Noncircular Motions in the Outer Perseus Spiral Arm

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Abstract

We report measurements of parallax and proper motion for five 6.7 GHz methanol masers in the outer regions of the Perseus arm as part of the BeSSeL Survey of the Galaxy. By combining our results with previous astrometric results, we determine an average spiral arm pitch angle of 9°2 ± 1°5 and an arm width of 0.39 kpc for this spiral arm. For sources on the interior side of the Perseus arm, we find on average a radial inward motion in the Galaxy of 13.3 ± 5.4 km s⁻¹ and counter to Galactic rotation of 6.2 ± 3.2 km s⁻¹. These characteristics are consistent with models for spiral arm formation that involve gas entering an arm to be shocked and then to form stars. However, similar data for other spiral arms do not show similar characteristics.

Key words: Galaxy: kinematics and dynamics – ISM: individual objects (G094.60–1.79, G111.25–0.76, G136.84+1.16, G173.48+2.44, G188.94+0.88) – techniques: interferometric

1. Introduction

While spiral patterns can be prominent in disk galaxies, their formation mechanism and the dynamical evolution of spiral arms remain under discussion. Two general mechanisms for spiral arm formation have dominated the discussion in the literature: (1) density-wave theories (Lin & Shu 1964; Roberts 1969) and (2) dynamic theories (Goldreich & Lynden-Bell 1965; Toomre 1969). In density-wave theories, spiral structures are long-lived and rotate nearly uniformly, while stars and gas rotate differentially and pass through the arms. In dynamic theories, arms are short-lived and reform on open structures. They are seen in N-body simulations of multi-arm spirals (e.g., Sellwood & Carlberg 1984; Sellwood 2000, 2010; Sellwood & Binney 2002; Fuchs et al. 2005; Fujiij et al. 2011), unbarred grand-design spirals (Sellwood 2011), and barred spirals (e.g., Baba et al. 2009; Grand et al. 2012; Roca-Fàbrega et al. 2013; Baba 2015).

Comparing the spatial distributions of stars and gas in a spiral arm may help to distinguish between the two mechanisms (e.g., Dobbs & Baba 2014; Sakai et al. 2015; Egusa et al. 2017; Baba et al. 2018). Density-wave theories predict a spatial offset between the gravitational potential minimum of a spiral arm (traced by the distribution of old stars) and the peak of gas density (Roberts 1969). On the other hand, dynamic (nonstationary) spiral-arm models predict that both star and gas accumulate into a minimum in the spiral potential and hence are not separated (e.g., Dobbs & Bonnell 2008; Wada et al. 2011; Baba et al. 2015). In the future one could test these theories by comparing the three-dimensional (3D) positions of older stars measured by Gaia with that of masers from newly formed stars measured by Very Long Baseline Interferometry (VLBI).

If gas entering a spiral arm is shocked prior to the formation of stars, the resulting stars should display the kinematic signature of that shock. By measuring 3D velocity fields, one could therefore determine if such shocks occur and how strong they are. Such as the Bar and Spiral Structure Legacy (BeSSeL) Survey and VLBI Exploration of Radio Astrometry (VERA) have yielded precise distances and 3D velocity fields for high-mass star-forming regions (HMSFRs) associated with spiral arms (e.g., Reid et al. 2009b, 2014; Honma et al. 2012). Optical astrometric results from Gaia DR2 typically have parallax uncertainties larger than 20 μas (e.g., see Figure 7 in Gaia Collaboration et al. 2018) and are starting to become significant for this type of study.

Recently, Xu et al. (2006), Sakai et al. (2012), and Choi et al. (2014) showed evidence for systematic (radially) inward motion for HMSFRs in the Perseus arm. Here, we report new astrometric results obtained with the National Radio Astronomy Observatory (NRAO) Very Long Baseline Array (VLBA), which more clearly reveal the structure and kinematics of the Perseus arm. In Section 2, we describe our VLBA observations. In Section 3, we outline the data reduction. In Section 4, we show new astrometric results for five 6.7 GHz CH₃OH masers. In Section 5, we discuss the structure and kinematics of the Perseus arm, based on our new results and Gaia DR2 results for OB-type stars (taken from Xu et al. 2018) and compare those with spiral arm models. In Section 6, we summarize the paper.

2. Observation

We observed a total of six methanol masers (i.e., the CH₃OH (J_κ = 5_1 – 6_0 A⁻) transition at a rest frequency of 6.668519 GHz) under VLBA programs BR149S, T and U (see Table 4 in the Appendix). Each set of observations was optimized to sample the peaks of the sinusoidal parallax signature in R.A. over one year, as described for previous BeSSeL Survey observations (e.g., Xu et al. 2016; Reid et al. 2017). Each maser source, listed in Table 4, was observed with three or four background quasars (QSOs). A single observation involved (i) four
half-hour “geodetic blocks” spaced by about 2 hr for clock and atmospheric delay calibration, (ii) “manual phase-calibration” scans of a bright quasar (QSO) every 2 hr, (iii) fast switching between a target maser and each QSO, used for relative position determination.

Observational data was recorded on the Mark5A system at 512 Mbps. Geodetic block data was taken in left circular polarization with four 16 MHz bands spanning 496 MHz centered at both 4.3 and 7.3 GHz (8 IFs in total). Fast switching data was taken in dual circular polarization with four adjacent 16 MHz bands spanning 64 MHz. The data were correlated with the DiFX software correlator (Deller et al. 2011) in Socorro, NM. The fast switching data were correlated in two passes: for the maser (line) data the central 8 MHz of the third IF band was correlated with 1000 channels, giving a frequency (velocity) spacing of 8 kHz (0.36 km s\(^{-1}\)) at the rest frequency. The continuum data for all IFs were correlated with 32 spectral channels.

3. Data Reduction

The VLBA data reduction was conducted with the NRAO Astronomical Image Processing System and a ParselTongue pipeline described in previous BeSSeL Survey papers (e.g., Reid et al. 2009a). Details of the techniques employed to determine parallax and proper motion for 6.7 GHz CH\(_3\)OH masers are described in Reid et al. (2017). Here, we briefly outline the data reduction.

The largest source of relative position error for 6.7 GHz astrometric data is uncertainty in the ionospheric delay calibration. For the ionospheric delay calibration, we first applied the Global Ionospheric Maps obtained from NASA’s ftp server. However, at our observing frequency of 6.7 GHz, tropospheric and ionospheric delay residuals can still be significant, with residual path-delays of \(\approx\)5 cm for both components. Using the geodetic-block observations, tropospheric (nondispersive) delays were estimated by differencing delays at 4.3 and 7.3 GHz and subtracting these from the total delays. These were modeled as owing to a zenith delay for each observation’s block. To better calibrate the ionospheric delay residual, the delay differences between 4.3 and 7.3 GHz bands were scaled to the 6.7 GHz CH\(_3\)OH band and a residual zenith dispersive delay could also be determined.

After applying the geodetic-block calibrations to the phase-reference data, we used a bright maser spot as the phase reference for the associated QSOs. In cases where the maser displayed significant structure, we self-calibrated the maser data and applied these solutions to both maser and QSO data. All sources were imaged and the positions of compact components were determined by fitting elliptical Gaussian brightness distributions. The variations the positions of maser spots relative to background QSOs were then modeled as owing to parallax and proper-motion components.

Delay residuals at 6.7 GHz are generally dominated by the ionospheric miscalibration and can cause a systematic position shift across the sky (so-called ionospheric wedges). We used our multiple QSO data to account for these effects. As discussed in Reid et al. (2017), one can generate an “artificial QSO” at the position of the target maser to remove most of the effects of the ionospheric wedges. In this paper we incorporated an improved procedure that solved for the wedge effects at each

\[ \text{ftp://cdlis.gsfc.nasa.gov/gps/products/ionex/} \]

4. Results

We estimated trigonometric parallaxes and proper motions for five of the six sources we observed. For G098.03+1.44 the brightest maser spot was too faint (<0.5 Jy) to use as a phase reference. In order to estimate a single proper motion for each source, we averaged the values for all spots. We adopted these values for the proper motion of the central star, but added \(\pm 5\text{ km s}^{-1}\) in quadrature to the fitted error estimates for each motion coordinate in order to allow for uncertainty in this step. Note that Class II CH\(_3\)OH masers generally have internal motions of about 5 km s\(^{-1}\) (e.g., Moscadelli et al. 2010). The parallax and proper motions results are summarized in Table 1 (see also Figure 1).

Some sources have published parallax and proper motions for 22 GHz water or 12.2 GHz methanol masers as discussed below. When combining parallaxes, we used variance weighting. However, for combined proper-motion estimates of 6.7 GHz methanol and 22 GHz water masers motions, we adopted the methanol values, since water masers typically form in outflows of tens of km s\(^{-1}\), and transferring the maser motions to that of the central star is less certain than from methanol masers.

We now briefly discuss some individual sources.

4.1. G094.60−1.79

All background QSOs were northward of the maser, rather than surrounding it. When accounting for the effects of ionospheric wedges, this requires extrapolation of the fitted planar position tilt instead of interpolation, and we expect increased parallax uncertainty. To allow for this, we added \(\pm 0.05\text{ mas}\) per degree of offset times the offset of the nearest QSO in quadrature with the formal parallax uncertainty. This parallax gradient error source is a rough estimate based on BeSSeL Survey experience fitting for 6.7 GHz data for many sources.

Oh et al. (2010) used the VERA array and estimated a parallax of 0.326 ± 0.031 mas based on three 22 GHz water maser spots. In order to be conservative, we have inflated their uncertainty by \(\sqrt{3}\) to \(\pm 0.054\text{ mas}\) in order to allow for correlated systematic errors caused by similar differential atmospheric delay differences between maser spots and a background QSO. Generally, residual atmospheric delay errors dominate centimeter-wave VLBI parallax uncertainty. Another
result for this source comes from Choi et al. (2014), who obtained a 22 GHz parallax of 0.253 ± 0.024 mas using the VLBA. In order to assess if the three parallax results are statistically consistent we calculated parallax differences of 0.147 ± 0.072, 0.074 ± 0.054, and 0.073 ± 0.059 mas. Only the first difference is marginally statistically significant, while the other two are statistically insignificant. We conclude that these could reasonably have come from random differences and combine all three by variance weighting to give a best parallax for G094.60−1.79 of 0.250 ± 0.020 mas.

4.2. G111.25−0.76

Choi et al. (2014) derived a parallax of 0.299 ± 0.022 mas for water masers and the difference between this and our result is not statistically significant (0.035 ± 0.030 mas). Thus we variance weighted them to obtain a best parallax of 0.280 ± 0.015 mas.

4.3. G136.84+1.16

All background QSOs were northward of the maser, and, as discussed above for G094.60−1.70, we inflated the parallax uncertainty to account for a likely ±0.05 (mas/degree) parallax gradient. However, because the maser’s structure was fairly extended, the final parallax uncertainty is quite large (±0.123 mas).

4.4. G188.94+0.88

Oh et al. (2010) using VERA obtained a parallax of 0.569 ± 0.068 mas for water masers, while Reid et al. (2009a) using the VLBA found a value of 0.476 ± 0.006 mas based on 12 GHz methanol masers. The differences among the three parallax measurements are not statistically significant (0.104 ± 0.080, 0.011 ± 0.042, and 0.093 ± 0.068 mas), and we variance weighted them to obtain a best parallax of 0.476 ± 0.006 mas. For a combined proper motion, we use our 6.7 GHz and the published 12 GHz methanol maser result, yielding (μα cos δ, μδ) = (−0.30 ± 0.60, −1.95 ± 0.51) mas yr⁻¹, where we have added in quadrature ±5 km s⁻¹ for each component uncertainty.

5. Discussion

5.1. Pitch Angle and Arm Width of the Perseus Arm

Using the five astrometric results discussed above, along with other sources in the literature, we now evaluate the pitch angle and width of the Perseus arm based on 27 sources. Following Reid et al. (2014), we fitted a logarithmic spiral-arm model to the locations of the Perseus arm sources using the
Figure 2. Spatial distribution and noncircular motions of Perseus-arm sources. Large red and small black filled circles show our and previous VLBI astrometric results. For clarity, only sources whose motion uncertainties are less than 20 km s\(^{-1}\) are plotted. A scale of 20 km s\(^{-1}\) (thick arrow) is displayed at the lower left. The solid curve represents a fitted logarithmic spiral model and the dashed lines indicate \pm 1\sigma width. The Sun is at \((X, Y) = (0, 8.34)\) kpc. The noncircular motions are with respect to Galactic constants \((R_0 = 8.34 \text{ kpc} \text{ and } \Theta_0 = 241 \text{ km s}^{-1})\) and a solar motion of \((U_\odot, V_\odot, W_\odot) = (10.5, 14.4, 8.9) \text{ km s}^{-1}\) (Reid et al. 2014).

Table 2

| Interior Side | Middle Region | Exterior |
|---------------|---------------|----------|
| \(-\frac{\sigma_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) < -\frac{\sigma_{\text{Per}}}{2}\) | \(-\frac{\sigma_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) < \frac{\sigma_{\text{Per}}}{2}\) | \(\frac{\sigma_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) \leq \frac{\sigma_{\text{Per}}}{2}\) |
| \langle U \rangle (\text{km s}^{-1}) | \langle V \rangle (\text{km s}^{-1}) | \langle W \rangle (\text{km s}^{-1}) | \langle U \rangle (\text{km s}^{-1}) | \langle V \rangle (\text{km s}^{-1}) | \langle W \rangle (\text{km s}^{-1}) | \langle U \rangle (\text{km s}^{-1}) | \langle V \rangle (\text{km s}^{-1}) | \langle W \rangle (\text{km s}^{-1}) |
| 13.3 \pm 5.4 | -2.5 \pm 2.8 | 0.0 \pm 2.4 | 5.9 \pm 2.1 | -6.2 \pm 3.2 | -1.0 \pm 3.0 | 2.7 \pm 7.6 | 3.4 \pm 2.8 | -4.6 \pm 3.5 |
| (9 masers) | (10 masers) | | (5 masers) | |

Note. Columns 1–3 represent unweighted means of the noncircular motion components \((U, V, \text{ and } W)\) for masers at \(-\frac{\sigma_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) < -\frac{\sigma_{\text{Per}}}{2}\), where \(\sigma_{\text{Per}} = 0.39 \text{ kpc}\) is the arm width of the Perseus arm. The uncertainties are the standard error of the mean. The numbers of sources available are indicated in parentheses. Numbers in bold font emphasize a statistical significance greater than \(2\sigma\). Columns 4–6 are for masers at \(-\frac{\sigma_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) < \frac{\sigma_{\text{Per}}}{2}\). Columns 7–9 are for masers at \(\frac{\sigma_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) \leq \frac{\sigma_{\text{Per}}}{2}\).

The following equation:

\[
\ln(R/R_{\text{ref}}) = -(\beta - \beta_{\text{ref}}) \tan \psi,
\]

where \(R_{\text{ref}}\) and \(\beta_{\text{ref}}\) are a Galactocentric radius (kpc) at a reference azimuth (radians). Azimuth (\(\beta\)) is defined as zero toward the Sun as viewed from the Galactic center and increases with Galactic longitude, and \(\psi\) is the spiral pitch angle. \(\beta_{\text{ref}} = 135.2\) was chosen to be near the midpoint of the azimuth values. Our best-fitting values are \(R_{\text{ref}} = 9.93 \pm 0.09 \text{ kpc}\) and \(\psi = 9.52 \pm 1.05\). These results are consistent with those in Reid et al. (2014) within errors. The arm’s width, defined as the 1\(\sigma\) scatter in the sources perpendicular to the fitted arm, is 0.39 kpc.

5.2. Noncircular Motion in the Perseus Arm

We now assess the three-dimensional noncircular (peculiar) motions of Perseus arm sources, based on the parallaxes, proper motions, and LSR velocities. The LSR velocity of the central star is estimated from the masers and from observations of thermal line emission (e.g., CO) from the parent cloud. Peculiar motions are referenced to a model Galactic rotation curve, using Galactic parameters \((R_0 \text{ and } \Theta_0)\), and solar motion \((U_\odot, V_\odot, W_\odot)\). Note that \(U\) values are positive directed toward the Galactic center, \(V\) is in the direction of the Galactic rotation, and \(W\) is toward the north Galactic pole. In the following, we use 24 of the 27 sources available, removing three outliers (G043.16+0.01, owing to its large motion uncertainty of >20 km s\(^{-1}\), and G108.20+0.58 and G229.57+0.15 owing to their large deviation of >2.2\(\sigma\) from the spiral arm fit).

Figure 2 shows the noncircular motions of Perseus-arm sources with uncertainties less than 20 km s\(^{-1}\). The solid curve in Figure 2 represents a logarithmic spiral-arm fit and the dashed lines indicate \(\pm 1\sigma\) width (see Section 5.1). Figure 3 plots the noncircular motions as a function of distance perpendicular to the arm, \(\rho_\perp\), defined positive outward from the arm. Interestingly, we see a significant velocity gradient of \(-25 \pm 8 \text{ km s}^{-1} \text{ kpc}^{-1}\) in \(U\) versus \(\rho_\perp\). Note that excluding the two high points with \(U > 25 \text{ km s}^{-1}\) and \(\rho_\perp < -0.2 \text{ kpc}\) as potential outliers still yields a significant gradient of \(-16 \pm 7 \text{ km s}^{-1} \text{ kpc}^{-1}\). The other peculiar motion components \((V, W)\) do not show a statistically significant gradient across the spiral arm.

As an alternative approach to examining systematics in the peculiar motions, Table 2 presents unweighted means of \((\langle U \rangle, \langle V \rangle, \langle W \rangle)\) in three \(\rho_\perp\) bins: the interior given by \(-\frac{\rho_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) < -\frac{\rho_{\text{Per}}}{2}\), the middle given by \(-\frac{\rho_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) < \frac{\rho_{\text{Per}}}{2}\), and the exterior given by \(\frac{\rho_{\text{Per}}}{2} \leq \rho_\perp (\text{kpc}) < \frac{\rho_{\text{Per}}}{2}\). In the above, \(\rho_{\text{Per}}\) is a Gaussian 1\(\sigma\) width for the arm, which we estimate to be 0.39 kpc. For uncertainties, we adopt the
standard error of the mean, because the scatter evident in
Figure 3 (left) is much larger than would be suggested by the measurement uncertainties, indicating there is significant “astrophysical” noise.

As anticipated by the negative gradient of $U$ versus $\rho_\perp < 0$, the results in Table 2 show that sources toward the interior side of the arm are moving radially inward with $\langle U \rangle = 13.3 \pm 5.4$ km s$^{-1}$ (2.5$\sigma$ for 9 masers), while sources exterior to the arm show a small average $U$ motion of $= 2.7 \pm 7.6$ km s$^{-1}$ (for 5 masers). Regarding the $\langle V \rangle$ component of peculiar motion, the result in Table 2 provides marginally significant evidence for a small average motion counter to Galactic rotation of $\langle V \rangle = -6.2 \pm 3.2$ km s$^{-1}$ (1.9$\sigma$ for 10 maser) in the middle region of the Perseus arm. We investigated the sensitivity of the above results to the value of the pitch angle used to define the trace of the Perseus arm. Changing the pitch angle by $\pm 2\sigma$ and recalculating the average peculiar motions on the interior, middle, and exterior of the arm yielded no significant changes.

We now compare our observational results with basic predictions from various models for spiral arm formation.

5.2.1. Density Wave Model without Shock

Linear density-wave theories that rely purely on gravity have difficulty explaining the radially inward motion at the interior side of the Perseus spiral arm as observed in the VLBI astrometric data. This is because gas entering an overdense arm is accelerated gravitationally and should show radially outward motion at the interior side of the arm as shown in Figure 10 of Sakai et al. (2015).

5.2.2. Density Wave Model with a Shock

Our finding of a large positive $\langle U \rangle$ value, corresponding to radially inward motion, for the interior side of the Perseus arm is consistent with density-wave theories, which include a shock as gas in circular Galactic orbits encounters slower rotating spiral arms (Roberts 1969, 1972) triggering the formation of stars. The hydrodynamic shock model of Roberts (1972) with a pitch angle, $\psi$, of 12°, a pattern speed, $\Omega_p$, of 12.5 km s$^{-1}$ kpc$^{-1}$, a gaseous dispersion speed, $a$, of 8 km s$^{-1}$, and a spiral potential with an enhancement, $F$, of 7.5% compared to the axisymmetric potential, predicts a velocity jump in front of the gravitational potential minimum as shown by Figure 1 of Roberts (1972).

If we assume the full jump velocity is in the line-of-sight direction, the line-of-sight vector of Roberts’ (1972) model can be decomposed into $U$ (and $V$) jumps by subtracting the rotation curve model of Roberts (1972). This assumption is reasonable for the Perseus arm at the Galactic longitude range $l = 110-140$ (deg) because the noncircular motion vectors in Figure 2 are aligned in the line-of-sight direction at the section. The $U$ jumps with amplitudes of 20–30 km s$^{-1}$, shown by cyan and green curves in Figure 4, indicate large positive $\langle U \rangle$ values for the interior side of the Perseus arm and no significant $\langle U \rangle$ values for the exterior of the arm, which are consistent with the observational results. We also investigated the shock model of Roberts (1972) with $\psi = 8^\circ$ and $F = 5\%$ (taken from his Figures 7 and 8) and found similar characteristics, but with shock velocities decreased to 10–20 km s$^{-1}$ and the shock locations shifted by $<150$ pc.

5.2.3. Dynamic Spiral Arm Formation

We now compare the observational results with a dynamic spiral-arm model proposed by Baba et al. (2018). The dynamic spiral-arm model is a barred spiral galaxy generated from $N$-body/hydrodynamics simulations, and amplitudes, pitch angles, and pattern speeds of spiral arms change within a few hundred million years. Baba et al. (2018) picked spiral arms in growth and disruption phases, respectively, from the model. The growth phase has a negative $\langle U \rangle$ value for the interior side of an arm and thus is inconsistent with our observational results. While the disruption phase has positive $\langle U \rangle$ for the interior side of the arm, it has negative values for the exterior of the arm, and thus also does not agree with our observational results.

5.3. Universality of Noncircular Arm Motions

We confirm that the shock model of Roberts (1972) can explain the observed radially inward motions in the interior side of the Perseus arm. In order to investigate the universality of these motions, we examine the noncircular motions for other spiral arms using the same procedure applied to the Perseus arm and the VLBI astrometric results compiled in Reid et al. (2014). We also
Figure 4. Left panel: noncircular motion toward the Galactic center ($U$) is expressed as a function of distance perpendicular to the Perseus arm ($\rho_\perp$) for masers in the Galactic longitude range $l = 110^\circ$–$115^\circ$. Large red and small black circles show our and previous VLBI astrometric results, respectively. The cyan curve represents a hydrodynamic shock model with a spiral pitch angle of $12^\circ$, a pattern speed of $12.5$ km s$^{-1}$ kpc$^{-1}$, a gas dispersion speed of $8$ km s$^{-1}$, and a spiral potential with a $7.5\%$ enhancement compared to the axisymmetric potential (taken from Figure 4 of Roberts 1972). Middle panel: same as left panel, but for sources at the Galactic longitude range $l = 130^\circ$–$140^\circ$. A hydrodynamic shock model shown by a green curve is from Figure 3 of Roberts (1972). Right panel: same as left panel, but for VLBI astrometric results from the entire Perseus arm. The cyan and green curves from the other panels are superimposed.

Table 3

| Spiral Arm | Type   | Interior Side | # | Exterior Side | # |
|------------|--------|---------------|---|--------------|---|
|             |        | $\frac{\rho_\perp}{\sigma} \leq \rho_\perp$ (kpc) < $\frac{\sigma}{2}$ |   | $\frac{\rho_\perp}{\sigma} \leq \rho_\perp$ (kpc) < $\frac{\sigma}{3}$ |   |
| Perseus     | Masers | 13.3 ± 5.4    | 9 | 2.7 ± 7.6    | 5 |
| Local       | Masers | 2.3 ± 2.8     | 4 | –4.4 ± 4.1   | 6 |
|             | OB stars| 2.7 ± 0.9     | 119| 5.3 ± 3.9   | 50 |
| Sagittarius | Masers | 3.1 ± 4.6     | 3 | 11.1 ± 6.8   | 3 |
|             | OB stars| 0.9 ± 1.6     | 50 | 7.2 ± 1.3   | 32 |

Note. Columns 1–2 indicate the spiral arm and type of observational data. Columns 3–4 show unweighted means of the noncircular motion components ($U$, $V$) for sources at $\frac{\rho_\perp}{\sigma} \leq \rho_\perp$ (kpc) < $\frac{\sigma}{2}$, where $\sigma$ is the arm width and $\rho_\perp$ is perpendicular distance for each spiral arm (taken from Reid et al. 2014). Note that a positive $\rho_\perp$ value indicates the interior of each arm as viewed from the Galactic center. An error in each mean shows the standard error of the mean. Numbers with the bold font indicate a statistical significance greater than 2$\sigma$. Column 5 represents the number of the sources. Columns 6–8 are the same as Columns 3–5, but for sources at $\frac{\rho_\perp}{\sigma} \leq \rho_\perp$ (kpc) < $\frac{\sigma}{3}$.

We examine Gaia DR2 results for OB-type stars taken from Figure 2(a) of Xu et al. (2018). Table 3 displays the noncircular motion components ($\langle U \rangle$, $\langle V \rangle$) for the interior and exterior of the spiral arms. While there are some statistically significant average motions, no clear trend is evident for these spiral arms, suggesting a more complex picture than expected from the basic models discussed above.

6. Summary

We presented parallaxes and proper motions for five 6.7 GHz methanol masers associated with HMSFRs in the outer portion of the Perseus spiral arm as part of the BeSSeL Survey of the Galaxy (see Figure 1 and Table 1). Combining these new and previous VLBI results, we determined a spiral-arm pitch angle of $95^\circ$ ± $1^\circ$ and an arm width of 0.39 kpc (see Section 5.1).

We divided the sources into interior, middle, and exterior regions of the Perseus arm and averaged the noncircular motion components ($\langle U \rangle$, $\langle V \rangle$, $\langle W \rangle$) for each region. For nine sources in the interior of the arm, we found a radially inward motion of $\langle U \rangle = 13.3$ ± 5.4 km s$^{-1}$; for 10 sources in the middle of the arm, we obtained a marginal detection of motion slower than Galactic rotation of $\langle V \rangle = -6.2$ ± 3.2 km s$^{-1}$; and for 5 sources in the exterior of the arm, we found no statistically significant noncircular motion (see Section 5.2 and Table 2). These characteristics are consistent with predictions of models for spiral arm formation that involve gas entering an arm to be shocked and then forming stars as shown by Figure 4.

We performed a similar analysis on previous VLBI astrometric data, as well as on Gaia DR2 results for OB-type stars, for stars in other spiral arms. While some statistically significant noncircular motions are found in other arms, no clear pattern among arms was found (see Table 3). This suggests a more complex picture than expected from basic spiral-arm models.

Facility: VLBA.

Appendix

Here, we show supplemental materials to further document observations (Table 4) and detailed maser maps for (Figure 5).
### Table 4

| Project | Source | R.A. (hh:mm:ss) | Decl. (dd:mm:ss) | Epoch 1 (in 2012) | Epoch 2 (in 2013) | Epoch 3 (in 2013) | Epoch 4 (in 2013) |
|---------|--------|----------------|-----------------|-------------------|------------------|------------------|------------------|
| BR149S  | G136.84+1.16 | 02:49:33.609 | +60:48:27.92 | Dec 8 | May 19 | Jun 24 | Nov 24 |
|         | J0244+6228 | 02:44:57.6966 | +62:28:06.517 |                      |                  |                  |                  |
|         | J0248+6214 | 02:48:58.8920 | +62:14:09.678 |                      |                  |                  |                  |
|         | J0306+6243 | 03:06:42.6595 | +62:43:02.024 |                      |                  |                  |                  |
| BR149T  | G173.48+2.44 | 05:39:13.066 | +35:45:51.28 | Sep 22 | Mar 9 | Apr 5 | Sep 13 |
|         | J0530+3723 | 05:30:12.5493 | +37:23:32.620 |                      |                  |                  |                  |
|         | J0539+3308 | 05:39:09.6722 | +33:08:15.496 |                      |                  |                  |                  |
|         | J0541+3301 | 05:41:49.4359 | +33:01:31.890 |                      |                  |                  |                  |
|         | J0552+3754 | 05:52:17.9369 | +37:54:25.281 |                      |                  |                  |                  |
| G188.94+0.88 | 06:08:53.341 | +21:38:29.08 |                      |                  |                  |                  |                  |
|         | J0603+2159 | 05:30:12.5493 | +37:23:32.620 |                      |                  |                  |                  |
|         | J0607+2129 | 06:07:59.5657 | +21:29:43.720 |                      |                  |                  |                  |
|         | J0607+2218 | 06:07:17.4360 | +22:18:19.080 |                      |                  |                  |                  |
|         | J0608+2229 | 06:08:34.3109 | +22:29:42.981 |                      |                  |                  |                  |
| BR149U  | G094.60−1.79 | 21:39:58.258 | +50:14:21.02 | Dec 3 | May 12 | Jun 6 | Nov 23 |
|         | J2137+5101 | 21:37:00.9862 | +51:01:36.129 |                      |                  |                  |                  |
|         | J2145+5147 | 21:45:07.6666 | +51:47:02.243 |                      |                  |                  |                  |
|         | J2150+5103 | 21:50:14.2662 | +51:03:32.264 |                      |                  |                  |                  |
|         | (J2139+5300) | 21:39:53.6244 | +53:00:16.599 |                      |                  |                  |                  |
| G098.03+1.44 | 21:43:01.431 | +54:56:17.72 |                      |                  |                  |                  |                  |
|         | J2123+5452 | 21:23:46.8349 | +54:52:43.488 |                      |                  |                  |                  |
|         | (J2139+5300) | 21:39:53.6244 | +53:00:16.599 |                      |                  |                  |                  |
|         | J2139+5540 | 21:39:32.6175 | +55:40:31.771 |                      |                  |                  |                  |
|         | J2145+5147 | 21:45:07.6666 | +51:47:02.243 |                      |                  |                  |                  |
| G111.25−0.76 | 23:16:10.327 | +59:55:28.66 |                      |                  |                  |                  |                  |
|         | J2339+6010 | 23:39:21.1252 | +60:10:11.849 |                      |                  |                  |                  |
|         | J2354+6209 | 22:54:25.2926 | +62:09:38.723 |                      |                  |                  |                  |
|         | J2301+5706 | 23:01:26.6271 | +57:06:25.499 |                      |                  |                  |                  |
|         | (J2314+5813) | 23:14:19.0833 | +58:13:47.647 |                      |                  |                  |                  |

Note. Column 1 shows project name. Column 2 lists an observed 6.7 GHz CH$_3$OH maser source (as denoted by “G”) and background QSOs (as denoted by “J”). Parentheses indicate an extended source, which was removed from the parallax determination. Columns 3–4 represent equatorial coordinates for the source in (J2000). Columns 5–8 show dates of observations.
Figure 5. Maser spot distributions for (a) G094.60−1.79, (b) G098.03+1.44, (c) G111.25−0.76, (d) G136.84+1.16, (e) G173.48+2.44, and (f) G188.94+0.88. The distributions were made using 1st epoch data of individual sources. The origin of coordinates for each map is described in Table 4. The horizontal red arrow in each map, except for G098.03+1.44, shows an absolute spatial scale converted at a source distance (see Table 1). Color bar indicates the local standard of rest (LSR) velocity. The size of a maser spot is proportional to (Jy/beam).

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