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VLA observation of dMe stars

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Abstract. We present new VLA radio observations of a sample of dMe stars in X, U, K, and Q bands (from 8.4 to 43 GHz) obtained during an observing campaign in 1996 April-June. The aim of the project was to determine the spectral energy distributions of late-type dwarf flare stars to investigate the possible existence of an inversion of the spectrum slope at frequencies higher than 8 GHz. We also tried to constrain the possible emission mechanism at radio frequencies. We have detections in X band (8.4 GHz), for three sources (UV Cet, V 1054 Oph, and EV Lac), while all of our other measurements are upper limits. We discuss how the weak radio emission of some sources (e.g. AU Mic) and the coronal plasma properties deduced from X-ray observations constrain the coronal magnetic field properties.

Key words: stars: activity – stars: coronae – stars: late-type – stars: variables: general – radio continuum: stars

1. Introduction

Late-type dwarf flare stars have been widely observed in the radio domain during both flares and quiescence (see White et al. 1989 for a VLA survey of nearby flare stars). However, only few radio spectra of the quiescent emission have been obtained up to now. Quiescent radio emission from cool main-sequence stars is usually interpreted as gyrosynchrotron emission from mildly relativistic electrons (Gary & Linsky 1981, Güdel & Benz 1989, Linsky 1996). This interpretation is compatible with a spectrum that decreases to higher frequencies. However, some spectra show a U-shaped behaviour; the flux decreases with frequency until 5–8 GHz, then increases to higher frequencies.

For example, Güdel & Benz (1989) measured the spectrum of UV Cet from 0.33 to 22 GHz, and found that the flux decreased from 0.33 to 8 GHz and rose from 15 to 22 GHz. They interpreted the observed spectrum as consisting of a nonthermal component (gyrosynchrotron emission) dominant at low frequencies, and gyroresonance emission from the hot component of the corona plasma (detected in X-ray observations), which is dominant at the higher frequencies. This scenario may be appropriate only for some stars and only occasionally. In fact, White et al. (1994) showed that the observed 15 GHz fluxes of a sample of dMe stars, whose X-ray observations reveal the presence of a hot plasma component, are too low for the hot plasma to be cospatial with strong magnetic fields. Therefore, the plasma predominantly resides in weaker magnetic fields, perhaps higher in the corona.

The aim of the present work is to investigate the spectral energy distributions (SED) of active M dwarf stars in the frequency range between 8 and 43 GHz (35 to 7 mm), where U-shaped spectra of UV Cet and perhaps other dMe stars show the inversion of the spectrum slope, in order to constrain the possible emission mechanism in this radio frequency interval. Such constraints are also needed to understand the possible source of the millimeter and far infrared excess that have been reported for some M dwarfs by Mathioudakis & Doyle (1991, 1993). In fact, our working hypothesis was that the inversion of the spectrum at high frequencies could be due to the same cause responsible of the millimeter and far infrared excess. For this reason we selected a sample of targets for which an IR excess is suggested by published IRAS data and/or millimeter observations. The observations we report in this article were also planned to complement infrared observations by the Infrared Satellite Observatory (ISO) in the range 1–200 μ (Rodonò et al. 1999).

The outline of the paper is as follows: in Sect. 2 the observations and data reduction are presented, in Sect. 3 and 4 the results are given and discussed, and in the Sect. 5 we summarize our conclusions.

2. Observations and data reduction

With the VLA we observed a sample of 5 well known late-type dwarf flare stars in 4 different radio bands: X (8.42 GHz, 3.5 cm), U (14.96 GHz, 2 cm), K (22.48 GHz, 1.3 cm), and Q (43.31 GHz, 7 mm).

The sample stars were selected from the dMe stars with infrared excesses found by the Infrared Astronomical Satellite (IRAS) (Mathioudakis & Doyle 1993), and for which ISO observations in the range 1–200 μ were planned. In Table 1 we list some properties of the selected stars.

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Table 1. The dMe sample list.

Star	Sp	parallax mas	d pc	R/R$_\odot$	Coordinates [a] RA(h m s)	Dec(° ’ ”)	log L_X [erg s^{-1}] [b] min	max
GJ 65AB (UV Cet)	dM5.5	381±6 [c]	2.62	0.18[d]	01 39 01	−17 57 00	27.31 [e]	27.76 [f]
GJ 644 (V1054 Oph)	dM3	174.22±3.90 [g]	5.74	0.678[i]	16 55 28.76	−08 20 10.8	28.64 [e]	29.03 [f]
GJ 752A (V1428 Aql)	dM3.5	170.25±1.37 [g]	5.87	0.546[l]	19 16 55.26	+05 10 08.1	26.74 [e]	-
GJ 752B (V1298 Aql)	dM8	”	”	0.16[d]	19 16 58.10	+05 09 11.1	<25.77 [i]	-
GJ 803 (AU Mic)	dM0	100.59±1.35 [g]	9.94	0.59[m]	20 45 09.53	−31 20 27.2	29.43 [f]	29.97 [f]
GJ 873 (EV Lac)	dM3.5	198.07±2.05 [g]	5.05	0.41[n]	22 46 49.73	+44 20 02.4	28.52 [n]	28.68 [e]

[a] FK5 2000.0/2000.0, [b] X-ray luminosities corrected to the adopted distances, [c] Harrington et al. (1980),
[d] Rodonò (1992), [e] Schmitt et al. (1995), [f] Pallavicini et al. (1990),
[g] Perryman et al. (1997), [h] Hünsch et al. (1999), [i] Giampapa et al. (1996),
[l] Linsky et al. (1995), [m] Pagano et al. (2000), [n] Sciortino et al. (1999)

Table 2. VLA observation log of the dMe sample.

Star	Date (1996)	JD	IAT [a] start	IAT end	On source time (min) X	U	K	Q
GJ 65AB (UV Cet)	April 09	2450183.	17:09:30	19:58:00	29	40	40	106
GJ 644 (V1054 Oph)	June 26	2450260.	03:00:00	05:52:40	22	35	40	93
GJ 752A (V1428 Aql) [b]	April 28	2450202.	12:52:20	15:14:00	20	30	32	92
GJ 803 (AU Mic)	April 01	2450175.	14:14:50	17:25:50	30	40	42	115
GJ 873 (EV Lac)	April 11	2450185.	16:57:40	19:20:20	18	28	34	99

[a] International Atomic Time,
[b] GJ 752B (V1298 Aql) is also in the field.

In order to obtain multiband observations, we did split the VLA array into two sub-arrays. The first sub-array included all of the available antennas equipped with Q-band receivers (13), while the other 14 antennas were observing, alternatively, at the remaining microwave frequencies (X, U, and K bands). X-band observations of the calibrators were also done with the first sub-array for reference pointing in order to achieve an adequate pointing precision for the Q-band observations.

Our observations were carried out in C→D moving configuration, but most of the antennas were in the C configuration. As the primary flux calibrator we chose 0137+331. The phase calibrators were chosen within a few degrees of the target sources. In some cases it was necessary to chose different phase calibrators, depending on the band, for the same source.

The maximum allowed bandwidth (50 MHz) was used for each of the two observing frequencies inside the bands, so that a total of 100 MHz bandwidth was reached. Table 2 lists the complete schedule of observations.

The data were reduced using the Astronomical Image Processing System (AIPS), release 15APR1998[1]. Since we were looking for point sources, we chose to clean the maps using the Cotton-Schwab algorithm.

Due to the moving configuration, the original antenna positions included in the UV data files were sometimes wrong. Better antenna positions were constrained using the values available at the VLA WWW site. However, even though the quality of the maps was improved by better antenna positionings, the final noise level is sometimes affected by this problem.

The UV Cet data from the primary calibrator in the X-band were lost. In this case we have assumed for the phase calibrator the flux density listed in the VLA calibrators manual. We are confident that this assumption did not significantly affect the accuracy of the results, because in the other bands the phase calibrator fluxes determined from the measured fluxes of the primary calibrator are in agreement with the tabulated values.

The rms noise level was evaluated for every map in a region as large as possible where no sources were evident.

3. Results

Our working hypothesis was that the inversion of the spectrum at high frequencies observed for some dMe stars (Güdel & Benz 1996) is due to the same cause responsible for the millimeter and far infrared excess. We will address this point in a following paper on the related ISO observations. All the sources in our selected sample, except Gl 752AB, were detected by previous observations at one or more frequencies between 1.5 and 15 GHz (White et al. 1989, 1994). Therefore, the integration times (see Table 2) were selected to ensure detections if the sources had U-shaped radio spectra, as we expected on the basis of their millimeter and IR fluxes.

We obtained clear detections, however, only in the X-band and for three out of the five targets: GJ65AB (UV Cet), GJ 644

[1] AIPS is developed and supported by the National Radio Astronomy Observatory (NRAO)

Table 3. Observed fluxes and 3σ upper limits (in mJy).

Star	Observed fluxes X (8.4 GHz)	U (15 GHz)	K (22 GHz)	Q (43 GHz)	Predicted flux[a] X (8.4 GHz)	$T_B(R/R_\star)^2$ [b] (8.4 GHz)
GJ 65AB (UV Cet)	2.61±0.12	<0.70	<1.57	<0.95	0.14–0.39	$1.7\ 10^8$
GJ 644 (V1054 Oph)	1.39±0.06	<0.87	<1.53	<1.40	0.53–1.30	$3.1\ 10^7$
GJ 752A (V1428 Aql)	<0.14	<0.64	<1.27	<1.10	0.007	$<8.3\ 10^6$
GJ 752B (V1298 Aql)	”	”	”	”	0.001	$<9.7\ 10^7$
GJ 803 (AU Mic)	<0.22	<0.92	<1.75	<1.30	2.74–9.50	$<3.2\ 10^7$
GJ 873 (EV Lac)	0.63±0.11	<0.78	<1.24	<1.10	0.75–1.08	$3.0\ 10^7$

[a] From the range of X-ray luminosities, using the emipirical relation by Güdel et al. (1993) (see Sect. 5).
[b] $R/R_\star$ is the radius of the emitting region computed from the minimum X-ray flux. It is of the order of 1 (see Benz et al. 1998).

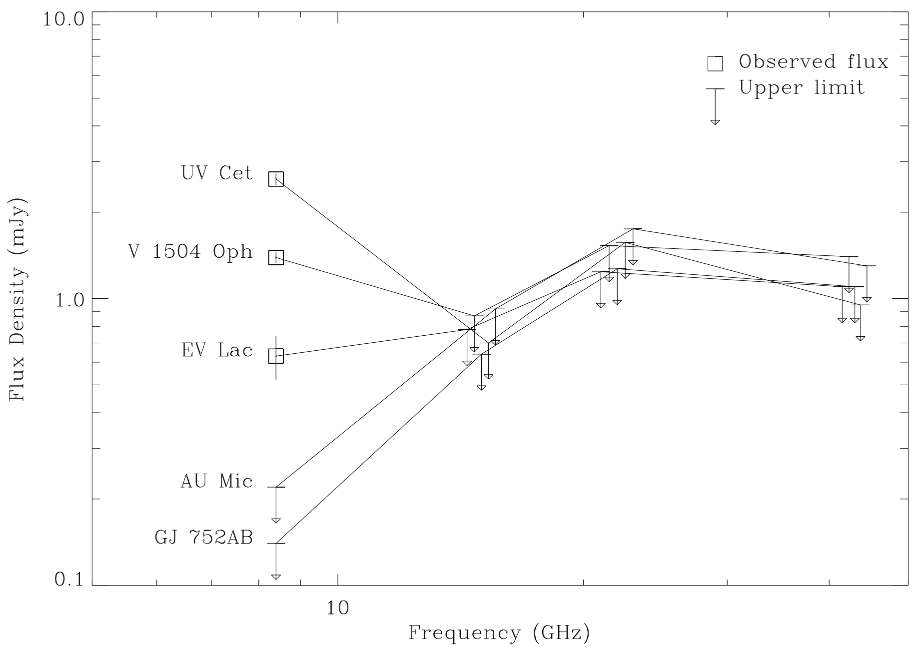

Fig. 1. Measured fluxes densities and upper limits versus frequency. The data at 15, 22, and 43 GHz are plotted with slight x-axis shifts for the sake of clarity.

(V1054 Oph), and GJ 873 (EV Lac). In all cases the coordinates of the detected radio sources agree with the Hipparcos coordinates to within the axes of the synthetic beams of the radio maps. For the other bands/sources we could determine flux upper limits (3σ). The results are summarized in Table 3 and plotted in Fig. 1.

GJ 65AB (UV Cet): This star was detected in X-band (8.4 GHz) at 2.61 mJy, that is more that 30 times the rms noise level. We have evaluated the map rms noise for the four bands to be 0.08, 0.23, 0.52, and 0.32 mJy/beam. Güdel & Benz (1996) report on eight observations of this source between 1987 and 1992 during which the source was always detected at 8.4, and 15 GHz with fluxes in the range 0.83–1.65 mJy and 0.47–1.62 mJy in the two bands, respectively, with a flux ratio f_{15}/f_8 varying from 0.44 to 1.46. Our observations indicate that in the X-band the source was definitely at a high level (2.61±0.12 mJy), while high X-band emission did not correspond to high emission in the U-band, as the flux ratio f_{15}/f_8 <0.44. Our 22 GHz flux density upper limit is below the detection at 1.85 mJy level found by Güdel & Benz (1989) for this source.

GJ 644 (V1054 Oph): We have a clear detection of V 1054 Oph only in the X band (1.4 mJy). Since the rms noise is 0.06 mJy/beam, the detection is at more than the 20σ level. The rms noise levels in the other bands are 0.29, 0.51, and 0.45 mJy/beam. In the X band, the source was fitted using the AIPS "imfit" task and was unresolved. In the X-band GJ 644 is about 5 times brighter than observed by Güdel et al. (1993). This star was detected at 15 GHz (Wendker 1995) at about 1.45 mJy, which is above our flux density upper limit at this frequency.

GJ 752AB (V1428 Aql, V1298 Aql): Neither of the two stars of the GJ 752AB binary system were detected. The rms noise levels are 0.05, 0.21, 0.42, and 0.37 mJy/beam for the four maps. As far as we know this star has never been detected in the radio domain. Krishnamurthi et al. (1999) determined an upper limit of 0.08 mJy at 8.4 GHz for GJ 752AB.

GJ 803 (AU Mic): The source was undetected in all four bands in our observation. From the analysis of a large region in the map, we have evaluated rms noise of 0.07, 0.30, 0.58, and 0.43 mJy/beam respectively for X, U, K, and Q bands. AU Mic was observed at 15 GHz by Cox & Gibson (1985) five times dur-

Table 4. Plasma temperatures from X-ray data analysis in the literature.

Star	Cool Component T (10^6 K)	Cool Component VEM (10^{50} cm^{-3})	Hot Component T (10^6 K)	Hot Component VEM (10^{50} cm^{-3})	refs.
GJ 65AB (UV Cet)	2.2	0.343	22.4	1.	a
GJ 644 (V1054 Oph)	1.97	49.	9.12	38.	b
G J 803 (AU Mic)	2.5	46.	20.	368.	a
GJ 873 (EV Lac)	7.8	184.	36.	106.	c

[a] Schmitt et al. (1990),
[b] Giampapa et al. (1996),
[c] Sciortino et al. (1999)

ing a 14 day period in 1983. The flux was 1.1±0.1 mJy steady over the observing period. However, White et al. (1994) did not detect AU Mic at 8 and 15 GHz during a HST campaign for this star in September 1991, with upper limits of 0.12 and 0.21 mJy, respectively, therefore at 15 GHz this star is certainly variable by at least a factor of 5.

GJ 873 (EV Lac): We have a clear 10σ detection of EV Lac in the X band (0.632 mJy) but no detections in the U, K, and Q bands. The rms noise levels are 0.06, 0.26, 0.41, and 0.37 mJy/beam. In the frequencies of our investigation, EV Lac was observed only once at 8.4 GHz, but it was not detected (Wendker 1995). White et al. (1989) reported a detection at 1.5 GHz, where flares are more commonly seen, while at 5 GHz, where quiescent emission is more easily observed, there are both detections and nondetections (Wendker 1995, White et al. 1989).

4. Discussion

We detected 8.4 GHz fluxes from three of the five stars in our sample, while all of the remaining measurements between 8.4 and 43 GHz are upper limits. How do the results of our radio observations compare with the coronal properties of these stars inferred from the X-ray observations? Güdel et al. (1993) found an empirical relation between the X-ray and radio luminosities of active stars: $log\, L_X \approx (1.06{\pm}0.10)\, log\, L_R{+}(14.52{\pm}1.31)$, where L_R is the radio flux at 3.6 or 6 cm (8.4 or 5 GHz). This relation is based on X-ray and radio observations for a broad range of spectral types including the M dwarfs. The ranges of X-ray luminosities observed for the stars in our sample are listed in Table 1. Table 3 lists the 8.4 GHz radio flux densities predicted by the Güdel et al. (1993) relation for the minimum and maximum observed X-ray luminosities. A comparison of the predicted and observed fluxes and upper limits indicates that only Gl 752AB should not have been detected. The 8.4 GHz fluxes of V1054 (GJ 644) and EV Lac (GJ 873) are consistent with the Güdel et al. (1993) relation, and the 8.4 GHz flux for UV Cet (GJ 65AB) is well above the prediction, presumably due to a flare. The nondetection of AU Mic (GJ 803) is surprising in the light of the empirical X-ray/radio relation. In fact, the Güdel et al. (1993) relation strongly implies that the quiescent microwave emission and the coronal heating (measured by X-rays) arise from a common source or a correlated set of sources. In this scenario AU Mic, which is the most luminous nondegenerate X-ray source within 10 pc (Wood et al. 1994) and has the very large radiative output of $\sim 10^{-2} L_{bol}$ from the transition region and corona (Pagano et al. 2000), should have an 8.4 GHz flux about 10 times larger than the measured upper limit.

The 8.4 GHz brightness temperatures at of the stars not detected at this frequency are very low (see Table 3), suggesting that the emission is not from nonthermal electrons but rather from thermal electrons, either free-free emission or gyroresonant emission from electrons in a coronal field (cf. Linsky 1996). Nevertheless, an optically thin high-frequency tail of the gyrosynchrotron spectrum is a viable alternative to the thermal emission process. In the following, we compare the 8.4 GHz observed fluxes or upper limits with the fluxes predicted by free-free and gyroresonant emissions from two-temperature coronal plasmas, under the assumption that all of the emission is thermal. Thus, the inferred magnetic fields and plasma volumes must be considered as maximum values since there may be a nonthermal contribution to the emission. In Table 4 we list the plasma temperatures and volume emission measures (VEM) from the literature. For GJ 752AB we have not found any X-ray spectral data analysis, therefore this source will not be further discussed.

4.1. Thermal Bremsstrahlung

The minimum flux density in the radio domain is due to thermal bremsstrahlung of the electrons in the same plasma that produces the thermal X-ray emission. Therefore, the radio flux densities due only to thermal bremsstrahlung must be less than or equal to our measurements and upper limits if the X-ray luminosity at the time of the VLA observations is similar to the minimum value of L_x listed in Table 1. To compute the flux densities expected only from thermal bremsstrahlung we follow the treatment of Gary & Linsky (1981), and Güdel & Benz (1989).

The optical depth due to a free-free process in the radio wavelengths range can be evaluated from:

$$\tau_{ff} = 2.1 \times 10^{-22}\, \frac{\lambda^2\, VEM}{2\,\pi\, R_S^2\, T^{3/2}}\,, \qquad (1)$$

where VEM $[cm^{-3}]$ is the Volume Emission Measure, T $[K]$ is the temperature derived from X-ray measurements, and R_S is the source radius measured from the center of the star.

Table 5. Expected flux densities in the 8.4–43 GHz range for thermal bremsstrahlung emission.

Star	Cool Component (mJy)	Hot Component (mJy)
GJ 65AB (UV Cet)	0.001	0.001
GJ 644 (V1054 Oph)	0.030	0.010
GJ 803 (AU Mic)	0.009	0.025
GJ 873 (EV Lac)	0.080	0.020

Using the plasma temperatures and the VEMs listed in Table 4, even assuming a compact radio source ($R_S = 1.1\,R_\star$), both plasma components are optically thin at all observed frequencies for all of the stars, with optical depths τ_{ff} ranging from 0.001 to 0.1.

For an optically thin corona the flux density due to free-free emission is:

$$S\,[mJy] = \frac{1}{10^{-26}}\,\frac{2\,k\,T}{c^2}\,\tau_{ff}\,\nu^2\,\pi\left(\frac{R_S}{d}\right)^2, \tag{2}$$

where k is the Boltzmann constant, c the light speed, ν is the frequency in Hz, and d the stellar distance.

Because τ_{ff} is proportional to ν^{-2}, S is independent of ν. The resulting flux densities (see Table 5) are lower than the observed fluxes and upper limits. If the radio source is greatly extended, the emission is still optically thin and the predicted fluxes are even lower than the values in Table 4. The observed 8.4 GHz fluxes thus do not rule out a small free-free emission contribution from the coronal plasma even if the corona is very compact ($R_S \sim 1.1\,R_\star$).

Also, the cooler chromospheric and transition region plasmas can contribute to the radio emission by the free-free mechanism. In fact, the plasma at T$\sim$1–2$\times 10^4$ K is optically thick for the typical VEM values of these regions ($\sim 10^{50-51}$ cm^{-3}, for example see Pagano et al. 2000). If the emission comes from the entire surface, the plasma at T$\sim 2\times 10^4$ K produces for all of our targets a flux density less than 10^{-3} mJy at 8.4 GHz, and less than 0.015 mJy at 43 GHz. These values are smaller than or comparable to (for the higher frequencies) the computed coronal free-free contribution. The total chromospheric, transition region, and coronal free-free emission are much less than the observed fluxes and upper limits.

4.2. Gyroresonance emission

Another possible contribution to the radio flux density is that produced by the thermal electrons, which are responsible for the X-ray emission, emitting gyroresonant emission in the presence of a magnetic field of strength B. A comparison of the observed flux densities and upper limits with the flux densities predicted by a gyroresonant emission model gives information on the magnetic fields in the coronae of the observed stars. To evaluate the expected flux densities for gyroresonance emission, we follow Gary & Linsky (1981), White et al. (1994), Dulk (1985), and Zheleznyakov (1970).

Table 6. Constraints deduced from the observed 8.4 and 15 GHz data under the assumption that the major contribution to the flux is gyroresonance emission from an optically thick plasma (see Sect. 4.2).

Star	8.4 GHz		15 GHz	
	B *(Gauss)*	R_S[a]/$R_\star$	B *(Gauss)*	R_S[a]/$R_\star$
GJ 65AB (UV Cet)	600	2.0	<1000	2.0
GJ 644 (V1054 Oph)	600	1.8	<1000	2.0
GJ 803 (AU Mic)	<500	1.2		
GJ 873 (EV Lac)	600	1.8	<750	1.2

[a] R_S is measured from the center of the star.

The gyroresonance emission is concentrated at the fundamental frequency and its harmonics up to $s = 10$. When averaged over angle and polarisation, the optical depth (τ_g), according to White et al. (1994), depends only on the frequency and the harmonic number s:

$$\tau_g(s,\nu) = 1.45\,\frac{L_B}{R_\odot}\,\frac{n}{\nu}\,A(s)\,T^{2s-1}, \tag{3}$$

where the number density n is derived from the VEM, L_B is the scale height of the magnetic field, and $A(s)$ is a function of the harmonic number:

$$A(s) = \frac{s^2(2s-2)!}{2^{2s-2}s![(s-1)!]^2}\left(\frac{sk}{2mc^2}\right)^{s-1}. \tag{4}$$

The emission frequency ν is related to the harmonic number s by means of the magnetic field ($\nu = 2.8\times 10^{-3}\,s\,B$ GHz). Therefore, the magnetic field B necessary for the gyroresonant process to be efficient can be evaluated for each frequency as a function of s.

The flux density due to gyroresonance emission mechanism for an optically thick source is:

$$S\,[mJy] = 2.24\,\frac{T}{2\times 10^7}\left(\frac{\nu}{15}\right)^2\left(\frac{d}{5}\right)^{-2}\left(\frac{R_S}{0.5R_\odot}\right)^2, \tag{5}$$

where T is in Kelvin, ν in GHz, d in pc, and R_S the source radius measured from the stellar center.

The average magnetic flux density in the photosphere ($B\,f$, with f the fractional area covered by the magnetic field B) is very large for the dMe stars. For example, AU Mic has $B\,f$=2,300 G (Saar 1994). It is reasonable to infer, therefore, that at least the lower portion of the coronae of these stars have strong magnetic fields.

In the following we use the formulation of White et al. (1994), who assume a magnetic field scale height L_B=0.3 $R_\star$. Our results do not change appreciably when we assume a different scale height, unless $L_B \ll 0.01\,R_\star$ for which the corona becomes optically thin.

Our results, listed in Table 6, for each source follow:

GJ 65AB (UV Cet): At 8.4 GHz the cool plasma component is optically thick for gyroresonance emission up to the 3th harmonic, that implies a magnetic field of about 1kG. The contribution to the observed 2.61 mJy flux of the cool plasma component could be significant only if a high magnetic flux ($\sim$ 1kG) is present in a very extended corona (of the order of 10 $R_\star$, see Eq. (5)). The hot component contribution to the gyroresonance emission must be dominant. In fact, this component is optically thick in a magnetic field of the order of 600 G (fifth harmonic), which predicts a flux comparable to the observed flux if the coronal radius is $\sim$2.5 $R_\star$. We conclude that during our observation the observed 8.4 GHz flux could be explained by the coronal plasma of UV Cet being cospatial with a magnetic field of the order of 600 G in a region extending out to $\sim$ 2 $R_\star$. Moreover the 15 GHz flux upper limit indicates that the magnetic field must be lower than 1000 G in the emitting region, otherwise, the gyroresonance emission at 15 GHz originating from the hot component would exceed the observed upper limit.

GJ 644 (V1054 Oph): The gyroresonance emission due to the cool plasma component is optically thick at 8.4 GHz for a magnetic field of 1kG ($s = 3$). If the observed flux (1.4 mJy) were due only to gyroresonance emission from the cool component, the 1 kG magnetic field on V1054 Oph would have to be extended out to $\sim$4 $R_\star$. This scenario does not seem realistic. At the same frequency the hot component of the coronal plasma is more efficient for gyroresonance emission as it requires only 600 G ($s = 5$) to be optically thick. The observed flux density could then be generated in a corona extending out to about 1.8 $R_\star$ with a 600 G magnetic field. At 15 GHz the gyroresonance emission from the cool component could reach the upper limit level only if the radius of the emitting region were as large as 2 $R_\star$ and the magnetic field were at least 2kG. Again this is an unrealistic scenario. However, the hot component, which is optically thick in a 1 kG magnetic field ($s = 3$), gives a flux density at 15 GHz well above our upper limit if extended out to 2$R_\star$. We conclude that the larger contribution to the 1.4 mJy flux density detected at 8.4 GHz is probably due to the hot plasma component in a magnetic field of the order of 600 G. The radius of the emitting region must be of the order of 2$R_\star$ if the gyroresonance emission is the main contributor to the 8.4 GHz flux, or less than 2$R_\star$ if other emission mechanisms, for example nonthermal gyrosynchrotron radiation, are important. The cool component contribution is much less important. The 15 GHz measurement constrains the magnetic field to be less than 1 kG near 2 $R_\star$.

GJ 803 (AU Mic): The cool plasma component at 8.4 GHz is optically thick for gyroresonance emission up to the 4th harmonic in a magnetic field of the order of $\sim$750 G. The flux density exceeds the upper limits at 8.4 GHz if the source dimension is greater than 2.6 $R_\star$. The hot plasma component is optically thick at 8.4 GHz in a magnetic field of 500 G (6th harmonic). The 8.4 GHz flux density would be 0.25 mJy even for a source as small as the photosphere radius. Since the empirical upper limit is 0.22 mJy, the hot component of the coronal plasma cannot be located where the magnetic field is as large as 500 G, unless the emitting volume is small. We note that White et al. (1994) came to a similar conclusion.

GJ 873 (EV Lac): At 8.4 GHz the predicted gyroresonance emission from the cool component can reach the observed flux for a radio source size $\sim$1.8 $R_\star$ in a magnetic field of 600 G. The hot component, which would be optically thick in a 400 G magnetic field, gives a flux density greater than the observed value even for a source radius of 1.0 $R_\star$. We therefore believe that the hot component plasma occurs mostly in coronal regions with B<400 G. The cool component could contribute to the emission only if located in regions of larger magnetic fields than the hot component. This is unlikely because in the solar corona the hotter plasma is found in high pressure active region loops (e.g., Rosner, Tucker, and Vaiana 1978), which require stronger magnetic fields for confinement than the low pressure loops found in the quiet Sun. The gyroresonance emission due to the cool component at 15 GHz would be significant if located in a corona with a 1 kG magnetic field. If this plasma had a size $\sim 1.2R_\star$, the radio emission would equal the measured upper limit. The emission from the hot component, which is optically thick in a 750 G magnetic field, would be three times the 15 GHz upper limit even for a 1.0 $R_\star$ radio source. We therefore conclude that magnetic fields of the order of 600 G must be confined within $\sim$1.8 $R_\star$ in EV Lac's corona. If the 600 G coronal region is more compact, other emission mechanisms, such as nonthermal gyrosynchrotron radiation, must operate to explain the observed flux at 8.4 GHz.

5. Conclusions

Our objective was to study the radio spectra of a sample of dMe stars at four frequencies between 8.4 and 43 GHz, but we detected 8.4 GHz fluxes from three out of the five stars in our sample, and the remaining measurements are upper limits. The increase of the flux upper limits with frequency for all the sources does not allow us to determine whether the flux decreases with frequency as predicted for gyrosynchrotron emission from mildly relativistic electrons, or whether the flux increases at high frequencies as observed for some dMe stars (cf. Güdel & Benz 1996).

We found that the 8.4 GHz fluxes observed for EV Lac and V 1054 Oph are of the order of the radio flux expected from the empirical relation between X-ray and radio fluxes found by Güdel et al. (1993). On the other hand, UV Cet was 6–20 times above the predicted flux, while AU Mic was a factor of 8–26 times weaker than the predicted value.

We computed the radio fluxes due to the free-free emission of the electrons in the coronal plasma, for both components of a two temperature plasma, and found that these predicted fluxes lie far below the observed fluxes and upper limits, as expected. Compared to the coronal free-free emission, the free-free contribution from chromosphere and transition region is not negligible. However the resulting total flux densities are much less than the observed fluxes and upper limits.

If the thermal electrons of the two temperature components are cospatial with a magnetic field B, they emit gyroresonance radiation. Therefore, under the assumption that the dominant emission is thermal, we have used the observed fluxes and upper limits at 8.4 and 15 GHz to constrain the characteristics of the radio source. For UV Cet, V 1054 Oph, and EV Lac, we found that coronal magnetic fields of the order of $\sim$600 G must be confined to a region extending out to less than 1.8–2.0 $R_\star$ for gyroresonance emission to explain the observed flux. Otherwise nonthermal gyrosynchrotron radiation or a coherent emission mechanism would be important at the time of our observations. For AU Mic, magnetic fields of the order of 500 G cannot be more extended than 1.2 $R_\star$.

Assuming that these stars have surface magnetic fields of ∼3,000 G, a value compatible with the measurements of Saar (1994) for similar dMe stars and also with the equipartion argument (cf. Pagano et al. 1997), we conclude that the magnetic fields expand with height and thereby decrease in field strength by a factor ∼5 on a typical scale smaller than $R_\star$ for UV Cet, V 1054 Oph, and EV Lac and on the smaller scale 0.1–0.2 $R_\star$ for AU Mic.

Gary & Linsky (1981) proposed the following scaling law for the magnetic field in the outer atmospheres of late type stars: $B(R) = \frac{B_0}{4}\left(\frac{R}{R_\star} - \frac{1}{2}\right)^{-2}$. Our results are in agreement with the Gary & Linsky (1981) scaling law for UV Cet, V 1054 Oph, and EV Lac, while for the other star we found that the magnetic field strength decreases with radial distance much more rapidly.

For AU Mic and EV Lac the 8.4 and 15 GHz fluxes or upper limits constrain the hot plasma component of their coronae, revealed by X-ray spectral data analysis, to be cospatial with coronal magnetic fields of less than 0.5–1 kG.

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