The Milky Way spiral structure parameters from data on masers and selected open clusters

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Abstract
To estimate the parameters of the Galactic spiral structure – namely the pitch angle $i$ and the number of spiral arms – data on Galactic masers with known trigonometric parallaxes were used. We applied the well-known method based on analysis of the ‘position angle – distance logarithm’ diagram. Estimates of the pitch angle $i$ obtained from four segments of different arms belonging to the global Galactic structure are self-consistent and close to $i = -13^\circ \pm 1^\circ$. The segment which is most interesting is that of the Outer arm. It contains only three masers. Hence, in order to obtain correct estimates, we also used the data on 12 very young star clusters with distances determined by Camargo et al. from infrared photometry. The estimates obtained allow us to conclude in favour of the four-armed model of the Galactic spiral structure.

Key words: Masers – Galaxy: structure.

1 INTRODUCTION
Up to now, the question of the number of spiral arms in our Galaxy still has no unequivocal answer. As follows from the analysis of spatial distribution of young Galactic objects (young stars, star-forming regions, open star clusters, hydrogen clouds), two-, three- and four-arm models of the Galactic spiral structure are possible (Russell 2003; Vallée 2008; Hou, Han & Shi 2009; Efremov 2011; Francis & Anderson 2012). More complicated models are also known – for example, the kinematical model of Lépine, Mishurov & Dedikov (2001), where two- and four-arm patterns are combined in the solar neighbourhood. According to Englmaier, Pohl & Bissantz (2011), the distribution of neutral hydrogen suggests that there is a two-arm pattern in the inner part ($R < R_0$) of the Milky Way which splits into four arms in its outer part ($R > R_0$). Note also the spiral ring model Mel’nik & Rautiainen (2009) that contains two outer rings stretched in the perpendicular and parallel directions to the central bar, the inner ring stretched parallel to the bar, and also two small spiral arm fragments.

In our previous kinematic analysis aimed at determining the spiral density wave parameters, we adopted the most simple two-arm model (Bobylev, Bajkova & Stepanishchev 2008; Bobylev & Bajkova 2010, 2011), which allowed us to estimate the spiral pitch angle $i$ directly from the estimate of the spiral wavelength $\lambda$ (Bajkova & Bobylev 2012) that binds both parameters – pitch angle and the number of spiral arms. Therefore, a direct method of estimating the pitch angle would be of great interest.

In this paper, a study of the Galactic spiral pattern is done on the basis of data on spatial distribution of the youngest Galactic objects tracing the Galactic spiral arms. The data consist of coordinates and trigonometric parallaxes of Galactic masers obtained by several very long baseline interferometry (VLBI) groups during long-term radio interferometric campaigns within the various projects (Reid et al. 2009a; Brunthaler et al. 2011; Honma et al. 2012).

In addition, we use 12 very young star clusters recently discovered in the Outer spiral arm of the Galaxy, whose distances and ages were estimated with high accuracy from infrared photometry (Camargo, Bica & Bonatto 2013). This allowed us to considerably extend the sample of objects in the Outer arm for determining the pitch angle.

Thus, the aim of this work was to determine Galactic spiral structure parameters from young objects (basically masers as well as young clusters in the Outer arm) distributed in a wide range of Galactocentric distances and position angles. The use of the ‘position angle – distance logarithm’ diagram allowed us to directly estimate the spiral arm pitch angle and determine the number of spiral arms.

2 METHOD
The equation describing the position of a Galactic object on the logarithmic spiral can be written in the following way:

$$R = a_0 e^{(\theta-\theta_0)\tan i},$$

where $a_0 > 0$, $\theta$ is the object’s position angle measured in the direction of Galactic rotation: $\tan \theta = y/(R_0 - x)$, where $x$, $y$ are Galactic heliocentric rectangular coordinates of the object; $\theta_0$ is angle at which $R = a_0$; $i$ is pitch angle ($i < 0$ for leading spirals) which is related to other spiral structure parameters as

$$\tan i = \frac{m \lambda}{2\pi R_0},$$

where

$$m = \frac{1}{2\pi}.$$
where \( m \) is the number of spiral arms, \( \lambda \) is the wavelength of spiral wave which is equal to the distance (in Galactocentric radial direction) between adjacent segments of spiral arms in the solar neighbourhood, \( R_0 \) is Galactocentric distance of the Sun which is adopted to be \( R_0 = 8 \) kpc. Radial phase of the spiral wave \( \chi \) is

\[
\chi = m[\cot(i) \ln(R/R_0) - (\theta - \theta_0)] + \chi_0,
\]

(3)

where \( \chi_0 \) is radial phase of the Sun in the spiral wave.

Putting \( \theta_0 = R_0 \) in equation (1), we can estimate the value of pitch angle \( i \) as

\[
\tan i = \frac{\ln(R/R_0)}{\theta - \theta_0},
\]

(4)

where obviously, \( \theta_0 = 0 \). For this purpose, a ‘position angle – distance logarithm’ diagram is constructed, where arms of a logarithmic spiral are presented as line segments. Such method is widely used for studying the Galactic spiral structure based on the various object data (Popova & Loktin 2005; Xu et al. 2013). The advantage of this approach is that the estimate of pitch angle \( i \) does not depend on the number of spiral arms.

3 DATA

We use coordinates and trigonometric parallaxes of masers measured by VLBI with errors of less than 10 per cent in average. These masers are connected with very young objects (basically proto stars of high masses, but there are ones with low masses too; a number of massive giants are known as well) located in active star-forming regions.

One of such observational campaigns is the Japanese project VERA (VLBI Exploration of Radio Astrometry) for observations of water (\( \text{H}_2\text{O} \)) Galactic masers at 22 GHz (Hirota et al. 2007) and SiO masers (such masers are very rare among young objects) at 43 GHz (Kim et al. 2008).

Water and methanol (\( \text{CH}_3\text{OH} \)) maser parallaxes are observed in USA (VLBA) at 22 and 12 GHz (Reid et al. 2009a). Methanol masers are observed also in the framework of the European VLBI network (Rygl et al. 2010). Both these projects are joined together in the BeSSeL programme (Brunthaler et al. 2011).

VLBI observations of radio stars in continuum at 8.4 GHz (Dzib et al. 2011) are carried out with the same goals.

Complete information on 54 masers with measured trigonometric parallaxes is given in the papers by Bajkova & Bobylev (2012) and Stepanishchev & Bobylev (2013). Apart from that, we use data on new sources as well as data from the recent measurements published in the following papers.

(i) A study by Wu et al. (2012) of the star-forming region RCW122 (G348.70−1.04). It is a very important source that considerably widens the available range of position angles, which is very important for estimation of the pitch angle value (in Fig. 1, it belongs to arm I and has the following coordinates: \( \ln(R/R_0) = -0.52 \) and \( \theta = -0.14 \) rad.).

(ii) Imai et al. (2012) on the IRAS 22480+6002 source which is associated with a massive supergiant of spectral class K from Perseus arm.

(iii) Sakai et al. (2012) on the IRAS 05168+3634 source from Perseus arm.

(iv) Xu et al. (2013) devoted to the study of peculiarities of the local spiral arm (Orion arm) using data on 30 masers.

(v) Immer et al. (2013) containing parallax measurements for a number of masers in star-forming regions W33 and G012.88+048.

As a result, a sample of 82 sources has been compiled. The sample was extended by the data on 12 very young star clusters whose distances and ages (2 Myr average, 10 Myr maximum) were estimated by Camargo et al. (2013) with high accuracy from 2MASS infrared photometry (Skrutskie et al. 2006). These objects are known as nebula-embedded clusters. They have not been discovered in optical until recently due to a strong absorption in their direction. Actually, they are just young star associations and clusters with gas still not having swept by supernovae explosions because massive stars had no time to evolve to that stage. As it was shown by Camargo et al. (2013), all these objects along with large number of massive stars of high luminosity contain many stars of T Tau type, which is typical to very young star clusters and associations. All these clusters CBB10, CBB11, CBB12, CBB14, CBB15, FSR486, FSR831, FSR843, FSR851, FSR909, FSR1099 and NGC1624 are located in the Outer spiral arm.

4 RESULTS AND DISCUSSION

4.1 Grand-design structure

In Fig. 1, the ‘position angle – distance logarithm’ diagram is shown. When plotting Fig. 1, we visually indicated the four possible arms. We considered the following masers as belonging to arm I: G23.43−0.20, G23.01−0.41, G27.36−0.16 and RCW 122; those belonging to arm II: G14.33−0.64, G35.20−0.74, IRAS 19213+1723, W51, G5.89−0.39, G48.61+0.02 and MSXDC G034.43+0.24; those belonging to arm III: IRAS 00420+5530, NGC 281-W, S Per, W3-OH, S252A IRAS 06058+2138, IRAS 06061+2151, S255, AFGL 2789, NGC 7538, G192.16−3.84, IRAS 5168+3634, PZ Cas and IRAS 22480+6002; and those belonging to arm IV: WB89−437, S269 (G196.45−1.68) and G75.30+1.32. Two masers marked in Fig. 1 (G09.62+0.24; those belonging to arm III: IRAS 05137+3919 that were located at the edges of the diagram were not used. A group of masers associated with star-forming regions W33 and W48 was not used as well since it is falling in the interarm space (between arms I and II). All masers (37 sources) falling into the interarm space between arms II and III (Fig. 1) belong to the local (Orion) arm. As for other masers, there was no doubt in attributing them to one or another arm.
The spiral arms characteristics were obtained from linear regression $\ln(R/R_0) = a\theta + b$ (see equation 4). The problem was solved both with unit weights (Table 1) and with weights inversely proportional to the squared errors of distances (Table 2).

The errors of Galactocentric distance $\sigma_R$ and position angle $\sigma_\theta$ can be easily found from the error of heliocentric distance $\sigma_r$. Then the error of $\ln(R/R_0)$ is $\sigma_{\ln(R/R_0)} = \ln(1 + \sigma_R/R_0)$.

When solving the problem of linear regression, the errors of unknowns $a$ and $b$ were determined by the Monte Carlo method using 1000 random samples along both coordinates $\ln(R/R_0)$ and $\theta$ varying within errors.

Weights for equations (we used weights equal to $1/\sigma^2_{\ln(R/R_0)}$) are usually used in case of heterogeneous data. As it has been found out, the use of weights is especially relevant for arm IV where the data are really mixed. As it is seen by comparing Tables 1 and 2, this approach had a favourable effect on the results obtained for arm IV because the error of $i$ has decreased.

Parameters of the fitted lines shown in Fig. 1 were taken from Table 2.

In Fig. 2, a four-armed spiral pattern constructed for pitch angle $i = -13^\circ$ is shown (see discussion below). Spiral pattern can be easily drawn using equation (1) for each $k$th-order spiral arm with known pitch angle $i$ and parameters $d_0 = R_k$, $k = 1, \ldots, 4$; each arm is drawn independent of the others.

It is seen that the clusters from the paper by Camargo et al. (2013) are good tracers of the Outer arm. We can see two masers from the region Sgr B2 in the centre of the Galaxy (Reid et al. 2009b).

Xu et al. (2013) obtained an estimate of the pitch angle for Orion arm $i = -10.1 \pm 2.7$ from 30 masers. All these masers are shown in Figs 1 and 2. Evolutionary status of the Local arm is discussed below.

As it is seen from Fig. 2, almost every object used in estimations of the pitch angle belongs to a certain arm. If we assume that our model of arms is true, then it is possible to improve the statistics for arm I, where two masers G23.43–0.20 and G27.36–0.16 have very large errors $\sigma_\theta$. To achieve this, we can complement four masers located in the inner part of the Galaxy with the most distant maser IRAS 05137+3919, also belonging to this arm but located in the outer part of the Galaxy. Then the position angle of this object is

$$\theta = \theta - 2\pi$$

which widens the dynamical range of position angles to as large as $440^\circ$. As the final result, a new estimate of the pitch angle for arm I obtained using five masers is $i = -13.0 \pm 2.9$, which is much more accurate than the estimate given in the first line of Table 1.

Using the values of $R_k$ from Table 2, it is easy to estimate the values of the wavelength $\lambda$ and radial phase of the Sun in spiral

Table 1. Parameters of linear regression $\ln(R/R_0) = a\theta + b$, found using unit weights.

| Arm               | $n_*$ | $a$     | $b$     | $i$ (deg) | $R_k$ (kpc) |
|-------------------|-------|---------|---------|-----------|-------------|
| I (Scutum–Crux)   | 4     | −0.174 ± 0.099 | −0.597 ± 0.041 | −9.8 ± 5.4 | 4.40 ± 0.24 |
| II (Carina–Sagittarius) | 7     | −0.163 ± 0.014 | −0.161 ± 0.008 | −9.3 ± 0.8  | 6.81 ± 0.25 |
| III (Perseus)     | 14    | −0.207 ± 0.024 | +0.200 ± 0.005 | −11.7 ± 1.3 | 9.77 ± 0.36 |
| IV (Outer or Cygnus) | 15    | −0.214 ± 0.072 | +0.563 ± 0.033 | −12.2 ± 3.9 | 14.02 ± 0.69 |

Note. $R_k$ is the value of $b$, in kpc, and a point of intersection of the $k$th spiral arm with the direction from the Sun to the centre of the Galaxy ($\theta = 0^\circ$).

Table 2. Parameters of linear regression $\ln(R/R_0) = a\theta + b$, found using weights $1/\sigma^2_{\ln(R/R_0)}$.

| Arm               | $n_*$ | $a$     | $b$     | $i$ (deg) | $R_k$ (kpc) |
|-------------------|-------|---------|---------|-----------|-------------|
| I (Scutum–Crux)   | 4     | −0.199 ± 0.075 | −0.570 ± 0.030 | −11.2 ± 4.0 | 4.52 ± 0.21 |
| II (Carina–Sagittarius) | 7     | −0.163 ± 0.040 | −0.166 ± 0.026 | −9.3 ± 2.2  | 6.78 ± 0.32 |
| III (Perseus)     | 14    | −0.265 ± 0.015 | +0.210 ± 0.002 | −14.8 ± 0.8 | 9.87 ± 0.37 |
| IV (Outer or Cygnus) | 15    | −0.203 ± 0.036 | +0.524 ± 0.017 | −11.5 ± 1.9 | 13.51 ± 0.54 |

Simple average

Weighted average

−10.7 ± 0.7

−9.9 ± 0.6

−11.7 ± 1.1

−13.7 ± 1.1

Figure 2. Four-arm spiral pattern of the Galaxy with pitch angle $i = 13^\circ$, location of the Sun and the centre of the Galaxy are indicated by dotted lines, masers are marked by black triangles, young open star clusters in the Outer arm (IV) are shown by squares and the central bar is shown as an ellipse.
wave $\chi_\odot$ (at $\theta = 0^\circ$): $\lambda = R_{\odot} - R_0 = 3.1$ kpc and $\chi_\odot = 2\pi(R_{\odot} - R_0)/\lambda = -140^\circ$.

From the analysis of kinematics of 44 masers done by Bajkova & Bobylev (2012), the following parameters were found: $\lambda = 2.2^{+0.4}_{-0.1}$ kpc, $i = -8^{+6.2}_{-6.9}$ and $\chi_\odot = -147^{+30}_{-17}$ for the two-arm model ($m = 2$) of spiral pattern. First, we can see very good agreement with the result obtained in the present study for $\chi_\odot$. Secondly, for the four-arm model of spiral pattern ($m = 4$), the value of $i$ obtained for the two-arm model should simply be doubled, then $i = -10^\circ$. Taking into account that a considerable fraction of masers belongs to arms II, III and the Local (Orion) arm, from which the value of $i \approx -10^\circ$ was obtained (see Table 1 and the result by Xu et al. 2013 mentioned above), we can confirm a good agreement with the earlier kinematic results.

It is necessary to note that, in the paper by Bajkova & Bobylev (2012), the wavelength $\lambda$ was determined first by periodogram analysis of maser residual velocities, followed by calculating the pitch angle $i$ from $\lambda$ using equation (2) and assuming $m = 2$. Obviously, the results of this work are of major interest as we determine here the pitch angle $i$ directly, without any assumptions on the number of spiral arms. Comparing the estimates obtained, we can conclude that different methods give fairly consistent results.

In the paper by Bobylev & Bajkova (2013), the values $i = -6.0 \pm 0.4$ and $\lambda = 2.6 \pm 0.2$ kpc were derived from kinematic analysis of young massive spectral binaries (of spectral classes O–B2.5) for the two-arm model of spiral pattern ($m = 2$). We can see that the consistency with results obtained in this work is achieved after doubling the pitch angle value.

This all means that the four-arm model of spiral pattern is most probable in our Galaxy. Note that the scheme shown in Fig. 2 coincides, to within small details, with a cartographical model with parameters $i = -12.8$ and $\lambda = 3.0$ kpc for $m = 4$ constructed by Vallée (2008, 2013). Our conclusion is consistent with the one made by Efremov (2011) on the basis of analysis of the large-scale Galactic distribution of neutral, molecular and ionized hydrogen clouds.

4.2 The Local arm

Currently, the evolutionary status of the Local arm is still not fully clear. In the paper by Xu et al. (2013), three possibilities for the nature of the Local arm in relation to the spiral structure of the Milky Way were discussed in detail, with an extensive bibliography:

(i) the Local arm could be a branch of the Perseus arm,

(ii) the Local arm could be part of a Carina arm,

(iii) the Local arm is an independent spiral arm segment.

These authors conclude that it is necessary to have much more masers with measured trigonometric parallaxes in order to make a final conclusion about the nature of the Local arm.

The value of pitch angle $i = -10.1^\circ$ found by Xu et al. (2013) from data on masers in the Local arm is in good agreement with the results obtained by us for the other four arms (Tables 1 and 2). Therefore, we can only conclude that whatever the nature of the Local arm, its formation took place under the influence of the Galactic spiral density wave. Following the opinion of the majority of authors, we believe that the Local arm is a spur rather than an independent spiral arm segment.

As we have already noted, a number of masers are associated with protostars or low-mass stars. It is important to know whether there is a difference in the spiral structure parameters determined independently from massive stars and from stars of low masses. The reason is that, for example, a part of low-mass stars can be formed, with a certain delay, as a result of triggered star formation process after massive star explosions. Such a process is observed, for example, in the nearest Sco–Cen OB Association (Preibisch & Zinnecker 1999). To answer this question, we have taken the example of the Local arm as it has enough masers to identify the possible effects.

Thus, we have formed two samples: 26 high-mass stars and 12 low-mass stars, so the total number of objects was 38.

We have added eight stars to the list of Xu et al. (2013). Three of them have been included into the high-mass star sample, while five others – into the low-mass sample. The high-mass stars are: X-ray binary with a massive companion Cyg X-1 (Reid et al. 2011), maser source in the Cygnus bubble region IRAS 20143+3634 (Ao, Yang & Sunada 2004; Yamaguchi et al. 2012) and radio star HW9 CepA (Dzib et al. 2011) of mass $\sim 6 M_\odot$. Note that two masers of intermediate masses EC 95 and IRAS 22198+6336 in Lynds 1204G from the list of Xu et al. (2013) were included in the sample of high-mass stars.

The following masers were included into the sample of low-mass stars: SVS/NGC 1333, IRAS 16293-2442 in $\rho$ Oph, L1 448C, S1 Oph, DoAr21 Oph, G074.03−01.71 and G090.21+02.32 from the list of Xu et al. (2013). We have added also five stars from Taurus to this sample: Hubble 4, HDE 283572, T Tau N, V773 Tau and HP Tau/G2, according to Torres et al. (2007, 2009, 2012).

Results of calculations are given in Tables 3 and 4. We can see that, when using the whole sample of 38 masers, the pitch angle value $i$ is in good agreement with the result obtained by Xu et al. (2013); however, $i$ changes significantly when splitting the

| Table 3. Parameters of linear regression $\ln(R/R_0) = a\theta + b$, found using unit weights. |
|-----------------------------------------------|
| Local arm | $n_*$ | $a$ | $b$ | $i$ (deg) | $R_0$ (kpc) |
| All | 38 | $-0.162 \pm 0.010$ | $0.023 \pm 0.001$ | $-9.2 \pm 0.6$ | $8.18 \pm 0.31$ |
| High-mass stars | 26 | $-0.206 \pm 0.015$ | $0.038 \pm 0.002$ | $-11.6 \pm 0.8$ | $8.31 \pm 0.31$ |
| Low-mass stars | 12 | $-0.189 \pm 0.005$ | $0.009 \pm 0.001$ | $-10.7 \pm 0.3$ | $8.07 \pm 0.31$ |

| Table 4. Parameters of linear regression $\ln(R/R_0) = a\theta + b$, found using weights $1/\sigma^2_{\ln(R/R_0)}$. |
|-----------------------------------------------|
| Local arm | $n_*$ | $a$ | $b$ | $i$ (deg) | $R_0$ (kpc) |
| All | 38 | $-0.181 \pm 0.005$ | $0.016 \pm 0.001$ | $-10.2 \pm 0.3$ | $8.13 \pm 0.31$ |
| High-mass stars | 26 | $-0.244 \pm 0.036$ | $0.029 \pm 0.008$ | $-13.7 \pm 2.0$ | $8.23 \pm 0.32$ |
| Low-mass stars | 12 | $-0.222 \pm 0.005$ | $0.017 \pm 0.001$ | $-12.5 \pm 0.3$ | $8.15 \pm 0.30$ |
sample by masses. We obtained solutions with unit weights (Table 3), as well as weighted according to distance measurement errors (Table 4). However, there is no special need to apply weights for masers in the Local arm, because almost all VLBI measurements are homogeneous. Therefore, the most interesting result of Table 3, obtained from high-mass objects, is \( i = -11.6 \pm 0.8 \). This value, as compared with the previous one \( i = -10.1 \pm 2.7 \), turned out to be more accurate and closer to the granddesign spiral pattern pitch angle \( i = -13^\circ \pm 1^\circ \), which further confirms our idea about genetic relationship of the Local arm with the Galactic spiral density wave.

In addition, we are interested in the parameter \( R_0 \). As it can be seen from these tables, there is a small shift of \( \Delta R_0 \approx 0.3 \) kpc, although its value is below \( 1\sigma \) error. Still it seems that, for a larger number of masers, the study of this subtle effect can give interesting results.

5 CONCLUSIONS

To estimate the parameters of the Galactic spiral structure – namely pitch angle and the number of arms – we used data on Galactic masers with known trigonometric parallaxes measured by VLBI, with an average error of less than 10 per cent. These masers are associated with extremely young objects located in active star-forming regions.

A well-known method based on the analysis of ‘position angle – distance logarithm’ diagram has been used. Estimates of the pitch angle \( i \) obtained from four segments of different arms belonging to the Galactic global structure are consistent with each other and are \( i = -13.7 \pm 1.1 \).

The most interesting one is the segment of the Outer arm, because its objects lie in a wide range of position angles \( \theta \) (up to 80°). However, it contains only three masers, so, in order to obtain reliable estimates, we added the data on 12 very young star clusters with distances determined by Camargo et al. from infrared photometry. Using the combined data set, we determined the value of pitch angle as \( i = -11.5 \pm 1.9 \).

Note that different methods of analysis give slightly different estimates of the pitch angle \( i \), in the range 10°–14°. Error of calculation of this angle is about \( 1^\circ \). In average, the value of the pitch angle is close to \( i = -13^\circ \pm 1^\circ \).

A comparison of the pitch angle \( i \) found in the present study with parameters obtained from kinematic analysis of masers (radial phase of the Sun in spiral wave \( \chi_c \) and wavelength \( \lambda_c \)) allowed us to conclude that the four-arm spiral pattern model of our Galaxy is the most probable one.

We have made an attempt to find systematic differences between the Local arm structure parameters using stars of different masses. This revealed some slight differences in estimates of pitch angle, but we did not find any significant shift across the arms (parameter \( R_0 \)), which is probably due to a relatively small amount of data. The most reliable pitch angle estimate seems to be the new one \( i = -11.6 \pm 0.8 \) obtained from the sample of massive stars.

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