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The variable light curves of some mCP stars†

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Abstract. The use of the Four College Automatic Photometric Telescope at the Fairborn Observatory in Southern Arizona with its ability to observe stars every clear night and for continuous runs has played a major role in our very successful cooperative program of Strömgren differential *uvby* photometry of magnetic CP (mCP) stars. Out of about 100 stars observed only a few have variable light curves. But more may be found when additional observations are made. We review the published theoretical basis and observations as well as present new results for CU Vir, V1093 Ori, MW Vul, and HR 7224. We interpret some observations as possibly requiring a more robust theory of the variability of mCP star light curves.

Keywords. Stars: chemically peculiar, stars: individual (CU Vir, V1093 Ori, HR 7224), stars: variables: other, techniques: photometric

1. Introduction

The light, magnetic and spectrum variations of the magnetic chemically peculiar (mCP) stars are generally accepted as being the result of observing spotted rotating stars. The large scale magnetic fields, which usually are primarily dipolar, are variable over the photosphere and produce changes in the local chemistry, via hydrodynamical process including diffiusion, which in turn affect the radiated energy distribution. Shore & Adelman (1976) inspired by the changes in the line profiles of 56 Ari at a given phase interpreted these results as due to variations produced by the precession of the rotation axis. It could be the result of a forced precession due to a companion or to free-body precession caused a change in the moment of interia along the magnetic field axis when the magnetic and rotational axes are highly inclined to one another. The precessional periods were predicted to be about 6 years for mCP stars having rotational periods of less than one day. If rotation is the dominant perturbation, an analog of the Chandler wobble will result. Thus, we included searches for such effects in our long-term observation program using the Four College Automatic Photometric Telescope (FCAPT) at the Fairborn Observatory in Southern Arizona, which has completed its 14th year of operations.

Several observational consequences of precession are expected: 1). The timings of the maximum, the minimum, and of any identifiable portion of the light curves will experience periodic changes during the precessional cycle. 2). The observed value of $v_s \sin i$ will be found to change, being smallest when the rotational pole is most nearly towards us. If the change of i is large enough, high dispersion spectra should be able to measure it and

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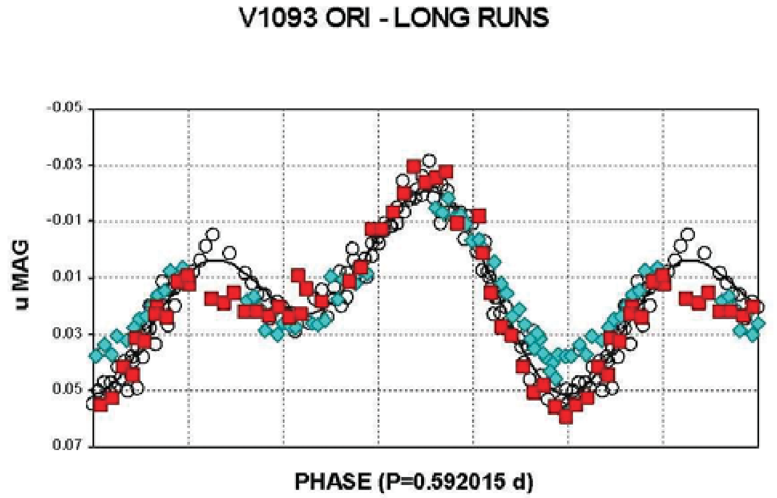

Figure 1. Changes in the shape of the u light curve of V1093 Ori. Open circles represent data for 1996-97; the solid line is the fit for these data (Fourier series, 5 parameters). Diamonds represent data for 1995-96 and squares represent data for 2003-04. Each horizontal interval is 0.2 of the period.

provide information on the geometry. and 3). If the stars are rapidly rotating, they will be flattened ellipsoids of rotation with their polar diameters smaller than their equatorial diameters. Thus they will appear to be brighter when their polar axes point more nearly towards us.

Photometrc variations that can be attributed to precession have been definitely found for 108 Aqr (Adelman 1999), 20 Eri (Adelman 2000), 56 Ari (Adelman *et al.* 2001), MW Vul (Adelman & Young 2004), and V1093 Ori (Pyper, in preparation). In addition, we have found some surprising, even bizarre, variations in some other program mCP stars, such as the abrupt change in period in 1984 of the short-period mCP star CU Vir (Pyper *et al.* 1998) and the extraordinary switch from predominantly short (order 1 day) to longer (order 100 days) period variations of HR 7224 (Adelman 2004). We report on both published and recent results of this program. Variable light curves are found for only a small percentage of the some 100 stars we are observing and that the amplitudes of such variability as detected are of order 1%. In many cases the periods of mCP stars that we have derived are refinements of those found by earlier photometric studies. For some stars additional observations may reveal variable light curves. The use of one telescope and filter set has helped us in making comparisons between observations taken in different years.

2. Variable light curves just indicating precession

We have found four mCP stars which show variable light curves consistent with precession. For them we do not have observations over a sufficiently long time to discover the expected small increase in their rotation periods. FCAPT $uvby$ data from 1995-2004 of V1093 Ori (HD 36313) show variations in the shape and amplitude of the light curves from year to year, as seen in Figure 1 for the u magnitude. Data for 2000-01 (not shown) display similar differences with more scatter. The v, b and y filter data show changes similar to u. All FCAPT data agree with the period of 0.592015 days determined by North (1984), making this the second shortest period mCP variable in our program.

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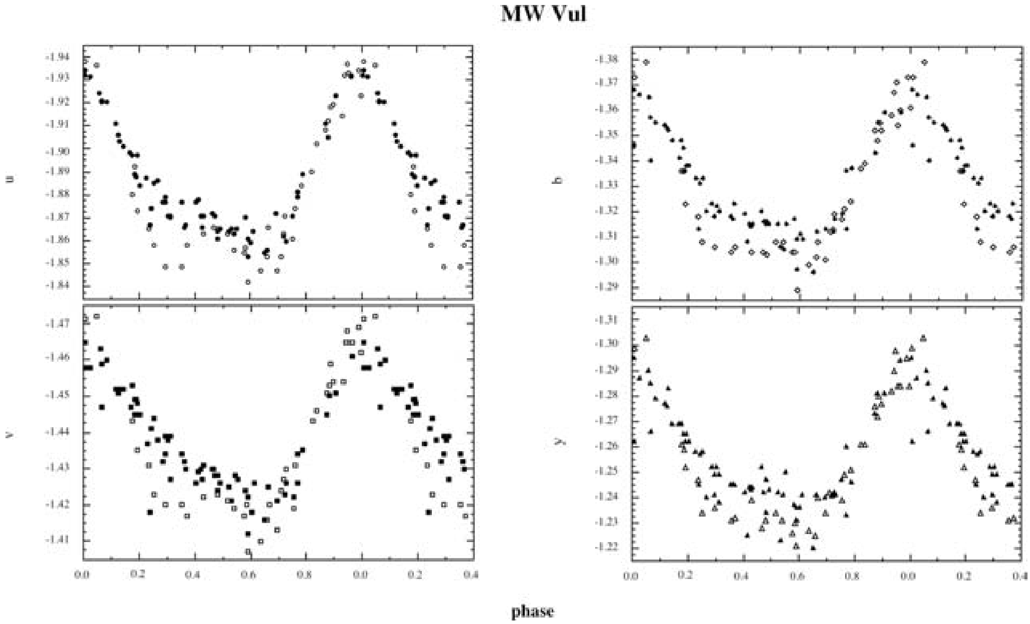

Figure 2. Changes in the shape of the FCAPT *u, v, b,* and *y* light curves of MW Vul. The solid and open symbols represent, respectively, observations made in 1990-91 and 2003-04.

Interestingly, the light curves of North are shifted slightly with respect to the FCAPT curves. A slightly longer period of 0.592035 days makes the two data sets agree, but this introduces shifts between successive years of the FCAPT observations. Thus we see an apparent phase shift between the 1984 and 1995-2004 data but no change in period which is likely to be due to the precessional period.

The variability of V1093 Ori is similar to that found by Adelman (2000) for 20 Eri (HD 22470) and by Adelman (1997) for 108 Aqr (HD 223640) with a periods of 1.92889 days and 3.735239 days, respectively. Small differences are found between data in the Strömgren *uvby* photometric system which were taken in different years.

Recently Adelman & Young (2004) found that MW Vul (HD 192913) whose period is 16.840 days (Adelman & Knox 1994) is also undergoing precession. There are clear differences in the shapes and amplitudes of the light curves for the same Strömgren passband in years 1 and 14 in Figure 2. Values for year 1 (1990-91) are solid symbols and those for year 14 (2003-04) are open symbols. Examination of more fragmentary data obtained in other years support the conclusion that MW Vul has variable light curves.

These four stars have rotational periods that range from the original expectation of Shore & Adelman (1976) to one that clearly violates it. Thus instead of just concentrating our efforts on the fastest rotating stars, we also need to look at those which are more slowly rotating. We need to try to determine when the slowly rotating stars which are now precessing begin this motion.

3. Two stars whose rotational periods have increased

Adelman (2002) found some evidence for the expectation that as mCP stars move away from the ZAMS their rotational velocities decrease. But only in the last few year have the first observed small period increases been well established for 56 Ari and CU Vir, two of the fastest rotating mCP stars.

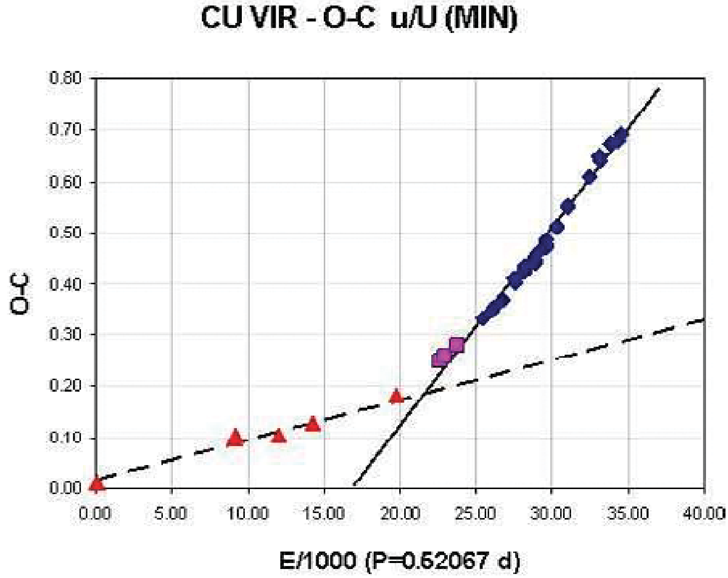

Figure 3. The period of CU Vir abruptly increased in approximately 1984 from 0.5206778 days (dashed line) to 0.52070854 days (solid line).

3.1. *56 Ari*

Adelman *et al.* (2001) used extensive sets of *U*BV and FCAPT *uvby* photometry as well as spectroscopic data to investigate the light and equivalent width variations of 56 Ari (HD 19832). Its rotational period is increasing at a rate of about 2 s per century. There is evidence for a second period whose length is about 5 years which is attributed to the precession of the axis of rotation. *U*BV (see, e.g. Fried & Adelman 2003) and *uvby* photometry from different years show changes in the light curve shapes and amplitudes.

3.2. *CU Vir*

Based on spectroscopic data and FCAPT *U*BV and *uvby* data, Pyper *et al.* (1998) found that the period of CU Vir (HD 124224) abruptly increased in approximately 1984 from 0.5206778 days (dashed line) to 0.52070854 days (solid line) in Figure 3. The latter period is the average for 1987-1997. The data points on the upper O-C curve are as follows: red triangles represent the JDmin of the *U* mags. for 1958-83, pink squares represent *U* mags for 1987-89 and blue diamonds represent *u* mags. for 1991-2004 (Pyper *et al.* 1998).

The lower O-C curve in Figure 4 represents the *U* and *u* data from 1980-2004 based on the period 0.5206778 days. The pink square represents *u* mags for 1980-83, green triangles represent *U* mags for 1987-89, yellow circles represent *u* mags. for 1991-93 and blue diamonds represent *u* mags. for 1994-2004. These data can be interpreted in two ways, both indicating that the rotation of CU Vir is still slowing down.

1) CONTINUALLY CHANGING PERIOD: The parabolic fit (solid red line) corresponds to a period increase of P = 1.32E-06 d/yr, starting with P = 0.5206778 days in 1983. For this fit, R2 = 0.9959.

2) TWO CONSTANT PERIODS: A linear regression through the 1993-2004 data gives almost as good a fit as the parabolic fit and indicates a constant period P = 0.5207125 days (solid black line; R2 = 0.9929), but only if the 1987-1992 data are fit to a different constant period P = 0.5206999 days (dashed line; R2 = 0.9968).

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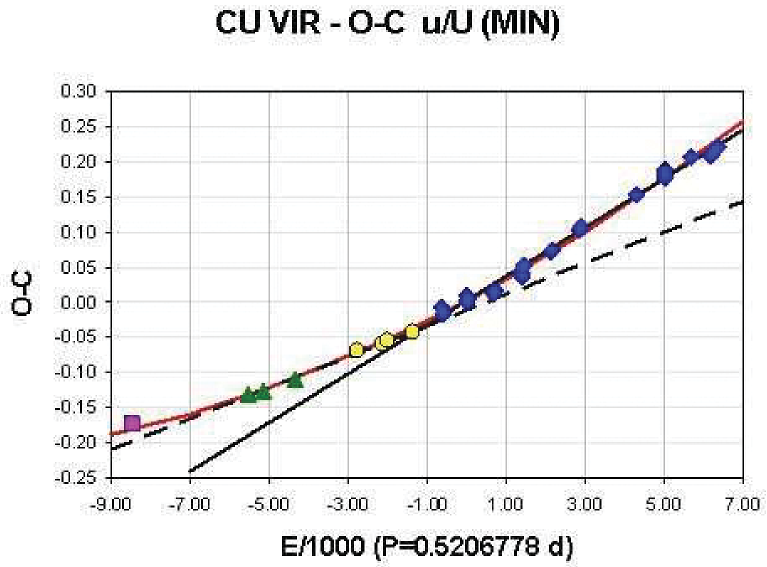

Figure 4. Another way to look at the u photometry of CU Vir.

Thus CU Vir is still showing period changes following its major slowdown in 1984. It has either experienced another discrete change in period or is continually slowing down. The former interpretation is perhaps preferable as it could be explained by a modification of the outer envelope of the star by its magnetic field, as suggested by Stepien (1998). A continual slowdown is more difficult to explain as there is no evidence for mass loss, unless there is a continual slowing effect by the magnetic field. CU Vir as the fastest rotating mCP star has the largest rotational deformation. Thus it may be undergoing a Chandler-like wobble.

4. HR 7224

Adelman (1997) obtained 154 sets of FCAPT differential Strömgren *uvby* observations in the 1993-94 and 1994-1995 observing season of HR 7224 (HD 177410). When a periodogram analysis was performed, a period of 1.123095 days was obtained. Figure 5 shows the b values plotted as a function of this period. The u, v, b, and y light curves are in phase with amplitudes of 0.05, 0.045, 0.035, and 0.03 mag., respectively. There is a narrow single maximum with a much broader miminium with two subminima. Winzer's (1974) 16 V magnitudes when transformed to y agree with those from Adelman (1997). Celestia 2000 (ESA 1998) gives a period of 1.12323 days from Hipparcos photometry. Adelman (1997) used Winzer's values to refine his period. and thus his result is based on a longer time period. But still the agreement is quite satisfactory.

In Spring 2003, a new set of FCAPT *uvby* observations was started to improve the period and to search for any rotational slowdown. As before the u, v, b, and y light curves are in phase, but soon it became apparent that there was something very different (Adelman 2004). At the end of observations for Fall 2003, a periodogram analysis indicated a period of 101 days. The amplitude of variability was about 0.21 mag. This was a result without presidence. Observations in Spring 2004 began to show a different picture. The simplist way to have a periodic light curve was to double the period to about 215 days and assume that the portion of the light curve now being seen was not previously

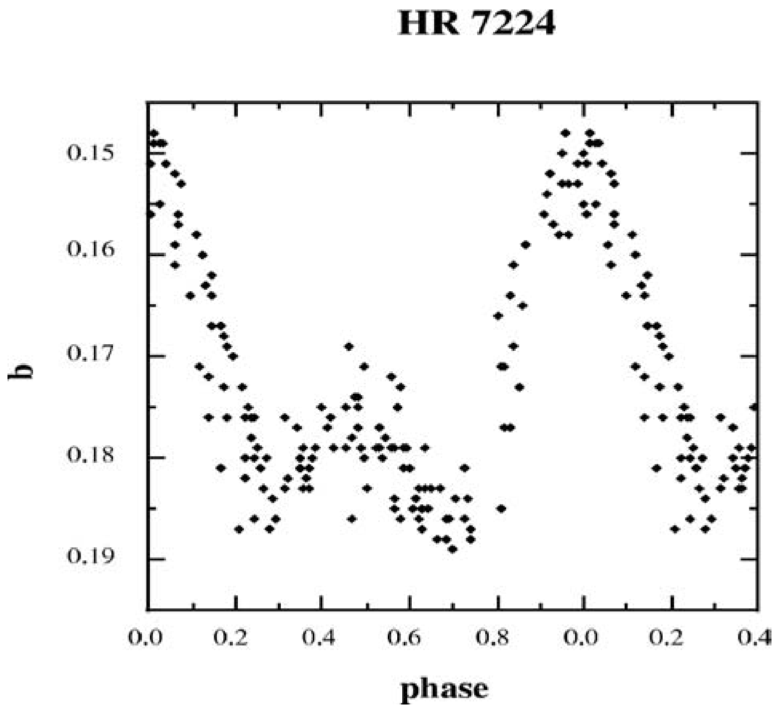

Figure 5. The b photometry of HR 7224 of Adelman (1997) plotted with a 1.123095 day period.

observed. The u, v, b, and y light curves are still in phase and have not too differing amplitudes which supports a geometric explanation.

A scenario which decreases the rotational period by such a large amount causes substantial theoretical difficulties. Fortunately we are saved from that fate. In June 2004, Adelman obtained two spectrograms of HR 7224 at the Dominion Astrophysical Observatory at $S/N = 200$ and a two pixel resolution of 0.072 Å. If the rotational rate had decreased, one would expect to see the spectrum of a sharp-lined star while if its rotation rate was around a day the star would be fast rotating. Observations of the Hβ region do not reveal any sharp-lines, the core of Hβ is rounded, and $v \sin i$ close to 100 km s^{-1}. The signature of a shell is missing. Mkritchian (private communication) has also obtained spectrograms, but his estimate of $v \sin i$ is smaller.

The 215 day period may be due to precession. We are now seeing a much larger portion of the surface than before when we watch long enough. If HR 7224 is still rapidly rotating, then there should be photometric evidence for this. Adelman had observed this star once a night. But in June 2004 he observed it continuously for about six hours for three nights. During the these runs, the amplitude of variability was about 0.04 mag. which is the previous rotational amplitude. The task now is to try to determine what is the rotational period.

But HR 7224 had another surprise. The mean light curve should have begun to go through a decline of 0.20 mag. if the dominant period was constant before this meeting began. But it was not to be (see Figure 6). The dynamical state of HR 7224 is evolving with the dominant period increasing. It is very important to measure the full amplitude for it may well decrease with an increasing precessional period. The FCAPT closed down the day this meeting began. Observations should resume in September.

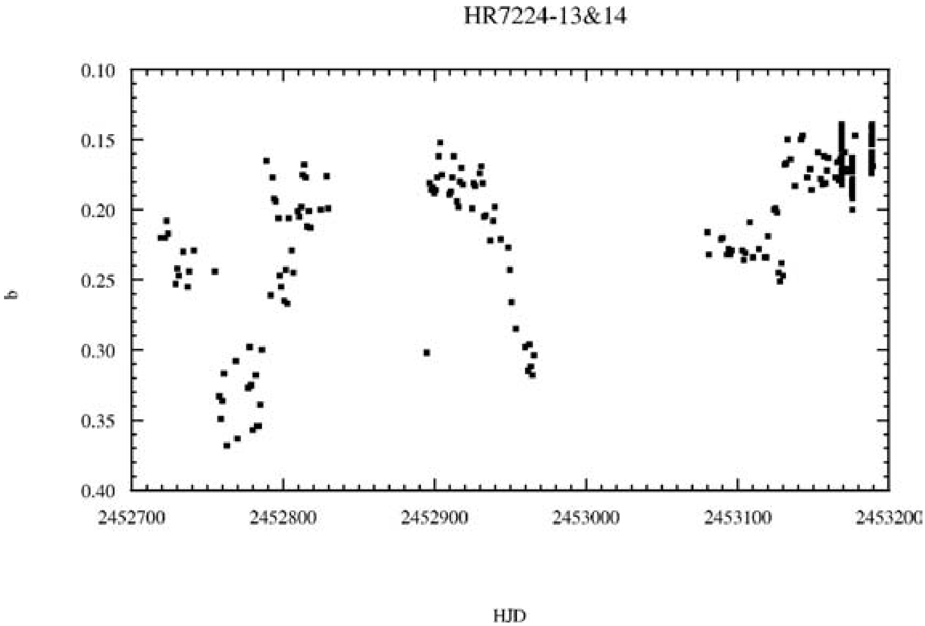

Figure 6. The b photometry of HR 7224 as a function of HJD beginning in Spring 2003.

What caused the changes in the dynamical state? There is a period of some 8 years without observations for HR 7224. The star was a well-behaved mCP star through the time the 1994-95 observations were taken. Sometime between then and Spring 2003 the precessional behavior was initiated.

HR 7224 is located near the Zero Age Main Sequence. It is unclear how to produce an internal mass inhomogeneity that would cause the star to start precessing. Increasing the magnetic field strength by a factor of 2 increases the difference in the moment of inertia between the magnetic and polar axes by a factor of 4 (Shore & Adelman 1976). Bohlender *et al.* (1993) failed to detect a significant magnetic field, Wade and colleagues will try again very shortly.

HR 7224 does not have any known close companions. Thus forced precession is not likely. It would probably involve a change in the orbit of a companion. Adelman's other current scenario is that it was hit by, captured, and now is slowly absorbing some object which survives for awhile and losses mass slowly to account for the changes we see. Possibilities include planets, black dwarfs, and the least massive stars.

If any of these possibilities are correct, HR 7224 poses interesting theoretical challenges. On the other hand, another explanation is still possible. HR 7224 has produced one surprise after another so we would not be surprised with new ones.

5. Conclusions

For all of the stars discussed in this paper, further photometric observations are desirable. Due to the type of coverage desired, the use of automated telescopes is the most feasible approach. Further our results to date show that it is desirable to obtain several sets of observations for 50 or more mCP stars to better define their light curves and to do a proper census of the class for light curve variability. Measurements of their $v \sin i$ values obtained throughout their apparent precessional cycles might yield important geometric information.

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Discussion

Breger: The (O-C) curve of CU Vir resembles that of many pulsating stars. A very sudden change of period will not fit the observations; neither will a constant period change (no parabola). A possibility might be chaotic changes, since the curve shows structures beyond the main period jump. What are the sizes of the error bars?

Adelman: CU Vir has a magnetic field while δ Scuti stars do not. CU Vir is also not in the classical instability strip. The magnetic field helps stabilize the atmosphere. The mean periods of mCP stars increase with age from the ZAMS, chaotic processes are not likely. The error bars are about the same size as the symbols in this Figure.

Moss: Any plausible, ever quite implausible(!), extrapolation of Ap stars surface fields to the interior predicts magnetic distortions that are much less than than the rotational, especially for a rotational period of 0(1) d.

Adelman: The magnetic field change the moment of interior along the magnetic axis relative to that perpendicular to it. The difference of the moments of interior along and perpendicular to the rotational axes need to be sufficiently large to come precession. The observations are consistent with precession in terms of phase shifts and magnitude differences at the same phase for the best determined case 56 Ari. What is needed for further proof is the observation of the change in $v \sin i$.

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