Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Mapping the Far Side of the Milky Way

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Abstract. Great progress has been made using VLBI techniques to measure trigonometric parallaxes to masers associated with young, high-mass stars, in order to map the spiral structure of the Milky Way. However, large numbers of parallax distance have only been obtained over about half of the Galaxy. Here I discuss the use of 3-dimensional kinematic distances for completing the map with many sources well past the Galactic Center.

Keywords. Milk Way, Spiral Structure, Distances, VLBI

1. Introduction

Over the last decade, the Bar and Spiral Structure Legacy (BeSSeL) Survey and the VLBI Exploration of Radio Astrometry (VERA) have been measuring trigonometric parallaxes for large numbers of maser sources associated with high-mass star forming regions. These masers are extremely young, < 1 Myr, and are excellent tracers of spiral arms. A major goal of these projects is to map the spiral structure of the Milky Way and to date they have done this across a large portion of the Galaxy, including the 1^{st} quadrant out to distances from the Sun of ~ 10 kpc, and the 2^{nd} and a portion of the 3^{rd} quadrants. What remains to be mapped in detail is the entire 4^{th} quadrant and the 1^{st} quadrant beyond the Galactic Center.

The near side of the 4^{th} quadrant is currently being surveyed by the Southern Hemisphere Parallax Interferometric Radio Astronometry Legacy Survey (SπRALS) using four antennas spanning the Australian continent and a fifth antenna in New Zealand. However, measuring parallaxes for sources well past the Galactic Center in both the 1^{st} and 4^{th} quadrants would require tens of thousands of hours of time on VLBI arrays to achieve distant accuracies of better than $\pm 10\%$. For a source at 20 kpc distance (parallax = 0.05 mas), this would require a ± 0.005 mas uncertainty which is difficult to achieve. And, even if achieved, this would correspond to ± 2 kpc distance uncertainty, which is roughly the separation of spiral arms and marginal for mapping spiral structure.

In this talk, I discuss a novel method for estimating distances to sources well past the Galactic Center, which promises to finish the mapping of the spiral structure of the Milky Way. The method uses 3-dimensional (3-D) kinematic distance estimates and only requires measurements of Doppler velocities and proper motions. The first application of this method was by Yamauchi *et al.* (2016) using the VERA array. They obtained a distance to a water maser in the massive star forming region G007.47+0.06 of 20 ± 2 kpc, which places this source 12 kpc past the Galactic Center. This result was confirmed by Sanna *et al.* (2017) with an extremely accurate trigonometric parallax measurement (uncertainty of ± 0.006 mas). Reid (2022) presented a detailed evaluation of the accuracies and limitations of 3-D kinematic distances, which I summarize here.

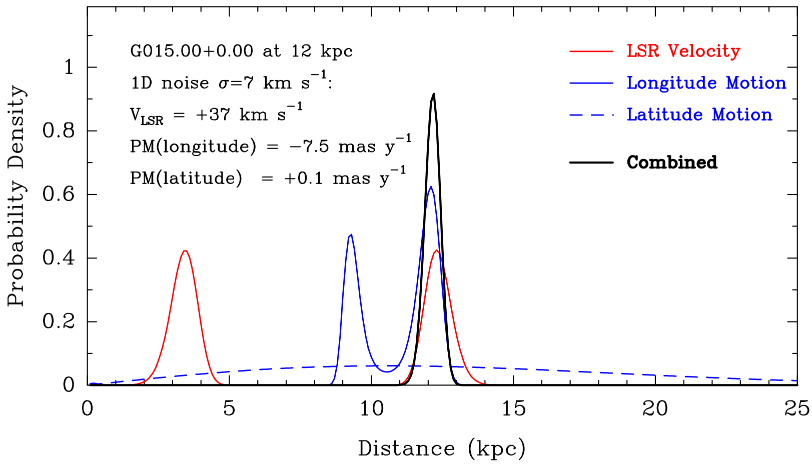

Figure 1. 3-D kinematic distance simulation after Reid (2022). Plotted are distance probability densities for each of three components of motion as listed in the legend. The simulated measurements are for a source at 12 kpc distance and Galactic longitude of 15° experiencing a near circular Galactic orbit with Gaussian random noise of 7 km s^{-1} added.

2. 3-D Kinematic Distance Method

For over a half-century, distances to many sources, including atomic and molecular clouds of gas, ionized hydrogen regions, and stars have been estimated from their Galactic coordinates and line-of-sight component of velocity (V_{lsr}), and called kinematic distances. These use 1-dimension of a source's velocity vector in conjunction with a model of Galactic rotation. 3-D kinematic distances expand on kinematic distances and offer not only improved accuracy, but also greater robustness.

A simulation of a 3-D kinematic distance estimate is shown in Fig. 1. The red line gives the probability density as a function of distance for a source at Galactic longitude 15°, based on its $V_{lsr} = 37$ km s^{-1} (i.e. standard kinematic distance). There are two probability peaks, one at 3 kpc and one at 12 kpc, demonstrating the well-known distance ambiguity problem for sources toward the inner Galaxy. While there are ways to decide between "near" and "far" kinematic distances, for example using hydrogen emission along the same line-of-sight, these are not always robust. In the figure, the solid blue line gives the probability density for the proper motion component in Galactic longitude, which peaks at 9 and 12 kpc distances. This distance information comes from proper motion measurement and is independent of, and complementary to, that from V_{lsr}. Finally, the dashed blue line gives the probability density for the proper motion component in Galactic latitude. While usually not strongly constraining, this extra distance information comes from the fact that, for a fixed velocity dispersion perpendicular to the Galactic plane, one expects a smaller angular motion the more distant a sources is.

In this example, the posterior likelihood for distance, which comes from the product of the three probability density functions, gives a distance estimate of $12.2 \pm 0.3 \pm 0.1$ kpc (where the first uncertainty is the formal statistical value and the second uncertainty is an estimate of systematic error. The formal statistical uncertainty is derived from the width of the combined posterior likelihood function, and the systematic error is estimated as half of the separation between the V_{lsr} and longitude motion peaks nearest the combined value. This provides a way to evaluate possible systematic error owing, for example, to a large peculiar (non-circular) motion or a significant error in the assumed rotation curve.

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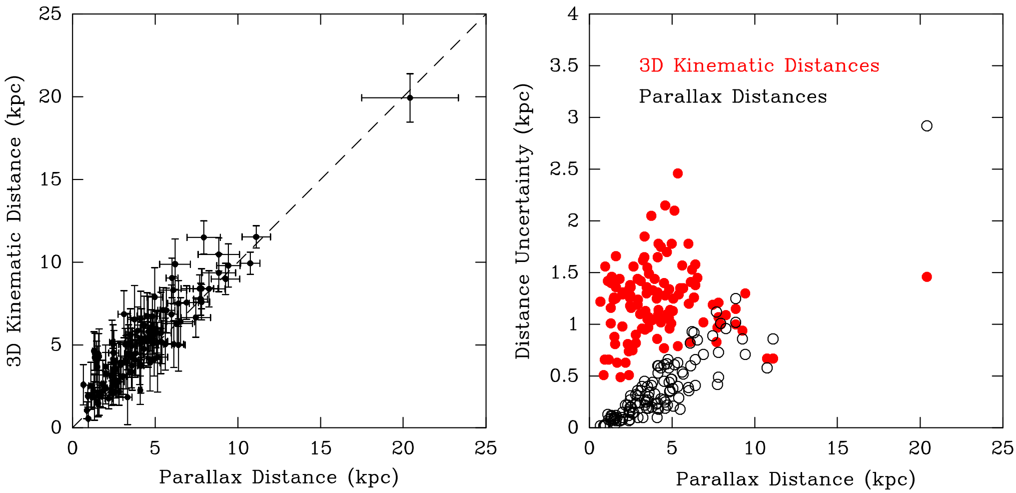

Figure 2. Comparison of trigonometric parallax and 3-D kinematic distances after Reid (2022). Plotted are data from Table 1 of Reid *et al.* (2019), collated from BeSSeL Survey and VERA project results and filtered to exclude sources with fractional parallax uncertainty greater than 15%. Note the general good agreement between the two methods and especially for G007.47+0.06 at near 20 kpc distance. The left panel plots 3-D kinematic distances vs. parallax distances. The right panel plots the distance uncertainties from the two methods: black circles for parallaxes and red dots for 3-D kinemtic distances.

3. The Accuracy of 3-D Kinematic Distances

Given the more than 200 sources with published parallaxes and proper motions from the BeSSeL Survey and the VERA project, we can empirically evaluate the accuracy and robustness of 3-D kinematic distances against their trigonometic parallax distances. This is shown in Fig. 2. The left panel directly compares the two distance estimates on a source-by-source basis. As can be seen, the 3-D kinematic distances generally agree well with the direct parallax estimates. For sources with (parallax) distance less than about 5 kpc, there is a tendency for the 3-D kinematic distances to be ~ 1 kpc too large. This bias can be traced to astrophysical noise, owing to non-circular motions of ≈ 7 km s^{-1} (Gaussian 1σ) per motion component, which leads to an asymmetric probability density function for Galactic longitude when dividing velocity by distance to get angular motion. This bias increases as distance decreases. (There are some other regions which have 3-D kinematic distance biases; see Reid (2022) for details.)

The right panel of Fig. 2 plots the uncertainties in the two methods. For sources with (parallax) distances less than about 8 kpc parallax distances are generally superior to 3-D kinematic distances. However, for greater distances the situtation is reversed, with 3-D kinematic distances generally yielding better results. Indeed, the 3-D distances tend to have uncertainties of ≈ 1.5 kpc, with no obvious increase in uncertainty with distance. This is in contrast to a parallax with uncertainty, σ_π, when converted to distance uncertainty, σ_d, formally scales as $\sigma_d = d^2\sigma_\pi$. (Note, the parallax-distance uncertainties plotted in Fig. 2, seem to scale roughly as d^1, which may be partially explained by our selection criterion.)

Why are 3-D kinematic distances so precise at great distances? Firstly, it is worth noting that proper motion uncertainty, σ_{pm}, scales with time spanned, Δt, as $\sigma_{pm} \propto \Delta t^{-1} \times \Delta t^{-1/2}$ assuming uniform measurement sampling in time. The first term comes from fitting a straight line to position vs time data and the longer the time spanned the lower the uncertainty in the slope. The second term comes from $1/\sqrt{N}$ statistics for N

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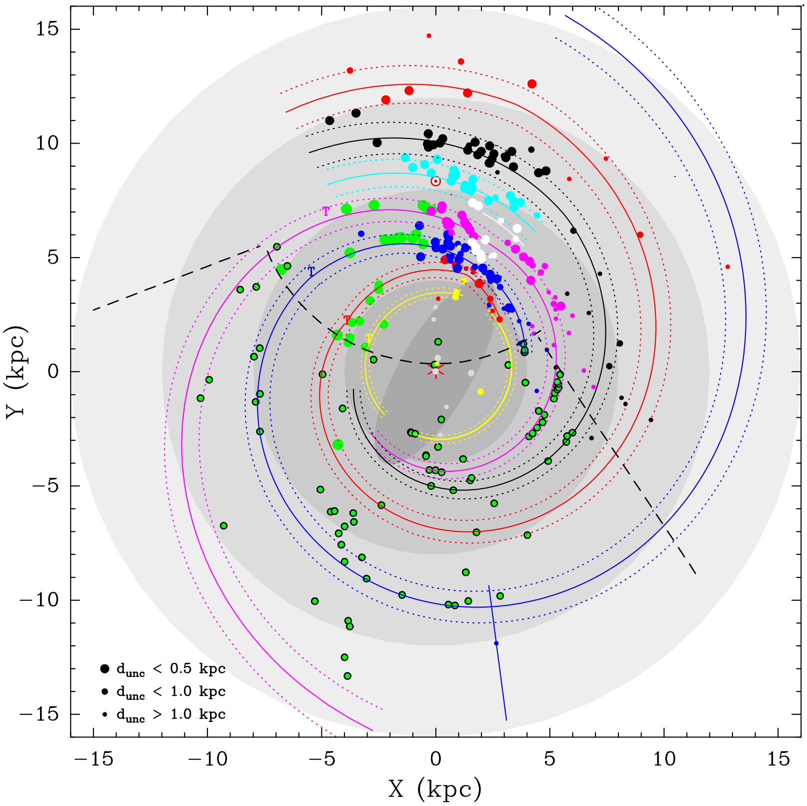

Figure 3. Plan view of the Milky Way showing high-mass stars with trigonometric parallaxes after Reid *et al.* (2019). Different colors indicate spiral arms/spurs from previous and on-going parallax measurements. Dashed black lines enclose candidate sources *(green with black circles)* for 3D kinematic distances. Note the locations of current and proposed sources are from 1D velocities and are quite uncertain.

measurements. Thus, proper motion uncertainty improves as $\Delta t^{-3/2}$, much faster than parallax uncertainty which scales as $\Delta t^{-1/2}$.

Secondly, the proper motion "signal" for a source on the far side of the Galaxy at the same distance from the Galactic center as the Sun (i.e., about 16 kpc from the Sun), has a (heliocentric) proper motion of twice the circular speed, $\Theta_0 \approx 236$ km s^{-1}, since the Sun and the source are moving in opposite directions. Thus, the proper motion "signal" is about $2 \times 236/16$ km s^{-1} kpc^{-1}, which is roughly 6 mas y^{-1}. Compared the parallax at 16 kpc of 0.06 mas, the proper motion is about 100-times larger and much more easily measured. Even if one admits a rather large ± 20 km s^{-1} uncertainty in either the speed of the source or the rotation curve of Galaxy, this is only a 4% effect. In conclusion, 3-D kinematic distances should be the method of choice for sources on the far side of the Milky Way, provided one avoids the Galactic bar region where very large non-circular motions are expected.

4. Masers in High-Mass Star Forming Regions

Fig. 3 presents a map of the Milky Way. Maser sources with parallax measurements are shown with dots, which are color coded by spiral arm mostly based on $l - V$ plots of CO emission. Green dots circled in black are methanol masers, placed using standard (inaccurate) kinematic distances, which are candidates for 3-D kinematic distances. Efforts

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are currently underway to measure proper motions to these methanol and other water masers (not shown) in order to better constain the spiral arm model of the Milky Way.

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