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uvby Photometry of Ap Stars: The Nature of the Light Variations

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Four-color (*uvby*) observations of eight Ap stars have been obtained at the Mauna Kea Observatory. For Ap stars cooler than about spectral type B9, large-amplitude light variations appear to occur only in those objects which also show pronounced spectrum variations. It is suggested that photometric variability may result from a redistribution of energy, which is caused by variable absorption in the region below about λ3000.

I. INTRODUCTION

RECENT work by Preston and others has lent strong support to the rigid-rotator model of the spectrum and magnetic variations in Ap stars (e.g., Pyper 1969; Wolff 1969; Preston 1970). This model, which was proposed by Stibbs (1950) and elaborated by Deutsch (1958a) assumes that the axis of a static magnetic field is inclined at some angle to the axis of rotation. Magnetic variations are then a consequence of rotation, which brings regions of predominantly positive and negative polarity alternately into view. The spectrum variations are similarly explained by the assumption that concentrations or "patches" of various elements exist on the surface of the star and co-rotate with it.

Relatively little effort has been made to incorporate the light variations into the framework of the rigid-rotator model. In part this is undoubtedly due to the fact that nearly all the available light curves are based on broad-band photometry. Since the wavelength dependence of the light variations can be fairly complicated (Stepień 1968a) and since the *U* filter of the *UBV* system in particular includes a number of hydrogen lines as well as the region below the Balmer discontinuity, it is difficult to interpret broad-band observations. The *uvby* system, on the other hand, makes use of fairly narrow filters (half-width ~200 Å) which, except for the *v* band, avoid all of the very strong lines found in A stars. Light curves measured with these filters can be readily compared with predictions of the various models (e.g., Peterson 1970) proposed to account for the photometric variability of magnetic stars.

In the present paper, we report *uvby* observations of eight Ap stars. Since most of these stars have previously been observed spectroscopically, it is possible to compare the light variations with the magnetic and spectrum variations. Such comparisons suggest that, for the cooler Ap stars, light variability is closely related to and may even be a necessary consequence of spectrum variability.

II. OBSERVATIONS

The observations were made with a 24-inch Boller & Chivens telescope atop Mauna Kea. The telescope is presently equipped with a Tinsley photometer, an unmodified GR amplifier, and a strip-chart recorder. All observations were made with a 9558A photomultiplier cooled thermoelectrically to a temperature of −20°C. The *uvby* filters were purchased according to the specifications employed at Kitt Peak (Hoag, private communication), and the derived transformation coefficients indicate that these filters do closely match the ones used to establish the *uvby* system.

Since Mauna Kea, at 13800 ft, is the highest permanent astronomical observatory, it is of some interest to compare the observed extinction coefficients with those measured at a lower altitude. In Table I, mean extinction coefficients for Kitt Peak (Crawford 1966; Cameron 1966) and Mauna Kea are listed.

Observations of individual stars were made in the order *u*, *b*, *v*, *y*, *y*, *b*, *v*, *u*, followed by sky measurements. Observations of the comparison and variable stars were in the order: comparison star, variable, variable, comparison star. This complete series was repeated once, either with the same comparison star if it was known to be constant from the work of other observers, or else with a second comparison star. This repetition of observations was necessary in order to reduce the random errors involved in reading deflections from the chart paper.

The colors of the comparison stars transformed to the *uvby* system are listed in Table II together with median values of the colors for each variable. The *V* magnitudes are only approximate. Variations in the *y* extinction coefficient and in the over-all sensitivity of the photometer, which was not monitored, may combine to produce errors as large as 0.05 in *V*. Since precise *V* magnitudes are not required in the discussion which follows, no attempt was made to derive them. The color sensitivity of the photometer is quite stable, the extinction coefficients for $b-y$, m_1, and c_1 have shown little if any variation, and the transformed colors are

Table I. Comparison of mean extinction coefficients.

Observatory	Mean coefficients y	$b-y$	m_1	c_1	b	v	u
Kitt Peak	0.12	0.060	0.052	0.181	0.18	0.29	0.58
Mauna Kea	0.11	0.037	0.050	0.138	0.15	0.24	0.47

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TABLE II. Mean colors for the variable and comparison stars.

Star name	V	$b-y$	m_1	c_1
53 Cam	6.05	+0.059	0.266	0.746
HR 3106	5.75	+0.264	0.177	0.489
HD 71866	6.80	+0.010	0.272	0.843
HD 71844	7.10	+0.080	0.207	1.145
3 Hya	5.80	−0.030	0.190	1.015
HD 73431	6.65	−0.020	0.133	0.923
21 Com	5.45	+0.018	0.186	1.096
23 Com	4.80	+0.009	0.140	1.104
α^2 CVn	2.90	−0.052	0.178	0.621
14 CVn	5.20	−0.023	0.129	0.854
78 Vir	4.90	+0.000	0.207	0.930
HR 5037	5.70	+0.015	0.165	1.004
HD 125248	5.90	−0.026	0.247	0.844
HR 5332	5.55	+0.004	0.141	0.979
HR 5438	6.50	+0.090	0.166	1.176
β CrB	3.65	+0.150	0.250	0.738
HR 5676	5.30	+0.026	0.169	1.076
HR 5702	6.35	+0.128	0.210	0.840

of photometric accuracy. Two of the comparison stars are included in the Strömgren–Perry catalogue, and all of the Ap stars were observed by Cameron (1966). A comparison of these and other unpublished observations with the measurements of Strömgren, Perry, and Cameron indicates that the mean errors in all three indices are about 0.01 mag.

In order to save space, the photometric observations are displayed graphically only. Tables of the measurements can be obtained from the authors. For all but two of the stars, *UBV* data are already available in the literature.

III. DESCRIPTIONS OF INDIVIDUAL STARS

A. 53 Cam

Simultaneous *UBV* and magnetic observations of 53 Cam have been reported by Preston and Stepień (1968a), who also give references to earlier work. Light minimum in *V* was found to occur at the same phase as *U* maximum. The *B* variation was small but suggested the possibility of a progressive increase in the phase of minimum light with increasing wavelength.

The present observations were made on 14 nights between the end of January and mid-April 1970, and the results are shown in Fig. 1. The elements used are those given by Preston and Stepień (1968a):

$$\text{J.D.}_{\odot}\text{(positive crossover)} = 2436120.3 + 8.0278E.$$

In this and all further figures, each point represents the average of one night's observations. This means, for example, that the three points between $\phi=0.75$ and 0.80 were obtained during three different cycles. The quantity plotted, Δy, is given by the equation

$$\Delta y = y\ \text{(variable)} - y\ \text{(comparison star)},$$

where y is, of course, the magnitude measured with the y filter; analogous equations give Δb, Δv, and Δu. The standard deviation of each magnitude difference plotted in Fig. 1 and in subsequent figures is on the average, 0.005 mag. This value was estimated from the variation in the magnitude differences observed for the two nonvariable comparison stars in those cases where two different comparison stars were used (see, for example, the discussion of the observations of 21 Com).

The measurements of 53 Cam show that u and v vary in phase with each other and 180° out of phase with b and y. The amplitude apparently passes through a minimum somewhere between λ4100 and λ4700, and the variations on either side of this minimum are in antiphase. Longitudinal magnetic minimum occurs at $\phi=0.8$, and the present measurements, like those of Preston and Stepień (1968a), suggest that y maximum and u minimum may occur about 0.1 cycle before magnetic minimum. There is no evidence of a change in the period (Rakos 1968) or in the shape of the light curve since Preston and Stepień made their observations. Both series of measurements indicate that the u curve is sharper at magnetic maximum than at magnetic minimum.

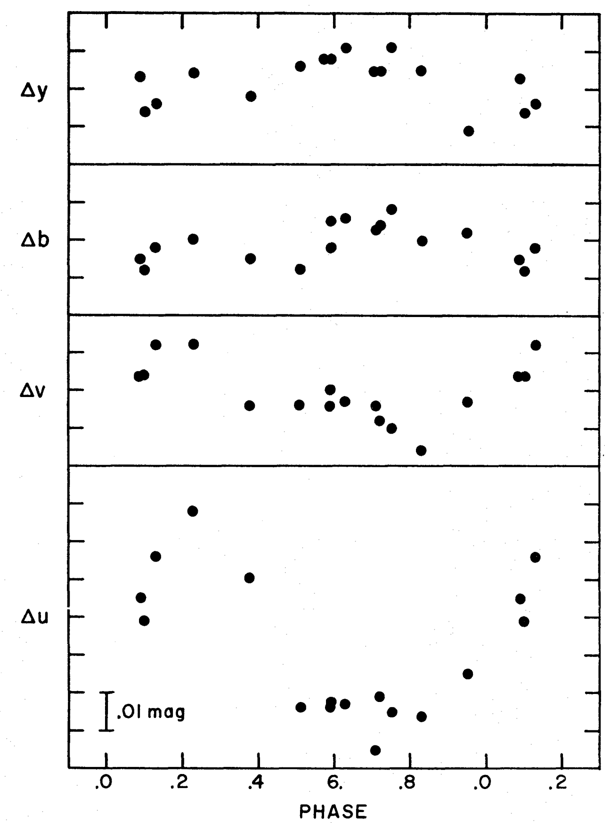

FIG. 1. The light variations of 53 Cam plotted according to the ephemeris J.D.⊙ (positive crossover) = 2436120.3+8.0278*E*. The scale indicated in the *lower panel* applies to all four curves.

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1971AJ.....76..422W

B. HD 71866

Observations of HD 71866 were made on 21 nights in February and March 1970. Phases were computed according to the ephemeris of Preston and Pyper (1965):

$$\text{J.D.}\odot\text{(positive crossover)} = 2432957.90 + 6.80001E,$$

and the results are shown in Fig. 2. The observations in y, b, and u show a double wave. Earlier observations in V by Stępień (1968a) confirm the presence of a double maximum in the vicinity of λ5450. Strengths of the Eu and Gd lines also show a double wave (Babcock 1956), the principal maximum occurring at about $\phi = 0.25$ with a secondary maximum at $\phi = 0.8$. The y light curve shows a strong minimum at about $\phi = 0.3$ and is nearly constant throughout the rest of the cycle.

C. 3 Hya

Zeeman observations by Babcock (1958) show that the magnetic field of 3 Hya varies from −500 to +700 gauss. Babcock also suspected that there are changes in the intensity of the Sr II lines and in the profile of the K line.

Photoelectric observations of 3 Hya were made on 30 nights between 30 January and 19 April 1970. The constancy of the primary comparison star, HD 73431, was checked by observations of HD 73451 which were made on ten nights. The technique described by Lafler and Kinman (1965) was used to search for periodic variations of 3 Hya. The best elements based on the photoelectric data alone are

$$\text{J.D.}\odot\text{(maximum light)} = 2440619.8 + 5.57E,$$

and the observations have been plotted according to this ephemeris in Fig. 3. The amplitudes are less than 0.03 mag at all four observed wavelengths. The period of 5.57 days was derived from the b measurements alone, and this period also satisfactorily represents the observations at the three other wavelengths.

Figure 4 shows Babcock's measurements of the magnetic field intensity plotted in the same period, with J.D.⊙ 2435525 adopted arbitrarily as the time of zero phase. Since 13 years have elapsed between the last Zeeman observation and the present photoelectric measurements, no attempt has been made to phase the two sets of data together. The value $P = 5.57$ days satisfactorily represents all the magnetic observations except for two near zero phase which fall approximately 800 gauss below the mean curve. Preston's (1969a) analysis of 78 Vir, however, shows that such deviations are not at all unusual even in a star which has much sharper absorption lines than 3 Hya. The proposed period cannot, therefore, be rejected on the basis of the available magnetic observations.

Pyper and Steinitz (private communication) have found that a period of 4.606 days provides the best

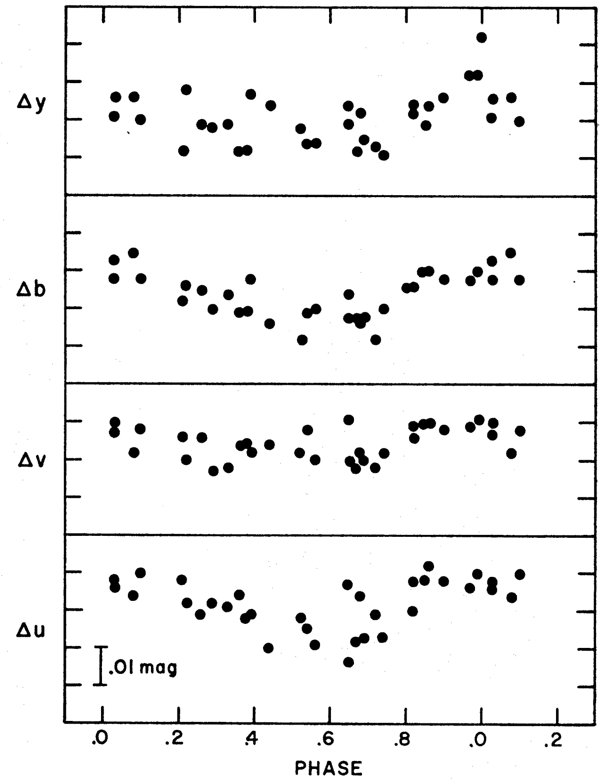

Fig. 3. The light variations of 3 Hya plotted according to the ephemeris J.D.⊙ (max. light) = 2440619.8+5.57E.

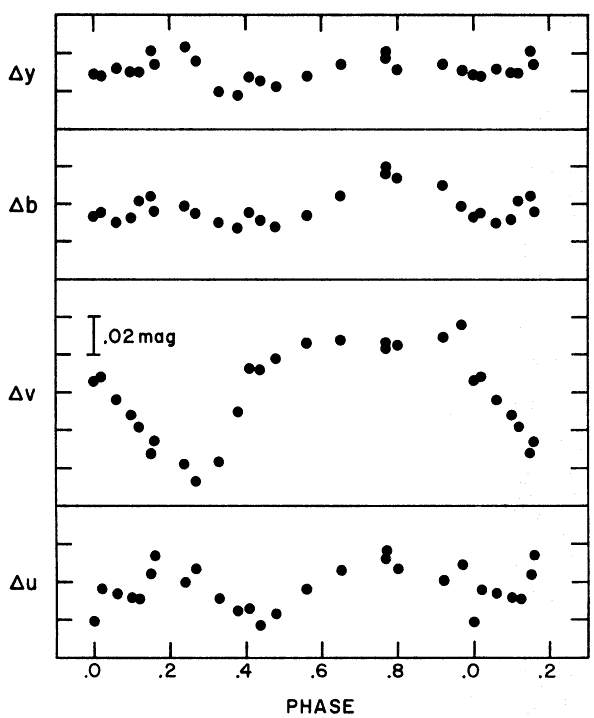

Fig. 2. The light variations of HD 71866 plotted according to the ephemeris J.D.⊙ (positive crossover) = 2432957.90+6.80001E. Note that the scale is only half that of Fig. 1.

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1971AJ.....76..422W

representation of the magnetic data alone. The photoelectric observations provide no support for this value. However, since the magnetic and light variations are both only slightly larger than the expected observational errors, more data will be required before either of these periods can be accepted.

D. 21 Com

Observations of 21 Com were made on 12 nights from mid-February to mid-March 1970. When it became apparent that the amplitudes at all four wavelengths are extremely small, this star was dropped from the observing program. In Fig. 5, the observations have been plotted on the assumption that $P=1.026$ days, with J.D.$_\odot$ 2440630.03 chosen arbitrarily to be at $\phi=0.0$. This value of P was derived by Deutsch (1955) from a study of Ca II and Sr II spectrum variations. Although the photometric amplitude is less than 0.02 mag at all wavelengths, the y, b, v, and u variations appear to be in phase and do lend some support to the period proposed by Deutsch. The second panel in Fig. 5 shows the difference in the y magnitudes observed for 23 Com, which was the primary comparison star, and 16 Com, which was used to check the constancy of 23 Com. The differences show a scatter of only about 0.01 mag, and there is no evidence of the systematic variation which was found for 21 Com. Photometry of 21 Com has also been obtained by Bahner and Mawridis (1957), and their measurements cannot be represented by $P=1.026$ days. Either very precise photometry or a new study of the spectrum variations is necessary to establish the period of this star.

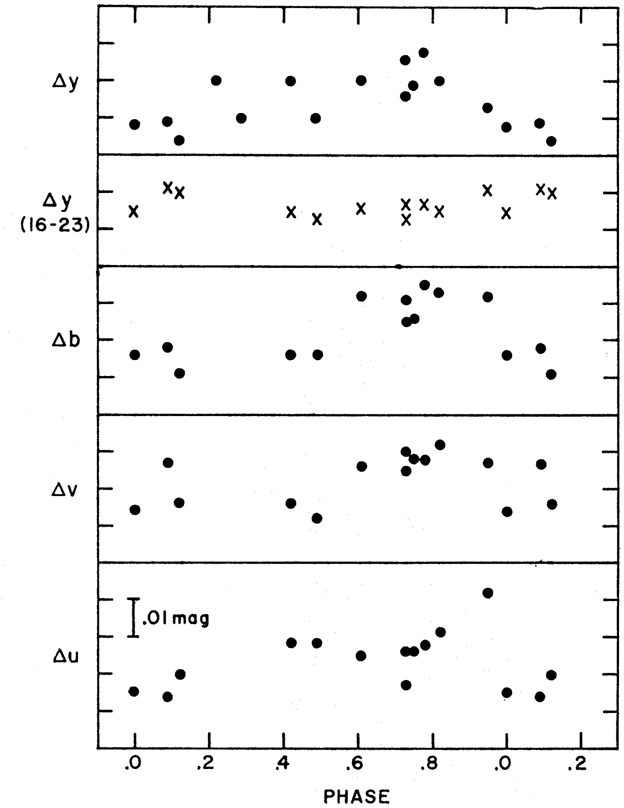

FIG. 5. The light variations of 21 Com plotted on the assumption that $P=1.026$ days.

E. α^2 CVn

This star is perhaps the most thoroughly observed of all the Ap stars. A recent study by Pyper (1969) includes references to earlier work. From measurements of a series of high-dispersion spectrograms, Pyper concluded that the rigid-rotator model can account adequately for the spectrum and magnetic variations shown by this star. The present *uvby* observations are plotted in Fig. 6 according to the elements

$$\text{J.D.}_\odot(\text{Eu maximum}) = 2439012.61 + 5.46939E.$$

The period is that derived by Farnsworth (1932). The stars α^2 CVn and α^1 CVn form a visual binary system with a separation of 20 arc sec. The secondary, α^1 CVn, was excluded from the diaphragm, and the light curves represent measurements of α^2 CVn alone. The observations confirm earlier *UBV* observations by Pyper (1969) which showed that the variations at all wavelengths are in phase and that the amplitude is greater around λ5470 than at shorter wavelengths.

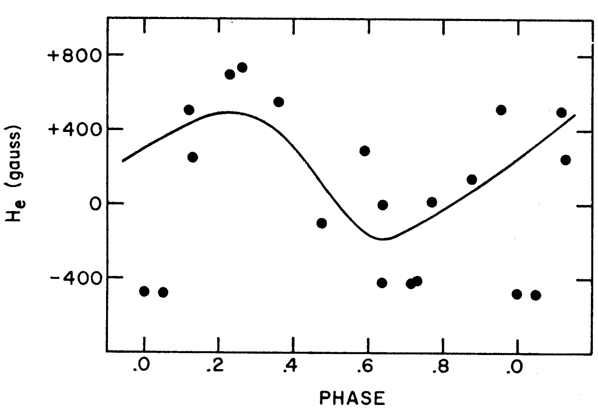

FIG. 4. Zeeman observations of 3 Hya (Babcock 1958) plotted on the assumption that $P=5.57$ days.

F. 78 Vir

From an analysis of the times of crossover, Preston (1969a) found that the magnetic variations in 78 Vir could be represented by the elements

$$\text{J.D.}_\odot(\text{magnetic maximum}) = 2434816.9 + 3.7220E.$$

The photometric observations of 78 Vir, which were made in April and June 1970, are shown in Fig. 7. All four light curves are in phase, with minimum amplitude occurring in the vicinity of λ4100. Maximum light co-

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1971AJ.....76..422W

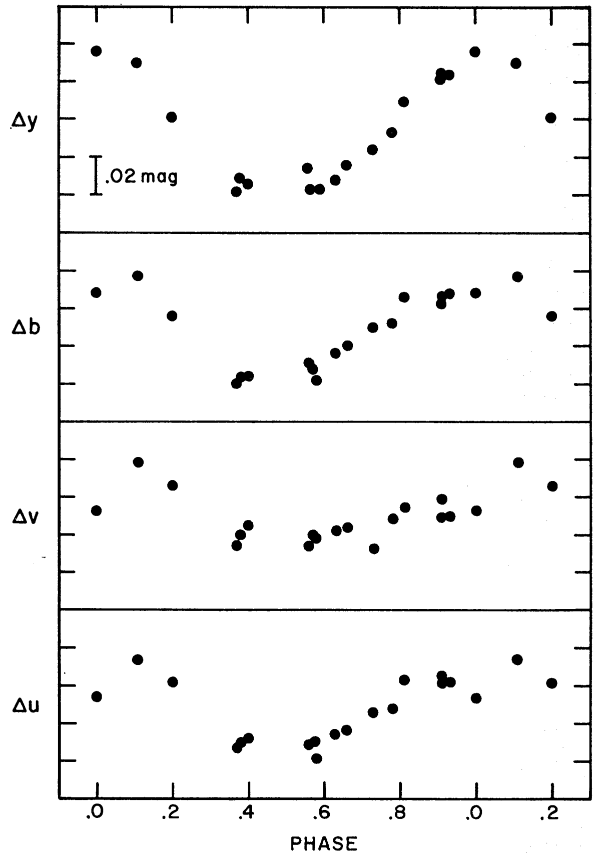

FIG. 6. The light variations of α^2 CVn plotted according to the ephemeris J.D.⊙ (Eu max.) $=2439012.61+5.46939E$.

incides with minimum longitudinal field. The V light curve based on Stepień's (1968a) photometry showed a similar phase relationship (Preston 1969a), but in that case the observed amplitude was only marginally greater than the scatter in the observations.

G. HD 125248

Because the spectrum and magnetic variations in HD 125248 are pronounced, this star has been the subject of a number of spectroscopic studies (e.g., Deutsch 1947, 1958b; Babcock 1951; Hockey 1969). However, because it is not well situated for most observatories in the northern hemisphere ($\delta=-18°$), little photometric work has been done. A light curve at an effective wavelength of about λ4100 was obtained by Stibbs (1950), who showed that light maximum coincided with Cr maximum. Very recently, UBV photometry has been carried out by Maitzen and Rakosch (1970). They find two maxima in the V light curve, each corresponding in phase with a magnetic extremum. The B and U light curves are in phase with each other and show only a single maximum.

The *uvby* observations are plotted in Fig. 8 according to the elements

$$\text{J.D.}\odot(\text{Eu max.}=\text{Cr min.})=2430143.07+9.2954E.$$

This ephemeris adequately describes all the spectroscopic observations over an 18-yr interval through 1965 (Hockey 1969) and is therefore well enough determined so that the present observations can be phased together with earlier studies of magnetic and spectrum variability.

The *uvby* light curves in Fig. 8 substantiate the UBV study of Maitzen and Rakosch and add some information about the wavelength dependence of the variations. The u and v curves are in phase, and the u amplitude is somewhat smaller. At λ5450, a double wave is clearly present, and the maximum at $\phi=0.0$ is more marked than the one at $\phi=0.5$. Minimum longitudinal field occurs at $\phi=0.5$ (Babcock 1951).

H. β CrB

From a study of the longitudinal magnetic field measurements made by Babcock (1958), Steinitz (1964) concluded that the magnetic period of β CrB was 18.5 days. This period was confirmed by Preston and Sturch (1967), who derived the elements

$$\text{J.D.}\odot(\text{positive crossover})=2434217.50+18.487E.$$

The mean surface field varies in the same period, with

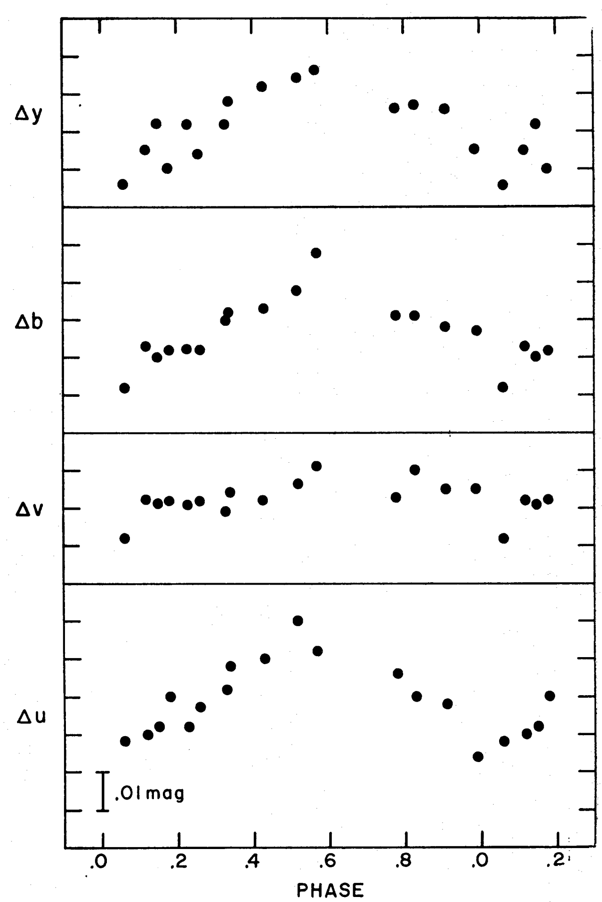

FIG. 7. The light variations of 78 Vir plotted according to the ephemeris J.D.⊙ (magnetic maximum) $=2434816.9+3.7220E$.

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1971AJ.....76..422W

minimum total field occurring at or perhaps slightly earlier than longitudinal minimum (Wolff and Wolff 1970). The photometric observations are plotted in Fig. 9. The v amplitude is the largest, and minimum v coincides with minimum longitudinal field. The amplitudes of the light curves observed with the u, b, and y filters are very small, but apparently they are in phase with the v curve. Similar conclusions can be drawn from UBV photometry of β CrB (Brodskaya 1970; Burke, Rolland, and Boy 1970), which shows that the variations in U, B, and V are in phase and that the B amplitude is largest.

The amplitude of the magnetic field variation in β CrB may vary in a 10.5-yr period (Preston 1967a), and the field apparently stopped reversing in 1969 (Severny 1970). It would be interesting to continue observations of this star in order to see whether the photometric amplitude also varies in a 10.5-yr period.

IV. DISCUSSION

A. Cause of Light Variations

It has been clear for some time that changes in effective temperature cannot account for the light variations

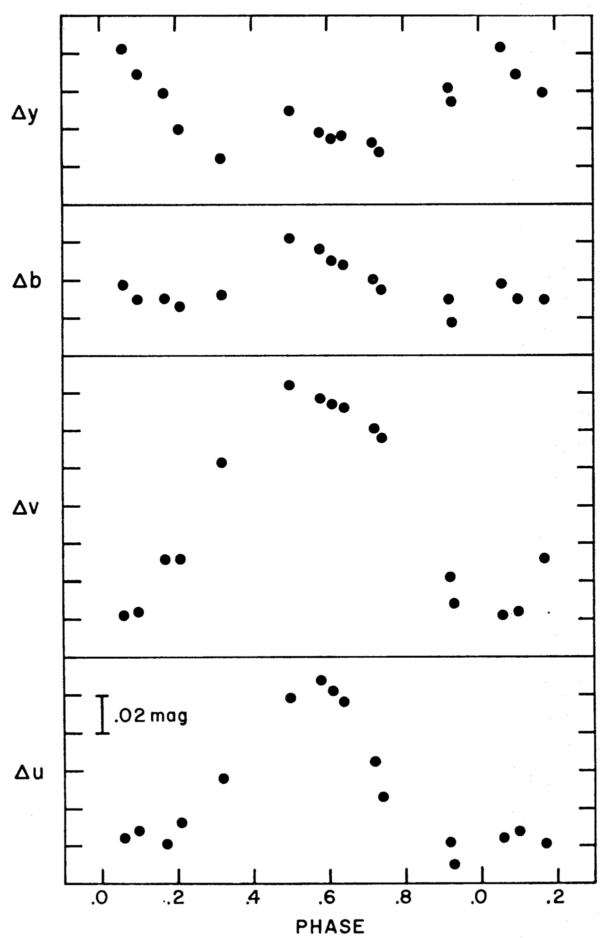

FIG. 8. The light variations of HD 125248 plotted according to the ephemeris J.D.⊙ (Eu max. = Cr min.) = 2430143.07 + 9.2954E.

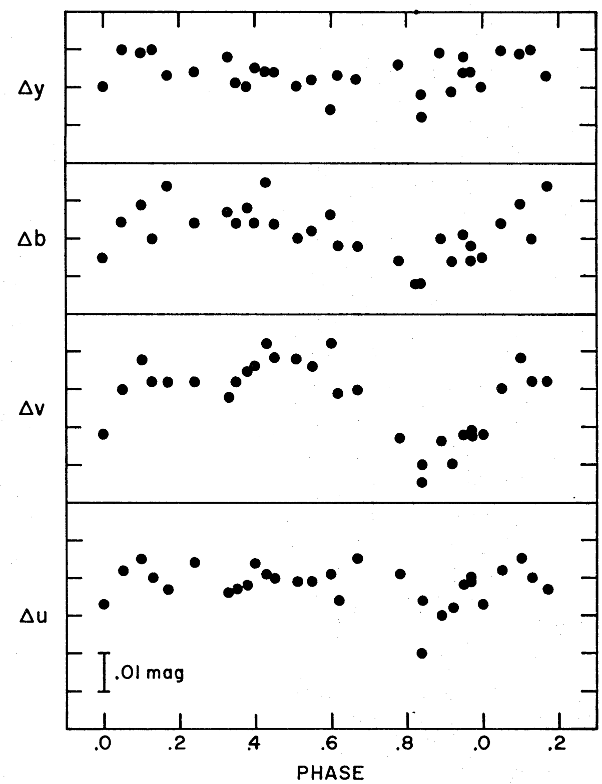

FIG. 9. The light variations of β CrB plotted according to the ephemeris J.D.⊙ (positive crossover) = 2434217.50 + 18.487E.

which are observed in Ap stars. The star α^2 CVn, for example, is bluest at minimum light, while a simple temperature variation would produce precisely the opposite effect. Even in those cases in which the color changes mimic temperature changes (Stepień 1968a), the amplitude in V is typically smaller than one would expect for the temperature change implied by the $B-V$ variation.

Recently, Peterson (1970) has noted that variations in the apparent abundances of certain metals may affect the continuous opacity enough to result in light variations. He has considered the effects of silicon in some detail, since this element is known to be strongly overabundant and variable in many Ap stars, and he has shown that an increase in the Si opacity in the ultraviolet will force a redistribution of flux into the visible. Therefore, a rotating star with large Si abundance variations across its surface will show photometric variations. Among other results, the calculations predict that Si should always vary in phase with the ultraviolet flux.

Of the stars in Table II, only α^2 CVn is known to have an overabundance of Si. The equivalent widths vary by about a factor of 1.2 in this star and are a maximum at $\phi=0.4$ (Pyper 1969). As Fig. 6 shows, α^2 CVn is at minimum light at this phase. Since the u filter includes no Balmer lines, there can be no question about whether variations in the strengths of the hydrogen lines are affecting the observations. Line blanketing in α^2 CVn

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1971AJ.....76..422W

is nearly independent of phase (Cohen 1970), so that the lack of agreement with Peterson's model cannot be attributed to variable line-blanketing effects. Two other Si stars, HD 215441 and HD 32633, vary by at least 0.05 mag, but no Si variations have been observed in either (Preston 1969b; Preston and Stepień 1968b).

Even though variations in the Si opacity are evidently not the cause of the light variations in α^2 CVn, or very likely in any of the other stars observed here, it is worthwhile to pursue further Peterson's suggestion that light and spectrum variability are related. In Table III, the spectrum variations of each of the Ap stars in Table II are described briefly. The spectrum variations of 3 Hya, 21 Com, 78 Vir, and β CrB are small or absent, or else are confined to lines of Ca II and Sr II, and in each case the light variations are smaller than about 0.03 mag. The stars with marked spectrum variations, on the other hand, all show light variations which exceed 0.05 mag at one or more of the observed wavelengths. The observations of Stepień (1968a) include a larger sample of objects, and also suggest that in the cool Ap stars (cool is used in this context to exclude the Si and Mn stars), large-amplitude light variations occur only in those stars that also show pronounced spectrum variations. Small-amplitude variations in phase at all wavelengths appear to be characteristic of those objects that display little or no spectrum variability.

The data presently available in the literature suggest that the rare earth variations are most closely linked with the light variations. Several Ap stars, including HD 71866 (Babcock 1956), 73 Dra (Preston 1967b; Stepień 1968b), and 21 Per (Preston 1969c) are known to show two maxima in the rare earth lines during each complete cycle. In each case, a double wave is also present in at least the V light curve. In HD 71866 the double wave is present at all the observed wavelengths except λ4100. Those Ap stars in which the rare earth lines show only a single maximum, including α^2 CVn and possibly 78 Vir, display only a single maximum in the light variations. The star HD 125248 is the only one known to show a double maximum in the light curve and a single maximum in the rare earth curve.

TABLE III. Observations of spectrum variability.

Star name	Spectrum variations
53 Cam	Ti maximum $\phi\simeq0.8$; Mg II variable, phase relation unreported; amplitudes of variations unreported (Babcock 1960)
HD 71866	Eu II, Gd II only variable elements; principal maximum at $\phi\simeq0.25$; weaker maximum at $\phi\simeq0.8$; amplitude large, but only eye estimates of intensity have been reported (Babcock 1956)
3 Hya	Possible variations in profile of K line and in intensity of Sr II (Babcock 1958)
21 Com	Sr II, Ca II, possibly Mg I vary in phase (Deutsch 1955)
α^2 CVn	Rare earth maximum $\phi\simeq0.0$, line strengths vary by factor of 10; four Fe-peak maxima during cycle, total equivalent widths integrated over all components vary only slightly (Pyper 1969)
78 Vir	K line varies by about a factor of 2; Eu variations marginal, but Eu maximum at $\phi\simeq0.6$ is probable (Preston 1969a)
HD 125248	Eu, Ce maxima at $\phi\simeq0.0$, equivalent widths vary by about a factor of 3; Fe maximum at $\phi\simeq0.0$, variation by a factor of 1.3; Cr II maximum at $\phi\simeq0.5$, variation by slightly more than a factor of 3
β CrB	None reported

The question that arises, then, is whether the connection between the rare earth spectrum variations and the light variations is a causal one. Nearly all of the doubly and triply ionized rare earth elements, including Gd and Eu, have very strong absorption features in the region λλ2000–3000 (Dieke, Crosswhite, and Dunn 1961). Enhanced absorption in this part of the spectrum at rare earth maximum will redistribute energy into the visible, and it seems entirely possible that this redistributed energy is the primary cause of the light variations. If such a mechanism is effective, then one would expect maximum brightness to coincide with rare earth maximum. Such a relationship does exist for most of the stars which have been observed. In HD 71866, the u, b, and y variations are in phase with the rare earths, but the v light curve shows a deep minimum at the time of the principal rare earth maximum. By far the strongest line absorption in the visible occurs in the region λλ4000–4500 (Wolff 1967), and the minimum in v may be the result of strong and variable blanketing effects in this part of the spectrum. The light curves of HD 125248 can also be accounted for only if the redistributed flux is strongly modified by variable blanketing in the visible.

Not all of the light variations in Ap stars can be ascribed to the effects of rare earth spectrum variability. The elements Ti and Mg are the only ones which have been reported to show variable line strengths in 53 Cam. If Mg is markedly overabundant, then changes in the Mg abundance may affect the continuous opacity in much the same way as changes in the Si abundance (Peterson 1970), so Mg variations may be an important factor in 53 Cam. In HD 125248, a maximum in the y curve occurs at $\phi=0.5$. Only Cr II is at maximum strength at this phase (Hockey 1969). There are a large number of Cr lines below λ3000, and variations in the Cr line strengths may also result in a significant redistribution of flux. Observations of other stars in which Cr varies in antiphase to the rare earths could be used to test this suggestion. None of the stars observed here is suitable. Although α^2 CVn is often considered an example of such a star, variations in the total equivalent widths of the Cr lines are much smaller than in HD 125248 (Pyper 1969).

It is tempting to postulate that a redistribution of ultraviolet flux either by variations in line blanketing or opacity (Peterson 1970) produces light variations in

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1971AJ.....76..422W

the silicon Ap stars as well. These stars are typically hotter than the rare earth variables, and the amplitudes of the light curves tend to be somewhat larger (Stepień 1968a). These larger amplitudes would then be ascribed to the fact that, since a relatively greater proportion of the flux is emitted below λ3000, variable absorption in this region would be more important. There are, however, difficulties with this suggestion. The Si stars HD 32633 and HD 215441 are photometric but not spectrum variables. In the case of HD 215441, the lack of spectrum variability may not be significant, since the star is of spectral type B3 or B4 (Preston 1969b), and rare earth lines in the visible would no longer be prominent. The hypothesized absorption below λ3000, on the other hand, is due to both doubly and triply ionized rare earths and would persist even at such a high temperature. However, the other star, HD 32633, has nearly the same intrinsic colors, and presumably therefore the same temperature, as α^2 CVn. Lines of the rare earths, of the Fe-peak elements including Cr, and of Mg and Si are strong in α^2 CVn, and so the lack of spectrum variations in HD 32633 suggests that some entirely different mechanism, unrelated to spectrum variability, may cause the light variations in the silicon Ap stars. The star 17 Com A is another example of an object in which the light variations apparently are not the direct consequence of spectrum variability (Preston, Stepień, and Wolff 1969). This star is unique among the Ap stars studied so far in that magnetic maximum appears to precede light maximum by one-quarter of a cycle. The spectrum variations are small but appear to proceed in phase with the magnetic variations, not with the light variations as one would expect if spectrum variability were the sole cause of the light variations.

Although the observations of HD 32633 and 17 Com A suggest that spectrum and photometric variability may be unrelated in Si stars and in objects in which the light and spectrum variations are very small, a redistribution of flux by variable ultraviolet absorption does seem to be the most promising way to account for the large light variations which are observed in the rare earth spectrum variables. This hypothesis can be tested in a number of ways. For example, one would expect small-amplitude light variations at wavelengths beyond λ6000 for stars cooler than about A0 (Peterson 1970). High-dispersion spectroscopic observations of HD 71866 and HD 125248 would show whether the deep minima in v observed for these two stars can be ascribed to the effects of variable line blanketing in the vicinity of λ4100. Studies of a larger sample of representative Ap stars would also be very useful, since it then would be possible to determine precisely what kind of spectrum variations are most closely associated with variability in light.

B. Phase Relationship between Light and Magnetic Variations

There has been considerable discussion of the possibility that there is a fixed phase relationship between the light and magnetic variations of Ap stars (see, for example, Preston and Stepień 1968a; Stepień 1968a; Preston and Stepień 1968c). The most recent suggestion is that the V maximum may coincide with the maximum of the mean surface magnetic field (Wolff and Wolff 1970). In β CrB, the present observations indicate that the y amplitude is very small, but if there is any variation at all it is in the sense that it is y minimum that coincides with the maximum in the surface field. If the light variations in the cool Ap stars are actually the consequence of spectrum variability, then one would expect a correlation between the magnetic and photometric variations only if the distribution of elements over the stellar surface were uniquely related to the distribution of the magnetic field. In those cases where the rare earths vary in phase with the Fe-peak elements, it appears that both groups of elements are concentrated in the region of strongest magnetic field (Preston 1970), and the presently available data suggest that for such stars V maximum does coincide with the maximum in the surface field. The light curve of HD 126515, for example, follows this pattern (Wolff, in preparation). In α^2 CVn, however, the rare earths are found predominantly near the negative pole, which is the weaker one, and this star is brightest at Eu maximum, rather than at magnetic maximum (Pyper 1969).

C. Applications of Intermediate-Band Photometry

Narrow- or intermediate-band photometry is particularly well suited for determining the periods of Ap stars. Not only can such photometry be expected to be somewhat more accurate than broad-band photometry, since the corrections for differential color extinction are eliminated (Hardie 1967), but narrower bands are better suited for isolating the limited wavelength regions in which large-amplitude variations occur. For example, the v amplitude observed for HD 71866 is larger than the corresponding B variation measured by Stepień (1968a).

The observations presently available suggest that, among the cooler Ap stars, large-amplitude light variations are always associated with spectrum variability. The development of a model that can account for the time-varying properties of these stars will depend to a great extent on detailed analyses of spectrum variables, such as the studies already made of HD 125248 (Deutsch 1958b), α^2 CVn (Pyper 1969), and HD 126515 (Preston 1970). Several hundred Ap stars have been discovered in recent objective-prism surveys (e.g., Bidelman, private communication; Bond 1970). Photometry, which can be carried out with a small telescope,

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1971AJ.....76..422W

may be the most efficient way of choosing potentially interesting objects from these surveys.

Note Added in Proof: Lockwood and Hartman (1970, *Publ. Astron. Soc. Pacific* **82**, 1346) have found that the atmsopheric extinction at Kitt Peak increased during the interval 1960–1970. The coefficients given for Kitt Peak in Table I were measured during the early 1960's. For the years 1966–1969, the median extinction coefficients observed at Kitt Peak for y, b, v, and u were 0.179, 0.235, 0.353, and 0.638, respectively.

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