The space distribution of nearby star-forming regions

Authors: **Laurent Loinard (UNAM)**
Luis F. Rodríguez (UNAM)
Amy J. Mioduszewski (NRAO)

Contact Author: **Laurent Loinard**
Centro de Radiostronomía y Astrofísica,
Universidad Nacional Autónoma de México,
Morelia , Mexico
e-mail: l.loinard@astrosmo.unam.mx

Frontier Area 1: The Planetary Systems and Star Formation

Goal: Determine the distance, structure and dynamics of all northern star-forming region within 1 kpc of the Sun

- *What is the local space distribution of star-formation in the Solar neighborhood?*
- *Is the internal structure and dynamics of nearby star-forming regions in agreement with theoretical models?*
- *What are the precise intrinsic properties of low-mass young stars?*
- *How do those properties compare with theoretical expectations?*

ABSTRACT

Multi-epoch radio-interferometric observations of young stellar objects can be used to measure their displacement over the celestial sphere with a level of accuracy that currently cannot be attained at any other wavelength. In particular, the accuracy achieved using carefully calibrated, phase-referenced observations with Very Long Baseline Interferometers such as NRAO's *Very Long Baseline Array* is better than 50 micro-arcseconds. This is sufficient to measure the trigonometric parallax and the proper motion of any radio-emitting young star within several hundred parsecs of the Sun with an accuracy better than a few percent. Using that technique, the mean distances to Taurus, Ophiuchus, Perseus and Orion have already been measured to unprecedented accuracy.

With improved telescopes and equipment, the distance to all star-forming regions within 1 kpc of the Sun and beyond, as well as their internal structure and dynamics could be determined. This would significantly improve our ability to compare the observational properties of young stellar objects with theoretical predictions, and would have a major impact on our understanding of low-mass star-formation.

1. Introduction

Astrometric observations of young stellar objects can provide a wealth of important information on their properties. First and foremost, an accurate trigonometric parallax measurement is a pre-requisite to the derivation, from observational data, of their most important characteristics (luminosity, age, mass, etc.). Unfortunately, even in the current post-Hipparcos era, the distance to even the nearest star-forming regions (Taurus, Ophiuchus, Perseus, etc.) is rarely known to better than 20 to 30% (e.g. Knude & Hög 1998; Bertout et al. 1999). At this level of accuracy, the mass of a binary system derived from observations of its orbital motion would be uncertain by a factor of two. This unsatisfactory state of affairs is largely the result of the fact that young stars are still embedded in their opaque parental cloud. They are, therefore, dim in the visible bands that were observed by Hipparcos. The proper motions that can be derived from astrometric observations of young stars are also of interest, particularly to study the internal dynamics of star-forming regions.

Since observations of young stars in the visible range is limited by the effect of dust extinction, one must turn to a more favorable wavelength regime in order to obtain high quality astrometric data. Radio observations, particularly using large interferometers is currently the best prospect because (i) the interstellar medium is largely transparent at these wavelengths, and (ii) the astrometry delivered by radio-interferometers is extremely accurate and

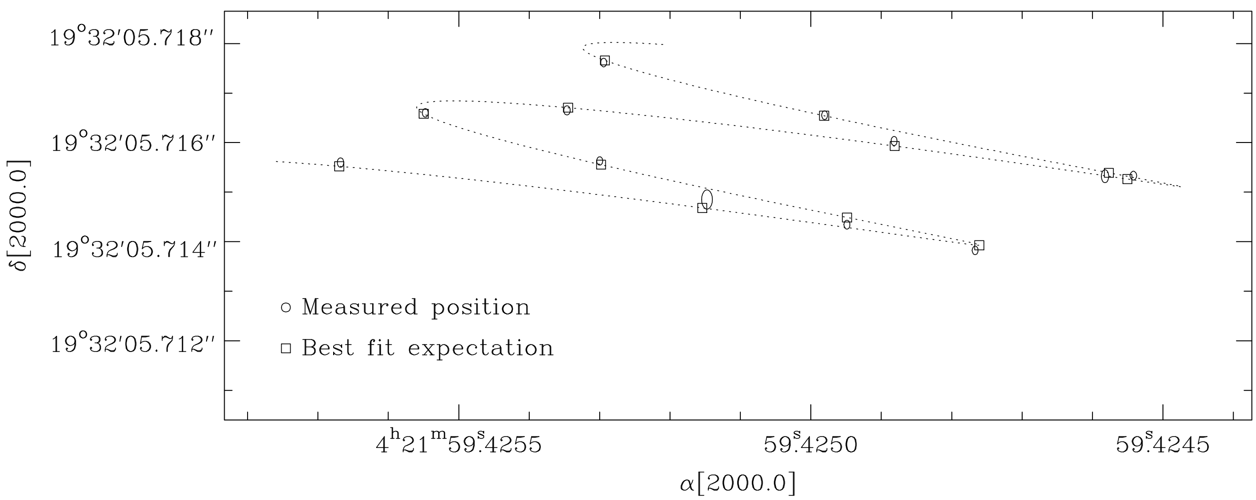

Fig. 1.— Measured positions of T Tau Sb and best fit combining proper motion and trigonometric parallax (from Loinard et al. 2007). The observed positions are shown as ellipses, the size of which represents the magnitude of the errors.

calibrated against fixed distant quasars. Of course, only those young stars associated with radio sources are potential targets. This is currently a significant limiting factor, which restricts the number of accessible targets to a few handfuls. With a relatively modest increase (a factor of 10) in the sensitivity of Very Long Baseline Interferometers, however, hundreds of young stars would become adequate targets.

2. The distance to nearby star-forming regions

Using multi-epoch observations obtained using Very Long Baseline Interferometry (VLBI), the mean distance to several nearby star-forming regions have already been measured with unprecedented accuracy. We will briefly describe these results here to demonstrate the potential of VLBI instruments.

2.1. Taurus

Until now, the distances to 4 young stars embedded in the Taurus complex have been measured using multi-epoch Very Long Baseline Array (VLBA) observations (see Loinard et al. 2005, 2007, Torres et al. 2007, 2009). As an example, the case of T Tau Sb (one of the southern companions of the famous young star T Tauri) is shown in Fig. 1. The trigonometric parallax obtained from these observations is 6.82 $\pm$ 0.03 mas, corresponding to a distance of 146.7 $\pm$ 0.6 pc (Loinard et al. 2005, 2007). Similar results were obtained for the other three sources, resulting in a mean distance of about 142 pc for the entire Taurus complex. This is in good agreement with the value of 140 ± 15 pc traditionally used for Taurus (e.g. Kenyon et al. 1994, Bertout et al. 1999).

Perhaps more interesting than that mean distance, however, is the information on the three-dimensional structure of Taurus revealed by our observations. The extent of Taurus on the plane of the sky is about 10° (25 pc), and one would expect its depth to be similar. Our observations confirm this (Fig. 2) since HP Tau, to the east of the complex is at 161.2 ± 0.9 pc, about 30 pc farther than Hubble 4 or HDE 283572 in the central region (the mean distance of Hubble 4 and HDE 283572 is 130.7 ± 0.6 pc). T Tau appears to be at an intermediate distance. It is important to realize that because of this significant depth, even if the mean distance of the Taurus association were known to infinite accuracy, we could still make errors as large as 10–20% by using the mean distance indiscriminately for all sources in Taurus. To reduce this systematic source of error, one needs to establish the three-dimensional structure of the Taurus association, and our existing observations represent the first step in that direction.

In addition to their trigonometric parallaxes, the VLBA astrometry of the several stars in Taurus provides an accurate determination of their proper motions. Combining this information with existing radial velocity measurements, we can reconstruct the full velocity vector of each star. As Fig. 2 shows, there is a systematic difference in the orientation and amplitude of the tangential velocity between the central and the eastern portions of Taurus. This echoes the situation with radial velocities which systematically differ by about 3 km s^{-1} between the western and the eastern edge of the complex. Clearly, if data similar to those presented here were available for tens of stars, it would become possible to study in detail the internal dynamics of the Taurus complex.

2.2. The Ophiuchus core

Ophiuchus is, together with Taurus, one the best studied regions of low-mass star-formation. It has long been thought to be at 165 pc (Chini 1981), but somewhat shorter distances (120–135 pc) have recently been proposed (Knude & Hög 1998; Mamajek et al. 2008).

Two young stars embedded within Ophiuchus were observed with the VLBA at 6 and 7 epochs, respectively (Loinard et al. 2008). The weighted mean of their parallaxes is 8.33 ± 0.30, corresponding to a distance of $120.0^{+4.5}_{-4.3}$ pc for the Ophiuchus complex. This is in good agreement with the value proposed by Knude & Hög (1998) and, more recently, by Lombardi et al. (2008). Note that this determination of the distance to Ophiuchus is accurate to better than 4% (≡ 5 pc). This is to be compared to the situation prior to our observations, when the uncertainty was between 120, 140 or 160 pc. It should be noticed, however, that this distance is that of the Ophiuchus core. Other parts of the Ophiuchus (especially the so-called streamers) could be at a somewhat different distance. Also, we observed a third star in the

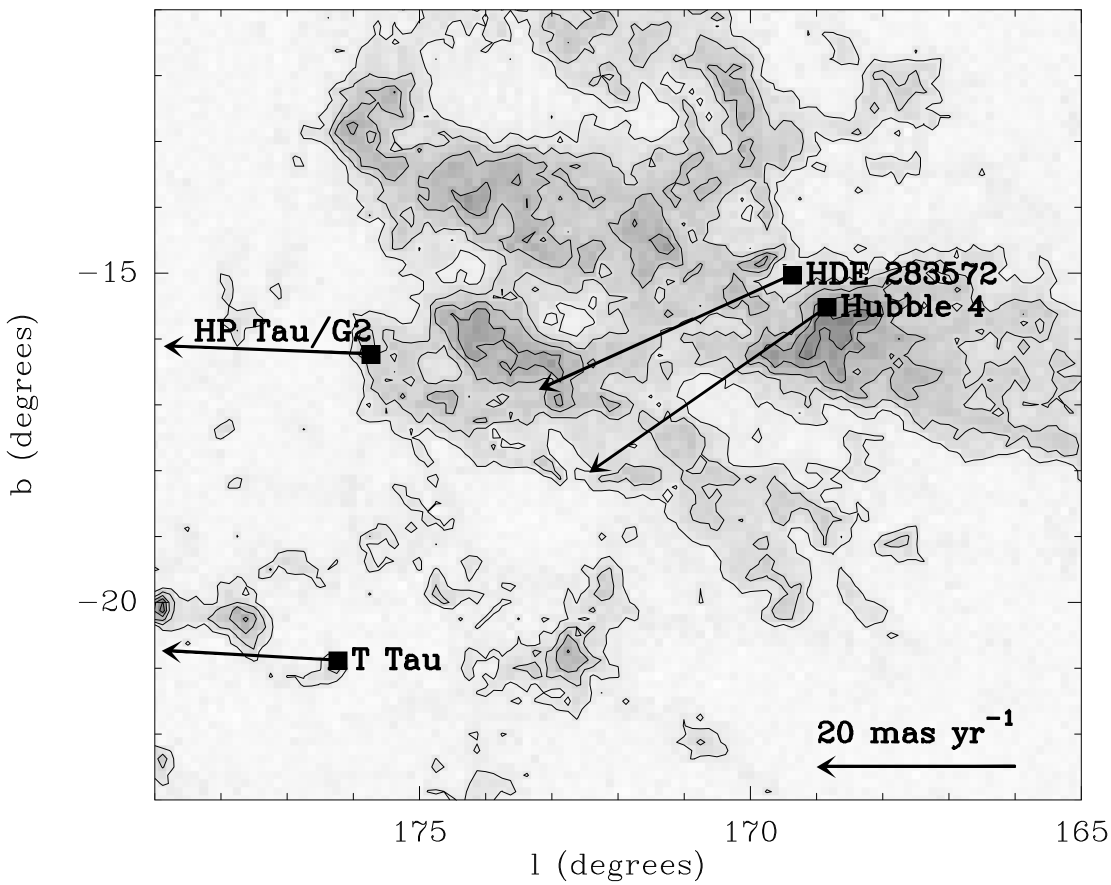

Fig. 2.— Position and tangential velocity vectors of the four young stars in Taurus considered here, superimposed onto the CO(1-0) map of Taurus from Dame et al. (2001).

direction of Ophiuchus, and found to be at about 170 pc. If confirmed, this result could indicate the presence of several (unrelated) regions of star-formation along the line of sight.

2.3. Perseus and Orion

The distance to NGC 1333 within the Perseus region was measured using the Japanese VLBI system (called VERA) by Hirota et al. (2008). Rather than using continuum radio emission from the active magnetospheres of young stars, Hirota et al. used water masers associated with the outflow powered by SVS13. They obtain a distance of 235 ± 18 pc. It is still not completely clear if this distance should be used for the entire Perseus complex or if other regions with Perseus (e.g. IC 348) might be somewhat farther.

The distance to the Orion Nebula was measured by Menten et al. (2007) using VLBA observations of 4 embedded stars. They obtain 414 ± 7 pc. As in the case of Ophiuchus or Perseus, it is not clear if this value should be used for the entire Orion complex or if regions far from the nebula might be at somewhat different distances.

3. Future possibilities and instrumentation needs

The observations presented above have already improved significantly our knowledge of the distribution of star-forming regions around the Sun. Yet, they merely represent the "tip of the iceberg" of what could be done in the coming decades with improved VLBI systems.

The sensitivity of existing VLBI instruments, and of the VLBA in particular, is limited. As a consequence, observations such as those described above can only be obtained for relatively bright sources, and even then, they require fairly large amounts of telescope time (over 500 hours of VLBA time were necessary to collect the Taurus and Ophiuchus data presented in §2). The luminosity function of radio sources associated with young stars is still poorly constrained, but it is clear that increasing the sensitivity of the VLBA by one order of magnitude would allow similar observations to be obtained for hundreds of stars instead of a handful of them.

This would allow the determination of the distance to all northern star-forming regions within 1 kpc of the Sun. By including tens of stars in each of these regions, it would also become possible to establish their structure and internal dynamics. This would, in particular, allow a direct comparison between the observed dynamics of star-forming regions, and the predictions of theoretical models. A direct product of the observations described above would be the construction of an unprecedented sample of young stellar sources with extremely well-measured intrinsic properties. This would allow a very detailed comparison with theoretical model of early stellar evolution. In summary, the proposed observations would allow us to answer the following four important questions:

- **What is the local space distribution of star-formation in the Solar neighborhood?**
- **Is the internal structure and dynamics of nearby star-forming regions in agreement with theoretical models?**
- **What are the precise intrinsic properties of low-mass young stars?**
- **How do those properties compare with theoretical expectations?**

Of course, the answer to these question would have important consequences for various related issues, such as the determination of the low-mass end of the IMF, or the eventual formation of planets around low-mass stars.

It is interesting to note that the sensitivity increase necessary to carry out much this program does not require new technology. The sensitivity of the VLBA could be improved by one order of magnitude by increasing the frequency bandwidth recorded (from 32 MHz currently to 2 GHz). Besides increasing enormously the number of stars that could be studied, such a significant increase in sensitivity would also improve the astrometry for each target. The reason for this is the following. The quality of the astrometry reached in a VLBI observation depends directly on the distance between the target and the calibrating quasar. An increase in sensitivity would make many weak quasars suitable calibrators, and would, therefore, reduce dramatically the distance between any target and the nearest available calibrator. The gain would be very significant: a VLBA one to tow orders of magnitude more sensitive could routinely deliver micro-arcsecond astrometry!

If the above improvements in recording capabilities were combined with a significant increase in collecting area, observations similar to those presented earlier could be extended to much larger distances, and it would become possible to effectively map out the Milky Way (recall that the trigonometric parallax of a source at 20 kpc is 50 micro-arcseconds). Note, indeed, that the distances to several massive star-forming regions along nearby spiral arms (at a few kpc) have already been measured to remarkable precision using the VLBA (the targets in these cases were water masers, see Xu et al. 2006). The necessary increase in collecting area could be achieved as part of the SKA-High project, if some of the groups of antennas for that project were built near existing VLBA antennas, or between the current VLBA antennas and the EVLA site.

Finally, we would like to point out that the improvements proposed here would fit naturally within the framework of the *North America Array* initiative (http://www.nrao.edu/nio/naa/) coordinated by Jim Ulvestad and submitted to the decadal survey.

4. Conclusions

In this paper, we showed that multi-epoch VLBI observations young stars allows the determination of their trigonometric parallaxes with accuracies of a few percent. In the next decade or two, it would become possible to establish the distribution of star formation in the Solar Neighborhood ($d < 1$ kpc) or farther using improved VLBI systems. This would have a major impact on our understanding of star-formation because it would allow us to compare the both the structure and dynamics of star-forming regions and their intrinsic properties with theoretical expectations.

REFERENCES

Bertout, C., Robichon, N., & Arenou, F., 1999, A&A, 352, 574

Chini, R. 1981, A&A, 99, 346

Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792

Hirota, T., et al. 2008, PASJ, 60, 975

Kenyon, S.J., Dobrzycka, D., & Hartmann L., 1994, AJ, 108, 1872

Knude, J., & Hog, E. 1998, A&A, 338, 897

Loinard, L., Mioduszewski, A. J., Rodríguez, L. F., González, R. A., Rodríguez, M. I., & Torres, R. M. 2005, ApJ, 619, L179

Loinard, L., Torres, R. M., Mioduszewski, A. J., Rodríguez, L. F., González, R. A., Lachaume, R., Vázquez, V., & González, E. 2007, ApJ, 671, 546

Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodríguez, L. F. 2008, ApJ, 675, L29

Lombardi, M., Lada, C. J., & Alves, J. 2008, A&A, 480, 785

Mamajek, E. E. 2008, Astronomische Nachrichten, 329, 10

Menten, K. M., Reid, M. J., Forbrich, J., & Brunthaler, A. 2007, A&A, 474, 515

Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2007, ApJ, 671, 1813

Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2008, ApJ, in press

Xu, Y., Reid, M.J., Zheng, X.W., & Menten, K.M. 2006, Science, 311, 54

This preprint was prepared with the AAS LaTeX macros v5.2.