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COMMENT ON THE RADIUS OF THE COOLER COMPONENT OF THE ECLIPSING RS CVn BINARY CF Tuc (HD 5303)

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There appears to be a discrepancy between values of the rotational $v \sin i$ for the cooler component of the RS CVn system CF Tuc, as measured by Donati *et al.* (1997) from a high signal-to-noise ratio line profile using Least Squares Deconvolution (LSD), and as derived by fitting the photometric light curves, by for example Budding & McLaughlin (1987) and Anders *et al.* (1999). The stellar radius implied by the LSD technique does not appear to give a satisfactory fit to the light-curve of this well observed system.

CF Tuc is an eclipsing RS CVn binary, of period of $2\overset{\mathrm{d}}{.}7978$. Many light curves have been obtained of this system by various workers, and basic stellar parameters have been deduced from these data (see for example Budding & McLaughlin 1987; Anders *et al.* 1999). The only published radial-velocity data for CF Tuc are those of Balona (1987) and Collier Cameron (1987), from which we calculate the result $a \sin i = 10.06\ R_\odot$. Assuming that the stars are in synchronous rotation with the orbital period and have rotation axes parallel to the orbital axis, we have used the stellar parameters deduced by Budding & McLaughlin (1987) and Anders *et al.* (1999), together with the result for $a \sin i$, to derive the data in the first two rows of Table 1. (Other recent measured values for $v_c \sin i$ for CF Tuc, based on the same observed spectrum, are 35 $\mathrm{km\,s^{-1}}$ by Pallavicini *et al.* 1992, and 65 $\mathrm{km\,s^{-1}}$ by Randich *et al.* 1993.)

Table 1: Parameters of CF Tuc derived from various sources

i [°]	a [$R_\odot$]	R_c [$R_\odot$]	$v_c \sin i$ [$\mathrm{km\,s^{-1}}$]	R_h [$R_\odot$]	$v_h \sin i$ [$\mathrm{km\,s^{-1}}$]	Source
69.3	10.8	3.26	55	1.80	30	Anders *et al.* (1999)
71.4	10.6	3.05	52	1.58	27	Budding & McLaughlin (1987)
64.5	11.2	4.29	70 ± 2	1.53	25 ± 1	Donati *et al.* (1997)

We derived the results in the third row of the table from measurements of rotational $(v \sin i)_{\mathrm{LSD}}$ by Donati *et al.* (1997). The value for i was estimated from the phases of contact at primary eclipse, as described later. The three values of R_h agree reasonably well, but for the cooler star the $(v \sin i)_{\mathrm{LSD}}$ datum leads to a much larger radius.

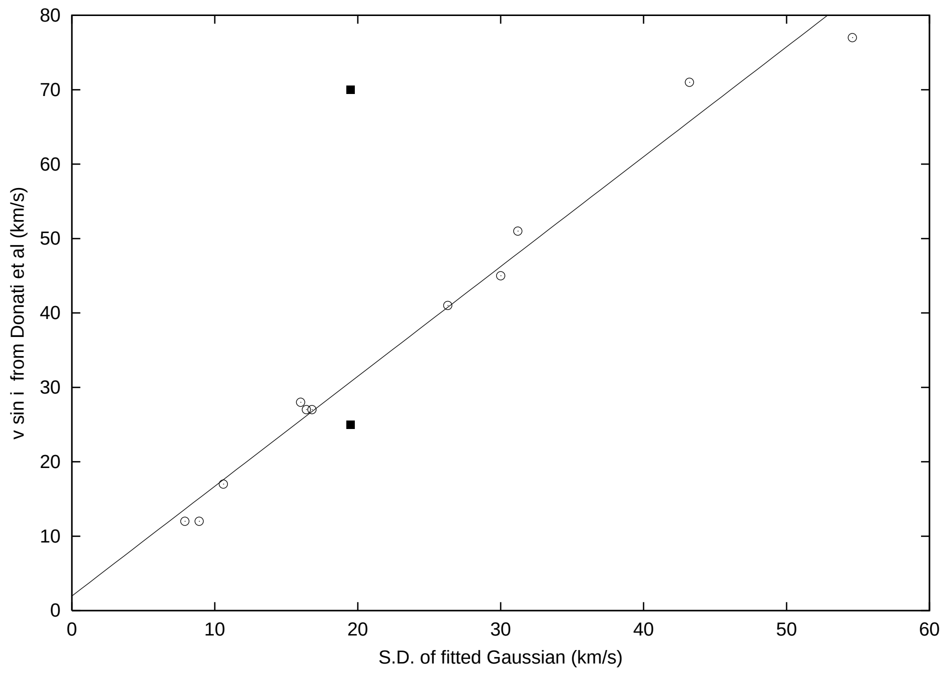

Figure 1. $v \sin i$ from Donati *et al.* (1997) versus σ for the fitted Gaussians. The points marked as filled-in squares are for the components of CF Tuc, the circles are for the other stars. The line is the fit given in the text

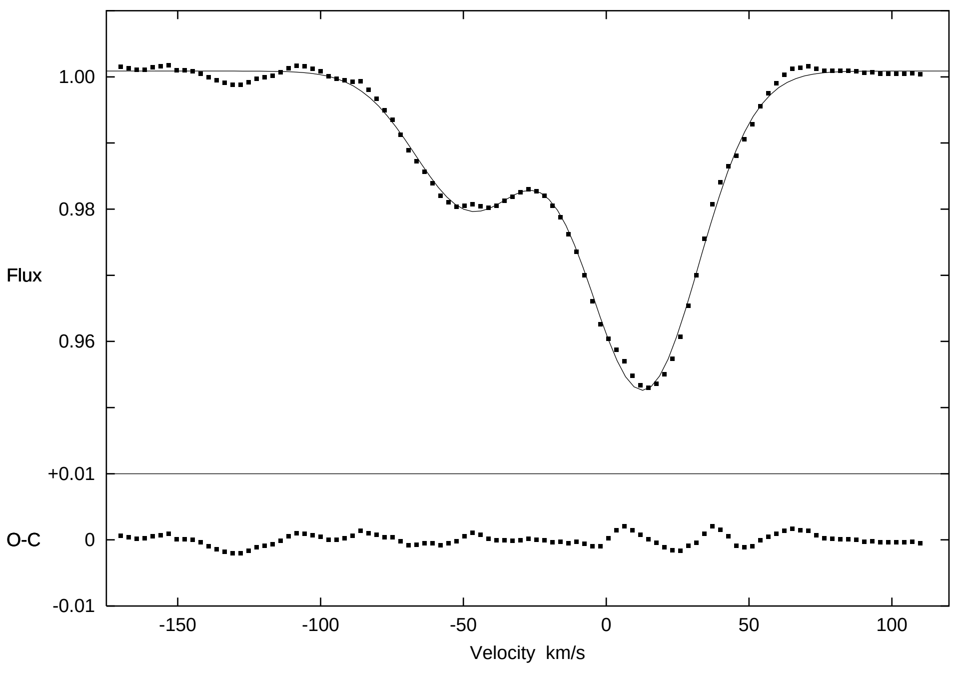

Figure 2. Gaussian fits to the overlapping profiles of Fig. 16 of Donati *et al.* (1997). Each Gaussian has about the same width, approximately equivalent to a $v \sin i$ of 30 $\mathrm{km\,s^{-1}}$

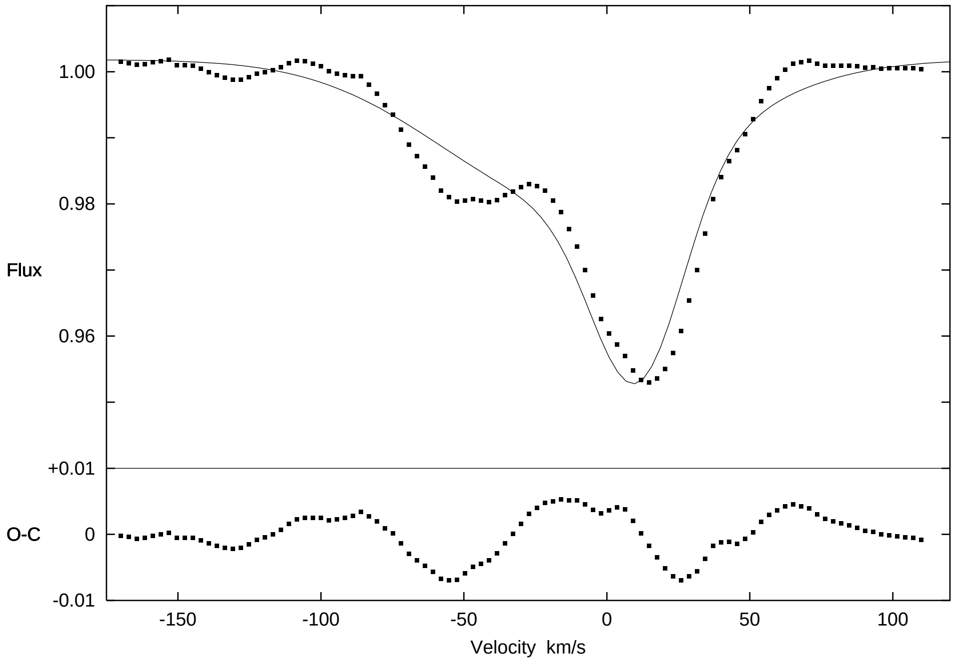

Figure 3. As for Fig. 2, but with Gaussians of widths implied by $(v \sin i)_{\rm LSD}$ values of 70 and 25 $\rm km\,s^{-1}$ from Donati *et al.* (1997), and radial velocities of 10.9, -12.9 $\rm km\,s^{-1}$

The high precision of the result $(v_c \sin i)_{\rm LSD} = 70 \pm 2$ $\rm km\,s^{-1}$ obtained by Donati *et al.* (1997) led us to examine its consequences. The implied absolute radius for the cooler star is significantly higher than that to which the light-curve fitting procedures converged (Budding & McLaughlin 1987, Anders *et al.* 1999). It is difficult to see how such a radius could yield a good fit to the light curves. As a possible solution to this problem, Collier Cameron (private communication) suggested that the cooler star may have a large number of small, dark spots, which reduces its surface brightness significantly below the value implied by the photometric colours. Hilditch & Collier Cameron (1995) found evidence for similar behaviour in the RS Cvn system XY UMa, in which the depth of primary eclipse varies with overall mean light level over many years, in just the way expected if the long term variation is caused by uniformly distributed spots.

So we assumed uniform maculation of the cooler star, as suggested by Collier Cameron, and attempted to fit the light curve of CF Tuc using the relative stellar radii implied by the rotational speeds obtained by Donati *et al.* (1997). We selected the light curve of Budding & McLaughlin (1987), which was measured at an epoch when there were almost certainly no large starspots on the cooler star, and thus no significant maculation wave on the light curve. Firstly we used the $v \sin i$ measurements of Donati *et al.* (1997) to derive $R \sin i$ for both stars. Then, using the program Binary Maker 2.0 (Bradstreet 1993), we adjusted the inclination i to give the correct times of contact at primary eclipse. This yielded $i \sim 64^\circ\!.5$, as in the third row of Table 1 above. However we found it impossible to adjust the surface brightness of the cooler star to obtain a fit to the light curve within primary eclipse. The fitted curve was always too shallow, even when the surface brightness of the cooler star was reduced to unrealistically low levels, at which also the light curve outside the eclipses was clearly too flat. Similarly we were unable to obtain a fit by adjusting the surface brightness of the hotter star.

We are left with two possibilities. Firstly, the value of $(v_c \sin i)_{\rm LSD}$ for the cooler star is correct, and phenomena at present not understood explain the form of the light curve. Secondly, the value of $(v_c \sin i)_{\rm LSD}$ for the cooler star may be in some way anomalous.

To investigate the second possibility, we scanned most of the line profiles published in Donati *et al.* (1997), digitised them and fitted Gaussians to the lines. A plot of the $(v \sin i)_{\rm LSD}$ values from Donati *et al.* (1997) versus the standard deviations, σ, of the corresponding Gaussians gives a reasonably tight linear relationship which, without the data for CF Tuc, is fitted by $(v \sin i)_{\rm LSD} = 1.477\sigma + 1.85$ km s^{-1}. However the point for the cooler component of CF Tuc falls far from this line: hence the anomaly. See Fig. 1.

Our fit to the profiles of Fig. 16 of Donati *et al.* (1997) is shown in Fig. 2. The residuals are small, as can be seen in the lower part of Fig. 2 which is at the same scale as the fit. σ for each of the Gaussians corresponds to $(v \sin i)_{\rm LSD}$ values of approximately 30 km s^{-1}. The radial velocities of the hotter and cooler stars at the time of the observations were 10.9 and -12.9 km s^{-1} according to the radial velocity data of Balona (1987) and Collier Cameron (1987), together with the ephemeris $2444219.270 + 2.797715 \times E$ of Anders *et al.* (1999). The Gaussian fits of Fig. 2 indicate radial velocities of 12.9 and -47.4 km s^{-1} for the hotter and cooler stars, the latter value again being anomalous. A possible explanation of the anomalies is that the lineshape for the cooler star is strongly distorted by the presence of starspots. However the fit using Gaussians has small residuals, so this explanation does seem unlikely. We examined this a little further by constraining the radial velocities to be 10.9 and -12.9 km s^{-1} and the values of $(v \sin i)_{\rm LSD}$ to be 25 and 70 km s^{-1}, as in Donati *et al.* (1997), and then fitting two Gaussians to the profile. The result, shown in Fig. 3, is not a good fit. While our method is admittedly rather crude, the results show that the value of $(v_c \sin i)_{\rm LSD}$ of 70 km s^{-1} is almost certainly not consistent with the overlapping line profiles for CF Tuc in Fig. 16 of Donati *et al.* 1997.

We conclude that there are still problems to be solved in the case of CF Tuc. Perhaps a subtle maculation process is confounding the fitting of the light curves. On the other hand, the value of $v \sin i$ for the cooler star of CF Tuc as found by Donati *et al.* (1997) is open to some question. The method of Least Squares Deconvolution is so powerful that this particular case where it may fail is well worth further study.

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