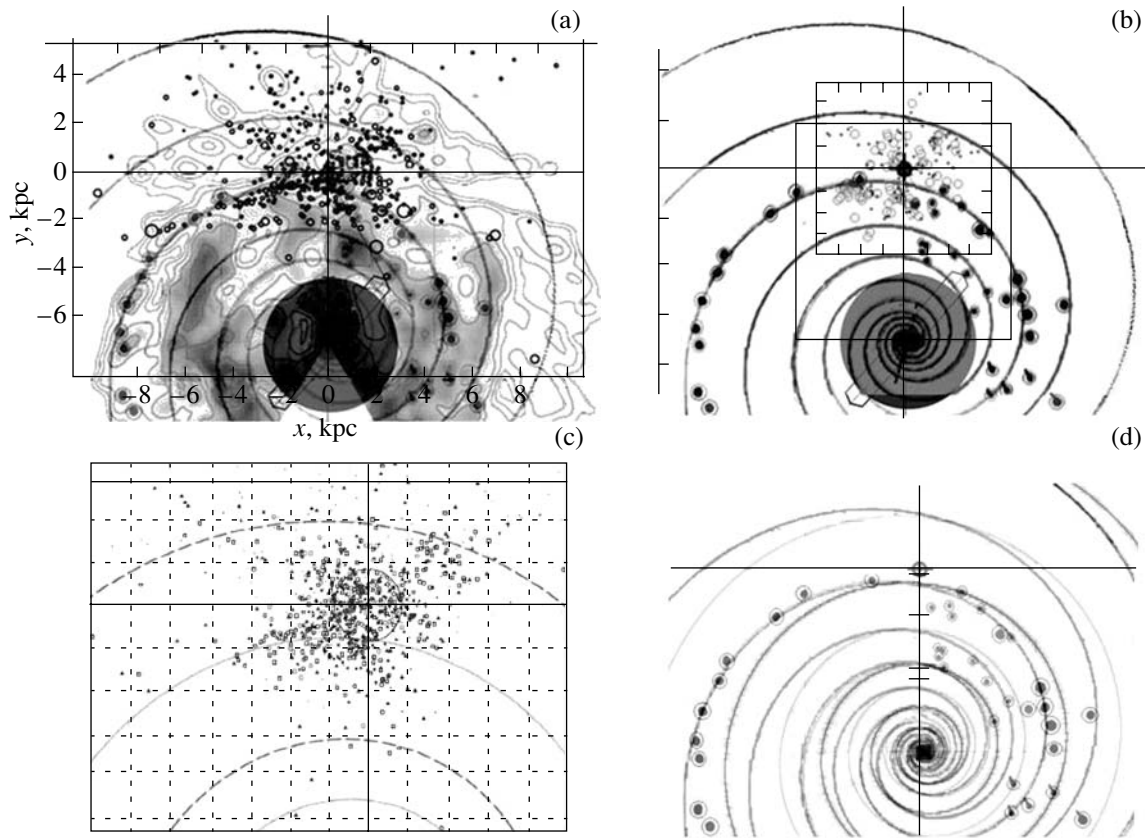


Fig. 6. Top: four-arm scheme overlaid with the distributions of CO [31] and of Cepheids [32] (left) and with the distributions of young clusters [33] and of O associations [34] (right). The probable position of the Galaxy's bar is marked. Bottom: the distribution of open clusters overlaid with a two-arm spiral structure with a pitch angle of 6° [35] (left) and fragments of the four-arm and two-arm schemes in the solar neighborhood (right). See text.

superclouds. According to Levine et al. [25], the Carina arm is somewhat below the mean plane of the Galaxy, while the Z coordinate of the HI layer in quadrant II, beyond the Cygnus arm, is already 2 kpc at distances of about 15 kpc, continuing to increase with distance from the center.

5. SPIRAL ARMS IN THE INFRARED

Let us now consider the longitude distribution of old stars detected in the medium IR by the Spitzer Space Telescope [37, 38]. An excess (by 20–30%) of old stars was detected in the directions of the tangents to the Scutum–Centaurus arm (in the terms used by Vallée and other authors, the Crux–Scutum cloud), and it was suggested that these two directions corresponded to an arm originating at the end of the Galaxy's bar closest to us [37, 38]. No such excess was detected along the tangents to the Sagittarius–Carina arm, indicating that this arm possesses an enhanced density of gas (as discussed above) but not of old stars (Fig. 8). Note, however, that young red supergiants are bright in the IR, and, though their spatial density is much lower than that of old red

giants, their relative contribution to red-star counts is expected to increase at large distances. This problem must be studied. James and Seigar [39] present data indicating that the contribution from red supergiants is from 3 to 33% in the K band.

We have already noted that the Carina–Sagittarius arm and the Outer (Cygnus) arm are better defined in HI than the other arms. We used the data on HII regions collected in Hou et al. [27] to plot Fig. 8 (top right), which demonstrates a maximum in the HII-region distribution along the tangent to the Scutum arm, which is sharper for stronger HII regions (Fig. 8, bottom left). This indicates that the Scutum–Crux = Scutum–Centaurus arm concentrates gas as well as stars, both young and old.

At first glance, it seems that the scheme of the Galaxy's spiral arms of Churchwell et al. [38] (top left) contradicts the Vallée–Efremov scheme, but Figs. 9 and 10 proves that this is not the case. The positions of the spiral arms virtually coincide in the two schemes; there is a disagreement only in connection with the question of whether particular arms originate at the ends of the bar.

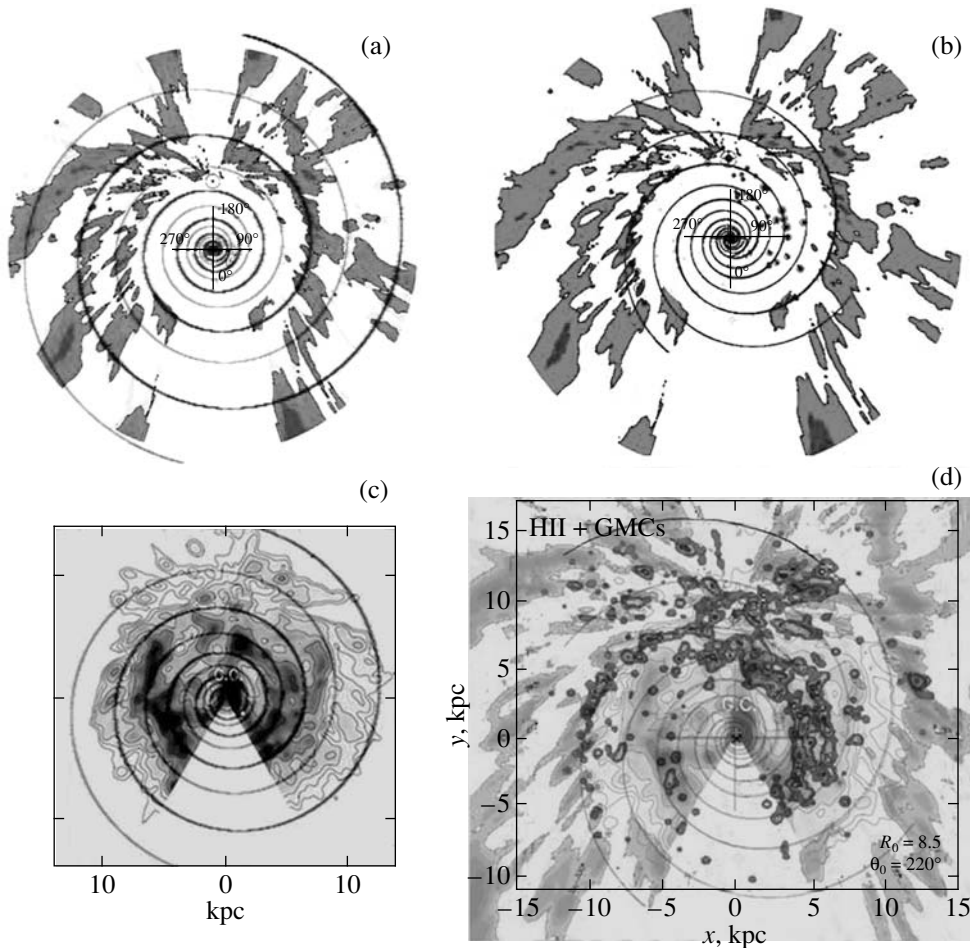


Fig. 7. Left: two-arm spiral structure overlaid with the distributions of neutral hydrogen [26] (top) and of molecular hydrogen [31] (bottom). Right: four-arm scheme overlaid with the distribution of HI [26] (top) and the same map supplemented with the CO distribution [31] and the mean positions of HII regions and GMCs [27] (bottom).

Figure 9 shows especially clearly that young rich clusters are located near the spiral arms, and that a group of four clusters is situated near the end of the bar. It is also known for other galaxies that star-forming regions tend to positions near the ends of bars.

Figure 10 is a master picture of the spiral structure traced by the four-arm scheme suggested by us and Vallée [9], shown together with molecular clouds and HII regions [27] and the star counts in IR [38]. Again, this shows the good agreement of existing schemes for the structure of the inner Galaxy. The presence of young stars in the Carina–Sagittarius arm is beyond doubt, as follows from the concentration of molecular hydrogen and HII regions, but the Cygnus (Outer) arm, which is equally bright in HI, contains only one region of concentration of clouds of both molecular and ionized hydrogen.

We note especially that, according to the four-arm scheme, these two strongest arms of the Galaxy originate at opposite ends of the bar, as is usually

the case, and both consist of a chain of superclouds. These superclouds are already extended along the line of sight due to the large velocity dispersion within them (and hence the large dispersion in the distances determined from the rotation curve); uncertainty in their mean distances is also possible, but the supercloud Galactic longitudes (and hence the distances between them along the arm) are determined with certainty.

It would be interesting to check what modifications of the Galactic rotation curves at distances from the center larger than 8 kpc would be needed for the northern and southern sky in order to achieve exact coincidence of the Cygnus and Carina arms after a rotation by 180° .

6. HI SUPERCLOUDS IN THE CARINA AND CYGNUS ARMS

Both arms most clearly defined in HI reveal a clear fragmentation into superclouds. These were first detected by McGee and Milton [40], whose maps of HI

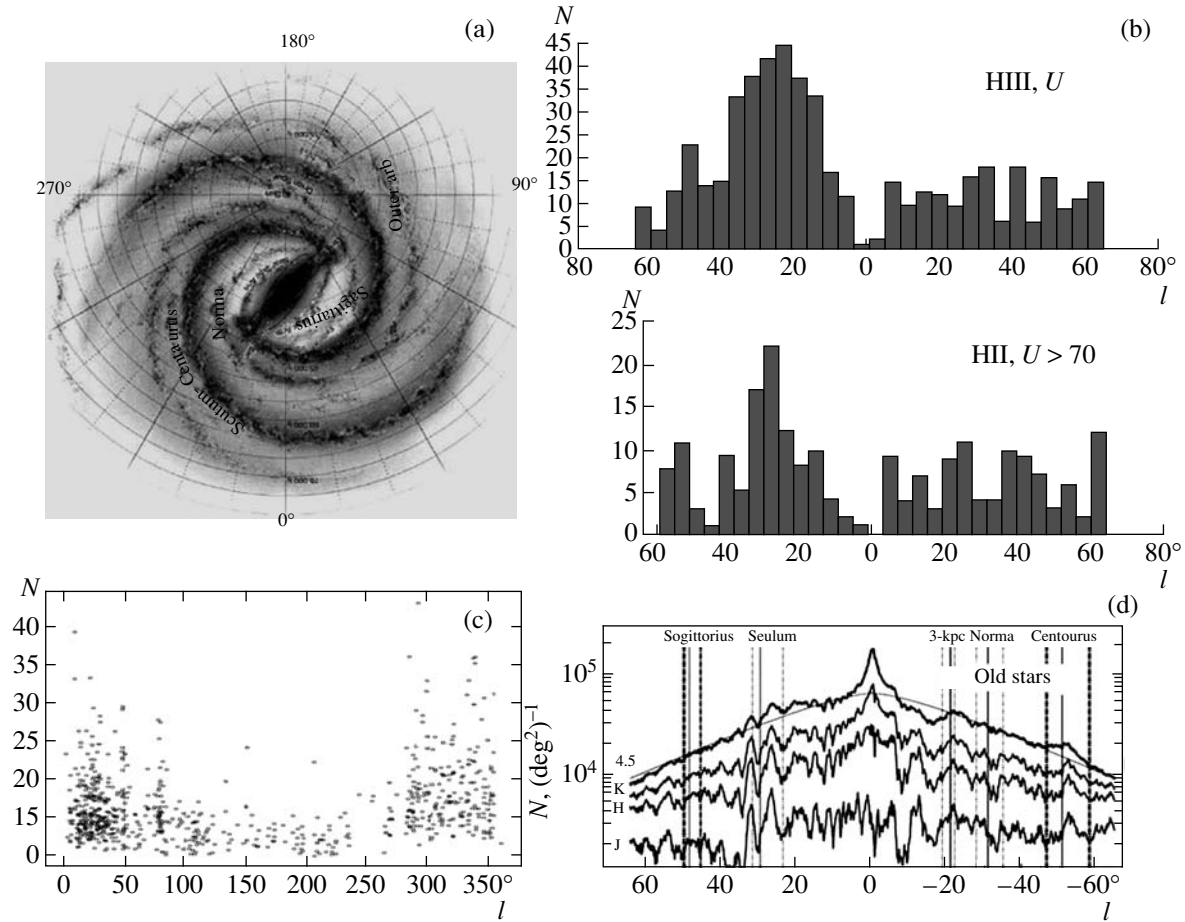


Fig. 8. Left: scheme of the spiral structure presented in [38] (top) and the longitude distribution of HII regions based on the data of [27] (bottom). Right: longitude distribution of HII regions (top) compared to the distribution of red stars (bottom) taken from [38].

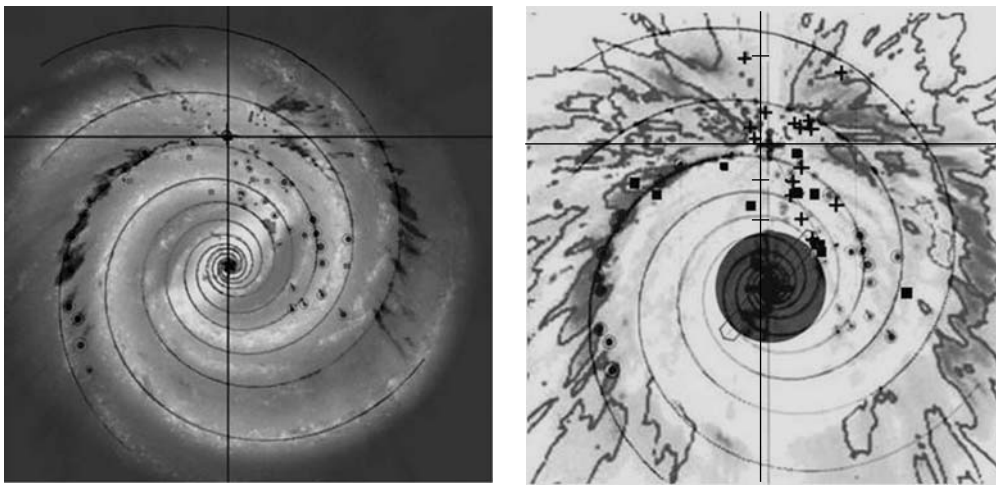


Fig. 9. Left: four-arm scheme overlaid with the scheme of [38], similarly aligned, and with the distributions of HI [24] and of young high-mass clusters. Right: a fragment of the bottom right map from Fig. 3 with young high-mass clusters added [28].

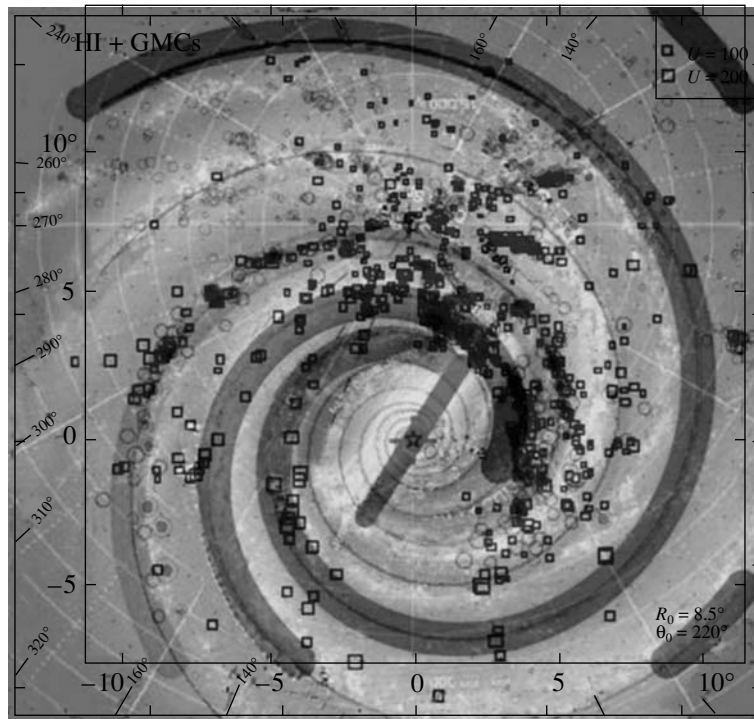


Fig. 10. The four-arm Vallée–Efremov scheme overlaid with the positions of HII regions (squares) and GMCs (circles) [27] and with the spiral-structure scheme of [38].

emission in the outer Galaxy exhibit a chain of superclouds with mean masses of $10^7 M_\odot$ and longitudes corresponding to the superclouds seen in Figs. 1 and 3 in the Carina and Cygnus arms. It was found fairly recently [7, 13, 14] that the distances between the superclouds were concentrated near two values, probably due to their formation under the influence of a magnetic and gravitational instability developing along the arm. This hypothesis is supported by the discovery [8] of a regular chain of star complexes in a particular fragment of one of the spiral arms of the Andromeda Galaxy, where Beck et al. [41] detected a regular wave-like magnetic field along the arm.

Figure 11 displays the distribution of the distances between superclouds measured along the arm in units of the Sun's distance to the Galactic center (black rectangles for the Carina arm and gray rectangles for the Cygnus arm). Adding the Cygnus arm confirms the tendency we found earlier for the Carina–Sagittarius arm: the superclouds tend to occupy positions along the arm separated predominantly by distances D of $0.1R_0$ or $0.2R_0$, where R_0 is the Galactocentric distance of the Sun. Figure 11 shows two cases of separations that are approximately twice these, but in both, we find a GMC between the corresponding superclouds (No. 21 and No. 38 in Table 2 of [11]), with no counterpart among the HI superclouds. Elmegreen and Elmegreen [42] describe a similar situation for four of the 22 galaxies where

they found quasi-regular chains of star complexes (called HII regions in [42]). The most probable explanation for this is that the complexes form *only* near extrema of a regular wave-like magnetic field along the arm, though there are no complexes at some of the extrema. However, as was noted above, star-forming regions less extended than complexes are also found at the corresponding positions in such cases. This is an instructive, though indirect, indication that it is precisely the regular magnetic field along the arm and the associated magnetic and gravitational instability that are responsible for the formation of quasi-regular chains of gas and star complexes.

The correlation between the positions of star complexes and magnetic-field parameters detected earlier in a segment of a spiral arm in M31 [7, 8] supports our suggestion, but we note that the presence of regular magnetic fields along arms remains unconfirmed for our Galaxy. Quasi-regular distributions of star complexes along arms were detected by Elmegreen and Elmegreen [42] for 22 spiral galaxies, while a total of some 200 galaxy images from the Palomar atlas were selected for their search for star-complex chains (B. Elmegreen, private communication). We conclude that regularity of this kind is rare. In seven cases, chains of complexes could be found in only one of the arms.

This suggests that cases of regular magnetic fields along arms are rare, and may be limited to some arm

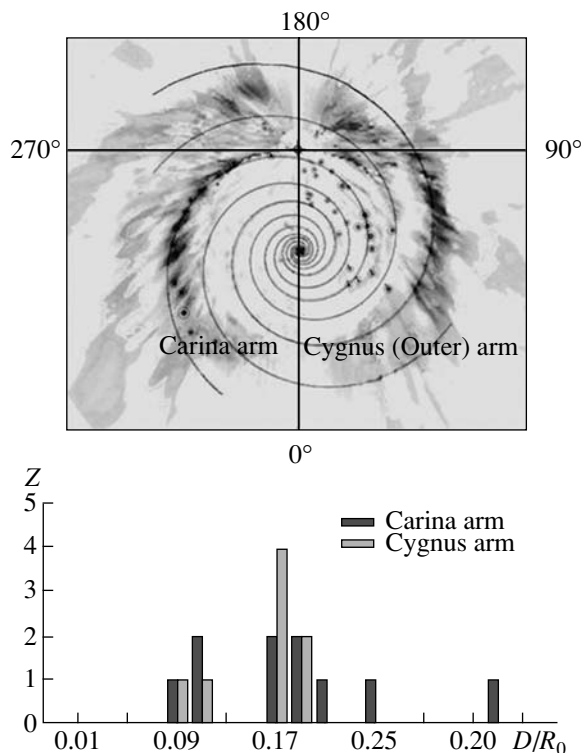


Fig. 11. Top: four-arm scheme overlaid with the distribution of HI [24, 26]. Bottom: the distribution of mutual distances between HI superclouds in the Carina and Cygnus arms.

fragments, thus explaining why chains of star and gas complexes are rarely seen in spiral arms of galaxies. However, it is certainly possible that, in the presence of such fields, some other conditions are also needed for regular chains of complexes and/or superclouds to form.

7. DISCUSSION

In the previous sections, we mainly considered the distribution of gas and young stars in the Galaxy. Let us now turn to the morphology of the spiral pattern taken as a whole.

The doubtless presence of long arms (in particular, the Carina–Sagittarius arm), traced by both gas and young and old stars, indicates that our Galaxy is not a flocculent spiral, but distinguishing whether its spiral pattern forms a wave (a GD galaxy) or it is a multi-arm galaxy is difficult (and possibly not needed, as we will see below).

In the ideal case, an age gradient across an arm (far from corotation; cf. [43]) is expected in GD galaxies with spiral-density waves. Strict symmetry via rotation by 180° is often observed, as was clearly demonstrated for M51 in [17] (i.e., the galactic center is an axis of symmetry of second order). There is no symmetry in multi-arm galaxies, at least far from their centers, and there is no reason to expect abundance

or age gradients across their arms, since the potential well is in the middle of the stellar arm [44].

An important argument supporting the idea that the inner regions of the Galaxy's spiral structure are generated by an all-Galaxy density wave is provided by the rigid-body-rotation fragments observed in the rotation curve of the Galaxy at distances from the center corresponding to the locations of spiral arms [22]. Earlier, Elmegreen [23] demonstrated from the wave theory of the arms that the rotation within the arms should indeed be closer to rigid-body than differential. Luna et al. [22] found three fragments displaying rigid-body rotation within the Galaxy's spiral arms in quadrant IV, and confirmed the conclusion of Elmegreen that this type of rotation favored the formation of star-generating gas clouds.

Note that the inner arms in M101 and NGC 1232 are more symmetric, and display dust lanes along the inner edges of their stellar arms; a knee-like, multi-arm structure appears only far from the center. The arms identified by Levine et al. [25, 26] in the outer Galaxy based on the excess HI density over the local level (Figs. 3 and 7) obviously consist of straight fragments, and continue the inner four-arm spiral structure in quadrants III and IV.

An inspection of the figures in [44, 45] suggests that knee-like arms can be formed due to the development of an internal gravitational instability (unrelated

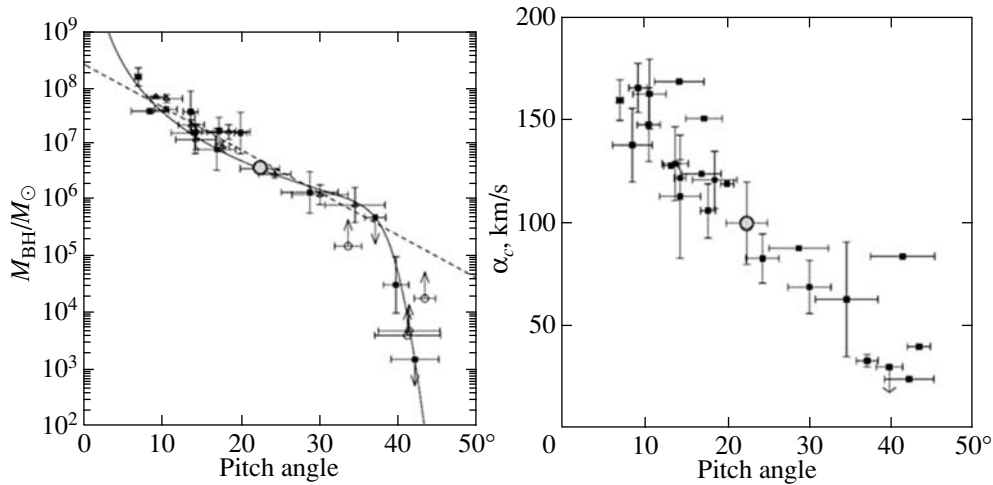


Fig. 12. Dependence of the spiral-arm pitch angle on the mass of the central black hole (left) and the central velocity dispersion (right). The data were taken from [51], with the data for our Galaxy (large circle) added.

to any influence from a bar or close neighbors) in the Galaxy's gaseous disk (see also [46]), resulting in a transient multi-arm spiral pattern. The individual arms appear and disappear, but the general pattern is always visible. In contrast to those due to a spiral-density wave, such arms rotating as a rigid body should not display transverse density gradients, while indications of such a gradient are known in the solar neighborhood [47] and there is kinematic evidence that the parts of the Carina–Sagittarius arms nearest to the Sun are consistent with the idea that the spiral arms are density waves [48].

According to Chernin [49], knee-like spiral structure can originate in a spiral shock whose front tends to flatten, so that the arm becomes subdivided into straight rows, as he noted for M51. In this case, there should obviously exist an age gradient across the arm (from dust and molecular hydrogen to HII regions and then older and older stars), as is observed in a straight fragment of the S4 arm in M31 [50].

We saw that the inner spiral arms had a pitch angle of about 12° ; however, this angle is clearly larger for the outer parts (the spirals are not so tight). The “global” value for the pitch angle of the Galaxy's spiral arms can be estimated from the relation between the mass of the central black hole and the velocity dispersion in the galactic bulges, which correlate with these parameters [51].

Figure 12 demonstrates that these relations give a pitch angle of about 22° for our Galaxy, which is acceptable for the outer regions only.

Figure 13 shows that the scheme for the Galaxy's outer arms of Levine et al. [25, 26] is compatible with the knee-like structure of the spiral pattern of the outer parts of the Galaxy, as well as the increased pitch angle of the arms (to 20° – 25°). These outer

arms are continuations of our four arms (whose pitch angle is 12°), and the Cygnus arm, which deviates from symmetry with the Carina arm in the quadrant I, exhibits an obvious bend in quadrants II and III, returns to its “natural way” in quadrant IV, and exactly continues a regular logarithmic arm over some distance, but with a larger pitch angle. The Perseus arm is also continued; however, it is clear that this arm and the Cygnus arm follow straight lines in their outmost sections.

This fact, along with the bends of both arms, the known gap in the Perseus arm towards the anticenter, and a straight spur originating at the Cygnus arm in quadrant II (Fig. 13), suggest our Galaxy is a M101-type multi-arm galaxy.

However, it can be noted in Fig. 13 that a continuation of the two arms along approximately logarithmic spirals but with a larger pitch angle is not ruled out. This would agree with the relation between a galaxy's rate of shear S and its pitch angle PA found by Seigar et al. [52], who derived the following relation from the rotation curves of galaxies:

$$\text{PA} = 64 - 73S,$$

where the rate of shear is:

$$S = A/\Omega = A/(A - B),$$

and A and B are Oort's constants.

Adopting $A = 15$ and $B = -10 \text{ km s}^{-1} \text{ kpc}^{-1}$ for our Galaxy, we find $S = 0.60$, $\text{PA} = 20^\circ$. Oort's constants have been determined for the solar vicinity (i.e., for Galactocentric distances of about 6–10 kpc), where the pitch angle is definitely smaller. However, for a flat rotation curve (observed, for our galaxy, approximately from 5 kpc to the center), we have $A = -B$ and thus $S = 0.5$, so that we get $\text{PA} = 28^\circ$ using

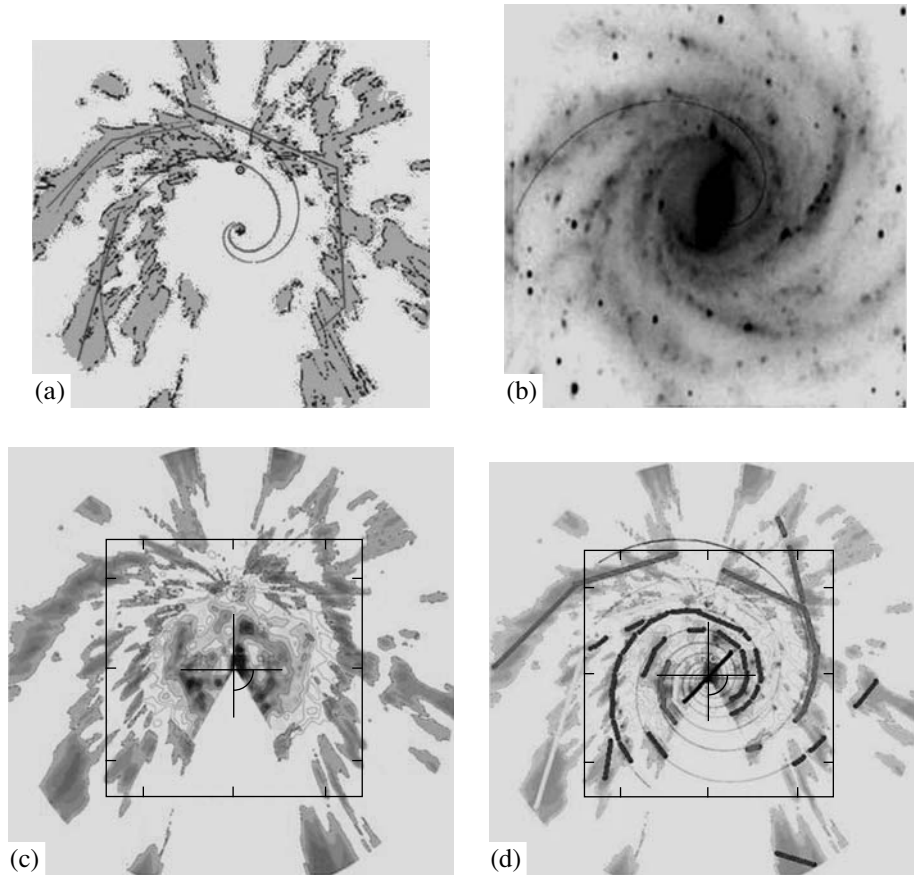


Fig. 13. Top left: attempt to plot knee-like segments and arms with a large pitch angle. Top right: fragment of a spiral with a pitch angle of 26° overlaid on one of the arms of NGC 2336. Bottom left: master plot of the neutral and molecular hydrogen distribution in the Galaxy (a combination of data from [26] and [31]). Bottom right: possible knee-like structure of the Galaxy's spiral arms.

the formula of Seigar et al. [52]. A similar value of the pitch angle is consistent with the scheme of Levine et al. [26] in quadrants II and III for the continuation of the Outer arm to distances exceeding 10–12 kpc (Fig. 13).

A large pitch angle at large distances from the center thus agrees with the relation of Seigar et al. [52], which is based on observations of other galaxies. This angle should increase when the rotation curve becomes flat, and such an increase can be observed for some galaxies, such as NGC 2336 (Fig. 13). However, the rotation curve of our Galaxy becomes flat starting approximately 5 kpc from the center, though the pitch angle of the arms in the inner Galaxy is certainly within 12° .

8. CONCLUSIONS

Generally speaking, it seems that the possibility that regular logarithmic spiral arms in the inner Galaxy become knee-like arms (consisting of straight fragments) in the outer Galaxy is most plausible. The

Milky Way is a spiral galaxy resembling (among the best-known systems) M101, but with a lower star-forming activity. Certain features also resemble M31, where the star formation is still less active, but the Milky Way differs from these two galaxies in the presence of a (relatively small) bar. Figure 14 displays images of the galaxies closely resembling the Milky Way, taken from the DSS and reduced to a face-on appearance. The classification of these galaxies is from the Sandage–Bedke atlas.

Levine et al. [25, 26], who were the first to identify continuations of spiral arms at large distances from the center, concluded that our Galaxy was an asymmetric multi-arm spiral. The knee-like shape of its outer arms and the straight shapes of some fragments of its inner arms provide evidence that such arms are transient features formed due to gravitational instabilities in the gaseous disk. The high velocities of some star-forming regions recently found using VLBA data [29] are also difficult to explain if the spiral arms are GD density waves.

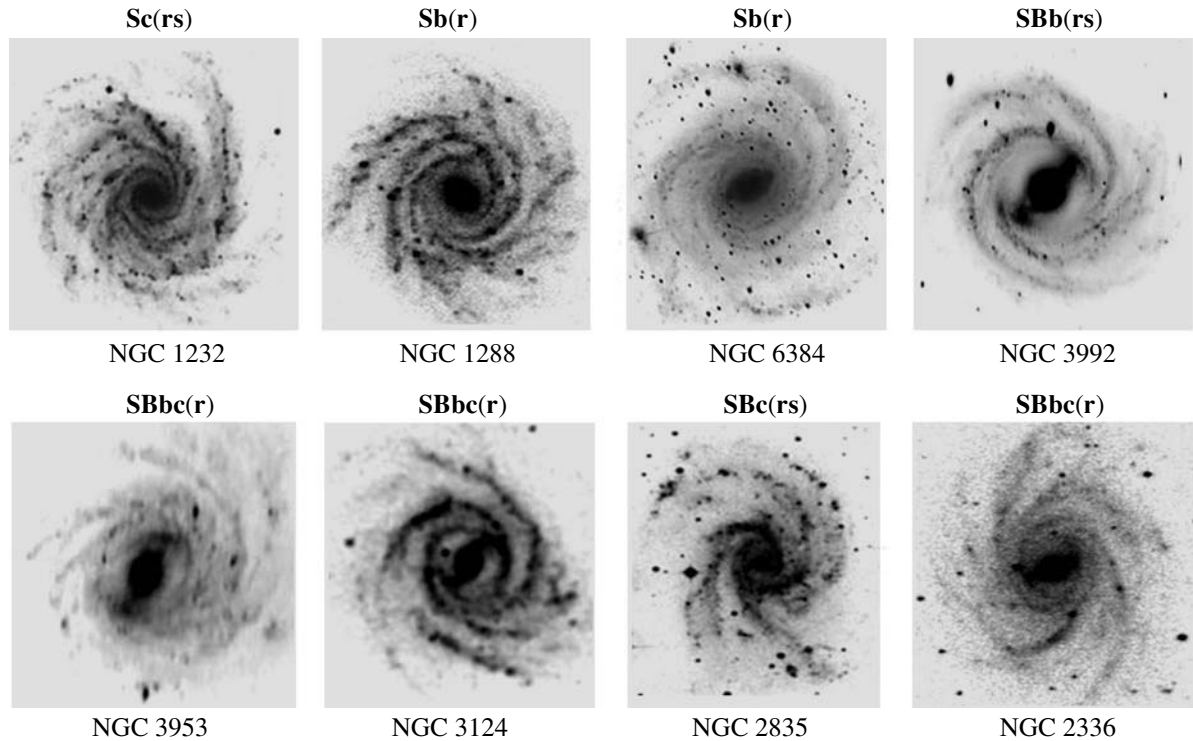


Fig. 14. Galaxies resembling our Galaxy.

However, the inner arms are more symmetric and can clearly be represented as logarithmic spirals. The presence of a bar and regular distances between superclouds in the two most clearly defined arms in HI testify that these arms are related to spiral density waves. At Galactocentric distances less than the solar value, we must choose between the four-arm scheme with a pitch angle of about 12° and the two-arm scheme with a pitch angle of about 6° . The first option is much more probable: it is closer to the mean value for arms of spiral galaxies, while the pitch angle of 6° is very small, such angles being observed only for galaxies with a high concentration of mass toward their centers and with well-developed bulges (Sa Hubble type), which is not the case for our Galaxy.

The distances between the HI superclouds in the two arms that are the brightest in neutral hydrogen, the Carina and Cygnus (Outer) arms, are concentrated near two values, possibly indicating that it is the regular magnetic field along the arm and the corresponding magnetic and gravitational instability that is responsible for the formation of quasi-regular chains of gas and star complexes. Recall that the chain of equidistant complexes of HII regions and young stars observed in M31 is observed in the arm where the presence of a regular magnetic field has long been known [7, 8].

We concur with the conclusion of deVaucouleurs [10] drawn more than 40 years ago: the structure of our Galaxy resembles that of NGC 4303 (M61), classified by him as SAB(rs). His conclusion was based on limited data on inner regions of the Milky Way. M61 is a good example of a galaxy with knee-like spiral arms. However, our Galaxy resembles even more strongly galaxies such as NGC 1232 and NGC 2336, whose regular symmetric arms originate at the ends of a small bar and a central ring and then become knee-like, so that the overall structure at large distances from the center is far from symmetrical. Note, however, that, in the case of parts of our Galaxy that are distant from the center, we can only discuss the morphology of arms traced by neutral hydrogen, which often extends to distances far beyond the optically visible structure of the spiral galaxy.

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