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# Strömgren *uvby* Photometry of the Magnetic Chemically Peculiar Stars HR 1643, $\theta$ Aur, 49 Cam, and HR 3724

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**ABSTRACT.** Differential Strömgren *uvby* photometric observations from the Four College Automated Photoelectric Telescope of four magnetic chemically peculiar stars are used to refine rotational periods and to define the shapes of the light curves. HR 1643 ($P$=2.73475 d) shows large in-phase variability in all four magnitudes. $\theta$ Aur ($P$=3.6188 d) exhibits large amplitude variations with two components contributing to the minima. For 49 Cam ($P$=4.28679 d), we probably are observing both polar regions and much of the surface. The values for HR 3724 ($P$=33.984 d) confirm Wolff's result that the main variability is in $v$.

## 1. INTRODUCTION

Many magnetic CP (chemically peculiar) stars exhibit variability in light, spectra, and magnetic-field strength (e.g., Wolff 1983). According to the rigid rotator model (Babcock 1949; Stibbs 1950), the axis of the magnetic field, which may be a decentered dipole or have dipolar and higher-order terms, is often inclined by a large angle to the rotational axis. At a given photospheric location the magnetic field is assumed to have a fixed intensity. As the star rotates the magnetic field appears to have a variable intensity to a distant observer. The spectral and light variations can be explained by assuming that the elemental abundances are nonuniformly distributed over the stellar surface. The existence of regions of apparent local enhancements of elemental abundances or "spots" has been confirmed by phenomenological studies of several variable magnetic CP stars. Within the framework of the radiative diffusion mechanism (Michaud 1970), the magnetic field over periods of time long compared to the human lifespan acts on the photospheric and envelope material to produce regions with elemental abundances and flux distributions which are different from those of the undisturbed star. Stellar rotation then produces the observed components in the line profiles and causes changes in the stellar flux distribution.

During the first five years (1990 September–1995 July) (year 1 is 1990 September–1991 July, year 2 is 1991 September–1992 July, etc.) of the 0.75-m Four College Automated Photoelectric Telescope (FCAPT) on Mt. Hopkins, AZ, I obtained differential photometry of some magnetic CP stars in the Strömgren *uvby* system, e.g., Adelman et al. (1994) and North and Adelman (1995). These studies better determined the periods and shapes of the light curves so that observations of various types taken at different times can be correctly phased together. The telescope measured the dark count and then in each filter the sky-*ch-c-v-c-v-c-v-c-ch*-sky where sky is a reading of the sky, *ch* that of the check star, *c* that of the comparison star, and $v$ that of the variable star. This paper presents results for four magnetic CP stars HR 1643, $\theta$ Aur, 49 Cam, and HR 3724. Table 1 gives important information on the variable, comparison, and check stars from Hoffleit (1982) and Hoffleit et al. (1983).

Tables 2–5 (these tables can be found in the AAS CD-ROM Series, Vol. 8, 1997; the first page of Table 2 can be found here to show form and content) contain the observations along with their yearly and total means and standard deviations (with *v-c* being the variable−comparison-star observations and *ch-c* being the check−comparison star observations). No corrections have been made for neutral density filter differences among each group of variable, comparison, and check stars. For each variable star with a known period I plotted my data using the best published period to see if the data approximately confirmed this period. When I used the Scargle periodogram (Scargle 1982; Horne and Baliunas 1986) on my data which except for HR 1643 was the most extensive dataset for each star, the periodograms confirmed the published periods. Finally I adjusted each period to make the FCAPT photometric data coincide as well as possible in phase with published observations.

## 2. HR 1643 (=HD 32650=BN Cam)

Babcock (1958) noted that HR 1643 might be a magnetic star. Winzer's (1974) *UBV* photometry showed that this B9pSi star (Cowley et al. 1969) was a large-amplitude variable, almost 0.1 mag in $U$, with a period of possibly 0.7325 days. As this star has a declination of +73°, it was observed always through an air mass greater than 1.5. Ziznovsky et al. (1992) obtained *UBV* photometry on 17 nights, obtaining of order 350 observations per magnitude. Their ephemeris was

$$\text{HJD (maximum light)} = 2448232.5843 + 2.7332E.$$

Seventy *uvby* observations of HR 1643 were obtained in years 2–5. The periodogram analysis indicated that the period was 2.7351 days with an alias of 1.5697 days. I adopted Ziznovsky et al.'s time of maximum light. To bring Winzer's $V$ data into phase coincidence with my $y$ data required changing the period to 2.73475±0.00002 days. This period also brought the best agreement with Ziznovsky's $V$ data, but there are differences. The periodogram of Ziznovsky's data is very similar to my data. The alias period has less power

TABLE 1
Photometric Groups

| Star | Type | V | B-V | Spectral Type |
|---|---|---|---|---|
| HR 1643 | v | 5.43 | ... | B9pSi |
| HR 1683 | c | 5.74 | ... | A0 V |
| HR 1510 | ch | 6.37 | -0.08 | A0 IV |
| θ Aur | v | 2.62 | -0.08 | A0pSi |
| HR 2025 | c | 6.45 | +0.09 | A2 V |
| HD 37339 | ch | 6.96 | +0.00 | B9 |
| 49 Cam | v | 6.18 | +0.26 | F0pSrEu |
| 24 Lyn | c | 4.99 | +0.08 | A3 IVn |
| HD 62976 | ch | 6.78 | +0.09 | A2 |
| HR 3724 | v | 6.53 | +0.22 | A5pSrCrEu |
| HR 3702 | c | 6.62 | +0.08 | A2 Vs |
| 24 Hya | ch | 5.47 | -0.09 | B9 III |

TABLE 2
*uvby* Photometry for HR 1643*

| Heliocentric | u | | b | | v | | y | |
|---|---|---|---|---|---|---|---|---|
| Julian Date | v-c | ch-c | v-c | ch-c | v-c | ch-c | v-c | ch-c |
| 2448531.9511 | -0.700 | 2.032 | -0.466 | 1.921 | -0.408 | 1.869 | -0.368 | 1.866 |
| 2448532.9484 | -0.765 | 2.026 | -0.488 | 1.918 | -0.430 | 1.863 | -0.382 | 1.862 |
| 2448533.9466 | -0.761 | 2.029 | -0.493 | 1.919 | -0.433 | 1.864 | -0.385 | 1.866 |
| 2448534.9081 | -0.688 | 2.023 | -0.456 | 1.920 | -0.406 | 1.864 | -0.362 | 1.863 |
| 2448543.8415 | -0.749 | 2.028 | -0.488 | 1.927 | -0.419 | 1.861 | -0.390 | 1.877 |
| 2448544.9423 | -0.758 | 2.025 | -0.488 | 1.919 | -0.426 | 1.856 | -0.383 | 1.858 |
| 2448545.9195 | -0.691 | 2.024 | -0.457 | 1.918 | -0.398 | 1.859 | -0.364 | 1.861 |
| 2448546.9279 | -0.790 | 2.030 | -0.509 | 1.925 | -0.441 | 1.865 | -0.400 | 1.870 |
| 2448547.9248 | -0.730 | 2.033 | -0.478 | 1.927 | -0.415 | 1.866 | -0.379 | 1.872 |
| 2448548.9302 | -0.705 | 2.039 | -0.462 | 1.929 | -0.403 | 1.865 | -0.367 | 1.875 |
| 2448561.9092 | -0.705 | 2.035 | -0.463 | 1.919 | -0.400 | 1.864 | -0.363 | 1.870 |
| 2448562.9122 | -0.743 | 2.045 | -0.480 | 1.923 | -0.414 | 1.855 | -0.377 | 1.867 |
| 2448563.9142 | -0.779 | 2.025 | -0.499 | 1.921 | -0.438 | 1.860 | -0.391 | 1.869 |
| 2448564.9027 | -0.689 | 2.029 | -0.463 | 1.925 | -0.399 | 1.862 | -0.360 | 1.863 |
| 2448565.8970 | -0.776 | 2.023 | -0.491 | 1.915 | -0.434 | 1.860 | -0.393 | 1.863 |
| 2448566.9000 | -0.740 | 2.031 | -0.481 | 1.929 | -0.416 | 1.861 | -0.383 | 1.878 |
| 2448567.9444 | -0.689 | 2.025 | -0.456 | 1.918 | -0.404 | 1.865 | -0.360 | 1.865 |
| 2448568.9453 | -0.793 | 2.023 | -0.501 | 1.916 | -0.441 | 1.859 | -0.395 | 1.857 |
| 2448577.9448 | -0.733 | 2.026 | -0.481 | 1.921 | -0.414 | 1.856 | -0.375 | 1.851 |
| 2448598.8675 | -0.782 | 2.021 | -0.495 | 1.914 | -0.440 | 1.867 | -0.396 | 1.866 |
| 2448604.8515 | -0.783 | 2.023 | -0.502 | 1.921 | -0.446 | 1.863 | -0.391 | 1.863 |
| 2448605.8525 | -0.684 | 2.014 | -0.464 | 1.915 | -0.395 | 1.852 | -0.354 | 1.862 |
| year 2 | | | | | | | | |
| average | -0.738 | 2.028 | -0.480 | 1.921 | -0.419 | 1.862 | -0.378 | 1.866 |
| std. dev. | 0.038 | 0.007 | 0.017 | 0.005 | 0.016 | 0.004 | 0.014 | 0.007 |
| 2449019.7156 | -0.754 | 2.026 | -0.482 | 1.916 | -0.424 | 1.856 | -0.383 | 1.862 |
| 2449052.6214 | -0.763 | 2.036 | -0.487 | 1.928 | -0.435 | 1.869 | -0.391 | 1.867 |
| 2449053.6217 | -0.768 | 2.035 | -0.497 | 1.930 | -0.444 | 1.869 | -0.396 | 1.860 |
| 2449054.6225 | -0.696 | 2.021 | -0.459 | 1.914 | -0.405 | 1.854 | -0.367 | 1.864 |
| 2449056.6284 | -0.725 | 2.024 | -0.475 | 1.912 | -0.412 | 1.859 | -0.366 | 1.869 |
| 2449057.6263 | -0.705 | 2.022 | -0.463 | 1.916 | -0.407 | 1.860 | -0.365 | 1.866 |
| 2449058.6251 | -0.795 | 2.018 | -0.502 | 1.926 | -0.448 | 1.857 | -0.396 | 1.864 |
| year 3 | | | | | | | | |
| average | -0.744 | 2.026 | -0.481 | 1.920 | -0.425 | 1.861 | -0.381 | 1.864 |
| std. dev. | 0.036 | 0.007 | 0.016 | 0.008 | 0.018 | 0.006 | 0.014 | 0.003 |
| 2449253.8931 | -0.706 | 2.029 | -0.453 | 1.913 | -0.402 | 1.853 | -0.363 | 1.858 |
| 2449257.8822 | -0.778 | 2.030 | -0.501 | 1.928 | -0.441 | 1.860 | -0.395 | 1.874 |
| 2449259.8780 | -0.699 | 2.027 | -0.459 | 1.915 | -0.406 | 1.857 | -0.363 | 1.873 |
| 2449261.8737 | -0.713 | 2.032 | -0.468 | 1.925 | -0.412 | 1.861 | -0.371 | 1.870 |
| 2449290.9785 | -0.793 | 2.032 | -0.507 | 1.920 | -0.452 | 1.861 | -0.404 | 1.872 |
| 2449291.9422 | -0.718 | 2.030 | -0.470 | 1.912 | -0.417 | 1.856 | -0.367 | 1.864 |
| 2449294.8717 | -0.702 | 2.020 | -0.468 | 1.911 | -0.408 | 1.850 | -0.370 | 1.861 |
| 2449295.8793 | -0.741 | 2.029 | -0.478 | 1.916 | -0.425 | 1.856 | -0.385 | 1.864 |
| 2449311.9204 | -0.702 | 2.006 | -0.462 | 1.918 | -0.404 | 1.861 | -0.360 | 1.868 |
| 2449312.9164 | -0.803 | 2.029 | -0.508 | 1.924 | -0.447 | 1.859 | -0.405 | 1.869 |
| 2449316.9141 | -0.700 | 2.038 | -0.454 | 1.918 | -0.402 | 1.859 | -0.365 | 1.873 |
| 2449318.9033 | -0.768 | 2.028 | -0.492 | 1.918 | -0.434 | 1.858 | -0.386 | 1.868 |
| 2449324.8931 | -0.709 | 2.030 | -0.468 | 1.915 | -0.403 | 1.856 | -0.365 | 1.866 |
| 2449328.8816 | -0.768 | 2.021 | -0.489 | 1.908 | -0.437 | 1.847 | -0.390 | 1.856 |
| 2449336.8535 | -0.726 | 2.034 | -0.473 | 1.915 | -0.418 | 1.857 | -0.375 | 1.872 |
| 2449337.8550 | -0.793 | 2.023 | -0.497 | 1.918 | -0.436 | 1.856 | -0.395 | 1.874 |
| 2449346.8239 | -0.694 | 2.033 | -0.464 | 1.920 | -0.411 | 1.863 | -0.368 | 1.861 |
| 2449351.8214 | -0.746 | 2.017 | -0.483 | 1.917 | -0.432 | 1.853 | -0.384 | 1.859 |

*This table can be found in the AAS CD-ROM Series, Vol. 8, 1997. Only the first page is shown here for form and content. Tables 3, 4, and 5 show the same format as Table 2 and can also be found in Vol. 8, 1997.

and results in less smooth light curves. Combining the two sets of data, increases the power of the adopted period compared to its alias.

Figure 1 shows the resulting light curves with the FCAPT data as plus signs, Winzer's transformed $V$ data as solid diamonds, and Ziznovsky et al.'s transformed $V$ data as open circles. The variability is approximately in phase with the amplitude of variability decreasing with wavelength, being 0.11 mag in $u$, 0.055 mag in $v$, and 0.05 mag in $b$ and $y$. There are suggestions that the shape of the light curves near minimum may be asymmetric, but additional observations are needed for confirmation. There are also some differences between datasets on the rising curve in $y(V)$ which might indicate that there are slight changes in the light curve with time or simply differences between $y$ and $V$ magnitudes.

## 3. θ Aur (=HR 2095=HD 40312=37 Aur)

Hiltner and Morgan (1944) found that the second magnitude A0p Si star θ Aur (Cowley et al. 1969), the brighter member of the close visual binary ADS 4566, was a spectrum variable. Winzer (1974) performed *UBV* photometry and derived a period of 1.3717 days. Borra and Landstreet (1980) found that the magnetic variations have a period of 3.618 days which is an alias of that given by Winzer. Musielok and Madej (1988) showed that the H$\beta$ index is variable with an amplitude of 0.02 mag in this period. Several studies have mapped the abundances of elements on the surface of this star, the most recent being that of Hatzes (1991) who determined a period of 3.6187 days.

Forty-seven *uvby* observations of θ Aur were obtained in years 2–5. To perform the photometry in a timely manner the variable was observed through a 5 mag neutral density filter. The periodogram analysis shows two peaks corresponding to periods of 1.376 and 3.618 days. To make Winzer's (1974) $V$ values and the FCAPT $y$ values coincide in phase, I increased the period to 3.6188±0.0001 days and made a slight modification to Hatzes' zero phase. HJD 2446337.465±0.010 represents a mean maximum of the four light curves. Still the shape of the maximum makes it difficult to determine exactly which point on the curve to select.

Figure 2 shows the photometry plotted according to this ephemeris. θ Aur is clearly a large amplitude variable and additional photometry is required to better define some of the light curve characteristics. There are at least two components producing the minimum. In $u$ the one earlier in phase produces less of a depression while the reverse is true for the other three magnitudes. The amplitude of variability is 0.07 mag for $u$, 0.035 mag for $v$, 0.04 mag for $b$, and 0.035 mag for $y$.

The light curves are approximately in phase with the effective magnetic field measurements of Borra and Landstreet (1980) phased to this paper's ephemeris. But, they differ somewhat from the equivalent width variations of the Si II and Cr II lines shown by Hatzes (1991). This is not unexpected as the filter photometry involves an integration over the visible hemisphere.

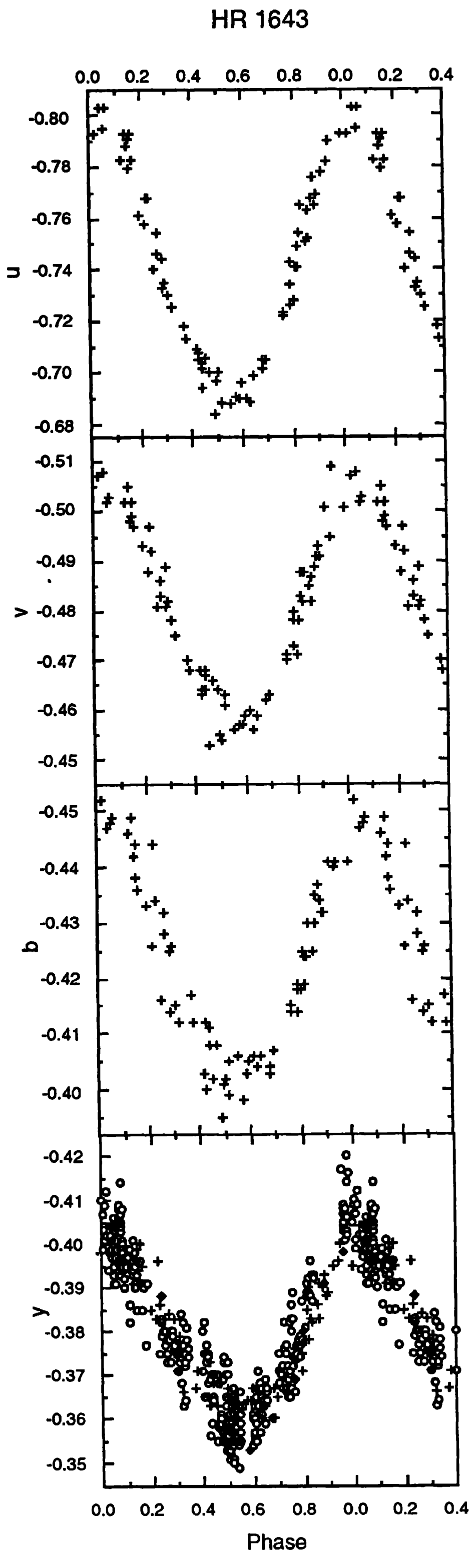


FIG. 1—Differential Strömgren *uvby* photometry of HR 1643 plotted with the ephemeris HJD (maximum light)=2448232.5843+2.73475*E*. Values from the Four College APT are indicated by plus signs while *V* values from Winzer (1974) and Ziznovsky et al. (1992) transformed to the *y* scale as solid diamonds and open circles, respectively. Note the vertical scales change between figure panels.

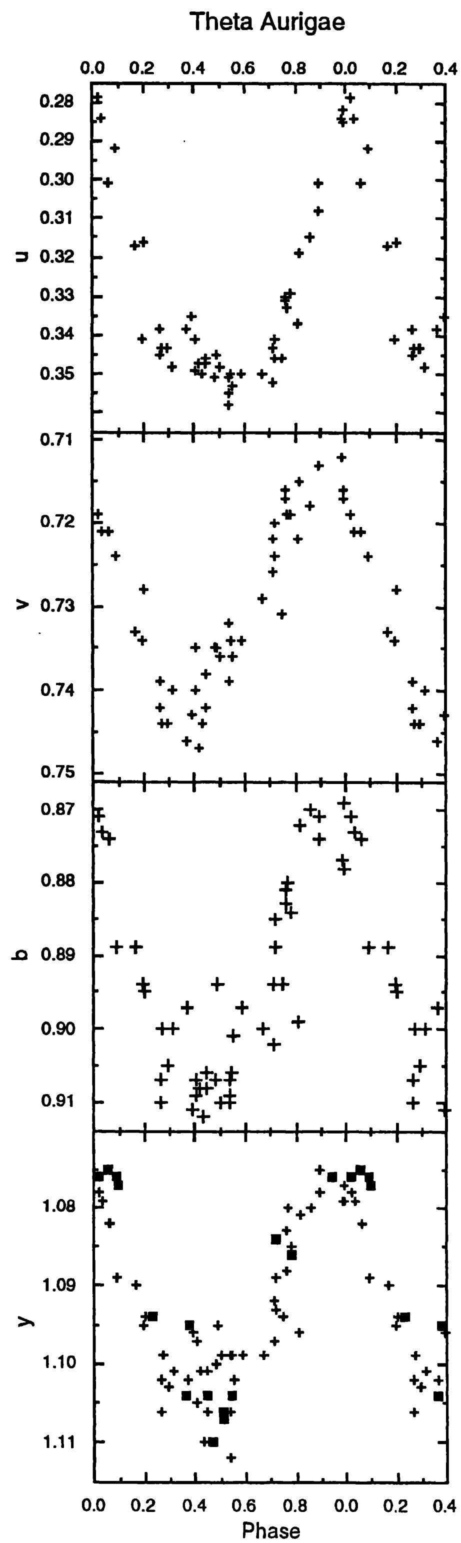


FIG. 2—Differential Strömgren *uvby* photometry of $\theta$ Aur plotted with the ephemeris HJD (*y* maximum)=2446337.465+3.6188*E*. Values from the Four College APT are indicated by plus signs and *V* values from Winzer (1974) transformed to the *y* scale as solid squares.

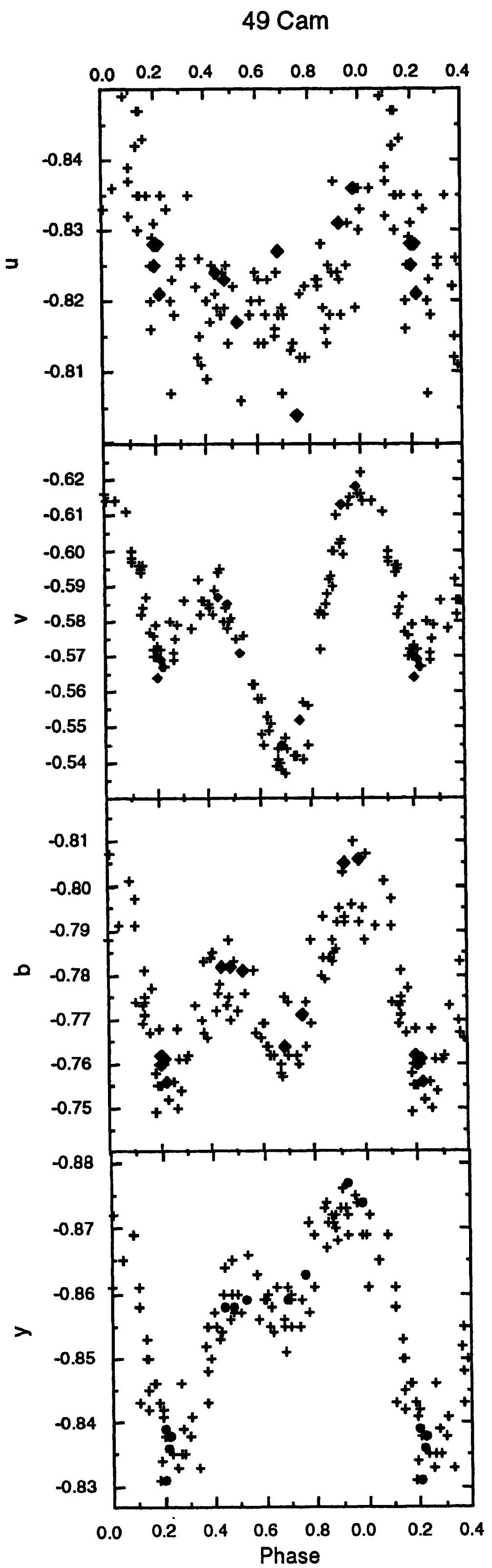


FIG. 3—Differential Strömgren *uvby* photometry of 49 Cam plotted according to the ephemeris HJD ($v$ maximum)=2441254.08+4.28679$E$. Values from the Four College APT are indicated by plus signs and those from Bonsack et al. (1974) by either solid diamonds or circles.

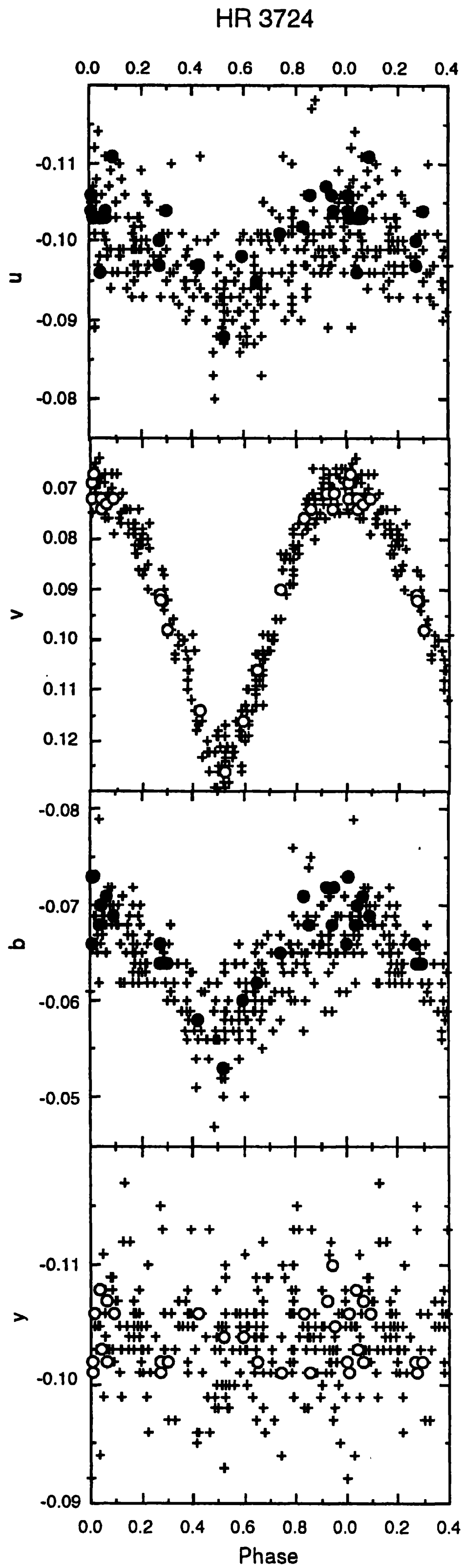


FIG. 4—Differential Strömgren *uvby* photometry of HR 3724 plotted according to the ephemeris HJD ($v$ maximum)=2444483.42+33.984$E$. Values from the Four College APT are indicated by plus signs and those from Wolff (1975) by either solid or open circles.

## 4. 49 Cam (=HR 2977=HD 62140=BC Cam)

Leroy et al. (1994) found that the F0p SrEu (Cowley et al. 1969) magnetic CP star 49 Camelopardalis displayed a remarkable linear polarization whose periodic variations were larger than those of other CP stars. Their ephemeris was

$$\text{JD (negative crossover)} = 2441254.08 + 4.2866 \pm 0.0005E.$$

The origin is that of Bonsack et al. (1974) while the period is slightly different. Bonsack et al. obtained eleven *uvby* observations using HR 2946 (=24 Lyn=HD 61497) and HR 3106 (=HD 65301) as comparison stars. The largest variability appears to be in $v$. Winzer (1974) obtain a similar number of *UBV* observations, but was not able to completely cover one period. Matthews and Wehlau (1985) identified a possible coherent oscillation with a period of about 62 min on two of three nights of observing in 1984, but this lacks confirmation.

Primarily during the first, fourth, and fifth years of operation 89 Four College APT *uvby* observations were made (Table 4). The check−comparison star data between years agree well except for $u$ whose average value has a range of 0.02 mag.

A periodogram of the $v$ values shows two strong peaks corresponding to 1.866 and 2.155 days and a weaker one corresponding to 4.289 days. When the data are plotted according to these three periods, the 4.289-day period is the only one which yields a sensible light curve. As 49 Cam shows a double peak light curve with a secondary maximum near phase 0.50, the periodogram suggests an incorrect answer of one-half of the period. To bring the Bonsack et al. (1974) data into phase agreement with the FCAPT data the period became 4.28679±0.00005 days. Leroy et al.'s zero point corresponds to primary light maximum. Recently, Leroy (1995) determined that the period was 4.2867±0.0005 days, a value in reasonable agreement with that derived in this paper.

Figure 3 shows the FCAPT data (pulses) and the Bonsack et al. (1974) data (solid diamonds and circles). The $v$, $b$, and $y$ light curves show two minima per period. The first inphase minimum is stronger in $b$ and $y$. In $u$ no such structure is seen with a brightening only near primary maximum. The amplitude of variability is 0.035 mag in $u$, 0.08 mag in $v$, 0.055 mag in $b$, and 0.045 mag in $y$. The light curve symmetry suggests that the star has two spots located about 180° away from one another. If these are associated with the magnetic poles, then the large variations in linear polarization are a natural consequence of alternatively viewing magnetic polar and equatorial regions.

## 5. HR 3724 (=HD 81009=KU Hya)

Wolff (1975) obtained four color (*uvby*) photometry of HR 3724 and discovered that it was variable with a 69-day period. Her observations included two pronounced minima in $v$. The observed light curves show a large amplitude in $v$, a smaller in phase variation in $u$ and perhaps $b$, and little variation in $y$. HD 80447 (=HR 3702) and 29 Hya (=HR 3744=HD 87128) were her comparison stars. Hensberge et al. (1991) obtained $u$ and $v$ photometry as well as that for the peculiarity index $\Delta a$. They found a 33.97±0.02-day period. Waelkens (1985) discussed Geneva photometry of HR 3724 and improved the period to 33.96±0.01 days. Martinez and Kurtz (1994) did not find that this star was a rapidly oscillating Ap star contrary to Wu et al. (1993).

Preston (1971) and Mathys (1990) report resolved Zeeman split lines. This visual binary (ADS 7334) has almost equal brightness components which are separated by less than 0.2 s of arc and photometrically are observed together. Recent solutions for the period yield values between 25.4 and 58.9 yr (van Dessel 1972; Starikova 1981).

I made 253 differential observations of HR 3724 over about a 4.5-yr period (Table 5). On some occasions there is almost continuous coverage for several hours, but most of the time only one observation per night was obtained. Examination of the data from the continuous runs showed that the variable−comparison star variability was similar to that for check−comparison star data and thus short term variability was not found in agreement with Nelson and Kreidl (1993). The average check–comparison values for the first three years tend to be slightly less than those for the last two years. But in the average variable−comparison star data no such trends are seen. A periodogram analysis was run only for the $v$ data. It indicated a period of 33.973 days.

To bring the $v$ minimum from the FCAPT and Wolff's data into agreement, I adjusted the period to 33.984±0.002 days. Initially I tried Waelkens (1985) epoch of maximum brightness, but from $v$ photometry a better value is 2444483.42±0.04. In retrospect it would have been better to use the time of minimum as this should be somewhat easier to determine.

Figure 4 shows Wolff's photometry (solid and open circles) and that from this study (pluses). The $u$, $v$, and $b$ variations are in phase with $b$ clearly variable. Both sets of photometry show a similar amount of scatter. The shapes of the light curve appear to be the same in both sets of data. There is an apparent change in slope in the $v$ light curve as the star becomes fainter which is not seen as the star becomes brighter. The amplitude of variability is 0.015 mag in $u$ and $b$, 0.06 mag in $v$, and less than 0.005 mag in $y$.

## 6. FINAL COMMENTS

This study used considerably more data than previous photometric studies of these stars except for HR 1643. This leads to improved determinations of the light curves. That the quality of the data was at least similar to that of previous photometry obtained by astronomers manually operating a telescope confirms that automated operations can result in high-quality data. The extensive datasets are a result of four schools being able to share telescope time among many projects each night. On the other hand, previously published photometry was crucial to the improvement in the periods.

Since the photometry is an average over the visible surface, observations of light variability imply that the maximum variations between localized regions on the surface will be even greater. As these stars have strong magnetic fields organized over the entire stellar surface, we are observing the effects of these fields both directly as they affect the stellar opacities and influence the photospheric shapes and indirectly as they influence the hydrodynamics of the atmospheres and envelop layers through which they penetrate. Some of the light curves instead of being quite smooth show structure or incipient structure, which should provide constraints for modelers of inhomogeneity in CP star photospheres. The differences between the light curves for different magnitudes are also important clues, but may require higher resolution photometry to properly interpret.

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