

Observations of radio pulses from CU Virginis

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ABSTRACT

The magnetic chemically peculiar star CU Virginis is a unique astrophysical laboratory for stellar magnetospheres and coherent emission processes. It is the only known main-sequence star to emit a radio pulse every rotation period. Here we report on new observations of the CU Virginis pulse profile in the 13- and 20-cm radio bands. The profile is known to be characterized by two peaks of 100 per cent circularly polarized emission that are thought to arise in an electron–cyclotron maser mechanism. We find that the trailing peak is stable at both 13 and 20 cm, whereas the leading peak is intermittent at 13 cm. Our measured pulse arrival times confirm the discrepancy previously reported between the putative stellar rotation rates measured with optical data and with radio observations. We suggest that this period discrepancy might be caused by an unknown companion or by instabilities in the emission region. Regular long-term pulse timing and simultaneous multiwavelength observations are essential to clarify the behaviour of this emerging class of transient radio source.

Key words: radiation mechanisms: non-thermal – stars: individual: CU Virginis – stars: magnetic field – stars: rotation – radio continuum: stars.

1 INTRODUCTION

CU Virginis (HD124224, hereafter CU Vir) is unusual in that it is a stable source of coherent, polarized radio emission. Observations in the 13-, 20- and 50-cm radio bands have revealed one or more short duty-cycle emission peaks per rotation period (0.5207 d) that reappear at the same rotation phases (Trigilio et al. 2000, 2008; Stevens & George 2010). These peaks are distinguished from the quiescent emission also observed from the source by their 100 per cent circular polarization, short durations (<1 h) and flux densities of up to a factor of six above the quiescent levels. Together, we refer to the peaks as the CU Vir pulse.

As a magnetic chemically peculiar A0 (sometimes B9) star, CU Vir is thought to possess an offset dipole magnetic field (Deutsch 1952; Hatzes 1997), with a pole strength of ~ 3 kG (Trigilio et al. 2000), misaligned from the rotation axis (Borra & Landstreet 1980). Various stellar parameters are summarized in Table 1, with errors in the last decimal places given in parentheses. The pulses are thought to be emitted in the vicinity of one magnetic pole (Trigilio et al.

2000). The pulse emission geometry is strikingly similar to the canonical model for radio pulsars (e.g. Manchester & Taylor 1977). The beaming of the CU Vir pulsed emission, the 100 per cent circular polarization of the pulse, the high brightness temperature of $>10^{12}$ K and the flat spectrum between 13 and 20 cm are all indicative of coherent emission from an electron–cyclotron maser (ECM) mechanism (Trigilio et al. 2000; Kellett et al. 2007; Trigilio et al. 2008). ECM emission is characterized by narrow bandwidths corresponding to either the fundamental or any of the first few harmonics of the local cyclotron frequency,

$$\nu_B = \frac{q_e B}{2\pi m_e}, \quad (1)$$

where q_e and m_e are the elementary charge and electron mass respectively, and B is the magnetic field strength (Melrose & Dulk 1982).

By comparing 20-cm observations of two pulses in 1999 with a pulse recorded in 1998, Trigilio et al. (2008) measured a radio period that was 1.2 s slower than the latest optical rotation period (Pyper et al. 1998). The Pyper et al. (1998) rotation ephemeris for CU Vir was derived using data extending up to 1997, and no new optical rotation ephemeris has since been published. Pyper et al.

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Table 1. Stellar parameters of CU Vir from Triglio et al. (2000) and SIMBAD.

Property	Value
Position (J2000)	14:12:15.80, +02:24:34.0
Spectral type	A0p (α^2 CVn)
Distance	80(6) pc
Rotation period	0.5207 d
Stellar radius	2.2(2) solar radii
Magnetic field strength	$3.0(2) \times 10^3$ G
Mass ^a	~ 3 solar masses

^aThis mass estimate is from Stępień (1998).

(1998) also found that the optical period itself had reduced by ~ 2 s in 1998. These periodicity ‘glitches’ are not well understood.

Here we present new observations of CU Vir pulse profiles in the 13- and 20-cm bands. In Section 2 we detail the observations and data reduction. We describe our results, for both our data and for archival data, in Section 3 and confirm the radio period discrepancy reported by Triglio et al. (2008). In Section 4 we discuss implications for the CU Vir magnetic field, and in Section 5 we outline various hypotheses for the period discrepancy. We present our conclusions and discuss future work in Section 6.

2 OBSERVATIONS AND DATA ANALYSIS

We observed CU Vir on 2008 October 31 with the Australia Telescope Compact Array (ATCA). The array of six 22-m dishes, in its fully extended 6A configuration,¹ recorded data in 32 channels across 128-MHz bandwidths centred at 1.384 GHz (20 cm) and 2.638 GHz (13 cm). Complex cross-correlations (visibilities), integrated over 10-s intervals, were recorded for all baselines in all Stokes parameters. The absolute flux density scale and the frequency response over the receiver bandpasses were characterized using the radio galaxy PKS B1934–638. The gains of the individual antennas, atmospheric and instrumental path-length variations for each antenna and signal path, and the cross-talk between the orthogonal linear feeds in each antenna were calibrated using 5-min observations of the radio galaxy PKS B1416–067 at 20-min intervals during the observations. The total observing time on CU Vir was 7.75 h. We pointed the antennas 10 arcsec south of CU Vir to avoid source contamination by ‘non-closing’ correlator offsets.

We reduced our data using the MIRIAD set of software routines (Sault, Teuben & Wright 1995). In order to optimize our source-subtraction technique, the four shortest baselines in each configuration were removed from the data, along with radio-frequency interference. Multifrequency synthesis images with extent of four primary beam full-width half-maxima were made of the source field in the 13- and 20-cm bands. Attenuation caused by the spatial response of the primary beam was corrected for. All sources detected at greater than five standard deviations of the noise in the images were subtracted. Our subtraction technique involved producing CLEAN models of each source and subtracting them from the visibility data using the MIRIAD task UVMODEL. We then shifted the phase centre of the visibilities to the CU Vir position, and inspected the time-series of the real components of the visibilities, averaged over 2-min intervals, for Stokes V pulses. Having identified the pulse durations, we imaged the off-pulse emission, produced CLEAN

Table 2. Basic parameters and detections from the three data sets analysed. Q : quiescent detections. P : Number of peaks detected. The Stokes I quiescent ($Q_{20,13}$) and the Stokes V peak ($P_{20,13}$) flux densities (in mJy) for all peaks detected are also given. The errors in the peak flux densities are approximately 1 mJy.

	Epoch A	Epoch B	Epoch C
Date (UT)	29/05/99	29/08/99	31/10/08
Time-span (h)	9.3	9	9
ATCA config.	6A	6D	6A
20-cm Q	Yes	Yes	Yes
13-cm Q	Yes	Yes	Yes
20-cm P	2	2	2
13-cm P	1	1	2
Q_{20}	3.4(3)	2.3(2)	2.5(3)
P_{20}	5, 13	3, 6	11, 12
Q_{13}	3.4(2)	3.0(2)	2.9(2)
P_{13}	0, 14	0, 6	12, 8

models in the 13- and 20-cm bands and subtracted them from the visibility data.

Light curves of the pulsed emission were then produced in Stokes I and V from the source-subtracted visibility data by averaging the real visibility components over 2-min intervals. Stokes I light curves of the off-pulse emission were also produced by averaging the real visibility components of the off-pulse data sets over 50-min intervals and the errors were scaled appropriately.

We repeated our data reduction procedure for the CU Vir data sets (obtained from the Australia Telescope Online Archive²) described in Triglio et al. (2008). In summary, we analysed observations of CU Vir from three epochs: Epoch A (1999 May 29), Epoch B (1999 August 29) and Epoch C (2008 October 31). Data from Epochs A and B were collected by Triglio et al. (2008), and the Epoch C observations were ours. Details of all observations are summarized in Table 2.

3 RESULTS

We observed two peaks of 100 per cent right-circularly polarized emission from CU Vir during Epoch C at both 13 and 20 cm, as well as time-variable quiescent emission. The pulse and quiescent light curves are shown in Fig. 1. No significant linear polarization was detected in the pulses, and the quiescent emission was found not to be significantly polarized. Our analysis method reproduces the results of Triglio et al. (2008) for Epochs A and B. In Fig. 2, we plot the Stokes V light curves for all three epochs aligned according to the rotation ephemeris of Pyper et al. (1998). The average quiescent flux densities are presented in Table 2 along with the peak flux densities for all epochs.

Our Epoch C observations clearly show two peaks at both 13 and 20 cm, in contrast to the lone 13-cm peaks in the Epoch A and B observations (see Fig. 2). The Epoch C peak separations are smaller in the 13-cm band (separation of ~ 4 h) than in the 20-cm band (separation of ~ 5 h), but the mid-points between the peaks in both bands occur at the same time. This implies that, if pulse arrival times at different frequencies need to be compared, the ‘arrival time’ of the pulse should be taken as the mid-points between the peaks.

¹ <http://www.narrabri.atnf.csiro.au/observing/>

² <http://atoa.atnf.csiro.au>

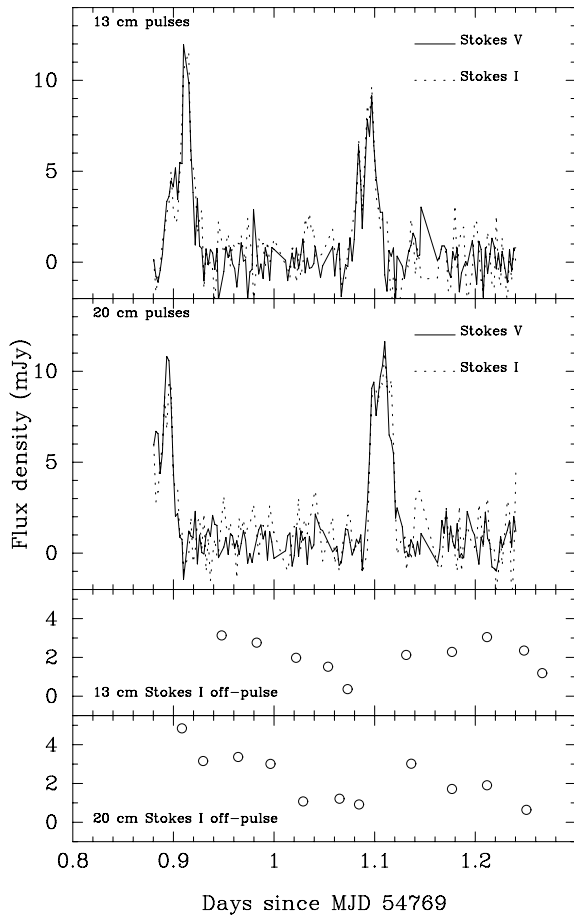


Figure 1. Epoch C pulses and quiescence from CU Vir. From top to bottom: 13-cm Stokes I (dotted) and V pulses, 20-cm Stokes I (dotted) and V pulses, 13-cm Stokes I off-pulse flux densities and 20-cm Stokes I off-pulse flux densities. The pulse light curves are averaged in 2-min bins, and the off-pulse light curves in 50-min bins. The off-pulse measurements have errors of 0.4 mJy.

Fig. 2 clearly shows that the rotational ephemeris of Pyper et al. (1998) is not able to align the observed pulses. In order to obtain an accurate ephemeris for CU Vir, we obtained pulse times-of-arrival (TOAs), as described above, and used standard pulsar timing software (Hobbs, Edwards & Manchester 2006) to fit simple periodicity models to these TOAs using uniform weighting. The TOAs are listed in Table 3. The resulting best-fitting period was $44989.967(8) \text{ s} = 0.52071721(9) \times 10^{-8} \text{ d}$. The post-fit rms timing residual was 46 s. No significant period derivative could be determined. Our measured period is 1.221(8)s slower than that of Pyper et al. (1998), and is consistent with that determined by Trigilio et al. (2008) using pulses separated by $\sim 1 \text{ yr}$.

4 THE MAGNETIC FIELD OF CU VIR

Spectrally peculiar A and B stars (Ap/Bp stars), such as CU Vir, have long been known to be highly magnetic (Babcock 1947), commonly with large dipolar components (e.g. Borra & Landstreet 1980). A leading hypothesis for the field origins is that of ‘frozen-in’ fossil fields from early evolutionary stages (Donati & Landstreet 2009). The frozen-in field paradigm, numerically simulated by Braithwaite & Nordlund (2006), involves an unstable protostellar magnetic field, concentrated in the core, that quickly stabilizes over a few Alfvén

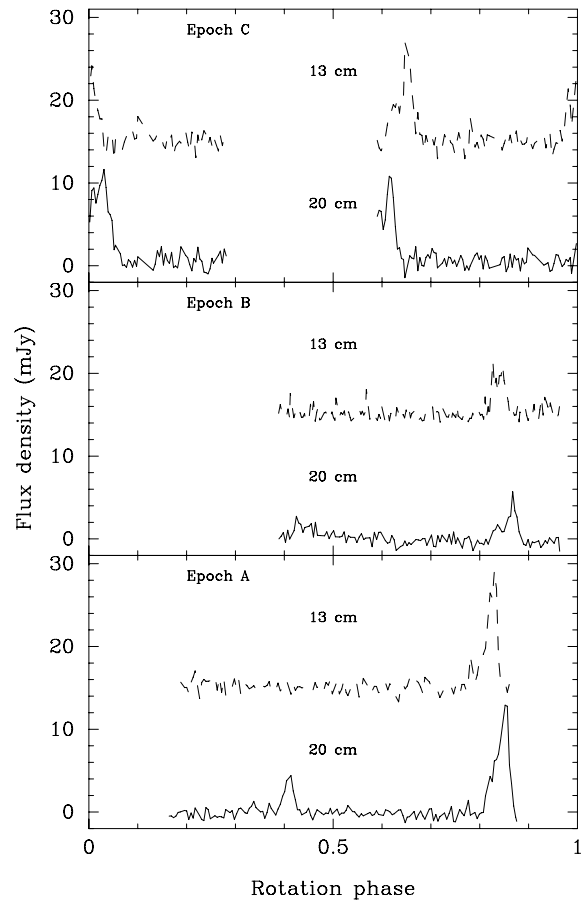


Figure 2. Illustration of the varying pulse phases with respect to the ephemeris of Pyper et al. (1998). The pulse profiles from Epochs A, B and C are shown in the bottom, middle and top panels, respectively. The 13-cm Stokes V pulses (dashed lines) are placed at +15 mJy to differentiate them from the 20-cm Stokes V pulses (solid lines).

Table 3. List of TOAs with references derived from all light curves of CU Vir.

TOA (MJD)	ν_{obs} (GHz)	Epoch	Reference
50966.159(8)	1.425	98 June	Trigilio et al. (2000)
51327.535(3)	1.380	A	Trigilio et al. (2008)
51419.189(3)	1.380	B	Trigilio et al. (2008)
54770.007(3)	1.380	C	this paper
54770.007(3)	2.368	C	this paper

time-scales, given by $\tau_A = \frac{R_*}{v_A}$, where R_* is the stellar radius and v_A is the Alfvén speed. For Ap stars such as CU Vir, $\tau_A \sim 10 \text{ yr}$. For most of the main-sequence life of the star, the field then slowly expands outwards through ohmic diffusion, creating a slowly increasing atmospheric poloidal field component.

Simultaneous observations of the CU Vir pulse at many radio frequencies could provide interesting insights into the magnetic field structure. ECM emission frequencies directly map to magnetic field strengths (see equation 1), and the emission is tightly beamed at fixed angles to field lines determined by the kinematics of the radiating electrons (Melrose & Dulk 1982). Our dual-frequency observations of the CU Vir pulse show a time difference of $\sim 30 \text{ min}$ between corresponding peaks. This translates to a difference in the

angle of emission with respect to the magnetic axis of 14° . Assuming ECM emission at the fundamental cyclotron frequency, the 13- and 20-cm bands correspond to emission from magnetic field regions of 850 G and 500 G, respectively. If the pulse is emitted from field lines occupying a narrow range of magnetic co-latitudes (Leto et al. 2006; Trigilio et al. 2008), the tangents to the field lines at field strengths of 850 G and 500 G regions must also differ in angle to the magnetic axis by 14° . Assuming a dipole field for CU Vir, this occurs for field lines that intersect the magnetic equator at radii of $\sim 1.5R_*$. This is much closer than the $12\text{--}17R_*$ predicted in the magnetospheric model of Leto et al. (2006) for field lines along which the radiating electrons propagate. Hence, we suggest that either the magnetic field is more curved than for a pure dipole in the polar regions or that the Leto et al. (2006) model for the CU Vir magnetosphere does not adequately account for the CU Vir pulses. We are conducting wide-band radio studies of the CU Vir pulse to further probe the magnetic field structure in the pulse emission regions.

5 THE ANOMALOUS RADIO PERIODICITY

The offset between the radio pulse- and optical-variability periods of CU Vir can be interpreted in a variety of ways. Pyper et al. (1998) reported a reduction in the optical period of CU Vir of ~ 2 s that occurred in 1984. This was derived by fitting different periods to time-resolved spectrophotometric data gathered before and after 1984. A possible interpretation of the period discrepancy between the radio pulse data taken after 1998 and the latest ephemeris published by Pyper et al. (1998) is that the CU Vir rotation period has again decreased, sometime between the epoch of the last data analysed by Pyper et al. (1998) (1997 May) and the Epoch A radio observations.

Trigilio et al. (2008) suggested that the loss of all the confined magnetospheric mass, as modelled by Havnes & Goertz (1984), at the epochs of the period changes could explain the apparent 0.2 Myr spin-down time-scale. Besides CU Vir, some Ap/Bp stars have been observed to have steadily reducing rotation periods (Townsend et al. 2010), but with spin-down time-scales of ~ 1 Myr. Such spin-down time-scales are predicted by simulations of steady angular momentum loss from Ap/Bp stars to the magnetic field and magnetically confined wind, with episodes of confinement-breaking during which the magnetosphere is emptied (Ud-Doula, Owocki & Townsend 2009). In contrast to the suggestion of Trigilio et al. (2008), the emptying episodes are associated with *less* angular momentum loss, as the star can no longer lose angular momentum to its surroundings. These simulations cannot reproduce the apparent spin-down of CU Vir. We therefore explore other possibilities for the CU Vir period discrepancy.

5.1 A drifting pulse emission region

If we assume that the CU Vir rotation period has *not* changed, then two possibilities exist: either the pulse periodicity we measure is real and represents a stable, persistent effect, or the periodicity is coincidental and future radio pulse measurements will not follow our fitted pulse period. We first consider the former case, and the latter case in Section 5.2.

Our measured period discrepancy could imply a non-fixed emission region that steadily drifts in azimuth about the rotation axis. The rate of drift corresponds to the period difference, ~ 1.2 s, per optical period. Thus the drift period is approximately 53 yr. This drift

could be caused by a mechanism that is analogous to the differential rotation in the solar magnetosphere (Stenflo 1989).

The emission region might also be coupled to the orbit of an object with a 53-yr orbital period. This would cause the emission region to drift about the orbital axis. Whatever the relative orientation of the orbital angular momentum axis and CU Vir rotation axis may be, a systematic change with time in the pulse profile, both in shape and frequency characteristics, is expected because the emission region would be drifting relative to the magnetic field. Keplerian dynamics place such an object at a radius of approximately 20 au. Such a system could be directly analogous to the Jupiter–Io interaction, where the orbital phase of Io around Jupiter is strongly correlated with the occurrence of Jovian decametric emission (Bigg 1964).

5.2 An unstable emission region

The discrepant radio pulse periodicity could be ascribed to coincidence, and could be indicative of an unstable emission region. In this interpretation, future measurements of the radio light curve will not fit the currently measured pulse period.

Pulse shape variability is also prevalent among the only other stable emitters of coherent radio pulses: radio pulsars. Indeed, single pulses from pulsars vary greatly in both structure and power from pulse to pulse. It has however been shown that pulsars have extremely stable characteristic pulse profiles, formed by averaging large numbers of individual pulses together (Manchester & Taylor 1977). A similar average pulse profile for CU Vir, attempted by Kellett et al. (2007), will be useful in ascertaining the emission region structure and stability, as well as aiding in pulse timing.

6 CONCLUSIONS AND FUTURE WORK

For more than a decade, CU Vir has been known to be unique among main-sequence stars in producing strong, periodic peaks of coherent radio emission. Our observations reveal, for the first time, twin peaks in the CU Vir pulse profile at both 13 and 20 cm. While the 13-cm peak separation is 1 h less than the 20-cm peak separation, the mid-points of the peaks occur simultaneously in both bands. We show that the arrival-time difference between the 13- and 20-cm peaks could indicate that the field structure is more complex than a pure dipole. We demonstrate that a characteristic pulse arrival time can be determined from the mid-point of the peaks in the profile. Using four arrival times derived with this technique from archival data as well as our own observations, we find that the radio pulses fit a periodicity that is 1.221 s slower than the most recently published optical rotation period. This confirms, over a 10-yr period, the initial trend evinced by Trigilio et al. (2008) using pulses separated by 1 yr. We suggest that, in contrast to the explanations of Trigilio et al. (2008) for the period discrepancy, the anomalous radio periodicity could be caused by a drifting or unstable emission region.

Targeted observations can reveal the cause of the period discrepancy. We plan a simultaneous measurement of a radio pulse and the optical light curve of CU Vir to determine whether a period change has indeed occurred. If a mass-loss event is the cause of the period change, a detached mass shell could be directly detected and its shape measured using infrared or optical interferometry. Thermal emission from electron–hydrogen atom collisions could be expected from a cooling mass shell (Tatebe & Townes 2006). Hydrogen recombination lines could also be a significant emission component, particularly at optical and near-infrared wavelengths.

Furthermore, if a mass-loss event was associated with the 1984 optical period reduction, a much bigger shell might also be visible. If the pulse emission region is coupled to the orbit of a companion, sensitive radio very long baseline interferometry could detect radio emission from plasma flows between the companion and CU Vir, as well as possible reflex motion of CU Vir. Conventional planet detection techniques (Johnson 2009), such as time-resolved optical photometry and radial velocity measurements, are not applicable to CU Vir given its large degree of intrinsic variability. However, long-period binarity could be indicated by variations in the timing of the extrema of the optical light curve caused by gravitational effects in the binary.

Despite the many remarkable properties of CU Vir, including its close proximity to the Earth and its fast rotation rate, it is unlikely that it will remain unique as a source of radio pulses. Future large-area continuum surveys by next generation radio telescopes, such as the Australian Square Kilometre Array Pathfinder, the Karoo Array Telescope and eventually the Square Kilometre Array will potentially find many similar objects, leading to further insights into this fascinating class of radio transient.

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