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Photometric Variability of the Be Star θ Corona Borealis

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Four-color *uvby* and Hα filter observations were made of the Be star θ CrB in June and September 1970. Photometric variations as large as 0.7 mag in the u and v bands were observed in June. There appear to have been no spectroscopic changes accompanying this light variation. The variability is interpreted in terms of particulate matter in the atmosphere of the star. The size distribution of the particles must change rapidly with time to explain the detailed structure of the light curves in a single night and from night to night.

IT is well known that stars of class Be exhibit temporal changes in their spectroscopic, polarimetric, and photometric properties. In many of these stars the emission-line spectrum appears and disappears at irregular periods on the order of 10 years (Underhill 1966). Line profiles exhibit changes on time scales of minutes and weeks (Hutchings 1970). Feinstein (1968) has reported progressive or irregular variability of 33 bright southern Be stars with changes in V larger than 0.06 over a 3-year interval. Feinstein transformed his observations to the *UBV* system and has a time resolution of approximately 1 year. Shorter time-scale light variations of the order of days and weeks have been reported by Lynds (1959) for several early Be stars. Lynds' observations were limited to yellow wavelengths with time resolution usually on the order of 1 to 2 hours.

Prior to the observations reported in this paper there do not appear to be any published data indicating that θ CrB (=HD 138749=HR 5778) varied photometrically. It has a visual magnitude of $V=4.22$ (Hoffleit 1964). The star is classified as type B5e and has a large rotational velocity, i.e., $v \sin i=400$ km/sec (Slettebak 1966). Although Lockyer (1930) reported that θ CrB had emission lines in its spectrum from 1922 to 1930, none have reappeared since that latter date although the star has been and is being kept under spectroscopic surveilance (Slettebak 1970).

I. THE OBSERVATIONS

θ CrB was observed from 16 June 1970 (U.T.) through 20 June 1970 (U.T.) and again on 10, 15, 16 September 1970 (U.T.). The June observations were made with the 72-inch Perkins telescope of the Ohio Wesleyan and Ohio State Universities located at the Lowell Observatory in Flagstaff, Arizona. The September observations were made with the Lowell 42-inch reflector. Both sets of observations were made using an EMI 9558QA photomultiplier with an S-20 photocathode. The tube was maintained at $-10°$C with the aid of a thermoelectric coldbox.

The filter characteristics are given in Table I. As can be seen, they approximate the filters used in the Strömgren intermediate-band four-color photometry (with the exception of the Hα pair) (Crawford and Barnes 1970). All are interference filters except for the u band which is 8 mm of Schott glass UG-11 plus 1 mm of Schott glass WG-3.

η CrB (=HD 137107/8=HR 5727/8) was used as the primary comparison star. This system is made up of two stars of type G2 V separated by 1.4 sec of arc. They have a period of 41.56 yr and a combined magnitude of $V=4.98$ (Hoffleit 1964).

Pulse-counting equipment was used to obtain the unreduced data at the telescope. θ CrB was observed for a minimum of five 1-sec counting intervals through each of the six filters. The primary comparison star was then immediately observed in like manner. Sky brightness in each filter band was monitored at roughly 30-min intervals. Except for the Hα measures, typical 1-sec counts on the program and comparison stars ranged from about 15 000 to 55 000, while sky-plus-dark counts were no larger than 30 in the same time interval.

Averages of the five or more observed counts in each filter were reduced using a Wang 700 programmable calculator. Dr. W. Protheroe kindly provided the program. Magnitude differences in the sense of η CrB *minus* θ CrB were calculated using mean extinction coefficients (except for the Hα measures) for both observing periods. Since the largest air-mass difference is 0.1 for the program and comparison stars, the effect of nightly deviations from the mean extinction coefficients are small—much smaller than the photometric variations reported here. The adopted mean extinction coefficients are 0.41, 0.3, 0.2, and 0.1 for the u, v, b, and y bands, respectively. The Hα measurements were treated in a somewhat different manner. In this instance, we have formed the difference:

$$\Delta m_{\mathrm{H}\alpha}=(m_{\mathrm{n}}-m_{\mathrm{w}})_{\eta}-(m_{\mathrm{n}}-m_{\mathrm{w}})_{\theta},$$

TABLE I. Filter specifications.

Band	Center wavelength	Half-width
u	3479 Å	366 Å
v	4140	163
b	4708	192
y	5507	234
Hα (wide)	6570	126
Hα (narrow)	6565	28

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1971AJ.....76..634R

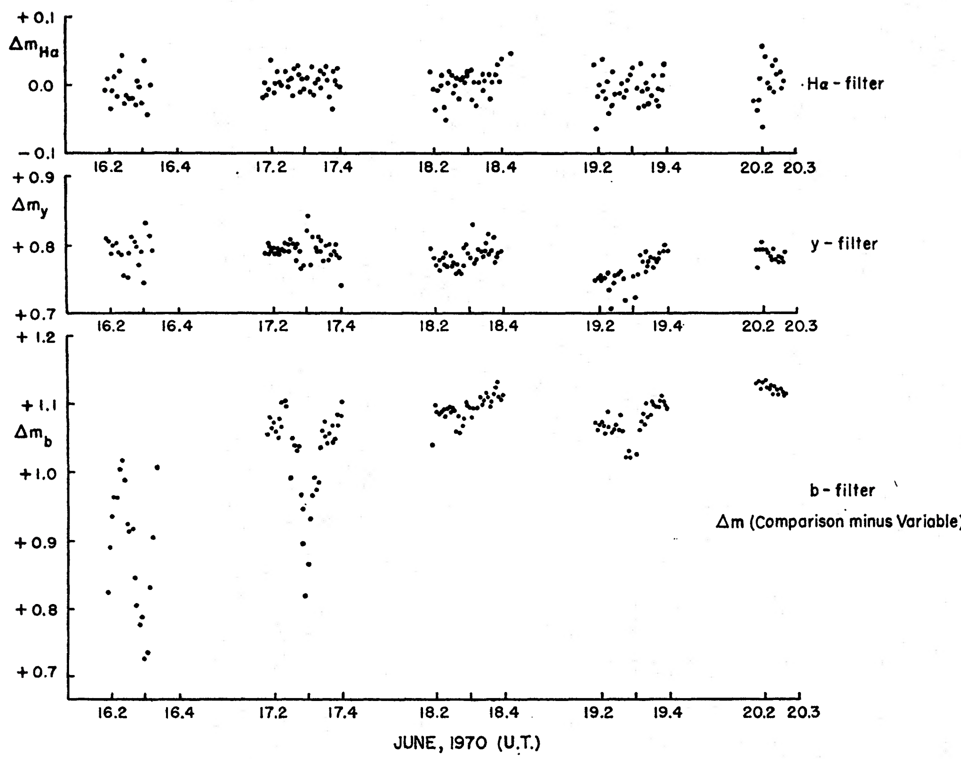

FIG. 1. Hα-, *y*-, and *b*-band magnitude differences in the sense η CrB minus θ CrB for June 1970.

where m_n and m_w refer to the instrumental magnitudes measured through the narrow and wide Hα filters, respectively.

Magnitude differences in the sense η CrB minus θ CrB are shown in Figs. 1 through 3 for the June 1970 series of observations. Averaged differences obtained in September 1970 are given in Table II. No entries are given for 10 September 1970 (U.T.) as the data are of low quality. All errors in Table II are standard errors. An estimate of the error in the data shown in Figs. 1 through 3 may be made by considering the standard error for a single observation of the comparison star

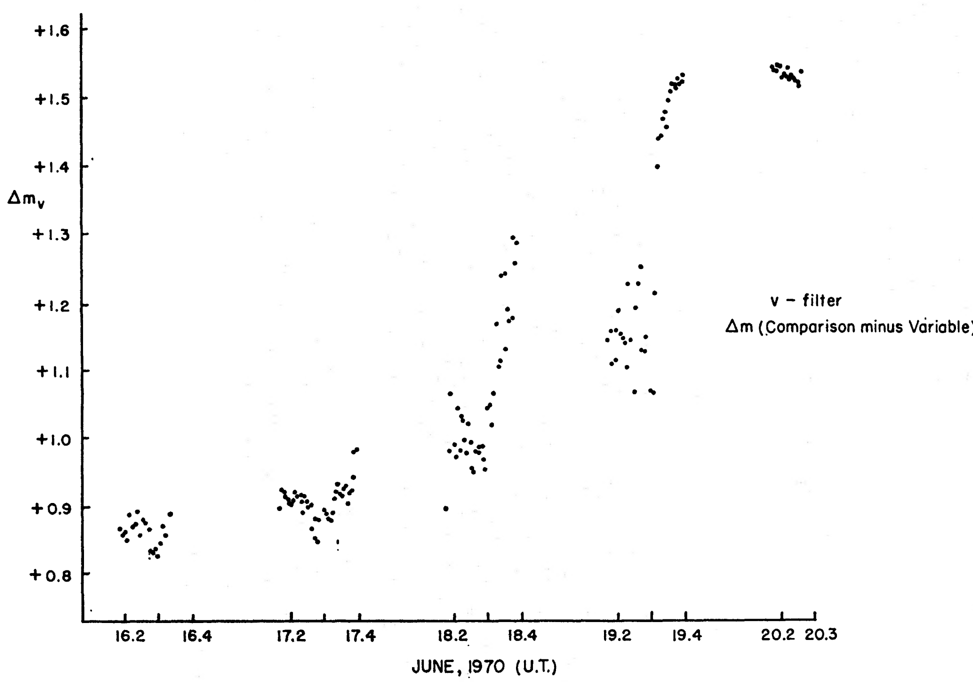

FIG. 2. *v*-band magnitude differences to the same scale as Fig. 1.

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1971AJ.....76..634R

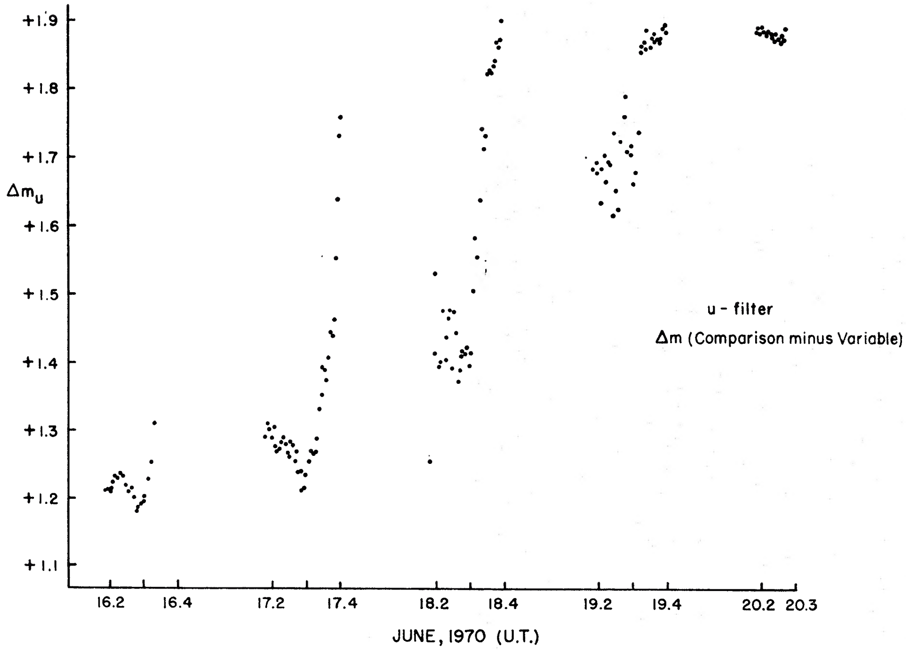

FIG. 3. u-band magnitude differences to the same scale as Fig. 1.

corrected to above the atmosphere. This ranges between ±0.01 and ±0.04 mag with ±0.02 being the most frequent irrespective of wavelength bands.

The time resolution of the points plotted in Figs. 1 through 3 is not better than 2 or 3 minutes due to the lack of simultaneous recording of the time of observation and the raw count through a given filter.

II. DISCUSSION OF THE OBSERVATIONS

It was not possible to secure simultaneous spectrograms of θ CrB during the entire June 1970 observing run. However, John Baumert did obtain nine spectra of the star throughout the night of 20 June 1970 (U.T.) on baked IIa-O plates using the Meinel Spectrograph attached to the 32-inch Schottland reflector of the Perkins Observatory in Delaware, Ohio. These are all well exposed and have a dispersion of about 85 Å/mm. The spectrum looks exactly as it has for the past 40 years with no emission present in Hβ or the higher Balmer lines. This negative result combined with the constancy of the Hα filter measurements (see Fig. 1), leads to the conclusion that shell activity probably was not responsible for the observed changes in the light output of θ CrB. This conclusion is further strengthened by the fact that in September 1970 the Hα magnitude differences are the same as those in June 1970. Spectra obtained at the same time (September 1970) with the 72-inch Perkins telescope by Dr. A. Slettebak do not show emission features. These latter spectra are also well exposed IIa-O plates and have a dispersion of 20 Å/mm.

Table III gives the $(b-y)$ colors of θ CrB and η CrB for the observing periods reported in this paper and also $(b-y)$ colors for θ CrB for three dates in 1963. These latter data were kindly supplied by Dr. D. L. Crawford in a private communication. The entries for June and September 1970 are average values over an entire night's observations. Our instrumental colors were transformed to the Strömgren $(b-y)$ index through the relation (Crawford and Barnes 1970)

$$(b-y)=C+D(b-y)_i,$$

where $(b-y)_i$ is our instrumental index corrected for atmospheric extinction. We have assumed that the transformation coefficients are constants during a given run and find from observations of standard stars (Crawford and Barnes 1970; Strömgren and Perry 1962) that in June 1970, $C=+0.349$ and $D=+1.171$. We further used a mean $(b-y)$ extinction coefficient of $+0.088$ mag per unit air mass for both observing runs.

TABLE II. Magnitude differences for September 1970 (U.T.).

Date	u	v	b	y	Hα
15	+2.13 ±0.02	+1.72 ±0.01	+1.21 ±0.01	+0.83 ±0.01	−0.05 ±0.02
16	+2.15 ±0.02	+1.73 ±0.01	+1.21 ±0.01	+0.84 ±0.01	0.00 ±0.01

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1971AJ.....76..634R

TABLE III. $(b-y)$ colors of θ CrB and η CrB.

Date	θ CrB	η CrB
29 April 1963	−0.030	...
3 May 1963	−0.041	...
3 May 1963	−0.047	...
29 June 1963	−0.032	...
16 June 1970	+0.269 ±0.023	+0.369 ±0.002
17 June 1970	+0.100 ±0.011	+0.363 ±0.002
18 June 1970	+0.018 ±0.003	+0.361 ±0.002
19 June 1970	+0.017 ±0.002	+0.366 ±0.002
20 June 1970	−0.002 ±0.003	+0.370 ±0.002
15 September 1970	−0.090 ±0.006	+0.365 ±0.006
16 September 1970	−0.080 ±0.007	+0.360 ±0.004

The standard errors quoted in Table III are actually indicative of the uncertainty in the instrumental colors and do not represent systematic errors which may be present in the transformations to the standard system.

It can be seen from Table III that during the period of photometric variation of θ CrB (June 1970) the effective color of the star reddened. Since during this time the y-band magnitude remained nearly constant, the variation in the bluer bands must represent a diminution of the light from θ CrB. In other words, there seems to be present broad-band extinction in the continuous energy output of θ CrB and this extinction is variable with time. Furthermore, this extinction is small or absent in the yellow but quite strong in the ultraviolet and violet.

A cloud of free electrons near the star would give broad-band extinction, but this extinction should be wavelength independent. This is not what is observed. A cloud or clouds composed of small particles could give rise to stronger extinction in the blue than at longer wavelengths. The degree of enhanced extinction in the blue would, of course, depend strongly on the size distribution of these particles. Figure 4 illustrates the wavelength dependence of the observed extinction. The plotted points were obtained on the assumption that the magnitude differences shown in Table II for September 1970, represent the unobstructed, quiescent continuum of θ CrB. A simple mean magnitude difference was obtained in each color for all the points plotted in Figs. 1 through 3 for a given night in June 1970. The differences between these two sets of magnitude differences are then assumed to represent a measure of the extinction at the central wavelengths given in Table I. The inset graph in Fig. 4 shows the shape of theoretical λ^{-1} and λ^{-4} extinction dependencies. One would expect a λ^{-1} law if the extinguishing particles had a characteristic dimension about that of the wavelength of light used for observation. A λ^{-4} law would result if the particles were much smaller than the wavelength.

The curves shown in Fig. 4 could be interpreted in terms of a temporally changing size distribution for

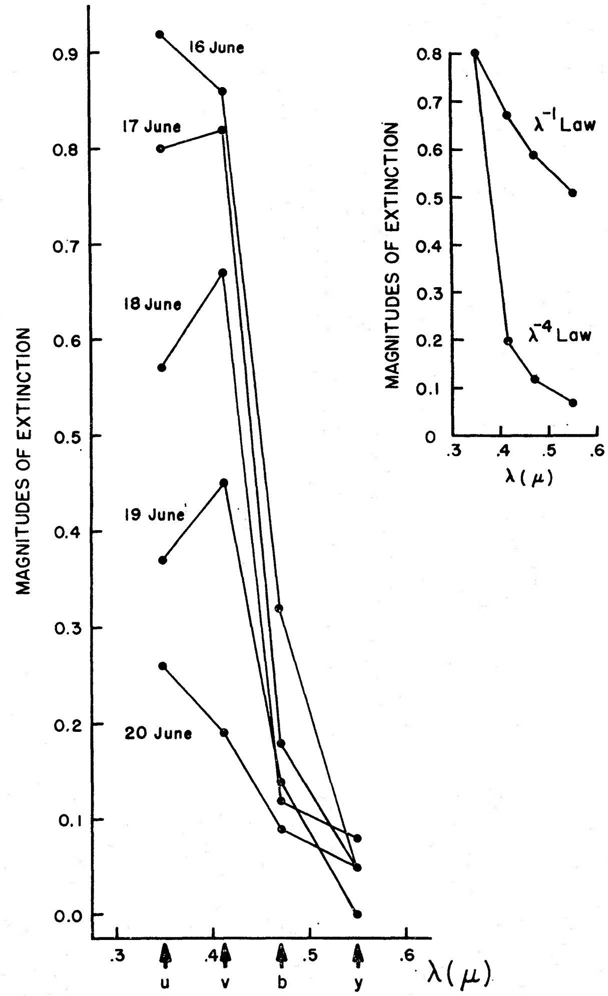

FIG. 4. Wavelength dependence of the extinction of light from θ CrB during June 1970. *Inset* shows theoretical extinction laws assuming 0.8-mag extinction at the u-band central wavelength.

the extinguishing medium. This change must take place in the rather short time of 5 days. During the early stages of the episode, the observed curves are more nearly like the theoretical λ^{-4} law while at the end of the observing period they have flattened and look more like the extinction expected from larger particles. It is as if the smaller particles had been selectively removed from the extinguishing medium by radiation pressure effects or by some destruction mechanism. In neither case, of course, is the correspondence between simple theory and observation exact but the theoretical laws are based on the assumption that only particles of a single size are present in each instance. Such would certainly not be true for the actual conditions present in the atmosphere of θ CrB.

The possibility of particulate matter existing in the atmospheres of some hot B stars has been proposed as an interpretation of polarimetric data for these stars (Serkowski 1968, 1970). Hall (1958) observed θ CrB

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1971AJ.....76..634R

on six nights in 1952 and 1953 and is uncertain whether polarization was present or not.

The rapid and large variations in the extinction of θ CrB lead to some interesting possibilities. These variations seem to have a quasiperiodicity of about 1 day. A B5 V, III, or I star with an equatorial velocity of 400 km/sec might have an equatorial rotation period of 0.5 to 4 days (Allen 1955) depending on the radius of the star and the degree of rotationally induced flattening. Hence, if the extinction is of a localized nature and is close to the surface of the star, one might expect the time variation observed. Furthermore, a star rotating this rapidly might have its equatorial gravity and temperature conditions changed to approximate those present in the atmospheres of pulsating stars (Roxburgh 1970). As is well known, some Cepheid stars have pulsation periods of a day or less. One might speculate that the apparent commensurability of the rotation and pulsation periods are coupled such that the pulsations are driven by the rotation. Then, at some phases of the localized pulsation cycle the temperature and pressure conditions might be such that solid particles would appear in the equatorial portions of the atmospheres and give rise to the broad-band extinction reported here. Such conjecture concerning the availability of favorable grain-growth conditions should be subjected to a more detailed theoretical treatment, however.

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