The Visual Orbit of the $0''.002$ RS CVn Binary Star TZ Triangulum from Near-Infrared Long-Baseline Interferometry

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ABSTRACT

We report new observations of the RS Canum Venaticorum (RS CVn) binary star TZ Triangulum with the Palomar Testbed Interferometer (PTI). The object exhibits fringe visibilities below the measured instrumental visibility, indicating that it is partially resolved at the angular scales detectable by our observations. In most respects, the visibility data are consistent with the predictions of previous photometric and spectroscopic measurements. Comparison with a simple binary-star model reveals clear evidence of orbital motion with the expected period and phase. The evolved primary star is resolved, and its size is found to be close to that derived by Hall (1990). The relative brightness of the secondary star appears to be somewhat smaller than expected at the 2.2 μm wavelength of the new observations. We conclude that the interferometric observations, which represent a new and nearly independent test of the models for this binary star, essentially confirm the spectroscopic results.

Subject headings: stars: individual (TZ Triangulum) — techniques: interferometric — binaries: close

1. Introduction

The RS Canum Venaticorum (RS CVn) stars are a large class of close binaries which exhibit strong spectral line and X-ray emission activity. This activity is generally attributed to hot ($10^{6-7.5}$ K) coronae which are produced by strong stellar dynamos resulting from tidal spin-up of the stellar rotation. The stars themselves are typically of late spectral type, with the active component or components having evolved beyond the main sequence. The total mass of an RS CVn system is typically 2-5 $M_{\odot}$, and the orbital periods range from a few days to a few tens of days in most systems.

RS CVn binaries generally have Roche-lobe filling factors smaller than unity (*e.g.*, Welty & Ramsey 1995) and are therefore not expected to undergo rapid mass exchange. This interpretation is supported by the observation that in RS CVn systems, unlike the typically semidetached Algol binaries, the more evolved component generally has the larger mass. On the other hand, a few RS CVn systems do have components that fill their Roche lobes, and a few of the RS CVns whose components are smaller than their Roche lobes also show spectroscopic evidence for ongoing mass transfer. To explain the latter observations, it has been suggested that large eruptions, analogous to solar quiescent prominences, may carry material beyond the Roche lobe of the erupting star (Welty & Ramsey 1995).

The angular separations of even the nearby RS CVn binaries are of the order of milliarcseconds. As a result, observational studies of these systems have been limited to spectroscopy and photometry of the components' combined light. These studies have produced an extensive literature of orbital parameters derived from radial velocity curves and photometric light curves. The latter are especially interesting, as the brightness of the stars varies with the orbital phase even in non-eclipsing systems due to the descriptively-named "ellipticity" and "pointed-end" effects. The Catalog of Chromospherically Active Binary Stars (CABS2; Stassmeier *et al.* 1993) summarizes the data for some 206 RS CVn and similar systems including TZ Triangulum.

The advent of practical long-baseline optical interferometry has made it possible to approach these close binary systems in a fundamentally new way, by directly measuring their visual orbits and the angular sizes of their component stars. Visibility data can serve as a basic "sanity check" on spectroscopically- and photometrically-derived models of these binaries, and point the way toward more extensive studies capable of precisely measuring the full set of basic system parameters.

This *Letter* presents the results of exploratory interferometric observations of the double-lined spectroscopic RS CVn binary TZ Triangulum, made using the Palomar Testbed Interferometer (PTI). The system is clearly resolved, and an orbital solution is derived independently of any spectroscopic results except for the orbital period. It is found that the PTI data are largely consistent with the earlier spectroscopic results, provided that the relative brightness of the warm secondary star is smaller than anticipated in the near-infrared.

2. Observations

The observations were conducted using standard single-beam techniques (Colavita *et al.* 1998) between the nights of 21 August and 20 October 1997 (see Table 1). Briefly, the observations consisted of 35 "scans", during each of which the interferometric fringe was tracked and measured for 125-130 sec. A comparable number of scans on calibrator stars, which were chosen to have predicted angular diameters less than 1 mas, no known companions, and angular distances from the science targets of typically less than 10 deg, were interspersed with the science scans. The scans were taken over a series of nights in order to provide coverage of the orbital phase. The baseline D of the instrument was 110 m and the observing wavelength λ was 2.2 μm, producing a formal angular resolution $\lambda/D = 4.1$ mas.

3. Data Reduction and Model Fitting

The raw visibility data were calibrated using the standard PTI techniques (Colavita *et al.* 1998). The detailed reduction was based on an average of the signals in the instrument's central spectral channels, as these have been found to offer the lowest biases. For each scan, the measurements of the raw squared fringe visibility V^2_{raw} in 25-sec samples were averaged. The uncertainty in the V^2_{raw} value for each scan was estimated from the scatter between the 25-sec samples. Because the ratio correction has been found empirically to introduce significant biases, it was not applied to correct the measurements themselves, but instead was treated as an independent contribution to the uncertainty in each scan. A phase jitter correction was applied to compensate for the visibility loss caused by imperfect tracking of the fringe, and this was found to improve the quality of the fit. The calibrated visibility data are plotted as points in Figure 1.

The system visibility V^2_{sys}, which is the value of V^2_{raw} that would be measured for a pointlike source, was estimated by the weighted average of the V^2_{raw} in the calibrator scans, after correcting for the effects of the finite sizes of the calibrator stars. The weighting function was chosen to give the greatest weight to the calibrator scans taken closest to the time of the science scan. The weighting function also took into account the unequal uncertainties in the V^2 measurements of the individual calibrator scans. Dividing the V^2_{raw} measured for a science scan by the appropriate V^2_{sys} produced the final V^2 measurement for the each science scan.

Because of the very limited coverage of the visibility space provided by this two-element interferometer, it was not possible to construct a true image of TZ Triangulum. Instead, we fit a simple binary-star model to the calibrated V^2 measurements. The chosen model treats the stars as uniform circular disks of angular diameters θ_1 and θ_2, moving in a circular orbit with angular semimajor axis a and period P. The pole of the orbit is inclined by angle i with respect to the line of sight, and the long axis of the projected orbit is oriented along position angle PA, measured east from north. The ratio of the brightness of the secondary to that of the primary is R. The final parameter is $\Delta\phi$, which accounts for the unknown phase of the binary orbit at the time of the first observation. Note that because the visibility phase is not measured, there is a 180-degree ambiguity in the position angle of the binary.

The binary-star model was fit simultaneously to all 35 V^2 measurements for TZ Triangulum. The parameters were adjusted to minimize the overall chi-squared using the POWELL multi-parameter minimization routine (Press *et al.* 1992). The model orbital period was fixed to the spectroscopic value. The best-fit model is plotted for comparison with the data in Figure 1. The uncertainties in the parameters were estimated using a Monte Carlo technique, in which a series of hundreds of sets of simulated data, generated by adding Gaussian noise to the best-fit model, were fit using randomly-chosen starting parameters. These starting parameters were allowed to vary over wide ranges to prevent the fitting procedure from repeatedly converging to a single local minimum. A histogram was computed for each of the resulting fitting parameters, excluding the fits that converged with chi-squared greater than 2 per data point, and the acceptable range for each parameter at the 90% confidence level was derived from the histogram.

4. Results and Interpretation

The companion star in TZ Triangulum was clearly detected in the visibility data, and it was possible to derive values or limits for the binary parameters. The results of the fitting procedure are given in Table 2.

The orbital phase inferred from the PTI data provides a simple cross-check between the new interferometric result and the spectroscopic data in the literature. It implies a time of conjunction which differs by 0.24 days (0.016 orbits) from the time expected for the conjunction of the warmer star for the period and phase listed in Kaye *et al.* (1995). This difference is consistent with the uncertainty in the PTI measurements.

The other model parameters derived from the fit are listed in Table 2. It is worth noting that the large uncertainties in the brightness ratio R and semimajor axis a are slightly misleading. This is because the observations only partially resolve the binary. It can

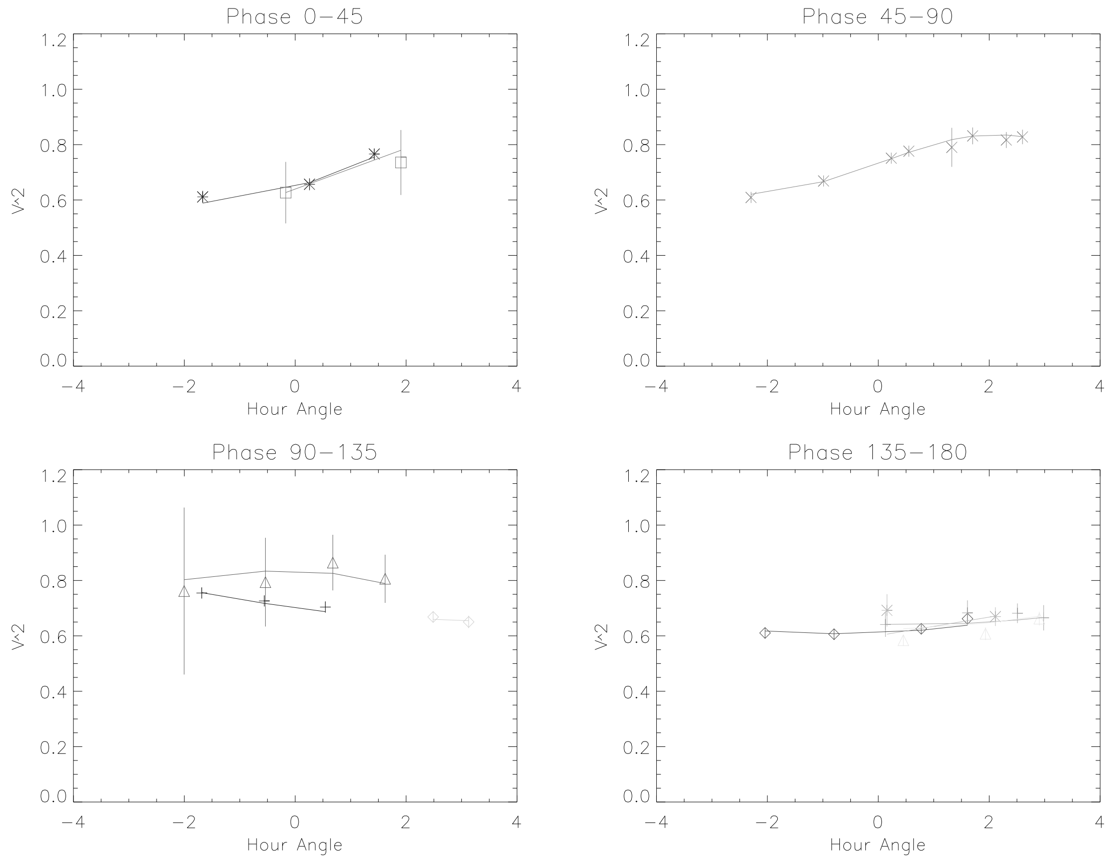

Fig. 1.— The calibrated visibility data for TZ Triangulum are plotted as points. The various symbols refer to the nights on which the data were taken. The points are grouped into four bins of orbital phase, primarily to avoid excessively cluttering the plots. The visibilities change with both the phase of the binary's orbit and with the hour angle, which determines the length and direction of the interferometer's projected baseline vector. The curves represent the best-fit binary-star model.

be shown that in this situation there exists a family of binary models which differ only in R and a such that R approaches unity as a becomes small, and these models produce nearly the same V^2 as a function of the projected interferometer baseline. The data therefore define a one-to-one relationship between R and a, so that if either quantity is known then the other can be constrained substantially better by the V^2 data. This effect is illustrated in rows 3–5 in Table 2, which displays the results for a series of monte-carlo runs in which the assumed brightness ratio was fixed at values between 0.1 and 0.3. For these fits, the angular size θ_2 of the secondary star was fixed at 0.12 mas, as expected for an F5V star (Popper 1980); the results are insensitive to the value of θ_2 because it is so small compared to the resolution of the instrument. The best-fit a decreases with R, and the uncertainty in a is only ~ 0.1 mas for a given value of R.

TZ Triangulum is a double-lined spectroscopic binary. Its brightness ratio in the V band has been estimated by Hall (1990) as $R \sim 0.5$, with the cooler star being brighter. Assuming that the stars have colors appropriate for F5 and K0 III spectral types (CABS2) leads to $R \sim 0.3$ at 2.2 μm. This value is consistent with the visibility data, and would imply that $a = 1.2 \pm .1$ mas. Given a Hipparcos distance of 94 ± 9 pc (ESA 1997) and an orbital period of 14.72946 days (Kaye *et al.* 1995), the 1.3 mas upper limit on a would imply that the total mass of the system is no more than 1.5 $M_\odot$. This is much smaller than the 5.14 $M_\odot$ derived by Hall (1990). It is also smaller than the lower limit derived by assuming that the warmer star is on the main sequence, which would give it a mass of 1.5 $M_\odot$ by itself (Popper 1980); the total mass of the system would be close to 3.0 $M_\odot$ since the radial velocity measurements imply that the masses of the two stars are quite similar.

This mass discrepancy could be relieved if the infrared brightness ratio is significantly smaller than 0.3. The visibility data permit values of R as small as 0.07. $R = 0.1$ would imply $a \sim 2.2$ mas, consistent with the Hall (1990) mass. Such a small value of R might be explained by a change in the luminosity of one or both stars since the epochs of the visible-light measurements, some of which are many decades old. Alternatively, it could in principle be the result of an infrared excess associated with the cooler star, although the evidence for infrared excesses in RS CVn systems is presently ambiguous (Mitrou *et al.* 1996).

The angular radius of the primary star derived from the PTI fits with fixed R is consistent with the 13 $R_\odot$ linear radius derived by Hall (1990).

Table 1. Observations of TZ Triangulum

Night	Calibrator Stars (SAO)	TZ Triangulum Scans
21 Aug 97	55427, 56047	3
1 Sep 97	55427, 56047	3
6 Sep 97	55427, 56047	4
18 Sep 97	56047, 75596	4
23 Sep 97	55427, 56047, 75596, 75391	2
24 Sep 97	55427, 75391, 75596	8
5 Oct 97	55427, 75051	4
6 Oct 97	55427, 75051	2
19 Oct 97	55427, 75391	2
20 Oct 97	56047, 75391	3

Table 2. Model Parameters for TZ Triangulum

Model	R	a (mas)	i (deg)	PA (deg)	$\Delta\phi$ (deg)	θ_1 (mas)	θ_2 (mas)
PTI	$0.2 \pm .1$	$2.1 \pm .9$	58 ± 4	81 ± 5	164 ± 3	$1.1 \pm .7$	1.3 ± 1.3
PTI (fixed θ_2)	$0.14 \pm .06$	$2.1 \pm .8$	58 ± 4	80 ± 5	165 ± 3	$1.7 \pm .7$	0.12
PTI (Fixed R, θ_2)	0.1	$2.2 \pm .2$	58 ± 3	79 ± 7	164 ± 3	$1.2 \pm .1$	0.12
PTI (Fixed R, θ_2)	0.2	$1.5 \pm .1$	56 ± 4	79 ± 6	162 ± 3	$1.3 \pm .1$	0.12
PTI (Fixed R, θ_2)	0.3	$1.2 \pm .1$	56 ± 3	80 ± 5	162 ± 3	$1.3 \pm .1$	0.12
Hall (1990)	~ 0.3	2.2	49	—	—	1.3	—

5. Conclusions

The exploratory interferometric observations presented here have provided an interesting comparison to the results of previous spectroscopic and photometric studies of TZ Triangulum. The results are largely consistent with the previous spectroscopic work, with the exception of the inferred brightness ratio, which implies that the warm secondary star contributes a somewhat smaller fraction of the total 2.2 μm flux than expected from the visible-light data.

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