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THE GOULD'S BELT DISTANCE SURVEY

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RESUMEN

Observaciones que utilizan la interferometría de muy larga línea de base (VLBI por sus siglas en inglés) pueden proveer la posición de radiofuentes compactas con una precisión del orden de 50 micro-segundos de arco. Esto es suficiente para medir la paralaje trigonométrica y los movimientos propios de cualquier objeto localizado hasta 500 pc del Sol con una precisión mejor que unos porcientos. Por ser magnéticamente activas, las estrellas jóvenes a menudo emiten emisión radio compacta detectable usando técnicas VLBI. Aquí, mostraremos cómo observaciones VLBI ya han restringido la distancia a las regiones de formación estelar cercanas más frecuentemente estudiadas (Tauro, Ofiuco, Orión, etc.) y han empezado a revelar su estructura y su cinemática interna. Luego, describiremos un gran proyecto (llamado *The Gould's Belt Distance Survey*) diseñado para proveer una vista detallada de la formación estelar en la vecindad Solar, usando observaciones VLBI.

ABSTRACT

Very Long Baseline Interferometry (VLBI) observations can provide the position of compact radio sources with an accuracy of order 50 micro-arcseconds. This is sufficient to measure the trigonometric parallax and proper motions of any object within 500 pc of the Sun to better than a few percent. Because they are magnetically active, young stars are often associated with compact radio emission detectable using VLBI techniques. Here we will show how VLBI observations have already constrained the distance to the most often studied nearby regions of star-formation (Taurus, Ophiuchus, Orion, etc.) and have started to provide information on their internal structure and kinematics. We will then briefly describe a large project (called *The Gould's Belt Distance Survey*) designed to provide a detailed view of star-formation in the Solar neighborhood using VLBI observations.

Key Words: astrometry — radiation mechanisms: non–thermal — radio continuum: stars — stars: pre-main sequence — techniques: interferometric

1. INTRODUCTION

An recurrent obstacle in the study of star-formation has been the fairly large uncertainties (typically 20 to 50%) affecting the distances to even the nearest sites of active star-formation. Such large errors imply even larger uncertainties on the derived parameters (such as the luminosity, mass or age) of the young stellar objects under study, and limit our ability to compare theoretical predictions with observational results.

Trigonometric parallax measurements provide the only direct way of gauging distances to objects outside of the Solar system, but they are difficult to obtain even in the Solar neighborhood. For an object at 500 pc, for instance, the trigonometric parallax is only 2 milli-arcseconds (mas). To obtain a parallax measurement accurate to 2% in this case would require astrometric observations accurate to about 40 μas. Even expensive space missions dedicated to astrometry (such as Hipparcos; Perryman et al. 1997) did not reach such a level of accuracy.

Very Long Baseline Interferometry (VLBI; e.g. Thompson, Moran, & Swenson 2001) is an observing technique that can readily provide astrometric accuracies of order 50 μas, for compact radio sources of sufficient brightness ($T_b \approx 10^7$ K). Such sources exist in all star-forming regions, because low-mass young stars are often magnetically active. The gyration of relativistic electrons in the strong magnetic fields surrounding low-mass young stars produce radio emission detectable with VLBI instruments (Dulk 1985). This emission is normally confined to regions extending only a few stellar radii around the stars, and therefore remain very compact even in the nearest star-forming regions (at

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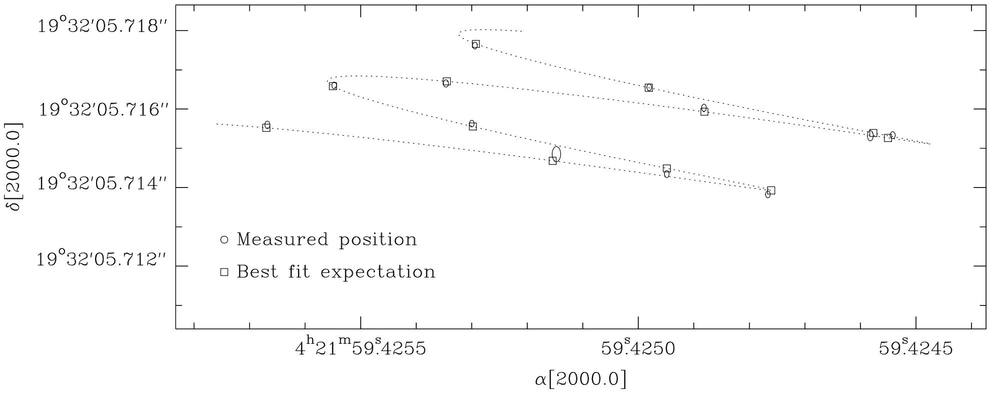

Fig. 1. Trajectory of T Tau Sb on the plane of the sky as measured by multi-epoch observations. The data were collected at 12 epochs from September 2003 to July 2005, and are shown as ellipses whose sizes represent the error bars. The dotted curve shows the best fit with a combination of parallax and proper motion. The squares are the positions predicted by the best fit at the twelve epochs (see Loinard et al. 2007 for details).

$d \approx 100$ pc). In high mass star-forming regions, water and methanol masers (which are also detectable with VLBI instruments) are common, and offer an interesting alternative to magnetically active low-mass stars. Although we will mention a few results obtained from maser observations, we will be primarily concerned here with low and intermediate mass star-forming regions where masers are of limited use because they are rare and often strongly variable.

2. RESULTS

Over the last five years, we have measured the distance to several nearby young stars using multi-epoch VLBI observations. As an example, we show in Figure 1 the trajectory described on the plane of the sky by T Tau Sb, one of the southern companions of the famous object T Tauri as characterized by multi-epoch VLBI observations (see Loinard et al. 2007 for details). That trajectory is the combination of an elliptic parallax component and the proper motion of the source – oriented towards the south-east, in this specific case. Note that the entire size of the figure is only about 10 mas.

The young stars considered so far are all located in the five most prominent nearby star-forming regions (Ophiuchus, Taurus, Perseus, Serpens, and Orion). These regions belong to Gould's Belt, the ring-like structure where most star-formation within a few hundred parsecs of the Sun is concentrated. In the coming sections, we will summarize these results, and discuss some pending issues.

2.1. *Ophiuchus*

During many years, Ophiuchus was thought to be at 165 pc (Chini 1981). More recently, however, shorter distances have been preferred. For example, de Geus et al. (1989) found a mean photometric distance of 125 ± 25 pc for the stellar population associated with Ophiuchus. Knude & Hög (1998), who examined the reddening of stars in the direction of Ophiuchus as a function of their Hipparcos distances, found a clear extinction jump at 120 pc and agued that this corresponds to the distance of the main dust component in Ophiuchus. Using a similar method, Lombardi et al. (2008) also reported a distance of about 120 pc for the Ophiuchus core.

Using VLBI observations, Loinard et al. (2008) measured the trigonometric parallax of two stars in the Ophiuchus core (S1 and DoAr21), and found a mean value of 120.0 ± 4.5 pc. The Ophiuchus core is only about 2 degrees across, corresponding to a linear radius of about 2 pc. The depth of the region is expected to be similar, so systematic errors on the distance to individual objects in the Ophiuchus core due to its depth are expected to be of that order. To account for that effect, we add quadratically 2 pc to the formal errors reported by Loinard et al. (2008), and conclude that the distance to the Ophiuchus core should be assumed to be 120 ± 5 pc.

In addition to its core, Ophiuchus contains several filamentary structures known as the *streamers* (see Wikling et al. 2008). The streamers correspond to prominent dust clouds (such as Lynds 1689, 1709, 1712, or 1729) and extend to about 10 pc from the core. They are thought to be physically associated with the Ophiuchus core, and should therefore be at similar distances (within about 10 pc, their physical extent on the plane of the sky). There are several indications that this might indeed be the case. For instance, Lombardi et al. (2008) found some indica-

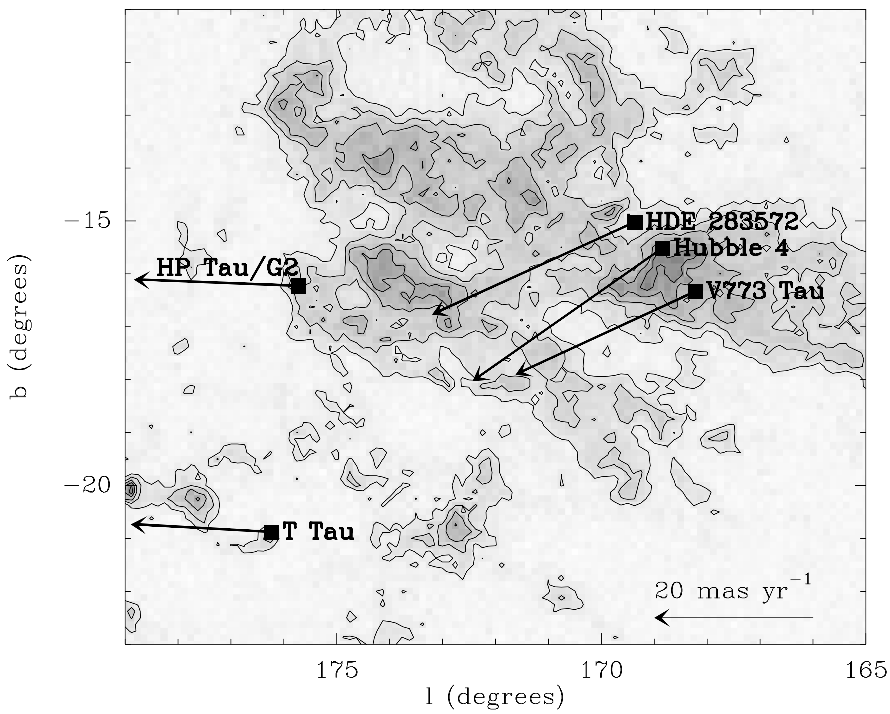

Fig. 2. Image of Taurus in the CO(1-0) line from Dame et al. (2001). The location of the five stars in the complex, and their proper motions are indicated.

tions that the streamers might be 5 to 10 pc nearer than the core. Similarly, Schaefer et al. (2008) found a distance (based on orbit modeling) to the binary young stellar object Haro 1–14c, located in the north-eastern streamer, of 111^{+19}_{-18} pc.

A somewhat puzzling result in that respect comes from the determination by Imai et al. (2007) of the trigonometric parallax of the very young stellar system IRAS 16293–2422 in the eastern streamer L1689. Based on VLBI observations of water masers associated with IRAS 16293–2422, they determine a distance of 178^{+18}_{-37} pc. Since the entire Ophiuchus complex is only about 10 pc across on the plane of the sky, it is very unlikely to be 60 pc deep. Thus, if the distance determination of Imai et al. (2007) were confirmed, it would indicate that at least two unrelated star-forming regions coexist along the line of sight toward Ophiuchus. One region, associated with the core and north-eastern streamers, would be at 120 pc, while the region associated with the eastern cloud L1689 would be several tens of pc farther. It would clearly be very important to obtain an independent confirmation of the distance to L1689.

2.2. *Taurus*

Taurus is perhaps the region that has been most instrumental to the development of our understanding of star-formation (see Kenyon et al. 2008 for a recent review). Its mean distance has long been known to be about 140 pc (Kenyon et al. 1994), and the total extent of the region on the plane of the sky is about 10 degrees (or 25 pc). Roughly speaking, Taurus is composed of three parallel filaments (Figure 2) each about 2 degrees thick. Since those filaments have no reason to be orientated perpendicularly to the line of sight, it is quite conceivable that the near side of each filament might be about 25 pc closer than its far side.

In a series of papers (Loinard et al. 2005, 2007; Torres et al. 2007, 2009, 2011), we have reported measurements of the trigonometric parallax of five young stars distributed across the Taurus complex. Three of these stars (Hubble 4, HDE 283572, and V773 Tau – Figure 2) are located toward the same portion of Taurus, associated with the prominent dark cloud L1495. Interestingly, all three stars are found to be at a similar distance (132.8 ± 0.5 pc, 128.5 ± 0.6 pc, and 132.9 ± 2.4 pc). They also appear to share the same kinematics as measured by their proper motions and radial velocities (Figure 2), and therefore appear to belong to a coherent spatio-kinematical structure. The weighted mean of the three distance measurements (131.4 pc) clearly provides a good estimate of the distance to that specific portion of Taurus. The dispersion about that mean

(2.4 pc), on the other hand, must provide of good estimate of the local depth of the Taurus complex. Interestingly, L1495 and its associated stellar population is about 2 degrees across. This corresponds to a physical radius of about 2.5 pc for that region; the stellar population associated with L1495 appears to be about as deep as it is wide.

The other two stars for which VLBI trigonometric parallaxes have been measured are T Tauri Sb and HP Tau/G3. They are located, respectively, to the south-east and north-east of the Taurus complex (Figure 2). T Tauri was found to be at 146.7 ± 0.6 pc, while HP Tau is at 161.9 ± 0.9 pc (Loinard et al. 2007; Torres et al. 2009). Their proper motions are similar to one another, but significantly different from those of the stars associated with L1495 (Figure 2). The errors on our distance measurements (a few pc) are about 10 times smaller than the separation (about 30 pc) between the nearest and farthest stars in our sample. Thus, we are clearly resolving the depth of the Taurus complex along the line-of-sight.

Additional accurate distance measurements will be needed to reach definite conclusions regarding the three-dimensional structure of Taurus, but a few preliminary conclusions can be made. Taurus clearly appears to be about as deep as it is wide (25–30 pc), with the near edge associated with the western side and the far edge corresponding to the eastern side. In that configuration, the filaments in Taurus would be oriented almost along the Galactic center-Galactic anticenter axis (Ballesteros-Paredes et al. 2009). The space velocity of stars near the western edge of the complex are significantly different from that of the stars near the eastern edge.

Clearly, observations similar to those described here for several tens of young stars distributed across the entire complex would have the potential to reveal both the three-dimensional structure and the internal kinematics of the stellar population associated with Taurus. This would have important consequences for our understanding of star-formation.

2.3. *Perseus*

The Perseus cloud (Bally et al. 2008) contains a number of important sub-regions (for instance NGC 1333 and IC 348; Walawender et al. 2008; Herbst 2008) where star-formation is particularly active. For a long time, the distance to Perseus as a whole was assumed to be 350 pc, following Herbig & Jones (1983). Specifically, this distance was for NGC 1333, and was obtained from an analysis of several previous measurements. Somewhat later, Cernis et al. (1990) argued for a shorter distance to NGC 1333 (220 pc) based on extinction measurements. Many authors, however, have continued to use values between 300 and 350 pc. Indeed, it is not entirely clear if the different sub-regions are physically associated, and even if they are, there could be a significant distance spread because the entire region is about 6 degrees across (corresponding to 25–30 pc).

Hirota et al. (2008, 2011) have measured the distance to two young stellar objects in Perseus using VLBI observations of their associated water masers. They obtain a distance of 235 ± 18 pc for the source SVS 13 in NGC 1333, and 232 ± 18 pc for a young stellar source associated with the dark cloud L 1448 at the western edge of the Perseus complex. The projected separation between the two sources considered by Hirota et al. (2008, 2011) is about 1.5 degrees, or 6 pc. Their result that the two sources are at similar distances indicates that the western portion of Perseus can be assumed to be located at about 230–235 pc from the Sun. VLBI determination of the distance to young stars in the central part of Perseus (associated with B1) and of the eastern portions (B5 and IC 348) would enable a complete description of the structure of that important region.

2.4. *Serpens*

The Serpens molecular cloud complex (Eiroa et al. 2008) is an important region of star-formation extending for several degrees on the plane of the sky. Its distance has been a matter of some controversy over the years, with estimates ranging from 250 pc to 650 pc (see Eiroa et al. 2008 and Dzib et al. 2010 for a discussion). The distance used by most authors in the last 15 years is that reported by Straizys et al. (1996) based on stellar photometry: $d = 259 \pm 37$ pc. More recently, Straizys et al. (2003) extended their work to include many more stars covering an area of about 50 square degrees, and concluded that the front edge of the cloud was at 255 ± 55 pc, and its depth about 80 pc. In projection, Serpens is located toward a larger complex of molecular clouds called the Aquila Rift (Dame & Thaddeus 1985; Prato et al. 2008) believed to be at a distance of about 200 pc. The similarity between the distance to the Serpens cloud found by Straizys and coworkers, and that of the Aquila Rift suggests a physical association between the two.

Using VLBI observations, Dzib et al. (2010) measured the trigonometric parallax of the binary system EC95 in the Serpens core region. They obtain a distance of 414.9 ± 4.4 pc, significantly larger than the value usually adopted for Serpens. The Serpens core is a dense sub-region of the Serpens cloud, with an extent of only about $5'$ (0.6 pc) on the plane of the sky. As a consequence, the contribution of depth to the uncertainty of the distance to the Serpens core is expected to be very limited, and that distance can be assumed to be 415 ± 5 pc. The Serpens cloud, on the other hand is about 3 degrees across, or 25 in diameter. The distance to the cloud as a whole should therefore be taken to be 415 ± 25 pc.

A detailed analysis of the possible reasons for the discrepancy between the most popular distance used for Serpens in the last 15 years, and that obtained directly from a trigonometric parallax is given in Dzib et al. (2010). Their conclusion is that the method used by Straizys et al. (1996, 2003) would naturally be sensitive to the first dust contribution along the line of sight, which might be associated with the clouds in the Aquila Rift rather than those of Serpens. In that interpretation, the Serpens and Aquila Rift clouds would not be physically associated, but merely located along the same line of sight. This is certainly not unexpected since that line of sight is roughly in the direction of the Galactic plane. It will be very important to obtain VLBI parallax measurements of other stars in the direction of Serpens to confirm the distance measurement of Dzib et al. (2010) and clarify the relation between Serpens and the Aquila Rift.

2.5. *Orion*

Together with Taurus, Orion is undoubtedly the most often studied region of star-formation. The efforts to measure the distance to Orion have largely been concentrated on the Orion Nebula region (an interesting and entertaining account of the history of the distance to Orion is given by Muench et al. 2008). For decades, the accepted distance was 480 pc following Genzel et al. (1981). In the last five years, however, several VLBI parallax measurements have been published. Hirota et al. (2007) obtained a distance of $437{\pm}19$ pc using VLBI observations of water masers in the BN/KL region, whereas Sandstrom et al. (2007) found 389 ± 23 pc from VLBI continuum observations of a flaring star. The issue was settled by Menten et al. (2007) and Kim et al. (2008) who independently obtained highly consistent measurements (414 ± 7 pc and 418 ± 6 pc, respectively).

It should noted, however, that the distances quoted so far are only for the Orion Nebula region. The Orion cloud complex is about 100 pc across, so different parts of the complex are most certainly at different distances. In addition, there are a number of dark clouds (e.g. L1617 and L1622; Reipurth et al. 2008) located in the vicinity of the Orion complex, but whose relation to the Orion clouds themselves is unclear. There are some indications that some of these clouds might be significantly closer than the Orion Nebula. Thus, a comprehensive VLBI program aimed at establishing the distance to the different parts of the Orion and surrounding clouds appears to be necessary.

3. THE GOULD'S BELT DISTANCE SURVEY

The VLBI observations described so far have targeted a total of only about a dozen different objects, but have already significantly refined our knowledge of the distance to the nearest regions of star-formation. In several cases, they have provided the first direct indications of the three-dimensional structure of these regions.

One of the world's premier VLBI instruments (the Very Long Baseline Array - VLBA) is currently undergoing a major upgrade, which will increase its bandwidth (and therefore its sensitivity) by a factor of several. Thanks to that upgrade, observations similar to those presented here will become feasible for several hundred young stars. Taking advantage of that possibility, we have initiated a large project (the *Gould's Belt Distance Survey*) aimed at measuring the distance to about 200 young stars distributed across the five regions described in § 2 (Ophiuchus, Taurus, Perseus, Serpens and Orion). The first stage of the project will use about 120 hours of observing time on the Expanded Very Large Array (EVLA) to identify adequate targets. Following that first stage, a total of about 2000 hours of VLBA time will be dedicated to the astrometric observations themselves. The EVLA observations have started in February 2011, and will continue until the summer/fall of that year. The VLBA observations, on the other hand, will start in the fall 2011 and last for a total of about 4 years.

The final goal of the *Gould's Belt Distance Survey* is to estimate with unprecedented accuracy the mean distance, three-dimensional structure and internal kinematics of the five regions described in § 2. This will have important consequences both for the study of star-formation, and for our understanding of the local structure of the Milky Way. In particular, our observations will shed new light on the very origin of Gould's Belt.

4. CONCLUSIONS

Multi-epoch VLBI astrometry of young stellar sources in nearby regions of star-formation have been used to measure their distance with an unprecedented accuracy better than a few percent. These observations have already improved our knowledge of the space distribution and kinematics of star-formation in the Solar neighborhood. In the coming few years, a large on-going VLBA project called *The Gould's Belt Distance Survey* will vastly improve that knowledge by providing accurate distance estimates to about 200 young stars distributed across the five most prominent nearby regions of star-formation: Ophiuchus, Taurus, Perseus, Serpens, and Orion.

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