A NEW OPTICAL SOURCE ASSOCIATED WITH T TAURI

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ABSTRACT

A faint optical source close to T Tauri has been detected using speckle imaging techniques in a photon-counting mode of operation. This second optical source is located at position angle $358^{\circ} \pm 5^{\circ}$ with a separation of 0''.27 \pm 0''.04 from the optical astrometric position of T Tauri. The visual magnitude difference with respect to the primary, measured at 521 nm, is $m_v = 4.33 \pm 0.09$. Speckle imaging techniques have produced true images which eliminate the 180° ambiguity normally associated with speckle interferometry, allowing the correct position of the source to be determined. Since the new source is located north of T Tauri, it is distinct from the radio/infrared object recently reported to be located 0''.61 south of T Tauri. As expected from the predicted temperature of the southern component, the optical speckle observations did not detect the infrared source. If the new source is a stellar object, it appears to have a mass of between 0.2 and 0.35 M_{\odot} and has a surface temperature of 3000 \pm 200 K corresponding to spectral types M4–M8. This would be one of the lowest mass pre-main-sequence stars yet detected.

Subject headings: interferometry - stars: individual - stars: pre-main-sequence

I. INTRODUCTION

T Tauri is the well-known prototype for a class of emission-line variable stars associated with dark cloud complexes. As discussed by Rydgren, Strom, and Strom (1976), the properties defining the class are (1) irregular optical variability; (2) the presence of emission lines, both permitted and forbidden; (3) "veiling" of the spectrum by overlying continuous emission; (4) broad absorption lines suggesting rapid rotation; (5) P Cygni and inverse P Cygni emission-line profiles; and (6) infrared excesses. These objects are recognized as pre-main-sequence stars which have only recently formed from the dense cloud complexes with which they are associated.

T Tauri [$\alpha(1900) = 4^{h}16^{m}09^{s}, \delta(1900) = +19^{\circ}17'54''$] has a K0 or K1 spectrum with an unusual history of variability: it is reported to have fluctuated irregularly between $m_{p} = +10$ and +14 until 1910, and has remained between +10 and +11 since that time (Lozinskii 1949). The star is located in the Taurus-Auriga cloud complex inside an emission nebula 20"-30" across which has the spectrum of a Herbig-Haro object (Schwartz 1975). Recent observations of T Tauri have found an infrared (Dyck, Simon, and Zuckerman 1982) and radio (Schwartz, Simon, and Howell 1984) source located 0"61 south of the optical position of T Tauri. It is fainter than T Tauri itself at all infrared wavelengths measured and has an estimated temperature of 800 K. However, at radio wavelengths from 1.3 to 20 cm it is much the stronger source. It has a spectral index of $\alpha < 0.7$ suggesting that the 6 cm flux is thermal emission from a warm, constant expansion velocity stellar wind (Schwartz, Simon, and Howell 1984). Emission at 6 cm is also seen at the optical astrometric position of T Tau. The faint infrared and bright radio sources south of T Tau are now assumed to coincide, despite some early confusion due to

the 180° ambiguity in the infrared speckle interferometry data.

This *Letter* reports the discovery of a third component in the T Tauri system, a faint optical source located 0".27 north of the bright optical component. This source was discovered by using a new two-dimensional photon counting camera (Papaliolios, Nisenson, and Ebstein 1985) and the techniques of speckle imaging. Speckle imaging allows recovery of both the amplitude and phase in the Fourier transform of the recovered image so that a true image may be reconstructed. This image unambiguously demonstrates that the source is located to the north, on the opposite side of T Tau from the radio source.

II. OBSERVATIONS

Speckle observations of T Tauri at optical wavelengths were carried out on 1983 November 15 and 16 with the Steward Observatory 2.2 m telescope and on 1984 October 21 with the Mount Wilson observatory 2.5 m telescope. Both sets of observations were made using the Precision Analog Photon Address (PAPA) detector (Papaliolios, Nisenson, and Ebstein 1985), a two-dimensional photon counting sensor which records a catalog of sequential photon positions. This version of the PAPA has a maximum data recording rate of 100,000 photons s^{-1} in a field of 256×256 pixels. The photon addresses are encoded on a video carrier and stored using a conventional VCR for later digital processing. Speckle data recording uses a foreoptics package which provides (1) magnification of the image so that the diffraction-limited scale of the telescope is matched to the pixel size of the camera, (2) narrow-band filtering which yields temporal coherence sufficient for the optical path errors introduced by the atmospheric

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aberrations, and (3) atmospheric dispersion correction with a prism compensator. An optics package developed by K. Hege of the Steward Observatory, University of Arizona was used for the run of the 2.2 m, and an equivalent system built at CfA was used for the Mount Wilson observations. The Steward observations were made with a 24 nm wide filter centered at 659 nm. At Mount Wilson, three different filters were used: a 74 nm wide filter centered at 673 nm, a 36 nm filter centered at 521 nm, and a 50 nm filter centered at 450 nm. Count rates ranged from 6000 photons s⁻¹ in the red to 500 photons s⁻¹ in the blue.

III. DATA PROCESSING

Digital processing of the recorded data involves conversion of the VCR format to standard digital tape storage using a buffered interface. The photon addresses are then divided into subsets with lengths matched to the characteristic correlation time of the atmosphere. This approach allows regrouping of the data for maximization of the signal-to-noise ratio in the integrated result. Typical correlation times range from a few to tens of milliseconds. Individual images are built from the photon list by incrementing the array position corresponding to a photon address. The Fourier transform for each image is calculated and accumulated into the complex correlation arrays required for speckle reconstruction (Nisenson and Papaliolios 1983). Compensation for the atmospheric and telescope transfer function is accomplished by the use of the data taken for an unresolved reference star, which is recorded close in time to the object data. This star is chosen to be as close in angular position to the object as possible so that the long-term atmospheric statistics are similar. Deconvolution by the reference star results in enhancement of the high angular frequencies in the reconstruction.

Until recently, compensation for the effects of photon noise on the reconstructed images has been difficult and inaccurate. However, the form in which the data is available from the PAPA detector, in which each photon's centroid and the total count is exactly known, allows precise compensation for the photon noise bias (Nisenson and Papaliolios 1983).

IV. RESULTS AND ANALYSIS

Processing of the data from the Steward 1983 November observing run revealed a previously undetected companion source to T Tauri in the visible. Low-contrast fringes in the power spectrum indicated the existence of a second source located in a north-south direction. An autocorrelation and an image were then reconstructed from the data set, and these revealed that the second source was located 0".27 \pm 0".04 from the primary source, at a position angle of 358° \pm 5°. Figure 1 (Plate L1) shows the recovered power spectrum, autocorrelation, and image from the T Tauri data. For comparison, the results from processing data for a binary star, SAO 93840, are shown. This data set was recorded a few minutes after the T Tauri observation, and this star was not known to be a binary until after processing. This binary has a separation of 0".38, a

TABLE 1 Measured Magnitude Differences

Filter Width (nm)	Filter Center (nm)	Magnitude Difference	Telescope
		·	F
74	673	3.53 ± 0.04	Mount Wilson 2.5 m
24	659	3.62 ± 0.05	Steward 2.2 m
36	521	4.33 ± 0.09	Mount Wilson 2.5 m
50	450	5.3 ± 0.2	Mount Wilson 2.5 m

NOTE.—Average separation (ρ) and position angle (θ) from four measurements: $\rho = 0.27 \pm 0.04$; $\theta = 358^{\circ} \pm 5^{\circ}$.

position angle of 10°, and the two stars are 8th and 9th mag, respectively. The apparent size of the star images in these figures is related to their relative brightnesses and not their angular size.

A key finding, resulting from the image reconstruction, was that the new source is located north of the astrometric position for T Tauri, distinct from the southern infrared and radio source. A second set of observations from the Mount Wilson 2.5 m run in 1984 October confirmed the existence of the northern source and allowed determination of some of its physical characteristics. Table 1 summarizes the results from the different observations.

The angular resolution obtained from these data sets is better than 0.10, and the companion is unresolved at this scale. The brightness of the companion is too great relative to T Tauri to be explained either by reflection from a nearby cloud or by production from a jet; however, these possibilities cannot be completely ruled out without additional observations. We believe it more likely that the second source is a stellar companion.

The bolometric corrections for main-sequence stars are not generally applicable to pre-main-sequence stars without including, for example, the star's infrared excess. The bolometric luminosity of the northern companion may not be directly derived using only its visual magnitude difference from the primary. However, from the measured magnitude differences as a function of color, a probable spectral class for the companion was determined. Spectral classification from the data is not trivial since (1) the strong H α emission is included in the bandpass of the filters for two of the data sets, and (2) the difference in extinction between the two components is unknown. For our calculations, the assumptions were that both stars had the same extinction, and, to first approximation, both stars could be represented as blackbodies. The color temperature of T Tauri has been estimated by Cohen and Kuhi (1979) to be 5000 K (K0-K1 spectral class). The measured magnitude differences yield a temperature for the companion of 3000 + 200 K. The range of temperature reflects the accuracy of the magnitude difference estimates and corresponds to spectral types from M4 to M8. With this determination of spectral type, some of the physical characteristics of the companion may be derived, using the convective-radiative



FIG. 1.—(a) Power spectrum, (b) autocorrelation, and (c) image reconstruction for T Tauri from data recorded on the Steward Observatory 2.25 m telescope in 1983 November. Due to the large magnitude difference between T Tauri (north) and T Tauri (astrometric), the near-horizontal fringes in the power spectrum are very low contrast, and the primary source is heavily overexposed in the image and autocorrelation. For comparison, the (d) power spectrum, (e) autocorrelation, and (f) image of the 8th and 9th mag binary SAO 93840 are shown (data recorded on the same observing run).

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FIG. 2.—Evolutionary diagram for pre-main-sequence stars (from Cohen and Kuhi 1976) with T Tauri (north) and T Tauri (astrometric) plotted on it. Error bars introduce a possible range of temperatures and indicate the corresponding range of bolometric luminosities.

evolutionary tracks given by Cohen and Kuhi (1979) for pre-main-sequence stars.

Figure 2 is the evolutionary diagram from Cohen and Kuhi (1979) with T Tauri and its companion plotted on it, assuming coeval formation of the two sources (isochrone between 3×10^5 and 10^6 yr). The error bars show the range of temperatures and the corresponding range of bolometric luminosities. The bolometric luminosity of the companion is between 0.3 and 0.5 L_{\odot} . The mass and radius of the companion may be extrapolated as $0.2-0.35 M_{\odot}$ and $2.5 R_{\odot}$, respectively. If this estimate is correct, this would be one of the least massive pre-main-sequence stars yet detected.

V. DISCUSSION

The discovery of this new source in the T Tauri system raises as many questions as it answers. If both this source and the southern source are stellar companions to T Tauri, the geometry of the system is unexpected; dynamics of triple systems do not allow stable orbital spacings closer than about 5:1. Therefore, the near equal spacing of this system would have to be a projection effect, or the system would have to be young enough not to have reached dynamic equilibrium. The near alignment of the three sources is also surprising. Further observations of both the northern and southern sources are clearly needed. Measurement of the spatial distribution of the $H\alpha$ emission is required in order to verify the estimated spectral type of the northern source and to rule out the possibility that its emission is produced by a jet, since the output of a jet in the red is almost entirely in H α (Mundt and Fried 1983). The two observations made with filters that include the H α line at 659 and 673 nm yield magnitude differences which are identical within the error bars, which is not consistent with the strong H α emission from a jet. The infrared speckle observations reported to date do not have sufficient angular resolution to have detected the northern source. New high angular resolution infrared observations and high-sensitivity radio observations of both the northern and southern sources would be very useful.

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