COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS
Number 4629

Konkoly Observatory
Budapest
8 September 1998
HU ISSN 0374 – 0676

VARIATIONS OF LUMINOSITY, RADIUS, AND TEMPERATURE OF THE PULSATING RED SUPERGIANT CE TAURI

RICK WASATONIC, EDWARD F. GUINAN

Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085, USA

CE Tauri (HD 36389; HR 1845; 119 Tau) is a bright semi-regular pulsating M2 Iab-Ib variable star. It is easily observable with a mean V-mag = +4.45 and B−V = +2.07. Although CE Tau may be a possible twin to the SRc M2 Iab supergiant α Orionis, it has been the target of few long-term photometric studies. Boyd et al. (1984) found the star to have a nearly sinusoidal visual light curve with an amplitude of 0.25 mag and a half-period of nearly 80 days. This estimate corresponds well with the AAVSO reported period of 165 days. Several V-band measures have also been published by Krisciunas (1986). Recent measurements by the Hipparcos satellite yield a parallax of 1.7 ± 0.8 mas, which corresponds to a distance of about 588 ± 277 pc. Morever, near-IR interferometric measurements by Quirrenbach et al. (1993) and Dyck et al. (1996), and lunar occultation measurements by Di Benedetto et al. (1993) yield an average angular diameter of 10.3 mas. This corresponds to a stellar radius of R = 654 $R_\odot$ or 3.04 AU, based on the given Hipparcos distance.

Because CE Tau is a cool M2 star, its maximum energy output is in the near-infrared and its spectrum is dominated by temperature dependent TiO molecular bands. For these reasons, and because of a lack of long-term photometric monitoring, CE Tau is an excellent candidate for Wing (1992) near-IR TiO photometry. Furthermore, using the Wing near-IR photometry presented here, and methods developed by us (see, e.g., Morgan et al. 1997; Mahler et al. 1997), it is possible to estimate the temperature, radius, and luminosity changes of CE Tau over its pulsation cycle. Hence, CE Tau was added to our program of V-band and Wing (1992) near-IR photometry of bright red giants and supergiants being carried out at the Wasatonic and Villanova observatories.

Two seasons of variability are discussed, covering 12 nights from November 1996 to March 1997 and 17 nights from November 1997 to March 1998. Differential photometry of CE Tau was carried out with a 20 cm Schmidt-Cassegrain telescope coupled to an Optec silicon PIN-photometer. The comparison star was HD 35802 and HD 35296 served as the check star. No significant light variations were found between the comparison and check stars. In addition, ϵ Tau served as a near-IR Wing standard star (Wing, 1979).

The photometry was conducted using a filter closely matched to the Johnson V-band system and the Wing near-IR three filter system, which uses near-IR intermediate-band filters centered at 719 nm, 754 nm, and 1024 nm. These filters are designated as A, B, and C by Wing (1992), respectively. TiO-indices, near-IR color indices, and IR apparent magnitudes are calculated from the observations. As defined, a numerical increase in the

TiO-index corresponds to an increase in TiO absorption at 719 nm. For M-type stars the C(1024) magnitude closely approximates the apparent bolometric magnitude (m_{bol}). Wing (1992) gives a detailed description of the three-color near-IR photometric system.

Nightly means were formed from the individual observations and plotted against Julian Day Number in Figure 1. The V-mag, TiO-index, and the near-IR C(1024)-mag are plotted. As shown in the figure, the star varies with time on a time-scale of several months. During the 1996-97 observing season CE Tau has a nearly sinusoidal light variation in which the V-mag varies from V_{max} = +4.29 mag to V_{min} = +4.46 mag. Fitting the data with a sinusoid suggests a characteristic period of about 140d for this interval. Also during the 1997/98 season the light variations are less regular and the light ranges slightly smaller. The observed V-mag amplitude of about 0.20 mag during 1996/97 is smaller than the total V-mag range of 0.40 mag found from Hipparcos photometry of CE Tau secured from 1990 to 1993.

Variations in the TiO-index are shown in the second panel of Figure 1. The TiO-index varies inversely in phase with the V-mag light variations. During 1996/97 the TiO-index reaches its minimum value of +0.54 during light maximum and reaches its maximum value of +0.64 near light minimum. These values correspond to spectral types of about M2.0 Iab to M2.4 Iab, respectively. From the TiO-index the star (at least during 1996/97) is hottest at light maximum, and coolest at light minimum. As shown in Fig.1, the mean seasonal TiO-index is more positive during 1997/98, than during 1996/97. This indicates that the mean TiO absorption is stronger during the second season, corresponding to an overall decrease in the mean temperature over the two years.

The C(1024) mag is plotted against time in the bottom panel of Figure 1. As shown, the C(1024) mag varies in a similar manner to the V-mag, but with an amplitude only $\approx$ 0.05 mag. From observations of standard stars with reliable bolometric magnitudes, the C(1024) mag was transformed to apparent bolometric magnitude (m_{bol}) by adding 1.10 to the C-mags. From prior TiO Index–temperature calibrations using near-IR standard star information supplied by Wing (1978), the T_{eff} of CE Tau was determined for each night. These effective temperatures are plotted in the top panel of Figure 2. Using these temperature and m_{bol} values, and adopting the Hipparcos distance, the luminosity ($L_\star$) and radius ($R_\star$) of the star were computed for each nightly data set. The resultant values of $L_\star/L_\odot$ and $R_\star/R_\odot$ are plotted in Figure 2. In converting from M_{bol} to $L_\star/L_\odot$, the value of $(M_{bol})_\odot$ = +4.75 mag was adopted.

As shown in Fig. 2, for 1996/97 the temperature and luminosity variations of CE Tau are correlated but there appears to be no corresponding correlated changes in the stellar radius. As shown, the star is hottest at a time when it is most luminous and vice versa. However the radius of the star appears to increase systematically from $R_\star/R_\odot$ = 553 to about $R_\star/R_\odot$ = 570 over the 1996/97 observing season. The apparent systematic increase in the star's radius appears to continue over the 1997/98 observing season. By the end of the 1997/98 season, the inferred stellar radius is $R_\star/R_\odot$ = 580. This change is accompanied by an apparent decrease in the T_{eff} over the two years. These systematic changes in $R_\star$ and T_{eff} could be part of a long-term pulsation cycle lasting a few years. α Ori shows similar long-term behavior (Morgan et al. 1997).

It is interesting that the 140d light variation seen during 1996/97 is driven chiefly by temperature changes without the expected accompanying radius changes expected from pulsation. This suggests that the 140-160d light variation arises chiefly from the growth and decay of huge granulation cells over the star's surface rather than from primary pulsation (see Schwarzschild, 1975).

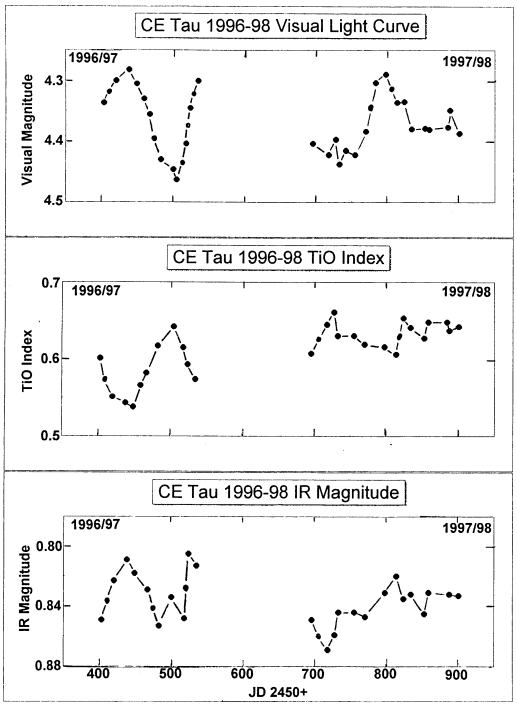

Figure 1. CE Tau visual light curve, TiO index, and IR magnitudes for the 1996/97 and 1997/98 observing seasons

Wing photometry of α Ori has also been carried out by us with the same equipment; the observed temperature, luminosity, and radius changes are slightly larger than those of CE Tau. From the TiO-indices α Ori is on average about 80 deg K warmer than CE Tau. Also α Ori appears somewhat larger and more luminous than CE Tau but the large uncertainty in CE Tau's parallax makes these comparisons less reliable. The mean photometric and physical properties of CE Tau and α Ori are listed in Table 1 for comparison. At face value, CE Tau is a close match to α Ori.

Table 1: Averaged common properties and parameters

Avg. Properties	Alpha Ori	CE Tau	Comments
Spec. Type	M2 Iab	M2 Iab - Ib	
V-Mag.	+0.50	+4.45	Data from current photometry
d(pc)	131 ± 30	588 ± 287	From Hipparcos
(B−V)	+1.85	+2.07	
E(B−V)	≈ 0.05	≈ 0.25	Using $A_V = 3.2E(B-V)$
A_V	≈ 0.16	≈ 0.80	
M_V	−5.24	−5.20	
TiO Index	0.73	0.60	Data from current photometry.
T_{eff}	3430K	3510K	Data from current photometry
Ang. Diameter	55.0 mas	10.3mas	
Radius	775 $R_\odot$	654 $R_\odot$	
Luminosity	69000 $L_\odot$	44500 $L_\odot$	Data from current photometry.
Period(s)	≈ 400d	≈ 140d-165d	Data from current photometry
	≈ 4.05yr	> 2 yrs.	P = 140d from 1996/97 photometry

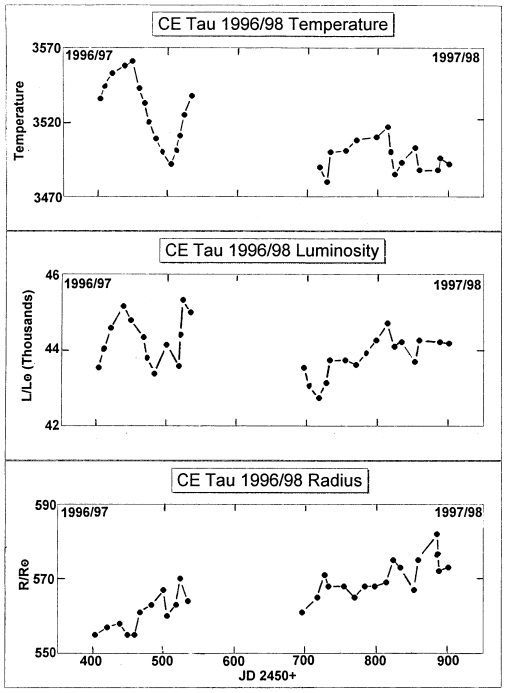

Figure 2. CE Tau derived effective temperature, luminosity, and radius variations for the 1996/97 and 1997/98 observing seasons

The authors would like to thank Dr. Robert Wing for his advice and support. We also acknowledge the use of the SIMBAD database and the Hipparcos Main Catalog. This research is supported by NSF grants AST-9315365 to Villanova University and AST-9528506 to the Four College Consortium.

References:

Boyd, L.J., Genet, R.M., Hall, D.S., 1984, *IBVS*, No. 2563
Di Benedetto, G.P., 1993, *A&A*, **270**, 315
Dyck H.M., Benson J.A., Van Belle G.T., Ridgway, S.T., 1996, *AJ*, **111**, 1705
Krisciunas, K.L., 1986, *JAAVSO*, **15**, 15
Mahler, T., Wasatonic, R.P., Guinan, E.F., 1997, *IBVS*, No. 4500
Morgan, N., Wasatonic, R.P., Guinan, E.F., 1997, *IBVS*, No. 4499
Quirrenbach, A. et al., 1993, *ApJ*, **406**, 215
Schwarzschild, M., 1975, *ApJ*, **195**, 137
Wing, R.F. 1978 in Spectral Classification and Color Temperatures for 280 Bright Stars in the Range K4 - M8, Astronomy Department, Ohio State University
Wing, R.F., 1979, Standard Stars for Eight-Color Photometry, Dudley Obs. Report 14, ed. A.G. Davis Philip
Wing, R.F., 1992, *JAAVSO*, **21**, 42