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A comparison of the local spiral structure from *Gaia* DR2 and VLBI maser parallaxes[*]

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ABSTRACT

Context. The *Gaia* mission has released the second data set (*Gaia* DR2), which contains parallaxes and proper motions for a large number of massive, young stars.
Aims. We investigate the spiral structure in the solar neighborhood revealed by *Gaia* DR2 and compare it with that depicted by VLBI maser parallaxes.
Methods. We examined three samples with different constraints on parallax uncertainty and distance errors and stellar spectral types: (1) all OB stars with parallax errors of less than 10%; (2) only O-type stars with 0.1 mas errors imposed and with parallax distance errors of less than 0.2 kpc; and (3) only O-type stars with 0.05 mas errors imposed and with parallax distance errors of less than 0.3 kpc.
Results. In spite of the significant distance uncertainties for stars in DR2 beyond 1.4 kpc, the spiral structure in the solar neighborhood demonstrated by *Gaia* agrees well with that illustrated by VLBI maser results. The O-type stars available from DR2 extend the spiral arm models determined from VLBI maser parallaxes into the fourth Galactic quadrant, and suggest the existence of a new spur between the Local and Sagittarius arms.

Key words. Galaxy: structure – stars: early-type – stars: massive – masers

1. Introduction

The Milky Way has been thought to be a spiral galaxy since as far back as the 1850s (Alexander 1852), but it is extremely difficult to observe its spiral structure due to our edge-on view from its interior and limited by copious dust extinction. It was not until the 1950s that researchers started to use high-mass stars (OB stars) and H II regions to trace spiral arm segments in the solar neighborhood (Morgan et al. 1952, 1953). Such work, augmented by radio wavelength data, was extended to cover most of the Galaxy by Georgelin & Georgelin (1976) and Russeil (2003). In the last decade, Very Long Baseline Interferometry (VLBI) at centimeter wavelengths has provided hundreds of parallaxes to very young, massive stars with accuracies often as good as ±0.01 mas (Xu et al. 2006, 2016; Honma et al. 2007; Reid et al. 2014), substantially increasing our knowledge of the spiral arms in our Galaxy. Recent VLBI parallaxes, however, have mostly been limited to stars visible from the northern hemisphere, leaving the fourth Galactic quadrant largely unexplored.

The *Gaia* satellite (Gaia Collaboration 2016), launched in 2013, will ultimately achieve parallax accuracy comparable to that of VLBI for approximately 10^9 stars, although the current release (Gaia Collaboration 2018) is limited by systematic error of up to <0.1 mas, depending on celestial positions, magnitudes, and colors (Lindegren et al. 2018). Still, even with this limitation, distances to many OB stars within a couple of kiloparsec from the Sun are now available. We note that even when *Gaia* reaches its target accuracy, direct measurement of spiral structure will be limited by dust extinction in the plane of the inner Galaxy to stars typically within a few kiloparsec.

2. OB star sample

Owing to their short main sequence lifetimes, high-mass stars are generally located near their birth places, and consequently can trace Galactic spiral structure. However, due to the absence of effective temperatures (Gaia Collaboration 2018) for bright stars (>10 000 K) in *Gaia* DR2, we are unable to identify OB stars straightforwardly. In order to identify OB stars, we started with a sample of them from the Catalog of Galactic OB Stars (Reed 2003), which gives coordinates accurate to ≈1″, along with stellar classifications and Heliocentric radial velocities from SIMBAD[1]. We then cross-matched these stars with the *Gaia* DR2 catalog using a match radius of 1″. After having eliminated those with multiple matches, 5772 O-B2 stars remain (see Table 1). Our analysis starts with this sample.

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[1] http://simbad.u-strasbg.fr/simbad/sim-fcoo

Table 1. Parallaxes and proper motions of OB stars.

Name	*Gaia* DR2 ID	RA (°)	Dec (°)	π (mas)	μ_x (mas yr^{-1})	μ_y (mas yr^{-1})	V_{LSR} (km s^{-1})	Spectral type
ALS 13358	528563384392653312	0.1219	67.2168	1.079 ± 0.051	-1.72 ± 0.07	-2.39 ± 0.08		B1
ALS 13363	423149081478526464	0.2867	58.9799	0.302 ± 0.030	-3.26 ± 0.05	-2.62 ± 0.04		B0
ALS 13366	4231577744922796800	0.3113	59.1428	0.305 ± 0.028	-3.04 ± 0.04	-1.34 ± 0.04		B2
ALS 13367	429338850909909760	0.3485	60.3555	0.950 ± 0.054	1.94 ± 0.09	-3.82 ± 0.07	-5.2	B2ne
ALS 13375	528594342521399168	0.4453	67.5070	1.016 ± 0.031	-1.57 ± 0.04	-1.77 ± 0.04		O9.5 V
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Notes. Column 1 is the OB star identity in the catalog of Reed (2003); Column 2 is the unique source identifier in *Gaia* DR2. Columns 3 and 4 are barycentric right ascension (RA) and declination (Dec). Columns 5–7 give the parallax and proper motion in the eastward ($\mu_x = \mu_\alpha \cos\delta$) and northward directions ($\mu_y = \mu_\delta$). Column 8 lists local standard of rest (LSR) velocity converted from the heliocentric value. Column 9 is the spectral type of the stars. In *Gaia* DR2, the reference epoch is J2015.5. The full table is available at the CDS.
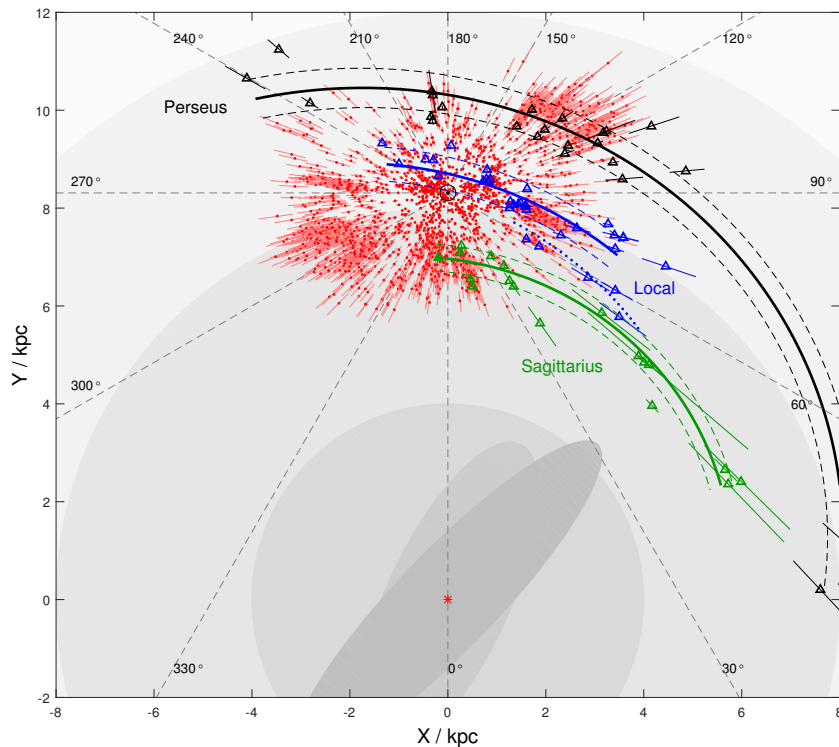
Fig. 1. Locations of *Gaia* DR2 OB (O–B2) stars (red circles) and masers (triangles) (Reid et al. 2014; Xu et al. 2016). The formal parallax uncertainties of the OB stars shown here are better than 10%, but do not include a possible ±0.1 mas systematic error. The Galactic center (red star) is at (0,0) and the Sun (Sun symbol) is at (0, 8.31). The solid and dashed curved lines denote the center and ±1σ widths of spiral arm models based on VBLI maser parallaxes. The Perseus arm (black), the Local arm (blue), and Sagittarius arm (green) are shown. Straight dashed lines indicate Galactic longitude.

Following the recommendation of the *Gaia* team (Arenou et al. 2018), we have not corrected the parallaxes of the individual OB stars in our sample by the average systematic bias of 0.029 mas on the parallax zero-point. Such a correction would, in any case, be very small for the nearby OB stars that we examine here. Table 1 lists coordinates, parallaxes, proper motions, radial velocities, and classifications of these OB stars. We believe this is the largest sample of O–B2 stars with parallaxes and proper motions to date.

3. Spiral structure

In this section, we investigate the spiral structure of the Milky Way within ≈3 kpc as revealed by OB stars and compare it with that determined from maser parallaxes associated with extremely young ($<10^5$ yr) high-mass star forming regions, whose parallaxes have been measured accurately with VLBI. Most of the stars in the sample have parallax uncertainties larger than ±20%, which can lead to distance uncertainty comparable to the spacing between spiral arms. Therefore, only stars with parallax accuracies better than ±10% are adopted, yielding a reduced sample of 2800 sources. We plot the locations of these stars in Fig. 1, along with stars with VLBI parallaxes from Reid et al. (2014) and Xu et al. (2016), which extend much further into the Galaxy.

As expected, most of the *Gaia* OB stars in our reduced sample gather around the Sun within a radius of about 3 kpc, as distant OB stars have been rejected owing to their large distance uncertainties and/or extinctions. The *Gaia* data generally
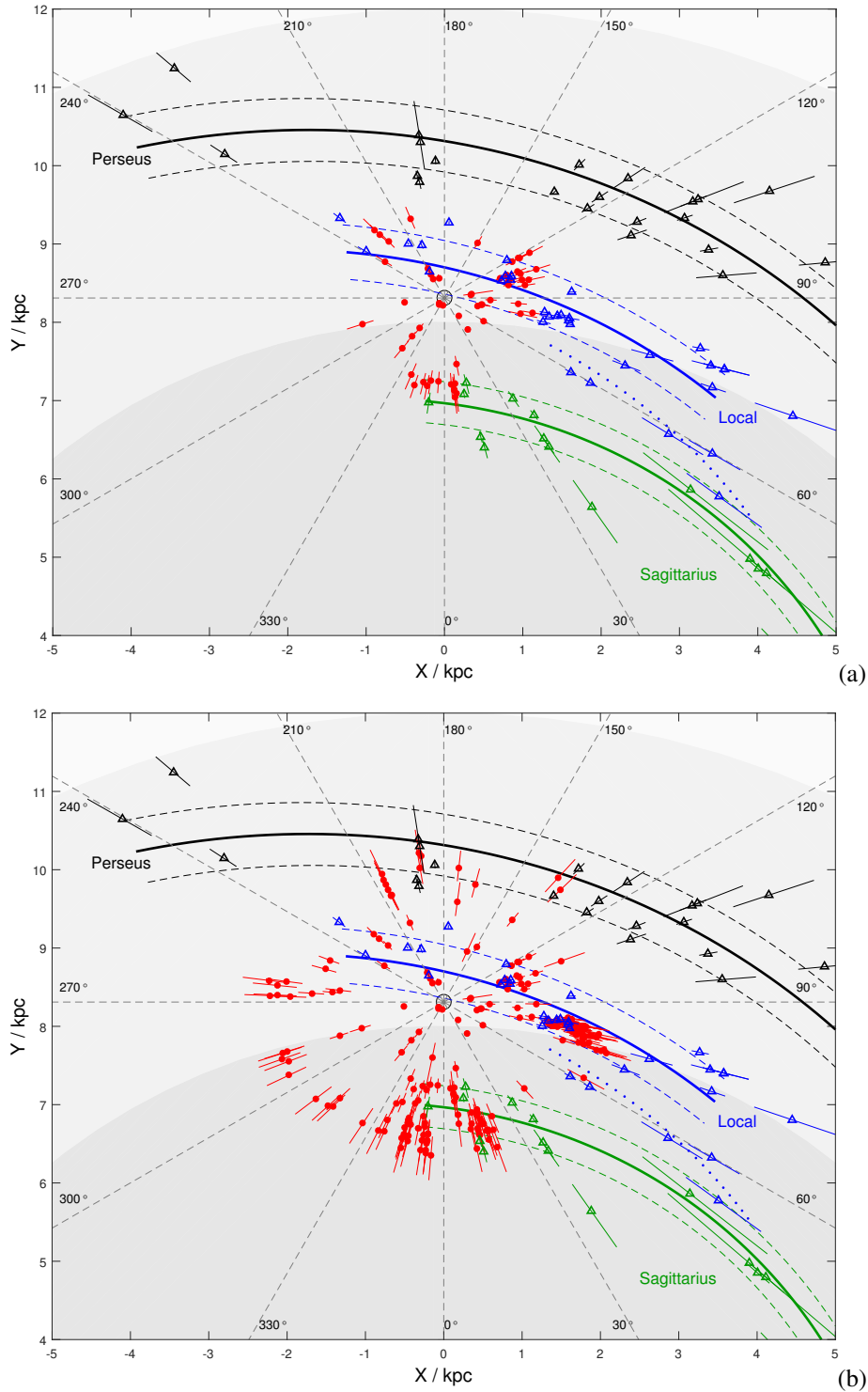
Fig. 2. Locations of only the identified O-type stars in *Gaia* DR2 (red circles): *panel a*) with ±0.1 mas systematic errors added in quadrature to the formal DR2 errors; only stars with corresponding absolute distance uncertainties <0.2 kpc are shown; *Panel b*) with ±0.05 mas systematic errors added in quadrature to the formal DR2 errors; only stars with corresponding absolute distance uncertainties <0.2 kpc are shown. See Fig. 1 caption for other details, but note that the 10% error threshold in that figure is not used here.

confirm the locations of spiral arms from VLBI in the Perseus, Local, and Sagittarius arms. Between Galactic longitude 240° and 360°, they can be used to extend our knowledge of the latter two arms.

As is also apparent in Fig. 1, OB stars presumably at nearly the same distance are spread out along the line of sight,

suggesting that the 10% threshold for parallax uncertainties is insufficient at distances beyond about 1.4 kpc. In addition, a substantial number of OB stars appear to fall between spiral arms. Since this is rarely the case for the maser sample of very young and massive stars, it suggests that allowing stars as late as type B2 into the sample is blurring spiral structure. These stars can

live long enough to orbit roughly half the way around the Galaxy and may have left the spiral arms.

In order to obtain an OB star sample that is truly capable of tracing spiral arms, we start over from our initial sample of 5772 stars, abandoning the 10% uncertainty constraint and removing B-type stars. For the remaining O-type stars, we incorporate the systematic error 0.1 mas on parallaxes recommended by Lindegren et al. (2018) and require absolute distance uncertainty <0.2 kpc and peculiar motions <20 km s^{-1} (the calculations of peculiar motions are given in the appendix). This leaves a sample of 59 O-type stars. These stars of O9.7V or earlier should have main sequence lifetimes of <8 Myr (Weidner & Vink 2010), and with peculiar motions <20 km s^{-1}, they should not have moved more than 0.2 kpc from their birthplaces. Because the widths of the spiral arms neighboring the Sun are ≈0.3 kpc (Reid et al. 2014) and lines of sight usually are not perpendicular to spiral arms, these stars should still be in their birth spiral arms.

In Fig. 2a, we display the distribution of those 59 O-type stars. Most of them are consistent with being in the Local and Sagittarius spiral arms, as traced by masers. Interestingly, about 10 of the stars appear to be between these two arms. This observation should be reliable as it comes from a very conservative treatment of the *Gaia* DR2 parallaxes.

If we relax the assumed DR2 systematic parallax uncertainty from ±0.1 to ±0.05 mas and loosen the absolute distance error constraint from ±0.2 kpc to ±0.3 kpc, the sample increases to 241 stars and is displayed in Fig. 2b. Significant linear arrangements that point toward the Sun ("fingers of God") are now more apparent, suggesting that caution should be exercised when gleaning information about spiral structure from this sample. However, some interesting features, which are not strongly dependent on the distance uncertainty, can be seen.

The abundance of stars between about 240° and 270° longitude at distances >1 kpc suggest that the Local arm continues into the fourth quadrant and bends somewhat inward toward the Galactic center. Similarly, the stars between 300° and 320° longitude at distances >1 kpc extend the Sagittarius arm into the fourth quadrant with about the same pitch angle as that determined from the maser parallaxes. Finally, a small cluster of stars centered near longitude ≈290° at a distance of ≈2 kpc appear to extend upward from the Sagittarius arm at a fairly high angle, as one might expect for a Galactic spur. This should not be surprising as the maser parallaxes have already shown some spurs; for example, the Aquila spur (Cohen et al. 1980; Dame et al. 1986).

4. Conclusions

VLBI parallaxes have traced the Milky Way's spiral structure within about 10 kpc of the Sun in Galactic quadrants 1, 2, and 3. The *Gaia* DR2 data supplement the maser VLBI measurements

and extend the map of the Local and Sagittarius arms into quadrant 4. They also suggest an additional spur-like feature between those arms.

References

Alexander, S., 1852, AJ, 2, 95
Arenou, F., Luri, X., Babusiaux, C., et al. 2018, A&A, 616, A17
Cohen, R. S., Cong, H., Dame, T. M., & Thaddeus, P. 1980, ApJ, 239, L53
Dame, T. M., Elmegreen, B. G., Cohen, R. S., & Thaddeus, P. 1986, ApJ, 305, 892
Gaia Collaboration (Prusti, T., et al.) 2016, A&A, 595, A1
Gaia Collaboration (Brown, A. G. A., et al.) 2018, A&A, 616, A1
Georgelin, Y. M., & Georgelin, Y. P. 1976, A&A, 49, 57
Honma, M., Bushimata, T., Choi, Y. K., et al. 2007, PASJ, 59, 889
Lindegren, L., Hernandez, J., Bombrun, A., et al. 2018, A&A, 616, A2
Morgan, W. W., Sharpless, S., & Osterbrock, D. 1952, AJ, 57, 3
Morgan, W. W., Whitford, A. E., & Code, A. D. 1953, ApJ, 118, 318
Reed, B. C. 2003, AJ, 125, 2531
Reid, M. J., Menten, K. M., Zheng, X. W., et al. 2009, ApJ, 700, 137
Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2014, ApJ, 783, 130
Russeil, D. 2003, A&A, 397, 133
Weidner, C., & Vink, J. S. 2010, A&A, 524, A98
Xu, Y., Reid, M. J., Zheng, X. W., & Menten, K. M. 2006, Science, 311, 54
Xu, Y., Reid, M., Dame, T., et al. 2016, Sci. Adv., 2, e1600878

Appendix A: The calculation of the peculiar motions of O stars

With distances, proper potions, and radial velocities, one has full three-dimensional (3D) velocity information in a heliocentric reference frame. Adding the Sun's full motion with respect to a reference frame at rest at the Galactic center transfers the O-star motions to that frame. Then removing a model of pure circular motion gives Galactic peculiar motions, expressed by (U_s, V_s, W_s), which are velocity components toward the Galactic center (GC), in the direction of Galactic rotation, and toward the north Galactic Pole at the location of each star.

We estimate peculiar motions of the O stars following Reid et al. (2009), using updated Galactic parameters of 241 km s^{-1} for the Galactic rotation speed, Θ_0, at a distance of 8.31 kpc to the GC, R_0, and solar motion parameters of $U_\odot = 10.5$ km s^{-1}, $V_\odot = 14.4$ km s^{-1}, and $W_\odot = 8.9$ km s^{-1} from Reid et al. (2014). We used the "Universal" rotation curve model, which produces a relatively flat rotation curve between 5 and 15 kpc.