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An update on the rotational period of the magnetic chemically peculiar star CU Virginis

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ABSTRACT

In order to measure the variations of the magnetic chemically peculiar star CU Vir, we obtained 2821 good Strömgren *uvby* photometric values from the Four College Automated Photometric Telescope in the period 1998–2012 and 5529 values from the Solar Mass Ejection Imager in the period 2003–2006, allowing us to further clarify the situation concerning its rotational period, described previously by Pyper et al. Our main result is that the O−C data since 1993 are consistent with a constant period of 0.520 7137 ± 0.000 0010 d, which is longer than the period 0.520 703 08 d of Pyper et al. The data during the time period 1993–2012 show no evidence of glitches. The data between 1987 and 1993 correspond to a shorter period of 0.520 701 d, and the inclusion of those data in the previous study made the published period come out shorter. We also cannot rule out a constantly lengthening period if the data since 1987 are included; however, the fit is slightly better for a constant period. At least five more years of consistent data will be required to distinguish between these two models. Radio astronomy data published since 1998 show phase shifts in the radio emission peaks that are inconsistent with the rotation period inferred from the optical photometry. These shifts may be due to instabilities in the region where the radio emissions originate; they indicate that the photosphere and the upper atmosphere are not rigidly coupled.

Key words: stars: chemically peculiar – stars: individual: CU Vir – stars: individual: HD 124224 – stars: individual: HR 5313 – radio continuum: stars.

1 INTRODUCTION

The bright magnetic chemically peculiar (mCP) star, CU Vir (HD 124224 = HR 5313), has been studied by many observers over the years (e.g. see Pyper et al. 1998). It is typical of a hot mCP star on or close to the main sequence with published parameters $M = 3\,\mathrm{M}_{\odot}$, $R = 2\,\mathrm{R}_{\odot}$ (Stepien 1998) and $T_{\mathrm{eff}} = 13\,000$ K, $\log g = 4.0$ (Kuschnig et al. 1999).

Hatzes (1997) obtained spectra and used Doppler imaging with a rigid-rotator model, which yielded a polar magnetic field Bp = 3200 G (0.3 T) with $i = 60^{\circ}$ and $\beta = 70^{\circ}$. Kuschnig et al. (1999) obtained a similar model from their spectroscopy. Both models show spots in the stellar photosphere where principally He I and Si II are enhanced.

CU Vir is the shortest known periodic mCP star, with its brightness and spectra varying with a period of 0.5207 d. Further, it is also the only mCP star that has displayed a sudden shortening of its period. To summarize the conclusions of Pyper et al. (1998), there was an abrupt phase change at about JD = 244 6000 in 1984, which was interpreted as a slowing in the rotation period of the photosphere at this time. The glitch is seen in both optical photometric and spectroscopic data. Within the errors of measurement, the variations in the light curves, the equivalent widths (He I, Si II) and the magnetic field show the same shapes and amplitudes both before and after the glitch; only the phases seem to have changed.

Also, CU Vir is one of the brightest mCP star radio sources. Observations at 1.4 GHz show two emission peaks. Those made in 2006 (Kellett et al. 2007), in 1998, 1999 and 2008 (summarized in Ravi et al. 2010) and in 2010 (Trigillio et al. 2011) show progressive shifts of the radio emission peaks towards larger phase values, in comparison with the period derived from the optical photometry. There are also abrupt phase shifts in these data that appear to be intrinsic, not due to errors of measurement.

2 OBSERVATIONS AND REDUCTIONS

Our data are from two sources: Strömgren differential *uvby* photometry obtained using the Four College Automated Photometric Telescope (FCAPT) originally on Mt. Hopkins, AZ, and later at

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Fairborn Observatory, Washington Camp, AZ, and photometry from the Solar Mass Ejection Imager (SMEI).

2.1 FCAPT photometry

Both the FCAPT and the photometric reduction procedure are discussed by Pyper et al. (1993). All of the good photometric observations of CU Vir taken with the FCAPT from the first 1990–91 observing season to the last 2011–2012 observing season (2821 observations) are given in Table 1 in electronic form (a sample stub table is in the text).

When Adelman continued the observations beginning in the fall of 2003, he followed the pattern established by Pyper and used the same sky patch and comparison and check stars. Each group of observations consists of a dark count measurement and then each of the four filters, two sky measurements, three variable star measurements, four comparison star measurements and two check star measurements. The integration time for each was 10 s. For the variable, check and comparison stars, more than 10 000 counts are obtained in this time. Over the entire data set the check–comparison average values for each filter have remained constant. The data were reduced by Pyper and by Adelman using a spreadsheet reduction procedure, written by Pyper. To minimize small night-to-night seeing and extinction differences, continuous runs of measurements lasting up to about 6 h were made. With the short period of CU Vir, it is possible to obtain complete phase coverage on three well-chosen nights. We tried to avoid observing CU Vir near full moon to minimize the sky count and increase the S/N of the data. We also tried to obtain at least two light minima during continuous runs in each observing season, although this was not possible during every observing season. Fig. 1 shows the FCAPT u light curve for 2011–12. For this time period, the comparison–check star values for u, v, b and y are -0.543 ± 0.006, -0.646 ± 0.005, -0.527 ± 0.005 and -0.449 ± 0.006 mag, respectively, which is typical for these data.

Table 1. Strömgren photometry of CU Vir. The values are: variable star minus comparison star (comparison star = HD 122408).

1990–91 HJD	Δu	Δv	Δb	Δy
244 8367.8756	0.292	−0.472	−0.620	−0.739
244 8370.8583	0.282	−0.451	−0.609	−0.733
244 8371.8028	0.207	−0.481	−0.636	−0.763
244 8376.7776	0.241	−0.498	−0.644	−0.759
244 8377.8008	0.254	−0.487	−0.638	−0.758

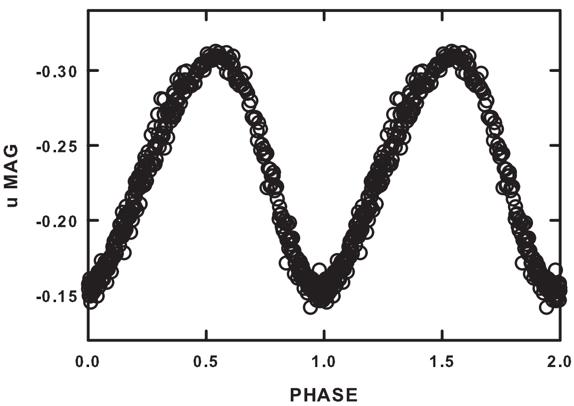

Figure 1. Strömgren u photometry of CU Vir for the 2011–12 observing season.

2.2 SMEI photometry

The SMEI was launched on 2003 January 6, onboard the *USAF Coriolis satellite*. SMEI was designed to study Coronal Mass Ejections from the Sun. However, since the instrument has a wide field of view, it has been possible to obtain photometric light curves for most of stars brighter than sixth magnitude in the sky. A full description of the SMEI instrument can be found in Eyles et al. (2003) and a detailed description of the stellar photometric pipeline in Spreckley (2008). SMEI data have been used to study the variability of a number of bright stars, for example, Arcturus (Tarrant et al. 2007), Polaris (Spreckley & Stevens 2008), β Ursae Minoris (Tarrant et al. 2008a), γ Doradus (Tarrant et al. 2008b), Cepheid variables (Berdnikoy & Stevens 2010), the Be star Achernar (Goss et al. 2011) and even novae explosions (Hounsell et al. 2010).

The satellite is in a polar synchronous orbit with an orbital period of 101 min. SMEI has three optical cameras (Cameras 1, 2 and 3) each with a field of view of 60° by 3°. The optical system is unfiltered, so the pass band is determined by the CCD response. The CCD quantum efficiency is 45 per cent at 700 nm, falling to 10 per cent at roughly 460 and 990 nm, and is roughly equivalent to a broad R band. The cameras are mounted such that they scan nearly all of the sky every 101 min.

Each camera takes images with an exposure time of 4 s, and a given star is viewed by a specific camera for a (variable) number of frames as the satellite scans across the sky. These data points are combined to give a single photometric data point per satellite orbit. Therefore, the notional Nyquist frequency for the data is 7.086 cycles d^{-1}.

The CU Vir SMEI data presented here cover the period from 2003 April to 2006 March. Data only from Cameras 1 and 2 are used in this analysis. The data consist of 5529 separate photometric data points, with one data point per satellite orbit. This corresponds to a fill factor of around 42 per cent, in the sense that this is the fraction of satellite orbits that have a data point. Within each orbit, the star is only being observed for a fraction of the orbit. The data are complementary to those of the FCAPT because for CU Vir the variation of brightness with phase is almost the same in each of the *UBV* and *uvby* filters, so the broad bandpass of the SMEI camera sensors should not make a difference in the epochs of light minima. Fig. 2 shows a light curve for the period HJD 245 3179–245 3198.

2.3 O−C diagram analysis

Based on *UBV* data from various investigators from 1958 to 1989 and KPNO and FCAPT *uvby* data, Pyper et al. (1998) found that the period of CU Vir abruptly increased in approximately 1984 from 0.520 6778 d to 0.520 708 54 d. The latter period is the average for 1987–1997. Spectroscopic data that were published during this same period were not used in the determination of the period change as they are much less precise than are the photometric data and did not fill any gaps in the photometric data. However, the spectroscopic minima are consistent with the photometry. We interpreted this period increase as a decrease in the rotation rate of the photosphere of CU Vir. Our conclusions are illustrated in Fig. 3, which shows the O−C plot for the *U/u* photometric data from 1958 to 1997 (see Pyper et al. 1998 for references). As can be seen, these data are much better represented by linear fits to the two different constant

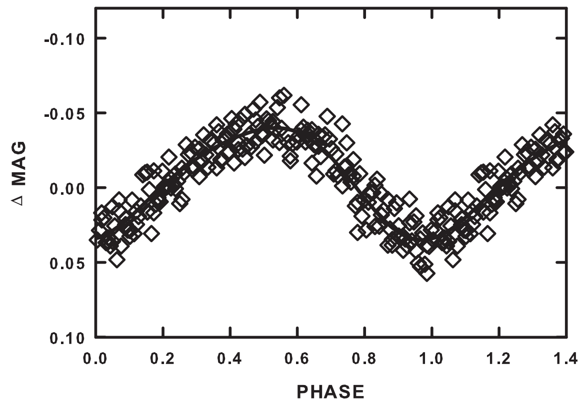

Figure 2. SMEI light curve for CU Vir for data from HJD 245 3179 to 245 3198. The solid line represents the five-parameter Fourier curve fit.

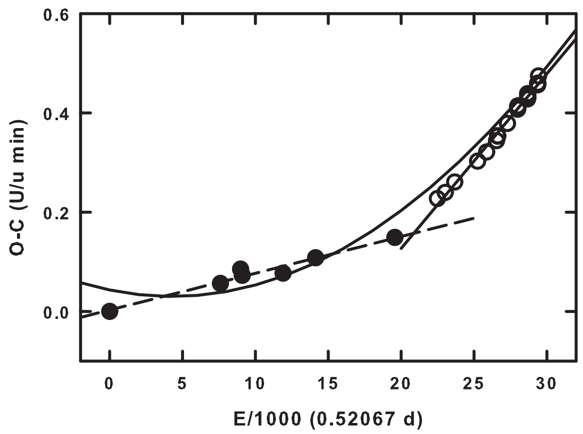

Figure 3. O−C plot for photometric *U*/*u* data, 1958–1997. The solid black line represents a linear fit to the 1987–1997 data (open circles), the dashed line represents a linear fit to the 1958–1983 data (closed circles) and the solid curve represents a second-order polynomial fit to all the data. The error bars for the 1987–1997 data are of the size of the symbols or less.

periods than by a second-order polynomial fit, which would indicate a continual change in period.

We now have FCAPT *uvby* data for CU Vir through 2012 in addition to the 2003–2006 SMEI data described above. We decided to determine light minima for the FCAPT *u* data, since the amplitude of variation is greatest in that filter. It should be noted that light minima determined using the *b*, *v* and *y* filters fall about 0.02–0.03 earlier in phase than those found using the *u* filter. The minima determined from the SMEI data are at the same phase as the *u* minima, thus, we can compare the data from both of these systems. Initially, we determined times of minima from FCAPT data obtained during individual cycles using a second-order polynomial fit. Such data are available in most observing seasons from 1993 to 2012. An O−C plot based on these data alone shows a linear relationship, resulting in a period of 0.520 7134 d. As there were several years when we did not obtain minima from continuous runs in a single cycle, we determined minima for each year from 1993 to 2012 using a five-parameter Fourier series to fit the *u* magnitude versus phase curve for that year. Adding these minima to the O−C plot also results in a period of 0.520 7134 d. As a final step, we similarly determined minima for the SMEI magnitude versus phase data with a five-parameter Fourier fit. The resulting ephemeris using both the FCAPT and the SMEI data is

$$\mathrm{HJD}_{\mathrm{min}} = 244\,9115.7814 + 0.520\,7137(\pm 0.000\,0010)E, \quad (1)$$

where $R^2 = 0.996\ 67$. We found a systematic difference in the minima found from the five-parameter Fourier fits and those found from a sine curve (three-parameter Fourier fit) as was used in Pyper et al. (1998). This is due to the sine curve not being a precise enough fit because of the slight asymmetry in the light curves. To be consistent, we fit all the photometric *U*/*u* magnitude versus phase data from 1958 to 1997 using the five-parameter Fourier series. The ephemeris determined from the data previous to 1984 remains the same as in Pyper et al. (1998)

$$\mathrm{HJD}_{\mathrm{min}} = 243\,5256.7551 + 0.520\,6778(\pm 0.000\,0005)E, \quad (2)$$

where $R^2 = 0.9856$. The *U* 1987–89 data fall above the linear fit for the 1993–2012 data; the FCAPT 1990–91 data were not used in the analysis because of uncertainty due to the small number of measurements those years. In the 1998 paper, we found the same results for the *U*/*u*, *B*/*b* and *V*/*y* data. As a check, we also carried out the analysis outlined above for the *V*/*y* photometric data; the results are the same within the errors of measurement.

These data can be interpreted in two ways, both indicating that the rotation of the photosphere of CU Vir has slowed down.

Hypothesis 1. The period has been continually changing since the glitch occurred. A second-order polynomial fit to the O−C data from 1987 to 2012 corresponds to a period increase of P = 5.19E−07 d yr^{-1}, starting with $P = 0.520\ 6778$ d in 1983. For this fit, $R^2 = 0.9971$.

Hypothesis 2. Two glitches occurred; the first in 1984 and the second in 1993, but there was no continual change in the period between the glitches or after the 1993 glitch. A linear regression of the 1993–2012 O−C data gives a slightly better fit than the parabolic fit for 1987–2012 and indicates a constant period P = 0.520 7137 d ($R^2 = 0.9980$). The 1987–1993 data can be fit to a different constant period $P = 0.520\ 700$ d ($R^2 = 0.9891$). This implies that a second smaller glitch occurred in about 1992–93 but the period has remained constant since that time.

3 RADIO EMISSION MEASUREMENTS

Several radio astronomy investigations (Kellett et al. 2007; Trigillio et al. 2008; Ravi et al. 2010; Trigillio et al. 2011) found evidence for more recent glitches in the rotation rate of CU Vir in about 1998 and/or 2002 to explain shifts in the phases of the radio emission peaks they measured. All of these groups assume that the radio-emitting region at about one stellar radius above the photosphere is in synchronous rotation with the photosphere. Such glitches in the rotation are inconsistent with the optical photometry, since there are no abrupt changes in the slope of the photometric O−C data in the period 1993–2012. In order to illustrate how the phases of the radio emission peaks differ from those of the photometric light minima, we used the data published in Trigillio et al. (2011), Ravi et al. (2010) and Kellett et al. (2007) to obtain the HJD of peak emissions at 1.4 GHz for the 1998, 1999, 2006 and 2008 observations and calculated O−C values based on the pre-glitch period of 0.520 6778 d (Table 2), as was done for the photometric data. The phase shifts of the emission peaks relative to the photometric minima is shown in Fig. 4 by the steeper slope of the radio data in the O−C plot. We estimate that the period derived from these data is approximately 0.520 717 (±0.000 001) d, which is essentially the same as the period of 0.520 716 01 d derived by Trigillio et al.

Table 2. Times of maxima of the RF peaks at 1.4 GHz and O−C values.

Peak No.	HJD (peak)	*E*/1000	O−C	Reference
1	245 0966.553	3.554	0.126	Trigilio et al. (2000)
2	245 0976.670	3.574	0.132	Trigilio et al. (2000)
1	245 1327.921	4.248	0.144	Leto et al. (2006)
2	245 1328.148	4.249	0.152	Leto et al. (2006)
1	245 1419.576	4.424	0.160	Leto et al. (2006)
2	245 1419.797	4.425	0.162	Leto et al. (2006)
1	245 3880.480	9.150	0.341	Kellett et al. (2007)
1	245 4769.898	10.858	0.441	Ravi et al. (2010)
2	245 4770.109	10.859	0.433	Ravi et al. (2010)
1	245 5309.839	11.895	0.439	Trigilio et al. (2011)
1	245 5316.614	11.908	0.445	Trigilio et al. (2011)
2	245 5316.818	11.909	0.430	Trigilio et al. (2011)

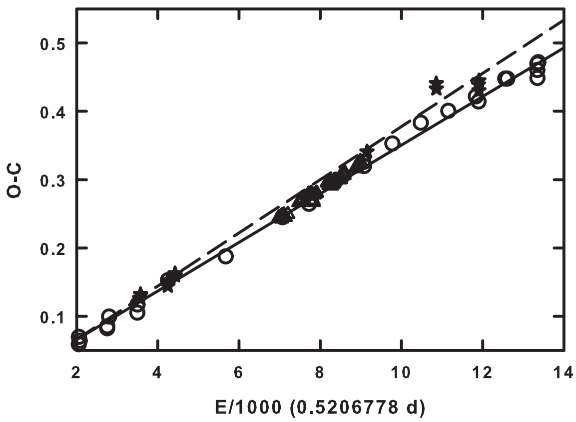

Figure 4. The data points on the O−C curve are as follows: the open circles represent the JDmin of the FCAPT *u* minima for 1993–2012, the open triangles represent SMEI minima for 2003–06 and the stars represent 1.4 GHz RF peaks discussed in the text. The solid line represents a linear fit to the FCAPT/SMEI data and the dashed line a linear fit to the RF data.

(2011) and longer than the 0.520 7137 d period from our optical region 1993–2012 photometric data. Lo et al. (2012) also measured radio emission peaks and found that their measurements are consistent with the period derived by Trigillio et al. (2011). Their data are not plotted in Fig. 4, as they did not publish the times of observation of their emission peaks. Due to the precision of the determination of the times of peak emission, the scatter in the radio frequency plot in Fig. 4 seems to be real, as are the claims of shifts in the peak emissions reported by the various investigators.

Perhaps the RF phase shifts imply that the region where the radio emissions originate is rotating more slowly than the star's photosphere or that there are shifts of the radio emission region with respect to the star's outer atmosphere or both. The radio data are too sparse to make any firm conclusions at this time.

4 CONCLUSIONS

Based on the *UBV*, *uvby* and SMEI photometric data, CU Vir has shown period changes following its major slowdown in 1984. It has either experienced another discrete change in period in about 1993 or is continually slowing down. The former interpretation could perhaps be explained by two modifications of the stellar outer envelope by its magnetic field, as suggested by Stepien (1998) (see also Shore & Adelman 1976). As was discussed in Pyper et al. (1998), there is no indication that the surface distribution of elements or the magnetic field structure changed after the glitch in 1984. Additionally, the *uvby* light curves show very little change from year to year in the period 1990–2012, implying a stable surface structure during that time period. As is also discussed in the 1998 paper, there is no evidence for a stellar companion of CU Vir, so mass exchange between two binary components can be ruled out. A continual slow down is more difficult to explain, since there is no evidence for mass loss, unless there is a continual slowing effect by a stellar wind interacting with the magnetic field. However, any stellar wind predicted by the presence of the radio radiation, as discussed in Trigillio et al. (2011), would probably be too weak to account for the possible slowdown indicated by the 1987–2012 data. Further, the photometric data prior to 1984 show no evidence for a continual lengthening of the period, which would imply that any wind causing the slow down must have started after the 1984 glitch. Improving the key parameters of CU Vir could rule out any effects due to rapid stellar evolution. At present, based on the observations, we cannot distinguish between the two-glitch and continual slowdown models. We estimate that at least five more years of carefully obtained FCAPT *uvby* observations will be necessary before we will be able to decide.

The possible glitches in the period 1998–2010 indicated by the radio data are probably real, but are not present in the photosphere of CU Vir, since our visual photometric data do not show evidence of glitches from 1993 to present (Fig. 4). The radio radiation originates much higher in the stellar atmosphere and reflects activity and conditions at those levels, not the photosphere. Thus, models that assume rigid coupling between the photosphere and higher atmospheric levels are contradicted by the evidence.

The *y* data since 2004–2005 are slightly fainter with respect to previous FCAPT *y* observations, but there are no changes of shapes of the yearly light curves. The most likely explanations are slight changes in either the *y* -filter transmission or the nightly atmospheric extinction. These possibilities can be checked with observations of other stars that have been observed in a similar manner with the FCAPT.

The CU Vir light curves do not show the presence of a secondary period which has been seen by Adelman et al. (2001) in 56 Ari and probably seen in other mCP stars (Pyper & Adelman 2004). This means that we have not found evidence that the rotational axis precesses about the magnetic axis in CU Vir which was proposed to occur in 56 Ari and other mCP stars (Shore & Adelman 1976) (see also Stepien 1998). CU Vir is a star with a weak variable λ5200 broad, continuum feature. The equivalent width of the Hβ line is 180° out of phase with the spectrophotometric fluxes and the optical region *uvby* photometry (Pyper & Adelman 1985). Further, the value of 150 km s^{-1} for v sin i (Hiesberger et al. 1995) indicates that CU Vir is slightly flattened with its polar regions being slightly hotter than the equatorial region. Thus, lines of each element are produced in slightly different parts of the photosphere. The modellers need to put these effects in their models (see Gulliver, Hill & Adelman 1994).

5 FUTURE WORK

At the present time, CU Vir is the only mCP star known to display emission in the radio wavelengths. Whether this phenomenon is a result of its rapid rotation rate is not known, since no other known CP star has such a short rotation period. Due to its rapid rotation, CU Vir is assumed to be on or slightly evolved from the zero-age main sequence. This conclusion is supported by various models, as mentioned in the Introduction. In the future, a re-determination of the mass, radius, v sin i, temperature and surface gravity would be desirable. High S/N, high-resolution spectra would result in a better value for v sin i, provided that a variety of line profiles of important lines were obtained at different phases. Comparing the predictions of model atmospheres with observed optical fluxes (spectrophotometry) and coudé-type spectra about 400 Å long, with a resolution of 20 000 or more covering the profile of Hβ or Hγ including sufficient continuum could yield the effective temperature and surface gravity.

The few radio observations of CU Vir indicate that the upper atmosphere may be more dynamic than the photosphere. Thus, there is a need for additional measurements in radio wavelengths; ideally, closely spaced observations for several years with the same equipment. Simultaneous optical/radio measurements would also be desirable. It should be emphasized that the study of variations in CU Vir especially should involve such closely spaced observations in order to obtain meaningful results. Due to the differences between the photospheric variations measured in this paper and the radio observations, these sets of data should not be combined in a study of the variations as was done by Mikulášek et al. (2011).

Adelman and Pyper plan to continue their *uvby* photometric monitoring, with complete phase coverage and multiple observations of light minima, in order to confirm the stability of the photosphere. Also, it is desirable to obtain sufficient spectra for several years for Doppler imaging to confirm the stability of the surface magnetic and element distribution.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Strömgren photometry of CU Vir. The values are: variable star minus comparison star (comparison star = HD 122408). (http://www.mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt256/-/DC1).

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