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FCAPT *uvby* Photometry of the mCP Stars HD 86592, HR 4330, HR 6958, and HR 7786

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ABSTRACT. New differential Strömgren *uvby* Four College Automated Photoelectric Telescope (FCAPT) observations of four magnetic CP stars HD 86592, HR 4330, HR 6958, and HR 7786 are presented. These observations are analyzed along with published FCAPT data to improve the periods and the light curves. The period of HD 86592 is that of Babel & North, 2.886669 days. The new periods of HR 4330, HR 6958, and HR 7786 are 3.152, 18.0642, and 8.5295 days, respectively, almost the same as their previous values from FCAPT data. The first three stars can be characterized as having constant light curves and periods. However, the small differences among the seasonal light curves of HR 7786 indicate it is a star whose rotational axis is precessing about its magnetic axis.

Online material: color figures, extended table

1. INTRODUCTION

My published studies using Strömgren photometry from the Four College Automated Photoelectric Telescope (FCAPT) at Fairborn Observatory, Washington Camp, Arizona, have found the periods and the light curves of 68 magnetic chemically peculiar (mCP) stars. They relate observations taken at different times and can be used to detect variable light curves (see, e.g., Adelman 2006). Adelman & Woodrow (2007) showed that this ensemble consists of photometric variables. By extension, all mCP stars are intrinsic photometric variables. A significant number have variable light curves. Shore & Adelman (1976) predicted the existence of such stars produced by the precession of their rotational axes about their magnetic axes. A 5-yr secondary period was found in 56 Ari by Adelman et al. (2001), who had a decade of FCAPT Strömgren photometry and spectroscopic and other photometric data (see Pyper & Adelman 2004 for information on other mCP stars with variable light curves).

To find evidence for such variable light curves requires seasons of observations. With 75 or more high-quality observations per observing season, suggestions for such behavior have been found in as few as two or three seasons, but often more are needed. To progress beyond the discovery of variable light curves and find the secondary period, if any, one needs even more data. Many seasons of consistent high-quality observations are needed. Adelman et al. (2001) found the rotational period of 56 Ari is increasing at a rate of about 2 s per 100 yr. Pyper et al. (1988) discovered that the rotational period of the mCP star CU Vir had decreased between 1983 and 1987. It is probably performing an analog of a Chandler wobble.

Here I study the mCP stars HD 86592, HR 4330, HR 6958, and HR 7786 with new FCAPT single-channel differential Strömgren *uvby* photometry in the instrumental system, which supplements their already published FCAPT data. I am analyzing them to try to improve the periods and the light curves and to search for light curve variability. I am still obtaining second epoch observations for some previously observed stars and am trying to predict which stars are most likely to have variable light curves. A considerable spread in the range of observing seasons is useful. I have recently concentrated on those mCP stars with larger than average amplitudes, as seeing small changes in their light curves should be easier to find than for stars with small amplitudes. However, some stars with amplitudes less than the average values show variable light curves.

The FCAPT 0.75-m automated telescope obtains the dark count and then sky-ch-c-v-c-v-c-v-c-ch-sky values in the four Strömgren filters for each group of variable (v), check (ch), and comparison (c) stars where sky is a reading of the sky. No corrections are made for any neutral density filter differences among the stars of a group. When the four Strömgren light curves show in-phase variability, *Hipparcos* satellite data may be useful in refining the period in the absence of simultaneous good-quality ground-based photometry.

I chose comparison and check stars with the help of *Hipparcos* photometry (ESA 1997) from the least variable stars whose sky positions were close to those of the variables and had somewhat similar V magnitudes and $B - V$ colors. Table 1 provides some basic information on each group from Hoffleit (1982), Hoffleit et al. (1983), and SIMBAD. The mCP star periods were determined using the Scargle periodogram (Scargle 1982;

TABLE 1
PHOTOMETRIC GROUPS

HD	Name	Type[a]	V	Sp. Type	Filter[b]
86592	V359 Hya	v	7.85	Ap	1
88182	HR 3988	c	6.24	Am	1
83754	38 Hya	ch	5.06	B5 V	3
96707	HR 4330	v	6.06	F0pSr	1
97138	HR 4340	c	6.40	A3 V	1
98772	HR 4391	ch	5.98	A3 V	1
170973	HR 6958	v	6.43	A0pSiCr	1
169578	HR 6900	c	6.74	B9 V	1
172046	BD+5 846	ch	6.64	B8	1
193722	HR 7786	v	6.50	B9pSi	1
192514	30 Cyg	c	4.83	A5 IIIn	3
190781	HR 7684	ch	6.01	A2 IV	1

[a] Type of Star: v = variable, c = comparison star, and ch = check star.
[b] Filters: 1 = no neutral density filter, 2 = 1.25 mag neutral density filter, and 3 = 2.50 mag neutral density filter.

Horne & Baliunas 1986). Table 2 contains their new photometric values, means, and standard deviations of v-c and ch-c for each filter. Since those for ch-c are of order 0.005 mag, the errors for v-c are probably similar. The first observing season for the FCAPT was from 1990 fall through 1991 spring. This paper includes data from observing seasons 1 through 17 (2006 fall through 2007 early summer).

Theory tells us that the emergent energy distributions, abundances, and magnetic field strengths of mCP stars change with photospheric location. As their magnetic and rotation axes are usually not aligned, a distant observer sees photometric, spectrum, and/or magnetic variability as the star rotates. Hydrodynamical processes, especially radiative diffusion and gravitational settling in radiative envelopes with strong magnetic fields, produce their anomalous photospheric abundances, which depend on the local magnetic field strength and the evolution of the field and elemental abundances since at least the time when the stars were on the Zero Age Main Sequence (Michaud & Proffitt 1993 and references therein). For moderately rotating mCP stars, surface abundance maps derived from Doppler imaging techniques and spectra can test mCP star theories. Examination of light curves taken with different filters may provide some idea of the complexity of the surficial abundances and/or the magnetic field geometry.

2. HD 86592

Bidelman (1981) classified HD 86592 (V359 Hya, BD-12 3045, HIP 48958) as a SrEu star. Later Babel & North (1997) found it possessed a very strong magnetic field of 15 to 16 kG. Using 24 Geneva system measurements, they found $\mathrm{HJD}\,(\text{max flux Geneva B mag}) = 2,446,896.801 + (2.886669 \pm 0.00030)E$. This ephemeris also worked for the 122 FCAPT Strömgren observations of Adelman (2000) taken during the 1997–98 and 1998–99 observing seasons. The variation in v has an amplitude of 0.13 mag.

In the 2005–06 (season 16) and 2006–07 (season 17) observing seasons, an additional 33 and 36 good FCAPT *uvby* observations, respectively, were taken. These data show small magnitude shifts relative to the earlier FCAPT observations. For u the season 16 and 17 values were shifted by -0.03 and -0.02 mag, respectively; for v, the season 16 data were shifted by 0.025 mag; for b the season 16 and 17 values were shifted by -0.025 and $+0.02$ mag, respectively; and for y the season 16 and 17 values were shifted by -0.02 and 0.03 mag, respectively. These shifts may be due to slow changes in the magnitudes of the comparison star. In Table 2, the values as observed are given.

As the ephemeris of Babel & North also worked with the new FCAPT data, it was used. The newer photometry exhibited

TABLE 2
UVBY PHOTOMETRY FOR HD 86592, HR 4330, HR 6958, AND HR 7786

HJD	u(v-c)	u(ch-c)	v(v-c)	v(ch-c)	b(v-c)	b(ch-c)	y(v-c)	y(ch-c)
HD 86592								
2,453,724.9694	1.564	0.138	1.847	−0.693	1.694	−1.046	1.651	−1.236
2,453,725.9711	1.548	0.140	1.753	−0.687	1.672	−1.032	1.660	−1.236
2,453,726.9669	1.529	0.140	1.734	−0.692	1.660	−1.040	1.646	−1.235
2,453,729.9502	1.536	0.131	1.750	−0.697	1.671	−1.049	1.659	−1.241
2,453,731.9496	1.566	0.122	1.753	−0.710	1.675	−1.052	1.659	−1.248
2,453,732.9239	1.542	0.146	1.768	−0.690	1.680	−1.046	1.652	−1.230
2,453,740.8933	1.534	0.150	1.721	−0.690	1.663	−1.045	1.664	−1.240
2,453,741.8926	1.555	0.120	1.832	−0.704	1.701	−1.057	1.657	−1.253
2,453,742.8873	1.559	0.142	1.764	−0.693	1.677	−1.040	1.653	−1.238
2,453,745.9046	1.550	0.143	1.758	−0.694	1.669	−1.042	1.643	−1.242

NOTE.—Table 2 is published in its entirety in the electronic edition of the PASP. A portion is shown here for guidance regarding its form and content.

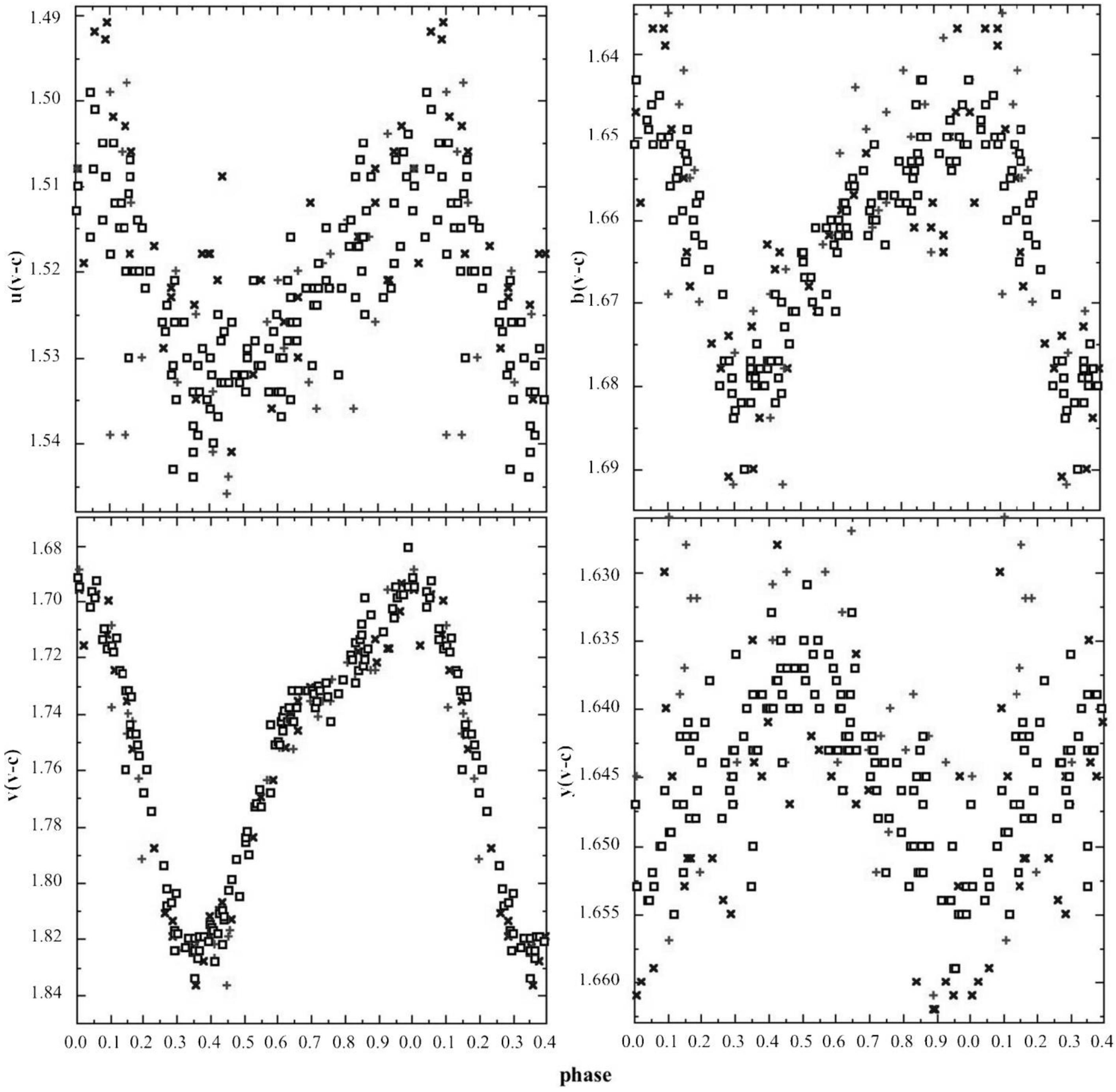

FIG. 1.—*uvby* photometry of HD 86592 for observing seasons 8 and 9 (open squares), 16 (crosses), and 17 (x's) plotted using the ephemeris of Babel & North (1997) HJD (max flux Geneva B mag) $-2,446,896.801 + (2.886669 \pm 0.00030)$ E. The u, v, and b light curves are nearly in phases as well as in antiphase to the y light curve. See the electronic edition of the PASP for a color version of this figure.

slightly greater scatter than the pervious FCAPT data as seen Figure 1. The y photometry is out of phase with the u, v, and b light curves. The amplitudes in u, v, b, and y are 0.037, 0.14, 0.04, and 0.018 mag, respectively, close to those of Adelman (2000). The values of Adelman (2000) are shown as open squares, those of 2005–06 as crosses, and those of 2006–07 as x's. For the v and b light curves, there are definite halts in the rising branch near phase 0.75.

3. HR 4330

Adelman et al. (1999) obtained 101 sets of differential photometry of HR 4330 (HD 96707, EP UMa) using data taken in 1995–96 (season 6), 1996–97 (season 7), and 1997–98 (season 8). Further, they found a period of 3.5160 days and amplitudes of variability of 0.02 mag in b, and 0.025 mag in y with those of u and v being much smaller. The scatter was somewhat larger than for most other mCP stars observed with the FCAPT. The b and the y light curves are in phase. Further, the light maxima came nearer phase 0.9, rather than 0.0 as intended, as they kept the zero point of Winzer (1974).

I observed 55 and 38 sets of additional Strömgren photo metry (see Table 2) in 2003–04 (season 14) and 2004–05 (season 15), respectively. A periodogram analysis yields a period of 3.5152 days. This data indicates that the check star HR 4391 was more constant than the comparison star HR 4340, whose amplitude of variability appears to be around 0.02 to 0.03 mag. Thus I analyzed the variable-check star values as these light curves fall more nearly on top of one another.

For the new ephemeris, I adjusted the zero point to agree with the minimum of the y light curve. Hence $\mathrm{HJD}(y_{\min}) = 2,441,447.542 + (3.5152 \pm 0.0001)\mathrm{E}$. The b and y light curves are plotted in Figure 2. There are differences near light minimum, with the shape of the b being more triangular with a minimum near phase 0.1. Those for u and v are not shown, as they are essentially constant with maximum amplitudes near 0.002 mag. The amplitudes of b and y are 0.015 mag and 0.018 mag, respectively. In Figure 2, but not in Table 2, small shifts of order 0.002 mag were applied to correct for small systematic errors

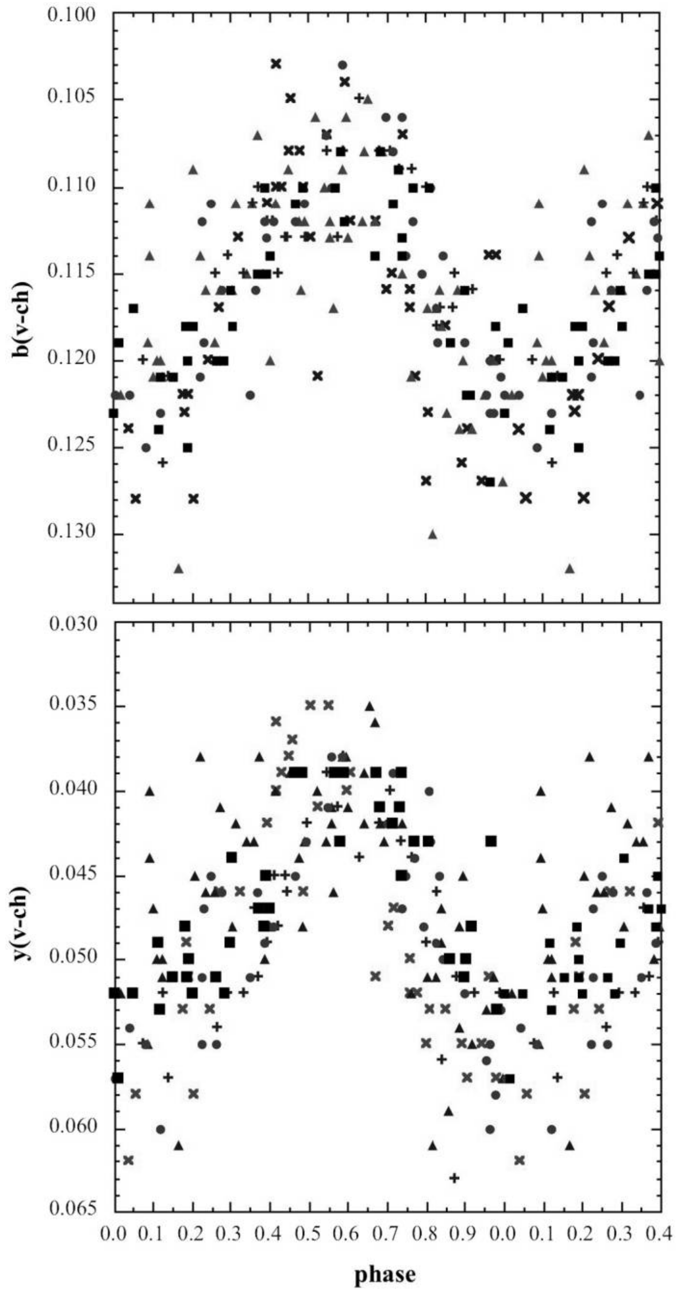

FIG. 2.—*uvby* photometry of HR 4330 for observing seasons 6 (filled squares), 7 (filled circles), 8 (crosses), 14 (filled triangles), and 15 (x's) plotted using the ephemeris $\mathrm{HJD}\,(y_{\max}) = 2,441,447.542 + (3.5152 \pm 0.0001)\,\mathrm{E}$. The b and y photometry are roughly in phase while the u and v photometry are nearly constant. The variable-check star data is shown in this figure. See the electronic edition of the PASP for a color version of this figure.

4. HR 6958

Adelman (1997) obtained 379 good *uvby* observations of the sharp-lined star HR 6958 (= HD 170973 = MV Ser) in the first five observing seasons of the FCAPT. He derived a period of 18.065 days, which was different from the 0.945-day period of Winzer (1974) and Burke & Barr (1981). The light curves are asymmetric especially for u and v, while those of b and y are nearly symmetric. Both the u and v light curves show a halt in the falling branch near phase 0.4.

For this study new FCAPT *uvby* observations were obtained: 68 in 2003–04 (season 14), 58 in 2005–06 (season 16) , and 37 in 2006–07 (season 17). When the u values of all the photometry were used, the period was found to be 18.0642 days. The zero point for $u_{\max}$ remains unchanged. The light maximum slightly increases in phase with increasing wavelength for Strömgren photometry, being about phase 0.05 for y. Thus $\mathrm{HJD}(u_{\max}) = 2441459.136 \pm 0.007 + (18.0642 \pm 0.0005)\mathrm{E}$.

In Figure 3, small vertical shifts are used to bring the values from some years into better agreement with other years ($u - 0.003$ mag for seasons 14, 15, and 16; $v + 0.003$ mag for seasons 5 and 14; $b + 0.004$, $+0.004$, -0.002, -0.010, and -0.015 mag for seasons 4, 5, 14, 15, and 16, respectively; $y + 0.005$ mag for seasons 4 and 5; and -0.200 mag for seasons 15 and 16). The scatter for seasons 14–16 tend to be larger than those of seasons 1–5. The amplitudes are 0.033 for u, 0.017 mag for v, and 0.015 mag for both b and y, similar to those of Adelman (1997). Table 2 contains the *uvby* data for seasons 14, 15, and 16. The data given there are not modified for the above shifts.

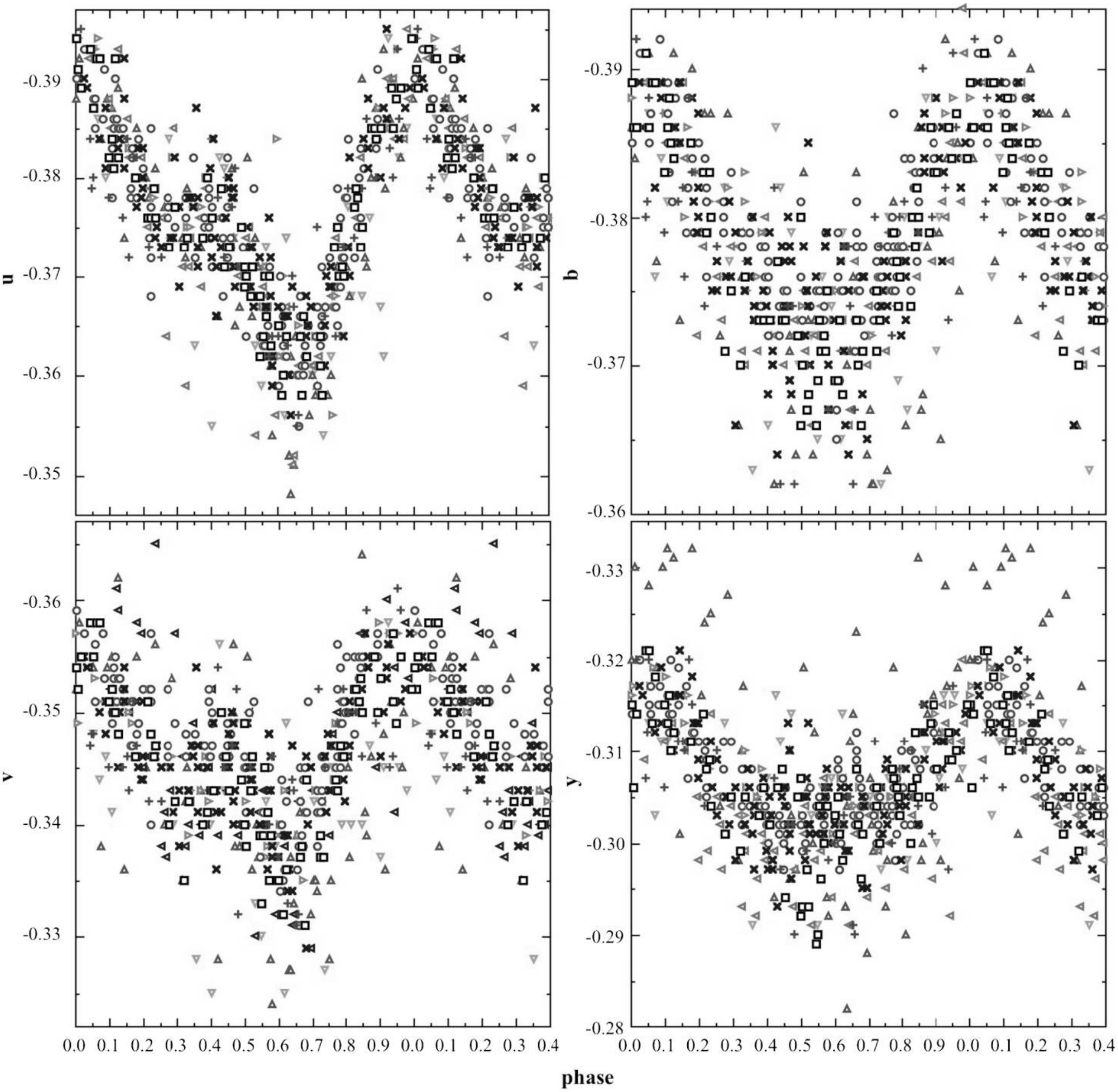

FIG. 3.—*uvby* photometry of HR 6958 for observing seasons 1 (open squares), 2 (crosses), 3 (x's), 4 (open circles), 5 (filled right-pointing triangles), 14 (filled left-pointing triangles), 15 (filled upward-pointing triangles), and 16 (filled downward-pointing triangles) plotted using HJD $(u_{\max}) = 2,441,459.136 \pm 0.007 + (18.0642 \pm 0.0005)$E. The b and y photometry are roughly in phase while the u and v photometry show a secondary component to the minimum. See the electronic edition of the PASP for a color version of this figure.

5. HR 7786

Winzer (1974) found that HR 7786 ($=$ HD 193722 $=$ V 1584 Cyg) was a large amplitude variable with a period of 1.13254 days. Later Adelman et al. (1998) obtained 90 FACPT Strömgren observations in observing seasons 1, 3, 4, and 5. They derived a period of 8.5297 ± 0.0002 days and found that the u, v, b, and y light curves were in phase. The comparison star HR 7721, a spectroscopic binary, was a small amplitude

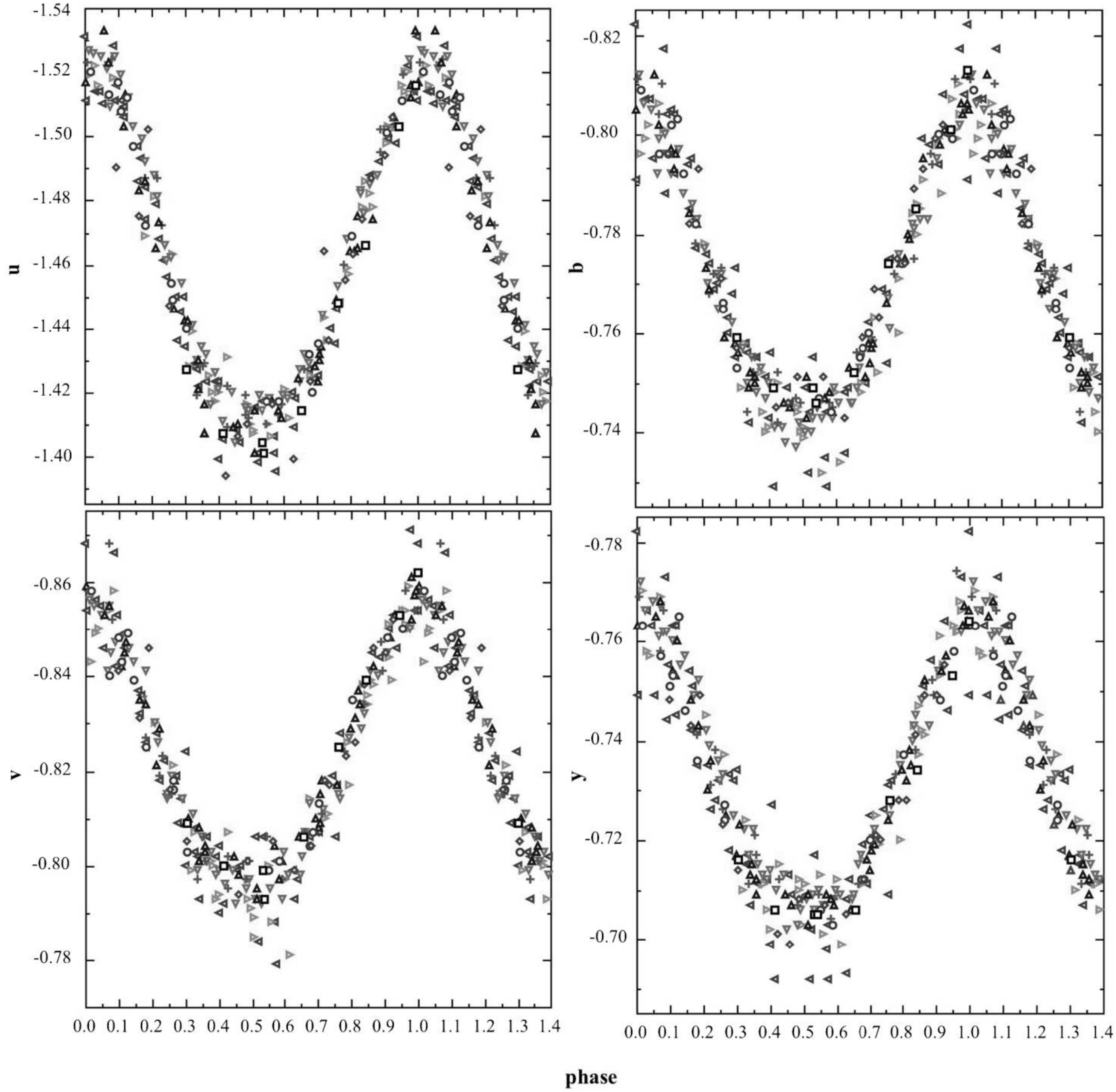

FIG. 4.—*uvby* photometry of HR 7786 for observing seasons 1 (open squares), 3 (filled diamonds), 4 (open circles), 5 (upward-pointing triangles), 14 (+), 15 (downward-pointing triangles), 16 (right-pointing triangles), and 17 (left-pointing triangles) using the ephemeris HJD (light maximum) $= 2,441,618.86 \pm 0.02 + (8.52951 \pm 0.0001)$E. The *uvby* light curves are in phase. However, season-to-season comparisons for the most complete light curves indicate slight differences. Hence, HR 7786 has variable light curves. See the electronic edition of the PASP for a color version of this figure.

variable. Thus, it was replaced by HD 190781 (HR 7684) starting with season 6. Table 2 contains 26, 53, 43, and 62 observations from 2003–04 (observing season 14), 2004–05 (season 15), 2005–06 (season 16), and 2006–07 (season 17), respectively, which are consistent with one another. In 1995–96 (season 6), 1996–97 (season 7), and 2002–03 (season 13) an additional 7, 35, and 7 observations, respectively, were obtained, but their magnitudes are not consistent with either the published values nor those of seasons 14 through 17 and so will not be studied. Their values were omitted from Table 2.

For the new ephemeris I kept the zero epoch of Adelman et al. (1998) and used a slightly different period found using a Scargle periodogram. Thus, HJD (light maximum) $= 2,441,618.86 \pm 0.02 + (8.5295 \pm 0.0001)$E. Small shifts were applied to part of the data to make the light curves for different seasons better agree with one another (for u seasons 5 and 16 values were shifted by $+0.005$ mag; for v seasons 4, 5, and 15 were shifted by $+0.005$ mag, and seasons 15 and 16 by 0.010 mag; for b the values for seasons 14, 15, 16, and 17 were shifted by $+0.005$, $+0.010$, $+0.007$, and -0.005 mag, respectively; and for y seasons 4, 14, and 15 were shifted by $+0.005$ mag, season 16 by 0.002 mag, and season 17 by -0.007 mag). However, even after this was done there are small differences in the light curves for each Strömgren magnitude. They are in the amplitudes and/or in the full widths at half the maximum amplitude of the minima. Further, they are signatures of slightly different stellar hemispheres being viewed at a given phase and suggest that the rotational axis is precessing about its magnetic axis. The maximum amplitudes for u, v, b, and y seen in Figure 4 are 0.11, 0.065, 0.065, and 0.06 mag, respectively, which are similar to those of Adelman et al. (1998).

6. SOME FINAL COMMENTS

The improvements in the light curves of HR 4330 indicate what a second set of data can do for a small amplitude star. Minor light curve differences have been found in the shapes of those of b and y, but more data is needed to assess their significance. For HD 85692, the period remains the same while for HR 6958 only a minor change in phase is made. For these stars the light curves from different observing seasons are similar when they are well defined.

To check light curve stability requires having good coverage with phase for several observing seasons. Without coverage particularly of the maxima and minima such tests cannot be properly performed. That HR 7786 has variable light curves strengthens the conclusion that about 12% of mCP stars behave in a similar manner (Pyper & Adelman 2004; Adelman & Sutton 2007).

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