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Outer Pseudoring in the Galaxy

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Abstract—The kinematics of the Sagittarius ($R = 5.7$ kpc), Carina ($R = 6.5$ kpc), Cygnus ($R = 6.8$ kpc), and Perseus ($R = 8.2$ kpc) arms suggests the existence of two spiral patterns in the Galaxy that rotate with different speeds. The inner spiral pattern that is represented by the Sagittarius arm rotates with the speed of the bar, $\Omega_b = 60 \pm 5$ km s^{-1} kpc^{-1}, while the outer spiral pattern that includes the Carina, Cygnus, and Perseus arms rotates with a lower speed, $\Omega_s = 12$–22 km s^{-1} kpc^{-1}. The existence of an outer slow tightly wound spiral pattern and an inner fast spiral pattern can be explained by numerically simulating the dynamics of outer pseudorings. The outer Lindblad resonance of the bar must be located between the Sagittarius and Carina arms. The Cygnus arm appears as a connecting link between the fast and slow spiral patterns.

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INTRODUCTION

The gas kinematics in the central region, infrared photometry, star counts, and other modern tests confirm the presence of a bar in the Galaxy. Elliptical orbits near the Galactic center allow many features of the gas kinematics, including the so-called 3-kpc expanding arm, to be explained (Peters 1975; Liszt and Burton 1980). There is ample evidence suggesting that the major axis of the bar is oriented in the direction of $\theta_b = 15°$–$45°$ in such a way that the end of the bar closest to the Sun lies in the first quadrant. However, the speed of the bar and its length determined from observations are unreliable (Kuijken 1996; Gerhard 1996; and references therein).

In this paper, we analyze the kinematics and distribution of OB associations within 3 kpc of the Sun. The model of a galaxy with an outer pseudoring formed by tightly wound spiral arms can explain the unusually small interarm distance, $\lambda = 2$ kpc, between the Carina and Perseus arm fragments (Mel'nik *et al.* 2001). The kinematics of young stars is clearly indicative of a slow rotation of the spiral pattern represented by the Carina, Cygnus, and Perseus arm fragments, in good agreement with the numerical simulations of the dynamics of outer pseudorings (Rautiainen and Salo 1999, 2000). The model of a galaxy with fast and slowly rotating spiral patterns at different galactocentric distances can explain the fact that the kinematics of young stars in the Carina, Cygnus, and Perseus arms differs from that in the Sagittarius arm.

NUMERICAL SIMULATIONS OF OUTER PSEUDORINGS AND COMPARISON OF MODELS WITH OBSERVATIONS

Schwarz (1981) was the first to show that the outer rings in galaxies result from the evolution of barred galaxies. His numerical simulations of the behavior of gaseous clouds showed that two tightly wound spiral arms forming a pseudoring emerge on the galactic periphery after ~10 bar revolutions. The location of the outer pseudoring corresponds to the outer Lindblad resonance (OLR) of the bar. Schwarz (1981) found the collisions between gaseous clouds to play a key role in the formation of outer pseudorings. Shocks in the spiral arms emanating from the bar produce a slow flow of gas clouds ($V_R \leq 1$ km s^{-1}) away from the center toward the periphery and contribute to the accumulation of gas in the OLR region of the bar. The characteristic time scale of this process is 10^9 yr. It determines the time it takes for the galaxy to form an outer pseudoring. Schwarz (1981) discovered two types of outer pseudorings, elongated along and across the bar, and associated them with two types of periodic orbits existing near the OLR. Periodic orbits between the CR (corotation radius) and the OLR are elongated across the bar, while

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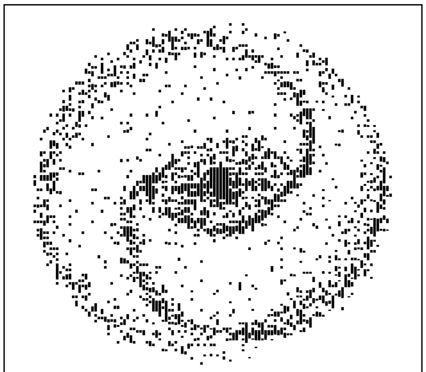

Fig. 1. Image of a typical galaxy with an R_2' pseudoring from Buta and Crocker (1991) (a mirror copy).

orbits farther than the OLR are elongated along the bar.

Buta (1986, 1995) discovered and studied more than 500 galaxies with outer rings or pseudorings (broken rings), 90% of which proved to be barred galaxies. Buta and Crocker (1991) found galaxies that have distinct features of each type of outer pseudoring and that may be considered as prototypes. Type-R_1' pseudorings are formed by spiral arms wound by ∼180° with respect to the bar ends. They are elongated across the bar and always lie inside the OLR of the bar. Type-R_2' pseudorings are formed by spiral arms wound by ∼270° with respect to the bar ends. They are elongated along the bar and lie mostly outside the OLR. Figure 1 shows an image of a typical galaxy with an R_2' pseudoring from Buta and Crocker (1991).

The simulations of ring galaxies by Byrd *et al.* (1994) showed that first a type-R_1' pseudoring appears and then it transforms into a type-R_2' pseudoring. Since the R_2' pseudoring is, on average, farther from the galactic center than the R_1' pseudoring, this sequence of pseudoring formation once again emphasizes the great role that the gas arrived from the central region plays in the formation of outer rings.

What is the speed Ω_p of the outer tightly wound spiral pattern that forms the pseudoring? It was implied in the above papers that the bar and the outer pseudoring rotate with the same speed.

Another approach to simulating barred galaxies revealed several patterns rotating with different speeds in galactic disks (Sellwood 1985; Sellwood and Sparke 1988; and other papers). A slowly rotating spiral pattern was found at a certain galactocentric distance. Tagger *et al.* (1987) and Sygnet *et al.* (1988) developed a mechanism of nonlinear coupling between a bar and a slow spiral pattern. They showed that the bar and the slow spiral pattern could exchange energy and angular momentum if the CR of the bar coincides with the inner Lindblad resonance (ILR) of the slow spiral mode.

Rautiainen and Salo (1999) were the first to find that the outer pseudoring could include spiral arms rotating more slowly than the bar. Numerical simulations showed that, in some cases, inner and outer spiral arms are present in the galaxy. The inner arms rotate with the speed of the bar, while the outer tightly wound arms rotate with a lower speed. The slowly rotating outer pseudoring is usually located at the outer edge of the bar OLR. Rautiainen and Salo (1999) also pointed out a possible nonlinear coupling between the two spiral modes in which the OLR of the inner spiral pattern coincides with the ILR of the outer spiral pattern. This mechanism must differ from that suggested by Tagger *et al.* (1987). The N-body simulations of the evolution of barred galaxies by Rautiainen and Salo (2000) showed that the slowly rotating outer pseudoring is usually located between the OLR of the bar and the CR of the slow spiral mode. Another interesting result of this work is the discovery of cyclic variations in the pseudoring morphology. First, an R_1' pseudoring is formed, then it acquires the features of a R_2' pseudoring, then again those of an R_1' pseudoring, and so on.

THE UNUSUAL SAGITTARIUS ARM

In our Galaxy, the young star clusters and OB associations located within 3 kpc of the Sun concentrate toward several regions of intense star formation, which are traditionally associated with the Sagittarius–Carina, Cygnus–Orion, and Perseus spiral arms (Morgan *et al.* 1952; Becker 1964; Humphreys 1979; and other papers). However, the kinematics of young objects in the Carina, Cygnus, and Perseus complexes differs from their kinematics in the Orion and Sagittarius regions (see Mel'nik *et al.* 2001 for more detail).

Figure 2 shows regions of intense star formation within 3 kpc of the Sun and the radial component V_R of the mean residual velocity of young stars in these regions. The components of the stellar residual velocity along the Galactic radius vector, V_R, and in the azimuthal direction, V_θ, were calculated as the differences between the observed velocities and the velocities due to the circular Galactic rotation law and the solar motion relative to the centroid of OB associations projected onto each direction. The parameters of the circular Galactic disk rotation law and the components of the solar motion were taken from Mel'nik *et al.* (2001). In all our calculations, we took the Galactocentric distance of the Sun to be

$R_0 = 7.1$ kpc (Dambis *et al.* 1995; Glushkova *et al.* 1998).

The radial velocity V_R is directed toward the Galactic center in the Carina, Cygnus, and Perseus complexes and away from the Galactic center in the Orion and Sagittarius regions. The locations of the Carina, Cygnus, and Perseus spiral arms correspond to the extreme negative radial velocities V_R, i.e., to the maximum velocities toward the Galactic center (Fig. 2).

The simulations of the behavior of gaseous clouds in a perturbed potential performed by Roberts and Hasusman (1984) showed that in the trailing spiral arms located within the CR, the radial and azimuthal velocity components must reach their extreme negative values at the shock front. This picture is observed in the Cygnus ($R = 6.8$ kpc) and Perseus ($R = 8.2$ kpc) arms, which strongly suggests that they are the trailing arms and lie within the CR. We see no statistically significant variations in the azimuthal residual velocity V_θ across the Carina arm ($R = 6.5$ kpc). However, the Carina arm is closer to the Galactic center than the Cygnus and Perseus arms, and, hence, it must also lie within the CR (Fig. 2). Thus, all three fragments of the Carina, Cygnus, and Perseus arms are parts of the slowly rotating spiral pattern. The requirement that the Perseus arm be located within the CR constrains the pattern speed, $\Omega_p < 25$ km s^{-1} kpc^{-1} (see Mel'nik 2003 for more detail).

The two regions of intense star formation in Orion and Sagittarius are located in the interarm space. What triggers star formation in these regions? The Orion region is probably a spur of the Cygnus arm, because it is located at its outer edge. This is consistent with the conclusions reached by Weaver (1970) and Elmegreen (1980) in their studies of spurs.

Intense star formation in the Sagittarius region is rather difficult to explain. This region contains two rich OB associations (Sgr OB1 and Ser OB1) and has a size of ∼500 pc in the azimuthal direction. We see no other spiral arm whose spur could be a complex of young objects in Sagittarius. High extinction ($A_V = 3^m$) at heliocentric distances of 1–2 kpc is reached in the direction ($l = 28°$, $b = -1°$), but it is moderate ($A_V < 1^m$) in the direction ($l = 8°$, $b = 0°$) up to $r = 2.5$ kpc and does not prevent us from discovering the "true" spiral arm (Neckel and Klare 1980; Efremov and Sitnik 1988). Nevertheless, there is probably no "true" spiral arm behind the Sagittarius region.

My principal assumption is that the star-forming region in Sagittarius is a fragment of a trailing spiral arm. It has been traditionally considered just in this way or, to be more precise, as a constituent of the Sagittarius–Carina arm. However, because of their kinematic differences, the Sagittarius and Carina arms cannot be considered to be fragments of the same spiral pattern. The sharp increase in extinction (from 2 to 4^m) at heliocentric distances of 2–3 kpc in the field centered at ($l = 18°$, $b = 0°$) (Neckel and Klare 1980) also indicates that the Sagittarius region is a trailing spiral arm. As soon as we adopt this point of view, we must inevitably conclude that the Sagittarius arm is a fragment of another spiral pattern that rotates with a higher speed Ω_p, in contrast to the Carina, Cygnus, and Perseus arms that represent the slow spiral pattern.

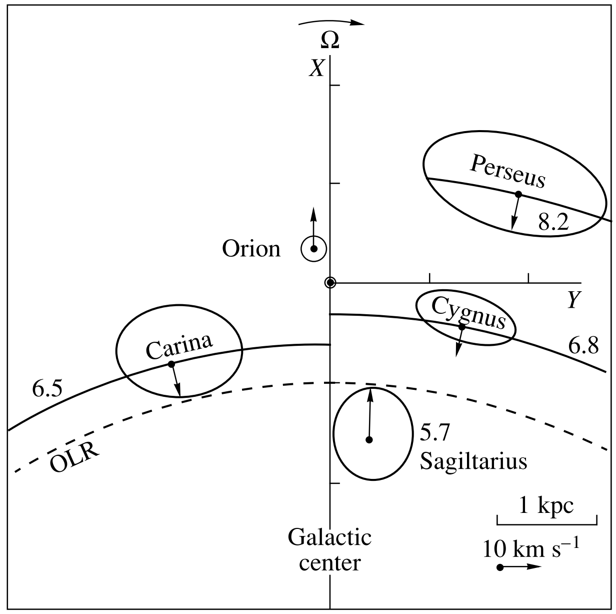

Fig. 2. Regions of intense star formation in the Galaxy and their mean radial velocity V_R. The locations of the Carina, Cygnus, and Perseus spiral arms correspond to the extreme negative radial velocities V_R. The dashed line indicates the location of the OLR of the bar. The numbers indicate Galactocentric distances in kpc.

Indeed, the fact that the radial velocity V_R of young stars in the Sagittarius arm is directed away from the Galactic center ($V_R = +10$ km s^{-1}) suggests that this arm is located between the CR and OLR of its spiral pattern. Analytical calculations of stellar motions in trailing tightly wound spiral arms show that the direction of the radial velocity perturbation component in the arm depends on the position of the arm with respect to the CR: it is directed toward and away from the Galactic center inside and outside the CR, respectively (Lin *et al.* 1969). In this paper, the spiral arms are everywhere assumed to be trailing ones.

In a spiral density wave, the deviation of the velocities of young disk objects from circular rotation is due to their coherent motions along epicycles and the crowding of orbits in the spiral arm corresponds to a certain phase of epicyclic motion. As long as the density wave exists, the crowding of orbits in the stellar and gaseous disk subsystems must correspond to approximately the same phase of epicyclic motion. Therefore, allowance for the collisions does not alter the conclusion that the Sagittarius arm is located outside the CR.

The location of the Sagittarius arm between the CR and OLR implies that the CR of this spiral pattern is closer to the Galactic center than the Sagittarius region ($R_{\rm CR} < 5.7$ kpc). Hence, the speed of this spiral pattern must be higher than that of the Galaxy at the distance of the Sagittarius arm, $\Omega_{\rm p} > 38$ km s^{-1} kpc^{-1}.

Thus, there are two spiral patterns in the Galaxy that rotate with different speeds. The spiral pattern closer to the Galactic center rotates faster ($\Omega_{\rm p} > 38$ km s^{-1} kpc^{-1}) than the spiral pattern farther from the Galactic center ($\Omega_{\rm p} < 25$ km s^{-1} kpc^{-1}).

THE IDENTIFICATION OF ARM FRAGMENTS WITH PSEUDORING ELEMENTS

The fact that the Galactic radius vector drawn at an angle of $\theta = 10°{-}15°$ crosses two spiral arms at once, Cygnus ($R = 6.8$ kpc) and Perseus ($R = 8.2$ kpc), points to the presence of a tightly wound spiral pattern rather than a multiarmed one in the Galaxy (Fig. 2). Fast periodic density variations along the radius are virtually impossible in a multiarmed pattern because of the large pitch angle of the spiral arms.

Owing to the ~270° winding of the spiral arms with respect to the bar, a type-R_2' pseudoring has regions where the galactic radius vector crosses two tightly wound spiral arms at once (Fig. 1). These regions lie at smaller angles θ relative to the direction of bar elongation, i.e., they slightly lag behind the bar (Buta and Crocker 1991). On average, the direction $\theta = 10°{-}15°$ in the Galaxy toward which the double spiral arms are observed slightly lags behind the direction of bar elongation, $\theta_{\rm b} = 15°{-}45°$, in good agreement with the type-R_2' pseudoring model.

The termination of the Perseus arm in the third quadrant provides further evidence for the presence of an R_2' pseudoring in the Galaxy. The R_2' pseudoring must be elongated along the bar. Hence, the tightly wound spiral arms forming the pseudoring must terminate in the direction of bar elongation. In the solar neighborhood, the Perseus arm is farthest from the Galactic center. The termination of the Perseus arm at the Per OB1 association ($\theta = 9°$) is in reasonable agreement with the direction of bar elongation, $\theta_{\rm b} = 15°{-}45°$.

Thus, the morphology and kinematics of the Galaxy point to the presence of a type-R_2' pseudoring. Numerical simulations suggest that the R_2' pseudoring lies predominantly outside the OLR of the bar. To ensure that the numerical models agree with the kinematic features of the observed spiral arms, we must assume that the OLR of the bar lies between the Sagittarius and Carina arms (Fig. 2). The Carina, Cygnus, and Perseus arms that represent the slow spiral pattern will then be located outside the OLR, while the Sagittarius arm that represents the fast spiral pattern will be located inside the OLR. This picture is consistent with the presence of inner and outer spiral arms in the Galaxy. The inner spiral arms must lie between the CR and OLR of the bar and rotate with the speed of the bar, $\Omega_{\rm b}$. The outer tightly wound spiral arms must lie at the outer edge of the OLR and rotate more slowly than the bar (Rautuainen and Salo 1999, 2000).

THE FAST SPIRAL PATTERN

The localization of the OLR of the bar between the Sagittarius ($R = 5.7$ kpc) and Carina ($R = 6.5$ kpc) arm fragments allows its speed $\Omega_{\rm b}$ to be determined fairly accurately:

$$\Omega_{\rm b} = \Omega(R_{\rm OLR}) + \kappa(R_{\rm OLR})/2, \qquad (1)$$

where $\Omega(R_{\rm OLR})$ is the mean speed of disk rotation and $\kappa(R_{\rm OLR})$ is the epicyclic frequency calculated at the distance of the OLR. Using the parameters of the circular Galactic rotation law from Mel'nik *et al.* (2001), we obtain $\Omega_{\rm b} = 60 \pm 5$ km s^{-1} kpc^{-1}. The error in $\Omega_{\rm b}$ is mainly determined by the OLR localization accuracy. In this case, no question about the number of spiral arms arises. Both the bar and the associated spiral pattern must have the $m = 2$ mode.

The CR of the bar rotating with the speed $\Omega_{\rm b} = 60 \pm 5$ km s^{-1} kpc^{-1} must lie at a distance of $R = 3.3 \pm 0.5$ kpc. Weiner and Sellwood (1999) obtained similar locations for the CR and OLR of the bar ($R_{\rm CR} = 3.6$ kpc and $R_{\rm OLR} \approx R_0$) by analyzing the $(l{-}V)$ diagrams of the HI and CO distributions in the central region of the Galaxy.

In Fig. 1, we clearly see the difference between the pitch angles of the spiral arms in the inner and outer galactic regions. The pitch angles of the spiral arms in the inner and outer regions are close to 90° and 0°, respectively. The change in the pitch angle of the spiral arms near the OLR of the bar was pointed out by Schwartz (1981), Combes and Gerin (1985), and other authors. Let us assume that the inner spiral arm begins at the CR of the bar at the point ($R = 3.3$ kpc, $\theta = 25°$) and passes through the Sagittarius complex ($R = 5.7$ kpc, $\theta = 3°$). The mean pitch angle of the inner spiral arms must then be $i = 55°$.

THE SLOW SPIRAL PATTERN

Let us consider the slow spiral pattern that is represented by the Carina, Cygnus, and Perseus arm fragments. In most cases, the pseudorings in galaxies consist of two tightly wound spiral arms (Buta 1995). In the Galaxy, the Carina and Perseus arms are probably such arms. For the two-armed model ($m_s = 2$), the pitch angle of the outer spiral arms must be $i = 5°$ (Mel'nik *et al.* 2001).

The Carina arm ($R = 6.5$ kpc) is probably located near the ILR of the slow spiral pattern. This is evidenced by its kinematic features and by the absence of other arms of the slow spiral pattern at smaller R. The fast spiral pattern is present even at $R =$ 5.7 kpc; therefore, the slow spiral pattern may extend inward only to Galactocentric distances of $R \approx$ 5.7 kpc (Mel'nik 2005).

One kinematic feature of the Carina arm, more specifically, the absence of significant cross-arm variations in the azimuthal velocity, probably suggests that the arm has degenerated into a ring. It is very difficult to explain the presence of a radial velocity gradient and the absence of an azimuthal velocity gradient across the Carina arm. In a spiral density wave, the cross-arm variations in both velocity components, V_R and V_θ, must necessarily be observed. Both velocity gradients are caused by the same factor: the displacement of the direction along which the orbits are elongated in the disk plane with increasing Galactocentric distance R.

The observed gradient in radial velocity V_R across the Carina arm may result from the contraction of the orbits located near the ILR. In the ILR region, the gaseous clouds must effectively lose angular momentum and acquire a radial velocity directed toward the Galactic center; the organized motions of clouds in the azimuthal direction may be absent.

Let us assume that the ILR of the slow spiral mode is located at the Galactocentric distance of the Carina arm, $R = 6.5$ kpc. If we knew the number m_s of spiral arms in the outer spiral pattern, then we would immediately find its speed Ω_s:

$$\Omega_s = \Omega(R_{ILR}) - \kappa(R_{ILR})/m_s, \quad (2)$$

where $\Omega(R_{ILR})$ and $\kappa(R_{ILR})$ are the mean speed of disk rotation and the epicyclic frequency, respectively, calculated at the distance of the ILR.

In the Galaxy, we are dealing with a small number of tightly wound spiral arms. However, we cannot say with confidence that the Galaxy has two rather than four arms. For $m_s = 2$ and $m_s = 4$, the pattern speeds must be $\Omega_s = 12 \pm 2$ and $\Omega_s = 22 \pm 2$ km s^{-1} kpc^{-1}, respectively. Both values satisfy the inequality $\Omega_s <$ 25 km s^{-1} kpc^{-1}, which expresses the requirement that the Perseus arm be located inside the CR. Note that in the two-armed model ($m_s = 2$), the CR of the slow spiral mode is located at a Galactocentric distance of $R_{RC} \approx 15$–17 kpc, while in the four-armed model ($m_s = 4$), it is located at a Galactocentric distance of $R_{RC} \approx 10$ kpc. It is rather difficult to choose one of the two models, but, in any case, the speed of the slow spiral pattern must lie within the range $\Omega_s = 12$–22 km s^{-1} kpc^{-1}.

Figure 3 schematically shows the spiral structure of the Galaxy constructed under the assumption of a two-armed symmetry. We took the angle between the major axis of the bar and the solar direction to be $\theta_b =$ 25° and the axial ratio of the bar to be 3 : 1 (Gerhard 1996; Weiner and Sellwood 1999). The pitch angles of the inner and outer spirals are $i = 55°$ and $i = 5°$, respectively. The dashed line marks the position of the OLR of the bar. The locations of the star–gas complexes within 3 kpc of the Sun were transferred from Fig. 2.

THE CYGNUS ARM AS A CONNECTING LINK BETWEEN THE FAST AND SLOW SPIRAL PATTERNS

Thus, the Galaxy possesses fast ($\Omega_b = 60 \pm$ 5 km s^{-1} kpc^{-1}) and slow ($\Omega_s = 12$–22 km s^{-1} kpc^{-1}) spiral patterns. How can we explain that the ends of these spiral patterns are joined so well? The complexes of young objects in Sagittarius ($\theta = 3°$) and Carina ($\theta = -15°$) are $\Delta\theta = 18°$ apart, which is only 5% of the circumference. This is why the concept of the Sagittarius–Carina arm arose, although different parts of this arm are displaced relative to one another with a speed of $\Delta\Omega = 40$–50 km s^{-1} kpc^{-1}.

We can answer this question by assuming that both spiral patterns are periodically deformed and adjust to one another. The Cygnus arm looks like a connecting link between the fast and slow spiral patterns. In Fig. 3, the Cygnus arm and the arm fragment that is symmetric to it are located at the places where the inner and outer spiral patterns are connected to form characteristic "visors". These visors make the outer spirals appear as if they lead the inner spirals in Galactocentric angle. Sellwood and Spark (1988) found similar connecting links between the fast-rotating bar and the slowly rotating spiral pattern.

Interestingly, the ILR of the slow spiral pattern ($R \approx 6.5$ kpc) is located near the OLR of the fast spiral pattern ($R \approx 6.1$ kpc). Rautiainen and Salo (1999, 2000) pointed out the close locations of the OLR and ILR of the two spiral patterns in numerical simulations. The gaseous clouds that can gather in the narrow ring between the OLR of the inner spiral mode and the ILR of the outer spiral mode must play a

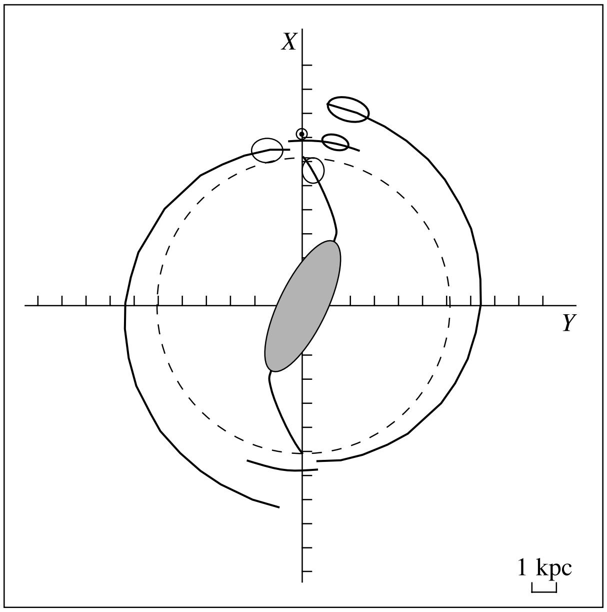

Fig. 3. Schematic view of the Galactic spiral structure. The pitch angles of the inner and outer spiral arms are $i = 55°$ and $i = 5°$, respectively. The position of the Sun is marked. The positions of the star–gas complexes within 3 kpc are indicated by the ovals, as in Fig. 2. The dashed line marks the location of the OLR of the bar.

great role in the OLR–ILR coupling mechanism. The fast spiral mode forms a flow of gaseous clouds away from the center toward the periphery (Schwarz 1981), while the slow spiral mode forms a flow in the opposite direction, from the periphery toward the center. It is possible that the two spiral modes can periodically exchange gaseous clouds and enhance one another.

CONCLUSIONS

The kinematics of the Sagittarius, Carina, Cygnus, and Perseus arms suggests the existence of two spiral patterns in the Galaxy that rotate with different speeds. The Sagittarius arm is a fragment of the spiral pattern that rotates with a higher speed than the pattern represented by the Carina, Cygnus, and Perseus spiral arms. The presence of a slow outer tightly would spiral pattern and a fast inner spiral pattern can be explained by using numerical simulations of the dynamics of outer pseudorings (Rautiainen and Salo 1999, 2000). In this case, the OLR of the bar must lie between the Sagittarius and Carina arms. The Carina, Cygnus, and Perseus arms that represent the slow spiral pattern will then be located outside the OLR, while the Sagittarius arm that represents the fast spiral pattern will lie inside the OLR of the bar.

The localization of the OLR of the bar between the Sagittarius and Carina arms allows us to determine the bar speed, $\Omega_b = 60 \pm 5$ km s^{-1} kpc^{-1}, and the bar corotation radius, $R_{RC} = 3.3 \pm 0.5$ kpc. The speed of the slow spiral pattern must lie within the range $\Omega_s = 12–22$ km s^{-1} kpc^{-1}.

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