RADIAL VELOCITY STUDIES OF SOUTHERN CLOSE BINARY STARS. II. SPRING/SUMMER SYSTEMS\textsuperscript{1}

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ABSTRACT

Radial velocity measurements and sine-curve fits to the orbital velocity variations are presented for 14 close binary stars, S Ant, TT Cet, TW Cet, AA Cet, RW Dor, UX Eri, YY Eri, BV Eri, CT Eri, SZ Hor, AD Phe, TY Pup, HI Pup, and TZ Pyx. All are double-lined binaries, and all except the last one are contact binaries. The orbital data must be considered preliminary because of the relatively small number of observations (6–12), a circumstance that is partly compensated by the good definition of the broadening functions used for the radial velocity determinations.

Key words: binaries: close — binaries: eclipsing — stars: variables: other

Online material: machine-readable table

1. INTRODUCTION

This is the second paper of a two-paper series of radial velocity (RV) observations of close binary systems conducted at the European Southern Observatory (ESO) in 1996 and 1998. The first paper (Rucinski & Duerbeck 2006, hereafter Paper I) presented data obtained on four nights in 1998 August for 17 targets, a mixture of contact binaries possibly offering reasonable orbital solutions with a selection of variables suspected to be contact binaries. The current paper is very similar in spirit: it gives RV data and preliminary orbital solutions for 14 similar targets observed on five nights, from 1996 November 28 to December 2, in the later part of the southern sky.

The goals of this paper, similar to those of Paper I, are close to those of the series of RV studies currently conducted at the David Dunlap Observatory (DDO). This series has recently reached, with the 11th paper (Pribulla et al. 2006, in which references to the previous papers and many common details can be found), the round number of 100 well-covered RV orbits. The instrumentation and data analysis techniques are explained in Paper I. The observations were carried out with the ESO La Silla 1.52 m telescope and a Boller & Chivens Cassegrain spectrograph. The broadening functions (BFs) were extracted from the wavelength region of 401.6–499.8 nm. The spectra have a BF resolution of, typically, \( \approx 23–27 \) km s\(^{-1} \) Stellar exposure times ranged between 10 and 20 minutes, depending on brightness; each stellar exposure was followed by a He-Ar spectrum. Spectrum extraction and wavelength calibration were carried out with the ESO MIDAS software system.\textsuperscript{2} As a comparison star template, we used 68 Eri (F5 V), for which a RV of +10.1 km s\(^{-1} \) was adopted (Nordström et al. 2004).

In terms of the presentation, we again stay close to the format of Paper I, the only difference being that the targets are simply discussed in the constellation order in \S 2. We see no obvious cases of pulsating stars in this group of targets; only CU Eri A and CU Eri B do not appear to be close binaries. We describe our results in the context of existing photometric data from the literature and the Hipparcos project. We also use the mean \(( B – V )\) color indexes taken from the Tycho-2 catalog (Høg et al. 2000) and the photometric estimates of the spectral types using the relations published by Bessell (1979). Spectral types are taken uniformly from the five volumes of the Michigan Catalogue of HD Stars (HDH; Houk & Cowley 1975; Houk 1978, 1982; Houk & Smith-Moore 1988; Houk & Swift 1999). Because of the high incidence of companions to contact binary stars (Pribulla & Rucinski 2006), we checked all stars for possible membership in visual systems using the Washington Double Star (WDS) Catalog.\textsuperscript{3}

Figures 1 and 2 present the BFs for all targets at phases selected for best visibility of both components. Figures 3 and 4 show the preliminary RV orbital solutions. The RV data are given in Table 1, while parameters of the orbital solutions are listed in Table 2. For most stars we used the primary eclipse predictions from the Cracow online database (Kreiner et al. 2001; Kreiner 2004).\textsuperscript{4} These predictions can be restored from the observed times of conjunctions \(( T_0 )\) and the observed minus predicted deviations \( O – C\), as given in Table 2.

2. INDIVIDUAL BINARY SYSTEMS

2.1. S Ant

S Ant (HIP 46810, HD 82610), with \( V_{\text{max}} = 6.29 \), is one of the brightest contact binaries (this and the following estimates of \( V_{\text{max}} \) were obtained from the Hipparcos magnitudes [Perryman et al. 1997] applying color-dependent corrections \( H_p – V \)). As its name implies, it is one of the first variable stars recognized as such in the southern hemisphere.

S Ant has been a frequent target of photometric observations, but the only previous spectroscopic observations were by Popper (1956), who saw only one component with \( V_0 = –1.2 \pm 1.0 \) km s\(^{-1} \) and \( K_1 = 92.3 \pm 1.5 \) km s\(^{-1} \). In contrast, we could easily detect the secondary component in the BFs, as shown in Figure 1. The center-of-mass velocity is very different from that observed previously, as are both semiamplitudes \( K_1 \) (Table 2). Russo et al. (1982) encountered some difficulties with producing a contact

\textsuperscript{1} Based on data obtained at the European Southern Observatory.
\textsuperscript{2} See http://www.eso.org/projects/esomidas.
\textsuperscript{3} Available at http://ad.usno.navy.mil/wds/.
\textsuperscript{4} 2006 May version, available at http://www.as.ap.krakow.pl/ephem/.
model for the binary, suggesting possible problems with Popper’s spectroscopic data. They derived the mass ratio $q_{ph} = 0.59 \pm 0.02$, which differs substantially from our $q_{sp} = 0.33 \pm 0.02$. This is not surprising for a partially eclipsing system with a featureless light curve, for which a photometrically derived mass ratio is notoriously unreliable. We note that our bootstrap errors of $K_i$ are quite large, primarily due to the small number—rather than the low accuracy—of individual observations; these uncertainty estimates are more realistic than the formal least-squares errors.

The moment of the minimum as given in Table 2 agrees perfectly well with the Cracow ephemerides given in Kreiner et al. (2001) on the assumption that the trend indicated by the $O - C$
diagram has continued and reached +0.060 days at the time of our observations. This value is uncertain and requires confirmation by photometric observations.

Judging by the light curve (e.g., from Hipparcos), the current RV data, and the shapes of the BFs, S Ant is a very typical A-type contact binary. Its spectral type is F3 V (HDH), which agrees with \( \text{B}/\text{C} = 0.30 \) from Høg et al. (2000). Its orbit almost certainly does not have any eccentricity, so its inclusion among early-type stars with potentially \( e \neq 0 \) (Abt 2005) and the spectral type A6–F0 IV–V is based on obsolete material.

2.2. TT Cet

TT Cet (HIP 8294) previously had not been observed spectroscopically, probably because of the relative faintness of the system at \( V_{\text{max}} = 10.83 \). The light curve suggests components of very different temperatures, giving TT Cet a classification of EB. The star appears in the compilation of Shaw (1994) as a “near-contact” binary. Indeed, the secondary is a faint and cool star because its signature is just barely present in our BFs (Fig. 1). However, the double-lined spectroscopic binary (SB2) orbit is relatively well defined, although we have only the second half of the orbit properly covered by observations (Fig. 3). The binary appears to be a semidetached or, more likely, a detached binary with a very faint secondary component. The mass ratio is \( q_{\text{ap}} = 0.39 \pm 0.07 \). The spectral type is unknown. From \( B - V = 0.40 \), derived from Tycho-2 observations, one can estimate the spectral type of the primary star to be near F4 V.

2.3. TW Cet

TW Cet (HIP 8447) is another relatively frequently photometrically observed binary with insufficient spectroscopic data. At \( V_{\text{max}} = 10.32 \) and with a short period of 0.32 days, it requires a moderately large telescope to avoid RV phase smearing. Struve et al. (1950) attempted to obtain radial velocities and obtained a preliminary orbit with \( V_0 = +20, K_1 = 135, \) and \( K_2 = 255 \text{ km s}^{-1} \). They stressed that the two components appeared to be equal in strength. Our BFs indeed show very similar components, but the orbital semi-amplitudes are different, resulting in a mass ratio \( q = 0.75 \pm 0.03 \).

With its mass ratio quite close to unity, \( B - V = 0.60 \) (Tycho-2), implying a spectral type of about G1 V, and very broad signatures of both components in the BFs (Fig. 1), TW Cet appears to be a genuine, late-type contact binary. The binary is a component of the visual system WDS 01489-2053. The fainter companion (\( \Delta m \approx 2 \)) slowly changed in angular separation from 8.3 in 1923 to 8.8 in 1998. It was not included in the spectrograph slit.

2.4. AA Cet

AA Cet (HIP 9258, HD 12180) is a relatively bright contact binary (\( V_{\text{max}} = 6.58 \)) with unequally deep eclipses, giving it
Fig. 3.—Radial velocity orbits for the first 8 of 14 close binary systems analyzed in this paper. All systems are SB2 binaries. RW Dor and YY Eri are the only W-type contact systems, while the rest are A-type systems. The filled circles and triangles indicate stronger and weaker components in the BFIs, while the open symbols signify observations of lower weight in the final solutions. The vertical dashes at the bottom of the panels mark phases of observations that could not be used for at least one of the components. The thin solid lines give the preliminary sine-curve solutions.
a light-curve classification of EB. It forms part of the visual binary WDC 01590-2255 and has a slightly fainter ($m' = 3$) companion at a separation of 8.6" that was not included in the spectrograph slit. We obtained, however, one spectrum of the companion giving a RV of 29.6 $\pm$ 1.2 km s$^{-1}$. This is marginally consistent with the center-of-mass velocity of the binary, $V_0 = 32.9 \pm 2.1$ km s$^{-1}$.

The RV orbit of AA Cet is well defined. The star appears to be a rather typical contact binary with a mass ratio of $q_{sp} = 0.35 \pm 0.02$. The spectral type in HDH, A7/8 V + G, might reflect the combined contribution of both visual components. However, $B - V = 0.38$ (Tycho-2) corresponds to F3 V rather than A7/8 V, so the spectral classification may have suffered from contamination by the visual companion. The color measurement $b - y = 0.256$ (Wolf & Kern 1983) also suggests F3 V. Chambliss (1981) gave the spectral type of the binary as F2 and noted that the companion, with a spectral type of F5, shows sharp, double-lined spectra, indicating that it is itself a close binary system. Our single spectrum of the companion does not show any doubling of the lines, while the BF is very sharp, as expected for a slowly rotating single star.

2.5. RW Dor

RW Dor (HIP 24763, HD 269320) has been known as an variable since its discovery by Leavitt in 1906, but it was Hertzsprung (1928) who classified it as a W UMa system. It has been a subject of numerous photometric studies. The only spectroscopic RV orbit is by Hilditch et al. (1992), who found $V_0 = 66.5 \pm 4.8$, $K_1 = 130.5 \pm 5.7$, and $K_2 = 191.5 \pm 3.1$ km s$^{-1}$, thus implying $q_{sp} = 0.68 \pm 0.04$. Our orbit is different in that $V_0$ is smaller by 25 km s$^{-1}$ and both semiamplitudes $K_i$ are larger; the mass ratio is, however, similar: $q_{sp} = 0.63 \pm 0.03$. An underestimation of the semiamplitudes is a typical problem of insufficient resolution, which may have been the result of the use of the cross-correlation function, in contrast to our much better resolving BF technique. On the other hand, our phase coverage is very

![Graphs of CT Eri, SZ Hor, AD Phe, TY Pup, HI Pup, and TZ Pyx showing light curves for six remaining binary systems analyzed in this paper. AD Phe is a W-type contact binary, and TZ Pyx is a detached binary. The remaining binaries are A-type contact systems.](image-url)
sparse, with only three observations not falling within the conjunctions.

Hilditch et al. (1992) assumed a spectral type of K1 V following Marton et al. (1989). The Tycho-2 color, $B - V = 0.66$, suggests an earlier spectral type of about G4/5 V with $V_{\text{max}} = 10.97$. The binary is a contact system of the W type; i.e., the less massive but brighter component is eclipsed at the primary eclipse.

### 2.6. UX Eri

The contact binary UX Eri (HIP 14699) was a subject of a recent DDO study (Rucinski et al. 2000, hereafter DDO 3) to which the reader is referred for more details. Four of the current ESO observations were used in that study in addition to 24 DDO observations. Thus, the results of DDO 3 are certainly more reliable and should be used in the future. The current data are included here only for completeness. A separate orbital solution based on only these seven points (Table 2) gives smaller values of $K_1$, which can be a result of a lower spectral resolution and a much smaller number of observations.

### TABLE 2

**Spectroscopic Orbital Elements**

| Name  | $n_{\text{obs}}$ | $V_0$ | $\sigma V_0$ | $K_1$ | $\sigma K_1$ | $K_2$ | $\sigma K_2$ | $T_0 - 2,400,000$ | $\sigma T_0$ | $O - C$ | $P$ |
|-------|-----------------|-------|--------------|-------|-------------|-------|-------------|-------------------|------------|--------|-----|
| S Ant | 8               | 26.22 | 2.85         | 77.94 | 3.73        | 234.10| 4.02        | 52,500.0659      | 0.0049     | -0.0002 | 0.648346 |
| TT Cet| 9               | 0.37  | 9.47         | 107.9 | 10.3        | 276   | 27          | 52,500.1306      | 0.0062     | -0.0009 | 0.485954 |
| TW Cet| 11              | -0.11 | 2.56         | 157.4 | 3.26        | 209.66| 3.84        | 52,500.2580      | 0.0012     | -0.0029 | 0.316851 |
| AA Cet| 12              | 32.70 | 2.14         | 77.98 | 2.27        | 224.24| 4.33        | 52,500.3699      | 0.0021     | +0.0047 | 0.516169 |
| RW Dor| 6               | 41.11 | 4.21         | 134.35| 3.46        | 216.03| 4.65        | 52,500.2302      | 0.0023     | -0.0035 | 0.285463 |
| UX Eri| 7               | 13.27 | 2.14         | 90.40 | 2.64        | 224.19| 3.37        | 52,500.5011      | 0.0027     | +0.0092 | 0.445286 |
| DDO 3 | 12              | 12.79 | 1.09         | 91.75 | 1.55        | 245.76| 1.86        | 50,416.5587      | 0.0014     | …       | 0.445279 |
| YY Eri| 8               | -21.42| 1.24         | 107.30| 2.27        | 242.57| 2.56        | 52,500.2976      | 0.0007     | -0.0098 | 0.321498 |
| BV Eri| 8               | -39.37| 3.26         | 65.71 | 2.90        | 221.1 | 9.9         | 52,500.2700      | 0.0044     | +0.0014 | 0.507654 |
| CT Eri| 8               | 3.4   | 11.06        | 68.3  | 14.9        | 229.1 | 17.2        | 52,500.2462      | 0.0077     | -0.0108 | 0.432616 |
| SZ Hor| 8               | 1.43  | 5.03         | 109.51| 6.60        | 231.34| 13.5        | 48,500.1019      | 0.0095     | -0.0063 | 0.625118 |
| AD Phet| 8               | 28.87 | 1.47         | 89.04 | 3.10        | 242.41| 1.42        | 52,500.0624      | 0.0007     | +0.0074 | 0.379923 |
| TY Pup| 6               | 41.86 | 4.01         | 55.68 | 5.22        | 226.8 | 15.4        | 52,500.1662      | 0.0090     | +0.0082 | 0.819244 |
| HI Pup| 5               | 59.89 | 1.74         | 50.2  | 15.4        | 265.2 | 17.2        | 52,500.2462      | 0.0077     | -0.0108 | 0.432616 |
| TZ Pux| 8               | -14.56| 1.08         | 126.22| 2.09        | 130.79| 1.52        | 52,500.3675      | 0.0072     | -0.0025 | 0.318555 |

Notes.—The column $n_{\text{obs}}$ gives the number of used RV measurements. The RV parameters $V_0$, $K_1$, and $K_2$ and their rms errors are in kilometers per second; $T_0$ is the Heliocentric Julian Date of the superior conjunction (eclipse) shifted back in time to the epoch of the original ephemeris. The periods $P$ are in days. The fixed quantities are given in brackets.

* Assumes a shift of $+0.06$ days in the Cracow ephemeris, as discussed in the text.
2.9. CT Eri

CT Eri (HIP 20943) is a system very similar to BV Eri, except that it is fainter \( V_{\text{max}} = 9.95 \) and has a fainter companion \( \Delta m \approx 1.8 \) at a separation of \( 10'' \), forming the double system WDS 04294-3335. The spectral type is probably also similar; judging by the mean \( B - V = 0.38 \) (Tycho-2), the spectral type may be F2/3 V. The SIMBAD database quotes F0. Its variability was announced by Strohmeier (1968). No light-curve solutions or RV studies have been attempted so far.

We see faint signatures of the secondary component of CT Eri in our BFs, although they are always difficult to measure. The formally derived mass ratio is practically identical to that of BV Eri, but its uncertainty is very large, \( q_{\text{sp}} = 0.30 \pm 0.09 \), mostly because we could detect the faint secondary in only two observations. The BFs in the second half of the orbit were very difficult to interpret with asymmetries of the primary peak and an absence of the secondary peak.

2.10. CU Eri

This visual binary has been included in our observations because it was given in the list of Wood et al. (1980) as an eclipsing binary with a period of 0.63 days. CT Eri, but its uncertainty is very large, \( q_{\text{sp}} = 0.30 \pm 0.09 \), mostly because we could detect the faint secondary in only two observations. The BFs in the second half of the orbit were very difficult to interpret with asymmetries of the primary peak and an absence of the secondary peak.

2.11. SZ Hor

SZ Hor (HIP 14488) has not been observed much since its discovery (Strohmeier 1967a), probably because of its faintness, \( V_{\text{max}} = 11.01 \). Judging by its Tycho-2 color, \( B - V = 0.37 \), its spectral type is about F3 V. Our orbit is well defined and could be taken to indicate a typical contact binary of the A type if not for the very different depths of the two eclipses, giving it the light-curve classification of EB. The mass ratio is \( q_{\text{sp}} = 0.47 \pm 0.04 \).

2.12. AD Phe

AD Phe (HIP 5955) has been recognized as a variable star for many years (Strohmeier & Bauernfeind 1969). McFarlane & Hilditch (1987) obtained a good light curve and attempted to solve it by making two doubtful (and recognized as such) assumptions of \( q = 0.5 \) and 1.0. In fact, we find \( q_{\text{sp}} = 0.37 \pm 0.01 \). Similar to YY Eri, the stronger and better defined component is the more massive one, but it is the one eclipsed at the slightly shallower minimum, so this is a W-type contact binary. No spectral type is available, but the mean \( B - V = 0.56 \) suggests F9 V or G0 V. The star is moderately faint at \( V_{\text{max}} = 11.28 \).

2.13. TY Pup

TY Pup (HIP 36683, HD 60265) is one of the brighter southern contact binaries \( V_{\text{max}} = 8.41 \) and, as such, the subject of many photometric investigations. The star appears as a variable for the first time in Hertzsprung (1928). The light curve suggests a contact binary possibly undergoing total eclipses. The only previous spectroscopic data have been obtained by Struve (1950), who saw two periodicities (0.58 and 9.7 days, both incorrect) and determined \( P_0 = +28 \) and \( K_1 = 32 \) km s\(^{-1}\). He classified the spectrum as A9n. The spectral classification of HDH is F3 V, which agrees very well with the Tycho-2 mean color index, \( B - V = 0.36 \).

The light-curve synthesis modeling was attempted by Maceroni et al. (1982), who obtained \( q_{\text{sp}} = 0.32 \pm 0.05 \), and by Gu et al. (1993), who obtained a very different and unrealistically accurate \( q_{\text{sp}} = 0.1846 \pm 0.0020 \). Although we only have a few observations, the mass ratio differs from both estimates, \( q_{\text{sp}} = 0.25 \pm 0.03 \). The system is a very typical A-type contact binary without any obvious complications.

2.14. HI Pup

HI Pup (HIP 36762) is a relatively faint \( V_{\text{max}} = 10.36 \) contact binary that has not had any photometric or RV observations. Discovered in 1949, the system was classified and its light curve constructed from photographic observations by Hoffmeister (1956). Sahade & Beron Dávila (1963) suggested that it is a possible member of the open cluster Cr 173, but this matter has not been established yet. The Tycho-2 mean, \( B - V = 0.51 \), corresponds to a spectral type of about F6 V, but no direct classifications of the star exist. A companion with \( B - V = 1.68 \) (approximately M3 V) is located 52'' away (Perryman et al. 1997), but the star is not included as a visual double system in the WDS catalog.

We have only five RV observations for HI Pup, so the RV orbit must be considered very preliminary. The mass ratio is small, \( q_{\text{sp}} = 0.19 \pm 0.06 \).

2.15. TZ Pyx

TZ Pyx (HIP 426219) was discovered as a variable star by Strohmeier (1966), who determined the orbital period to be 0.697 days (Strohmeier 1967b). Later Hipparcos observations (Perryman et al. 1997) showed that the binary has an orbital period of 2.3 days with a light curve showing relatively short, well-defined eclipses. It is definitely a detached binary with well-separated components, yet the star still appears as a W UMa-type binary in the SIMBAD database with the spectral type as uncertain A. The Tycho-2 photometric data, \( B - V = 0.27 \), suggest a spectral type of A8/9 V at \( V_{\text{max}} = 10.68 \).

Our RV orbit is the best among this group of targets, mostly because of sharp signatures in the BFs that were easy to measure for radial velocities. The mass ratio is very close to unity, \( q_{\text{sp}} = 0.965 \pm 0.020 \), with the slightly less massive component (i.e., the one showing the larger semiamplitude) giving a marginally stronger signature in the BFs.

3. SUMMARY

The current paper is the second of two papers describing a short program of RV observations of southern contact binary stars conducted at the European Southern Observatory in 1996 December and 1998 August. Paper I gave the full background and explanations for the rationale of this program and contained results for 17 targets observable in the August season in 1998.

The current paper presents results for 14 binary stars and two suspected variable stars (both components of the visual double CU Eri) that were observed in 1996. All of the observed 14 binaries turned out to be double-lined (SB2), permitting derivation of preliminary RV orbits for all of them. Thus, three that were previously considered SB1 systems, S Ant, BV Eri, and TY Pup, have new and complete, if sparsely covered, RV orbits. Our broadening function technique permitted us to obtain improved RV orbits for the previously known SB2 systems TW Cet, RW Dor, and YY Eri. We confirm that TZ Pyx is definitely not a contact binary star but rather a detached system of almost identical.
A-type stars, in full agreement with the results of *Hipparcos*, which showed that the period is 2.3 days.

We see very faint signatures of secondary components in some of our systems (TT Cet, CT Eri, BV Eri, and SZ Hor), but in all cases we are confident that these are real detections. We could detect them because of the advantageous properties of the BF technique; indeed, in most cases the secondaries are undetectable using the cross-correlation function approach. The phase dependencies of the secondary star velocities are exactly as expected. However, these results will be testable in the future when data with higher spectral resolution and signal-to-noise ratio become available.

Four systems discussed in this paper and in Paper I have been investigated independently from ESO and, at a later date, from DDO (the DDO solution for UX Eri used a small number of ESO observations, so it was not fully independent). For these systems, the mass ratios $q$ derived from ESO are, on average, 6% larger (with a range of 0%–15%), and the $V_0$ center-of-mass velocities from ESO are $5.7 \pm 3.1$ km s$^{-1}$ (standard deviation) more negative. It should be mentioned that the original goal of the current survey was to obtain reasonably accurate $V_0$ velocities for the determination of space motions, as well as first estimates of the system properties, within the allotted amount of observing time.

Concerning the statistics of southern hemisphere contact binary stars, the two parts of the current spectroscopic program resulted in observation of 23 contact binaries, of which 12 are brighter than $V_{\text{max}} < 10$. Taking into account that only about half of the southern sky was observed, we see that the numbers are small, much smaller than for the northern hemisphere. This dearth of data for the southern hemisphere was pointed out by Priibilla & Rucinski (2006) and is in great need of rectification. Within the strict limit of $V_{\text{max}} = 10$, there are currently 20 southern contact systems with reliable RV curves versus 58 similar northern systems. We note that the inequality between the hemispheres manifests itself not only in the lack of RV data but also in the number of detected contact binaries; to the same magnitude limit, we know of 56 southern systems versus 72 northern systems, as based on the catalog of Priibilla et al. (2003). On the basis of the apparent relative frequency among FGK dwarfs of 0.2%, derived by Duébeck (1984) and fully confirmed later (Rucinski 2002, 2006), one can expect about 800–1000 contact binaries on the whole sky brighter than $V_{\text{max}} = 10$. Most of them remain to be discovered, but most have small amplitudes (Rucinski 2002) additionally diminished by the very frequent presence of companions (Priibilla & Rucinski 2006). Thus, the large photometric amplitude systems discussed in our two papers form the tip of an iceberg that still remains to be seen and explored.

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