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The radio lighthouse CU Virginis: the spindown of a single main sequence star

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ABSTRACT

The fast rotating star CU Virginis is a magnetic chemically peculiar star with an oblique dipolar magnetic field. The continuum radio emission has been interpreted as gyrosyncrotron emission arising from a thin magnetospheric layer. Previous radio observations at 1.4 GHz showed that a 100% circular polarized and highly directive emission component overlaps to the continuum emission two times per rotation, when the magnetic axis lies in the plane of the sky. This sort of radio lighthouse has been proposed to be due to cyclotron maser emission generated above the magnetic pole and propagating perpendicularly to the magnetic axis. Observations carried out with the Australia Telescope Compact Array at 1.4 and 2.5 GHz one year after this discovery show that this radio emission is still present, meaning that the phenomenon responsible for this process is steady on a timescale of years. The emitted radiation spans at least 1 GHz, being observed from 1.4 to 2.5 GHz. On the light of recent results on the physics of the magnetosphere of this star, the possibility of plasma radiation is ruled out. The characteristics of this radio lighthouse provides us a good marker of the rotation period, since the peaks are visible at particular rotational phases. After one year, they show a delay of about 15 minutes. This is interpreted as a new abrupt spinning down of the star. Among several possibilities, a quick emptying of the equatorial magnetic belt after reaching the maximum density can account for the magnitude of the breaking. The study of the coherent emission in stars like CU Vir, as well as in pre main sequence stars, can give important insight into the angular momentum evolution in young stars. This is a promising field of investigation that high sensitivity radio interferometers such as SKA can exploit.

Key words: Stars: chemically peculiar – Stars: individual: CU Vir – Polarization – Stars: magnetic field – Radio continuum: stars – Masers

1 INTRODUCTION

CU Virginis (=HD124224) is an A-type magnetic chemically peculiar star (MCP) with a rotational period of 0.52 days, one of the shortest for this class of stars. As observed in all MCP stars, the variability of the light curve is correlated with the spectroscopic variations (Deutsch 1952; Hardie 1958) and with the effective magnetic field (Borra & Landstreet 1980). All those characteristics can be explained in the framework of the oblique rotator model, where the axis of the dipolar magnetic field is tilted with respect to the rotational one (Babcock 1949) and abundance of elements is not homogeneously distributed over the stellar surface. The observed variabilities are thus consequence of the stellar rotation.

MCP stars are in general slow rotators in comparison with normal B and A-type main sequence stars. This behaviour can be explained as the result of the action of a magnetic breaking. But, at the present, only two MCP stars have been found to increase their rotational period; they are 56 Ari and CU Vir. While the former shows a continuous breaking down at the rate of few seconds per century (Adelman et al. 2001), CU Vir has been subject of an abrupt increase of the rotational period (Pyper et al. 1998). From the analysis of photometric light curves collected over 40 years, it seems that a change of period of about two seconds occurred abruptly in 1984. The mechanism responsible for this event is still under debate, and precise timing of the ro-

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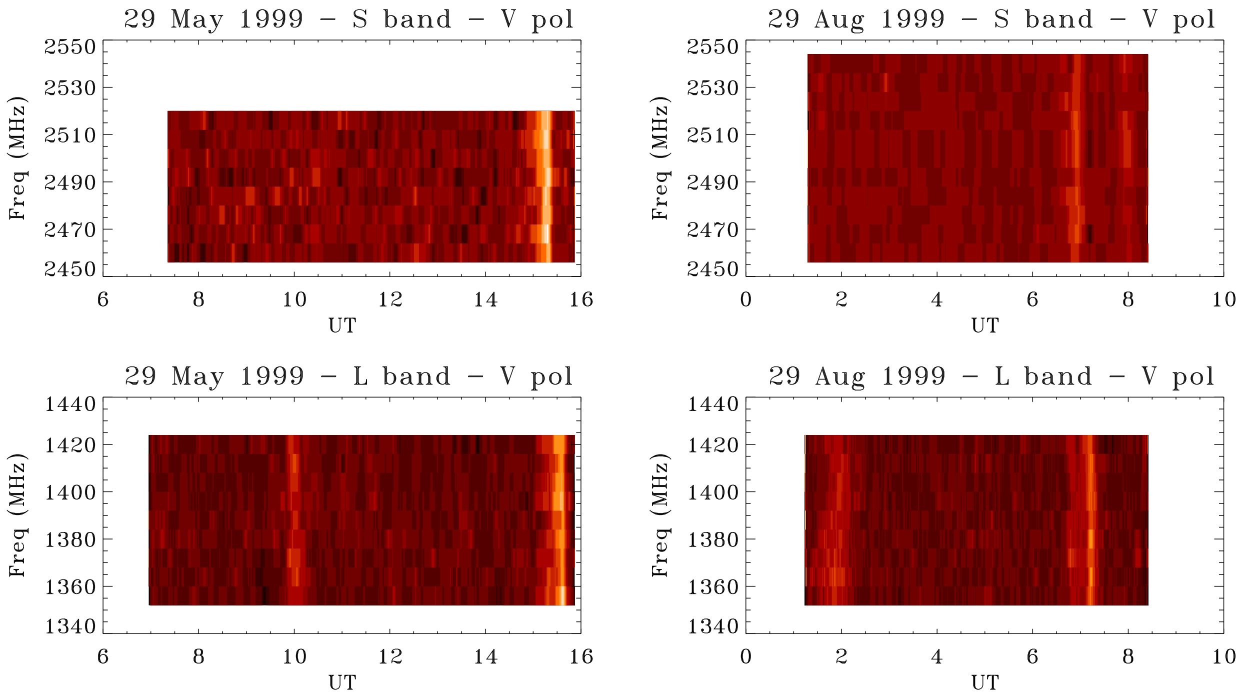

Figure 1. Dynamical spectra of CU Vir during the two days of observations (left panels: May 29, 1999) at 2.5 GHz (upper panels) and 1.4 GHz (lover panels). Some spectral channels have been removed, reducing the bandpass. The spectral resolution is 8 MHz; the spectra have been smoothed in time with a window 2 minutes wide. Strong enhancements of the radio emission are evident at two phases at 1.4 GHz, while only one peak is visible at 2.5 GHz.

tation is needed in order to detect any further slowing down of the star.

Radio emission has been observed in CU Vir (Leone et al. 1994). The radio spectrum is quite flat and extends up to mm wavelengths (Leone et al. 2004) with an high degree of circular polarization (Leone et al. 1996). The variabilities of total intensity and polarization are both correlated with the rotation of the star, suggesting we are in presence of gyrosyncrotron emission from an optically thick source. The anisotropic stellar wind inferred from spectral line variations in MCP star (Shore 1987), associated with the magnetic field justifies the radio emission.

Trigilio et al. (2004) developed a three-dimensional model to explain the radio emission from MCP stars. The dipolar magnetic field interacts with the stellar wind, that can freely escape from the polar regions outside the Alfvén surface (outer magnetosphere) but remains trapped in the equatorial belt (inner magnetosphere). Ionized particles flowing out in the transition region between outer and inner magnetosphere, called middle magnetosphere, stretch the magnetic field lines just outside the Alfvén radius and open the field generating current sheets, where particles are accelerated up to relativistic energies. They eventually propagate back toward the stellar magnetic poles following the field lines and radiating for gyrosyncrotron process. As the magnetic field intensity increases traveling to the star, they are reflected back outward by the magnetic mirroring effect and are definitively lost from the magnetosphere. This model, used to explain the observed fluxes and variability of MCP stars (HD37479 and HD37017) has been successfully applied to CU Vir by Leto et al. (2006). On the basis of multiwavelengths radio observations, important physical parameters of the stellar magnetosphere, as the Alfvén radius ($12-17\,R_*$) and the mass loss (about $10^{-12} M_\odot \mathrm{yr}^{-1}$) have been inferred.

A further observational evidence supporting the picture outlined above is the discovery of coherent, highly directive, 100% polarized radio emission at 1.4 GHz (Trigilio et al. 2000). The two peaks of radio emission have been observed at the rotational phases when the magnetic axis of the dipole is perpendicular to the line of sight. The two peaks have been observed in three observing runs spanning 10 days, indicating that the emission mechanism is persistent at least in timescales of weeks. This has been interpreted as Electron Cyclotron Maser Emission from a population of electrons accelerated in the current sheets at the Alfvén point, that developed a loss cone anisotropy after the mirroring and masing in a direction almost perpendicular to the motion, so to the field lines, just above the magnetic pole.

In this paper we present radio observations of CU Vir at 1.4 and 2.5 GHz carried out with the aim to confirm the maser emission and to study its spectrum. The directivity of the radiation is used to check the rotational period as the beam point toward the Earth two times per rotation.

Table 1. Stokes I flux densities

Date	$F_{1.4}$ (σ) mJy	$F_{2.5}$ (σ) mJy
29 May 1999	3.47 (0.30)	3.39 (0.23)
29 Aug 1999	2.24 (0.18)	2.93 (0.18)

2 OBSERVATIONS AND DATA REDUCTION

The observations have been carried out at the Australia Telescope Compact Array (ATCA) [1] in two days, the first on May 29th 1999, the latter on August 29th 1999. We used all the 6 telescopes for both the observing runs. On the first run the array was in configuration 6A, with a minimum and maximum antenna spacing of 628 and 5939 m; on the latter run in configuration 6D, with antenna spacing in the range from 367 to 5878 m. The acquisition has been obtained with the 20-cm/13-cm feedhorns receivers, observing simultaneously at two frequencies, namely L band, centered at 1384 MHz, and S band, centered at 2496 MHz, and two linear polarizations. For both frequencies we used a bandwidth of 128 MHz, split in 16 channels, with a spectral separation of 8 MHz. All the four correlator cross products of linear polarizations (XX, YY, XY, YX) for each couple of telescopes have been obtained with an integration time of 30 seconds. The target source CU Vir has been observed in cuts of 20 minutes, preceded and followed by 4 minutes observations of the compact quasar 1406-076, used as phase calibrator. The amplitude scale has been determined by observations on the radio galaxy PKS B1934-638, with a flux density of 14.9 and 11.6 Jy at L and S band respectively.

Data reduction and editing has been performed by using the MIRIAD package. All the channels have been inspected and some removed because of interferences, reducing in some case the total bandwidth. The four linear polarizations cross products have been converted into the Stokes parameters I, Q, U, V by using the standard calibration tasks.

Maps of CU Vir have been obtained at 1.4 and 2.5 GHz in Stokes I for the two days of observations. The average flux densities are shown in Table 1. Errors have been evaluated as $\sigma = \sqrt{(\Delta Imm)^2 + (\sigma_{\rm cal} F)^2}$, where ΔImm is the rms of the map and $\sigma_{\rm cal} F$ is the error associated to the flux calibration, assumed 5% of the measured flux density.

For each spectral channel ν and for each time t, the flux density $F(\nu, t)$ has been obtained by performing the DFT of the N observed visibilities $V(\nu, t)$:

$$F(\nu, t) = \frac{1}{N} \Sigma_{i=1}^{N} V_i(\nu, t) e^{-2\pi(u_i x_0 + v_i y_0)}$$

where x_0 and y_0 are the offsets of the target source from the phase tracking center in RA and Dec respectively.

2.1 Dynamical spectra

The dynamical spectra in Stokes V for L and S band as a function of time are shown in Fig. 1. The circular polarization is almost zero except for limited periods of time. In the 29 May observations, we note an enhancement of the Stokes V in the 2.5 GHz band with a maximum at 15:10 UT, and that the flux density is almost constant inside this band at a given time. In the 1.4 GHz band two peaks are visible, the first at 10 UT, the latter at 15:26 UT, about 16 minutes after the S band peak, and with a stronger intensity then the first one. A similar behavior is evident during the 29 Aug observations, with one peak at 2.5 GHz at 6:59 UT, and with two peaks at 1.4 GHz, at 1:54 UT and 7:13 UT, about 14 minutes after the 2.5 GHz one.

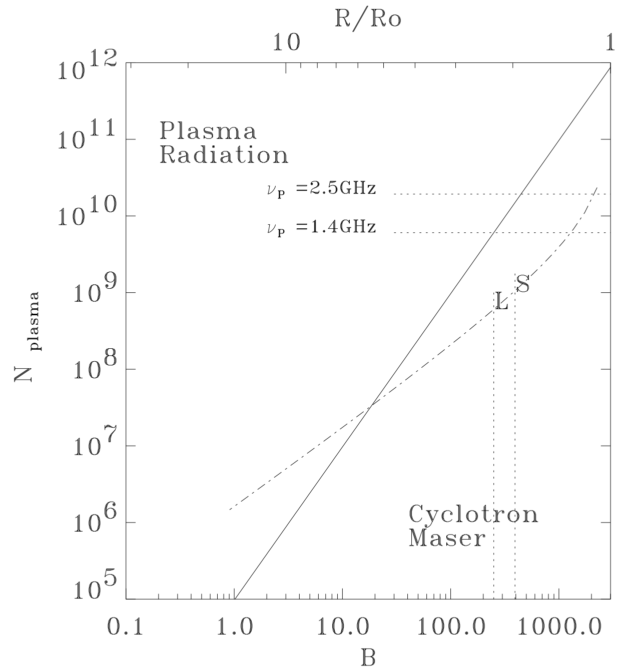

Figure 2. Plane $B - N_{\rm P}$: plasma radiation is possible only in the upper left part of the diagram; conversely, Cyclotron maser in the lower right part. The dashed line represents the plasma conditions along the field lines where the emitting particles flow. At the observed frequencies, only cyclotron maser is possible (points L and S).

3 THE CYCLOTRON MASER

The first result of our observations is that the two enhancements of the radio emission discovered in CU Vir by Trigilio et al. (2000) are still present at 1.4 GHz after one year. This means that the mechanism responsible for this coherent emission is persistent over a long time period. The radioemission has a broad band, since it is constant inside the observed band and it is also visible at 2.5 GHz.

In the following we will discuss in detail the behaviour of this component of radio emission and its implications.

3.1 ECME vs Plasma radiation

Two types of coherent radio emission are possible in a magnetized plasma; they are Electron Cyclotron Maser Emission (ECME) and plasma radiation due to Langmuir waves. In the ECME mechanism, electrons reflected by a magnetic mirror can develop a pitch angle anisotropy. When energetic

[1] The Australia Telescope Compact Array is part of the Australia Telescope which is funded by the Commonwealth of Australia for operations as a National Facility managed by CSIRO

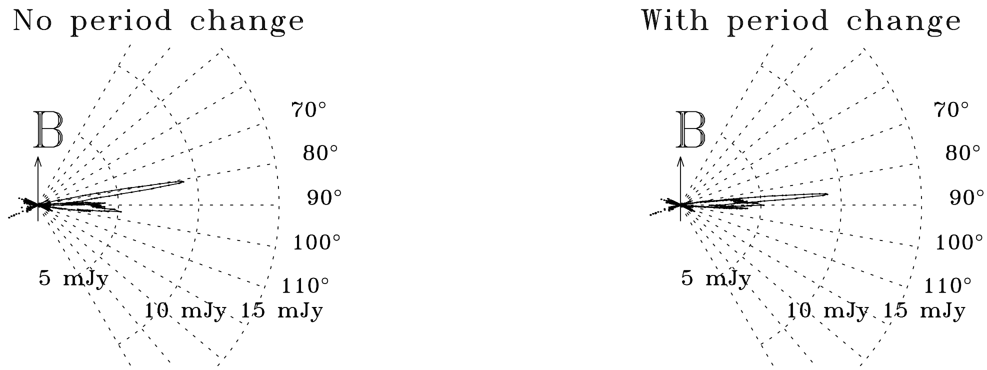

Figure 3. Polar diagram of the radio emission at 1.4 GHz in the Aug 29 observations. The magnetic axis of the dipole is vertical; the emission is plotted as a function of the angle $\theta_{\rm M}$ formed by the line of sight and the axis B. Left panel: $\theta_{\rm M}$ is computed by using the ephemeris given by Pyper et al. (1998). The direction of propagation of the radiation is not the same for the two peaks. Right panel: assuming a delay of about 13 minutes, the direction of propagation of the two peaks coincide. In this case an abrupt change of period of about 1 second is assumed. The behavior of the May 29 data is the same.

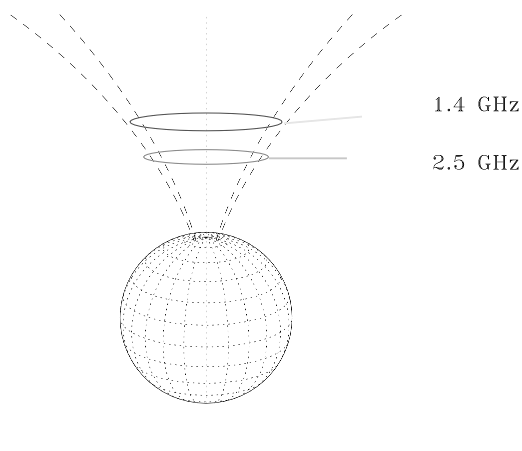

Figure 4. Picture of the cyclotron maser emission: electrons accelerated in the current sheets out of the Alfvén radius propagate back to the star inside the thin layer (the middle magnetosphere) between the two dashed lines; they are reflected back by magnetic mirroring, developing a loss cone anisotropy and emitting coherent radiation by cyclotron maser. Here the Alfvén radius is assumed to be 15 R_*, the radiation is emitted at harmonic number s=2, the 2.5 GHz radiation forms close to the star, while the 1.4 GHz at larger distance, where the magnetic field is weaker.

electrons propagate in a magnetic flux tube, with an initial pitch angle ψ_0, they can penetrate inside the magnetosphere up to a point where $B = B_0/\sin\psi_0^2$, where B_0 is the magnetic field at the point of injection. Electrons with a very small ψ_0 can propagate to the stellar photosphere, collide with the local thermal plasma and can not be reflected back outward, generating an hollow cone in the pitch angle distribution of the reflected particles.

3.2 The directivity of the polarized emission

In this condition, if the plasma density is relatively small and the condition $\nu_{\rm P} << \nu_{\rm B}$ can be satisfied (where $\nu_{\rm P} = 9000\sqrt{N_{\rm e}}$ Hz is the plasma frequency, $N_{\rm e}$ the plasma density number in cm^{-3}, and $\nu_{\rm B} = 2.8 \times 10^6 B$ Hz is the gyrofrequency, with B in gauss) ECME can arise. The frequency of the maser emission is $\nu \gtrsim s\,\nu_{\rm B}$, where s is the harmonic number ($s \leqslant 4$ in ECME). Since the first harmonic is generally suppressed by the gyromagnetic absorption of the local plasma, most of the emission is emitted at $s = 2$. The stimulated emission is directed almost perpendicularly to the electron travel direction, which in turn is the magnetic field line. Following Melrose & Dulk (1982), the radiation is confined in a hollow cone of aperture θ with respect to the field line, with $\cos\theta = v/c$, v the average speed of the emitting electrons along the field line. The beamwidth of this cone is $\Delta\theta \approx v/c$, and if the magnetic field is constant in the region, $\Delta\nu/\nu \approx \cos^2\theta$.

In the hypothesis of the 3D model (Leto et al. 2006) applied to CU Vir, the electrons accelerated in the current sheets travel through the middle magnetosphere. Here the local plasma is the ionized wind, that increases moving inwards as the section of the magnetic tube decreases ($N_{\rm plasma} \propto r^{-3}/v_{\rm wind}$). The corresponding plasma frequency in the inner magnetosphere varies as $r^{-3/2}$, while the gyrofrequency varies like the magnetic field strength, i.e. as r^{-3}. Therefore, moving inwards, the conditions for ECME are satisfied. The situation is shown in Fig. 2, where plane B vs $N_{\rm plasma}$ identifies the status of a magnetoactive plasma to be subject to plasma radiation or ECME. The diagonal line represents the loci where the condition $\nu_{\rm P} = \nu_{\rm B}$ is valid. The shaded-dotted line represents the middle magnetosphere, i.e. the path of the electrons, from the Alfvén radius (lower left corner) to the stellar surface (upper right corner). The plasma density has been derived from Leto et al. (2006), with a number density $N_{\rm alf} = 7 \times 10^5$ cm^{-3} at $R_{\rm alf} = 15\,R_*$. The number density for plasma emission at 1.4 and 2.5 GHz is $N_{\rm plasma} \approx 10^{10}$ cm^{-3} (horizontal dotted

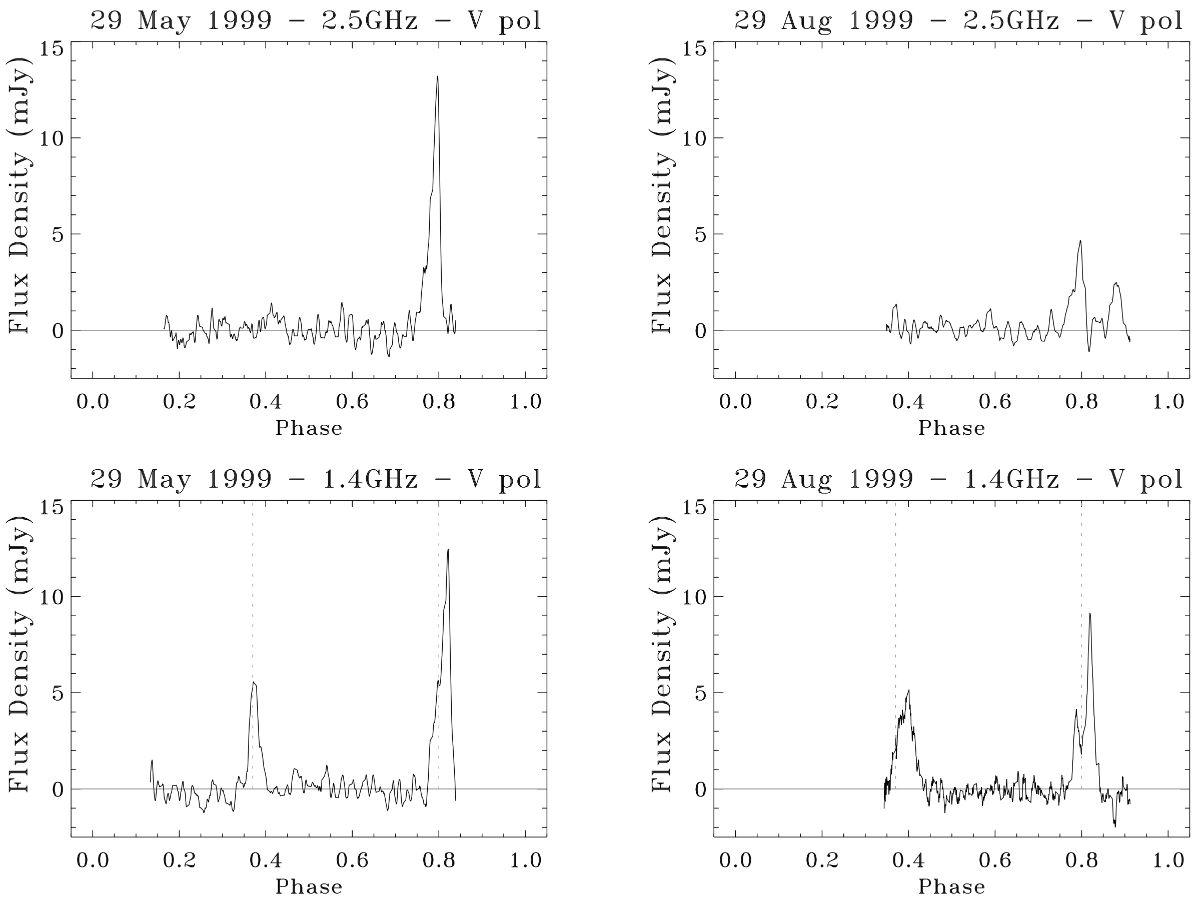

Figure 5. Flux density (Stokes V) at 2.5 GHz and 1.4 GHz as a function of the rotational phase in the two days of observation. The vertical dotted lines in the lower panels indicate the phases of the peaks observed in 1998, showing the delay cumulated in one year because of a new increase of the rotational period.

lines), but this condition is reached only very close to the stellar surface, where the magnetic field strength is too high (> 1000 Gauss) and only ECME is possible.

In conclusion, we rule out the possibility that the observed coherent emission is due to plasma radiation. Only cyclotron maser is possible.

Trigilio et al. (2000) found that the polarized emission is highly directive, and it propagates in direction almost perpendicularly to the magnetic dipole axis. The observed peaks have been explained as due to the different inclination that the oblique dipole forms with the line of sight as the star rotates. At particular rotational phases, highly beamed radiation is emitted toward the Earth. This happens two times per rotation, at two symmetric configurations. The behavior is like a lighthouse, similar to a pulsar, even if the emission mechanism is different.

Since the flux density is constant inside each band (Fig.1), it has been averaged in frequency in order to get a better S/N. Data have been folded using the ephemeris given by Pyper et al. (1998), used by Trigilio et al. (2000), referred to light minimum, valid for $JD > 2\,446\,000$, nominally from 1984:

$$HJD = 2\,435\,178.6417 + 0^{d}.52070308E$$

The angle $\theta_{\rm M}$ that the emitted radiation forms with respect to the magnetic axis is defined given the inclination i of the rotational axis, the obliquity β of the magnetic axis

$$\cos\theta_{\rm M} = \sin\beta\sin i\cos(\phi - \phi_0) + \cos\beta\cos i,$$

where $\beta = 74°$, $i = 43°$ and the phase $\phi_0 = 0.08$ corresponds to the delay of the magnetic curve with respect to the light curve (Trigilio et al. 2000). In Fig. 3 the direction of the emitted radiation at 1.4 GHz for the 29 Aug observation is shown as a function of the angle $\theta_{\rm M}$. Because of the symmetry, the two beams should be emitted at the same angle. Looking at the left panel, however, it appears that the first beam is at $\theta_{\rm M} \approx 80°$, while the second at $\theta_{\rm M} \approx 90°$. This difference since the previous observations in 1998 can be explained if we assume that the period has changed, and that the angle $\theta_{\rm M}$ should be re-computed consequently.

The possibility of a change of period is very interesting since the discovery of the abrupt increase of the rotational period of $\Delta P_1 = 2.18$ s between 1983 and 1987 reported by Pyper et al. (1998). The use of the peaks of the coherent radiation as marker of the rotational period is a powerful tool.

In order to get the new rotation period, we use the assumption that the two peaks must be symmetric with respect to the dipole axis. In section 3.4 we will compute the delay accumulated in one year by evaluating the shift of the

Table 2. Delay of the rotation markers at 1.4 GHz

Date	Phase delay $d\phi$	σ_ϕ	Delay (min)
May 1999	0.0120	0.008	9 ± 6
Aug 1999	0.0180	0.008	13 ± 6

phase ϕ_0. In Fig. 3, right panel, data have been reported assuming the change of period (see section 4). Here $\theta_{\rm M} \approx 85°$ at 1.4 GHz. In this geometry, at 2.5 GHz we get $\theta_{\rm M} \approx 90°$.

3.3 The bandwidth of the polarized emission

From the dynamical spectra shown in Fig. 1 it is evident that the spectrum of the radiation is constant inside each band. While the first peak is visible only at 1.4 GHz, the second one is visible at the two bands, even if not exactly at the same times.

The theory of the ECME foresees a narrow bandwidth when the magnetic field is constant. The existence of masing radiation in a broad range of frequency means that it arises from the region above the pole where the magnetic field strength ranges from 450 G down to 250 G, i.e. at $R = 1.9-2.8\,R_*$ when we assume $B_{\rm pole} = 3000$ G and $s = 2$. The scenario of the cyclotron maser emission is drawn in Fig. 4. Considering the angle between the magnetic field lines and the emitted radiation, we get $\theta_{\rm 2.5GHz} \approx 60°$ and $\theta_{\rm 1.4GHz} \approx 50°$ for the radiation emitted at the two frequencies.

3.4 The delay of the peaks at 1.4 GHz

The radio emission, averaged in frequency inside the observing bands, is shown in Fig. 5 as a function of the rotational phase. This has been computed by using the ephemeris of Pyper et al. (1998). Trigilio et al. (2000) found that in June 1998 the two main peaks were centered at phases $\phi_{\rm a} = 0.37$ $\phi_{\rm b} = 0.80$, with a phase difference between them of 0.43. The present observations show that the phase difference between the peaks a and b is always the same; in fact we now measure 0.439 and 0.418. This indicates that the geometry of the magnetic field (dipole configuration, inclination i, obliquity β) is preserved. In the lower panels of Fig. 5, where the 1.4 GHz curves are shown, the vertical lines mark the phases of the main peaks observed in 1998. A delay is evident.

In order to measure this delay, we search for the relative shift of the whole emission patters as a function of the phase for the different observational sets. This can be done by computing the cross correlations between the new curves with respect to the 1998 one. These are shown in Fig. 6. Maxima and associate errors have been found by fitting the cross correlation functions at a level greather than 75% of the amplitude with gaussians. Results are listed in Table 2

4 THE SPIN DOWN OF CU VIR

The phase delay $d\phi$ of the markers of the rotation of CU Vir indicates that the star is slowing down. New photometric data seem to indicate further slowdown (Pyper & Adelman 2004). But how does it happen? Continuously or suddenly?

In the case of a continuous breaking down, there should be a delay also in the 1998 observations with respect to the photometric observations reported by Pyper et al. (1998), that have been completed in 1997. In fact, the accuracy of the delay determination from the radio observations allow to detect the slowing down in one year. But we have not found any difference between the 1998 data and the photometric measurements of 1997, and we can rule out the continuous breaking down.

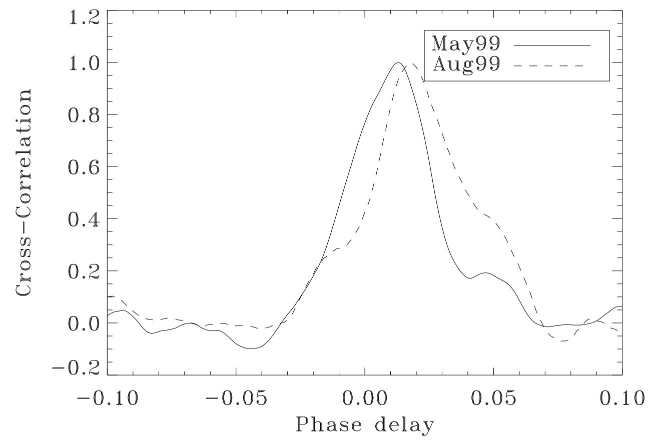

Figure 6. Cross correlation between the two emission at 1.4 GHz (May99 and Aug99 data) and the June 1998 data as a function of the rotational phase. The maximum of the functions indicates the phase delay accumulated in one year because of the change of the rotational period of the star.

In the following we assume a sudden change of rotational period. The average of the phase shifts during the two observations in 1999 is $d\phi = 0.015$ and a delay $d\phi * P = 0^{\rm d}\!.0081 \approx 700\,{\rm s}$. We don't know exactly when the change of period occurred; assuming that this occurred in 1998, just after the previous observations, in $dt = 1$ year (after $N_{\rm rot} = 700$ rotations of the star) P increased at least of

$$\Delta P_2 = \frac{d\phi * P}{N_{\rm rot}} \gtrsim 1\,{\rm s}$$

but if it occurred later, the change of period increases accordingly. The change of rotation rate is thus:

$$\frac{\Delta P_2}{P} \gtrsim 2 \times 10^{-5} \qquad (1)$$

quite close to the previous period jump. The period jumps are reported in Fig 7 as a function of the time.

The average spindown of the star can be evaluated by noting one period jump of $\Delta P_1 = 2.18$ s (Pyper et al. 1998) occurs in $\Delta t = 15$ years. Since $\Delta P_1 = 2.18$ s; this leads to an average breaking given by

$$< \dot{P} > = \frac{\Delta P_1}{\Delta t} = 5 \times 10^{-9}\,{\rm s\,s^{-1}} \qquad (2)$$

We can compute the characteristic breaking rate

$$\frac{< \dot{P} >}{P} \approx 10^{-13}{\rm s}^{-1} \qquad (3)$$

corresponding to a characteristic breaking time $\tau \approx 2 \times 10^5$years. This behaviour seems to be confirmed by recent

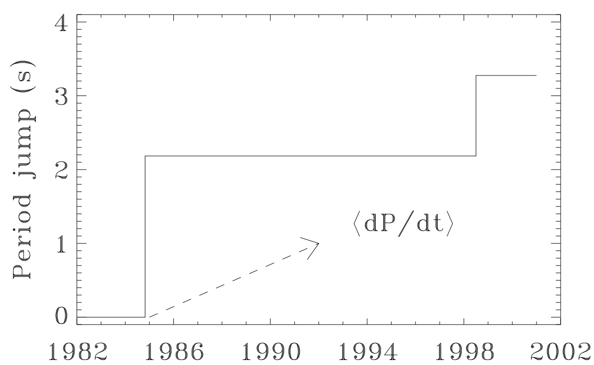

Figure 7. Period jumps as a function of the time.

observations (Kellett et al. 2007) at a slightly different frequency.

Three possible explanations for the spin down mechanism acting in CU Vir exist:

(i) there is a change of the moment of inertia due to a redistributions of the internal mass of the star (Stępień 2000);
(ii) the star loses angular momentum interacting with the external space via magnetic breaking;
(iii) violent emptying of the inner magnetosphere causes the loss of angular momentum, as hypothesized by Havnes & Goertz (1984).

The angular momentum $J = 2\pi I/P$, where $I = k^2 R_*^2 M$ is the moment of inertia with kR_* radius of gyration ($k = 0.3$ by Stępień (2000)) and M mass of the star, hence is

$$J \approx 1.7 \times 10^{51}\ \mathrm{g\,cm^2\,s^{-1}}$$

adopting $R_* = 2.2R_\odot$ and $M_* = 3M_\odot$ (North 1998). In the following we compute the change of rotational rate in the three hypothesis.

4.1 Change of the internal structure

If the star does not lose angular momentum, the change of period is only due to the change of the moment of inertia

$$\Delta P/P = \Delta I/I = 2\Delta k/k$$

This possibility has been investigated by (Stępień 1998), who concluded that the magnetic field of CU Vir is too weak to alter the moment of inertia of the whole star considered as a rigid rotator. However it should be possible a redistribution of the mass of the outer envelope of the star, where the magnetic energy dominates over the gravitational one.

4.2 Steady spindown due to the massloss

In the case that the star does not change its internal structure, I is constant and

$$\dot{J}/J = -\dot{P}/P.$$

Now we consider the possibility that the spin down is due the wind flowing continuously from the magnetic polar caps. In this case however there should be no abrupt change of rotational period. The angular momentum losses is given by

$$\dot{J} = \dot{M} R_{\mathrm{alf}}^2 \omega \approx 5 \times 10^{34}\mathrm{g\,cm^2\,s^{-2}}$$

where $\dot{M} = 10^{-12} M_\odot \mathrm{yr}^{-1}$ and $R_{\mathrm{alf}} = 15\,R_*$ are the actual mass loss and the Alfvén radius given by Leto et al. (2006). We get

$$\dot{J}/J \approx 2 \times 10^{-17}\ \mathrm{s^{-1}}$$

that is 4 orders of magnitude lower that the value of equation (3). We can conclude that the steady loss of angular momentum due to the stellar wind cannot explain the observed slowing down rotational period.

4.3 Violent emptying of the inner magnetosphere

We can instead assume that the material accumulated in the inner magnetosphere (Leto et al. 2006) reaches a maximum density, than suddenly opens the field lines close to the Alfvén radius in a single event. In this case

$$\Delta J/J = -\Delta P/P.$$

Following Havnes & Goertz (1984), the maximum density which can be kept by the magnetic field in a rotating magnetosphere is given by $1/2\rho_{\max} x^2 \omega^2 = B^2/8\pi$, where x and B are the distance from the rotational axis and the magnetic field respectively. In the inner magnetosphere, the magnetic field is given by $B = B_{\mathrm{p}}/(2r^3)\sqrt{1 + 3\cos^2\theta}$, where θ is the magnetic colatitude and B_{p} the magnetic field strength at the pole. We can get $\rho_{\max}(x, y)$ in all the points inside the inner magnetosphere, i.e. inside the magnetic line field reaching the Alfvén radius. The total mass that can be contained is given by

$$\Delta M = 2\,\pi \int_0^{R_{\mathrm{Alf}}} x \left[\int_0^{h(x)} \rho(x, y) dy \right] dx$$

Adopting $R_{\mathrm{alf}} \approx 15R*$ (Leto et al. 2006), in the magnetic equator, the maximum density varies as $\rho_{\max}(x, 0) \propto x^{-8}$, with a value at Alfvén radius of about $2 \times 10^{-19}\mathrm{g\,cm^{-3}}$ (corresponding to a number density of $10^5\mathrm{cm^{-3}}$) We get $\Delta M \approx 10^{25}$g. However, as Havnes & Goertz (1984) found that the density distribution in cool CP stars like CU Vir deviates from the Alfvén inside the magnetic loop of height about $5 - 8\ R_*$, we get $\Delta M \approx 3 \times 10^{24}$g. If during this kind of violent event all this mass is released and flows through the Alfvén surface, the corresponding jump of angular momentum is given by

$$\Delta J = \Delta M R_{\mathrm{alf}}^2 \omega \approx 2 \times 10^{45} - 10^{46}\ \mathrm{g\ cm^2 s^{-1}}$$

where the lower value refers to the case of magnetosphere not fully filled. In this hypothesis

$$\Delta J/J \approx 1.3 \times 10^{-6} - 10^{-5}$$

With all the uncertainty of the case (in R_{alf}, mass, magnetic field strength...) we can conclude that a violent release of material accumulated in the inner magnetosphere up to the critical Alfvén density could account for the observed change of rotational period (see eq. 1).

5 CONCLUSIONS

The observations of CU Vir carried out with the ATCA at 1.4 and 2.5 GHz confirm the presence of the coherent emission already reported by Trigilio et al. (2000) after one year from the discovery, indicating that this is a steady phenomenon. The emitted radiation is visible only at rotational phases corresponding to the instant when the oblique axis of the magnetic dipole lies on the plane of the sky. This indicates the high directivity of this component of the radio emission. All those characteristics, and the fact that it is 100% right hand circularly polarized, are in agreement with the process of electron cyclotron maser from electrons accelerated in the current sheets out of the Alfvén radius, propagating back to the stellar polar caps and reflected outward by the converging magnetic field. The lack of reflected electrons at small pitch angle, that fall in the stellar atmosphere, is the cause of the loss cone anisotropy that, in turn, generates this auroral radiation above the magnetic pole of the star. The polarization properties, the fact that the radiation is only right hand polarized, means that this process in efficient only above the north magnetic pole. This is possible as the magnetic field is not purely dipolar. The possibility of plasma radiation is ruled out since the high magnetic field strength in the region where the radiation is generated.

Since the magnetosphere rotates obliquely around the rotational axis, the cyclotron maser is visible only when it points toward the Earth, like a lighthouse. In this mode it is a good marker of the rotation of the star. The analysis done shows that the peaks are delayed of about 15 minutes with respect to the observations carried out one year before, indicating a possible change of the rotational period of the star, of the order of 1 second, occurred in the period 1998–1999. A similar change of period (Pyper et al. 1998), occurred around 1985, has been already reported. CU Vir is the unique single main sequence star with frequent abrupt spindown.

Different spinning down mechanisms are discussed: the possibility of a change of the moment of inertia of the star, the continuous spindown due to the wind flowing from the Alfvén surface and the violent emptying of the inner magnetosphere. In this latter hypothesis the material accumulated in the closed field lines of the equatorial magnetic belt reaches a maximum density and opens the field lines in a violent event, releasing an angular momentum which may account the observed breaking.

Cyclotron maser emission from stars provides important information on the magnetospheres, as it has been observed in flare stars, in dMe and brown dwarfs. In the future, when high sensitivity radio interferometers such as SKA will allow to discover more and more radio lighthouse of the same kind of CU Vir, a new possibility to study with high precision the angular momentum evolution of young main sequence and pre main sequence stars will be opened.

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