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NEAR-INFRARED, ADAPTIVE OPTICS OBSERVATIONS OF THE T TAURI MULTIPLE-STAR SYSTEM

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ABSTRACT

With high angular resolution, near-infrared observations of the young stellar object T Tauri at the end of 2002, we show that, contrary to previous reports, none of the three infrared components of T Tau seem to coincide with the compact radio source that has apparently been ejected recently from the system (Loinard, Rodríguez, & Rodríguez). The compact radio source and the infrared object it has previously been identified with, T Tau Sb, have distinct paths that departed from orbital or uniform motion between 1997 and 2000, perhaps indicating that their interaction led to the ejection of the radio source. The path that T Tau Sb took between 1997 and 2003 may indicate that this star is still bound to the presumably more massive southern component, T Tau Sa. The radio source (if indeed distinct from T Tau Sb) is absent from our near-infrared images and must therefore be fainter than $K = 10.2$ (if located within 100 mas of T Tau Sb, as the radio data would imply), still consistent with an identity as a low-mass star or substellar object.

Subject headings: astrometry — binaries: close — infrared: stars — instrumentation: adaptive optics — stars: individual (T Tauri) — stars: pre–main-sequence

1. INTRODUCTION

Stars frequently form in small, gravitationally bound groups of three or more (Ghez, Neugebauer, & Matthews 1993; Mathieu 1994), usually situated so that each perturbs the motion of the others significantly. In such systems the stellar orbits develop chaotically. Over time, gravitational interactions among the members and with the residue of the disks from which they formed result in large orbital changes and even escape, especially for the lighter components (see, e.g., Marchal 1990). As main-sequence stars are always seen in configurations that are quite different from those of young multiple stars, direct observation of orbital evolution in young multiple-star systems has long been sought.

Thus, the report by Loinard, Rodríguez, & Rodríguez (2003) was greeted with wide interest: one of the components of T Tauri has, in the last few years, undergone a dramatic change in orbital velocity, possibly resulting in ejection from the system. T Tau has long been the archetype of young solar-analog stars and, more recently, has become an archetype of young multiple-star systems. Since the discovery two decades ago that T Tau is not single but has a companion 0$''$.7 to the south (Dyck, Simon, & Zuckerman 1982), high-resolution infrared observations using speckle interferometry or adaptive optics (AO) have been used to resolve the system into three stars and to measure accurately the motions arising from their orbits: the visible, classic T Tau N and two heavily extinguished companions, T Tau Sa and T Tau Sb, separated by about 0$''$.1 (Koresko 2000; Köhler, Kasper, & Herbst 2000; Duchêne, Ghez, & McCabe 2002). Meanwhile, radio astronomers used the Very Large Array (VLA) at 2 cm wavelength to resolve the system also into two compact components, one coincident with T Tau N and a brighter one close to T Tau S (Schwartz, Simon, & Campbell 1986). The southern radio component exhibited motion that until recently was consistent with orbital motion around T Tau Sa (which does not appear in the radio images) and has been identified with T Tau Sb (Johnston et al. 2003; Loinard et al. 2003; Smith et al. 2003). The radio source is unresolved in VLBI images (diameter <0.5 mas; Smith et al. 2003), variable in brightness, and exhibits strong and variable polarization in its radio emission (Smith et al. 2003; Johnston et al. 2003). This is the object that has apparently been ejected.

Here we present new near-infrared observations which we use to show that the southern radio component is very unlikely to be the same as the star T Tau Sb. We suggest that T Tau has been a quadruple stellar system, with the lowest mass member probably ejected during the past few years.

2. OBSERVATIONS

We observed T Tau under good observing conditions on 2002 December 24 with the Palomar Observatory Hale 200 inch (5 m) telescope, the Palomar Adaptive Optics (PALAO) high-order image-correction system (Troy et al. 2000), and the Palomar High Angular Resolution Observer (PHARO) near-infrared camera/spectrometer (Hayward et al. 2001). The brightest visible component of the system, T Tau N ($V = 9.6$), served as the phase reference for the AO system. We also observed SAO 76481 as the flux calibrator and point-spread function (PSF) standard immediately after taking our images of the T Tau system. We chose the image scale to be 25 mas pixel^{-1}.

In order to calibrate the plate scale and orientation of the array, we used our observations of the multiple systems RW Aur (two components) and UX Tau (four components) and compared the measured separations and position angles with the corresponding measurements in White & Ghez (2001). We chose multiple systems whose components have separations wide enough that orbital motion should be negligible in the time period between the observations by White & Ghez (2001) (1996–1997) and ours (2002.98). The plate scale of our images comes out to 24.7 ± 0.4 mas pixel^{-1}, and the orientation of the detector array is such that north is up and east is to the left with $\pm 1°$ accuracy. Thus, position angles inferred from our data have an uncertainty $\pm 1°$.

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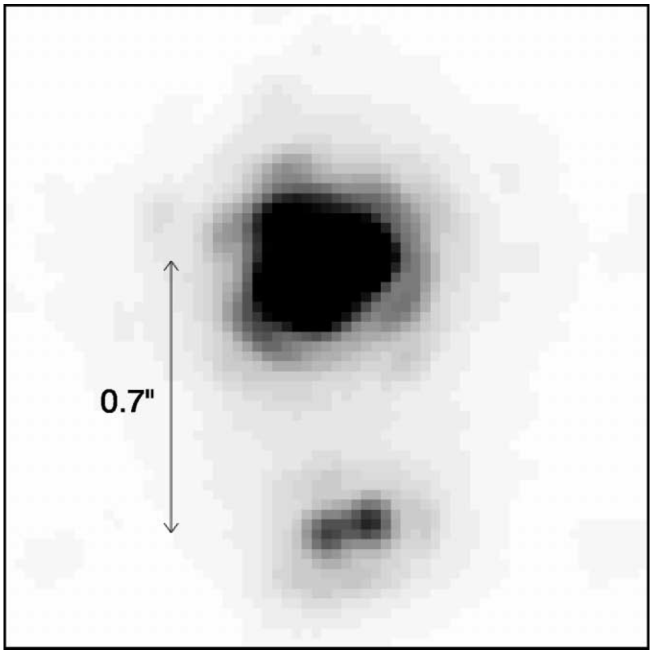

FIG. 1.—Narrowband 2.26 μm ($\Delta\lambda = 0.06$ μm) image of the T Tau system, on 2002 December 24: T Tau N (*top*), T Tau Sa (*bottom left*), and T Tau Sb (*bottom right*). The image is presented in the normal orientation (north up, east left) at a scale of 25 mas pixel^{-1}, and point sources are 102 mas in diameter (FWHM). Diffraction rings surround each of the objects; the brightest ring has a radius of about 150 mas. See Table 1 for a list of coordinates and magnitudes.

Figure 1 is the image of T Tau that we took in a narrowband filter ($\Delta\lambda = 0.06$ μm) in the infrared *K* band centered at 2.26 μm. (The components of T Tau are bright enough at near-infrared wavelengths that the use of the usual broadband filters is inconvenient, as will be seen below). A total of 20 frames, each with an exposure time of 1.8 s, were added to create this image. The resulting PSF is close to diffraction-limited, 102 mas in diameter (FWHM). The limiting 2.26 μm magnitude for parts of the image well separated from the brighter stars is 14.7 (5 σ pixel^{-1}). Within 200 mas (two PSF widths) of the stars T Tau Sa and Sb, diffraction rings reduce the limiting magnitude to a range from 10.2 to 11.2. All three of the previously identified stellar components of T Tau appear in Figure 1, well resolved from one another. Table 1 is a list of their positions and magnitudes. T Tau Sb lies 0.″107, at a position angle of 289°, from T Tau Sa, and the magnitudes of the two southern components are about the same, with T Tau Sb brighter by a factor of 1.05. Since in late 2000 the corresponding separation and position angle amounted to 0.″092 and 267°, respectively (Duchêne et al. 2002), we probably see orbital motion of T Tau Sb around Sa (see also Fig. 3 below).

The positions and fluxes of the three observed infrared components of the T Tau system were determined by applying a PSF fit to the data. Standard IDL procedures were used to perform a Gaussian fit to the given PSF, the one of SAO 76481, and to apply it to the target stars. The position uncertainty resulting from this method is estimated to be 0.2 pixels, which corresponds to 5 mas. The flux calibration was carried out by using the Two Micron All Sky Survey (2MASS) *K*-band flux density of SAO 76481; we estimate the uncertainty of the absolute photometry to be ±20%, and that of the relative photometry to be a few percent.

TABLE 1
EPOCH 2002.98 OFFSETS AND MAGNITUDES

Star	$\Delta\alpha$ (mas)	$\Delta\delta$ (mas)	*m* (2.26 μm)
T Tau N	+20 ± 13	+691 ± 12	5.6
T Tau Sa	0	0	8.2
T Tau Sb	−103 ± 5	+33 ± 5	8.2

Figure 2 is our K_S image ($\lambda = 2.145$ μm, $\Delta\lambda = 0.31$ μm) of T Tau Sa and Sb, taken 5 minutes before our narrowband *K* data. It is also a sum of 20 frames of 1.8 s exposure time each. Since T Tau N and our calibrator, SAO 76481, saturated even with this short integration time, we used the image of SAO 76481 observed with the 2.26 μm filter to perform PSF fitting on this image. The position difference between Sa and Sb is nearly the same in this image and the one taken in the 2.26 μm filter; the offsets listed in Table 1 are averages of the two. No absolute flux calibration was possible, but relative photometry was: T Tau Sb is brighter than T Tau Sa by the factor of 1.36, somewhat higher than we obtained with the narrowband data. In another image taken about 30 minutes later with the K_S filter and an occulting mask over T Tau N, the flux ratio of T Tau Sa and Sb was the same as in the previous K_S image. The difference between this result and the flux ratio seen in the narrowband *K* filter (Sb/Sa = 1.05) could be the result of differences in spectral features and the degree of extinction between the two components.

Comparing our narrowband *K* data with the results from late 2000 by Duchêne et al. (2002), T Tau Sa is fainter and T Tau Sb is brighter, each by about a magnitude at *K*. That T Tau Sb can be as bright as T Tau Sa in the *K* band means that the orbital motion of T Tau Sa relative to T Tau N is confused in all pre-1997 measurements because of the presence of T Tau Sb. Nevertheless, our position for T Tau Sa follows the trend of measurements since 1989 for the motion of T Tau S (Ghez et al. 1995; Roddier et al. 2000; Duchêne et al. 2002): a roughly constant separation from T Tau N and a roughly linearly increasing position angle. A range of position-angle derivatives of about 0.°2–0.°7 yr^{-1} would be consistent with the observations. Our data indicate that a slight adjustment to the relative registration between T Tau Sa and the southern radio source might be necessary once new radio data become available.

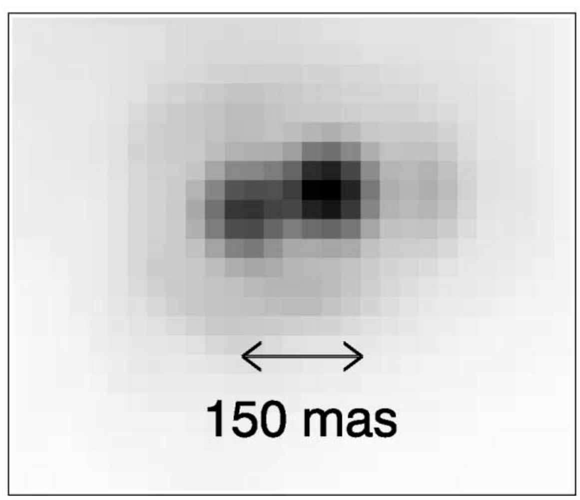

FIG. 2.—The 2.145 μm (K_S) image of T Tau Sa (*left*) and Sb (*right*), on 2002 December 24. The orientation and pixel scale are the same as in Fig. 1.

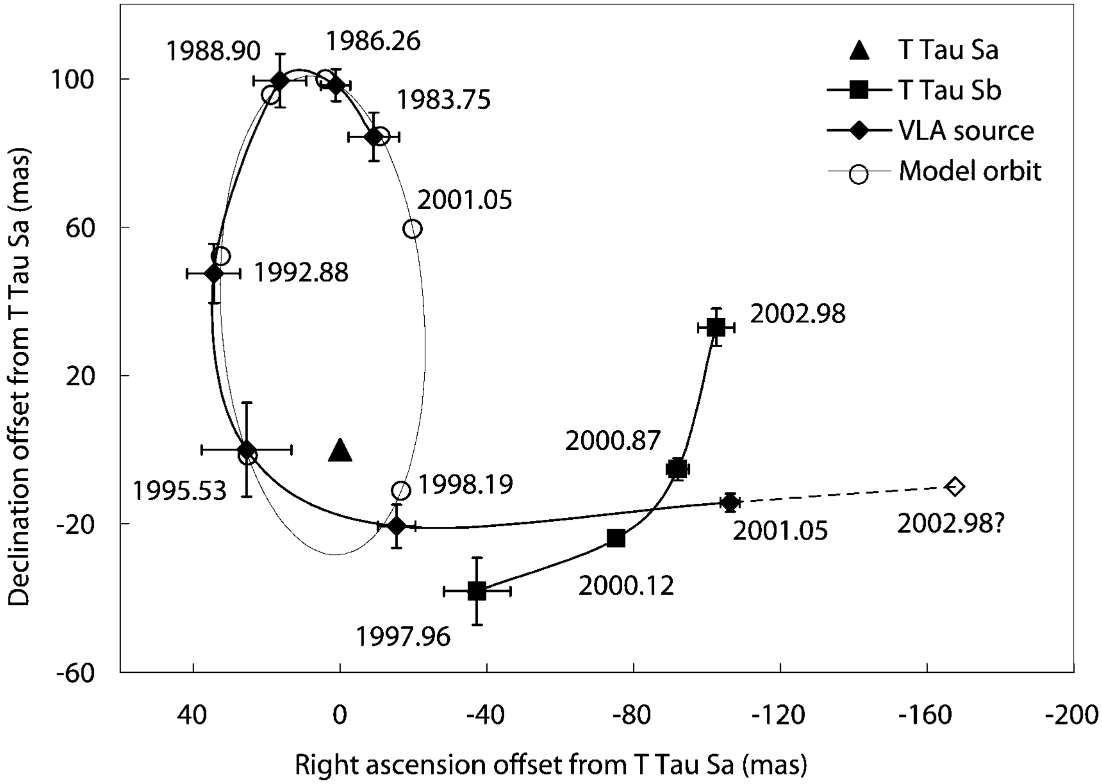

FIG. 3.—Positions of the compact radio source T Tau Sc (*filled diamonds*) and the infrared star T Tau Sb (*filled squares*), in the rest frame of T Tau Sa (*filled triangle*), labeled by epoch. The positions for T Tau Sc are those reported for the radio source by Loinard et al. (2003), shifted east by 4.5 mas for reasons discussed in the text. A model orbit, also discussed in the text, appears as a thin, solid curve, with the points corresponding to the VLA radio observation epochs appearing as open circles. The positions of T Tau Sb come from Koresko (2000), Köhler et al. (2000), Duchêne et al. (2002), and the present work (south to north). Solid curves connecting the observations of T Tau Sc and of T Tau Sb are included only to guide the eye. A hypothetical epoch 2002.98 position for T Tau Sc, extrapolated linearly from the two most recent VLA observations, is plotted as an open diamond.

In the following, we will adopt the rates -3.4 mas yr^{-1} and 0°.3 yr^{-1} suggested by Loinard et al. (2003) for the changing separation and position angle of T Tau Sa with respect to T Tau N. Since this object moves more slowly than the other components of T Tau S, our conclusions do not depend critically on this choice.

3. ANALYSIS AND CONCLUSIONS

Figure 3 is a plot of the radio and infrared positions of the southern components of T Tau between 1983 and 2003, in a frame of reference in which T Tau Sa is at rest. The radio positions in this plot differ very slightly from those determined by Loinard et al. (2003). They are based on the radio/infrared registration of T Tau N and include the estimated orbital motion of T Tau Sa with respect to T Tau N as discussed above; the uncertainty in the distance between origins of the radio and infrared reference frames is about 15 mas (radial, rms). The relative positions of T Tau Sa and Sb were measured directly in the infrared images. Our new position for T Tau Sb is quite inconsistent with anything along the track of the radio source between 1998 and 2001: it misses by 50–100 mas. For example, the linear extrapolation of the two most recent radio-source positions, the point indicated by an open diamond in Figure 3, lies 78 mas from the 2002.98 observed position of the infrared star T Tau Sb. We achieved similar results when the positions were registered on T Tau N and thus did not require a correction for the orbital motion of T Tau Sa around the northern component. If a single object were to have followed the path described by both the radio positions of T Tau S and the infrared positions of T Tau Sb, its velocity in the plane of the sky would have had to undergo major changes at least twice, once between 1995 and 1998, and once after 2001. Moreover, in at least one of the cases, the single object would have had no obvious partner with which to interact. Thus, the radio and infrared observations of the southern components of T Tau very likely detect different objects. In anticipation of its detection in future infrared observations, we will refer to the radio source as T Tau Sc henceforth.

Also appearing in Figure 3 is a model orbit, resulting from a minimum-χ^2 fit to the projected trajectory and transverse velocities of T Tau Sc measured at the VLA between 1983 and 1996 (Loinard et al. 2003; Johnston et al. 2003). In this exercise, we assumed T Tau Sa to be at one focus of the orbit. The fit to both trajectory and velocity improved after shifting all the VLA positions of T Tau Sc with respect to T Tau Sa by 4.5 mas to the east; this shift, small compared with the overall positional uncertainties, is present in the positions plotted in Figure 3. The agreement between model and observations is excellent. The parameters of the model orbit are as follows: period = 19.1 yr, semimajor axis = 9.1 AU, assuming a distance of 140 pc (leading to a total mass of 2.1 $M_\odot$ for T Tau Sa and T Tau Sc), axis inclination = 59° from the line of sight, eccentricity = 0.57, argument of periastron = 168°.5, position angle = 1°.5 for the line of nodes, and periastron epoch

1997.39. T Tau Sb is a young M1 $\pm$ 1 star (Duchêne et al. 2002), for which the mass is much smaller than 2.1 $M_\odot$; thus, we have neglected it in this model.

What is the nature of T Tau Sc? Its small size and large (kilogauss) magnetic field, indicated by the VLBI observations (Smith et al. 2003), are consistent with a starlike object. We did not detect any other object besides T Tau N, Sa, and Sb in our near-infrared images. At the position extrapolated for T Tau Sc at epoch 2002.98 (see Fig. 3), our upper limit for the detection of a point source is about 10.2 mag at 2.26 μm; T Tau Sc would be even fainter if it were farther from the infrared sources. Thus it is either lighter than the eighth-magnitude T Tau Sb or more heavily extinguished, or both. The velocities of T Tau Sb and Sc within the T Tau system are larger than those of T Tau Sa, which, if they have been gravitationally bound, indicates that both objects are less massive than T Tau Sa. Therefore T Tau Sc is probably an ordinary young star or a brown dwarf, similar in mass or lighter than T Tau Sb, although quite different from this star in its magnetic field strength.

The presence of two distinct objects, T Tau Sb and the radio source T Tau Sc, could provide a natural explanation for changes in each other's state of motion. As Loinard et al. (2003) point out, the path of T Tau Sc obeys Kepler's second law for an orbit around T Tau Sa from discovery through 1995 but departs strongly thereafter. The path of the infrared star T Tau Sb with respect to Sa shows a wide variation in area per unit time; between 2000 February and November, the rate of area swept out is about a factor of 2 greater than from late 1997 to early 2000, and about 30% larger than from 2000 November to 2002 December. The curvature and orientation of this path probably indicate that T Tau Sb has been, and is still, bound to T Tau Sa, but longer term observations will be necessary to demonstrate this. In any case, both T Tau Sb and Sc experienced large orbital-motion changes in the 1998–2001 period, when they were closest together in projection. We suggest that their gravitational interaction at this time has resulted in these orbit changes.[5] This would amend the suggestion by Loinard et al. (2003) that T Tau Sa has a close companion (separation <2 AU) whose interaction with the radio source T Tau Sc (which they identify as T Tau Sb) has resulted in the ejection of the latter; instead, we suggest that T Tau Sb is a somewhat more distant companion that has probably caused the ejection of T Tau Sc, which would be a fourth stellar or substellar member in the T Tau system.

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[5] If 20 years is a typical orbital period over the history of the T Tau S system, then there have been on the order of 10^5 revolutions since formation, during which there could have been only a few encounters that resulted in large orbital changes. It would seem that astronomers have been extremely fortunate to witness this event.

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ERRATUM: "NEAR-INFRARED, ADAPTIVE OPTICS OBSERVATIONS OF THE T TAURI MULTIPLE-STAR SYSTEM" (ApJ, 596, L87 [2003])

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The value of one model orbital parameter was reported incorrectly in the original Letter. The argument of periastron of the radio source T Tau Sc, equal to 191°.5 in our model, appeared in the article as 168°.5. This error does not change any of the other parameters or data in the Letter nor does it change the conclusions we reach.

We are grateful to V. Tamazian, whose questions led us to the discovery of this error.