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VERY LONG BASELINE ARRAY ASTROMETRY OF LOW-MASS YOUNG STELLAR OBJECTS

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RESUMEN

Usando observaciones radio-interferométricas obtenidas en multiples épocas, se puede medir el desplazamiento de objetos estelares jóvenes sobre la bóveda celeste con un nivel de precisión actualmente inalcanzable en cualquier otra longitud de onda. En particular, la precisión obtenida con observaciones tomadas con el *Very Long Baseline Array*, usando referencia de fase, puede ser mejor que 50 micro-segundos de arco si se sigue una calibración cuidadosa. Eso es suficiente para medir la paralaje trigonométrica y el movimiento propio de cualquier radio-estrella joven localizada a menos de unos cientos de parsecs del Sol con una precisión mejor que unos cuantos porcientos. Aprovechando esta situación, hemos empezado a desarrollar un gran proyecto cuya meta principal es medir la distancia a las regiones de formación estelar más cercanas (Tauro, Ofiuco, Cefeo, etc.). Aquí, presentamos los resultados para varias estrellas en Tauro y Ofiuco, y mostramos cómo la precisión alcanzada es ya un orden de magnitud mejor que la de estimaciones previas. Los movimientos propios obtenidos también son interesantes, particularmente en sistemas estelares múltiples. Para ilustrar este punto, presentamos el caso del famoso sistema T Tauri, donde los datos VLBA proveen información crucial para la caracterización de la órbita.

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 precision that currently cannot be attained at any other wavelength. In particular, the accuracy achieved using carefully calibrated, phase-referenced observations with the *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. Taking advantage of this situation, we have initiated a large project aimed mainly at measuring the distance to the nearest regions of star-formation (Taurus, Ophiuchus, Perseus, etc.). Here, we will present the results for several stars in Taurus and Ophiuchus, and show that the accuracy obtained is already more than one order of magnitude better than that of previous estimates. The proper motion obtained from the data can also provide important information, particularly in multiple stellar systems. To illustrate this point, we will present the case of the famous system T Tauri, where the VLBA data provide crucial information for the characterization of the orbital path.

Key Words: astrometry — binaries: general — radiation mechanisms: non-thermal — radio continuum: stars — stars: formation — stars: individual (T Tau, HDE 283572, HP Tau, Hubble 4, S1, DoAr21)

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 prerequisite 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, Robichon, & Arenou 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. They can be used to study the overall dynamics of star-forming regions as well as the kine-

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matics of the mass ejections that are often driven by young stars. If they are scheduled to adequately characterize the orbital paths of young multiple systems, astrometric measurements can also provide accurate mass estimates. This is particularly important to constrain pre-main sequence evolutionary models (e.g. Hillenbrand & White 2004).

Since observations of young stars in the visible range are 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 calibrated against fixed distant quasars. Of course, only those young stars associated with radio sources are potential targets. Moreover, radio interferometers effectively filter out any emission more extended than a certain limiting angular size. For instance, in the data presented below, only emission more compact than about 40 milli-arcseconds can be detected. In young stars, only non-thermal emission mechanisms can generate detectable emission on such compact scales, so we must concentrate on magnetically active sources. This is not a particularly limiting factor, fortunately, because low-mass young stars do tend to have intense surface magnetic fields (e.g. Johns-Krull 2007) that can generate detectable non-thermal emission.

2. OBSERVATIONS

In this paper, we will consider a total of six young stars: four in Taurus (T Tauri Sb, HDE 283572, Hubble 4 and HP Tau/G2) and two in Ophiuchus (DoAr 21 and S1). All six objects were previously known non-thermal radio sources. Each was observed at 6 to 12 epochs separated from one another by 2 to 3 months, and covering a total timespan of 1.25 to 2.5 years. All the observations were collected at a wavelength of 3.6 cm with the *Very Long Baseline Array*, an interferometer of 10 antennas, each 25 meters in diameter, spread over the entire US territory (see `http://www.vlba.nrao.edu/` for details). Phase-referencing –whereby observations of the scientific target and a nearby quasar used as calibrator are intertwined– was used for all the data. The calibration scheme is described in detail in Loinard et al. (2007a) and Torres et al. (2007).

The typical angular resolution of our data is 1 milli-arcsecond, and the typical astrometric accuracy is 50 to 100 micro-arcseconds. The final noise level in the images is 50 to 100 mJy, sufficient to always detect the sources at more than about 10σ. The source flux density varies from object to object and epoch to epoch, from a minimum of about 0.5 mJy to a maximum of nearly 50 mJy.

3. DISTANCE TO THE NEAREST STAR-FORMING REGIONS

The displacement of a source on the celestial sphere is the combination of its trigonometric parallax (π) and its proper motion. In what follows, we will have to consider three different situations in terms of proper motions. Two of our target stars are apparently single (Hubble 4 and HDE 283572), and one (HP Tau/G2) is a member of a multiple system with an orbital period so much longer than the timespan covered by the observations that the effect of the companions can safely be ignored. Thus, in these three cases, the proper motion can be assumed to be linear and uniform, and the right ascension (α) and the declination (δ) vary as a function of time t as:

$$\alpha(t) = \alpha_0 + (\mu_\alpha \cos\delta)t + \pi f_\alpha(t) \quad (1)$$

$$\delta(t) = \delta_0 + \mu_\delta t + \pi f_\delta(t), \quad (2)$$

where α_0 and δ_0 are the coordinates of the source at a given reference epoch, μ_α and μ_δ are the components of the proper motion, and f_α and f_δ are the projections over α and δ, respectively, of the parallactic ellipse.

On the other hand, two of our sources (DoAr 21 and S1) are members of compact binary systems with an orbital period of the order of the timespan covered by the observations. In such a situation, one should fit simultaneously for the uniform proper motion of the center of mass and for the Keplerian orbit of the system. This, however, requires more observations than are needed to fit only for a uniform proper motion. Thus, additional data are currently being collected to adequately constrain the required fits. In this paper, we will present preliminary results based on equations (1) and (2) where the Keplerian motion is not included. We will see momentarily that the main effect of not fitting for the Keplerian orbit is an increase in the final uncertainty on the distance.

Finally, one source (T Tauri Sb) is a member of a binary system with an orbital period longer than the timespan of our observations but not by a huge factor. While a full Keplerian fit would again, in principle, be needed, we found that including a constant acceleration term provides an adequate description of the trajectory. The fitting functions in this case

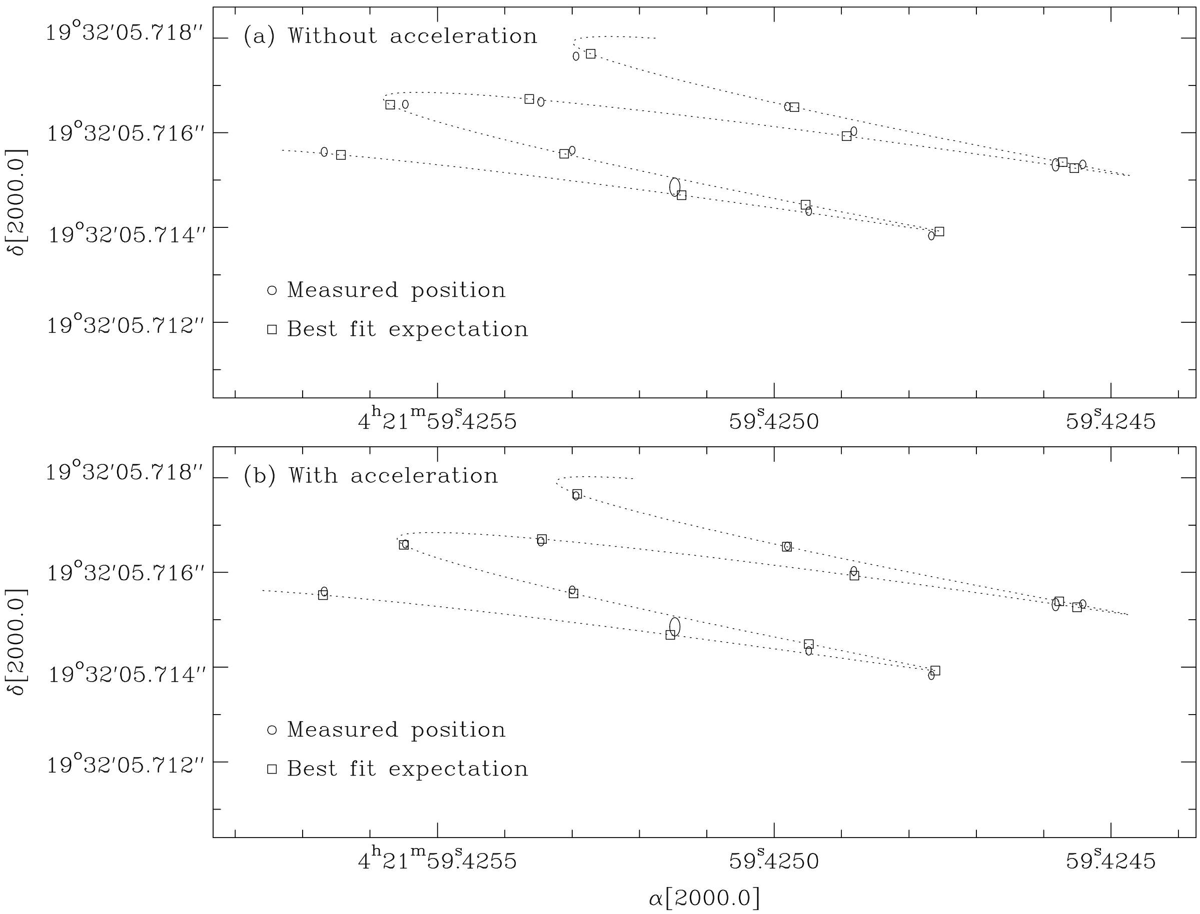

Fig. 1. Measured positions of T Tau Sb and best fit without (a) and with (b) acceleration terms. The observed positions are shown as ellipses, the size of which represents the magnitude of the errors. Note the very significant improvement when acceleration terms are included.

are of the form:

$$\alpha(t) = \alpha_0 + (\mu_{\alpha 0}\cos\delta)t + \frac{1}{2}(a_\alpha \cos\delta)t^2 + \pi f_\alpha(t) \quad (3)$$

$$\delta(t) = \delta_0 + \mu_{\delta 0} t + \frac{1}{2} a_\delta t^2 + \pi f_\delta(t), \quad (4)$$

where $\mu_{\alpha 0}$ and $\mu_{\delta 0}$ are the proper motions at a reference epoch, and a_α and a_δ are the projections of the uniform acceleration.

3.1. *Distance to Taurus*

In total, twelve observations of T Tau Sb were obtained between September 2003 and July 2005. The trajectory described by the source on the plane of the sky (Figure 1) can be adequately described as the superposition of a parallactic ellipse and a uniformly accelerated proper motion. The resulting parallax is 6.82 ± 0.03 mas, corresponding to a distance of 146.7 ± 0.6 pc (Loinard et al. 2005, 2007a; Table 1). For Hubble 4 and HDE 283572, six observations were obtained between September 2004 and December 2005. Fits with a uniform proper motion

TABLE 1

PARALLAXES AND DISTANCES TO THE SIX STARS CONSIDERED HERE

Source	Parallax (mas)	Distance (pc)
Taurus:		
T Tau Sb	6.82 ± 0.03	146.7 ± 0.6
Hubble 4	7.53 ± 0.03	132.8 ± 0.5
HDE 283572	7.78 ± 0.04	128.5 ± 0.6
HP Tau	6.20 ± 0.03	161.2 ± 0.9
Ophiuchus:		
S1	8.55 ± 0.50	$116.9^{+7.2}_{-6.4}$
DoAr21	8.20 ± 0.37	$121.9^{+5.8}_{-5.3}$

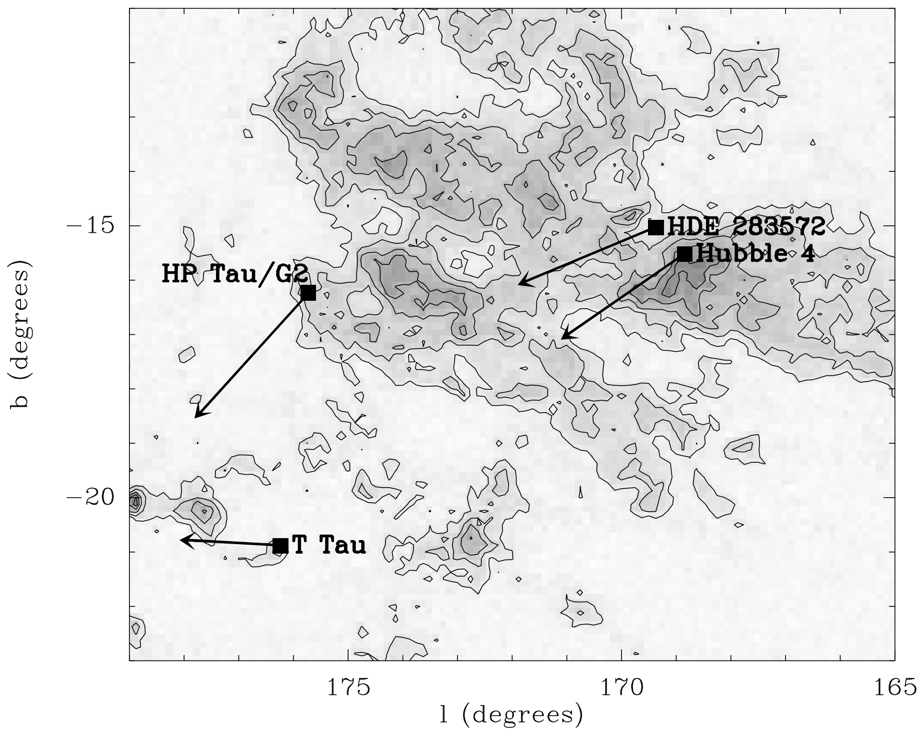

Fig. 2. Position and tangential velocity vectors of the four young stars in Taurus considered here, superimposed onto the CO(1-0) map of Taurus from Dame, Hartmann, & Thaddeus (2001).

adequately described the sources' trajectories (Torres et al. 2007), and the resulting parallaxes are 7.53 $\pm$ 0.03 mas ($d = 132.8 \pm 0.5$ pc) and 7.78 $\pm$ 0.04 mas ($d = 128.5 \pm 0.6$ pc), respectively (Table 1). Finally, nine observations of HP Tau/G2 were obtained between September 2005 and December 2007. Again, a uniform proper motion was sufficient to properly describe the source path. The best fit yields a parallax of 6.20 $\pm$ 0.03 mas, corresponding to 161.2 $\pm$ 0.9 pc (Torres et al., in prep.; Table 1).

Two of these four objects have measured Hipparcos parallaxes (Bertout et al. 1999): T Tau ($\pi_{\rm hip} = 5.66 \pm 1.58$) and HDE 283572 ($\pi_{\rm hip} = 7.81 \pm 1.30$). Our results are consistent with these values, but one to two orders of magnitude more accurate. Also, the trigonometric parallax to both Hubble 4 and HDE 283572 was estimated by Bertout & Genova (2006) using a modified convergent point method. Their results ($\pi_{\rm cp} = 8.12 \pm 1.50$ for Hubble 4 and $\pi_{\rm cp} = 7.64 \pm 1.05$ for HDE 283572) are also consistent with our results, but again more than one order of magnitude less accurate. Indeed, our measurements yield distances accurate to about 0.5% for all four sources.

Taking the weighted mean of our four measurements, we can estimate the mean parallax of the Taurus association to be $\bar{\pi} = 7.0$ mas, corresponding to a mean distance $\bar{d} = 143$ pc. This is in good agreement with the value of 140 $\pm$ 15 pc traditionally used for Taurus (e.g. Kenyon et al. 1994; Bertout et al. 1999).

As can be seen from Figure 2, the total spatial extent of Taurus on the sky is about 10°, corresponding to a physical size of about 25 pc. Our observations show that the depth of the complex is similar since HP Tau is about 30 pc farther than Hubble 4 or HDE 283572. 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 observations similar to those presented here currently represent the most promising avenue toward that goal. Indeed, the observations of the four stars presented earlier already provide some hints of what the three-dimensional structure of Taurus might be. Hubble 4 and HDE 283572 which were both found to be at about 130 pc and to share a similar kinematics (Torres et al. 2007, see Figure 2), are also located in the same portion of

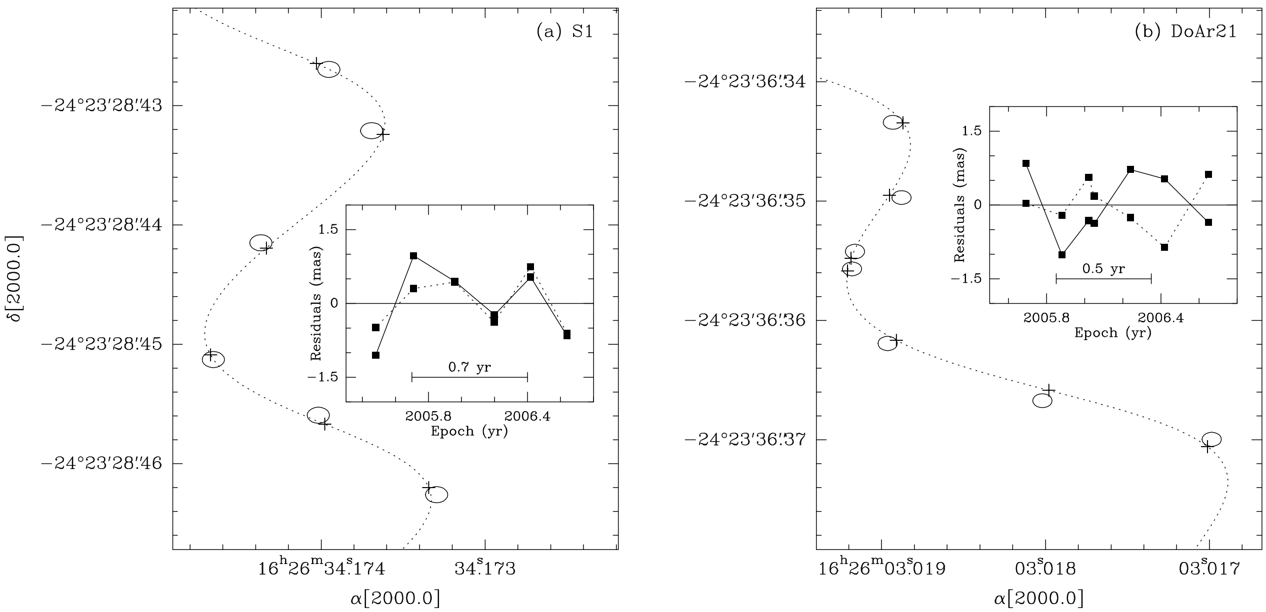

Fig. 3. Measured positions and best fit for (a) S1, and (b) DoAr21. The observed positions are shown as ellipses, the size of which represents the magnitude of the errors. The positions at each epoch expected from the best fits are shown as + signs. The insets show the residuals (fit-observation) in right ascension (full line) and declination (dotted line).

Taurus, near Lynds 1495. T Tauri is located in the southern part of Taurus near Lynds 1551, its tangential velocity is clearly different from that of Hubble 4 and HDE 283572, and it appears to be somewhat farther from us. Finally, HP Tau is located near the (Galactic) eastern edge of Taurus, and is the farthest of the four sources considered here. Although additional observations are needed to draw definite conclusions, our data, suggest that the region around Lynds 1495 corresponds to the near side of the Taurus complex at about 130 pc, while the eastern side of Taurus corresponds to the far side at 160 pc. The region around Lynds 1551 and T Tauri appears to be at an intermediate distance of about 147 pc.

3.2. *Distance to the Ophiuchus core*

Ophiuchus is, together with Taurus, one of the best studied regions of low-mass star-formation. Unlike Taurus, it is only a few parsecs across, so a reliable distance determination to a few of its stars would automatically provide an accurate distance to the entire region. Ophiuchus 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 2007).

Six observations of S1 and 7 observations of DoAr 21 were obtained between June 2005 and August 2006 (Loinard et al. 2008). Their observed trajectories can be adequately described as a combination of a parallactic ellipse and a uniform proper motion, but with a post-fit r.m.s. significantly larger than in the case of Taurus (Figure 3). Moreover, the residuals do not appear to be random, but instead show some indication of periodicity (see the insets of Figure 3), as would be expected if the studied sources were members of binary systems. Interestingly, S1 was previously known to have a nearby companion (Richichi et al. 1994), and the expected orbital period of the system is comparable to the period observed in Figure 3 (see Loinard et al. 2008 for details). DoAr21 was not previously known to be a multiple stellar system, but was found to be a double radio source in one of our observations. We conclude that the fairly large periodic residuals observed for S1 and DoAr 21 are a consequence of their unmodeled Keplerian motion. Additional VLBA observations are being collected to properly constrain the orbital paths.

The parallaxes that are obtained from the fits shown in Figure 3 are 8.55 ± 0.50 mas and 8.20 ± 0.37 mas for S1 and DoAr 21, respectively. The corresponding distances are $116.9^{+7.2}_{-6.4}$ pc and $121.9^{+5.8}_{-5.3}$ pc. Thus, the uncertainties in the distances to the stars in Ophiuchus are significantly larger than those for the stars in Taurus. This is a consequence of the larger post-fit r.m.s. mentioned earlier, and ought to be drastically reduced once full Keplerian fits are performed. The weighted mean of the two paral-

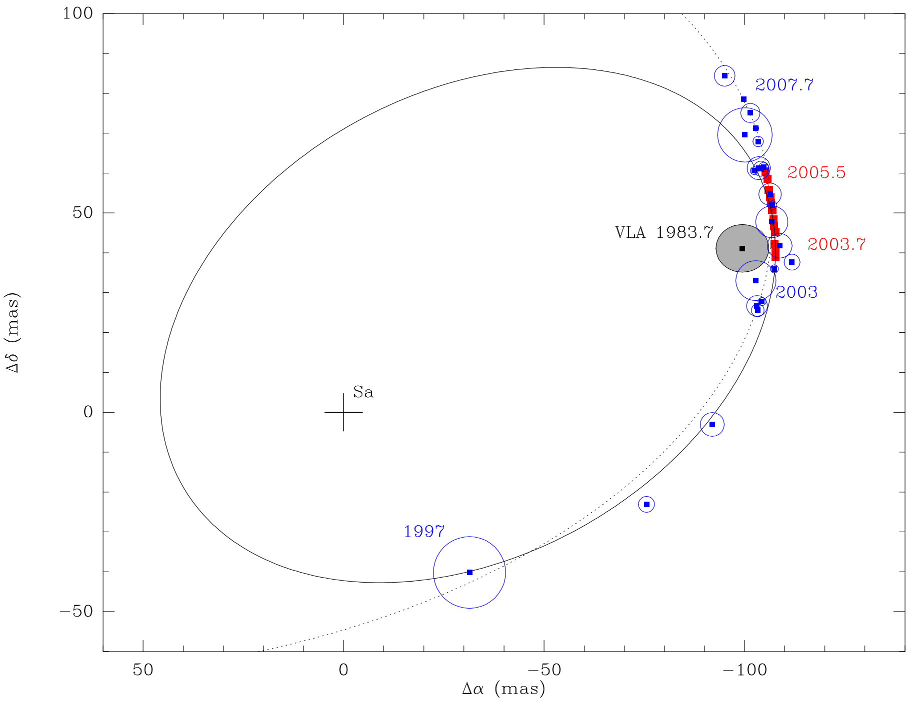

Fig. 4. Orbit of the T Tau Sa/T Tau Sb system (see the electronic version for this figure in color). The blue symbols correspond to all the infrared observations available at the beginning of 2008. All the data tabulated by Köhler et al. (2008) as well as more recent Keck observations kindly provided by G. Schaefer are included. The red dots show are the VLBA observations. The full line corresponds to the fit published by Duchêne et al. (2006) and the dotted line to the fit proposed by Köhler et al. (2008). The position of the VLA source in 1983.7 is shown as a grey symbol.

laxes is 8.33 ± 0.30, corresponding to a distance of $120.0^{+4.5}_{-4.3}$ pc. This is in good agreement with the value proposed by Knude & Hög (1998) and, more recently, by Lombardi, Lada, & Alves (2008). Note that, in spite of the enhanced errors related to the binarity of the sources, our 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.

4. ON THE ORBITAL MOTION OF T TAU SB

The eponym of an entire class of young stellar objects, T Tauri was first noticed for its variability by the British astronomer John Russell Hind in 1852. It was first recognized to be a young star by Joy (1945), and has been the subject of numerous studies ever since. Initially thought to be a single star, it was discovered by Dyck, Simon, & Zuckerman (1982) to have a companion located about 0$''$.7 to its south. As a consequence, the *historical* T Tauri star is now usually referred to as T Tau N, and the southern companion as T Tau S. Recently, T Tau S was itself discovered to be a tight binary (Koresko 2000; Köhler, Kasper, & Herbst 2000) formed by two stars called T Tau Sa and T Tau Sb, in fairly rapid relative motion (Duchêne, Ghez, & McCabe 2002; Duchêne et al. 2005, 2006; Schaefer et al. 2006; Köhler et al. 2008).

The structure of T Tau at radio wavelengths is somewhat complex (Loinard et al. 2007b). T Tau N is associated with a compact radio source tracing the base of its jet (e.g. Johnston et al. 2003). The southern companion, on the other hand, is comprised of a compact non-thermal source associated with the active magnetosphere of T Tau Sb, and an extended thermal halo presumably related to stellar winds (Loinard et al. 2007b).

The nature of the orbital motion between T Tau Sa and T Tau Sb has been somewhat disputed in recent years. Using 20 years worth of VLA observations, Loinard, Rodríguez, & Rodríguez (2003) concluded that the orbit between T Tau Sa and T Tau Sb had been dramatically altered after a recent perioastron passage. More recently, however, Duchêne et al. (2006) argued that these VLA observations, together with newer infrared data, could be adequately described by a single Keplerian orbit with a period of about 22 years. Finally, Köhler et al. (2008) found that the infrared data alone were best described by a Keplerian orbit with a period of about 90 years, and that the most recent infrared data were not easily reproduced by the fit proposed by Duchêne et al. (2006). The orbit favored by Köhler et al. (2008), however, is unable to explain the older radio observations.

Since T Tau Sb is a member of a triple stellar system, its trajectory on the plane of the sky results from the combination of several terms: its trigonometric parallax; the overall proper motion of the T Tauri system relative to the Sun; the Keplerian orbit of T Tau S about T Tau N; and the relative motion between T Tau Sb and T Tau Sa. The trigonometric parallax has been accurately measured using the VLBA observations (see § 3), and can easily be removed. The overall proper motion of the T Tauri system relative to the Sun as well as the orbit of T Tau S about T Tau N are well determined, and can also be taken into account (see Loinard et al. 2007a for details). Thus, our VLBA observations of T Tau Sb allow us to trace the relative motion between T Tau Sb and T Tau Sa for the period 2003.7 to 2005.5. The agreement between our radio observations and the infrared data for the same period is excellent (Figure 4), and the radio data can be used to further constrain the fits to the orbital path of the system. Indeed, the scatter in the radio data is less than that in the infrared observations, so the radio positions provide very strong constraints.

Also shown in Figure 4 are the fits proposed by Duchêne et al. (2006) and Köhler et al. (2008). As noticed already by Loinard et al. (2007a), the VLBA data favor an orbital period somewhat longer than that proposed by Duchêne et al. (2006), and in better agreement with the most recent infrared observations and with the fit proposed by Köhler et al. (2008). The difficulty with such a long orbital period is related to the older VLA positions of T Tau S reported by Loinard et al. (2003). To illustrate this problem, we show in Figure 4 the position of the VLA source associated with T Tau S around 1984. Clearly, the observed VLA position would be consistent with the 20–22 yr orbital period proposed by Duchêne et al. (2006): between the old VLA observation and the IR or VLBA data corresponding to 2003–2005, T Tau Sb would have completed a full orbit. For a 90 yr orbital period, however, the position expected for 1984 is located at about $\Delta\alpha \sim +100$ mas; $\Delta\delta \sim -70$ mas. This is clearly inconsistent with the VLA position observed at that epoch. Additional observations (infrared, VLA, and VLBA) are clearly needed to settle this issue.

5. CONCLUSIONS AND PERSPECTIVES

In this paper, we presented the results of multi-epoch VLBA observations of several low-mass young stars, which allowed us to measure their trigonometric parallaxes with unprecedented accuracy, and –in some cases– study their orbital motions. Our main conclusions, and some perspectives are presented in the following.

5.1. *Distance and structure of Taurus*

Using observations of four stars in Taurus, we confirmed that the mean distance to this important region of star-formation is about 143 pc. In addition, the total depth of Taurus could be estimated to be about 30 pc, and the first indications of the three-dimensional structure of the complex could be obtained. Exploring further the spatial structure of Taurus is very important because, given its depth, using a mean distance indiscriminately for all Taurus members could result in systematic errors of 10–20%. Observations similar to those presented here of a larger sample of stars currently represent the best avenue toward an accurate determination of the three-dimensional structure of Taurus. Nowadays, however, only a few stars in Taurus –besides those considered here– are known non-thermal radio emitters. Observations of these few additional cases are already underway or will be obtained soon. To further increase the sample of possible candidates for multi-epoch VLBA observations, identification of new magnetically active objects with adequate non-thermal emission will be required.

5.2. *The distance to Ophiuchus*

The mean distance to the Ophiuchus core was also measured using multi-epoch VLBA observations, and was found to be $120^{+4.5}_{-4.3}$ pc. This value is in good agreement with several recent determinations (Knude & Hög 1998; Lombardi et al. 2008) and represents a very significant advance, since the distance to Ophiuchus was previously uncertain by about 20 pc. Our distance determination ought to be further improved once additional data designed to characterize the orbital motion of the sources are available. These data are currently being obtained and reduced. Since the total extent of the Ophiuchus core on the plane of the sky is only a few parsecs, there is little need for a larger sample of stars. However, several large extensions (known as *streamers*) are known to exist around the Ophiuchus core, and those could be at somewhat different distances. Since these streamers harbor a number of interesting young stellar sources, it would be interesting to also measure their distances accurately.

5.3. *Other regions*

Several other nearby star-forming regions have been studied in detail at many wavelengths but have poorly determined distances (e.g. Perseus, Serpens, etc.). Non-thermal sources are known to exist in these regions, so multi-epoch VLBA observations would allow significant improvements in the determination of their distances. The corresponding observations are being obtained and will be published in forthcoming papers.

Note that the distance to the nearest region of high-mass star-formation (Orion) has recently been measured using Very Long Baseline Interferometry observations similar to those presented here (Menten et al. 2007; Hirota et al. 2007; Sandstrom et al. 2007).

5.4. *Orbital motions and mass determinations*

Finally, our observations also allow us to measure the proper motions of the sources under study. This is particularly interesting to study the orbital motion of multiple stellar systems. In the case of T Tauri, we showed that the VLBA data are in excellent agreement with infrared observations taken over the same time period, and that they already provide very important constraints for the orbital fits. Future observations will allow further improvements in the determination of the orbital elements, and –combined with archival VLA data– will help resolve the existing dispute on the nature of the orbital path. Eventually, the mass of the individual stars will be measured very accurately; this will provide very important constraints for pre-main sequence evolutionary models.

Another very interesting case is that of V773 Tau which is described in Torres et al. (2008). There, the VLBA observations spatially resolve the two members of a tight spectroscopic binary with a period of only about 50 days. The combination of spectroscopic observations at visible wavelengths and multi-epoch VLBA astrometric data will allow us to fully characterize the orbital elements and the mass of the stars.

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