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BRIGHTNESS VARIATIONS OF THE COOL SUBGIANTS OF TOTALLY ECLIPSING ALGOL BINARIES

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ABSTRACT

In a monitoring program lasting several years, we have searched for eclipse-to-eclipse variations in the light levels of totality in 10 Algol-like binaries. Significant variations were found in U Cep, RW Tau, X Tri, U Sge, and RV Oph. Five-color observations of the first three are adequate to show that the cool contact subgiants were responsible for these variations. We show that brightness increases of the subgiants in U Cep and RW Tau are correlated with eruptive transfer events, and therefore are directly related to instabilities in the lobe-filling subgiants.

Subject headings: stars: eclipsing binaries — stars: variable

I. INTRODUCTION

Observational studies of mass transfer in close binary systems usually treat circumstellar effects, hot spots that may appear on the mass-gaining star ("gainer") or on a surrounding accretion disk, and orbital period changes produced by transfer or loss of angular momentum. In semidetached systems, the nominally contact star ("loser") from which mass flow originates can rarely be studied because of the overpowering luminosity of the gainer or surrounding accretion disk. During primary eclipse totality of completely eclipsing Algols, however, the outer hemispheres of the losers are visible for up to several hours. A photometric study of these stars may help in understanding their instabilities and resulting irregular mass flows characteristic of these, and possibly other, binaries.

Koch (1972) noted that many subgiant losers are suspected of brightness and color changes. Batten (1974) described evidence for variations in the cool component of U Cephei (B7 V+G5–8 III–IV, $P=2.49$ day), and suggested chromospheric activity as a possible cause. Hall and Walter (1974) recognized that light curves slanted up or down during totality in many systems, suggesting circumstellar matter as a probable cause. Using five-color photometry, Olson (1980*a*) separated light excesses seen at various times during totality in U Cep into (1) an optically thick hot ($\sim$12,000 K) part due to material around the B gainer, and (2) a cooler part characteristic of a brightening of the G loser. Thus, multicolor photometry is required to distinguish circumstellar effects around the gainer from intrinsic variations of the cool loser. We show in this paper that cool star variations are present in several bright Algols.

II. OBSERVATIONS

Many of these observations were part of a three-year search for eruptive mass-transfer events in Algol-like binaries. Five-color *uvbyI* observations were obtained at Prairie Observatory, and supplemented with observations at Kitt Peak National Observatory (KPNO) and Mount Laguna Observatory of San Diego State University. Observing techniques have been discussed by Olson (1980*a*). Table 1 lists the systems observed, *n*, the number of eclipse totalities observed for each binary, and related information. All observations were corrected for differential extinction and transformed to the standard Strömgren-Crawford and Kron systems. Yellow magnitudes were transformed to Johnson *V*. Standard colors of comparison stars were obtained at Prairie Observatory and KPNO by usual techniques of observing standard and comparison stars together on photometric nights. In a few cases, comparison indices were obtained by differential observations with respect to the nearest standard stars.

We are attempting to measure small brightness changes ($\lesssim$0.2 mag) in faint subgiants ($V\sim$9–12) near the cool limit of the four-color standard system. Large accidental or systematic photometric errors will render such measurements useless. Since repeated observations were made during eclipse totality, accidental errors are known. Possible sources of systematic errors include electronic amplification nonlinearities or calibration errors, filter red leaks, and uncertainties in transformation coefficients. Pulse-counting electronics were used at Prairie Observatory and KPNO, and counting rates were low enough to assure that coincident-pulse correc-

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TABLE 1

OBSERVATIONS OF ALGOL BINARIES DURING TOTALITY

Binary (1)	n (2)	$E(by)$[a] (3)	Sp(Cool)[b] (4)	T[c] (5)	Comments (6)
S Cnc[d]	5	0.00	G8	4800	No variation $\lesssim$0.02 mag, except in u.
U Cep	15	0.05	G8	5150	
SW Cyg	3		K1		No variation, but faint.
W Del	3		G5		No variation, but faint.
RW Mon ...	2		G4		No variation.
RV Oph	2	0.15	G1	5600	Small contribution from third light.
ST Per	4		K1–2		No variation, but faint.
U Sge	7	0.05	G2	5350	
RW Tau	6	0.10	K0	4900	Includes close visual companion.
X Tri	4	0.05	G3	5120	Includes close visual companion.

[a]Reddening determined from colors observed outside eclipse, corrected for cool star (U Cep, U Sge, RV Oph, X Tri); from Bookmyer (1977) (RW Tau).

[b]Spectral types from Wood *et al.*(1980), except that of RV Oph, which is from Koch (1973).

[c]Temperatures of outer hemispheres of cool components which show light variations, derived from flux fitting § III.

[d]Crawford and Olson (1980*b*).

tion errors were negligible. Gain steps in the DC integrator used at Mount Laguna Observatory were calibrated at the start and end of each night, yielding calibration errors $\lesssim$0.001 mag. A direct check on possible red leaks in *uvby* interference filters was available from observations of totality in S Cnc with EMI 6256 blue-sensitive and RCA C31034 A-02 red-sensitive tubes at Prairie Observatory. No evidence for red leaks above 0.01 mag was found. RCA red-sensitive tubes were used at Prairie Observatory and at KPNO.

To avoid any problem with Hδ emission in the standard violet (v) filter, most observations were made with a violet interference filter centered $\sim$100 Å longward of the Hδ line. To minimize standardization problems, A-type four-color standards, with strong Hδ absorption, were usually not observed. It is possible that these violet differential magnitudes are not precisely on the standard system, but for all observations analyzed in this paper, the same violet filter was used.

The largest source of systematic errors was in transformation coefficients. For visual, blue, and ultraviolet transformations, for example,

$$\mathrm{V}=\mathrm{A}+\mathrm{B}(b-y)+y_{\mathrm{obs}}$$

$$(b-y)=\mathrm{C}+\mathrm{D}(b-y)_{\mathrm{obs}}$$

$$(u-b)=\mathrm{L}+\mathrm{M}(u-b)_{\mathrm{obs}},$$

where the 'obs' subscript refers to quantities on the instrumental system and corrected for differential extinction. The differential standard magnitudes become, for example,

$$\Delta\mathrm{V}=(1-\mathrm{BD})\,\Delta y_{\mathrm{obs}}+\mathrm{BD}\Delta b_{\mathrm{obs}}$$

and

$$\Delta u=\mathrm{M}\Delta u_{\mathrm{obs}}+(\mathrm{D}-\mathrm{M})\Delta b_{\mathrm{obs}}+(1-\mathrm{D})\,\Delta y_{\mathrm{obs}}.$$

Errors in differential standard magnitudes are

$$\delta(\Delta\mathrm{V})=(\mathrm{B}\delta\mathrm{D}+\mathrm{D}\delta\mathrm{B})(\Delta b_{\mathrm{obs}}-\Delta y_{\mathrm{obs}})\quad\text{and}$$

$$\delta(\Delta u)=\delta\mathrm{M}(\Delta u_{\mathrm{obs}}-\Delta b_{\mathrm{obs}})+\delta\mathrm{D}(\Delta b_{\mathrm{obs}}-\Delta y_{\mathrm{obs}}).$$

Typical values are $(\Delta b_{\mathrm{obs}}-\Delta y_{\mathrm{obs}})\sim0.5$, $(\Delta u_{\mathrm{obs}}-\Delta b_{\mathrm{obs}})\sim0.8$, $\mathrm{B}\lesssim0.1$, and D and M$\sim$1. Errors in transformation coefficients are conservatively $\sim$0.01 to 0.02, giving differential magnitude errors $\sim$0.005 to 0.01 mag. Accidental errors are comparable to or somewhat larger than transformation errors. We tentatively assign only accidental errors in the observational/theoretical comparisons discussed below. Finally, we note that a pulse preamplifier was added to the Prairie Observatory system in 1979, considerably improving signal-to-noise ratio. Earlier observations were of somewhat lower quality, and some results discussed in this paper fall slightly short of the currently obtainable precision.

III. RESULTS

a) Light Variations of the Subgiant Losers

Figure 1 shows infrared variations on two nights near midprimary eclipse in RW Tau. Variations of comparable size, $\sim$0.1 to 0.2 mag, are present at all wavelengths in RW Tau, U Cep, and X Tri; smaller changes were seen in U Sge and RV Oph. The wavelength dependence of the added light is nearly identical to the normal photospheric light of the cool loser, so circumstellar light cannot be responsible for these variations. Analysis of ingress and/or egress parts of primary eclipse light curves of RW Tau and X Tri shows conclusively that surface brightness, not radius, changes account for all variations (see Fig. 1). Light curves of U Cep are too unstable to disprove small radius changes of its cool component. Therefore, temperature variations of part or all of the visible hemispheres of the subgiants must be responsible for most observed changes in light level from eclipse to eclipse. We model these brightness changes using theoretical fluxes obtained from grids of model stellar atmospheres.

Let minimum and maximum subgiant brightness be "reference" and "active" levels, respectively. We convert the observed subgiant magnitudes to relative monochromatic fluxes. Let l_λ and l_λ(ref) refer to active and reference levels, and treat fluxes normalized to the yellow reference flux [e.g., l_λ/l_y (ref)]. Observed colors, corrected for interstellar extinction, were converted to relative fluxes with the relations given by Olson (1980*a*), except that the ultraviolet-blue calibration was modified slightly to agree with $(u-b)$ given by Kurucz (1979) for his 5500 K model:

$$(u-b)=0.77-2.5\log(l_b/l_u).$$

Theoretical fluxes were interpolated between those of Kurucz (1979) and of Carbon and Gingerich (1969). Violet and ultraviolet fluxes of the latter grid were first modified slightly to bring predicted $(v-y)$ and $(u-b)$ colors into agreement with observations (Olson 1974). Log(surface gravity) $=\log g=3.5$ was used, as appropriate for subgiants.

Figure 2 shows observed fluxes, $l_\lambda(\text{ref})/l_y(\text{ref})$, for the coolest (S Cnc, *dashed lines*) and hottest (U Sge, *full lines*) subgiants. The observational spread contains estimated errors in comparison star magnitudes and differential (subgiant minus comparison) magnitudes. Theoretical fluxes are: *Triangles,* S Cnc, 4800 K; *circles*, U Sge, 5350 K. Similar comparisons yielded the temperatures listed in column (5) of Table 1. In all cases, theoretical fits to observations are satisfactory and reveal no peculiarities in the observed subgiant flux distributions (see also Figs. 3, 4, and 5).

Figure 3 shows fluxes observed for U Cep in its reference state (*full lines*, 1977 October 13) and in its active state (mean of 1980 April 5, 25, and May 5). A transfer burst was in progress on 1980 April 5 and the ultraviolet eclipse was partial, so this point was excluded from the active average. The remaining data, from *flat* portions of eclipse totality, clearly suggest subgiant brightness variations. Circles model the reference level at $T=5150$ K, and triangles represent the active state with uniform heating of the visible hemisphere to 5250 K. Nonuniform heating from a region as hot as $\sim$7000 K covering $\sim$3.5% of the projected radiating surface is about equally successful at explaining the brightening. Still hotter, smaller regions produce too much violet and ultraviolet, and too little infrared, to satisfy observations. Small cool regions might also be mixed in with hot regions. However, a 4000 K region covering 10% of the visible hemisphere would require a compensating hot region giving the same net effect of an excess of short-wavelength radiation. Thus, the observed brightening in U Cep was most likely caused by a slight warming of most of the visible outer hemisphere of the subgiant loser.

Similar comments apply to RW Tau (Fig. 4), where the reference level occurred on 1980 October 3 and the active level on 1978 November 8. Theoretical fluxes are for 4900 K and 5020 K, with uniform heating assumed

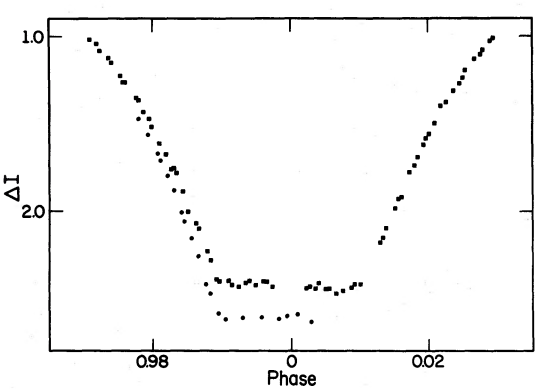

FIG. 1

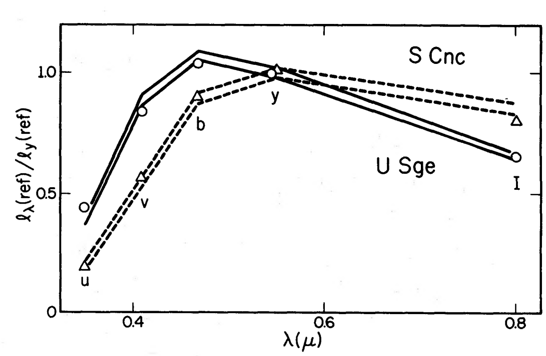

FIG. 2

FIG. 1.—Infrared observations of RW Tau, showing the effect of brightness variation of the cool subgiant on primary eclipse light curve.
FIG. 2.—Observed monochromatic flux distributions of the cool stars in S Cnc (*dashed lines*) and U Sge (*full lines*) in its reference, minimum brightness, state. Triangles and circles are theoretical atmospheric fluxes for 4800 K and 5350 K, respectively, and for log $g=3.5$.

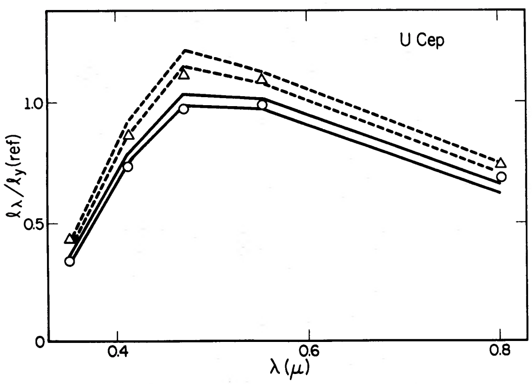

FIG. 3

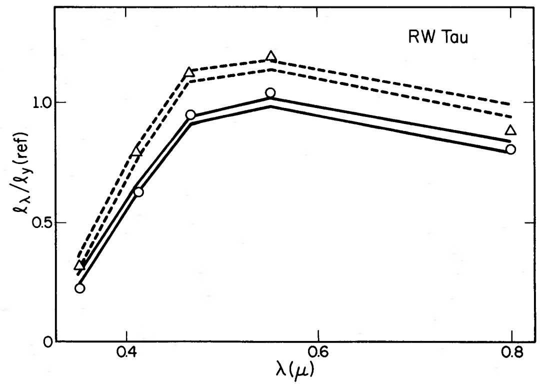

FIG. 4

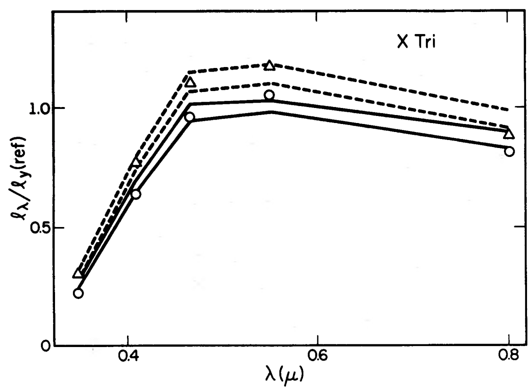

FIG. 5

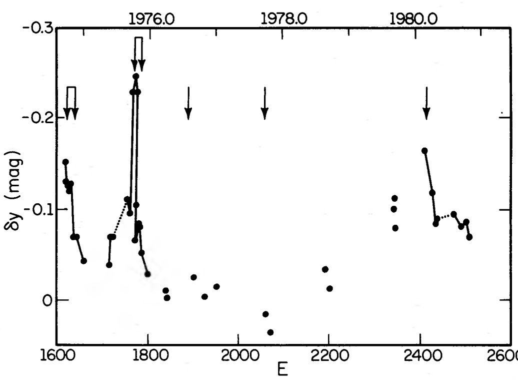

FIG. 6

FIG. 3.—Observations of the cool star in U Cep in reference (*solid lines*) and active (*dashed lines*) states. Observational spread corresponds to estimated errors in the comparison star and differential (U Cep minus comparison) magnitudes. Theoretical fluxes are: *circles*, 5150 K; *triangles*, 5250 K.

FIG. 4.—Observations of the cool star in RW Tau in reference (*solid lines*) and active states. Theoretical fluxes are: *circles*, 4900 K; *triangles*, 5020 K.

FIG. 5.—Observations of the cool star in X Tri in reference (*solid lines*) and active states. Theoretical fluxes are: *circles*, 4900 K; *triangles*, 5020 K.

FIG. 6.—Brightening of the cool subgiant in U Cep in yellow magnitudes, plotted against orbital cycle count E (see text). Vertical arrows mark episodes of mass transfer verified by multicolor photometry. In the 1976 and 1977 episodes, observations of the cool subgiant could not be made.

for the active state. Agreement with observations is satisfactory, except in the infrared. Figure 5 shows results for X Tri, where the reference level was 1978 November 19 and the active was a mean of 1978 September 9 and 1980 November 3. Theoretical fluxes are for 4900 K and 5000 K. Thus, a uniform photospheric temperature increase $\sim$100–150 K accounts in each case for the brightening of the subgiant. The only minor, but persistent, discrepancy is in the infrared, where a uniform temperature rise accounts for only about half of the observed brightening. Complete agreement with observations could formally be reached by allowing a much smaller temperature increase accompanied by a radius increase $\sim$5%. Such a radius increase, however, would be inconsistent with ingress and egress portions of primary eclipse.

b) *Correlations with Mass-Transfer Events*

Brightening of the subgiant loser in Algol-like systems may be correlated with irregular mass flow to the hot gainer. Of the five binaries where brightness changes of the cool star were seen, U Cep and RW Tau have shown sporadic mass transfer (Crawford 1979; Crawford and Olson 1979, 1980*a*; Olson 1980*a*, *b*, *c*, 1981*a*). In binaries showing no variation, none has shown eruptive transfer so far.

The case is clearest for U Cep: five isolated episodes of severe primary eclipse distortion resulting from mass transfer have been observed in the *uvby* system since late 1974 by Crawford and Olson (references above). Figure 6 correlates $\delta y \equiv \Delta y(\mathrm{obs}) - \Delta y(\mathrm{ref})$, the brightening of the cool loser relative to the adopted reference level, with transfer episodes shown as vertical arrows. E is the cycle count based on epoch JD 2,438,291.502 and period $2^{d}.4930410$. Cool star observations are lacking in the third episode because both visual companions had to be included in observations made by R. C. Crawford with the 61 cm telescope maintained by UCLA at Ojai, California, and in the fourth episode because the telescope was relinquished during totality to an astronomer visiting Prairie Observatory. With these allowances, the correlation is highly suggestive: brightening of the G star preceded and/or accompanied events. The G star variation could consist entirely of a series of incompletely observed "spikes" similar to the late 1975 event. Alternatively, such spikes may be superposed on a more gradual brightness variation that reached a minimum in late 1977. The most rapid variations occurred on a time scale $\sim$ 50 orbital cycles or 125 days.

Similar but less extensive data for RW Tau are shown in Figure 7 (Olson 1980*c*, 1981*a*). Only in the first observation of RW Tau was an appreciable brightening not accompanied by transfer activity.

Probably no change in subgiant radius occurred with any of the variations described above. The energy sources for brightness increases could be recombination energy of hydrogen, as matter moves upward toward the surface of the subgiant loser prior to flowing toward the hot star. We estimate this flow rate for U Cep by considering a typical $\delta y \sim -0.2$ mag (Fig. 6) and the absolute magnitude of the G subgiant given by Batten (1974), to find $\dot{M} \sim 4 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$. This value is certainly not unreasonable as a transient flow rate, and is not inconsistent with hydrogen recombination as the energy source for brightness fluctuations in the subgiants of some Algol-like binaries.

In summary, small photospheric temperature increases can account for brightness variations of the cool subgiants in the Algol-like eclipsing systems U Cep, RW Tau, and X Tri; similar smaller changes may also occur in U Sge and RV Oph. Enough data have been accumulated to suggest that subgiant brightening precedes and/or accompanies episodes of mass transfer.

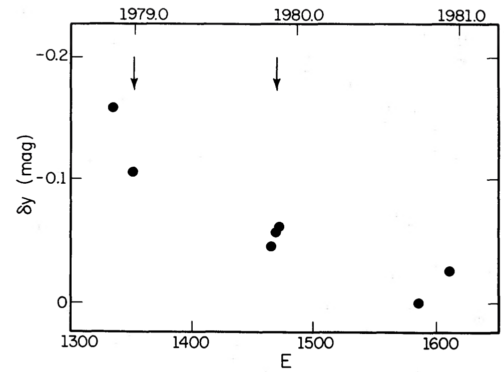

FIG. 7.—Brightening of the cool subgiant in RW Tau, plotted against orbital cycle count E based on epoch 2,440,127.1550 and period $2^{d}7688368$ (Olson 1981*b*). Vertical arrows mark episodes of mass transfer verified photometrically.

Such brightness variations are related to instabilities in the Roche lobe-filling components of these close binary stars. More accurate observations of these variations may lead to a clearer model of subgiant activity.

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