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PHOTOMETRY OF ALPHA ORIONIS, CE TAURI, AND MU CEPHEI

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Abstract

This paper presents **BV** photometry of three SRc variable stars: alpha Orionis, CE Tauri, and mu Cephei, made with careful consideration of the first and second order atmospheric extinction and reddening parameters. Betelgeuse displayed a 0.4 magnitude rise in brightness, peaking on approximately 26 February 1986 (JD 2446488). For Betelgeuse, <**B-V**> = 1.876 ± 0.014 from 17 differential measurements with respect to gamma Orionis over a span of four months. This is somewhat redder than other published values.

On a clear night at the 9200-foot level of Mauna Kea on the Island of Hawaii, the typical **V** band extinction is 0.15 magnitude/air mass, and the sky brightness at the zenith on a clear night is **V** = 21.2 magnitudes/square arc second.

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The supergiant M stars alpha Ori, CE Tau, and mu Cep exhibit irregular variability of a few tenths of a magnitude in **V**. Because they are extensively studied in various astronomical projects (e.g., speckle interferometry), photometric monitoring of these stars is particularly important. For a review on the variability of alpha Ori see Goldberg (1984).

The 1981 and 1982 observations were made in San Jose, California, at 200 feet above sea level. The January 1983 data on alpha Ori were obtained above Los Gatos, California, at the 2400-foot level. The 1985 and 1986 data were taken at Hale Pohaku at the 9200-foot level of Mauna Kea on the Island of Hawaii.

Data from October 1979 to March 1982 on alpha Ori have already been published (Krisciunas 1982a; 1982b). The latter paper reported variations in the **B-V** color of Betelgeuse on the order of 0.05 magnitude.

Our telescope is a 15-cm f/5.82 Newtonian reflector. The photometer employs an uncooled RCA 931A photomultiplier tube operated at -1000 V and **UBV** filters from Estafilter. The 1981/2 observations were made with a diaphragm giving an elliptical piece of the sky 72 by 151 arcsec. The other observations were made with a diaphragm giving a 132 by 209 arcsec beam. For the most part the data were reduced from strip chart records. Otherwise the data were read directly off the ammeter.

On several occasions I was able to carry out all-sky photometry, wherein the extinction, reddening, and transformation coefficients are explicitly derived each night. Otherwise I carried out differential photometry with respect to the comparison stars in Table I. In all cases where the differential extinction corrections would amount to more than a few hundredths of a magnitude, the extinction on those nights was explicitly derived. The adopted magnitudes and colors of the comparison stars were taken from the latest edition of the **Bright Star Catalogue** (Hoffleit and Jaschek 1982). For standard stars the **V** magnitudes and **B-V** colors in the **Bright Star Catalogue** are in most cases equal to or within 0.01 magnitude of the values given by Johnson et al. (1966) or in the much more extensive list of Nicolat (1978), which encompasses measurements by Johnson and his collaborators. This fact, plus the ready availability and up-to-date nature of the **Bright Star Catalogue** regarding the status of recently demonstrated or suspected variability of some stars, makes the data in the **Bright Star Catalogue** very useful, although officially "unstandardized."

For all-sky photometry, an average of 9 standard stars per night was used to obtain the transformation equations to the **UBV** system. Their magnitudes and colors were taken from the **Bright Star Catalogue.** When differential photometry was necessary I reduced the data with the transformation coefficients given in Table II. The 1981-3 transformation coefficients were determined from differential observations of 27 LMi and 28 LMi, for which delta **V** = 0.378, delta (**B-V**) = -1.03 (Hall 1983). The other values in Table II were determined on nights when all-sky photometry was possible. For the differentially derived data in this paper I derived the differential **V** magnitudes according to Equation 28a of Hardie (1962), while the differential **B-V** colors were determined according to Equation 9b of Welch (1979), in which the first and second order reddening coefficients are derived from instrumental colors **outside the atmosphere** (see Hardie 1962, pp. 186-7). Differential magnitudes and colors were added to the appropriate values in Table I to obtain standard magnitudes.

Tables III, IV, and V give data for alpha Ori, CE Tau, and mu Cep, respectively. Given are the double date (the second number being the UT date), the Universal Time, the geocentric Julian Date, the **V** magnitude, **B-V** color, the number of observations of the program star on that night, and the data reduction mode (either differential or all-sky). The magnitude and color errors given in Tables III-V are the "standard deviation of the mean" of a night's measurements. For CE Tau, when only one reading was taken in **V** and **B**, the error given is the RMS residual of the least-squares transformation of the instrumental magnitudes and colors of the standard stars to the **UBV** system. Figures 1, 2, and 3 are plots of the light curves of the three stars, giving **V** magnitudes vs. geocentric Julian Date. In Figures 1 to 3 circles represent differentially derived data; squares represent all-sky data. If no error bars are plotted, the errors are less than or equal to the size of the symbols.

A major difference between differential and all-sky photometry comes out in the quoted errors of the observations. In the differential mode one assumes stable transformation coefficients (which might only be determined once a year) and assumes some value of the **inside the atmosphere** second order reddening (typically k''_{bv} = -0.03). The plots of **V** or **B-V** vs. time are much smoother for differential values but contain various undetermined **systematic** errors. All-sky photometry, on the other hand, is much more complicated and requires very good sky, such as can be found at Mauna Kea. However, such things as volcano eruptions at nearby Kilauea or Mauna Loa affect the extinction and reddening and presumably also the transformation coefficients. The advantage of all-sky photometry is that one obtains standardized magnitudes and colors, instead of standardized differential colors with respect to one star. All-sky photometry is important for absolute calibration of fluxes required for other experiments such as speckle interferometry. While the values given for November 9 - 11 UT for alpha Ori show some raggedness, two of these values are from all-sky photometry. The differential values are **V** = 0.679, 0.690, and 0.681, respectively, showing the superior **internal** consistency of differential results. For CE Tau the value for November 10 and 11 UT should be taken as the average of the two values given in Table IV for those dates.

For others planning **V** band observations of these stars, Table VI gives mean **B-V** colors from the present data, as well as from Johnson *et al.* (1966, Table 9) and the values in the 1982 **Bright Star Catalogue.** The present value given in Table VI for alpha Ori was obtained from 17 measurements on six nights, taken differentially with respect to gamma Ori when both were high in the sky. Crucial to this measurement is the value of the second order atmospheric reddening parameter k''_{bv}, which must be determined from instrumental colors before the data can be fully reduced. (A systematic error of 0.04 in k''_{bv} while using the same value of the transformation coefficient mu leads to an error of 0.10 in the derived color of Betelgeuse, because it is so red and the comparison star is so blue.) From the averages of the out-of-atmosphere instrumental colors of alpha Ori and gamma Ori and the seasonal averages of the atmospheric reddening as measured by each star, I obtained the following values for the first and second order reddening coefficients for the sky at the 9200-foot level of Mauna Kea:

$$k'_{bv} = 0.107 \pm 0.011$$

$$K''_{bv} = -0.054 \pm 0.014.$$

Due to the inherent difficulties in accurately measuring the extinction, reddening, and transformation coefficients on a given night, it is not possible to measure variations in the color of Betelgeuse using all-sky photometry. If one does differential photometry with the same telescope, the same photomultiplier tube and filters, at the same site, always observing Betelgeuse and its comparison star gamma Ori high in the sky, variations of the **B-V** color can be measured if they exceed a few hundredths of a magnitude. The derived color of Betelgeuse also depends on the second order atmospheric reddening parameter k''_{bv}, which is **assumed** to have a stable value. This assumption, however, is difficult to test. Many more observations of extinction stars would be required to investigate this.

It is of course advantageous for differential photometry to have the comparison star and program star of comparable color, in addition to observing them at comparable air mass. These two conditions are not easily met for alpha Ori. However, for CE Tau the AAVSO recommends BS 1816 = 117 Tau (**V** = 5.77, **B-V** = 1.63) as the comparison star. For mu Cep the AAVSO recommends BS 8312 (**V** = 6.08, **B-V** = 1.34) as the comparison star.

The photometry done at Mauna Kea also allows some general conclusions about the quality of the sky in the **V** band. Observations of extinction stars of various colors confirm that the present system gives **V** band extinction values that are essentially not a function of instrumental color. Combining nights with comparable **V** band extinction, I find $k''_v = 0.044 \pm 0.028$. This is not statistically significant from 0. Given the expectation that the value was supposed to be 0 (Hardie 1962; Hall and Genet 1982) I therefore assumed that k''_v was indeed equal to 0. I found the following values of the **V** band extinction:

4 excellent nights $k_v = 0.154 \pm 0.006$ magnitude/air mass
4 good to poor nights $k_v = 0.304 \pm 0.053$ magnitude/air mass.

The overall range of nightly **V** band extinction was 0.137 to 0.446 magnitude/air mass.

It might be expected that the **V** band extinction on a good night at the 9200-foot level of Mauna Kea should be slightly better than 0.15 magnitude/air mass. The inversion level at Mauna Kea is usually just below this level, and there may be some mixing of the atmosphere still going on at 9200 feet. Eruptions of the two nearby volcanoes can affect the local sky as well.

Finally, observations of the night sky brightness at Mauna Kea have been made. The sky readings at the zenith were converted to magnitudes from measurements of standard stars and the known or assumed extinction. To calibrate the sky readings at the zenith to flux per unit area on the sky, I measured the focal length of the main objective to the nearest millimeter (to fix the plate scale) and measured the diaphragm dimensions to the nearest 0.01 mm in a microscope. Any systematic error in our beam size leads to an error in the night sky brightness readings of no more than 3 percent (0.03 magnitude).

For 8 clear, moonless nights I found that the S10, the number of 10th magnitude stars per square degree, is 421 ± 26. This is equivalent to **V** = 21.2 ± 0.1 magnitudes/square arc second. For comparison the value for the 7800-foot level of La Palma in the Canary Islands is **V** = 21.4 magnitudes/square arc second (Murdin 1985). However, the Mauna Kea mid-level facility area, where these observations were made, is not completely protected from artificial illumination, as is the summit area at 13,800 feet.

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TABLE I

Comparison Stars for Differential Photometry

Program *	Comp *	Comp * V	Comp * B-V
alpha Ori	gamma Ori	1.64	-0.22
CE Tau	iota Tau	4.64	0.16
mu Cep	nu Cep	4.29	0.52

TABLE II

Transformation Coefficients

Dates	epsilon	mu
Nov 1981 - Jan 1983	-0.047 ± 0.003	0.960 ± 0.003
Aug 1985 - Oct 1985	-0.032 ± 0.016	0.838 ± 0.017
Nov 1985 - Apr 1986	-0.094 ± 0.008	0.940 ± 0.010

TABLE III

Photometry of Betelgeuse (alpha Ori)

Date	UT	Geocentric JD (2440000+)	V	B-V	n	Mode
2/3 Jan 1983	0458	5337.7069	0.605 ± 0.012	1.849 ± 0.011	3	diff
21/22 Sep 1985	1221	6331.0146	0.576 ± 0.046	1.870 ± 0.046	3	all-sky
13/14 Oct 1985	1044	6352.9472	0.678 ± 0.015	1.938 ± 0.016	3	all-sky
8/9 Nov 1985	1337	6379.0674	0.679 ± 0.008	1.866 ± 0.028	4/2	diff
9/10 Nov 1985	1427	6380.1021	0.709 ± 0.015	1.835 ± 0.032	3	all-sky
10/11 Nov 1985	1400	6381.0833	0.643 ± 0.009	1.868 ± 0.012	3	all-sky
12/13 Dec 1985	0924	6412.8917	0.617 ± 0.032	1.982 ± 0.018	3	diff
4/5 Feb 1986	0614	6466.7597	0.346 ± 0.014		5	diff
16/17 Feb 1986	0627	6478.7688	0.284 ± 0.018	1.935 ± 0.039	4/3	diff
8/9 Mar 1986	0734	6498.8153	0.285 ± 0.028	1.853 ± 0.035	3	diff
12/13 Apr 1986	0608	6533.7555	0.360 ± 0.013		6	diff

TABLE IV

Photometry of CE Tau

Date	UT	Geocentric JD (2440000+)	V	B-V	n	Mode
28/29 Nov 1981	0648	4937.7833	4.426 ± 0.008		3	diff
2/3 Jan 1982	0528	4972.7278	4.457 ± 0.012		3	diff
29/30 Jan 1982	0730	4999.8125	4.531 ± 0.012		3	diff
23/24 Feb 1982	0438	5024.6931	4.500 ± 0.013		3	diff
21/22 Sep 1985	1139	6330.9854	4.433 ± 0.028	2.100 ± 0.036	1	all-sky
13/14 Oct 1985	1129	6352.9785	4.468 ± 0.041	2.073 ± 0.042	1	all-sky
9/10 Nov 1985	1517	6380.1368	4.392 ± 0.046	2.112 ± 0.034	1	all-sky
10/11 Nov 1985	1458	6381.1236	4.336 ± 0.030	2.124 ± 0.039	1	all-sky
12/13 Dec 1985	1009	6412.9229	4.330 ± 0.014		2	diff

TABLE V

Photometry of mu Cep

Date	UT	Geocentric JD (2440000+)	V	B-V	n	Mode
31 Aug/1 Sep 1985	0826	6309.8514	3.842 ± 0.002	2.310 ± 0.013	3	diff
19/20 Sep 1985	0745	6328.8229	3.831 ± 0.024		3	diff
21/22 Sep 1985	0920	6330.8889	3.863 ± 0.024	2.223 ± 0.034	3	all-sky
13/14 Oct 1985	0811	6352.8410	3.787 ± 0.022	2.330 ± 0.040	3	all-sky
17/18 Nov 1985	0609	6387.7563	3.725 ± 0.008		5	diff

TABLE VI

Mean **B-V** Colors

Star	This paper	Johnson et al.	Bright Star Cat.
alpha Ori	1.876 ± 0.014	1.84	1.85
CE Tau	2.102 ± 0.011	2.06	2.07
mu Cep	2.288 ± 0.033	2.26	2.35

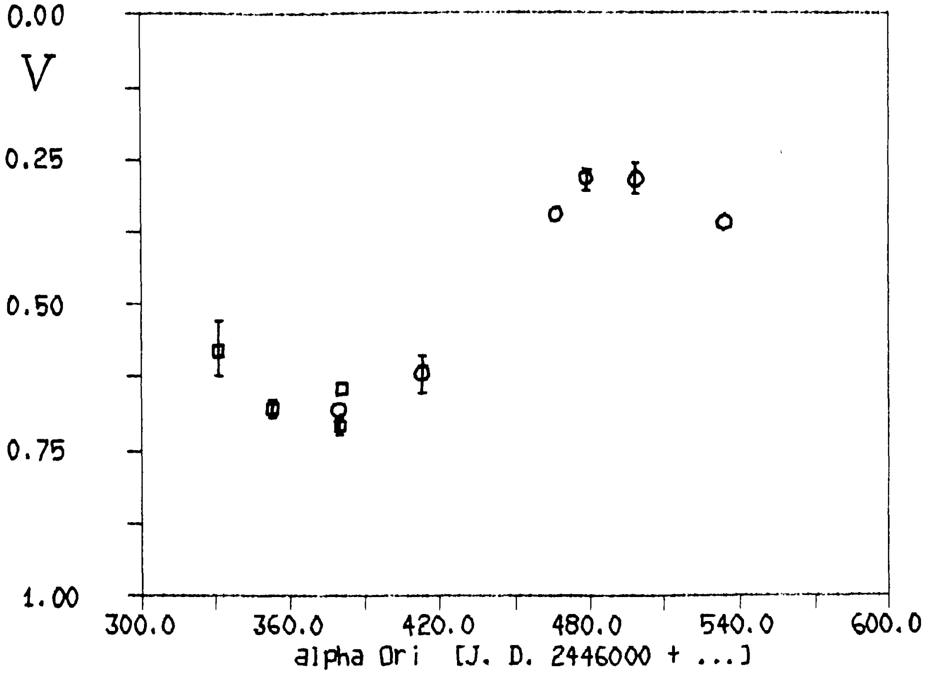

Figure 1. Light curve of alpha Ori in 1985/6. Plotted are photoelectric **V** magnitudes vs. geocentric Julian Date (2446000+). Squares represent all-sky data. Circles represent differential results with respect to gamma Ori.

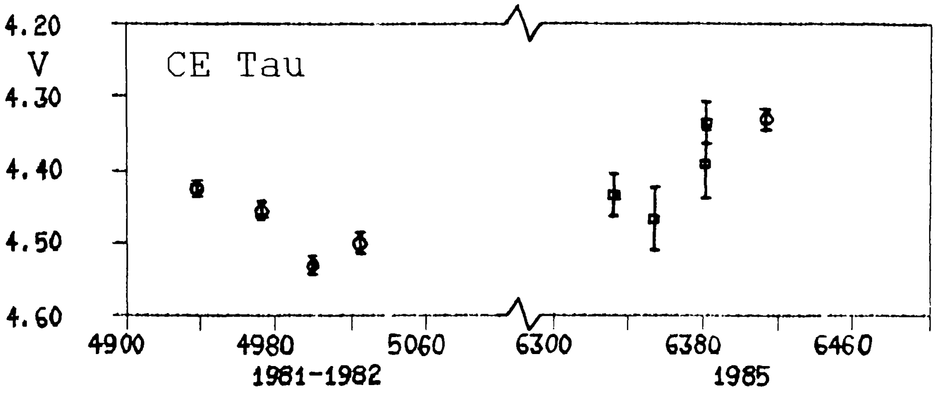

Figure 2. Light curve of CE Tau in 1981/2 and 1985. Plotted are photoelectric **V** magnitudes vs. geocentric Julian Date (2440000+). Squares represent all-sky data. Circles represent differential results with respect to iota Tau.

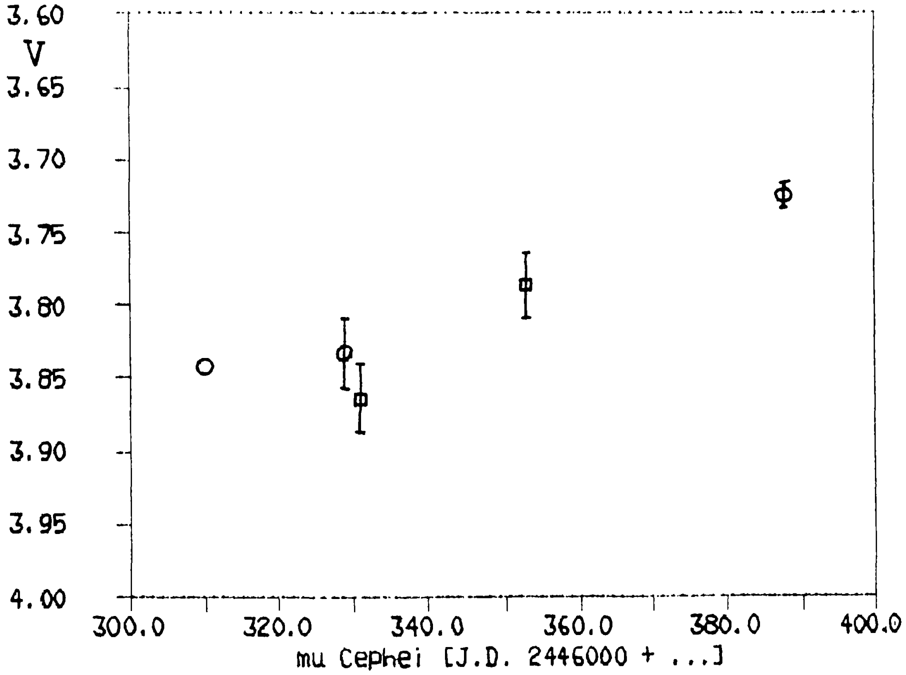

Figure 3. Light curve of mu Cep in 1985. Plotted are photoelectric **V** magnitudes vs. geocentric Julian Date (2446000+). Squares represent all-sky data. Circles represent differential data with respect to nu Cep.