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Structure and Kinematics of the Milky Way

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Abstract. Maser astrometry is now providing parallaxes with accuracies of ±10 micro-arcseconds, which corresponds to 10% accuracy at a distance of 10 kpc! The VLBA BeSSeL Survey and the Japanese VERA project have measured ≈ 200 parallaxes for masers associated with young, high-mass stars. Since these stars are found in spiral arms, we now are directly mapping the spiral structure of the Milky Way. Combining parallaxes, proper motions, and Doppler velocities, we have complete 6-dimensional phase-space information. Modeling these data yields the distance to the Galactic Center, the rotation speed of the Galaxy at the Sun, and the nature of the rotation curve.

Keywords. astrometry, Galaxy: structure, Galaxy: fundamental parameters, Galaxy: kinematics and dynamics

1. Introduction

While we have imaged galaxies throughout the observable universe, we know very little of the structure of our Milky Way. The reasons for this shortcoming are that we are inside the Milky Way, dust absorbs optical light in its plane, and distances are very great and hard to measured. The Milky Way may have some of the characteristics of UGC 12158 shown in Fig. 1. But, we really don't know.

Imagine sending a spacecraft on a million-year journey out of the Milky Way to take a picture and send it back to us. While this is clearly impractical, it turns out that we can generate a map of the Milky Way's spiral structure in only a few years. The Bar and Spiral Structure Legacy (BeSSeL) Survey and the VLBI Exploration of Radio Astrometry (VERA) project are measuring trigonometric parallaxes of molecular maser sources in regions of high-mass star formation across vast regions of the Milky Way. These parallaxes are now tracing the spiral structure of the Milky Way in great detail (eg, Reid *et al.* 2014).

2. Spiral Structure

Combining published BeSSeL Survey and VERA parallaxes with preliminary results from the last two years of BeSSeL Survey, we now have located upwards of 200 maser sources associated with high-mass star forming regions across large portions of the Milky Way (see Fig. 2). At least six spiral arm *segments* are clearly visible. Note that some of these segments may connect far past the Galactic center, such as suggested for the Scutum and Outer arms (Dame & Thaddeus 2011, Anderson *et al.* 2015). However, we caution against assuming a log-periodic spiral pattern with a constant pitch angle to trace a spiral arm around the Milky Way (Honig & Reid 2015).

Recent contributions of parallax measurements have been to point out that the Perseus arm, previously thought to be one of two dominant Milky Way arms, has a significant "gap" in high-mass star formation between Galactic longitudes of about 50° to 90°

Figure 1. UGC 12158, a galaxy sharing characteristics with the Milky Way (HST image).

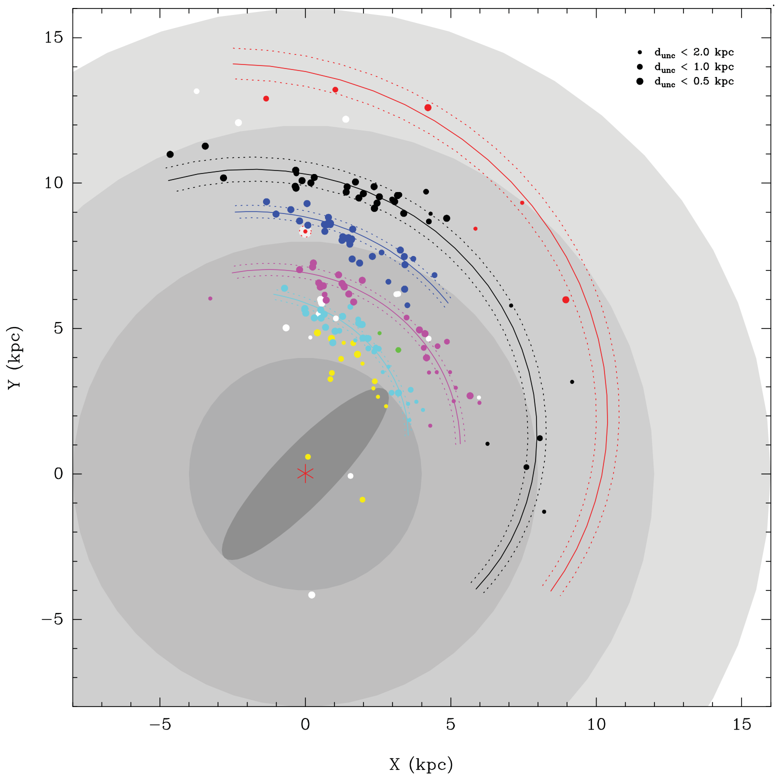

Figure 2. Parallax measurements for molecular masers associated with high-mass star formation across the Milky Way. These include published results from the VERA project and both published and unpublished results from the BeSSeL Survey. Starting from the outside, the Outer, Perseus, Local, Sagittarius, Scutum, and Norma spiral arms are indicated with lines.

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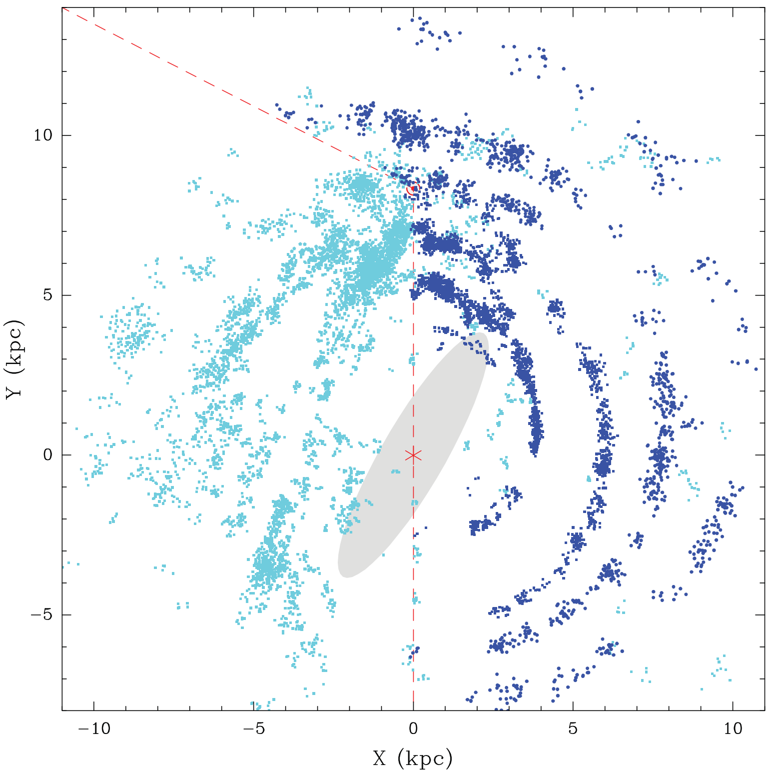

Figure 3. Visualization of the Milky Way from Reid *et al.* (2016).

(Choi *et al.*2014, Zhang *et al.*2013). This feature can also be identified in CO longitude-velocity emission. Of course, we cannot exclude some significant star formation in the gap, especially from low to intermediate mass clouds.

Whereas the Perseus arm has less massive star formation than one might have expected, the Local arm has the opposite. This arm has often been referred to in the literature as the "Orion spur," suggesting that it is a rather minor structure. However, many high-mass star forming regions toward longitudes 70° to 80°, which were suspected of being in the Perseus arm, are now definitely located in the Local arm by parallax measurements (Xu *et al.* 2016).

One can leverage the locations of spiral arms determined from parallax measurements to provide information to estimate distances to large numbers of star-forming regions. Basically, one can compare the (l, b, V) "coordinates" of a source with those traced by spiral arms. If one finds a single good match, then the distance to that section of the matching arm provides a good estimate of the distance to the source. In some cases, the (l, b, V) coordinates of the source may be consistent with those of two or more arms, and this can be used to distinguish among other distance indicators, such as from kinematic information. We have developed a Bayesian approach to combine all distance information when estimating the distance to individual sources (Reid *et al.* 2016). Using the Bayesian distance estimator for thousands of star-forming region sources in catalogs of molecular clumps, HII regions, infrared sources, and molecular masers, we can generate a visualization of the portion of the Milky Way where arm locations have been measured by parallax. Fig. 3 shows such a visualization.

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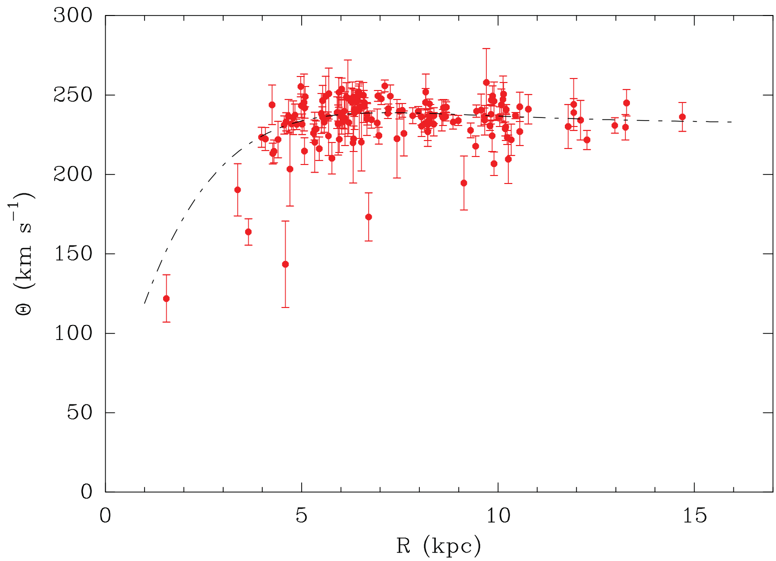

Figure 4. Rotation curve data from parallax measurements which supply full 6-dimensional phase-space information. The dashed line is a "universal" rotation curve (Persic, Salucci & Stel 1996) appropriate for spiral galaxies and fitted to the data.

In Fig. 3, dark blue points indicate star forming regions for which an arm association was likely. Cyan points indicate regions where an arm could not be assigned; these comprise a small fraction of sources visible from the northern hemisphere and could be inter-arm regions of star formation. The cyan points to the left of the dashed red lines are best observed from the southern hemisphere, and the locations of spiral arms there have yet to be determined. The locations of these sources come primarily from kinematic distances, which are not accurate enough to clearly trace spiral arms.

3. Kinematics

Given source coordinates, distances (from parallaxes), proper motions, and line-of-sight velocities, we have full 6-dimensional phase-space information for each source. These data are in a Heliocentric reference frame. One can easily transform to a Galactocentric frame, provided one knows the location of the Sun and its velocity vector as it orbits the Galaxy. All of these parameters can be estimated by fitting a simple model of rotation to the parallax data, yielding R_0=8.34 kpc and Θ_0=240 km s^{-1} (Reid *et al.* 2014). Adopting these parameter values, we can directly determine the rotation curve of the Milky Way as shown in Fig. 4. It is important to remember that this rotation curve is unique in that it uses 3-dimensional velocities (not only the line-of-sight component) and parallax distances (not more uncertain kinematic distances).

Fig. 4 shows that most high-mass star forming regions follow a rotation curve which is nearly flat between about 5 and 15 kpc from the Galactic center. There is an indication of a turn-down inside of 5 kpc, but more data are needed to properly characterize this portion of the rotation curve. Note that some outliers are expected as, for example, a result of super-bubbles giving rise to gas clouds with significant peculiar motions, which later form massive stars with molecular masers.

The rotation curve shown in Fig. 4 actually has a slight curvature for $R > 5$ kpc, which can explain a long-standing puzzle. The IAU recommended value for Θ_0 of 220 km s^{-1}

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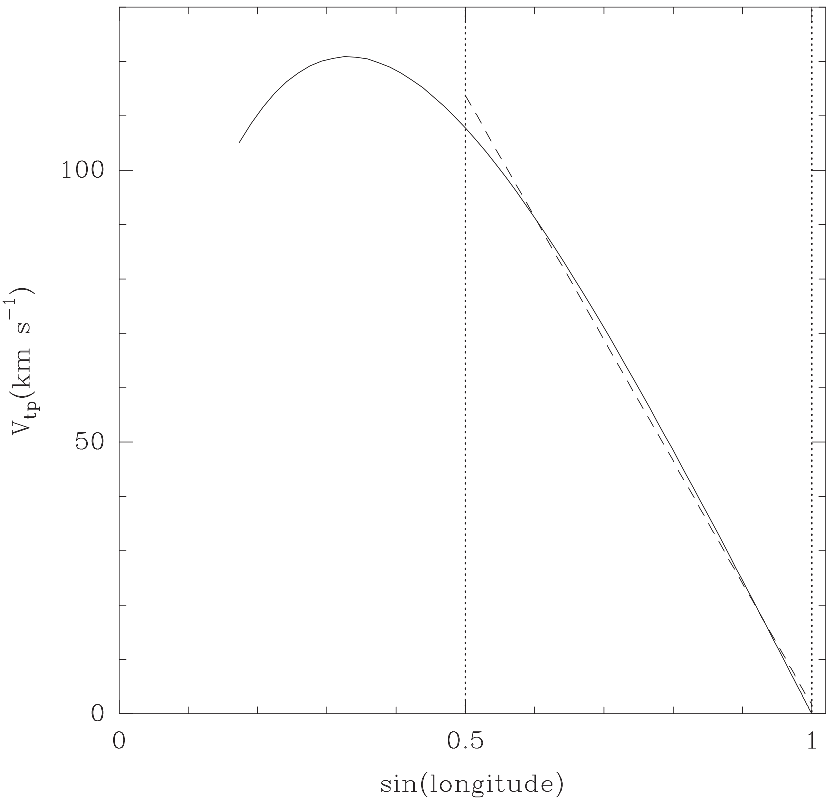

Figure 5. Maximum velocity for gas following a Persic "universal" rotation curve that best fits the parallax data as a function of sine of Galactic longitude (solid line) from Reid & Dame (2016). The dashed line is a straight line fit over the range $0.5 < \sin\ell < 1$, similar to that done for HI data by Gunn, Knapp & Tremaine (1979). The slope of the line of 220 km s^{-1} gives the rotation speed of the Galaxy at the Sun, Θ_0, if one assumes a flat rotation curve. The curvature in the rotation curve shown invalidates this assumption and explains why this method gives a value of Θ_0 lower than by direct fitting of the parallax data.

falls significantly below the 240 km s^{-1} value given by the rotation curve in Fig. 4. The IAU value was adopted largely based on fitting the maximum velocity seen in HI spectra as a function of $\sin\ell$, over the Galactic longitude range $0.5 < \sin\ell < 1$. The slope of a straight-line fit gives Θ_0, provided the rotation curve is flat over the fitting range (Gunn, Knapp & Tremaine 1979). Interestingly, if one instead uses the rotation curve shown in Fig. 4 to predict maximum velocities versus $\sin\ell$ and then fits those with a straight line, one recovers the IAU value of 220 km s^{-1}. This occurs even though the rotation curve never falls below 228 km s^{-1} over that longitude range and has an average value of 238 km s^{-1}. Thus, the discrepancy between the IAU and parallax-based values for Θ_0 can be attributed to assuming a flat rotation curve in the presence of some curvature (Reid & Dame 2016).

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