A PRECISE DISTANCE TO IRAS 00420+5530 VIA H$_2$O MASER PARALLAX WITH THE VLBA

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ABSTRACT

We have used the Very Long Baseline Array to measure the annual parallax of the H$_2$O masers in the star-forming region IRAS 00420+5530. This measurement yields a direct distance estimate of 2.17 ± 0.05 kpc (an error of less than 3%), which disagrees substantially with the standard kinematic distance estimate of ∼4.6 kpc (according to the rotation curve of Brand & Blitz), as well as most of the broad range of distances (1.7–7.7 kpc) used in various astrophysical analyses in the literature. The three-dimensional space velocity of IRAS 00420+5530 at this new, more accurate distance implies a substantial noncircular and anomalously slow Galactic orbit, consistent with similar observations of W3(OH) (Xu et al. and Hachisuka et al.), as well as line-of-sight velocity residuals in the rotation curve analysis of Brand & Blitz. The Perseus spiral arm of the Galaxy is thus more than a factor of 2 closer than previously presumed, and exhibits motions substantially at odds with axisymmetric models of the rotating Galaxy.

Key words: astrometry – Galaxy: structure – masers – stars: distances – stars: individual (IRAS 00420+5530) – techniques: interferometric

1. INTRODUCTION

Distance estimates to celestial objects are one of the most fundamental measurements in astronomy and astrophysics. Knowledge of the distance to astronomical sources in the sky is needed in order to estimate their physical properties, such as luminosities, masses, kinematics, and dynamics. In recent years, the technique of Very Long Baseline Interferometry (VLBI) has been used to make precise astrometric measurements (to a precision of a few tens of microarcseconds for a single observation) and thus holds the promise to extend the range of the direct distance measurements of annual parallax up to at least 10 kpc with 10% accuracy using radio telescopes such as the Very Long Baseline Array (VLBA) of the National Radio Astronomy Observatory (NRAO).

Compact, bright radio-emitting objects such as pulsars and masers are choice beacons for VLBI distance measurements across the Galaxy (e.g., van Langevelde et al. 2000; Brisk et al. 2002; Chatterjee et al. 2004; Xu et al. 2006). Such distance measurements enable enormous improvements in our understanding of Galactic structure and also the physics of individual objects. Reid (2008) reviewed the importance of measuring parallaxes and proper motions to help delineate Galactic structure and showed, in a survey for parallaxes and proper motions of young, high-mass stars, that kinematic distances are systematically too large.

In this paper, we report on using the VLBA to measure the annual parallax of the star-forming region IRAS 00420+5530, using the bright water masers associated with the IRAS source. IRAS 00420+5530 ($l = 122.0$, $b = -7.1$) is a star formation region exhibiting a molecular outflow (Zhang et al. 2005), 3.6 cm and 3 mm continuum emission (Molinari et al. 2002), and H$_2$O masers (e.g., Brand et al. 1994). It is also coincident with dense gas traced by HCO$^+$(1–0), indicating that the cluster of young stars remains deeply embedded in its natal cloud of molecular gas (Molinari et al. 2002). The systemic velocity of the gas around IRAS 00420+5530 is ∼51 km s$^{-1}$ with respect to the local standard of rest (LSR) based on the measurements of ammonia radial velocities (Molinari et al. 1996) and the HCO$^+$(1–0) (Molinari et al. 2002). The water masers occur at similar line-of-sight velocities as the surrounding gas, but with a somewhat broader range (LSR velocities −52 to −40 km s$^{-1}$).

Distances to IRAS 00420+5530 of 4.3–7.7 kpc (presumably kinematic, in most cases) have been used in recent papers, despite a much closer photometric distance of 1.7 kpc (Neckel & Staude 1984). Reflecting this broad range of distance estimates, luminosities of the IRAS source (presumably the exciting star) between $1.2 \times 10^4$ and $5.2 \times 10^4 L_\odot$ have been reported (e.g., Molinari et al. 2002; Zhang et al. 2005). Clearly, a better distance estimate is desirable for this object. In addition, IRAS 00420+5530 lies in the direction of the Perseus arm, which has been the topic of a recent distance study by Xu et al. (2006). Xu et al. (2006) addressed the large discrepancy between the luminosity and kinematic distance estimates in the Perseus arm by accurately measuring the distance (using VLBI techniques) of the methanol masers in the compact H ii region W3(OH). It is important that distances to other objects in the direction of the Perseus arm be precisely measured to compare to the work presented by Xu et al. (2006), and to determine small-scale deviations from the distances and kinematics in this region which could be due to peculiar motions of the studied objects.

We present here a careful analysis of the observing style, calibration techniques, data reduction, and parallax/proper motion fitting in order to provide the error analysis required to derive the most precise measurements of the distance to IRAS 00420+5530.

2. OBSERVATIONS

Between 2005 November and 2006 September, we made twelve hr VLBA observations (approximately monthly) of the H$_2$O masers in IRAS 00420+5530 to measure their annual parallax and proper motion. A large number of monthly epochs were chosen to ensure that the parallax and proper motion fits would not be confused by maser spots fading and disappearing between epochs. In the end, most of the spots persisted through most epochs, and this was not a problem. The observations were made from the VLBA’s dynamic observing queue, wherein our standardized observing script was initiated opportunistically and periodically in real time according to availability of the array, scientific ranking (relative to fixed-schedule programs and other
Table 1
Observations

| Epoch | Date      | Time Range (UTC) | Beam (mas) | Note                     |
|-------|-----------|------------------|------------|--------------------------|
| A     | 2005 Nov 24 | 02:30–06:30      | 1.00 × 0.34 @ −17.5 | Brewster did not participate |
| B     | 2005 Dec 19 | 00:51–04:51      | 0.98 × 0.33 @ −16.6 |
| C     | 2006 Jan 8  | 23:33–03:33      | 0.91 × 0.37 @ −16.3 |
| D     | 2006 Jan 26 | 22:22–02:22      | 0.86 × 0.46 @ −23.7 |
| E     | 2006 Feb 22 | 20:32–00:32      | 0.88 × 0.36 @ −18.3 |
| F     | 2006 Mar 17 | 19:01–23:01      | 0.87 × 0.37 @ −19.3 |
| G     | 2006 Apr 8  | 17:35–21:35      | 0.88 × 0.37 @ −14.3 |
| H     | 2006 May 8  | 15:37–19:37      | 0.84 × 0.62 @ −24.9 |
| I     | 2006 May 31 | 13:51–17:51      | 0.85 × 0.36 @ −13.3 |
| J     | 2006 Jun 22 | 12:40–16:40      | 0.85 × 0.36 @ −15.3 |
| K     | 2006 Aug 4  | 09:51–13:51      | 0.93 × 0.76 @ −21.7  |
| L     | 2006 Sep 2  | 07:57–11:57      | 0.84 × 0.34 @ −16.7  | Mauna Kea did not participate; epoch not used |

Table 2
Source Data

| Source Name | R.A. (J2000.0) | Decl. (J2000.0) | Flux Density (Jy) | Note                     |
|-------------|----------------|-----------------|-------------------|--------------------------|
| IRAS 00420+5530 | 00°44′58″39.77 | 55°46′47″600    | up to ~70.0       | Science target: H₂O masers |
| J0042+5708   | 00°42′19″4517   | 57°08′36″586    | ~0.18             | Primary phase-reference calibrator |
| J0047+5657   | 00°47′00″4288   | 56°57′42″395    | ~0.10             | Secondary phase-reference calibrator |

Figure 1. Phase-referencing geometry. J0042+5708 is the primary phase-reference calibrator; its phase solutions are used to calibrate both IRAS 00420+5530 and J0047+5657.

dynamically scheduled observations) and other operational constraints, such as observing direction and weather. Since IRAS 00420+5530 is at relatively high declination (and thus circumpolar at most VLBA sites), our 4 hr observation tended to rise to the top of the dynamic queue quite easily and often as a convenient schedule filler, and so the interval between epochs was often shorter than one month. The properties of the observations are listed in Table 1.

Four 16 MHz spectral windows were simultaneously observed in the VLBA’s 22 GHz band. One spectral window (the second) was set up to cover the H₂O maser lines in IRAS 00420+5530 at \( V_{\text{LSR}} \sim −46 \text{ km s}^{-1} \). The other three windows were distributed across the 500 MHz instantaneous intermediate frequency bandwidth of the VLBA to provide optimal delay sensitivity for calibration of the troposphere.

In addition to IRAS 00420+5530, nine compact background radio-loud quasars were observed as calibrators. Two of these calibrators were for phase-referencing purposes to provide for accurate relative astrometry (see Table 2 and Figure 1). The first of these calibrators (J0042+5708, \( \sim 1:41 \) from IRAS 00420+5530) was observed for primary phase referencing. For most of the observation, IRAS 00420+5530 and J0042+5708 were observed alternately on a \( \sim 60 \text{ s} \) timescale (30 s dwell on each). Once per hour, an alternate calibrator (J0047+5657, \( \sim 0:66 \) from J0042+5708) was observed to permit verification of the phase-referencing calibration.

The other seven calibrators, chosen from the VLBA calibrator list (Ma et al. 1998), were observed as a group once per hour (5 times in 4 hr) to enable determination of the residual macroscopic troposphere delay error at each antenna.

The accuracy of phase-referencing calibration at the VLBA is limited by a zenith-angle-dependent delay error arising from inaccuracies in the macroscopic troposphere model used at the VLBA correlator (Reid et al. 1999). The seasonal zenith troposphere delay model is typically in error by many centimeters, and this leads to a significant time-dependent delay error between the science target and phase-reference calibrator since they are observed at slightly different zenith angles. As a result, the phase referencing determined for the calibrator does not fully calibrate the target unless this macroscopic component is compensated.

This effect is calibrated by observing a set of bright (\( \gtrsim 1 \text{ Jy} \)) calibrators at a wide range of zenith angles and fitting the observed residual delays for the zenith troposphere error, assuming the delay increases away from the zenith as \( \sec \theta \), where \( \theta \) is the zenith angle. The standard approach (e.g., Reid & Brunthaler 2004) is to select approximately one dozen
such calibrators distributed over the entire sky and observe them 1–3 times over the course of the observation to get a few instantaneous measurements of the zenith delay. Such an approach does not permit tracking the delay error in time very accurately and makes no allowance for any azimuth dependence of the delay error, such as might be expected as weather changes over an antenna. Our approach was to select a smaller set of calibrators distributed sufficiently in zenith angle ($1 < \sec z < 2.5$) at the approximate azimuth of our target, and observe them more continuously during the observation.

After each observation, the data were correlated in two passes. The first pass correlated all four spectral windows at low spectral resolution (32 channels). The second pass correlated only the spectral window containing the H$_2$O maser lines with 1024 channels, yielding a channel spacing of 15.625 kHz, and thus a spectral resolution in the LSR of 18.75 kHz, or 0.253 km s$^{-1}$.

3. DATA REDUCTION

The visibility calibration was performed in NRAO AIPS (Greisen 2003), following the exact same procedure for each epoch. The low-spectral-resolution data were processed first, as follows.

First, several standard a priori calibrations were applied, including revised Earth orientation parameter corrections (EOP, important for good astrometry), parallactic angle phase, quantized sampling bias amplitude corrections, and system temperature/gain amplitude calibration.

Second, a scan on one of the bright macroscopic troposphere calibrators (J2202+4216 = BL Lac, $\sim 3.0$ Jy) was selected to serve as a reference for all subsequent phase and delay calibration solutions. For this scan, the net residual delay and nonlinear bandpass was determined in each spectral window. This solution, applied to the rest of the data, removes constant instrumental phase and delay errors, introduces a tropospheric delay residual offset (whatever the troposphere delay was toward J2202+4216 in this scan), and leaves behind only relative (and relatively small) delay residuals that are time and direction dependent. These errors include any residual instrumental clock drift, zenith-angle-dependent relative macroscopic troposphere delay errors (to be solved using the seven bright calibrators), and time-dependent (phase-) delay errors (to be phase referenced).

The macroscopic troposphere delay residual calibration is obtained by applying the calibrations described above and solving for the phase in each of the four spectral windows and in each of the scans on the seven bright calibrators. These phases are then fit for multiband delays. In general, the likelihood of ambiguity resolution problems in the multiband delay determination is small, since these delays are residuals, and the expected zenith delay errors are expected to be only a fraction of a nanosecond. The multiband delays are then used to jointly solve for the residual instrumental clock drift and time-dependent zenith troposphere delay error, assuming the $\sec z$ model. The separation of these two effects depends upon observing the calibrators out of zenith angle order, else a monotonic clock drift would be difficult to distinguish from a component of the elevation-dependent troposphere delay residual.

Solutions with constant, linear, quadratic, and cubic time dependence (and all combinations) in both clock and troposphere delay terms were attempted. The higher-order fits tended to diverge. Optimal fits were obtained for quadratic troposphere and linear clock. Typical zenith delay residuals were found to be a few to 15 cm, with variations over 4 hr at the 1–2 cm level. The overall accuracy of this delay calibration is approximately 0.5–1.0 cm, and is limited by the simplicity of the zenith angle dependence and unmodeled local time variation of the troposphere delay (of the sort we would otherwise phase reference). Since this is a residual effect, negative troposphere delay solutions are possible. Also, the troposphere delay solution is not referenced to any specific antenna since the zenith angle dependence and differential zenith angle sampling at each antenna breaks the usual degeneracy.

Figure 2 shows, for epoch A, the systematic phase-referencing errors for IRAS 00420+5530 and J0044+5657 due to their time-dependent zenith angle difference relative to J0042+5708 and the (mean) zenith delay model calibration determined as described above. The zenith delay errors range in magnitude from 0.6 cm for KP to 13.5 cm for HN (BR did not participate, and SC was excluded). The errors are generally larger for IRAS 00420+5530 since it has a larger separation from J0042+5708, and at a relatively unfavorable position angle (near transit) that maximizes the zenith angle difference. Only for the easternmost antennas in the array (HN, NL), which are observing farthest from transit, is the position angle of J0047+5657 relative to J0042+5708 sufficient to excessively amplify this systematic phase error.

The VLBA station at St. Croix (SC) was generally the worst performing station in the delay calibration, yielding poor multiband delay fits and/or poor zenith delay solutions. This is caused by excessive and highly variable tropospheric water vapor at SC’s sea-level location and humid climate. Since this station also yields the least accurate phase-referencing solutions for the same reasons, it was excised from all epochs. This results in the loss of many relatively long baselines, but the poor calibration of these baselines would be of questionable value.

At this point, the high-spectral-resolution data were processed, first with all of the same a priori calibrations as the low-resolution data. The tropospheric delay calibration solution (including the clock drift) was then transferred from the low-resolution data set, to be used as an additional a priori calibration for the high-resolution data. The same strong calibrator scan was selected to obtain the global instrumental reference calibration, except a polynomial bandpass was used since the per-channel signal-to-noise ratio (S/N) was insufficient for a sampled bandpass at the high spectral resolution. Finally, the phase-reference calibration was determined on J0042+5708. The full calibration was then applied to IRAS 00420+5530, J0042+5708, and the secondary phase-reference calibration, J0047+5657. After resampling the velocity axis for each epoch to the LSR, the data were exported in UVFITS format.

The data for each epoch were then imaged in Difmap (Shepherd 1997) selecting the channels with maser emission. First, a relatively low spatial resolution image of a wide field of view was generated to spatially locate significant maser regions, then each of these regions were imaged at full resolution. A simple multifield clean deconvolution script was developed in Difmap to optimize the imaging of channels with signal in more than one region. Figure 3 shows the spatial distribution of the maser regions (integrated clean components from epoch A), integrated in velocity. There are nine major maser spot regions, two of which (4 and 7) contain two distinct maser spots, with significant emission in a total of 44 channels. The typical imaging sensitivity achieved per channel was 100–200 mJy beam$^{-1}$, with maser peaks ranging up to $\sim 75$ Jy beam$^{-1}$. 
Figure 2. Time-dependent phase errors due to macroscopic troposphere delay residuals (correlator zenith delay model) per antenna. Right: for IRAS 00420+5530. Left: for the secondary calibrator, J0047+5657.

Figure 3. Spatial distribution of maser regions (epoch A). The phase center of the observation is at (100, −100). This image has a resolution of 1.01 × 0.354 mas at position angle −19°, a peak flux density of 74.5 Jy beam−1, and a minimum contour of 10 Jy beam−1. Each region is numbered for reference in the text and tables. The linear scale corresponding to the derived distance (described in the text) is indicated.

Figure 4 shows the spectrum of IRAS 00420+5530 integrated over all maser spot regions, for a representative set of epochs (A, D, G, and J), indicating the overall variability of the source. Figure 5 shows separately the time-dependent spectra for maser regions 1–4. A variety of spectral structure and behavior is observed. Regions 1 and 3 show strong, stable, and simple spectral structure. Region 2 shows a monotonic drift of five channels in the peak of emission. Region 4 shows two distinct spectral components: the feature at −45.0 km s−1 drifts by about one channel and fades, while the feature at −45.5 km s−1, indistinct at epoch A, grows in strength with epoch and is stationary in velocity. The remaining regions (not shown) are generally weaker, and show a similar range of structure and variability. Of these, maser region 5 is the most stable. As shown below, the spectral structure and variability has serious consequences for obtaining reliable parallax and proper motion fits.

To obtain an estimate of the fundamental phase-referencing accuracy of these observations, continuum images (bandwidth: 14 MHz) of the secondary phase-reference calibrator, J0047+5657 (S/N ∼ 20), were generated. For the ensemble of epochs (excluding epoch K), the rms peak position of J0047+5657 is ±30 μas in both right ascension and declination, with no evidence of any significant systematic motion. (Without the macroscopic troposphere solution applied, the declination rms increases by a factor of 2, indicating the importance of this calibration.) This estimate establishes a basis for estimating the astrometric precision (per S/N) of the maser observations. Specifically, an S/N of ∼20 nominally corresponds to an astrometric precision of ∼30 μas.

This error estimate cannot be transferred and scaled directly to the observations of IRAS 00420+5530. A variety of systematic errors render themselves differently for IRAS 00420+5530 and J0047+5657. J0047+5657 is only 0°66 from J0042+5708, the primary calibrator, less than half the 1°41 J0042+5708–IRAS 00420+5530 separation, and so the phase-referencing calibration is nominally more accurate for J0047+5657. Furthermore, near transit at the center of the VLBA, the position angle of the J0042+5708–J0047+5657 separation is mostly in azimuth while that of J0047+5657–IRAS 00420+5530 is mostly in zenith angle (see Figure 1), making any residuals in the zenith-angle-dependent macroscopic troposphere calibration more important for IRAS 00420+5530. As described below, these and other
systematic errors place more stringent limits on the astrometric precision of IRAS 00420+5530, despite the fact that most of the maser spots used in the parallax fitting have higher S/N than J0047+5657.

4. THE FIT FOR ANNUAL PARALLAX AND PROPER MOTION

Parallax and proper motion calculations rely on measurements of the time-dependent direction of consistently identified, small, physically coherent objects relative to a distant, presumed stationary, background reference, in this case, the phase-reference calibrator. Masers are among the most compact observable objects available, but at the resolution of the VLBA, they are generally not strictly pointlike. Furthermore, it is not clear to what degree masers can be characterized as distinct physical objects since they likely arise not from fixed discrete objects, but rather from coherent velocity structures within a presumably larger physical structure (e.g., gas cloud).

Indeed, most of the maser spots in IRAS 00420+5530 are clearly not strictly pointlike and are variable in their marginally resolved structure and flux density from epoch to epoch. Furthermore, the spectral structure of each maser spot is generally nontrivial, with the peak for some spots clearly drifting substantially in velocity from epoch-to-epoch. These factors make reliable epoch-to-epoch identification of distinct physical features difficult. Therefore, rather than fitting complicated multiple point and resolved Gaussian model components to the images or visibilities, and thereby introducing an additional unphysical component in the analysis, we have adopted the simple peak position (fitted from image pixels) as the best estimate of the maser position, and have accepted the inevitable intrinsic variation of this estimate (a form of traditional confusion within the synthesized beam) as an additional source of error in our analysis.

For each of eleven distinct spots in nine spot regions, and in each channel with significant power (see below), we have fitted the sequence of peak positions for parallax and two-dimensional proper motion, according to the standard equation

$$
\begin{align*}
\Delta \alpha \cos \delta &= \Pi f_\alpha + \mu_\alpha t + \alpha_0, \\
\Delta \delta &= \Pi f_\delta + \mu_\delta t + \delta_0,
\end{align*}
$$

where \( \Pi \) is the annual parallax, \( t \) is time, \((\mu_\alpha, \mu_\delta)\) is the two-dimensional proper motion, \((\alpha_0, \delta_0)\) denote the maser position at \( t = 0 \), and \((f_\alpha, f_\delta)\) is a two-dimensional function of direction.

Figure 4. Integrated spectra of IRAS 00420+5530 at epochs A, D, G, and J.
Figure 5. Spectral distribution and temporal evolution of maser regions 1–4.

and time describing the parallax ellipse (the reflection of the Earth’s orbit onto the sky). In using this equation, we nominally assume that any nonlinear internal motions with the maser spot regions are negligible.

This yielded 44 estimates of the proper motion and parallax of IRAS 00420+5530, and the results are listed in Table 3. An example fit is shown in Figures 6 and 7.

For the fitting, only channels with maser spot detections greater than \( \sim 1–2 \) Jy (corresponding to \( S/N \gtrsim 10 \), typically) were included. Additionally, after a trial fit, partial epoch ranges for some spots were discarded where it was evident that the assumption of a consistent discrete physical component following the relatively simple parallax and proper motion trajectory was violated. Presumably, the peak derived from our finite-resolution observations shifted abruptly as a result of intrinsic structural changes. Epoch K was excluded entirely since the Mauna Kea station, which provides the longest baselines, did not participate.

The fits for three maser regions (2, 6, and 7a) were rejected outright from further analysis on the basis of poor consistency among channels or unphysical (negative) parallax estimates. Each of these regions show substantial spectral complexity, including variation in the velocity of peak emission, indicating that they are nonideal test particles for parallax measurements. No degree of judicious epoch selection makes these maser regions recoverable for parallax estimation purposes.

Determining proper epoch- and maser-dependent weights for the fitting process is nontrivial, since accurate total errors, including systematics, for the peak position estimates are not readily available a priori. Formally, for a well-isolated point source with no systematic errors, the precision of the peak position estimates would be inversely proportional to the \( S/N \) of the peak emission, and the resulting formal weights would be proportional to the square of the \( S/N \). In practice, such an estimate of astrometric precision must be a lower limit due to systematic errors arising from the complicating maser structure considerations noted above, as well as to per-epoch residuals in the macroscopic troposphere and phase-referencing calibration. Additionally, the wide range of flux densities among maser regions and epochs (\( \sim 2–60 \) Jy) result in a range of weights of 2 orders of magnitude or more for some maser spots. Such weights could have a deleterious effect on the effective sampling of the parallax ellipse during the year, and lead to complicated biases in the parallax estimates. Therefore, we adopted weights proportional to \( S/N \) (i.e., the square root of the formal weights) for the final fits. For most of the fits, this choice was not consequential; use of the formal weights yields parameter estimates not significantly different from that obtained with \( S/N \) weights. Our parallax measurement is not
limited by per-epoch S/N, but rather by per-epoch systematic errors in the astrometry.

While the proper motions may be expected to vary among the spot regions (and even among channels in a single region) due to intrinsic internal motions, the parallax estimates should be consistent for all of them since the range of maser emission is very small (<300 mas) relative to its distance (kiloparsecs), and its depth is unlikely to be significantly greater than its width. In practice, the variation of the parallax estimates among maser spot regions and channels is more complicated. While several (but not all) maser regions show impressive internal consistency, the dispersion of parallax estimates over the entire ensemble is considerably larger than the formal errors would imply. This fact is related to residual systematic errors affecting the fits which originate in the complexity and evolution of the spectral and spatial structure of the maser regions, residual calibration errors, and the details of the time-dependent sampling of the parallax ellipse.

At any single epoch, calibration errors will affect different maser spot regions uniformly, and so are systematic, i.e., relative position measurements among masers at one epoch have no information about the magnitude of such errors. Over many epochs (up to 11, in this case), however, we assume such errors can be treated as approximately stochastic.

### Table 3

| Region | $V_{\text{LSR}}$ (km s$^{-1}$) | $N_{\text{epochs}}$ | Epochs | Parallax (Error) | Proper Motion (Error) | Fit Residuals |
|--------|-------------------------------|----------------------|--------|------------------|----------------------|---------------|
|        |                               |                      |        | ($\text{mas}$)   | ($\text{mas yr}^{-1}$) | ($\text{mas}$) |
|        |                               |                      |        | ($\text{mas}$)   | ($\text{mas yr}^{-1}$) | ($\mu\text{as}$) |

**Notes.**

- These velocities are in the traditional IAU LSR used to set observing frequencies.
- Values in boldface have been used in the final parallax estimate (see the text).

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Similarly, after excising obviously discrepant epochs as described above, we treat any nonlinear intrinsic variations in the peak position due to internal structural and flux density evolution as approximately stochastic over many epochs. These errors limit the precision of the parallax estimate, but are unlikely to bias it substantially. With up to 11 epochs per fit, we assert that the rms residuals determined in the fits are a reasonable estimate of the mean per-epoch astrometric precision achieved in our observations, typically ~20–30 μas in both dimensions. The error bars in Figure 7 reflect the relative weights used in the fit, and are conservatively scaled so that their minimum is 30 μas.

Of the remaining 27 fits in eight maser regions, most yield internally consistent parallax and proper motions (with channel), but the overall range of parallax results remains relatively large: 0.41–0.62 mas, with formal errors in the range of 0.01–0.1 mas (see Figure 8 which shows the distribution in the range of 0.40–0.52 mas). In addition to several obvious outliers (there are three such outliers greater than 0.55 mas and not shown in Figure 8), there is some evidence of maser-region-dependent systematic errors. A careful analysis of the time-dependent weighted sampling shows that those maser regions for which the later epochs were undetected or discarded tend to yield systematically higher parallax estimates (near or in excess of 0.50 mas) compared to those with more complete sampling. Fitting trials on the completely sampled maser regions (e.g., region 3) using only the early epochs confirm this effect. We, therefore, have discarded maser regions 4a, 7b, and 8 as insufficiently sampled and inadequate for further consideration. The remaining 16 maser region channels are shown in the filled histogram of Figure 8. The distribution still appears bimodal, but the two states cannot be segregated according to maser region. The unweighted dispersion of the remaining measurements is 0.02 mas, broadly consistent with the typical formal errors in the individual fits, which arise from a combination of pure statistics and per-epoch systematics that are stochastic over many epochs.

The individual parallax solutions for the remaining 16 maser region channels have been averaged with weights derived from their formal errors to yield a net parallax estimate of 0.458 ± 0.005 mas. Figure 9 shows the final parallax signature in right
ascension and declination as a function of time (bold curve). Also plotted are the per-channel data (filled and open dots, with error bars as in Figure 7) and the range of individual channel fits (hashed region), the fitted proper motions and relative position offsets from the individual solutions have been removed. It is clear that several epochs (e.g., epoch C in right ascension, epochs I and L in declination) are affected by a substantial residual systematic offset in one dimension or the other, but that for most epochs, the magnitude of these systematics is similar or smaller than the statistical distribution of measurements. Since the parallax solution has been derived directly from the data, it is difficult to accurately ascertain the true balance between the per-epoch systematic and statistical contributions. Although the formal errors in each individual maser channel solution nominally account for both sources of error (assuming the per-epoch systematics are approximately stochastic over many epochs), we nonetheless conservatively double the formal error estimate and adopt a final parallax estimate of 0.46 ± 0.01 mas. The distance to IRAS 00420+5530 is therefore 2.17 ± 0.05 kpc, a measurement with a precision of <3%.

5. IMPLICATIONS FOR GALACTIC ROTATION

With direct measurements of the distance and three-dimensional space velocity of objects such as IRAS 00420+5530 using the VLBA, it becomes possible to more accurately evaluate the veracity of the kinematic distances derived from Galactic rotation curves, and to do so over a larger portion of the Galaxy than with any other available means. This is especially important outside the solar circle where rotation curve fits (hashed region) are affected by a substantial residual systematic offset in one dimension or the other, but that for most epochs, the magnitude of these systematics is similar or smaller than the statistical distribution of measurements. Since our VLBA measurements provide the three-dimensional space velocity (relative to the Sun) of IRAS 00420+5530, it is possible to explore the nature of its Galactic orbit in detail. Adopting the maser component in region 3, \( V_{\text{LSR}} = -46.0 \text{ km s}^{-1} \) as representative for IRAS 00420+5530 we find a heliocentric line-of-sight velocity of \(-52.5 \text{ km s}^{-1}\), and, at a distance of 2.17 kpc, a (heliocentric) physical velocity of \(-26.2 \text{ km s}^{-1}\) in Galactic longitude and \(-7.9 \text{ km s}^{-1}\) in Galactic latitude (at the distance of IRAS 00420+5530, 1 mas yr\(^{-1}\) = 10.3 km s\(^{-1}\)). Figure 10 illustrates the in-plane components of these measurements in a plan view of the region of the Galaxy containing the Sun and IRAS 00420+5530. Formally, the error in these velocities is \(\sim 0.5 \text{ km s}^{-1}\), but there is a full range of \(\sim 10 \text{ km s}^{-1}\) in the line-of-sight and latitude components, and somewhat less in the longitude components among the brightest maser spot regions. We assume tentatively that the internal motion of this component is
not large enough to excessively bias our analysis (this point will be addressed in greater detail below).

The following analysis is limited by the accuracy of knowledge of the absolute orbital speed of the Galaxy and the Sun’s peculiar motion relative to the LSR. We have provisionally assumed standard IAU values for the LSR parameters, namely that it is \( R_\odot = 8.5 \) kpc from the Galactic center and moving at \( \Theta_\odot = 220 \) km s\(^{-1}\) on a circular orbit (Kerr & Lynden-Bell 1986). The Sun’s peculiar motion relative to the LSR has been assumed to be \( U = 10.0 \) km s\(^{-1}\) (toward the Galactic center), \( V = 5.25 \) km s\(^{-1}\) (along the orbit), and \( W = 7.17 \) km s\(^{-1}\) (out of the plane) as measured by Dehnen & Binney (1998) using Hipparcos data. The calculations have been done in three dimensions, but with no correction for the Sun’s uncertain distance from the Galactic plane.

Converting to the galactocentric frame by correcting for \( \Theta_\odot \) and solar peculiar motions, we find that IRAS 00420+5530 is moving toward the Galactic center at 23.0 km s\(^{-1}\), around the Galaxy (circular component) at 202.0 km s\(^{-1}\), and toward the plane (from below) at 5.8 km s\(^{-1}\). The in-plane components of IRAS 00420+5530’s velocity vector are shown in Figure 11. Thus, IRAS 00420+5530 is moving significantly slower than the circular speed of \( \sim 224 \) km s\(^{-1}\) predicted by the BB93 rotation curve, and has a substantial noncircular component toward the Galactic center.

By assuming a nominal orbital speed for IRAS 00420+5530, we can shift our velocity measurements to a standard of rest orbiting the Galaxy at the position of IRAS 00420+5530. Figure 12 shows the resulting in-plane peculiar motion of IRAS 00420+5530, assuming its orbital speed is 220 km s\(^{-1}\). (The BB93 rotation curve prediction is insignificantly larger; essentially, we nominally assume the rotation curve is flat in this region of the Galaxy.) Also shown is the peculiar motion of W3(OH) (also in its own standard of rest) as reported by Xu et al. (2006), also assuming an orbital speed of 220 km s\(^{-1}\). The peculiar motions of IRAS 00420+5530 and W3(OH) are in almost exactly the same direction, and very nearly in the direction of the Sun. Combined with the large-scale systematic line-of-sight velocity deficit observed in the BB93 rotation curve residuals, this is highly suggestive of a large-scale anomalous motion of the material in this region of the Galaxy, i.e., the Perseus spiral arm, in a direction toward the Sun. Such anomalous motion could be related to the formation and propagation of the Perseus spiral arm, and is evidence of the inadequacy of axisymmetric models of Galactic rotation.

An obvious alternative to this conclusion is that the Sun has a large velocity component in the direction of these objects, either in terms of the LSR orbital speed, the solar peculiar motion, or both. Indeed, the orbital speed component of the Sun’s velocity is the least well-understood component of its motion due to uncertainties in the overall scale of the Galaxy (\( R_\odot \) and \( \Theta_\odot \)), and the component of solar peculiar motion in the direction of Galactic rotation. However, the velocity adjustments required of the alternative scenarios are generally implausible. Increasing the Galactic orbital speed for the solar LSR to 250 km s\(^{-1}\) (the value favored by Reid & Brunthaler 2004) for \( R_\odot = 8.5 \) kpc according to measurements of the proper motion of Sgr A* and maintaining the flat rotation curve out to IRAS 00420+5530 and W3(OH) reduces the radial (toward the Galactic center) component of the anomalous velocity by only \( \sim 6 \) km s\(^{-1}\), without substantially changing the orbital component. The anomaly is even less sensitive to adjusting both the orbital speed and \( R_\odot \) in such a way as to keep the angular speed (\( \Theta_\odot / R_\odot \)) of the solar LSR constant (Reid & Brunthaler 2004). This insensitivity is a result of the relatively small angle (~11\(^\circ\)) subtended at the Galactic center by the Sun and IRAS 00420+5530, and that this angle changes very slowly for a fixed distance to IRAS 00420+5530 (our measurement) over the plausible range of \( R_\odot \) (8 \pm 1 kpc). Introducing a difference in nominal orbital speed between the Sun and these sources sufficient to account for the anomaly is also implausible, implying zero additional mass outside the solar circle, and would not compensate for the radial component of the anomaly. Finally, a sufficient correction to just the solar peculiar motion would require a change to the radial component of ~20 km s\(^{-1}\), entirely inconsistent with the Hipparcos measurements of Dehnen & Binney (1998).
Figure 10. Plan view of the Galaxy (from above), showing the observed relative positions and heliocentric velocities of IRAS 00420+5530 and the Sun. All quantities are projected onto the Galactic plane in a heliocentric frame (the Sun is stationary). The dotted lines indicate the nominal circular galactocentric orbits of the Sun and IRAS 00420+5530. The dashed lines connect the Sun, IRAS 00420+5530, and the Galactic center, which lies at (0,0) kpc.

Figure 11. Plan view showing the motion of IRAS 00420+5530 in a galactocentric frame, having corrected for solar peculiar motion ($U = 10$ km s$^{-1}$, $V = 5.25$ km s$^{-1}$, and $W = 7.17$ km s$^{-1}$; see the text) and assuming a circular orbital velocity of 220 km s$^{-1}$ for the (solar) LSR. The dotted line indicates the nominally circular orbit at the galactocentric radius of IRAS 00420+5530. The Brand & Blitz (1993) rotation curve predicts an orbital speed of 224 km s$^{-1}$ on this line. The dashed lines connect IRAS 00420+5530 to the Sun at (0,8.5) kpc and the Galactic center at (0,0) kpc.

It is also possible that we have failed to model a large internal motion of the H$_2$O masers in IRAS 00420+5530 that happens to lie in the direction of the apparent anomalous motion, a possibility noted by Hachisuka et al. (2006) for W3(OH). However, we consider this unlikely given the relatively modest range of three-dimensional velocities observed for the main H$_2$O masers in IRAS 00420+5530, and that they are near ($\lesssim 5$ km s$^{-1}$) the systemic velocity indicated by other molecular species in IRAS 00420+5530. The maser channel chosen for this analysis (region 3, $-46.0$ km s$^{-1}$) is reasonably representative of the available information for IRAS 00420+5530. Other choices are possible, but either can be excluded on grounds of insufficient constraints or do not substantively change the result. The maser regions excluded from the parallax analysis have proper motion estimates biased toward more negative velocities in longitude due to poor sampling of the parallax ellipse in the late epochs.

Of the remaining 16 well-sampled maser channels used in the parallax analysis, only region 9 differs in the longitude component of its proper motion by more than $\sim 5$ km s$^{-1}$ (at the longitude of IRAS 00420+5530, the equatorial and Galactic coordinates are approximately parallel, so $\mu_{\text{long}} \simeq \mu_{\text{ra}}$). The dispersion in the latitude component is somewhat larger, but it is irrelevant to the space velocity analysis within the Galactic plane. Region 9 has a velocity in longitude $\sim 25$ km s$^{-1}$ more negative than region 3. Alternatively, choosing region 9 as representative ameliorates the anomaly in the circular orbital component of the velocity found in the above analysis for region 3 quite well, but also increases the anomalous component in the direction of the Galactic center. While we consider the remarkable consistency with the W3(OH) anomalous space velocity compelling, it is not, by itself, sufficient evidence of any interpretation of possible internal motions in IRAS 00420+5530.
Without an absolute reference within the source, internal motion biases cannot be ruled out, but an anomalous motion in the general direction of the Sun and the Galactic center cannot be excluded by the available H$_2$O maser proper motion data. Distance and three-dimensional space velocity measurements of a larger sample of such objects in this and other regions of the Galaxy (e.g., Reid 2008) are necessary to resolve such issues conclusively, and establish the true bulk motion of material in the Perseus spiral arm. Such observations could possibly also better constrain the Galactic orbital speed and solar peculiar motion, but will be limited by the isotropy and homogeneity (i.e., the apparent lack of Galactic axisymmetry) of the available sample.

Sato et al. (2008) have measured the distance to NGC 281—a star-forming region only $\sim$1° from IRAS 00420+5530—using VERA (Honma et al. 2000) observations of H$_2$O masers and a similar analysis (using the same phase-reference calibrators). They find a distance for NGC 281 of 2.82 $\pm$ 0.24 kpc, 650 pc farther than IRAS 00420+5530, and postulate that these sources lie on opposite sides of the surface of an H i superbubble that is expanding out of the plane of the Galaxy. Their model is geometrically appealing, and consistent with a substantial anomalous velocity component toward the Sun for IRAS 00420+5530, on the near side of the bubble. NGC 281 is on the opposite side of the bubble, with line-of-sight velocity consistent with their model. However, their model also predicts a large velocity out of the plane for IRAS 00420+5530, which we do not observe. Unmodeled internal motions of the H$_2$O masers in IRAS 00420+5530 perpendicular to the Galactic plane could explain this discrepancy, but the available information cannot resolve this ambiguity. W3(OH) is not associated with the superbubble in their model.

6. CONCLUSIONS

Using the VLBA, we have measured the parallax and three-dimensional space velocity of H$_2$O masers in IRAS 00420+5530. The parallax of 0.46 $\pm$ 0.01 mas provides a purely geometric distance estimate of 2.17 $\pm$ 0.05 kpc (an error of less than 3%), a factor of 2 closer than popularly assumed kinematic distance estimates suggest, yet consistent with an older, far-less accurate photometric distance. At this distance, the space velocity of IRAS 00420+5530 shows a substantial anomalous component in the direction of the Sun, consistent with similar observations of W3(OH), implying a significant noncircular systematic motion of the Perseus spiral arm of the Galaxy.

Parallax observations of larger samples of maser sources using the VLBA have the potential to extend the distance estimates of a few percent accuracy to a large fraction of the Galaxy, and will contribute to more accurate nonaxisymmetric models of Galactic rotation.

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