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NARROW-BAND, SLOWLY VARYING DECIMETRIC RADIATION FROM THE DWARF M FLARE STAR YZ CANIS MINORIS

KENNETH R. LANG AND ROBERT F. WILLSON
Department of Physics and Astronomy, Tufts University
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ABSTRACT

Narrow-band, slowly varying microwave radiation has been detected from the dwarf M star YZ Canis Minoris at frequencies near 1465 MHz. This quiescent, or nonflaring, emission cannot be attributed to gyroresonant radiation from coronal loops; the loops would have to be more than 200 times the stellar radius in size with magnetic field strengths of $H \geq 100$ G at this distance. The narrow-band structure ($\Delta\nu/\nu \leq 0.1$) of the slowly varying radiation cannot be explained by continuum emission processes such as thermal bremsstrahlung, thermal gyroresonant radiation, or nonthermal gyrosynchrotron radiation. Our observations may be explained by coherent burst mechanisms like electron-cyclotron masers or coherent plasma radiation. Maser action at the second harmonic of the gyrofrequency implies a longitudinal magnetic field strength of 250 G and an electron density of $N_e \approx 6 \times 10^9$ cm^{-3}. Coherent plasma radiation at the second harmonic of the plasma frequency similarly requires $N_e = 6 \times 10^9$ cm^{-3} but a longitudinal magnetic field strength of $H_l \ll 250$ G. The slow variation of the narrow-band emission might be explained by the stochastic nature of continued low-level, coherent burst activity. There are possible analogies with narrow-band decimetric bursts observed on the Sun.

Subject headings: stars: coronae — stars: flare — stars: radio radiation

I. INTRODUCTION

Nearby main-sequence stars of late spectral type exhibit quiescent, or nonflaring, X-ray emission whose absolute luminosity may be as much as 100 times that of the Sun (Johnson 1981; Vaiana *et al.* 1981). This suggests that these stars may have hot stellar coronae and large-scale coronal loops with strong magnetic fields. Quiescent microwave radiation might be emitted by electrons trapped within stellar loops or by electrons spiraling about magnetic fields above starspots.

Quiescent microwave emission has, in fact, been detected from six dwarf M stars using the Very Large Array (VLA). They are UV Ceti (Gary and Linksy 1981), both components of the binary star system EQ Pegasi (Topka and Marsh 1982), YY Geminorum and Wolf 630 (Linksy and Gary 1983), the suspected spectroscopic binary AU Microscopii (Cox and Gibson 1985), and YZ Canis Minoris (Pallavicini, Willson, and Lang 1985; Kundu and Shevgaonkar 1985). YZ Canis Minoris is curiously unique in being the only single, or nonbinary, dwarf M star that is know to exhibit quiescent microwave radiation.

The quiescent radiation from dwarf M stars is slowly variable over time scales of hours (Linsky and Gary 1983; Pallavicini, Willson, and Lang 1985). An example is shown in Figure 1 where the 6 cm flux density from YZ Canis Minoris rises to 7 mJy over periods of half an hour. Kundu and Shevgaonkar (1985) have pointed out that the microwave radiation from this star is highly variable with a flux density that varied by a factor of 5 in 2 days and reached a peak value of 3 mJy at 20 cm wavelength, but their 2 hr synthesis maps may have underestimated the peak flux density of the slowly varying component that varies on time scales shorter than 2 hr. In addition, Rondonò *et al.* (1984) have reported variable microwave radiation from YZ Canis Minoris at 6 cm wavelength with a peak flux density of 5 mJy and a duration of ≥ 30 minutes. If this was the slowly varying radiation illustrated in Figure 1, its association with an ultraviolet flare that occurred 7 minutes earlier may have been purely coincidental.

Most of the dwarf M stars detected at microwave wavelengths exhibit X-ray radiation with absolute X-ray luminosities of $L_x = 10^{27.5}$ ergs s^{-1} (UV Cet), $10^{28.8}$ ergs s^{-1} (EQ Peg), $10^{29.6}$ ergs s^{-1} (YY Gem), $10^{29.3}$ ergs s^{-1} (Wolf 630), and $10^{28.5}$ ergs s^{-1} (YZ CMi). By way of comparison, the Sun has an average $L_x = 10^{27.0}$ ergs s^{-1} that is attributed to thermal bremsstrahlung of hot electrons trapped in the ubiquitous coronal loops that dominate the structure of the solar corona. This suggests that the slowly varying, quiescent microwave radiation of dwarf M stars may be due to thermal electrons trapped in extensive coronal loops.

The X-ray observations rule out detectable thermal bremsstrahlung at microwave wavelengths; the temperatures and emission measures inferred from the X-ray data indicate that the microwave bremsstrahlung flux density is at least two orders of magnitude below the detection threshold of the VLA. Thermal gyroresonant, or cyclotron, radiation might nevertheless account for the quiescent microwave emission from dwarf M stars. This process explains most, if not all, of the quiescent microwave emission from coronal loops on the Sun (Kundu and Lang 1985). However, gigantic coronal loops with intense magnetic fields (several hundred gauss) and enormous heights of three stellar radii are required to explain the

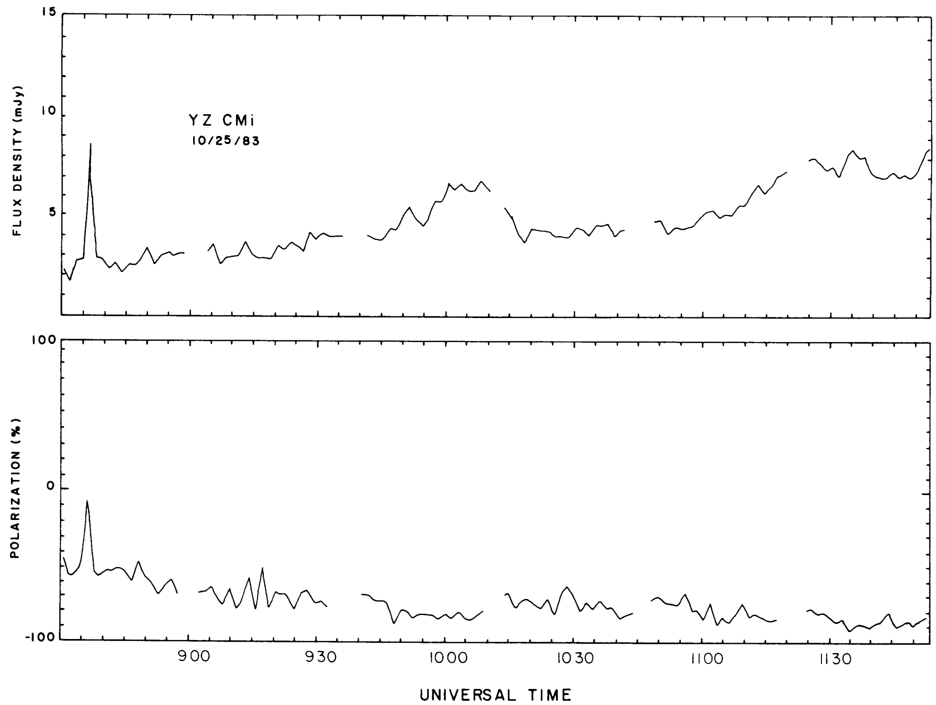

FIG. 1.—A plot of the total intensity I (*top*) and degree of circular polarization, ρ_c (*bottom*) observed at 4885 MHz from the dwarf M star YZ CMi on 1983 October 25. A circularly polarized impulsive ($\leq$ 20 s) burst and circularly polarized, slowly varying ($\sim$ 1 hr) radiation are observed. The visibility data were phase shifted to source center and then averaged, baseline by baseline, over a 30 s interval. They were then vector averaged to produce these time profiles. The theoretical 3 σ noise level of these data is $\sim$ 1.35 mJy.

6 cm (or 5000 MHz) emission from dwarf M stars. Gyroresonance radiation of thermal electrons in extensive coronae was nevertheless once believed to be the most likely explanation for the slowly varying quiescent emission from these stars (Gary and Linsky 1981; Topka and Marsh 1982).

An alternative microwave emission mechanism is nonthermal gyrosynchrontron emission by mildly relativistic electrons (Linsky and Gary 1983; Pallavicini, Willson, and Lang 1985). An attractive aspect of this mechanism is that the emitting sources can be relatively small with sizes comparable to those of starspots. The unattractive aspect of the nonthermal gyrosynchrotron hypothesis is that the mildly relativistic electrons must be accelerated more or less continuously in the magnetic fields of starspots.

Our recent VLA observations of YZ CMi indicate that neither thermal gyroresonant radiation nor nonthermal gyrosynchrotron radiation can account for the slowly varying, quiescent microwave radiation of this star. In § II we present observations of the slowly varying radiation with a maximum flux density of 20 mJy and narrow-band frequency structure ($\Delta\nu/\nu \leq 0.1$) at frequencies near 1465 MHz. Possible explanations for this radiation are examined in § II. Thermal gyroresonant radiation would require impossibly large coronal loops and magnetic field strengths. The narrow-band structure cannot be explained by continuum emission processes such as thermal bremsstrahlung, thermal gyroresonant radiation, or nonthermal gyrosynchrotron radiation. Coherent burst mechanisms seem to be required.

II. OBSERVATIONS

The dwarf M star YZ Canis Minoris (GL 285, dM4.5e) was observed with two subarrays of the VLA on 1984 December 10 in the A configuration. One subarray of 13 antennas had signal frequencies of 1415 MHz and 1515 MHz, and the other subarray of 14 antennas had signal frequencies of 4835 MHz and 4885 MHz. The bandwidth at all four frequencies was 50 MHz. The total intensity, I, and circular polarization, ρ_c or Stokes parameter V, were sampled for every 10 s, and the data were calibrated by observing 3C 286 (14.51 Jy at 1415 MHz and 7.4 Jy at 4885 MHz) and 0735+178 (2.2 Jy at 1415 MHz and 2.1 Jy at 4885 MHz).

The calibrated visibility data were used to construct a 4.5 hr synthesis map of the unresolved source. The calibrated data were then phase shifted to bring the microwave source exactly at the center of the 4.5 hr map. There were no confusing sources in the field of view.

The calibrated, phase-shifted visibility data were then averaged, baseline by baseline, with running means over a 1.5 minute time interval, and then vector averaged. The theoretical 3 σ noise level obtained in this way was 2.3 mJy at 4885 MHz and 2.9 mJy at 1415 MHz. The total intensity at 1415 MHz and 1515 MHz exhibited slowly varying fluctuations of as much as 20 mJy, which is well above the noise level (see Fig. 2). However, there were no detectable variations at 4885 MHz for this observation.

An examination of the calibration amplitudes at the times of the gaps in Figure 2 indicates that they are constant and

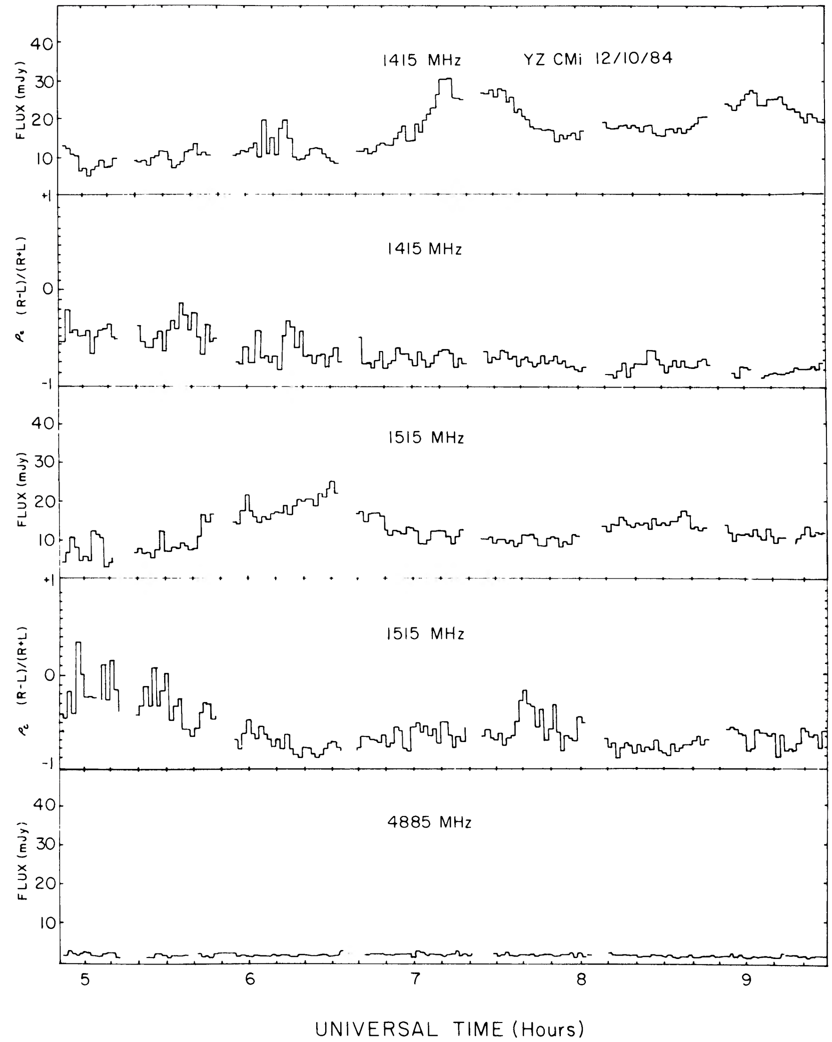

FIG. 2.—Plots of the slowly varying emission from the dwarf M flare star YZ CMi observed at two closely spaced frequencies of 1415 MHz and 1515 MHz and at 4885 MHz on 1984 December 10. Both the total intensity (flux) and degree of circular polarization (ρ_c) are plotted as a function of time. Notice that the total intensity at two frequencies separated by 100 MHz near 1465 MHz peak at different times, indicating a narrow-band radiation mechanism. Also notice that there are no detectable variations at 4885 MHz on this day. Here the visibility data were phase shifted to source center and then averaged, baseline by baseline, over a 1.5 minute interval. They were then vector averaged to produce time profiles with 3 σ noise levels of 2.9 mJy at 1415 MHz and 1515 MHz and 2.3 mJy at 4885 MHz. No quiescent emission was detected at 6 cm where the plot represents the nonzero vector-averaged noise level.

have the same value at 1415 MHz and 1515 MHz within the 5 σ noise level of 3.3 mJy for the 3 minute calibration interval. Changing calibrator amplitudes therefore do not produce the flux variations shown in Figure 2. This is confirmed by the unchanging peak-to-peak noise level of about 3 mJy depicted in the figure.

The interesting aspect of Figure 2 is that the slow variations in total intensity peak at different times for frequencies $\nu =$ 1415 and 1515 MHz, indicating narrow-band structure of bandwidth $\Delta\nu \ll 100$ MHz, or $\Delta\nu/\nu \ll 0.1$. This narrow-band structure was confirmed by constructing snapshot synthesis maps over time intervals of 1.5 minutes centered at 06:20 UT and 07:30 UT (Fig. 3). The snapshot maps had an effective half-power beamwidth of 1''.0 × 1''.6. The maximum flux values at 06:20 were 14 and 22 mJy per beam area at 1415 and 1515 MHz, respectively, while at 07:30 they were 25 and 10 mJy per beam area at 1415 and 1515 MHz, respectively.

Although 1415 MHz and 1515 MHz lie outside the protected band for radio astronomy, there was no indication of interference. This is reflected by the unchanging calibrator amplitudes and the absence of interference patterns in the 1.5 minute maps (Fig. 3) and in a 2 hr map (not shown).

III. DISCUSSION

What accounts for the observed narrow-band structure? Continuum emission processes like thermal bremsstrahlung, thermal gyroresonant radiation, or gyrosynchrotron radiation will not normally exhibit such spectral features. Of course, thermal electrons gyrate around magnetic fields, emitting

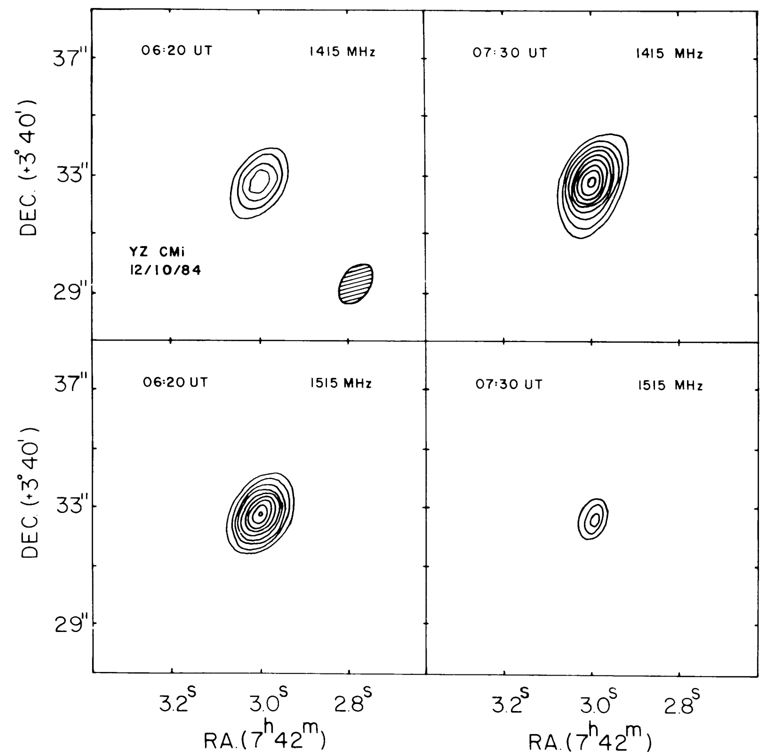

FIG. 3.—VLA snapshot synthesis maps of the total intensity over a 1.5 minute time interval centered at 06:20 UT and 07:30 UT for signal frequencies of 1415 MHz and 1515 MHz. The contour intervals of these maps are 6, 8, 10... mJy per beam area, and the synthesized beam (1"0 × 1"6) is illustrated by the cross-hatched ellipsoid at the upper left. Notice that the unresolved emission peaks at different times at two frequencies separated by only 100 MHz near 1465 MHz, indicating a narrow-band radiation mechanism.

cyclotron lines at harmonics of the gyrofrequency. Current sheets could lead to enhanced gyroresonant radiation from relatively thin coronal layers where the magnetic field is constant, and in this case, individual cyclotron lines might be observed. In fact, the VLA has been used to resolve individual coronal loops on the Sun, thereby detecting individual cyclotron lines (Willson 1985*a*). However, when an entire star is observed, the complex magnetic geometry should lead to varying magnetic field strengths and the cyclotron lines ought to be smoothed into a continuum.

Moreover, we can rule out gyroresonant radiation for the observations presented here. The gyroresonant layers in a stellar corona will lie fully outside the star and form closed surfaces around it. The observed radiation will be generated at the maximum harmonic, n, for which the corona still remains optically thick, for this outermost layer absorbs underlying radiation at lower harmonics. The maximum observed flux density, S, will be given by the Rayleigh-Jeans law (Lang 1980), and the radius of the emitting source will be given by

$$R^2 \approx 10^{13} \frac{SD^2}{\nu^2 T} \text{ cm}^2, \tag{1}$$

where S is the source flux density in Jy; D is the distance in cm; T is the temperature in K; and the observing frequency, ν, is given by

$$\nu = 2.8 \times 10^6 \, nH_l \text{ Hz}, \tag{2}$$

for a longitudinal magnetic field of strength H_l. (Slightly larger values of R will be obtained when the magnetic field geometry and the visible area of the gyroresonant surface are taken into account.) For YZ CMi, we substitute $S = 0.02$ Jy, $D = 5.99$ pc $\approx 1.8 \times 10^{19}$ cm, $\nu = 1.5 \times 10^9$ Hz, and $T \approx 10^6$ K to obtain $R = 5.4 \times 10^{12}$ cm.

Thus, the hypothetical gyroresonant radiator must have a radius of $R = 5.4 \times 10^{12}$ cm which is 200 times as large as the star's radius of 2.6×10^{10} cm (Pettersen 1980). (Smaller values of R amounting to a few stellar radii were previously obtained because lower flux densities were observed at higher frequencies.) Because the gyroresonant layers remain optically thick out to no more than $n = 6$ for normal stellar coronae (Zheleznyakov and Tikhomirov 1984), the required magnetic field strength for radiation at 1500 MHz is $H \geq 100$ G. Such strong magnetic fields at 200 stellar radii are simply inconceivable. Even a well-ordered dipolar field has a strength that goes as the cube of the radius, implying a surface magnetic field strength of 0.8×10^9 G.

Thus, the narrow-band, slowly varying radiation from YZ CMi cannot be explained by conventional radiation mechanisms. We might speculate that the star could be continually radiating coherent bursts. Coherent radiation processes like electron-cyclotron masers have been used to explain some microwave bursts on the Sun and nearby stars (Melrose and Dulk 1982; Holman 1983). Some solar bursts exhibit high brightness temperatures, $T_B \geq 10^{15}$ K, that require coherent mechanisms (Slottje 1978), and other solar bursts have exhibited narrow-band ($\Delta\nu/\nu < 10^{-2}$) structure that suggests coherent emission (Lang and Willson 1984; Willson 1985*b*). In addition, microwave bursts from the dwarf M star AD Leo have millisecond rise times and high brightness temperatures that require coherent emission processes (Lang *et al.* 1983; Lang and Willson 1986). Coherent burst mechanisms might therefore be adopted to explain the observed narrow-band, slowly varying microwave radiation through continuous burst activity.

High circular polarization would be expected to be occasionally observed if the coherent mechanism is associated with intense magnetic fields, and the stochastic nature of continued bursts might explain the variability of the observed microwave radiation.

If the electron-cyclotron maser radiates at the second harmonic, or $n = 2$, of the gyrofrequency as suggested by Melrose and Dulk (1982), then we obtain a longitudinal magnetic field strength of $H_l = 250$ G for a radiation frequency of 1400 MHz. The first harmonic radiation is expected to be attenuated by gyroresonant absorption in overlying atmospheric layers, and second harmonic radiation may dominate the emission when the gyrofrequency is roughly equal to the plasma frequency $\nu_P = 8.9 \times 10^3\ N_e^{1/2}$ Hz, where the electron density is in cm^{-3} (see Dulk 1985). This means that the electron density $N_e \approx 6 \times 10^9$ cm^{-3}.

The coherent process might alternatively be attributed to plasma radiation. For example, type IV bursts with $\Delta\nu/\nu \leq 0.1$ have been observed at frequencies $\nu = 200$–1500 MHz. Benz and Tarnstrom (1976) have shown that a coherent synchrotron mechanism for the narrow-band type IV bursts requires either an excessively large number of relativistic electrons or an unstable pitch angle anisotropy. They argue that plasma emission processes might explain these bursts. Plasma processes involving electron beams have also been invoked to explain weaker, narrow-band ($\Delta\nu/\nu \leq 0.1$) bursts or blips observed at decimetric wavelengths during other solar bursts (Furst, Benz, and Hirth 1982; Benz, Bernold, and Dennis 1983). However, analogies with these solar features may be constrained by their rapid temporal variations. The narrow-band type IV bursts have lifetimes of several minutes, and the weaker blips last less than 0.25 s. In contrast, the narrow-band slowly varying radiation from YZ Canis Minoris lasts for hours.

If YZ Canis Minoris has a solar-like corona, then the first harmonic of the plasma frequency will be absorbed by electron-ion collisions at frequencies $\nu = 1400$ MHz, but the second harmonic will escape. For this case we obtain $N_e = 6 \times 10^9$ cm^{-3}, but for plasma radiation to dominate we require $\nu_H \ll \nu_P$ or the longitudinal magnetic field strength $H_l \ll 250$ G.

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Note added in manuscript.—Dr. Ronald D. Ekers (private communication) has pointed out that the narrow bandwidths and long fluctuation times of the decimetric radiation from YZ CMi are comparable to the decorrelation frequencies and decorrelation times of the interstellar scintillation of pulsar radiation. Our observations might therefore be explained by interstellar scintillation, but YZ CMi is about 100 times closer than the scintillating pulsars. The fluctuating electron number density would therefore have to be 100 times greater than that detected along the line of sight to these pulsars if the observed decorrelation is attributed to interstellar scintillation. Multiple-wavelength VLA observations can be used to test the scintillation hypothesis; the decorrelation frequency and time, respectively, scale as the fourth and first power of the observing frequency. An emitter located at the distance of YZ CMi must have a linear size smaller than 10^4 km in order to give rise to detectable scintillation in this dense interstellar medium (see Lang 1971 for relevant formulae and pulsar data). If a source of this size accounts for the decimetric flux density from YZ CMi, then its brightness temperature is $T_B \geq 10^{14}$ K, which may again require a coherent radiation mechanism.

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Kenneth R. Lang and Robert F. Willson: Department of Physics and Astronomy, Robinson Hall, Tufts University, Medford, MA 02155