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MULTIEPOCH VLBA OBSERVATIONS OF T TAURI SOUTH

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ABSTRACT

In this Letter, we present a series of seven observations of the compact, nonthermal radio source associated with T Tauri South made with the Very Long Baseline Array (VLBA) over the course of 1 year. The emission is found to be composed of a compact structure most certainly originating from the magnetosphere of an underlying pre–main-sequence star and a low brightness extension that may result from reconnection flares at the star-disk interface. The accuracy of the absolute astrometry offered by the VLBA allows us to make very precise determinations of the trigonometric parallax and proper motion of T Tau South. The proper motion derived from our VLBA observations agrees with that measured with the Very Large Array over a similar period to better than 2 mas yr^{-1}, and it is fully consistent with the infrared proper motion of T Tau Sb, the pre–main-sequence M star with which the radio source has traditionally been associated. The parallax, $\pi = 7.07 \pm 0.14$ mas, corresponds to a distance of $141.5^{+2.8}_{-2.7}$ pc.

Subject headings: astrometry — binaries: general — magnetic fields — radiation mechanisms: nonthermal — radio continuum: stars — stars: formation

1. INTRODUCTION

T Tauri was initially identified as a single optical star, with unusual variability and peculiar emission lines (Barnard 1895, Joy 1945, and references therein). Early infrared observations then revealed the existence of a heavily obscured companion (hereafter T Tau S) located about $0\farcs7$ to the south of the visible star (Dyck et al. 1982) and most likely gravitationally bound to it (Ghez et al. 1991). Recently, this infrared companion was itself found to contain two sources (T Tau Sa and T Tau Sb; Koresko 2000 and Köhler et al. 2000) in rapid relative motion (Duchêne et al. 2002; Furlan et al. 2003). Thus, T Tau is now acknowledged to be at least a triple stellar system. At radio wavelengths, T Tau has long been known to be a double source (Schwartz et al. 1986). The northern radio component is associated with the optical star and mostly traces the base of its thermal jet (e.g., Johnston et al. 2003), whereas the southern radio source is related to the infrared companion and is thought to be the superposition of a compact component of magnetic origin and an extended halo, presumably related to stellar winds (Johnston et al. 2003; Loinard et al. 2003).

The relative motions between the various components of the T Tau system have recently been under enhanced scrutiny, following the suggestion, based on multiepoch Very Large Array (VLA) observations, that one of the components might have seen its path dramatically altered by a recent chaotic encounter (Loinard et al. 2003). This interpretation was disputed by Johnston et al. (2003, 2004a) and Tamazian (2004), who fitted the same VLA data with stable orbits. It is noteworthy, however, that the residuals between their best fits and the actual radio positions ($0\farcs03$–$0\farcs04$) are often significantly larger than the nominal observational errors ($\lesssim 0\farcs01$), especially at recent epochs (see Table 6 in Johnston et al. 2004a). To resolve this discrepancy, Johnston et al. (2004a, 2004b) proposed that the structure of T Tau S at radio wavelengths was affected by erratic internal variations, which made the centroid of the VLA source dither around the position of the underlying pre–main-sequence (PMS) star. To reconcile the radio observations obtained in the last few years with the orbital fits, the VLA source centroid needs to have moved about 25 mas yr^{-1} faster than the associated PMS star. Clearly, this would render the existing 20 years of VLA observations useless as tracers of the stellar trajectories, in spite of the high-quality astrometry naturally provided by radio interferometry.

The nonthermal mechanisms at the origin of the compact radio emission in T Tau S require the presence of an underlying, magnetically active star (Skinner 1993). Specifically, the emission is expected to be either gyrosynchrotron radiation associated with reconnection flares in the stellar magnetosphere and at the star-disk interface or coherently amplified cyclotron emission from magnetized accretion funnels connecting the disk to the star (Dulk 1985; Feigelson & Montmerle 1999; Smith et al. 2003). In all cases, the emission is produced within less than about 10 stellar radii (roughly 30 $R_\odot$) of the star itself. Indeed, 3.6 cm VLBI observations recently revealed the existence, near the expected position of T Tau Sb, of a source with an angular size less than about 15 $R_\odot$ (Smith et al. 2003). Because it is so small, any structural changes in this compact radio component would occur on such small scales that the effects on the astrometry would be very limited. Thus, observations focusing on it should accurately trace the path of the underlying PMS star.

2. OBSERVATIONS

Here, we present the results of a series of seven continuum 3.6 cm (8.42 GHz) observations of T Tau S obtained every 2 months between 2003 September and 2004 September with the 10-element Very Long Baseline Array (VLBA) of the National Radio Astronomy Observatory (NRAO; Table 1). Since the VLBA is only sensitive to compact emission structures with high surface brightness, it will effectively filter out the extended radio halo of T Tau S and will provide images of the nonthermal source alone. Our phase center was at $\alpha_{\mathrm{J2000.0}} = 04^{\mathrm{h}}21^{\mathrm{m}}59\fs4263$, $\delta_{\mathrm{J2000.0}} = +19°32'05\farcs730$, the position of the compact source detected by Smith et al. (2003). Each observation consisted of a series of cycles

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TABLE 1
Observational Parameters

UT Date	Epoch (yr)	Synthesized Beam $\Delta\theta_{max} \times \Delta\theta_{min}$; P.A. (mas × mas; deg)	rms (μJy beam^{-1})	Flux Density (mJy)	Peak Flux (mJy beam^{-1})
2003 Sep 24	2003.7300	1.88 × 0.78; −8.99	70.5	1.69	1.43
2003 Nov 18	2003.8804	1.87 × 0.79; −5.19	64.3	1.70	1.17
2004 Jan 15	2004.0387	2.17 × 1.00; +11.94	68.0	1.03	0.84
2004 Mar 26	2004.2349	1.90 × 0.80; −2.24	65.5	1.51	0.76
2004 May 13	2004.3657	1.92 × 0.76; −10.66	76.3	1.79	1.18
2004 Jul 8	2004.5183	1.90 × 0.78; −6.00	62.9	1.13	0.54
2004 Sep 16	2004.7090	2.06 × 0.80; −8.94	68.7	1.70	0.98

with 2 minutes spent on-source and 1 minute spent on the phase-referencing quasar J0428+1732 ($\alpha_{J2000.0}$ = 04^{h}28^{m}35^s.633679, $\delta_{J2000.0}$ = +17°32′05″.58799), located 2°.6 away. The secondary quasar J0431+1731 ($\alpha_{J2000.0}$ = 04^{h}31^{m}57^s.379244, $\delta_{J2000.0}$ = +17°31′35″.77538) was also observed periodically (about every 30 minutes); it was not used in the phase calibration process but served as a check on the final astrometry. Based on the dispersion on the measured position of that quasar, we estimate our astrometric uncertainties to be about 0.25 mas in both α and δ. Data editing, amplitude calibration, and fringe fitting (carried out only on the calibrators, since the target is much too weak) were made in a standard way using NRAO's AIPS software. Once calibrated, the visibilities were imaged with a pixel size of 0.25 mas after weights intermediate between natural and uniform were applied.

3. STRUCTURE OF THE EMISSION

The compact radio source associated with T Tau S was detected at all seven epochs with high signal-to-noise ratio (Table 1). Its flux density varies significantly, from a maximum of nearly 1.8 mJy down to a minimum of just over 1.0 mJy. Moreover, its peak brightness in units of millijanskys per beam is found to be always significantly smaller than its flux density in millijanskys (on average by 35%; Table 1). This suggests that the emission is somewhat extended since equal numerical values are expected for a point source. This possibility gains further credibility when one considers the restored images (Figs. 1*a*–1*c*), where the emission is consistently found to be composed of a compact source (most certainly associated with a stellar magnetosphere) and a low brightness "spur" extending eastward. Although this latter component was not reported by Smith et al. (2003), inspection of their published image (their Fig. 1) reveals a source structure quite similar to that found here, with a weak spur extending toward the northeast of a compact component. When our seven observations are combined, the low brightness spur becomes even more evident (Fig. 1*d*); its position angle (P.A.) is between +70° and +80°, and its deconvolved extent in that direction is about 1 mas. Since the measured parallactic and proper motions (§ 4) imply a maximum displacement of about 0.02 mas during any one of our 6 hr observing runs, the measured size is not affected by smearing effects. The observed spur is also very unlikely to be a consequence of random errors in the phase calibration, since its characteristics repeat themselves from one epoch to the next.

T Tau S contains two infrared sources, so one might be tempted to associate the eastern spur to this preferred direction of the system. However, extrapolating from the latest published infrared observations (Furlan et al. 2003; G. Duchêne et al. 2005, in preparation), we estimate that the position angle between T Tau Sb and T Tau Sa at the median epoch of our VLBA observations must have been about 110°, significantly larger than the position angle of the spur. Another unlikely possibility is that it would trace a weak secondary component. Given the short distance that would then separate the two VLBA sources, orbital motions should have been easily detected over the course of our observations. Interestingly, the spur is nearly exactly perpendicular to the jet acknowledged to be powered by T Tau S (Solf & Böhm 1999). This might suggest that the low brightness extension is associated with an accretion disk and that it results from reconnection flares at the star-disk interface. Indeed, Duchêne et al. (2002) reported the detection of a wavelength-dependent infrared excess around T Tau Sb, which strongly suggests the existence of an accretion disk there. Typically, the inner edge of that disk is expected to be at a radius of about $5R_*$, where R_* is the stellar radius (Ostriker & Shu 1995). A low-mass PMS star such as T Tau Sb is expected to have a radius of about 3 $R_\odot$ (Siess et al. 2000). Hence, the inner disk edge is expected to be at 15 $R_\odot$ (0.07 AU). At a distance of 141.5 pc (see § 4), this corresponds to an angular scale of about 0.5 mas. After convolution with our beam size in α (on average 0.82 mas), we obtain an ex-

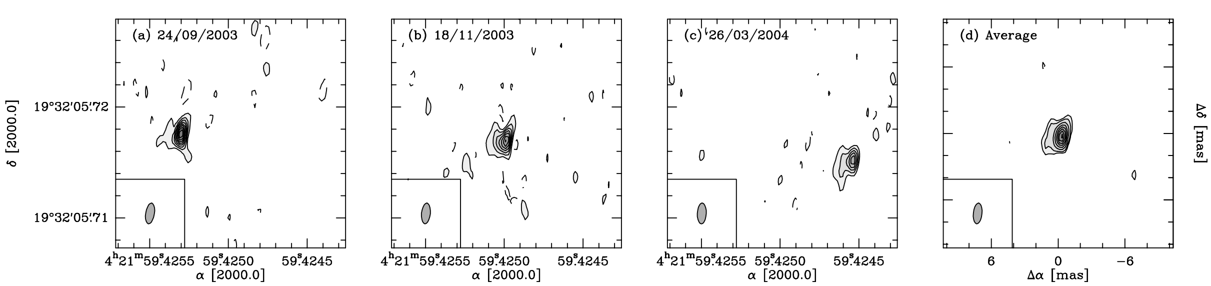

Fig. 1.—(*a*–*c*) 3.6 cm images of the T Tau system obtained at three different epochs. The first contour and the contour interval are at 0.165 mJy beam^{-1}. (*d*) Average of the 6 epochs. The first contour is at 0.08 mJy beam^{-1}, and the subsequent ones increase exponentially by a factor $\sqrt{2}$. The synthesized beam is indicated at the bottom left-hand corner of each panel.

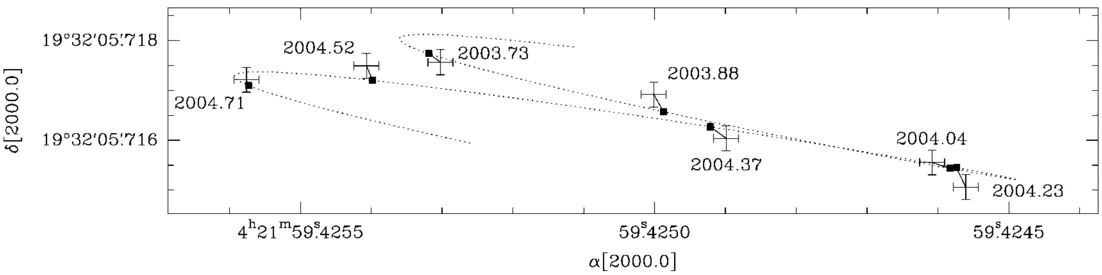

FIG. 2.—Trajectory on the plane of the sky of the compact radio component in T Tau S. The crosses represent the measured positions of the source with their error bars, the dotted line shows the best fit to the data, and the filled squares display the positions of the source as predicted by the best fit for each observed epoch.

pected observed extent of 0.9 mas for the spur. This is in very good agreement with the measured extent. In this scheme, however, it is somewhat puzzling that we only see structure on one side of the star.

4. ASTROMETRY

As Figures 1*a*–1*c* readily show, the absolute position of the source changes significantly from one epoch to the next. These displacements most certainly result from parallactic and proper motions[3] and can be modeled in terms of the source position at epoch J2000.0 ($\alpha_{\rm J2000.0}$ and $\delta_{\rm J2000.0}$), its proper motion in right ascension and declination (μ_α and μ_δ), and its parallax π. These five astrometric elements were deduced from the measured positions of the source by minimizing the χ^2 associated with this description using an iterative scheme (Fig. 2). The results for the five astrometric parameters are as follows:

$$\alpha_{\rm J2000.0} = 04^{\rm h}21^{\rm m}59^{\rm s}.424015 \pm 0^{\rm s}.000009,$$

$$\delta_{\rm J2000.0} = 19^\circ 32' 05''.71957 \pm 0''.00013,$$

$$\mu_\alpha \cos\delta = 3.29 \pm 0.30 \text{ mas yr}^{-1},$$

$$\mu_\delta = -0.75 \pm 0.31 \text{ mas yr}^{-1},$$

$$\pi = 7.07 \pm 0.14 \text{ mas}.$$

The postfit rms is found to be 0.25 mas in both α and δ, in agreement with our expected individual positional errors.

The parallax reported here for T Tau corresponds to a distance $d = 141.5^{+2.8}_{-2.7}$ pc, a value much more precise than, and barely within the 1 σ error bar of, that obtained by the *Hipparcos* satellite for T Tau N ($d = 177^{+70}_{-39}$ pc; Perryman et al. 1997). With this measurement, T Tau becomes the second PMS star in Taurus with a distance known to this level of precision. The first was V773 Tau, for which Lestrade et al. (1999) determined a parallax of 6.74 ± 0.25 mas ($d = 148.3^{+5.7}_{-5.3}$ pc) using multiepoch global VLBI observations. For V773 Tau, the VLBI distance was also significantly more precise than, and only marginally within the 1 σ error bar of, the *Hipparcos* value ($d = 101^{+40}_{-22}$ pc). As already discussed by Bertout et al. (1999), one must exercise caution when using *Hipparcos* parallaxes for faint individual PMS stars. In particular, while *Hipparcos* suggested that the southern part of the Taurus complex might be somewhat farther than its central regions (170 pc vs. 125 pc; Bertout et al. 1999), we find T Tau (which is part of Taurus South) and V773 Tau (which belongs to the central parts of Taurus) to be at very similar distance. Indeed, the two VLBI measurements are consistent with the entire Taurus complex lying at 145 ± 4 pc.

To decide if the magnetically active PMS star responsible for the compact radio source detected here can be identified with the infrared source T Tau Sb (as is usually believed) and if the VLA observations can be used to trace its motion, one would ideally like to compare the absolute positions of the infrared, VLA, and VLBA sources at a common time. The fit presented above can provide accurate estimates of the absolute position of the VLBA source at any time during or within a few years of our observing time span. Unfortunately, this cannot easily be compared with the infrared and VLA positions, because the infrared data lack accurate absolute astrometry information, while the VLA and VLBA reference frames may not match perfectly in spite of being both based on distant quasars. The latter effect is a consequence of the differing *u*-*v* plane coverages of the VLA and the VLBA, which will tend to make them sensitive to different components of even the same quasar. Consequently, it is preferable to compare the motions of the sources rather than their positions; if two sources share the same proper motion, it is very unlikely that they are different objects.

The proper motion of the VLA source was measured over a time span similar to that covered by our VLBA observations using the two most recent 2 cm images available to us: the 2001 January 19 observation reported in Loinard et al. (2003) and Johnston et al. (2003) and a more recent (still unpublished) image we obtained on 2003 August 19. The latter was processed following the exact same procedure as that used in Loinard et al. (2003). The phase-referencing quasar was 0403+260 ($\alpha_{\rm J2000.0} = 04^{\rm h}03^{\rm m}05^{\rm s}.5860$, $\delta_{\rm J2000.0} = +26^\circ 00' 01''.502$) for both observations. The calibrated visibilities were restored using pixels of 0″.02 and weights intermediate between uniform and natural. The VLA source positions (Table 2) were determined from two-dimensional Gaussian fits and were corrected for parallactic motions. They yield proper motions of

$$\mu_\alpha \cos\delta = 3.94 \pm 0.50 \text{ mas yr}^{-1},$$

$$\mu_\delta = 0.46 \pm 0.47 \text{ mas yr}^{-1},$$

very similar to those found for the VLBA source. The differences (<2 mas yr^{-1}) are at least an order of magnitude smaller

[3] At least one more year of observations will be needed before acceleration terms can be measured reliably.

TABLE 2
VLA SOURCE POSITIONS

Epoch	α_{2000} ($04^{\rm h}21^{\rm m}$)	δ_{2000} ($19^\circ 32'$)
2001.052 ……	$59^{\rm s}.42502 \pm 0^{\rm s}.00007$	$05''.7179 \pm 0''.0009$
2003.636 ……	$59^{\rm s}.42574 \pm 0^{\rm s}.00006$	$05''.7191 \pm 0''.0008$

than the values required to reconcile the VLA observations with the orbital fits proposed by Johnston et al. (2004a). Instead, it appears that the VLA and the VLBA observations trace the trajectory of the same magnetically active star.

Because of the lack of absolute astrometry information for the infrared observations, the proper motions required to compare the radio and infrared data must be measured relatively to a third source. Here, we shall register all motions on T Tau N, which is seen at both radio and infrared wavelengths and has a well-determined linear proper motion (e.g., Loinard et al. 2003). For the radio source, we obtain a relative motion between T Tau S and T Tau N of

$$\mu_\alpha \cos\delta = -8.3 \pm 0.8 \quad \text{or} \quad -8.9 \pm 0.7 \text{ mas yr}^{-1};$$
$$\mu_\delta = +13.2 \pm 0.8 \quad \text{or} \quad +12.0 \pm 0.7 \text{ mas yr}^{-1},$$

depending on whether the VLA or the VLBA data are used. Using the infrared data in G. Duchêne et al. (2005, in preparation), we can also estimate the relative motion between the infrared source T Tau Sb and T Tau N during a time span (2001 November–2003 December) similar to that covered by the radio observations. We obtain

$$\mu_\alpha \cos\delta = -10.4 \pm 3.5 \text{ mas yr}^{-1},$$
$$\mu_\delta = 12.4 \pm 3.5 \text{ mas yr}^{-1}.$$

The excellent agreement between the infrared and the radio proper motions confirms that the magnetically active PMS star generating the compact radio emission is T Tau Sb and that the radio data (from both VLA and VLBA) can be used to trace its trajectory.

5. CONCLUSIONS AND PERSPECTIVES

The VLBA data presented here have allowed us to make a detailed study of the structure and astrometry of the compact radio source associated with T Tau S. The emission is found to be composed of a compact core most certainly originating from a stellar magnetosphere and a low brightness extension that may result from reconnection flares at the star-disk interface. The accuracy of the absolute astrometry offered by the VLBA has made it possible for us to demonstrate that the infrared, the VLA, and the VLBA observations all trace the same underlying star (T Tau Sb). This implies, in particular, that any orbital fit to the T Tau system must be able to reproduce the positions measured by the VLA in the last 20 years. Finally, the VLBA data have allowed us to measure the distance to T Tau with unprecedented accuracy: $d = 141.5^{+2.8}_{-2.7}$ pc. This is in good agreement with the traditionally accepted value for Taurus ($d = 140 \pm 10$ pc; Kenyon et al. 1994) and seemingly rules out the possibility of large distance gradients across Taurus.

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