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CCD PHOTOMETRY OF DF Lyr, BY Peg, CW Peg, AND RW Tri

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Observed star(s):				
Star name	GCVS type	Coordinates (J2000) RA	Dec	Comp./check star(s)
DF Lyr	EW/D	$18^h53^m34\overset{s}{.}2$	$+28°04'20''$	CTI catalog
BY Peg	EW/KW	$21^h38^m52\overset{s}{.}2$	$+28°05'46''$	CTI catalog
CW Peg	EA/SD	$21^h48^m27\overset{s}{.}6$	$+28°06'29''$	CTI catalog
RW Tri	EA/WD+NL	$02^h25^m36\overset{s}{.}1$	$+28°05'51''$	CTI catalog

Observatory and telescope:
CCD Transit Instrument (CTI), 1.8-m f/2.2 meridian pointing telescope
US Air Force Academy Observatory (AFA), 0.61-m f/15.6 Cassegrain telescope

Detector:	CTI: RCA LN2-cooled CCD, 320 × 512 pixels, $8\overset{'}{.}3$ wide strip, AFA: Photometrics LN2-cooled CCD, 512×512 pixels, $3\overset{'}{.}6 \times 3\overset{'}{.}6$ FOV.

Filter(s):	CTI: *BVR*, AFA: *BVR*

Date(s) of the observation(s):
CTI: 1987.10–1991.05, AFA: 2004.02–2005.11

The original CCD/Transit Instrument (CTI) was a stationary, meridian pointing 1.8 meter, f/2.2 optical telescope that imaged a 8.26′ strip of the sky at all right ascensions. CTI operated on Kitt Peak from December 1984 to April 1992 and observed in the meridian at a declination centered at +28°02′ (1987.5 epoch, J2000 equinox), four degrees from the zenith. The resulting CTI survey area not only uncovered a multitude of previously unknown variable stars, but also observed many known variable stars (Wetterer et al. (1996)). This paper reports on observations at the US Air Force Academy (AFA) of four of these previously known variable stars that are eclipsing binary systems. All images were bias subtracted, flat fielded, and the magnitudes of the variable and its comparison stars were extracted using IRAF's aperture photometry.

Photometric characteristics for these stars are listed in Table 1. $V_{\rm Max}$, $V_{\rm MinP}$, and $V_{\rm MinS}$ are the average standard V magnitudes at maximum, primary minimum, and secondary minimum light. AFA magnitudes were transformed to CTI instrumental magnitudes via differential photometry with nearby CTI stars in the same AFA field of view and then to standard magnitudes using previously determined transformation coefficients as detailed in Equations (3) and (4) in Wetterer et al. (1996) and assuming constant $B-V$. Because of the differential photometry between stars on the same field the first order extinction correction is very small and is not applied, the second order term is neglected. Calculated random errors are shown in parentheses while estimated systematic errors introduced by not accounting for the changing $B-V$ with respect to phase are shown in square brackets. We estimated what the systematic error is by using what we know of the system from our Binary Star Maker 3.0 fit to estimate what the $B-V$ is during eclipses and how this would affect the standard magnitude calculation (for RW Tri we used the fact that the GCVS lists the system to have a M0V type star so assumed the primary eclipse's $B-V$ to be 1.4 based on Main Sequence tables we use). CTI/AFA obs is the number of observations from each site. The GCVS period, the Atlas of $O-C$ Diagrams of Eclipsing Binary Stars (Kreiner 2004) period, and period calculated using CTI and AFA V photometry and employing the standard period finding algorithm of Lafler and Kinman (1965) are in days. Finally, new calculated ephemeris light elements (HJD epoch − 2400000, linear term, quadratic term) using new and historical minima timings (uncertainties estimated for those timings whose uncertainties were not reported) are listed in days. The new minima timings were determined from those AFA nights where a minimum was adequately observed using the Kwee and Van Woerden method (Kwee and Van Woerden (1956)). This is not possible for the CTI data because CTI observed each star only once per night, however, approximate CTI minima timings were determined using the most prominent darkenings (close to known minimum magnitude and given an uncertainty related to sharpness of minima) and CTI/AFA period solution in Table 1. All minima timings (HJD − 2400000) are listed in Table 2.

We used Binary Maker 3.0 software and reference manual (Bradstreet (2004)) to obtain preliminary solutions for three of these binaries (RW Tri was excluded due to the volume of literature already available regarding the physical characteristics of this system). Both DF Lyr and BY Peg appear to have rounded minima and smoothly varying light curves characteristic of W UMa eclipsing binaries undergoing partial eclipses. CW Peg, on the other hand, has a deep primary eclipse and a shallow secondary eclipse that was never observed consistent with an Algol type system. For all systems, we assumed both stars were on the Main Sequence and used the measured colors and eclipse depth differences to estimate mass ratios and surface temperatures using tables adapted from Allen (2000). We then adjusted the fillout factor and inclination to most closely reproduce the lightcurve. We also compared the radii of the stars as determined by the fit to the model Main Sequence stars for self-consistency. In this analysis, we used standard values for gravity darkening coefficients (1.00 for radiative stars of $T > 7200$ K and 0.32 for convective stars), limb darkening coefficients (Van Hamme (1993)) and reflection coefficients (1.0 for radiative stars and 0.5 for convective stars) and assumed there was no third light contribution. Table 3 summarizes the results. The V light curves from CTI and AFA data (with Binary Maker 3's fit based on the preliminary solution where applicable) are shown in Figures 1 (DF Lyr), 2 (BY Peg), 4 (CW Peg), and 6 (RW Tri). $O-C$ values (against GCVS light elements) for available data, Kreiner's solution, and solution based on the new ephemerides of Table 1 are plotted in Figures 3 (BY Peg), 5 (CW Peg) and 7 (RW Tri).

Table 1: Photometric characteristics

	DF Lyr	BY Peg	CW Peg	RW Tri
$V_{\rm Max}$	13.031(4)	12.419(8)	11.917(2)	13.082(7)
$V_{\rm MinP}$	13.500(10)[+3]	12.919(9)[+2]	15.352(9)[+103]	15.5(1)[+1]
$V_{\rm MinS}$	13.353(7)[−2]	12.782(6)[−2]	-	-
$V_{\rm Mean}$	13.145(1)	12.585(1)	12.006(1)	13.210(14)
$(B-V)$	0.437(8)	0.849(7)	0.061(6)	0.140(15)
$E(B-V)$	0.27(3)	0.12(1)	0.09(1)	0.07(1)
CTI/AFA obs	27 / 542	22 / 364	22 / 458	54 / 135
GCVS period	0.577128	0.341937	2.372516	0.231883
Kreiner period	0.57712889	0.3419412(2)	2.372521(2)	0.23188318(2)
CTI/AFA period	0.5771285(10)	0.3419371(6)	2.3725201(5)	0.23188297(8)
new ephem epoch	53,522.7396(6)	45,565.4946(8)	53,630.9437(3)	53,639.92521(13)
new ephem linear	0.57712884(3)	0.34193423(8)	2.3725133(15)	0.231882976(6)
new ephem quad	-	$+1.08(3)\times10^{-10}$	$-4.3(5)\times10^{-9}$	$-3.12(6)\times10^{-12}$

Table 2: Minima timings

Object	HJD of Min.	E	Type	Filter
DF Lyr	47,681.91(1)	-10120.5	II	V
	48,101.77(1)	-9393	I	V
	53,513.7956(2)	−15.5	II	V
	53,515.8135(2)	−12	I	R
	53,518.69880(12)	−7	I	V
	53,519.8523(4)	−5	I	V
	53,522.7372(3)	0	I	R
	53,528.7986(3)	10.5	II	R
BY Peg	47,357.92(2)	−18456	I	V
	47,823.64(2)	−17094	I	V
	48,127.79(2)	−16204.5	II	V
	48,175.66(2)	−16064.5	II	V
	48,539.66(2)	−15000	I	B
	53,604.942(3)	−186.5	II	V
	53,628.7084(6)	−117	I	V
	53,628.8751(6)	−116.5	II	V
	53,647.6857(4)	−61.5	II	V
	53,657.7693(2)	−32	I	V
	53,666.6557(3)	−6	I	V
	53,668.71385(17)	0	I	B
CW Peg	47,357.99(3)	−2644	I	B
	47,419.67(3)	−2588	I	B
	53,630.9401(7)	0	I	V
RW Tri	47,475.777(3)	−26583	I	V
	47,823.833(3)	−25082	I	V
	47,833.804(3)	−25039	I	V
	53,626.9326(13)	−56	I	V
	53,639.9221(2)	0	I	V

Table 3: Binary Maker 3 preliminary solutions

	DF Lyr	BY Peg	CW Peg
Mass Ratio ($M_{\rm II}/M_{\rm I}$)	0.73	0.83	0.21
$\rm Fillout_I$	−0.05	0.10	−0.63
$\rm Fillout_{II}$	−0.10	0.10	0.30
$T_{\rm I}$	8400 K	5500 K	10200 K
$T_{\rm II}$	7100 K	5000 K	4300 K
Inclination	77 degrees	71 degrees	86 degrees

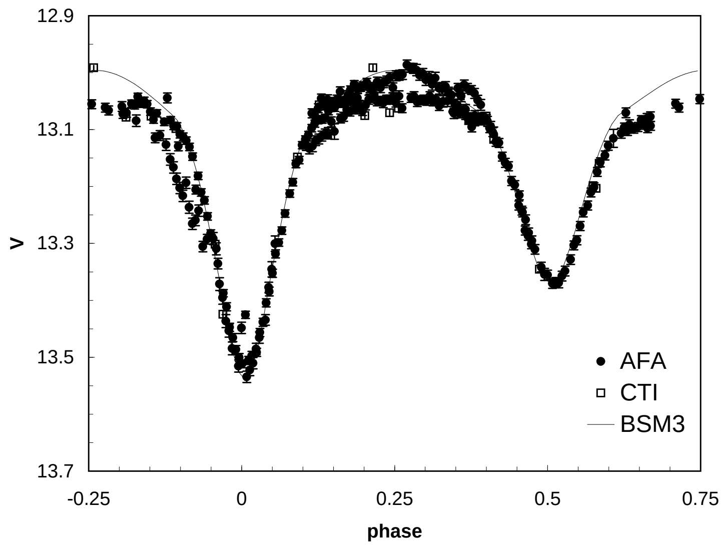

Figure 1. Lightcurve for DF Lyr: $P = 0.5771285(10)$ days, epoch = 2,453,522.7372(3)

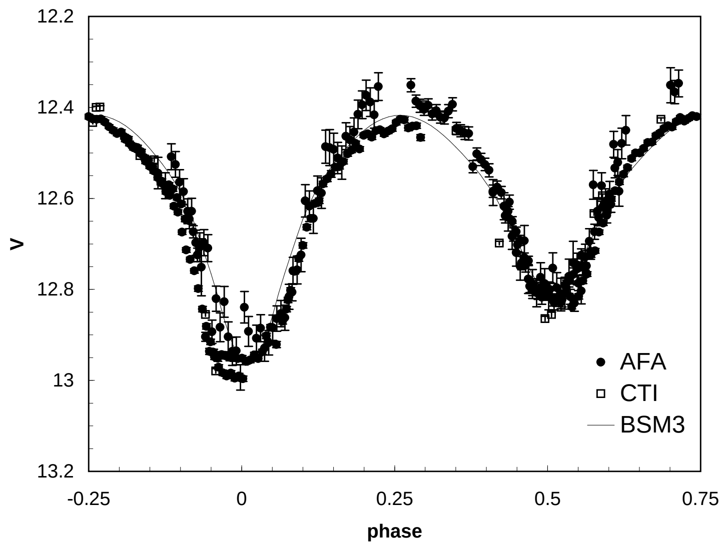

Figure 2. Lightcurve for BY Peg: $P = 0.3419371(6)$ days, epoch = 2,453,668.71385(17)

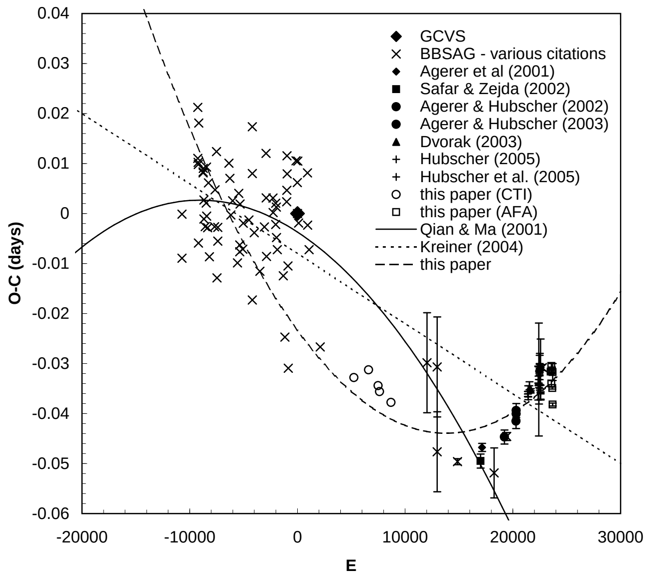

Figure 3. $O-C$ plot for BY Peg using GCVS light elements (BBSAG from Qian and Ma (2001), Diethelm (2005), and Kreiner (2006)

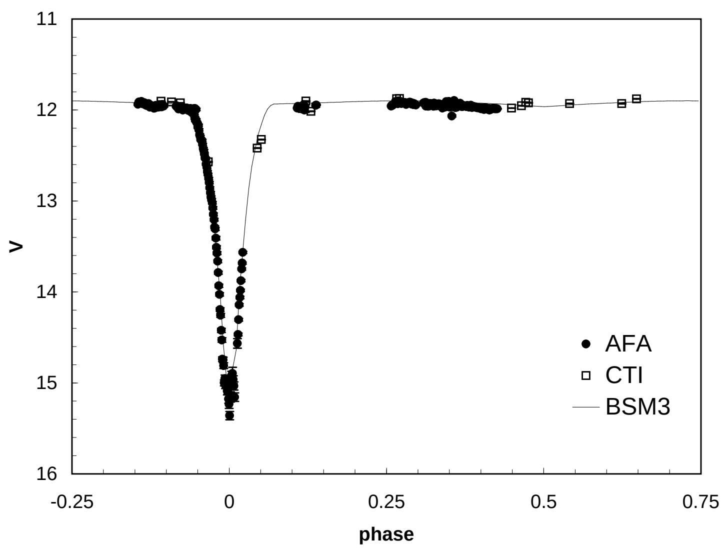

Figure 4. Lightcurve for CW Peg: $P = 2.3725201(5)$ days, epoch = 2,453,630.9401(7)

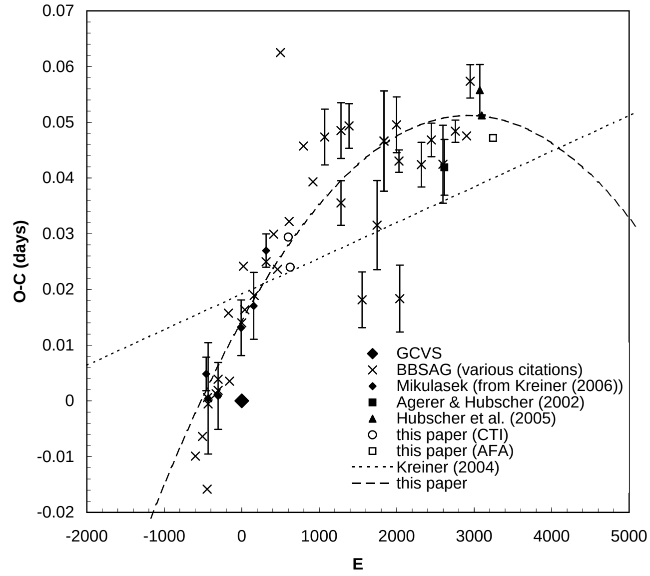

Figure 5. $O-C$ plot for CW Peg using GCVS light elements (BBSAG from Diethelm (2003), Diethelm (2004), and Kreiner (2006))

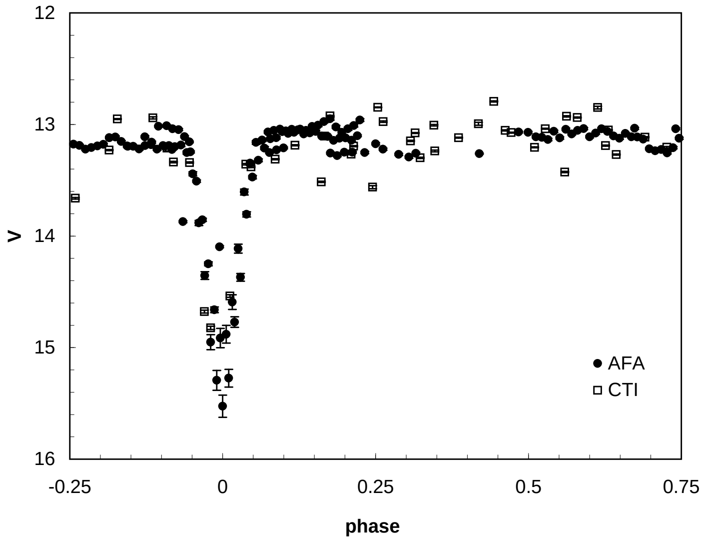

Figure 6. Lightcurve for RW Tri: $P = 0.23188297(8)$ days, epoch = 2,453,639.9221(2)

Notes on individual stars:

DF Lyr is a short-period binary with an EW-type light curve. The preliminary fit indicates a near contact system with radii ~ 7 % smaller than corresponding model Main Sequence stars of the same spectral class. A perfect match is achieved for stars 600 K cooler and is possible if a lower reddening is adopted. The light curve has differences from night to night indicating the possible presence of spots, which may also be producing a larger than expected scatter in the timings in the $O-C$ diagram. With so few timings and having to estimate uncertainties for earlier epochs, a weighted least squares fit to all

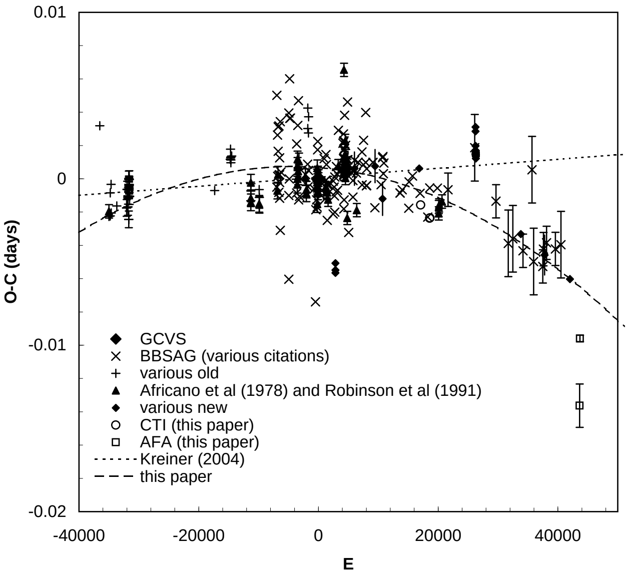

Figure 7. $O-C$ plot for RW Tri using GCVS light elements (BBSAG from Diethelm (2003), Diethelm (2004), Kreiner (2006), and Nelson (2006); "various old" from Walker (1963), Surkova and Skatova (1969), Warner (1973), Winkler (1977), and Protitch, Efimov and Prokofieva from Kreiner (2006); "various new" from Longmore et al. (1981), Smak (1995), Zejda (2004), Krajci (2006), ROTSE from Nelson (2006), and Mikulasek and BRNO observers from Kreiner (2006))

the data yields elements dominated by later epochs and obviously erroneous. The new ephemeris of Table 1 is from a simple least squares linear fit and is essentially identical to Kreiner's solution.

BY Peg is a short-period binary with an EW-type light curve. The preliminary fit indicates a contact system with the primary's radius consistent with the corresponding model Main Sequence star of the same spectral class and the secondary's radius ~ 10 % smaller. The light curve appears to have significant differences from night to night indicating the possible presence of spots or unknown systematic error. The timings in the $O-C$ diagram also displays a larger than expected scatter. Qian and Ma (2001) analyzed $O-C$ values and proposed a revised ephemeris indicating a decreasing period (note that there is an error in Qian and Ma's paper: the exponent of the quadradic term should be -11 and not -8) also shown in Figure 3. It is clear that Qian and Ma's ephemeris is not correct. This paper's new ephemeris of Table 1 uses data after 1970 and indicates the period may actually be increasing at a rate of $dp/dt = +2.31(6) \times 10^{-7}$ day/yr. The three historical timings (one in 1936 and two in 1956) not used do not fit the new ephemeris. Interestingly, the 1936 timing would be close to the new ephemeris if the measured minima was a secondary eclipse and not a primary eclipse.

CW Peg has a deep primary eclipse and very shallow secondary implying a possible semi-detached or Algol-type binary, with the preliminary solution parameters supporting this conclusion. The new ephemeris of Table 1 uses data after 1980 and indicates the period may be decreasing at a rate of $dp/dt = -6.6(8) \times 10^{-7}$ day/yr. The one historical timing from 1936 not used does not fit the new ephemeris.

RW Tri is a nova-like eclipsing binary, well-studied from a variety of perspectives and believed to consist of a late-type star which is transferring material to a companion white dwarf. Past observations have led to the conclusion that it exhibits long-term variations in its mass-transfer rate. The new ephemeris of Table 1 indicates the period may be decreasing at a rate of $dp/dt = -9.8(3) \times 10^{-9}$ day/yr, indicating RW Tri may have entered a period of increased mass transfer.

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