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## AURORAL RADIO EMISSION FROM STARS: THE CASE OF CU VIRGINIS

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### ABSTRACT

CU Virginis is a rapidly rotating Magnetic Chemically Peculiar star with at present unique characteristics as a radio emitter. The most intriguing one is the presence of intense, 100% circularly polarized radiation ascribed to a cyclotron maser. Each time the star rotates, this highly beamed emission points two times toward the Earth, like a pulsar. We observed CU Vir in 2010 April with the Expanded Very Large Array in two bands centered at 1450 and 1850 MHz. We covered nearly the whole rotational period, confirming the presence of the two pulses at a flux density up to 20 mJy. Dynamical spectra, obtained with unprecedented spectral and temporal sensitivity, allow us to clearly see the different time delays as a function of frequency. We interpret this behavior as a propagation effect of the radiation inside the stellar magnetosphere. The emerging scenario suggests interesting similarities with the auroral radio emission from planets, in particular with the Auroral Kilometric Radiation from Earth, which originates at few terrestrial radii above the magnetic poles and was only recently discovered to be highly beamed. We conclude that the magnetospheres of CU Vir, Earth, and other planets, maybe also exoplanets, could have similar geometrical and physical characteristics in the regions where the cyclotron maser is generated. In addition, the pulses are perfect “markers” of the rotation period. This has given us for the first time the possibility to measure with extraordinary accuracy the spin-down of a star on or near the main sequence.

*Key words:* masers – polarization – radiation mechanisms: non-thermal – stars: chemically peculiar – stars: individual (CU Virginis) – stars: magnetic field

*Online-only material:* color figures

### 1. INTRODUCTION

Among Magnetic Chemically Peculiar (MCP) stars (see Wolff 1983 for an extensive description of this class), CU Vir (HD124224) is one of the most intriguing. It is a rapidly rotating star, with one of the shortest rotational periods of this class ( $P_{\text{rot}} \approx 0^{\text{d}}.52$ ). According to the Oblique Rotator Model (Babcock 1949), it is characterized by a magnetic field with a mainly dipolar topology, with a strength of  $B_p = 3000 \pm 200$  G at the pole, whose axis is tilted at an angle  $\beta = 74^\circ \pm 3^\circ$  with respect to the rotational one, which in turn subtends an angle  $i = 43^\circ \pm 7^\circ$  (Trigilio et al. 2000) to the direction of the Earth. The magnetic field is also responsible for the inhomogeneous distribution of the chemical elements in the stellar photosphere, giving rise to photometric and spectroscopic variability.

CU Vir shows continuum radio emission (Leone et al. 1994, 2004), explained as being due to a gyrosynchrotron process from electrons spiraling in a corotating magnetosphere. According to the three-dimensional model developed by Trigilio et al. (2004) for MCP stars, a radiatively driven wind interacts with the magnetosphere, dividing it into three regions, namely, the “inner,” “middle,” and “outer” magnetosphere. In the “inner” equatorial zone, the kinetic energy density of the wind particle never exceeds the magnetic one,  $B^2/8\pi > (1/2)\rho v^2$ , generating a dense equatorial belt. In the outer region, the path of the ionized wind from the polar cups is first traced by the dipolar field, then, where  $B^2/8\pi < (1/2)\rho v^2$ , it is mainly radial. In the thin middle magnetosphere, particles evaporating from a ring around the magnetic poles propagate along the dipolar field lines, breaking them at the Alfvén radius ( $B^2/8\pi \approx (1/2)\rho v^2$ ), generating current sheets where particle acceleration occurs. The energetic particles spread into the middle magnetosphere, emitted by the gyrosynchrotron mechanism. For CU Vir, a weak wind with a

mass-loss rate of the order of  $10^{-12} M_\odot \text{ yr}^{-1}$  can explain the almost flat spectra and rotational modulation.

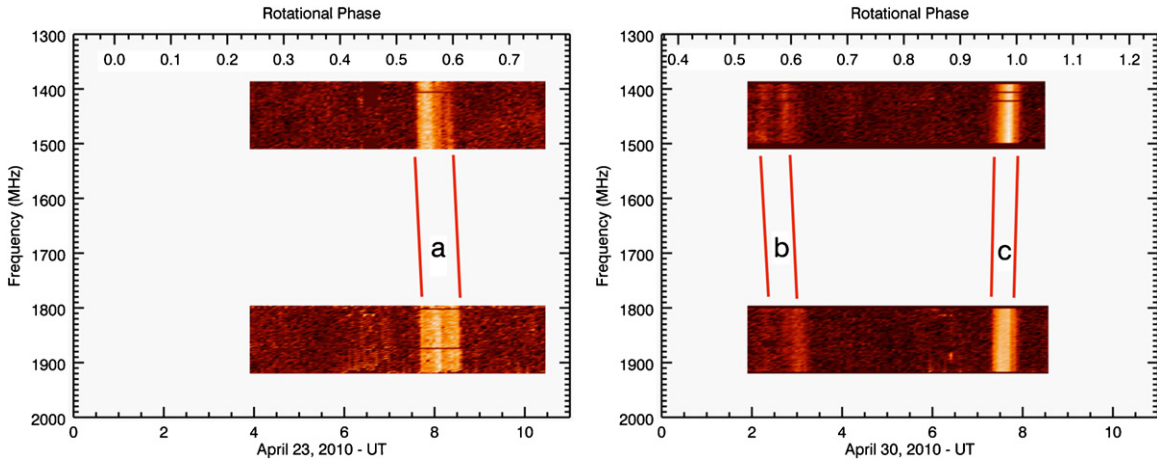
The distinctive behavior of CU Vir is the presence of pulses of coherent, 100% circularly polarized, highly directive radio emission at 1.4 GHz (Trigilio et al. 2000). Pulses are observed two times every stellar rotation, when the magnetic axis of the dipole is perpendicular to the line of sight. This process has been observed for over 10 years (Trigilio et al. 2000, 2008; Ravi et al. 2010), and it is interpreted as Electron Cyclotron Maser Emission (ECME) originating above the magnetic pole (Trigilio et al. 2000, 2008). In the framework of the previous model, the relativistic electrons in a converging flux tube reflect outward when they arrive close to the star, some fraction of them falling into the stellar photosphere. This causes a loss cone anisotropy which is responsible for the maser emission.

Another important aspect of the two pulses is that, assuming the emission source is fixed, they represent an ideal marker of the stellar rotation. An abrupt variation of the rotational period of CU Vir has been claimed from optical photometric study by Pypser et al. (1998). A change of the period from the radio pulses study has been measured with great accuracy by Trigilio et al. (2008).

In order to study the spectral and temporal behaviors of the pulses, the magnetospheric plasma, and the spin-down of this star, we observed CU Vir with the Expanded Very Large Array (EVLA) with unprecedented spectral and temporal sensitivity on two bands around the wavelength of 18 cm.

### 2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out with the EVLA (Perley et al. 2011) in D configuration, on two days, on 2010 April 23, from 03:36 to 10:35 UT, and on 2010 April 30, from



**Figure 1.** Dynamical spectra of the circular polarization (Stokes  $V$ ) flux density of CU Vir; the corresponding heliocentric rotational phase is also shown. Left panel (first day): a broad peak, labeled “a,” centered at 8 UT is visible. Right panel (second day): two peaks, one at 3 UT, “b,” and one at 7:30 UT, “c,” are visible. Peak “a” and “b” appear at the same rotational phase (0.5–0.6); peak “c” appears at phase 0.95–1. Vertical lines show that the peaks at  $\phi \approx 0.55$  occur early at low frequency; conversely, the peak at  $\phi \approx 0.95$  occurs early at high frequency. (A color version of this figure is available in the online journal.)

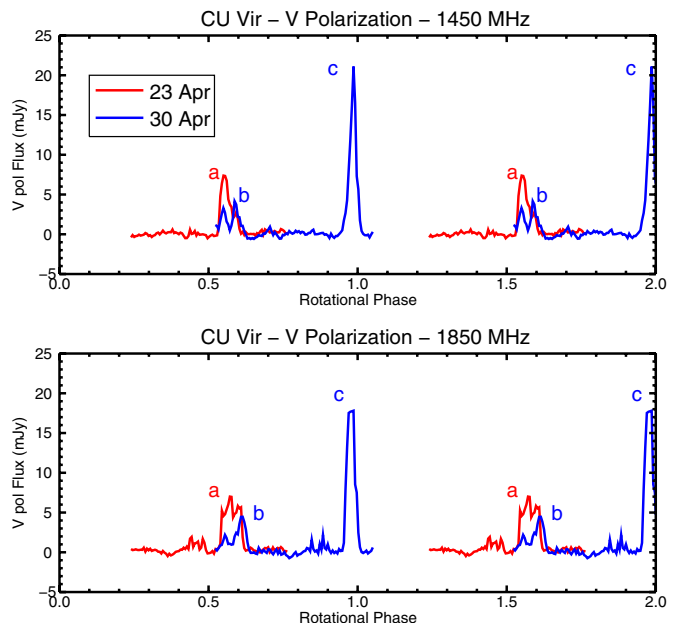
01:39 to 08:38 UT. The dates of the observations have been coordinated in order to cover the whole rotational period of CU Vir (about 12 hr) with two 7 hr slots, with a minimum overlap of rotational phase. We used all the 22 telescopes equipped with the  $L$ -band receivers, tuned in two bands centered at 1452 and 1860 MHz, respectively, each one with a bandwidth of 128 MHz split into 64 channels, with a frequency resolution of 2 MHz, in full polarization mode. The acquisition on CU Vir was alternated with those on the point-like source J1354-0206, used as phase calibrator, with a duty cycle of  $1^m30^s - 9^m30^s - 1^m30^s$ . The amplitude scale was determined by observations of the primary calibrator 3C286 ( $F_{1.4} = 14.58$ ,  $F_{1.8} = 12.9$  Jy). Data reduction and editing were performed by using the COMMON ASTRONOMY SOFTWARE APPLICATIONS package (CASA). Data inspection revealed much radio interference in both bands, occurring in certain blocks of time and of channels. Bad data have been edited first in the scans of the two calibrators. Bandpass correction has been eventually determined by using the visibilities of 3C286, then flux densities of J1354-0206 have been obtained ( $F_{1.4} = 774$ ,  $F_{1.8} = 854$  mJy). Complex gains have then been applied to the data of CU Vir which have been edited after calibration. Stokes  $I$  and  $V$  maps of the regions around the phase calibrator and the target have been obtained for the two days.

In order to get dynamical spectra of our target, visibilities of CU Vir have been imported into the ASTRONOMICAL IMAGE PROCESSING SYSTEM (AIPS), where the task DFTPL computes the direct Fourier transform at a given position in the sky as a function of time. Stokes  $V$  flux densities have been computed for all frequencies, with time and spectral resolution of 2 MHz and 4 minutes, respectively, giving an rms of about 1 mJy, as expected.

No Stokes  $I$  or  $V$  variability has been found for J1354-0206 or for the several sources close to CU Vir.

### 3. THE CYCLOTRON MASER

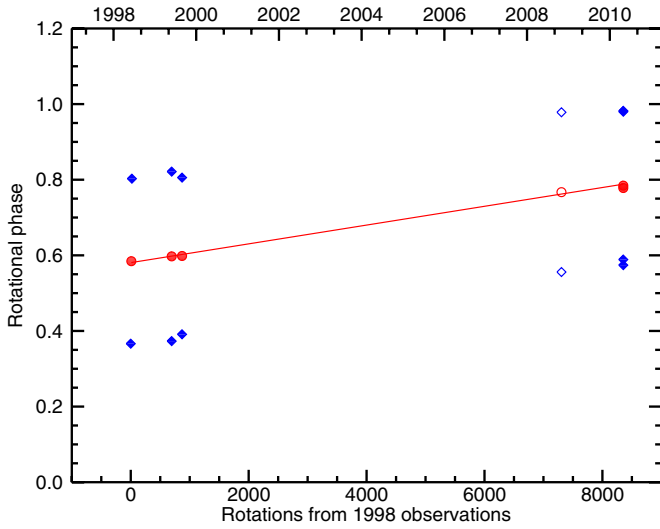
Dynamical spectra are shown in Figure 1. Heliocentric rotational phases, computed by using the ephemeris by Pyper et al. (1998), indicate that peak “a” of April 23 and “b” of April 30 occur at the same phase ( $\phi \approx 0.55$ ), when the star is oriented in space in the same way relative to the Earth. Figure 2 shows



**Figure 2.** Frequency average of the polarized emission as a function of the rotational phase for the two bands.

(A color version of this figure is available in the online journal.)

the polarized flux average in the two bands as a function of the rotational phase, stressing the coincidence in phase of “a” and “b” events and a significant level of variability between the two observations. All the three events last approximately 1 hr each; “c” exhibits a single peak of flux levels of about 20 mJy; “a” and “b” lower and broader emission, with two components in the “b” event. The phase difference between “a” (or “b”) and “c” events is about 0.4. This allows to recognize the same peaks of emission reported by Trigilio et al. (2000, 2008) and Ravi et al. (2010). The difference with the previous observations is the rotational phase of each peak, and not the difference of phase between them. The variability of the pulse shape, as well as the amplitude, could be due to some instability of the emission region, as proposed by Ravi et al. (2010). Many parameters enter in the growth rate  $\omega$  of the cyclotron maser (Mutel et al.



**Figure 3.** Phases of the peaks at the different epochs of observations, as a function of the number of rotations of the star from the first observation. Years are also shown at the top. The blue diamonds refer to the main emission beams, and red dots to the midpoints. From the slope of the linear fit the increment of the rotational period can be inferred.

(A color version of this figure is available in the online journal.)

2007) such as electron density, velocity distribution ( $f$ ) and its anisotropy ( $\partial f/\partial v_{\perp}$ ), plasma frequency ( $\nu_p$ ), and others. Since the growth rate is a nonlinear function of them, and the intensity of an unsaturated maser is  $I \propto \exp(\omega)$ , even a small variation of one of the above parameters can result in a significant variation of the emerging flux.

### 3.1. The Change of the Rotational Period

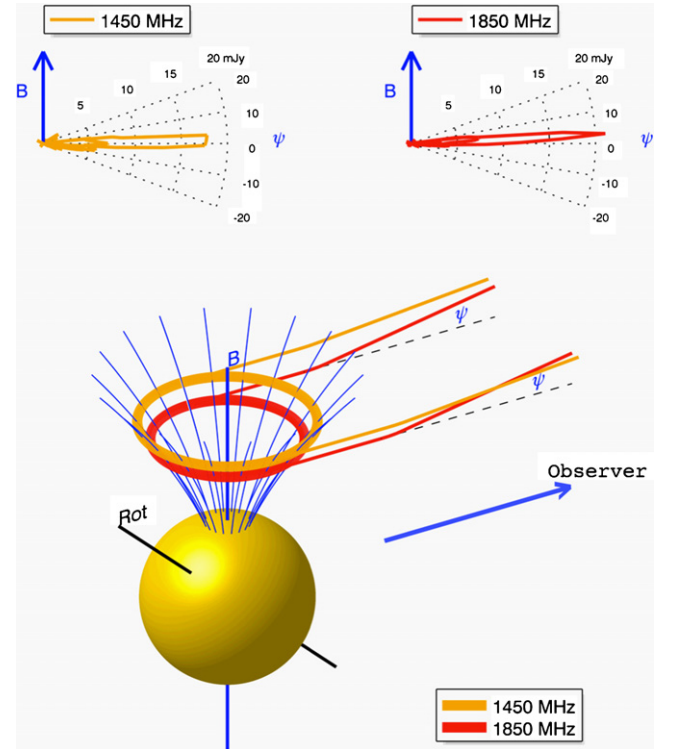
An abrupt period change of 2.18 s, occurring probably in 1985, has been claimed by Pyper et al. (1998) from the analysis of photometric data; a new spin-down of about 1 s has been inferred by Trigilio et al. (2008) from the phase shift of the coherent radio emission between 1998 and 1999. Now, with a new set of points after 12 years, and with the inclusion of the Ravi et al. (2010) results, the spin-down is confirmed and the increment of the rotational period  $\Delta P$  is determined with great accuracy by fitting the midpoints of the two peaks (circles and line in Figure 3):  $\Delta P = 1.12 \pm 0.03$  s. If we plot the phase of the peaks as a function of the epoch (Figure 3), we see that they appear with a regularly increasing delay, indicating that the rotational period of CU Vir has changed. Assuming that the change of period occurred close to the observations of 1998, we determine a new ephemeris of CU Vir:

$$\text{HJD} = 2450966.3601 + 0.52071601E$$

for  $\text{JD} > 2450966$ , nominally 1998 June. It is worthwhile to stress that this method of period determination gives a relative error of  $7 \times 10^{-7}$ .

### 3.2. The Direction of the Beams

After computing the actual rotational phases  $\phi$  with the new ephemeris, it is possible to get the orientation of the star and its magnetosphere, then the direction of emission with respect to the dipole axis. Assuming an inclination  $i = 43^\circ$  of the rotational axis and an obliquity  $\beta = 74^\circ$  of the magnetic axis (Trigilio et al. 2000), the angle  $\psi$  between the line of sight and



**Figure 4.** Top panel: polar diagrams of the pulses, showing their directivity. At 1450 MHz the emission is almost perpendicular to the magnetic axis  $B$ ; at 1850 MHz there is a deviation of about  $4^\circ$ . Bottom panel: picture of the proposed model: maser amplification occurs in annular rings around the pole, at a height determined by the gyrofrequency of the emitting electrons; the emission occurs tangentially, then refraction in the higher density region (the “cold torus” in the inner magnetosphere) deviates the radiation upward; this effect is greater at higher frequency. During the rotation, the pulses are observed from the Earth (supposed to be toward the right) two times, at slightly different moments at different frequencies.

(A color version of this figure is available in the online journal.)

the axis of the dipole is given by

$$\sin \psi = \sin \beta \sin i \cos(\phi - \phi_0) + \cos \beta \cos i;$$

here,  $\phi_0 = 0.08$  is the phase delay of the magnetic curve with respect to the light curve (Borra & Landstreet 1980). The maximum visibility of the North magnetic hemisphere is at  $\phi = 0.58$ , while at  $\phi = 0.38$  and  $0.78$  the magnetic axis lies in the plane of the sky.

By looking at the radio emission as a function of the inclination of the magnetic axis, we can see how it escapes from the emitting region, i.e., we can study its directivity. The direction of the emission beams at 1450 and 1850 MHz relative to the dipole axis is shown in Figure 4, top panel. Beams at higher frequency are emitted at  $\psi \approx 4^\circ$ , while those at lower frequency are emitted at  $\psi \approx 0^\circ$ , as the visibility of the peaks in Figure 1 indicates. The emitting beams subtend an angle  $\Delta\psi \lesssim 10^\circ$  HPBW.

The cyclotron maser hypothesis in CU Vir has already been proposed by Trigilio et al. (2000, 2008). To be possible, the emission must originate in a region of relatively strong magnetic field ( $\nu_B \gg \nu_p$ ), and the plasma density in the region above the magnetic pole must be relatively low. Following the ECME theory (Melrose & Dulk 1982), the direction of emission forms an angle  $\theta \lesssim 90^\circ$  ( $\cos \theta \approx v/c$ , where  $v$  is the upward velocity of the emitting electrons) to the magnetic field direction with an aperture ( $\Delta\theta \approx v/c$ ), forming a hollow cone. The



frequency of the radiation is  $\nu \gtrsim s \nu_B$ , where  $s$  is the harmonic number. It is probably the second harmonic which is the most efficient one, since emission at the first harmonic is subject to gyromagnetic absorption of nearby thermal plasma at  $s = 2$ , and for a higher harmonic number the maser has less efficient amplification. Assuming  $s = 2$ , the emission occurs where  $\nu = 2 \times 2.8B/G$  MHz. For our two observing frequencies of 1450 and 1850 MHz, the corresponding magnetic field is, respectively, 259 and 330 G and, with a polar field strength  $B_{\text{pol}} = 3000$  G, the observed emission arises, respectively, at  $R = 2.26$  and  $2.09 R_*$  from the center of the star.

There are however some problems with the hollow cone beaming model. In fact, if the emission arises from a ring around the polar axis and if the emission is in direction  $\theta \lesssim 90^\circ$ , we should observe much broader peaks, since the inclination of the magnetic field lines with respect to the line of sight changes in the emitting rings (see Figure 4 of Trigilio et al. 2008). So the open questions are:

- (1) why do we not observe broad peaks?
- (2) why does the angle of emission change with the frequency?

#### 4. “AURORAL” EMISSION

The cyclotron maser of CU Vir shares some characteristics with the radio emission from planets, suggesting a common scenario. There are five planets with magnetospheres in the solar system (Earth, Jupiter, Saturn, Uranus, and Neptune) known to show intense radio emission at low frequency (from 10 kHz up to few MHz), originating above the high magnetic latitude auroral regions (Zarka 1998). This emission is non-thermal, with high brightness temperature exceeding  $10^{15}$  K, 100% circularly polarized, highly beamed. All those characteristics indicate that the emission process is cyclotron maser. Except for the case of the Jovian decametric emission (DAM) at 10–40 MHz, which is due to the Io-magnetosphere interaction, the auroral emissions are controlled by the solar wind flowing into the open field lines above the polar caps. The analogy with CU Vir is unexpected, including the “pulsar-like” behavior due to the rotation of an oblique dipole axis.

Recent observations of the terrestrial Auroral Kilometric Radiation (AKR), performed with the four-spacecraft *Cluster* array, have allowed the location of the sources from which the emission originates (Mutel et al. 2003) and the determination of its angular beaming characteristics (Mutel et al. 2008). The emission seems to be the sum of several elementary bursts of radiation generated at a height where the gyrofrequency of the electrons corresponds to the magnetic field (at  $0.5$ – $2 R_\oplus$ ), in a ring around the magnetic axis where the density is very low (the so-called auroral cavity). Unlike the Jovian DAM, where the emission is beamed in a thin ( $\Delta\theta \approx 1^\circ$ ) hollow cone of half-angle  $\theta \lesssim 90^\circ$  (Dulk 1970), the AKR is radiated within  $\pm 15^\circ$  from the “plane tangent to the source’s magnetic latitude circle and containing the local magnetic field vector” (Mutel et al. 2008; Louarn & Le Quéau 1996). The important point we want to stress is that the emission is emitted tangentially to the auroral ring.

During the propagation in the close ambient medium, the AKR is deviated upward because of the refractive index of the dense magnetospheric plasma.

##### 4.1. A New Model for CU Vir

The results of AKR suggest that the ECME of CU Vir could come from the same geometry. We propose a new scenario,

where the masing emission does not follow the “hollow cone model,” but instead the “tangent plane beaming model.” Figure 4 shows a sketch of the cyclotron maser emission from CU Vir. Electrons traveling back from the acceleration region located at Alfvén radius  $R_{\text{Alf}} = 15R_*$  (Leto et al. 2006) emit at locations where the magnetic field strength corresponds to the first or second gyromagnetic harmonic ( $s = 1, 2$ ). These define annular rings above the magnetic pole. The amplification occurs tangentially, so that it is seen from Earth as coming from the two extreme points of the rings. They would be seen simultaneously at any frequency as the star rotates, in the absence of subsequent refraction.

Our three-dimensional model (Trigilio et al. 2004; Leto et al. 2006) foresees the existence of a cold torus around the magnetic equator. The absorption of this optically thick material can account for the rotational modulation of the continuous gyrosynchrotron emission, particularly in high frequency radiation ( $\nu > 15$  GHz), emitted exactly in the same region where the cyclotron maser originates. From the results of the simulation, the number density of the cold torus is  $N_{\text{torus}} \approx 10^9 \text{ cm}^{-3}$ , with a temperature  $T_{\text{torus}} \approx 10^4$  K.

We now consider the case of  $s = 2$  and will give some consideration for the case  $s = 1$ . During the propagation, the maser radiation crosses the torus. The plasma of the torus permeated by a magnetic field  $B \approx 260$  and  $330$  G (the levels of the propagation of the two frequency bands) has a refractive index in the extraordinary mode given by

$$n_{\text{refr}} \approx \sqrt{1 - \frac{v_p^2}{\nu(\nu - \nu_B)}}.$$

In the following, we will give an order-of-magnitude estimate of the deviation of the emission (angle  $\psi$ ) with respect to the original, horizontal, ray path. The refractive index inside the torus, assuming an average  $N_{\text{torus}}$  as above, but with higher density in the inner part, and the local field strength, can easily reach values of  $n_{\text{refr}} \approx 0.98$  and  $0.95$  for  $\nu = 1450$  and  $1850$  MHz, respectively. This means that the maximum deviation toward high values of the angle  $\psi$  occurs at 1850 MHz, in agreement with our observations. The actual angle  $\psi$  can be obtained in a simple way from the Snell law if the angle of incidence with the interface between the two media at different refractive index, i.e., the surface defined by the field lines confining the cold torus, is known. In the case that this angle is  $60^\circ$ ,  $\psi \approx 10^\circ$  at 1850 MHz and  $\psi \approx 5^\circ$  at 1450 MHz, accounting for the observed difference (see Figure 4).

In the case  $s = 1$ , this simple computation foresees bigger deviations upward, not in agreement with the observations. However, a more detailed numerical computation is needed in order to better constrain the actual harmonic number  $s$  and get more precise indications on the physical conditions of the emitting plasma and of the surrounding region.

#### 5. CONCLUSION AND FUTURE PERSPECTIVE

The observations reported here of CU Vir confirm the presence of a steady cyclotron maser operating for over more than 10 years in the magnetosphere of this star. Our model proposes that the process is triggered by the continuous injection of high energy electrons flowing from the Alfvén region, about 15 stellar radii from the star, to the inner parts of the magnetosphere. Those electrons are also responsible for the gyrosynchrotron emission. The overall mechanism is powered by the radiation-driven wind interacting with the magnetic field.

The high temporal and spectral resolution of the current EVLA allowed us to get dynamical spectra over two broad spectral regions. The observations have been carried on two days, covering almost the whole rotational period of CU Vir. This allowed us to measure with great accuracy the delay of the peaks of emission, and to therefore determine with unprecedented precision ( $\approx 10^{-7}$ ) the rotational period of the star, confirming the spin-down of this young star. Further observations are needed in order to monitor the rotation of CU Vir, since the emission peaks are believed to be “perfect markers” of this stellar clock.

There is an impressive similarity between the cyclotron maser of CU Vir and the coherent radio emission from planets. The recent observations of the AKR from the terrestrial magnetosphere and the new interpretation on the basis of the “tangent plane beaming model” gave the opportunity to formulate a new model for CU Vir, where the emission is “auroral-type,” emitted tangentially to the auroral circles.

The analysis of the dynamical spectra permitted us to clearly see that the pulses occurred at slightly different times inside the frequency band. In the framework of the new model, this could be due to refractive effects due to the propagation of the radiation inside a denser magnetized plasma surrounding the star in the magnetic equatorial belt. This is a further indication of the existence of a “cold torus,” which also acts as an absorber of the gyrosynchrotron continuous emission at centimeter wavelengths.

In the near future the EVLA will increase its maximum bandwidth up to 2 GHz. This will allow us to extend the dynamical spectra in a broader spectral region and to better define the low and high limits of the cyclotron maser. The time visibility of the peaks as a function of the frequency will allow us to study and model with great precision the propagation of the radiation in the magnetospheric plasma surrounding the

star. CU Vir is an excellent astrophysical laboratory for plasma physics in stellar and planetary environment.

We thank the NRAO scheduler who coordinated the times of the two observations to cover almost the whole rotational period of CU Vir. The EVLA is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc. under cooperative agreement with the National Science Foundation.

*Facility:* EVLA.

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