PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **118**:77–83, 2006 January

FCAPT *uvby* Photometry of the mCP Stars HD 20629, HR 3724, 45 Leo, and HD 192678

SAUL J. ADELMAN

Department of Physics, The Citadel, 171 Moultrie Street, Charleston, SC 29409; adelmans@citadel.edu

Received 2005 June 21; accepted 2005 September 21; published 2006 January 5

ABSTRACT. The Four College Automated Photoelectric Telescope obtained differential Strömgren *uvby* observations of the magnetic chemically peculiar (mCP) stars HD 20629, HR 3724, 45 Leo, and HD 192678. HD 20629, a moderately large amplitude variable, has a period of 2.9934 days. Analyses of this new photometry with published *uvby* values show that HR 3724 and 45 Leo had periods of 33.984 and 1.44404 days, respectively, for at least 30 yr. New observations of HD 192678 refine the period of this small-amplitude variable to 6.4193 days.

Online material: color figures, extended table

1. INTRODUCTION

Often the magnetic chemically peculiar (mCP) stars are photometric, spectrum, and/or magnetic variables, since their emergent energy distributions, abundances, and magnetic field strengths depend on photospheric location. Usually the magnetic and rotation axes are not aligned. Thus, a distant observer will see a variety of variable behavior as they rotate. Theory suggests that hydrodynamical processes, in particular radiative diffusion and gravitational settling in radiative envelopes containing 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).

Studies with the Four College Automated Photoelectric Telescope (FCAPT) at Fairborn Observatory, Washington Camp, Arizona, have determined the periods and light curves of mCP stars to relate observations taken at different times and detected variable light curves (see, e.g., Adelman 2002), and furthermore, to study their period distribution. For spectrum variables exhibiting moderate rotation, surface abundance maps, when derived, serve as tests of mCP star theories. By comparing light curves taken with different filters, one can gain some idea of the complexity of the surficial abundances and/or the magnetic field geometry. Series of observations separated by several years are useful for improving periods. When sufficient observations are taken during two or more observing seasons, one can check for changes in the shapes of light curves, which have been interpreted as evidence for the precession of the rotational axis about the magnetic axis (Adelman et al. 2001).

Here we study FCAPT single-channel differential Strömgren *uvby* photometry of the mCP stars HD 20629, HR 3724, 45 Leo, and HD 192678. For HD 20629, it is the first such set of observations. For the other stars, it is their second set. The FCAPT 0.75 m automated telescope measures the dark count and then sky-ch-c-v-c-v-c-v-c-ch-sky 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 were made for any neutral-density filter differences among the stars of a group. With the aid of *Hipparcos* photometry (ESA 1997), the comparison and check stars were selected from the least variable stars close on the sky to the variables that had somewhat similar V magnitudes and $B-V$ colors. Information on each group is given in Table 1 (Hoffleit 1982; Hoffleit et al. 1983; and the SIMBAD database). The periods of the variable stars were found with the Scargle periodogram (Scargle 1982; Horne & Baliunas 1986). Table 2 contains the photometric values, their averages, and the standard deviations of v − c and ch − c for each filter. As those for ch − c are of an order of 0.005 mag, the errors for v − c are probably similar. The first observing season for the FCAPT was from fall 1990 through spring 1991. This paper includes data taken during observing season 15 (fall 2004 through early summer 2005).

2. HD 20629

Cutispoto et al. (1990) found HD 20629 (XX Ari, HIP 15506) to be a variable mCP star. Leone & Catanzaro (1998) classify it as a Silicon star, as its metal abundances significantly differ from solar values. Celestia 2000 (ESA 1998), with sufficient *Hipparcos* magnitudes, finds a period of 2.4994 days. During observing season 15, 68 differential *uvby* observations of this star were obtained. Alone, their analysis yields a period of 2.4992 days. When both sets of data were used, a period of 2.49934 days was found. The adopted ephemeris uses the Celestia 2000 zero point. That the period is so well determined is due to sufficient data for both epochs, which are separated

TABLE 1
PHOTOMETRIC GROUPS

HD	Star Name	Type	*V*	Spectral Type	Filter
20629	BD +18 449	v	7.37	A0	1
21050	HR 1028	c	6.08	A1 V	2
21335	HR 1036	ch	6.57	A3 V	1
81009	HR 3724	v	6.53	A5pSrCrEu	1
80447	HR 3702	c	6.62	A2 Va	1
79931	24 Hya	ch	5.47	B9 III	2
90659	45 Leo	v	6.04	A0pSiCr:	2
89774	42 Leo	c	6.12	A1 V	1
95216	HR 4281	ch	6.53	F5 V	1
192678	BD +53 2368	v	7.35	A4p	1
194668	HR 7815	c	6.51	B9.5 III	1
193592	HR 7781	ch	5.76	A2 Vs	2

NOTES.—(1) Type of star: v = variable, c = comparison star, and ch = check star. (2) Filter: 1 = no neutral density, 2 = 1.25 mag neutral density. (3) The neutral filter for HD 80447 was changed after the 11th season of FCAPT observations.

by about 10 yr, the relatively short rotational (variability) period, and the relatively large amplitudes of light curves that are in phase for the four Strömgren filters. The ephemeris is

$$\mathrm{HJD\,(max)} = 2{,}448{,}501.601 + 2.49934 \pm 0.00002E$$

Figure 1 shows that HD 20629 is a photometric variable with moderately large amplitudes of 0.16, 0.055, 0.095, and 0.105 mag in *u*, *v*, *b*, and *y*, respectively. The in-phase light curves exhibit some minor asymmetries (e.g., near light minimum) and show only a small amount of scatter. The amplitude of the variability, the relatively short period, and the rather clean light curves make HD 20629 a good candidate to study its photometric stability.

3. HR 3724

Adelman (1997) found a period of 33.984 days for HR 3724 (HD 81009, KU Hya) using 253 differential FCAPT *uvby* observations and data from Wolff (1975). As the *v* light curve shows the largest amplitude (0.06 mag), which is much greater than the other amplitudes (0.015 mag, 0.02 mag, and constant, respectively, for *u*, *b*, and *y*), determinations are best done with *v* photometry. Hensberge et al. (1981) also studied this star's Strömgren photometry with 6 to 14 values per filter. Optical-region spectrophotometry of HR 3724 (Adelman 1981) shows that the 5200 Å feature is of at least moderate strength for the mCP stars. These observations can have markedly different 4200 Å features. As the latter feature lies within the *v*-filter bandpass, its variability contributes to that of *v*.

Wade et al. (2000) studied the orbital, component, and magnetic field properties. The photometric variability is due to the brighter of a pair of A-type stars in highly eccentric orbits. The cooler secondary component has not yet been detected spectroscopically, and probably is a faster rotator than the sharp-lined primary.

In the last few years, 135 new FCAPT observations have been obtained. When a Scargle periodogram of all *v* FCAPT observations is performed, a period of 33.986 days is found. But a comparison with the Wolff (1975) data requires that a period of 33.984 day be retained if the entire data set is to be phased together. The *v* light curves, when plotted with Adelman's (1997) zero point, suggest that the light maxima and minima are shifted by 0.04 in phase. The mean time between the two sets of FCAPT observations is about 11 yr, and the Wolff (1975) observations were taken some 20 yr before the first set. The only well-established cases of mCP stars with changing periods are 56 Ari (Adelman et al. 2001) and CU Vir (Pyper et al. 1998). These are among the fastest rotating mCP stars, and the periods increase about 2 s century^{-1}. As a solution with HR 3724 having a constant period for over 30 yr was found, it is con-

TABLE 2
uvby PHOTOMETRY FOR HD 20629, HR 3724, 45 Leo, AND HD 192678

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 20629 Photometry				
2453255.8744	−0.153	0.153	0.232	0.369	0.164	0.564	0.145	0.698
2453262.9435	−0.210	0.152	0.229	0.370	0.138	0.573	0.104	0.717
2453265.8463	−0.156	0.139	0.237	0.354	0.168	0.558	0.141	0.705
2453270.9234	−0.134	0.163	0.250	0.374	0.179	0.576	0.154	0.717
2453271.8330	−0.095	0.147	0.266	0.361	0.211	0.556	0.186	0.691
2453273.8325	−0.095	0.159	0.268	0.369	0.207	0.565	0.181	0.703
2453274.9048	−0.187	0.166	0.220	0.374	0.144	0.572	0.114	0.712
2453281.8937	−0.091	0.155	0.272	0.372	0.207	0.572	0.188	0.708
2453282.8927	−0.232	0.167	0.213	0.377	0.128	0.576	0.093	0.717
2453283.8957	−0.087	0.173	0.280	0.376	0.218	0.575	0.195	0.717

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.

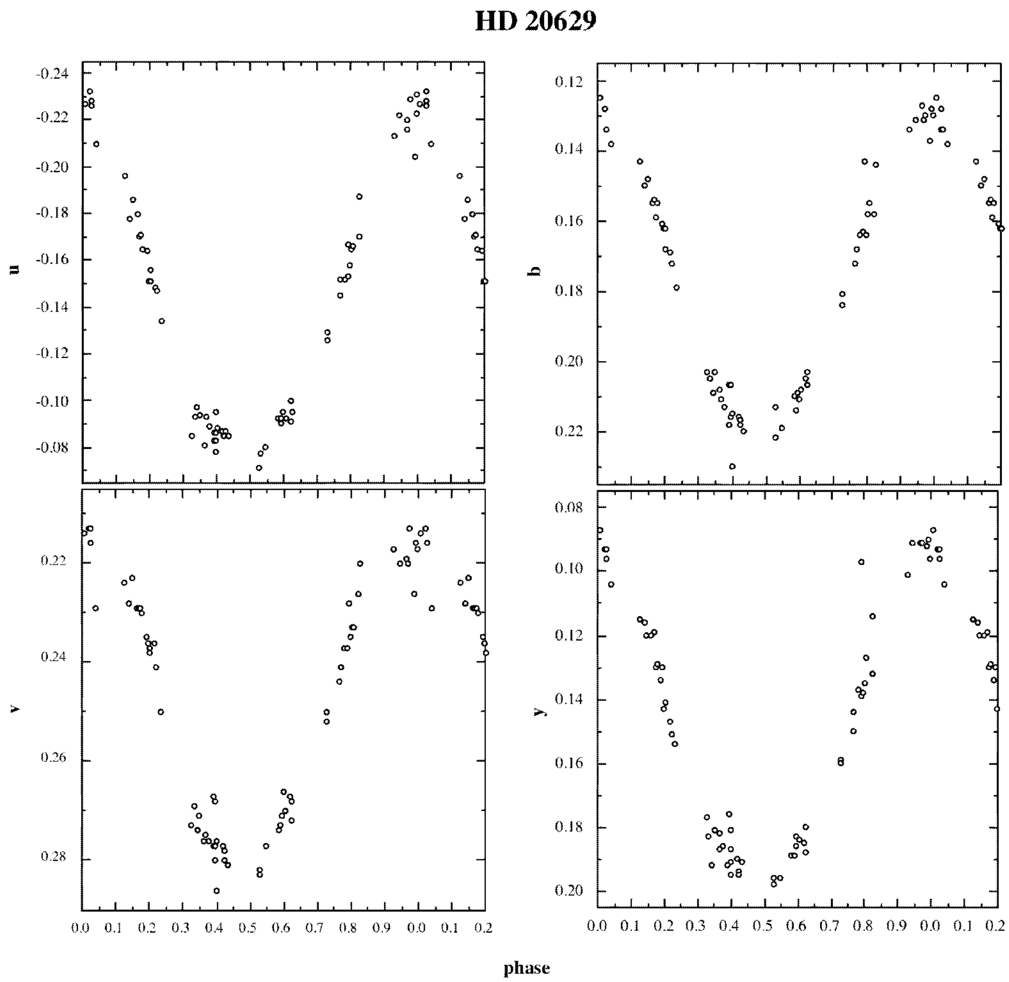

FIG. 1.—*uvby* photometry of HD 20629, plotted with the ephemeris HJD(max) = 2,448,501.601 + 2.44934E. The open circles show FCAPT observations published with this paper.

sidered the most probable. The new ephemeris is

$$\mathrm{HJD}\,(v_{\max}) = 2{,}444{,}484.78 \pm 0.40 + 33.984 \pm 0.002E.$$

In Figure 2, slight adjustments were applied to bring some mean magnitudes into agreement. The values of Adelman (1997) were used as the reference set. For u, the Wolff (1975) values were increased by 0.003 mag, and this paper's values by 0.004 mag; for b, the Wolff (1975) values were increased by 0.012 mag, while this paper's values were decreased by 0.012 mag; and for y, the other two sets were shifted by 0.010 mag with respect to the Adelman (1997) values. These differences most likely reflect small changes in the atmospheric extinction, which are most easily seen in the data of a star that does not pass close to zenith. The declination of HR 3724 is $-10°$.

4. 45 LEO

45 Leo (HR 4191, HD 90548, CX Leo) is sharp-lined ($v \sin i = 10$ km s^{-1}; Abt & Morrell 1995). This value and the adopted period indicate that we are looking at a polar region. Wolff & Morrison (1975) confirmed the results of photometry by Burke et al. (1970) and by Winzer (1974), showing that it was a low-amplitude variable. Adelman et al. (1999) obtained 109 FCAPT *uvby* values during the 1995–1996 and 1996–1997 observing seasons. Using the u values that were the most variable, a period of 1.4438 days was found. The U values of Winzer were rescaled so that they could be used in this determination.

In recent observing seasons 14 and 15, 94 new sets of FCAPT *uvby* observations were obtained. With a Scargle periodogram of all u values, a new period of 1.44404 days was

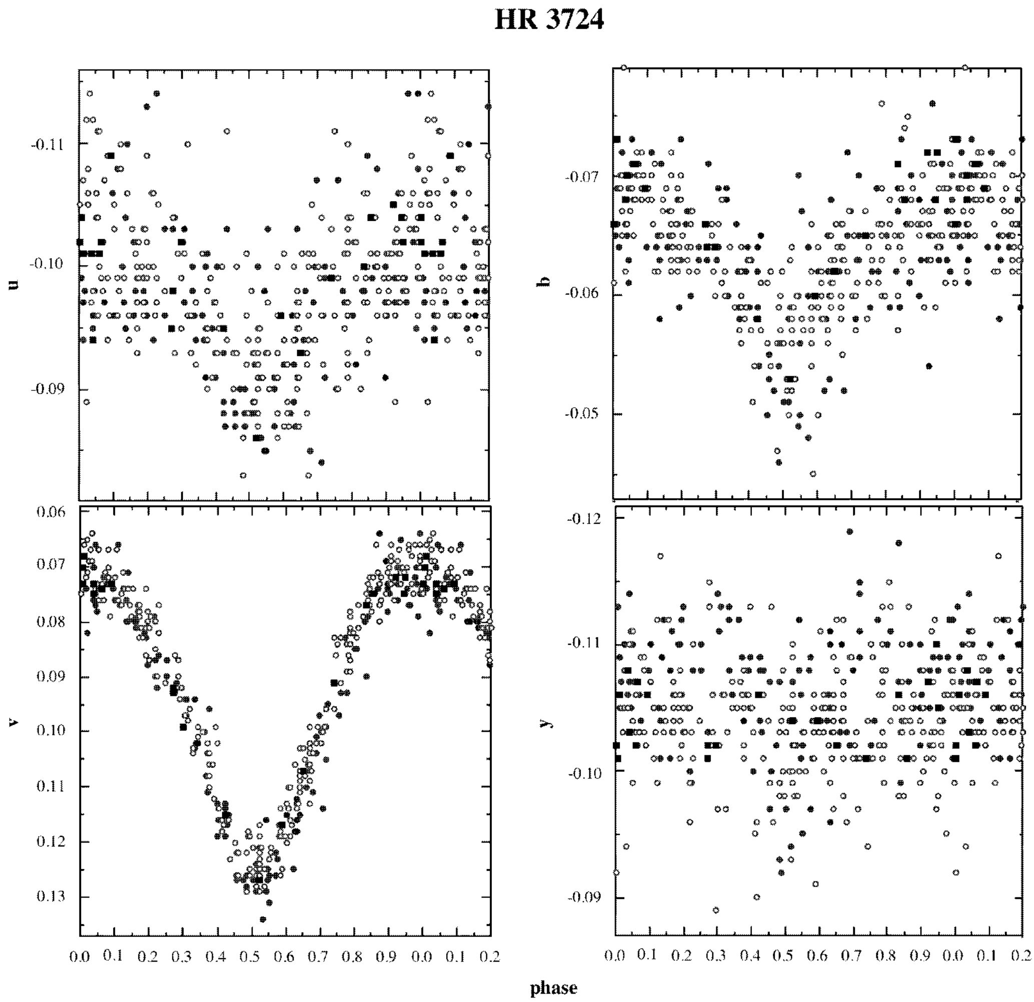

FIG. 2.—*uvby* photometry of HR 3724, plotted with the ephemeris HJD(v_{max}) = 2,444,484.78 + 33.984*E*. The filled circles show FCAPT observations published with this paper, the open circles give FCAPT observations of Adelman (1997), and the filled squares indicate observations by Wolff (1975). [*See the electronic edition of the PASP for a color version of this figure*.]

derived. In Figure 3, the amplitudes of variability of 0.04, 0.01, 0.005, and 0.003 mag for *u*,*v*, *b*, and *y*, respectively, are close to those of Adelman et al. (1999). Winzer's (1974) zero point of the ephemeris was found to be appropriate. Thus, one ephemeris represents the photometry of 45 Leo for more than 30 yr:

$$\mathrm{HJD}\,(u_{\max}) = 2{,}441{,}460.76 \pm 0.07$$
$$+1.44404 \pm 0.00001E.$$

5. HD 192678

In 1995–1997, Adelman & Rice (1999) obtained 77 *uvby* FCAPT observations of HD 192678 (V1372 Cyg, BD +53 2368), whose largest Strömgren amplitude was that of *u*, 0.017 mag. They used the ephemeris of Leroy (1995), who derived it from the time variability of the Stokes parameters. Wade et al. (1996) modeled its magnetic field by an oblique rotating dipole with modified field line inclinations. For this small-amplitude photometric variable, a good period of rotation was a major aid to finding the photometric variability.

In 2003–2005, an additional 67 differential *uvby* FCAPT observations were obtained. For HD 192678, only the *u* and *b* light curves show measurable variability, while those for *v* and *y* are best described as constant. Its *Hipparcos* photometry is appropriate for a constant star (ESA 1997, 1998). When the *u* and *b* light curves for the two epochs are compared, there is a phase shift of about 0.10. A slight increase of the period from Leroy's

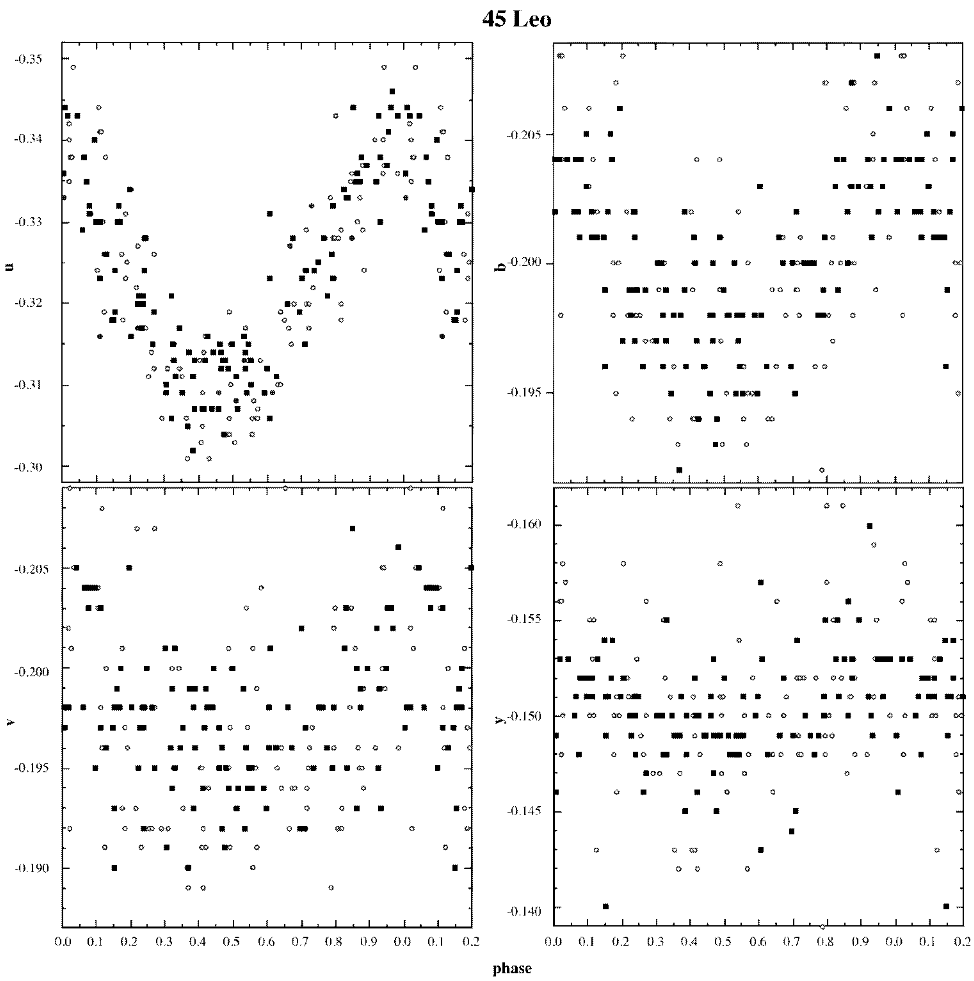

FIG. 3.—*uvby* photometry of 45 Leo as a function of the ephemeris HJD(u_{max}) = 2,441,460.76 + 1.44404E. The filled squares show the FCAPT observations published with this paper, and the open circles give the FCAPT observations of Adelman et al. (1999). [*See the electronic edition of the PASP for a color version of this figure*.]

(1995) 6.4186 days to the 6.4193 days found from the highest peak of a Scargle periodogram analysis brings both sets of data into agreement.

Figure 4 shows u and b values from both epochs of FCAPT photometry. Very slight systematic offsets of 0.002 and 0.004 mag, respectively, were found. The light minima are not well defined, but are in the vicinity of phase 0.90 and may be slightly different for u and b. Thus, the ephemeris retains Leroy's (1995) zero point:

$$\mathrm{HJD}\,(\mathrm{magnetic\ maximum}) = 2{,}444{,}890.17 + 6.4193 \pm 0.0003E.$$

The amplitudes in u and b are about 0.014 and 0.011 mag, respectively, close to those of Adelman & Rice (1999). The constant v and y light curves are not illustrated.

6. DISCUSSION

Both HR 3724 and 45 Leo appear to have had constant periods for at least 30 yr, as is found for six other mCP stars with three sets of good photometry taken at different epochs (see Adelman 2005 and below). The HD 192678 photometry shows that it is possible to get a good period for a small-amplitude mCP star, albeit with some difficulty. However, without good reasons for getting multiple sets of data, it is probably more profitable to observe mCP stars with amplitudes of ≥ 0.02 mag, including

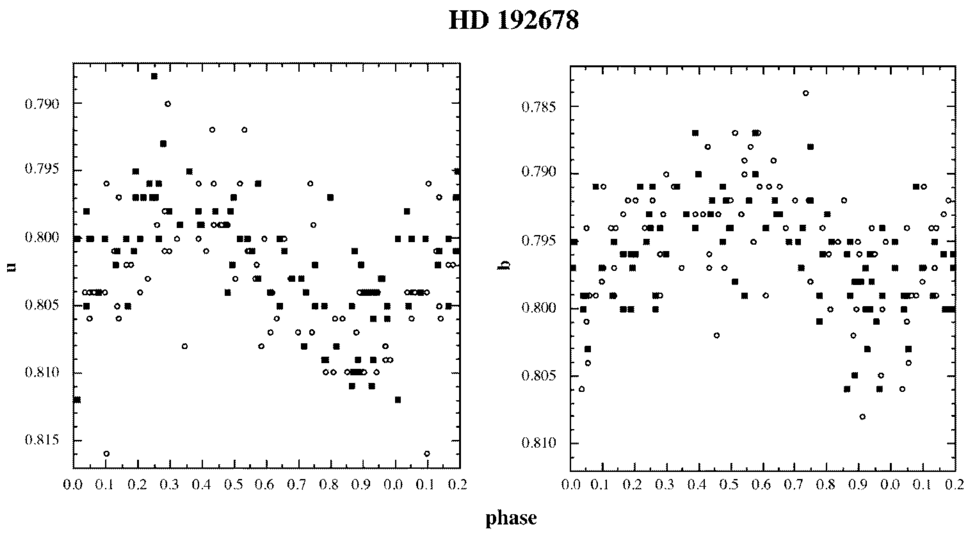

FIG. 4.—*ub* photometry of HD 192678, shown as a function of the ephemeris HJD(magnetic maximum) $= 2{,}444{,}890.17 + 6.4193E$. The open circles show FCAPT observations published with this paper, while the filled squares give values from Adelman & Rice (1999). The *v* and *y* light curves are constant and are not illustrated.

those found using *Hipparcos* photometry (Paunzen & Maitzen 1998). HD 20629 is an example of such a star.

Through the end of 2002, Adelman and his collaborators found periods and described the light curves of 64 mCP stars (Adelman 2002). A few were constant. This continuing aspect of their photometric program results in values for a few new stars each year. Among these 64 stars are 8 (Pyper & Adelman 2004) whose light curves have exhibited changes in period and/or amplitude. Might the other mCP stars also be such variables? To answer this question, a program of second-epoch *uvby* photometry has been started for those stars not previously found to have variable light curves. Older published photometry, including *Hipparcos* photometry (ESA 1997, 1998) when the four Strömgren magnitudes are in phase, can supply additional information on long-term stability. With results now for 10 stars, 8 appear to be constant for at least 30 yr, and 2 with just two photometric epochs for at least 10 yr.

If we assume in this sample that we have already found all the mCP stars with variable light curves, and that the others are all constant, then 12% have variable light curves. To improve this statistic requires a substantial number of new observations, along with careful analyses. That the percentage of variable light curve stars is this high indicates that such stars demonstrate an important new aspect of the photometric variability of the mCP stars (see Shore & Adelman [1976] and Pyper & Adelman [2004] for discussions showing that the precession of the rotation about the magnetic axis is the mechanism for much of this variability).

This research was supported in part by NSF grants AST-0071260 and 0507381 and by grants from The Citadel Foundation. The continuing efforts of Louis J. Boyd, Robert J. Dukes, Jr., and George P. McCook kept the FCAPT operating properly. The SIMBAD database, operated at the CDS, Strasbourg, France, was consulted.

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