

# Extending the radio spectrum of magnetic chemically peculiar stars to the mm range<sup>★</sup>

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**Abstract.** Magnetic chemically peculiar (MCP) stars can present radio emission at centimetre wavelengths. The steep decrement of the dominant dipolar component of the photospheric magnetic field results in each radio frequency being mainly emitted in a well localised shell of the circumstellar region. To explore the most internal regions of the magnetosphere, observations of a sample of eleven MCP stars known to be radio sources in the 1.4–22.5 GHz range were carried out at 87.7 GHz with the IRAM interferometer. Millimeter emission, with a flux density at about 4× the sensitivity limit of our observations, was detected towards two of the stars: HD 35298 and HD 124224.

Combining our mm-observations with previous cm-observations, it appears that MCP stars with a relatively *weak* magnetic field present a radio spectrum that increases with frequency up to 22.5 GHz and then decreases towards the mm range. In presence of *strong* fields, the radio spectrum is always decreasing with frequency.

A comparison of the observed cm-mm spectrum of HD 124224 with results of numerical simulations of the gyrosynchrotron emission suggests that circumstellar regions emitting in the mm-range cannot present magnetic fields larger than 1–2 kG.

**Key words.** stars: chemically peculiar – stars: individual: HD 35298, HD 124224 – stars: circumstellar matter – stars: magnetic field – radio continuum: stars

## 1. Introduction

Magnetic Chemically Peculiar (MCP) stars can be radio sources in the centimetre range (Cassinelli 1984). Based on the low expected mass-loss rates, Drake et al. (1987) ruled out free-free emission from the stellar wind and related the radio emission to the presence of magnetic fields. Linsky et al. (1992) suggested that the radio emission is due to optically-thick gyrosynchrotron emission from non-thermal electrons. The photospheric magnetic field of MCP stars is mainly dipolar with a polar strength of a few kG. As a result of the steep drop of the magnetic field strength with distance from the star, each observed radio frequency is mainly emitted in a well localised circumstellar shell, with the highest frequencies coming from the inner magnetosphere.

With the aim of studying the properties of the radio emitting regions, particularly the innermost regions, we have carried out observations at 87.7 GHz with the IRAM interferometer of a sample of MCP stars. This attempt follows

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SEST observations at 230 GHz carried out in 1993 (Leone et al. 1996) on HD 124224, HD 142301 and HD 171247 when only upper limits, 2–3 times larger than the 5 GHz flux, could be determined.

## 2. IRAM observations and data reduction

Eleven MCP stars known to be radio sources in the centimetre range (Table 1) were observed with the IRAM interferometer (Guilloteau et al. 1992) from May to December 1997 at 87.7 GHz. Visibilities were obtained for the most part with four antennas in the CD set of configurations. The cross-correlator was adjusted to a contiguous bandwidth of 450 MHz. All the observations were performed using on-source integration times of 20 min interlaced with 4 min integrations of nearby quasars in order to calibrate instrumental amplitude and phase. For each star, the distance between the adopted coordinates (Table 1) for pointing and the values listed in the Hipparcos or Tycho catalogue (ESA 1997), after the correction for proper motions, is smaller than 20% of the beam-size.

Data calibration was carried out in the standard antenna-based manner. Only visibilities with error  $\leq 40$  degrees were

**Table 1.** List of the magnetic chemically peculiar stars (HD number) observed with the IRAM interferometer at 87.7 GHz. We report the coordinates adopted for pointing, the measured flux densities at the Hipparcos or Tycho position and the associated error (rms of the real part of visibilities). If available, the polar value ( $B_p$ ) of the magnetic dipole is also quoted. Only HD 35298 and HD 124224 present flux densities in the mm-range about at four times the noise level.

Star HD	$\alpha$ (2000) hh : mm : ss	$\delta$ hh : mm : ss	Flux [mJy]	rms [mJy]	$B_p$ kG
35298	05:23:50.367	+02:04:55.70	<b>1.61</b>	0.43	
36485	05:32:00.380	-00 : 17 : 04.30	0.79	0.41	
37017	05:35:21.872	-04 : 29 : 39.09	0.28	0.39	6.8 <sup>a</sup>
37479	05:38:47.060	-02 : 35 : 38.90	1.03	0.38	7.7 <sup>a</sup>
37808	05:40:46.134	-10 : 24 : 32.66	0.36	0.29	
124224	14:12:15.807	+02:24:33.91	<b>1.32</b>	0.31	4.5 <sup>b</sup>
142301	15:54:39.557	-25 : 14 : 37.36	1.28	0.67	14.7 <sup>c</sup>
142990	15:58:34.80	-24 : 49 : 51.7	-0.54	0.71	5.0 <sup>d</sup>
144334	16:06:06.396	-23 : 36 : 23.04	0.92	0.97	
171247	18:33:23.270	+08:16:05.40	0.03	0.29	
215441	22:44:07.370	+55:35:21.20	0.34	0.17	62.4 <sup>e</sup>

<sup>a</sup> Leone (1991).

<sup>b</sup> Triglio et al. (2000).

<sup>c</sup> Landstreet et al. (1979).

<sup>d</sup> Bohlender et al. (1993).

<sup>e</sup> Landstreet & Mathys (2000).

retained to estimate the flux density in the millimetre continuum. The absolute flux density scale was based on the radio-star MWC 349 (0.95 Jy at 87.7 GHz). When MWC 349 was not available, the scale was bootstrapped using a set of strong quasars whose flux densities are monitored regularly at Plateau de Bure. Globally, the flux density scale is estimated to be accurate to about 10% for each epoch. The receiver passband shape was determined on 3C273 and was estimated with sufficient accuracy ( $\leq 1\%$ ).

Table 2 provides the details of the chronological logbook of the interferometric observations: number of antennas, minimum and maximum baseline and the Equivalent On-source Integration Time (EOIT) for an equivalent two-antenna array.

Of the observed stars, only HD 35298 and HD 124224 exhibit flux densities at about four times the noise level:  $1.61 \pm 0.43$  and  $1.32 \pm 0.31$  mJy, respectively. Errors are estimated as the rms of the real part of visibilities. For these two stars, Fig. 1 shows the obtained maps with the synthesized beams.

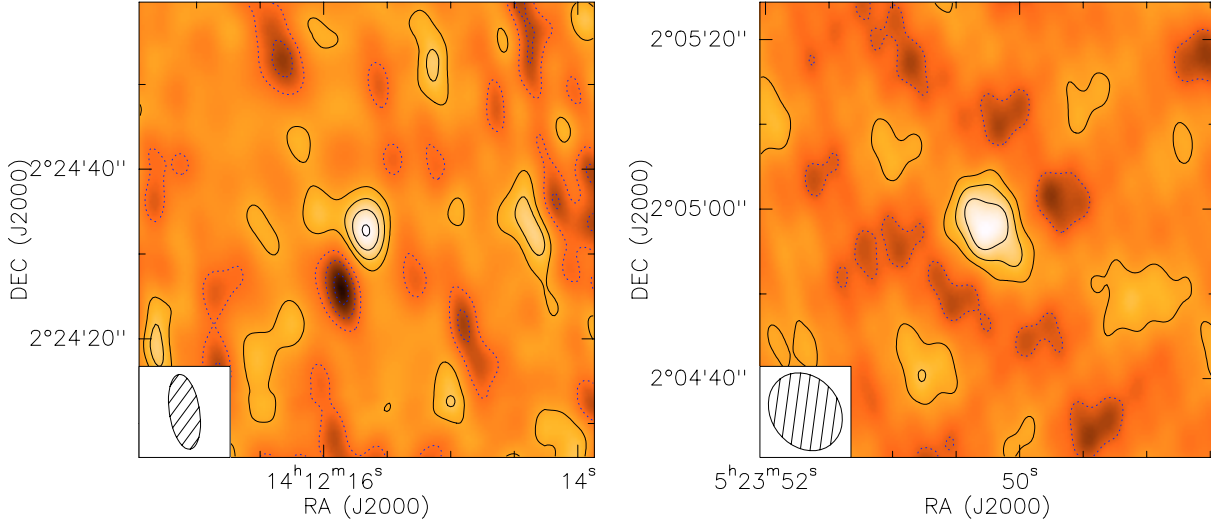
As to the undetected stars, Table 1 reports the measured fluxes at the Hipparcos or Tycho positions and the rms of the real part of visibilities.

In the gyrosynchrotron radiation model, frequency is proportional to the magnetic field strength, so that the highest observable frequency depends on the field strength at the stellar surface (Table 1). We focused our attention on HD 215441, the MCP star with the strongest known magnetic field. Landstreet & Mathys (2000) modelled its field variation with the

**Table 2.** Log of IRAM 1997 observations. For each date, we report the number of antenna used ( $N$ ), the minimum and maximum baseline (rounded to 5 m), the observed stars (HD number) and the equivalent on-source integration time (EOIT) for an equivalent two-antenna array.

Date	$N$	Min & max baseline (m)	Star HD	EOIT (h)		
May	15	4	15–140	124224	14.0	
	16	4	15–175	171247	31.5	
June			215441	10.7		
	17	5	20–175	215441	20.0	
	21	5	25–175	142301	11.3	
	7	5	20–225	215441	9.9	
	8	5	20–270	171247	8.7	
July			215441	16.6		
	10	4	20–165	215441	3.3	
	13	3	30–65	171247	8.0	
			215441	12.0		
	25	3	20–45	215441	2.0	
	28	3	15–45	215441	6.0	
	1	4	15–50	215441	16.0	
	6	4	15–65	124224	14.7	
			142301	7.0		
			144334	4.3		
Aug.			142990	8.0		
	19	4	50–175	124224	10.7	
	21	4	30–170	144334	2.0	
	24	4	30–175	142990	8.0	
			215441	21.3		
	13	4	40–175	171247	11.3	
	14	4	40–175	215441	16.0	
	21	3	105–140	36485	4.0	
	Sep.	18	4	15–45	124224	4.2
	Oct.	2	4	15–65	35298	2.4
				36485	8.0	
				37017	8.0	
			37479	8.0		
			37808	8.0		
		4	4	15–60	35298	5.4
			37808	8.0		
10		4	15–290	35298	2.0	
			36485	3.3		
			37017	0.7		
			37479	1.3		
			37808	2.0		
		22	4	30–180	37017	4.0
		37479	2.0			
		37808	2.4			
Nov.	30	5	20–65	35298	13.3	
Dec.	8	4	15–70	36485	8.0	
			37017	8.0		
			37479	8.0		
			37808	8.0		
		10	4	20–60	215441	8.0

rotational period under the assumption of an axisymmetric multipole expansion up to the octupole term and with dipole, quadrupole and octupole strengths equal to +62.4, -42.0 and +24.2 kG, respectively. Despite its very strong magnetic



**Fig. 1.** HD 124224 (left panel) and HD 35298 (right panel) were detected with  $\sim 4\sigma$  in a beam of  $8.9'' \times 3.6''$  at PA =  $9^\circ$  and  $9.1'' \times 8.1''$  at PA =  $37^\circ$ , respectively (shown as dashed areas). Contours start at  $1\sigma$  and are in steps of  $\sigma = 0.43$  mJy for HD 35298 and  $\sigma = 0.31$  mJy for HD 124224.

field and EOIT in excess of 140 h, no emission could be detected from HD 215441.

### 3. Proposed mechanisms for the radio emission

The photospheric magnetic field of MCP stars is mainly dipolar, even if higher multipoles can be important (Landstreet & Mathys 2000). In the circumstellar regions, the dipolar component is dominant.

Drake et al. (1987) proposed that the radio emission from MCP stars is gyrosynchrotron emission from mildly relativistic electrons trapped in a belt surrounding the equator of the magnetic dipole. In the case of HD 37017 and HD 37479 the dimension of the magnetic cavity is  $2 \leq R/R_\star \leq 10$ . André et al. (1988) noted that the characteristics of the magnetosphere of MCP stars, as quantified by Havnes & Goertz (1984), are not compatible with the emission model suggested by Drake and co-workers. André and co-workers suggested that the stellar wind, flowing along the field lines, draws these into current sheets, where electrons can be accelerated up to relativistic energies. Gyrosynchrotron emission is due to non-thermal electrons (whose energy distribution is  $N(E) \propto E^{-\delta}$ ) located far from the star where the magnetic field is 10–100 G. Thus for a 10 kG polar value of a magnetic dipole, the emitting region is located at  $\sim 10 R_\star$ . Adopting the previous scenario, Linsky et al. (1992) modelled the radio emission from HD 37479 assuming non-thermal electrons with a constant density and  $\delta = 2$ . The disks with area equal to the emitting regions at 5 and 1.4 GHz have radii equal to 3 and  $8 R_\star$ , respectively.

### 4. Numerical simulations of the high frequency emitting regions

We have computed the radio fluxes in the 1–90 GHz range, on the basis of a detailed theory of gyrosynchrotron emission and absorption (Ramaty 1969). For our computations, we have considered homogeneous emitting regions with magnetic

field  $B = 1, 2, 5$  and  $7$  kG whose inclination angle with respect to the line of sight is  $\theta = 20^\circ, 45^\circ$  and  $80^\circ$ ; electron energy distribution with exponent  $\delta = 1, 2, 3$  and  $4$ ; thermal electron density  $N_{\text{Th}} = 10^8 \text{ cm}^{-3}$ ; thickness of the emitting region  $L$  equal to 0.01 and 0.001 solar radii.

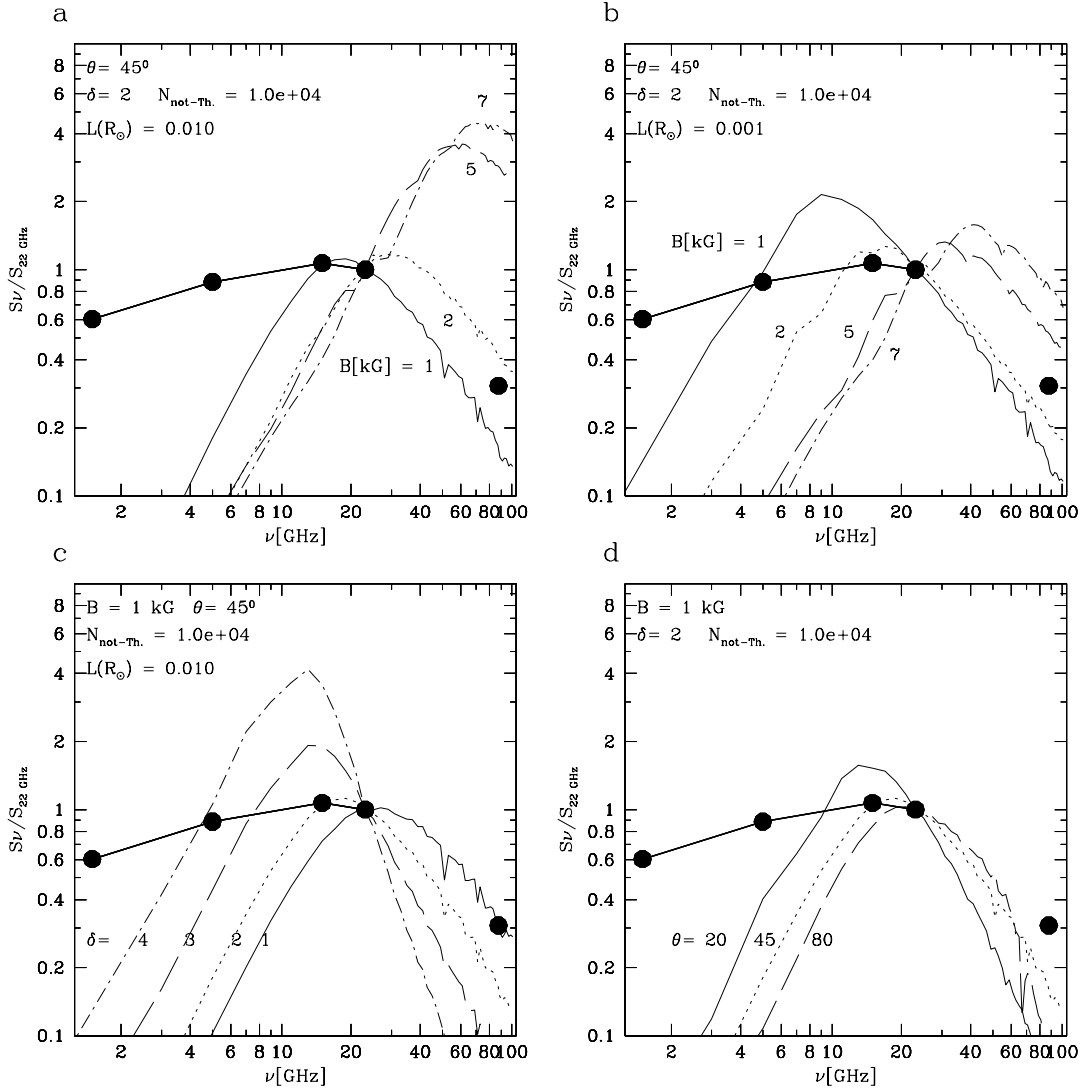
Figure 2 shows the computed radio spectra normalised to the 22.5 GHz value. For comparison, the spectrum of HD 124224, our best observed target, is also shown in this figure.

From the observed ratio between the radio fluxes at 87.7 GHz and 22.5 GHz, we conclude that circumstellar regions, close to HD 124224 where the field assumes several kG values, cannot be responsible for gyrosynchrotron emission. Panels a and b of Fig. 2 show that the radio emitting region cannot have a magnetic field larger than  $\sim 2$  kG. From the observed radio spectra, we note that the  $N_{\text{non-Th}} \times L$  cannot be much smaller than  $\sim 10^{13} \text{ cm}^{-2}$  and  $\delta < 3$  (Figs. 2a–c). Our results are not significantly dependent on the angle between the line of sight and the magnetic field (Fig. 2d).

### 5. Radio spectrum

Assuming an upper limit for the millimetre emission equal to  $4\sigma$ , Fig. 3 shows the observed spectra for those stars with complete 1.4–87.7 GHz coverage (VLA observations are from Leone et al. 1996). HD 124224, HD 37017 and HD 37479, which are MCP stars with relatively weak magnetic fields (Table 1), have positive spectral index  $\alpha$  ( $S_\nu \propto \nu^\alpha$ ) up to 22.5 GHz beyond which there is a drop in the flux. HD 142301 and HD 215441, with much stronger magnetic fields, are characterised by negative spectral index up to 15 GHz and were not detected at 22.5 GHz. The sharp decrement of the radio flux in a so small frequency interval could be indicative of a *cut-off* frequency.

Only two measurements of the 5 GHz flux density are reported by Linsky et al. (1992) for HD 35298:  $0.28 \pm 0.06$  and  $< 0.19$  mJy. Unfortunately, only an average value for a set



**Fig. 2.** Emerging flux distributions from a homogeneous source as computed for  $B = 1, 2, 5$  and  $7$  kG;  $\delta = 1, 2, 3$  and  $4$ ;  $\theta = 20, 45$  and  $80^\circ$ ; non-thermal electron density  $N_{\text{non-Th}} = 10^4 \text{ cm}^{-3}$ ; thickness of the emitting region equal to  $L = 0.01$  and  $0.001$  solar radii. Dots are flux densities observed towards HD 124224 in the cm range by Leone et al. (1996) plus the here measured  $87.7$  GHz flux.

of five measurements of the effective field is available in the literature:  $2.3 \pm 0.4$  kG (Borra 1981) and we therefore cannot estimate the polar value of the field for this MCP star. For this reason, the behaviour of this MCP star, whose radio spectrum seems to be the only one increasing from the cm ( $S_{5 \text{ GHz}} = 0.28$  mJy) up to the mm ( $S_{87.7 \text{ GHz}} = 1.61$  mJy), cannot be related to its surface magnetic field strength.

In the framework of the Linsky et al. model, the gyrosynchrotron radiation at frequency  $\nu$  is emitted from two optically-thick tori located symmetrically above the magnetic poles. Frequency and field strength are related by  $B_\nu \propto \nu/s$  ( $s$  is the harmonic number) and the dipolar component of magnetic field (which dominates far from the star) decreases as  $B \propto B_p r^{-3}$ , with  $B_p$  polar magnetic field and  $r$  the distance from the star in stellar radii units. The emerging flux is given by

$$S_\nu \propto \Omega_\nu I_\nu,$$

where  $\Omega_\nu$  is the solid angle subtended by the emitting region and  $I_\nu$  is the specific intensity. Pole-on projections of the

emitting regions show up as circular shell with radius  $r_\nu \propto [B_p/\nu]^{1/3}$  and thickness  $\Delta r \propto r\Delta B/B$ , hence

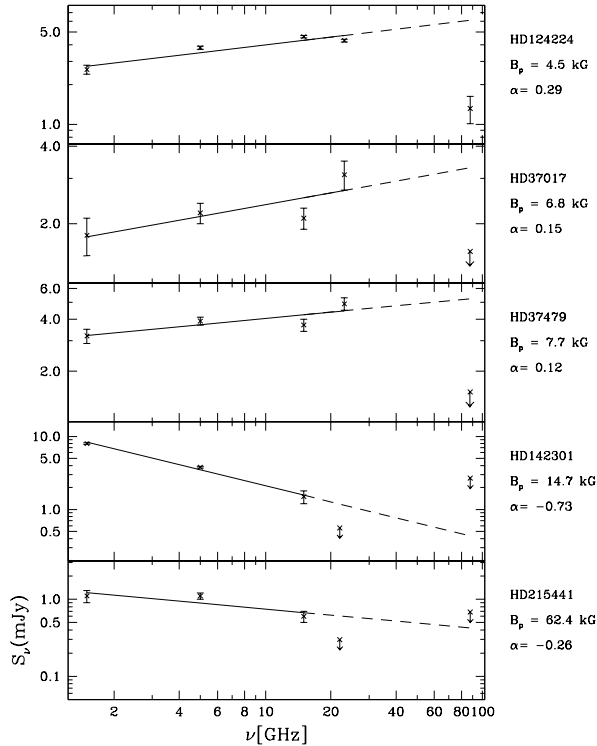
$$S_\nu \propto r_\nu^2 I_\nu \propto B_p^{2/3} \nu^{-2/3} I_\nu.$$

Since in the optically-thick approximation the specific intensity depends only on the frequency, the spectral index does not depend on the dipole strength. We conclude that the observed behaviour of the radio spectra is not consistent with the hypothesis of an optically thick region.

## 6. Conclusions

We have performed observations at  $87.7$  GHz with the IRAM interferometer on a sample of eleven MCP stars that have been previously observed with the VLA in the cm-range. Only two of these stars, namely HD 35298 and HD 124224, yielded a detection ( $\sim 4\sigma$ ) at mm-wavelengths.

Whenever possible, we have combined VLA and IRAM observations to cover the  $1.4$ – $87.7$  GHz range and found that



**Fig. 3.** Spectral energy distribution at 1.4, 5, 15, 22.5 and 87.7 GHz for those stars with a complete VLA spectrum. The continuous line is a linear fit, with spectral index  $\alpha$ , of the centimetre emission in the log-log plane. The dashed line is its extrapolation toward the mm-range. Arrows represent upper limits for the observed flux densities and are defined as four time the rms listed in Table 1. Stars show an inversion of  $\alpha$  when plotted for increasing value of the magnetic field from the top to the bottom.

the flux densities of the MCP stars HD 37017, HD 37479 and HD 124224, with relatively weak magnetic fields, increase with the frequency, up to a  $\nu > 22.5$  GHz, and then decrease in the mm range. On the other hand, the radio emission from HD 142301 decreases steadily with frequency. Only HD 215441 shows an almost flat spectrum between 1.4 and 15 GHz and no emission at the highest frequencies.

The radio spectra of HD 142301 and HD 215441 (with the strongest magnetic fields) exhibit a sharp drop in flux density between 15 and 22.5 GHz which suggests there is a *cut-off* frequency in this range. On the other hand, the MCP stars with relatively weak magnetic fields show flux densities that certainly decrease from the cm to the mm range. However, it is not clear if the spectra have a smooth decrement, as it is for HD 215441 at about 5 GHz, or also a *cut-off*.

Further observations of HD 37017, HD 37479 and HD 124224 are necessary in the 22.5–87.7 GHz range to establish the presence of a possible *cut-off* frequency.

Also HD 35298 should be observed in the 5–87.7 GHz range to ascertain if its spectrum is really increasing from the cm to the mm range. A determination of its photospheric magnetic field is also necessary to verify the apparent anti-correlation between slope of the radio spectrum and photospheric magnetic field strength.

Numerical simulations based on the exact emission and absorption coefficients by Ramaty (1969) for the gyrosynchrotron emission show that the ratio between the 22.5 and 87.7 GHz fluxes of HD 124224 is indicative of emitting regions where the magnetic field is less than a few kG.

To explain the observed centimetre radio emission, it has been suggested that non-thermal electrons are created where the stellar wind draws the field lines into current sheets and that these electrons travel toward the star and emit gyrosynchrotron radiation. Because of the sharp decrease in the strength of a dipolar field with stellar distance, any frequency would be mainly emitted in a well localised torus above the magnetic poles. However, the observed slopes of the radio spectra and the absence of the millimetre emission are not compatible with this model. The sharp drop seen in the radio spectra of HD 142301 and HD 215441 beyond 15 GHz is particularly difficult to explain.

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