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# PHOTOMETRY OF SIX PECULIAR A-TYPE STARS

SIDNEY C. WOLFF AND NANCY D. MORRISON
Institute for Astronomy, University of Hawaii

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Four-color (*uvby*) photoelectric observations are presented for six Ap stars. No variations were found for the Hg-Mn star $\kappa$ Cnc. The periods of $1^{d}4450$ for 45 Leo and $2^{d}8881$ for HR 5597 found by Winzer (1974) are confirmed. The period of HR 5153 is shown to be $2^{d}451$. Possible explanations for the photometric variations of 56 Ari and HR 4369 are discussed.

*Key words:* photometry — peculiar A-type stars

## I. Introduction

Four-color (*uvby*) photometry is an efficient way of finding periods for peculiar A-type stars and has also proved useful in determining the causes of the light variations (e.g., Wolff and Wolff 1971; Jones and Wolff 1973). In the present paper we give observations for six stars — 56 Arietis, $\kappa$ Cancri, 45 Leonis, HR 4369, HR 5153, and HR 5597 — that, in a variety of ways, illustrate and clarify the nature of the photometric variability of the Ap stars.

## II. Observations

All of the observations were obtained with a 24-inch telescope on Mauna Kea and were made and reduced with techniques that have been described elsewhere (Wolff and Wolff 1971; Wolff and Morrison 1973). The magnitudes of HR 5597 were measured from a strip chart recording of the direct current output of an unmodified General Radio amplifier; the remaining stars were observed with a photon-counting system. As the only comparison star for 56 Ari, we used HR 945, which Hardie and Schroeder (1963) have shown to be constant. Two comparison stars were used for each other variable, and their mean color indices are given in Table I, except that we did not obtain enough observations of standard stars in order to transform accurately the color indices of HR 5468 and HR 5533, comparison stars for HR 5597, to the standard system. The standard deviation of a single differential magnitude, i.e., of a measurement of the brightness of the variable star relative to the comparison stars, is about $\pm 0^{m}004$. The standard deviations of the transformed color indices, as estimated from a comparison of the measurements in Table I with those of other observers, are about $0^{m}02$ in $V$, $0^{m}01$ in $(b-y)$ and $0^{m}02$ in $m_1$ and $c_1$. Since, in most cases, the present observations confirm *UBV* observations already available, we have chosen not to publish the individual observations of each star; such tabulations are available from the authors. In the case of HR 5153, where we derive a period different from the ones already published, we do list our observations.

## III. Discussion of Individual Stars

A. *56 Arietis*

A key step in explaining the light variations in Ap stars was the recognition by Peterson

TABLE I

PHOTOMETRIC DATA FOR COMPARISON STARS

| Star | V | b-y | $m_1$ | $c_1$ |
|---|---|---|---|---|
| HR 945 | 6.405 | +0.007 | +0.142 | +1.079 |
| HR 3635 | 6.485 | +0.237 | +0.138 | +0.505 |
| HR 3689 | 6.400 | +0.043 | +0.173 | +1.186 |
| HR 4070 | 6.156 | +0.005 | +0.152 | +1.076 |
| HR 4227 | 5.313 | +0.026 | +0.155 | +1.126 |
| HR 4315 | 6.090 | +0.184 | +0.171 | +0.780 |
| HR 4368 | 4.466 | +0.133 | +0.173 | +1.030 |
| HR 5216 | 6.436 | +0.042 | +0.196 | +1.008 |
| HR 5238 | 5.691 | -0.009 | +0.134 | +1.054 |

(1970) that changes in ultraviolet opacity due to spectrum variability could lead to fluctuations in brightness in the visible. The importance of this basic mechanism has been amply demonstrated (e.g., Wolff and Wolff 1971; Molnar 1973; Leckrone 1974). In his original paper, Peterson (1970) suggested that variations in Si opacity are the most likely cause of the light variations in the Si stars. It has become clear, however, that in many Si stars the light variations cannot be caused in this way. For example, HD 215441 exhibits large-amplitude light variations in the visible (Stepien 1968), which are apparently the consequence of variations in the ultraviolet opacity (Leckrone 1974), even though this star is not recognized to be a Si variable (Babcock 1960; Preston 1969). In another Si star, 41 Tauri, maximum light coincides with Si minimum (Wolff 1973), exactly opposite to the phase relationship one would expect if variations in Si opacity were the primary cause of the light variations.

Although these observations demonstrate that variations in Si opacity cannot be the only source of the photometric variability in Si-type Ap stars, there have been few attempts to test Peterson's hypothesis quantitatively for stars in which Si variations are large. Most available photometry of the Si stars is on the *UBV* system, and the *U* and *B* magnitudes depend on the strengths of the Balmer lines as well as the flux in the continuum. Comparison of observed *B* and *U* magnitudes with the predictions of models is thus quite difficult.

In order to compare Peterson's models with a pronounced Si variable, we have obtained *uvby* observations of 56 Ari. The resulting light curves are plotted in Figure 1 according to the ephemeris (Hardie and Schroeder 1963)

$$\mathrm{JD}_{\odot}(V_{\min}) = 2437667.73 + 0\overset{d}{.}7278925E.$$

The double wave exhibited by the light curves is evident also from *UBV* photometry (e.g., Hardie and Schroeder 1963).

The equivalent widths of the lines of Si II reach a maximum near phase 0.3 (Bonsack and Wallace 1970), and there may (Peterson 1966) or may not (Bonsack and Wallace 1970) be a secondary maximum near phase 0.8. According to Bonsack and Wallace, the equivalent-width variations of λλ4128–31 correspond to a variation in the apparent Si abundance from about 10 times normal solar abundance at Si minimum to about 100 times normal at Si maximum. Peterson's models indicate that the corresponding amplitudes in *u*, *v*, and *y* should be approximately $0\overset{m}{.}12$, $0\overset{m}{.}06$, and $0\overset{m}{.}06$, respectively. The observed amplitudes from minimum light to the maximum at phase 0.3 are $0\overset{m}{.}05$, $0\overset{m}{.}04$, and $0\overset{m}{.}03$, respectively. (While the *v* band does include Hδ, the equivalent width of this line varies by less than 1 Å (Bonsack 1972), which would result in variability in *v* of less than $0\overset{m}{.}005$.) The models thus predict photometric amplitudes about two times larger than the observed ones, with the overestimate being largest in *u*. However, in view of the preliminary nature of Peterson's calculations, the agreement between the calculated and observed light curves is encouraging, and variations in Si opacity may therefore be the primary cause of the photometric maximum in 56 Ari at phase 0.3. However, the photometric maximum at phase 0.8 cannot be

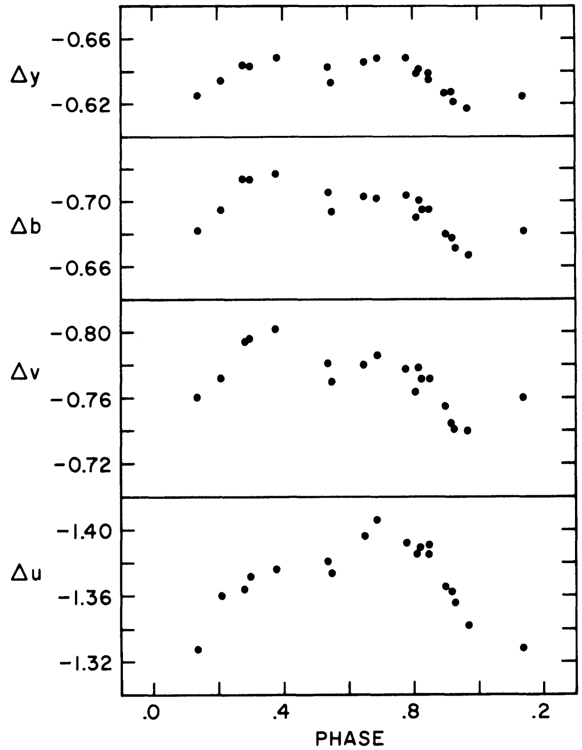


FIG. 1 — Photometric observations of 56 Ari plotted according to the ephemeris $\mathrm{JD}_{\odot}(V_{\min}) = 2437667.73 + 0\overset{d}{.}7278925E$. Magnitude differences are in the sense (56 Ari − HR 945).

due to changes in the Si opacity, since the secondary Si maximum found by Peterson (1966), even if real, is much too small to account for the observed amplitude of the light curves. Therefore, in 56 Ari, as in many other Si stars, the photometric variations cannot yet be explained fully.

B. *κ Cancri*

There are no confirmed periodic variations of light, spectrum, or magnetic field in any Hg-Mn star. From photometry and measurements of magnetic field strength, Preston, Stepien, and Wolff (1969) reported that κ Cnc appeared to vary periodically with $P = 5.0035$ days. The amplitude of the variability, however, was small, and the primary argument in support of the reality of the variations was the fact that two independent sets of data (magnetic and photometric) could be represented by the same period.

In an effort to confirm the photometric variability found by Preston et al. (1969), we observed κ Cnc during the first four months of 1973, and the derived $y$ magnitudes are plotted in Figure 2 as a function of phase according to the ephemeris (Preston et al. 1969)

$$\mathrm{JD}_{\odot}(\text{magnetic maximum}) = 2439633.5 + 5^{d}_{.}0035E \quad .$$

The $V$ light curve obtained by Preston et al. showed an amplitude of about $0^{m}_{.}015$, with minimum light at phase 0.25 and maximum light at phase 0.6. It is clear that the present observations do not support the earlier ones, but rather set an upper limit of $0^{m}_{.}01$ on the amplitude of any variability. The $u$, $v$, and $b$ magnitudes are also constant to at least $0^{m}_{.}01$, in agreement with recent *UBV* photometry by Winzer (1974).

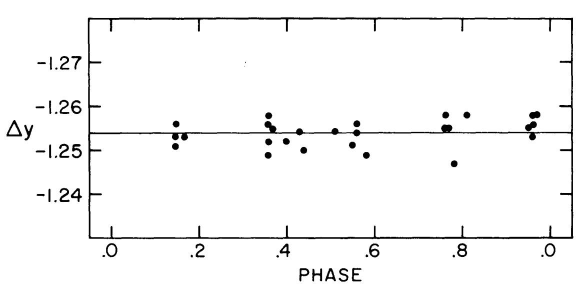


FIG. 2 — Photometric observations of κ Cnc plotted according to the ephemeris $\mathrm{JD}_{\odot}$ (magnetic maximum) = 2439633.5 + $5^{d}_{.}0035$E. Magnitude differences are in the sense (κ Cnc − HR 3635).

The mean color indices derived for κ Cnc are

$$V = 5.23 \qquad b-y = -0.037 \qquad m_1 = 0.119 \qquad c_1 = 0.546 \quad .$$

C. *45 Leonis*

The photometric, magnetic, and spectrum variations of the Sr-Cr star 45 Leo are all of very low amplitude, and as a consequence most attempts to determine a period for this star have been unsuccessful (e.g., Provin 1953; Babcock 1958; Burke, Rolland, and Boy 1970). Recently, Winzer (1974) has derived a period of $P = 1.4450$ days from variations in $U$. However, since the amplitude of the variability was only slightly more than $0^{m}_{.}02$, Winzer regarded the period as uncertain.

We obtained 13 observations of 45 Leo in 1973 February–April and from these data derived only the period 1.445 days, in agreement with the result of Winzer. The period is surprisingly short, since the apparent rotational velocity of 45 Leo is only 10 km s$^{-1}$ (Abt, Chaffee, and Suffolk 1972), but an effort to find longer periods was unsuccessful. The fact that we view 45 Leo nearly pole-on ($i \simeq 5°$) probably accounts for the very low amplitude of its spectrum and magnetic variability.

Our *uvby* observations of 45 Leo are plotted in Figure 3 according to the ephemeris (Winzer 1974)

$$\mathrm{JD}_{\odot}(U_{\max}) = 2441460.76 + 1^{d}_{.}4450E \quad .$$

D. *HR 4369*

The star HR 4369 (= HD 98088) is one of the few Ap stars known to be members of close binary systems, and in this case the magnetic and orbital periods are identical (Babcock 1958). In Figure 4 we show the *uvby* light curves for this star, plotted according to the elements (Abt et al. 1968)

$$\mathrm{JD}_{\odot}(\text{periastron passage}) = 2434419.13 + 5^{d}_{.}90513E \quad .$$

The light curves exhibit a double wave in both $v$ and $b$, with the primary and secondary minima coinciding in phase with primary and secondary maxima in the strengths of the lines

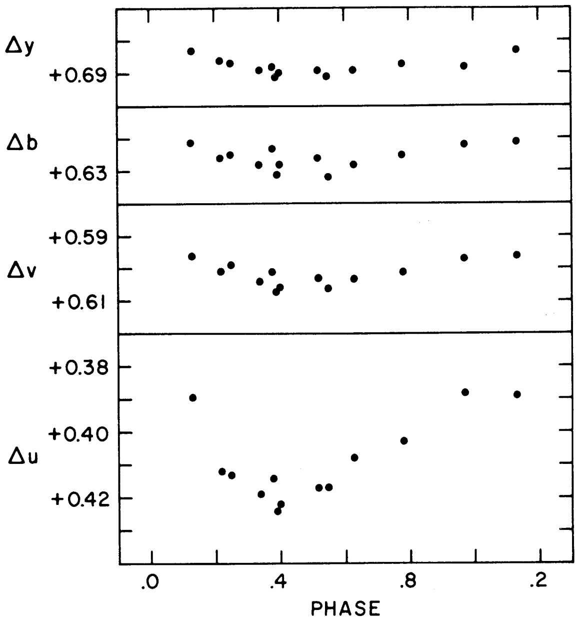


FIG. 3 — Photometric observations of 45 Leo plotted according to the ephemeris JD$_\odot$ ($U_{max}$) = 2441460.76 + 1$^d$4450E. Magnitude differences are in the sense (45 Leo − HR 4227).

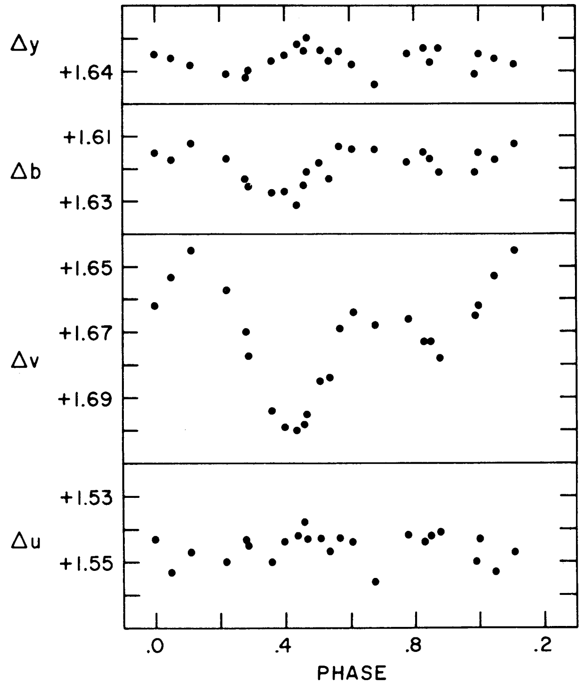


FIG. 4 — Photometric observations of HR 4369 plotted according to the ephemeris JD$_\odot$ (periastron passage) = 2434419.13 + 5$^d$90513E. Magnitude differences are in the sense (HR 4369 − 4368).

of Eu II and Sr II (Abt et al. 1968). The amplitude of the variation in $y$ is quite small and appears to be nearly in antiphase to the variation in $v$ and $b$. Maitzen (1973) obtained a light curve in $v$ that is in excellent agreement with the one shown here. He found no variations in $b$ and $y$, but the scatter in his observations is large enough to mask variability with amplitudes as small as the ones shown in Figure 4. By analogy with HD 188041 (Jones and Wolff 1973) and 49 Camelopardalis (Bonsack, Pilachowski, and Wolff 1974), it is probable that the maxima in $y$, which almost coincide in phase with the rare-earth maxima, are due to redistribution of flux from the ultraviolet, with relatively little modification by local line blocking within the $y$ filter. In $b$ and $v$, however, the light curves suggest that variations in local line blocking dominate. Spectroscopic measurements of local line blocking coefficients could determine whether this explanation of the photometric variations of HR 4369 is correct.

### E. *HR 5153*

The Sr-Cr-Eu star HR 5153 (Cowley et al. 1969) has recently been found to be a pronounced photometric (Burke and Howard 1972) and spectroscopic (Bonsack 1974) variable. The results of our own *uvby* photometry are given in Table II.

The photometric period derived for HR 5153 by Burke and Howard (1972) was 1.706 days; Winzer (1974) subsequently found that his own data could be better represented by $P = 1.6980$ days. Analysis of the *uvby* photometry in Table II yields two possible periods, 1.68 days and 2.45 days, with a maximum uncertainty of 0.01 day, and the periods found by Winzer and by Burke and Howard do not adequately fit our data. If we further require that maximum light in $B$, as determined from Winzer's data, coincide with $v$ maximum, we find that none of the possible periods near 1.68 days is satisfactory and that the data can best be represented by the elements

$$\mathrm{JD}_\odot(v_{max}) = 2441450.74 + 2^d451\mathrm{E} \quad .$$

The resulting light curves are shown in Figure 5. The amplitude is small at λ5500 but is large at the other wavelengths, having a maximum value of 0$^m$1 in $v$.

TABLE II

PHOTOMETRIC DATA FOR HR 5153

| HJD 2440000+ | Phase | Magnitude Differences (HR 5153 - HR 5216) Δy | Δb | Δv | Δu |
|---|---|---|---|---|---|
| 1731.09 | 0.38 | -0.170 | -0.147 | -0.064 | -0.229 |
| 1732.10 | 0.79 | -0.164 | -0.175 | -0.151 | -0.248 |
| 1767.93 | 0.41 | -0.169 | -0.144 | -0.064 | -0.230 |
| 1775.02 | 0.31 | -0.164 | -0.148 | -0.084 | -0.232 |
| 1776.04 | 0.72 | -0.161 | -0.171 | -0.134 | -0.250 |
| 1776.95 | 0.09 | -0.165 | -0.179 | -0.153 | -0.254 |
| 1780.99 | 0.74 | -0.160 | -0.175 | -0.145 | -0.240 |
| 1782.93 | 0.53 | -0.168 | -0.155 | -0.088 | -0.230 |
| 1784.97 | 0.36 | -0.169 | -0.148 | -0.064 | -0.231 |
| 1785.90 | 0.74 | -0.163 | -0.175 | -0.148 | -0.248 |
| 1786.91 | 0.16 | -0.164 | -0.168 | -0.133 | -0.243 |
| 1789.90 | 0.38 | -0.163 | -0.144 | -0.063 | -0.228 |
| 1790.98 | 0.82 | -0.165 | -0.177 | -0.152 | -0.245 |
| 1793.97 | 0.04 | -0.164 | -0.183 | -0.163 | -0.257 |
| 1796.89 | 0.23 | -0.168 | -0.161 | -0.109 | -0.241 |
| 1797.86 | 0.62 | -0.166 | -0.162 | -0.115 | -0.237 |
| 1798.87 | 0.04 | -0.167 | -0.181 | -0.162 | -0.258 |
| 1799.85 | 0.44 | -0.169 | -0.145 | -0.061 | -0.229 |
| 1821.88 | 0.42 | -0.168 | -0.145 | -0.061 | -0.233 |
| 1824.86 | 0.64 | -0.169 | -0.174 | -0.134 | -0.249 |
| 1825.85 | 0.04 | -0.173 | -0.188 | -0.166 | -0.264 |
| 1826.85 | 0.45 | -0.169 | -0.147 | -0.066 | -0.232 |
| 1827.85 | 0.86 | -0.165 | -0.181 | -0.157 | -0.255 |
| 1828.84 | 0.26 | -0.169 | -0.157 | -0.096 | -0.240 |
| 1832.86 | 0.90 | -0.166 | -0.178 | -0.160 | -0.262 |

The spectrum variations of HR 5153 have been described by Bonsack (1974), who finds variations of roughly a factor of 2 in the strengths of the Cr lines. Using the ephemeris given here, we find that Cr maximum coincides in phase with maximum light. The only other Ap star that has been studied both spectroscopically and photometrically and that is known to exhibit Cr variations of such large amplitude is HD 125248. Except for secondary maxima in the *b* and *y* light curves of HD 125248 that are associated with rare-earth maximum, the photometric variations of the two stars are quite similar (Hockey 1969; Wolff and Wolff 1971).

### F. *HR* 5597

It is natural to ask whether the periods of the Ap stars are constant. Renson (1972) has recently reviewed the evidence that at least some Ap stars may have variable periods, and he concludes that the only star in this category is HR 5597 (= HD 133029). Renson (1969) finds that the magnetic field measurements of this star by Babcock (1958) can be represented only by a period that varies approximately from

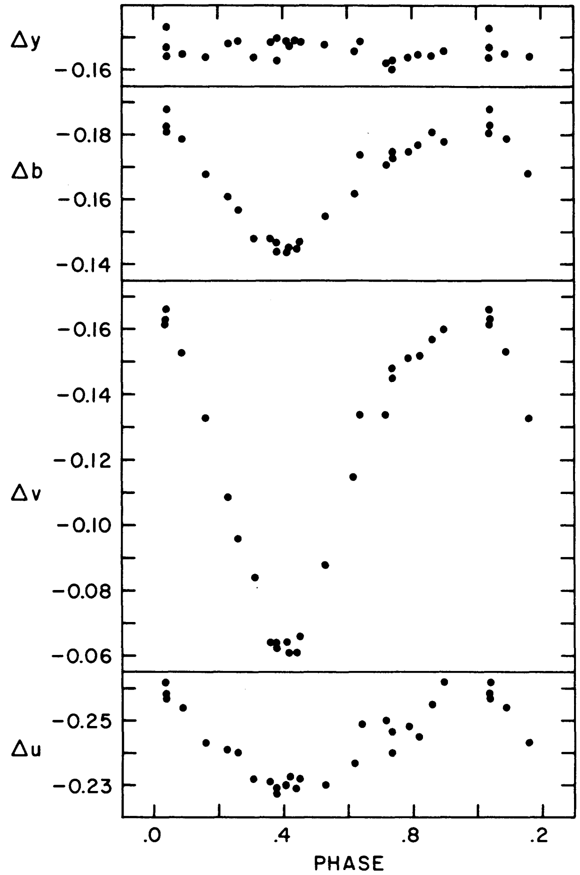


FIG. 5—Photometric observations of HR 5153 plotted according to the ephemeris $JD_\odot (v_{max}) = 2441450.74 + 2^d.451E$. Magnitude differences are in the sense (HR 5153 − HR 5216).

1.052 days to 1.056 days.

In 1970, we obtained an extensive series of *uvby* observations of HR 5597, and it was quite clear that these observations could not be satisfied by periods close to 1.05 days; indeed, the most likely period appeared to be about 3 days. However, because the amplitudes in all four colors are $0^m.02$ or less, and because the data are of inferior quality, we made no attempt to derive a period for HR 5597.

Recently, Winzer (1974) has derived the following elements for the photometric variations of HR 5597

$$JD_\odot(U_{max}) = 2441461.70 + 2^d.8881E \quad .$$

In Figure 6, we have plotted our own observations using this ephemeris and it is apparent that Winzer's elements represent these data satis-

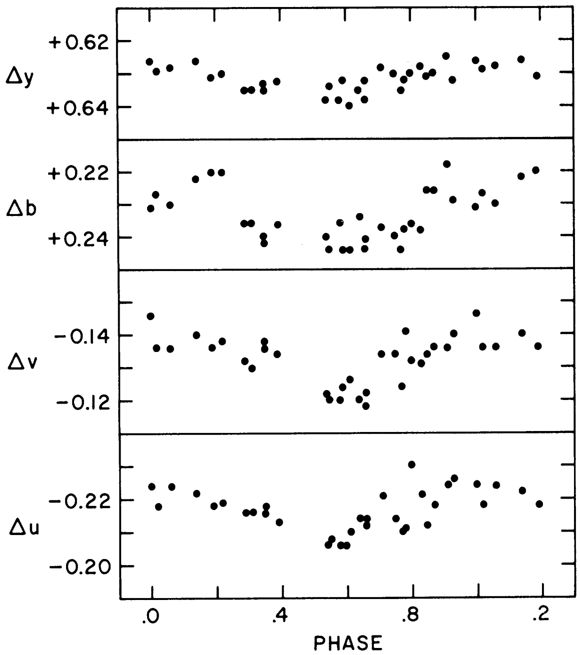


FIG. 6 — Photometric observations of HR 5597 plotted according to the ephemeris $JD_{\odot}$ $(U_{max})$ = 2441461.70 + $2^{d}.8881E$. Magnitude differences are in the sense (HR 5597 − HR 5533).

factorily. Since our observations were made in 1970 and Winzer's in 1971 and 1972, the period has remained constant to at least 0.001 day during this time. We believe this period from the photometry to be correct and suggest that a reliable period cannot be derived from the magnetic-field observations because the variations in the magnetic field are so small. This suggestion receives some support from recent Zeeman observations of HR 5597 (Bonsack, private communication), which show smaller scatter about the mean than Babcock's measurements and which cannot be fitted by periods around 1.05 days, 2.8881 days, or any other value. There is therefore no Ap star for which there is convincing evidence of variations in the period.

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