THE ASTROPHYSICAL JOURNAL, 326:300–304, 1988 March 1

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

KENNETH R. LANG AND ROBERT F. WILLSON
Department of Physics and Astronomy, Tufts University
Received 1987 May 29; accepted 1987 August 21

ABSTRACT

The Very Large Array has been used in the spectral-line mode to obtain the frequency spectra of the radiation from the dwarf M star YZ Canis Minoris at frequencies, ν, near 1465 MHz. The slowly varying (minutes) radiation was, within the observational uncertainties, 100% left-hand circularly polarized. The radiation during several 10 minute intervals exhibited evidence for narrow-band structure with a bandwidth $\Delta\nu \approx 30$ MHz and a fractional bandwidth of $\Delta\nu/\nu \approx 0.02$. Broad-band radiation with $\Delta\nu \geq 50$ MHz and $\Delta\nu/\nu \geq 0.03$ was observed during other 10 minute intervals. The highly polarized, slowly varying, narrow-band emission is attributed to coherent radiation from an electron-cyclotron maser in a magnetic field of strength $H \approx 260$ G. If this radiation is from coronal loops similar to those observed on the Sun, then a source size of $L_s \approx 2 \times 10^7$ cm and brightness temperature $T_B \approx 0.5 \times 10^{17}$ K are inferred for the narrow-band source. The observed broad-band radiation may be due to the superposition of many rapid, narrow-band bursts with different central frequencies. The fact that the observed narrow-band radiation persists for 10 minutes indicates that there was no substantial change in the source height, size, magnetic field strength, or electron density during this time. The "quiescent" microwave radiation of some dwarf M stars might be due to the superposition of nearly continuous, low-level coherent bursts; this activity might play a role in the heating of stellar coronae.

Subject headings: radiation mechanisms — stars: flare — stars: individual (YZ CMi) — stars radio radiation

I. INTRODUCTION

Radio and microwave bursts from dwarf M stars have been attributed to coherent radiation mechanisms. High brightness temperatures of $T_B \geq 10^{12}$–10^{15} K were, for example, inferred from the flux densities of rare, powerful bursts under the assumption that the radio emitter was smaller than the stellar disk; coherent processes are required to explain these high brightness temperatures (see Lang and Willson 1986*a* for a review). Observations with high time resolution indicated that the 20 cm bursts from one dwarf M star, AD Leonis, had rise times of milliseconds, relatively small sizes $L \leq 10^8$ cm, and high brightness temperatures $T_B \geq 10^{16}$ K (Lang *et al.* 1983; Lang and Willson 1986*a*). These bursts were up to 100% circularly polarized, suggesting an intimate connection with the star's magnetic fields.

Lang and Willson (1986*b*) first provided evidence for the narrow-band frequency structure expected from a coherent radiation process. They showed that the variation in the radiation from the dwarf M star YZ Canis Minoris had a bandwidth $\Delta\nu \leq 100$ MHz. This was because there was no correlation between the variations detected at 1415 and 1515 MHz.

This two-frequency experiment was repeated with similar results for the dwarf M stars AD Leonis and L726-8A (White, Kundu, and Jackson 1986). A 2 hr variation in the radiation from AD Leonis was observed at 1415 MHz but did not appear at 1515 MHz. The flux and evolution of a flare from L726-8A differed at the two frequencies.

Intensity was plotted as a function of both time and frequency (dynamic spectra) for radiation from the dwarf M star UV Ceti (L726-8B) near 1415 MHz (Bastian and Bookbinder 1987). One left circularly polarized burst showed no variation as a function of frequency across the 41 MHz band, but another right circularly polarized burst exhibited complex frequency structure with narrow-band components whose fractional bandwidths were as small as the frequency resolution (bandwidth $\Delta\nu \leq 3$ MHz and $\Delta\nu/\nu \leq 0.002$). Jackson, Kundu, and White (1987) similarly produced dynamic spectra for UV Ceti by observing four frequencies simultaneously. Although the bandwidths were not measured, the dynamic spectrum of one 10 minute burst suggested complex frequency-time structure with both positive and negative frequency drifts. The features that showed a positive drift were interpreted in terms of disturbances traveling downward in the star's corona where they excite radiation at higher frequencies or shorter wavelengths.

In this paper we report measurements of the frequency spectra of YZ Canis Minoris using 15 continuous 3.125 MHz bands. In § II we present observations of frequency structure with narrow bandwidths $\Delta\nu \approx 30$ MHz that persist over 10 minutes of time without evidence for a drift. The fractional bandwidth $\Delta\nu/\nu \approx 0.02$. Here we also show that radiation over other 10 minute intervals appears to be broad band with $\Delta\nu \geq 50$ MHz, but these spectra could represent the time average of many rapid, narrow-band events. In § III we interpret the narrow-band, 30 MHz structure in terms of electron-cyclotron maser emission. Here we also draw attention to certain solar bursts that may require a similar coherent radiation mechanism. We conclude by mentioning the implications of continued coherent burst activity for the heating of stellar coronae.

II. OBSERVATIONS

The dwarf M star YZ Canis Minoris (GL 285, dM4.5e) was observed with the Very Large Array (VLA) between 08:10 and 12:22 UT on 1987 January 6 in the C-configuration. The VLA

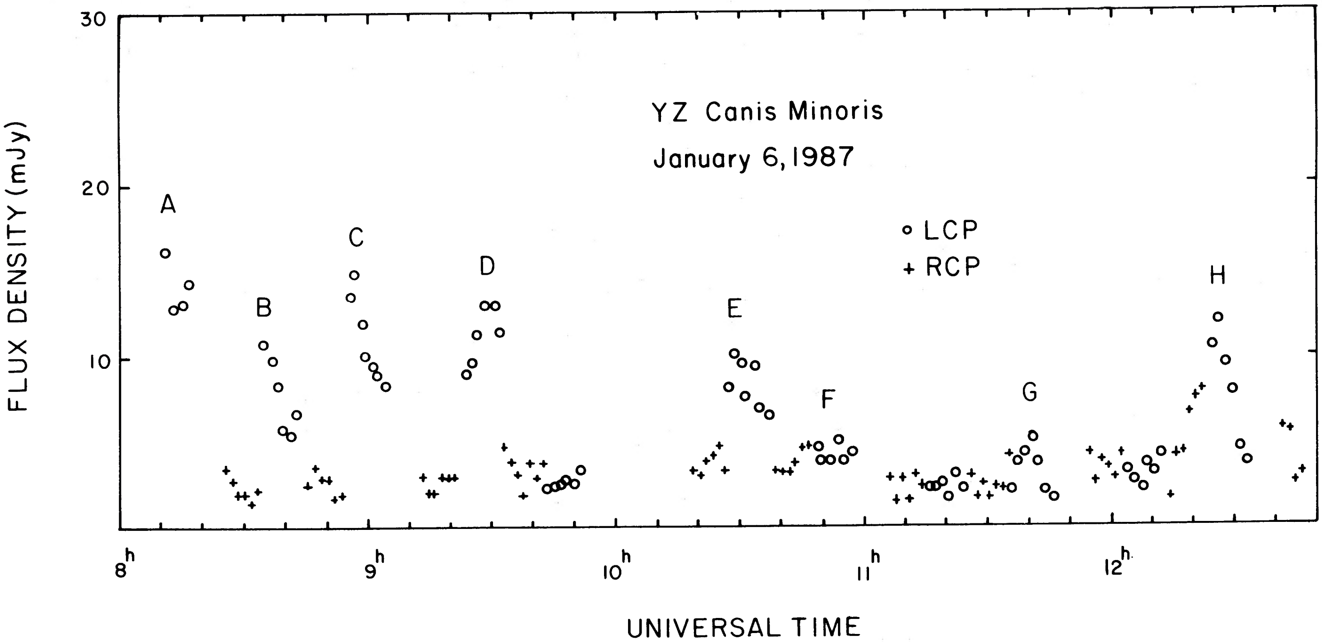

FIG. 1.—The total intensity of the radiation received from the dwarf M flare star YZ Canis Minoris is plotted as a function of time. The left circularly polarized (LCP) and right circularly polarized (RCP) signals were alternately recorded for 10 minute intervals within a 50 Hz bandwidth centered at 1464.9 MHz. Here the visibility data of all baselines from the 15 independent channels has been averaged over a 1.5 minute time interval with a 3 σ noise level of 2.9 mJy. Frequency spectra of the slowly varying LCP radiation marked by the letters A, B, C, ..., H are shown in Figs. 2 and 3.

was used in the 16-channel spectral line mode centered at 1464.9 MHz. At this frequency, the half-power beamwidth of the antennas is $\sim 31'$ and the synthesized beamwidth is $\sim 13'' \times 22''$. The 50 MHz bandwidth was divided into 15 continuous channels of 3.125 MHz width; the 16th channel was used to record the integral flux over the inner 37.5 MHz of the bandwidth. The full array of 26 antennas was used to sample the signal intensity every 10 s, and the left circularly polarized (LCP) and right circularly polarized (RCP) signals were observed for alternate 10 minute intervals. A bandpass calibration for each of the 16 channels was applied to the visibilities during the observations. The phase data were calibrated by observing PKS 0735+178 for a 3 minute interval every 40 minutes, and the flux density calibration was made from observations of 3C 286 whose flux density is 14.7 Jy at 1465 MHz (1 Jy = 10^{-23} ergs cm^{-2} s^{-1} Hz^{-1}).

The raw visibilities were first examined, baseline-by-baseline and channel-by-channel for interference or other corrupted data, and than edited. The calibrated visibility data for the 16 channels were then averaged, baseline-by-baseline, with running means over 1.5 minutes and then vector-averaged. A synthesis map was then made for each 1.5 minute time interval using the standard CLEAN procedure.

The source flux densities were determined from these maps and plotted as a function of time in Figure 1. Here the flux density scale is in mJy, 10^{-3} Jy, and the 3 σ noise level is 2.9 mJy. The observed radiation was 100% left-hand circularly polarized, within an observational uncertainty of about 10%. The highly polarized radiation also exhibited variations on time scales of minutes: these variations are relatively slow when compared with those of more impulsive stellar bursts (milliseconds to seconds).

The 10 s visibility data observed within each 3.125 MHz channel was then averaged, baseline-by-baseline, with running means over 10 minutes and then vector-averaged. A synthesis map was then made for each of the 15 channels using the standard CLEAN procedure. The flux densities determined from these maps are plotted as a function of observing frequency in Figures 2 and 3. Several of these 10 minute spectra provide evidence for narrow-band radiation with a bandwidth $\Delta\nu \approx 30$ MHz near a central frequency $\nu = 1465$ MHz, or $\Delta\nu/\nu \approx 0.02$. Other spectra have broad bandwidths $\Delta\nu \geq 50$ MHz, or $\Delta\nu/\nu \geq 0.03$.

III. DISCUSSION

The highly polarized emission may be attributed to coherent radiation from an electron-cyclotron maser. The maser will radiate at harmonics, n, of the gyrofrequency $\nu_H = 2.8 \times 10^6 H$ Hz, where H is the magnetic field strength. Although the first harmonic may be absorbed in overlying atmospheric layers, the second harmonic can escape with up to 100% circular polarization (Melrose and Dulk 1982). For $n = 2$ and our observing frequency of $\nu = n\nu_H = 1.465 \times 10^9$ Hz, the required magnetic field strength is $H \approx 260$ G.

The electron-cyclotron maser emission is confined to a thin cone at large angles $\theta_0 = 70°$ to $85°$ with respect to the magnetic field. A narrow relative bandwidth of $\Delta\nu/\nu \approx \cos^2 \theta_0 \approx$ 0.01 to 0.10 is expected.

The observed bandwidth will depend on the gradient of the magnetic field and the size of the source. A sharper field gradient will produce a wider range of gyrofrequencies and a broader bandwidth, while a smaller source size will limit the magnetic field variation and produce a narrower bandwidth.

If the emission is confined to magnetic loops like those on the Sun, then the magnetic scale height $L_H \approx 10^9$ cm. Such a scale height is plausible for coronal loops on YZ Canis Minoris

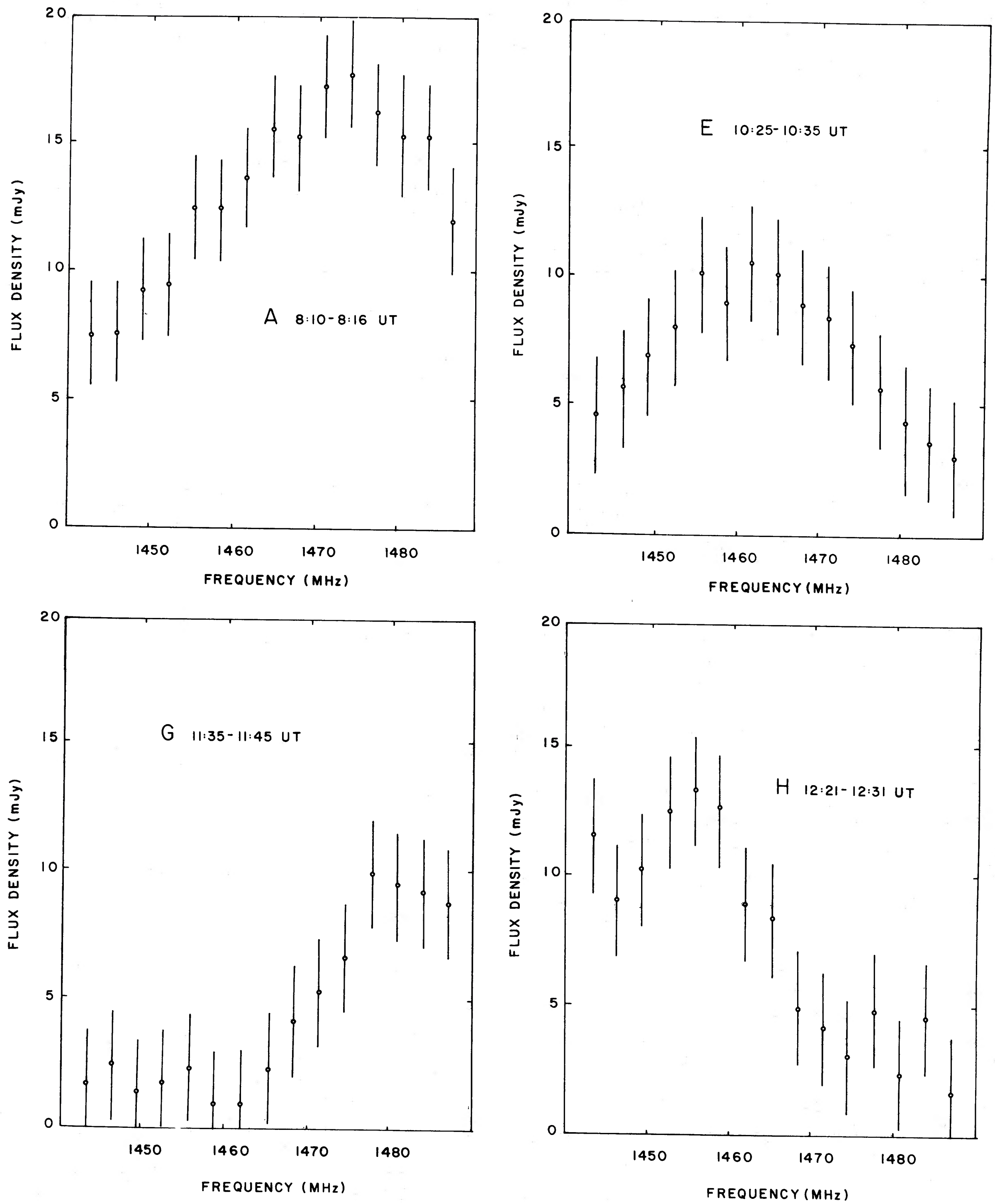

FIG. 2.—Frequency spectra of the left circularly polarized radiation from YZ Canis Minoris for the intervals marked A, E, G, and H in Fig. 1. Here we have plotted the total intensity received in 15 contiguous channels, each 3.125 MHz wide, during the time interval denoted on each plot. The observed value is plotted as a small circle with two vertical bars, each denoting the 3 σ noise level for the relevant time interval and bandwidth. These spectra have been grouped together because they all show evidence for narrow-band radiation with a bandwidth $\Delta\nu \approx 30$ MHz near a central frequency $\nu = 1465$ MHz, or $\Delta\nu/\nu \approx 0.02$.

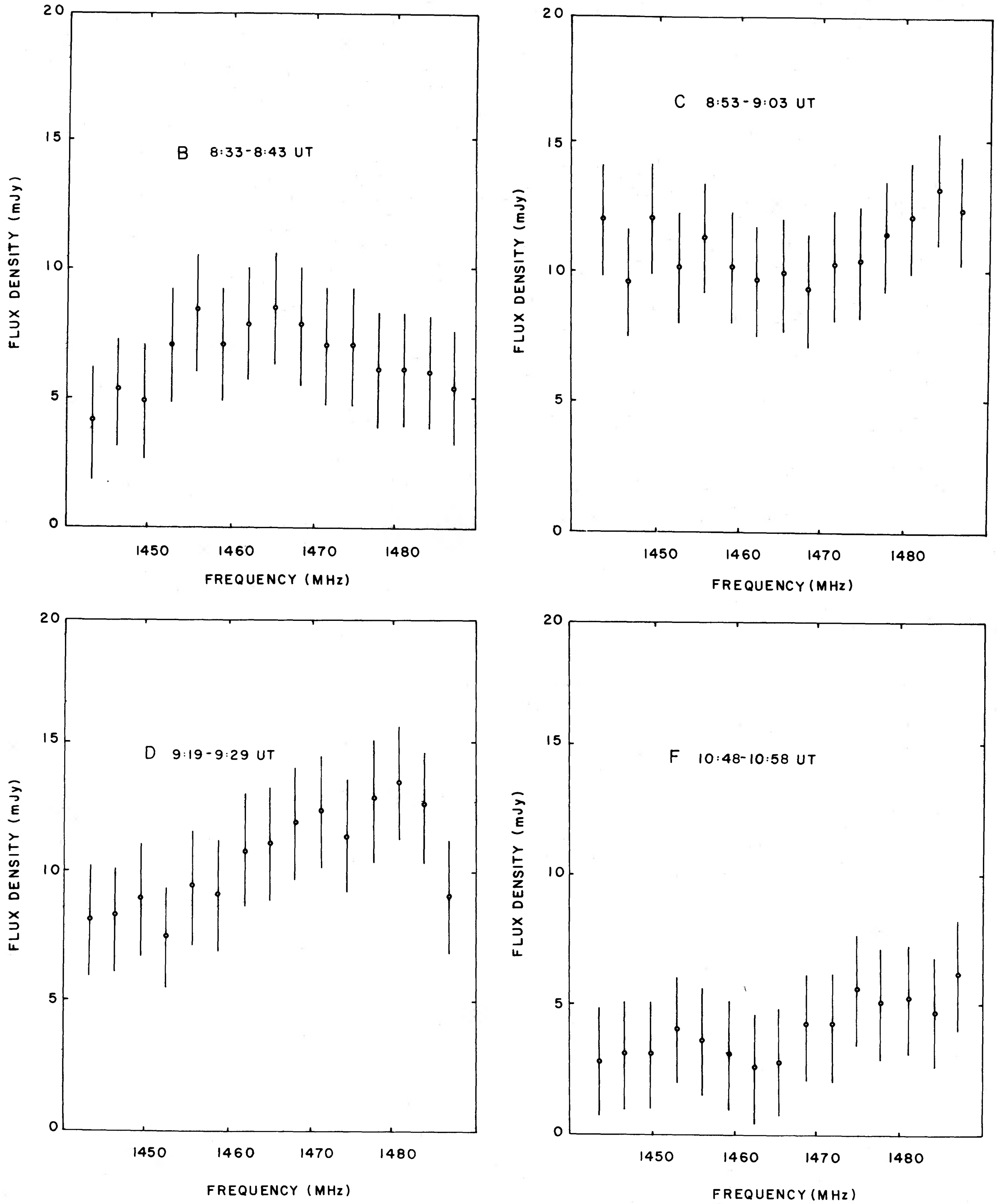

FIG. 3.—Frequency spectra of the left circularly polarized radiation from YZ Canis Minoris for the intervals marked B, C, D, and F in Fig. 1. Here we have plotted the total intensity received in 15 contiguous channels, each 3.125 MHz wide, during the time interval denoted on each plot. The observed value is plotted as a small circle with two vertical bars, each denoting the 3 σ noise level for the relevant time interval and bandwidth. These spectra have been grouped together because they all show evidence for broad-band radiation with a bandwidth $\Delta\nu \geq 50$ MHz near a central frequency $\nu = 1465$ MHz, or $\Delta\nu/\nu \geq 0.03$.

whose radius $R \approx 2.6 \times 10^{10}$ cm (Pettersen 1980). The size, L_s, of the masing source with a 30 MHz bandwidth is then given by

$$L_s = L_H \frac{\Delta\nu}{\nu} \approx 2 \times 10^7 \text{ cm} , \qquad (1)$$

and its brightness temperature, T_B, is

$$T_B \approx 10^{13} \frac{SD^2}{\nu^2 L_s{}^2} \approx 0.5 \times 10^{17} \text{ K} , \qquad (2)$$

where the flux density $S = 0.015$ Jy, the star's distance $D = 1.8 \times 10^{19}$ cm, our observing frequency $\nu = 1.465 \times 10^9$ Hz, and $L_s = 2 \times 10^7$ cm. Melrose and Dulk (1982) have shown that an electron-cyclotron maser can produce similar brightness temperatures of $T_B = 10^{16}$ to 10^{17} K.

Of course, the broad-band radiation from YZ Canis Minoris can also be attributed to coherent radiation from an electron-cyclotron maser. The 10 minute spectra may have averaged over several narrow-band bursts of short duration and different central frequencies, thereby producing broad-band spectra. In fact, microwave spikes emitted during solar burst have short durations of $\tau_D \leq 10$ ms, high brightness temperatures of $T_B \geq 10^{12}$ K, and relative bandwidths of $\Delta\nu/\nu \approx 0.015$ (Benz 1985), and these spike bursts have been attributed to electron-cyclotron maser emission (Holman, Eichler, and Kundu 1980). Decimetric bursts from the dwarf M star AD Leonis are also composed of millisecond spikes with rise times of $\tau_R \leq 5$ ms and durations of $\tau_D \leq 10$ ms (Lang and Willson 1986*a*). Such spikes would not be resolved with the 10 s integration time at the VLA.

In fact, the interesting aspect of the narrow-band radiation from YZ Canis Minoris is that is persists for 10 minutes with a well-defined bandwidth and central frequency. If this radiation is composed of bursts with shorter duration, they have to be coming from a region in which there is no substantial change of physical parameters such as height, size, magnetic field strength, and electron density. A substantial change in height, size, or magnetic field strength would produce a drift in the central frequency which is not observed. If there is any drift it has to be slower than 0.05 MHz s^{-1}. A substantial increase in the electron density above $N_e \approx 6 \times 10^9$ cm^{-3} would make the plasma frequency ν_p exceed the gyrofrequency, and plasma radiation would dominate the emission.

As discussed by Lang and Willson (1986*a*, *b*) and by Bastian and Bookbinder (1987), an alternative coherent process might be plasma radiation. Solar type II, III, and IVM bursts as well as weaker narrow-band decimetric bursts or blips with $\Delta\nu/\nu \leq 0.1$ have been attributed to plasma radiation (Furst, Benz, and Hirth 1982; Benz, Bernold, and Dennis 1983). As pointed out by Bastian and Bookbinder (1987) one difficulty with this interpretation is that plasma radiation tends to rapidly drift toward lower frequencies as the disturbance travels outward into the lower density corona. The drift rate, $\Delta\nu/\Delta t \approx 0.5 U_b \nu/H_g$, where U_b is the velocity of the distrubance and H_g is the scale height. For $H_g \approx 10^{10}$ cm, $\nu = 1465$ MHz, and $\Delta\nu/\Delta t < 0.5$ MHz s^{-1}, we require that $U_b < 7$ km s^{-1}, or about 30–200 times slower that the speeds observed in moving type IV bursts (Robinson 1978). For higher speeds, the frequency drift rate is correspondingly higher and would give rise to an apparently broad-band spectrum.

Finally, we also note that YZ Canis Minoris appears to undergo nearly continuous coherent burst activity for periods as long as 4 hr (see Fig. 1). The "quiescent" microwave emission of some dwarf M stars might therefore be due to the superposition of many low-level coherent bursts. Similar continued low-level variability has been reported for the X-ray emission from dwarf M stars (Butler *et al.* 1986; Ambruster, Sciortino, and Golub 1987). The continued variability might well be related to emerging magnetic flux that plays a role in heating the stellar coronae. It is interesting to note that Melrose and Dulk (1982) have shown that cyclotron maser emission at the second harmonic may heat the overlying coronal plasma to $T_e \approx 3 \times 10^7$ K, thereby giving rise to X-ray bursts.

Radio astronomical studies of the Sun and other nearby active stars at Tufts University are supported under grant AFOSR-83-0019 with the Air Force Office of Scientific Research. Related solar observations are supported by contract N00014-86-K-0068 with the Office of Naval Research (ONR). The Very Large Array is operated by Associated Universities, Inc., under contract with the National Science Foundation.

REFERENCES

Ambruster, C. W., Sciortino, S., and Golub, L. 1987, *Ap. J. Suppl.*, **65**, 273.
Bastian, T. S., and Bookbinder, J. A. 1987, *Nature*, **326**, 678.
Benz, A. O. 1985, *Solar Phys.*, **96**, 357.
Benz, A. O., Bernold, T. E. X., and Dennis, B. R. 1983, *Ap. J.*, **271**, 355.
Butler, C. J., Rodono, M., Foing, B. H., and Haisch, B. M., 1986, *Nature*, **321**, 679.
Furst, E., Benz, A. O., and Hirth, W. 1982, *Astr. Ap.*, **107**, 178.
Holman, G. D., Eichler, D., and Kundu, M. R., 1980, in *IAU Symposium 86, Radio Physics of the Sun*, ed. M. Kundu and T. Gergely (Dordrecht: Reidel), p. 457.
Jackson, P. D., Kundu, M. R., and White, S. M., 1987, *Ap. J.* (*Letters*), **316**, L85.
Lang, K. R., Bookbinder, J., Golub, L., and Davis, M. M. 1983, *Ap. J.* (*Letters*), **272**, L15.
Lang, K. R., and Willson, R. F. 1986*a*, *Ap. J.*, **305**, 363.
———. 1986*b*, *Ap. J.* (*Letters*), **302**, L17.
Melrose, D. B., and Dulk, G. A. 1982, *Ap. J.*, **259**, 844.
Pettersen, B. R. 1980, *Astr. Ap.*, **82**, 53.
Robinson, R. D. 1978, *Solar Phys.*, **60**, 383.
White, S. M., Kundu, M. R., and Jackson, P. D. 1986, *Ap. J.*, **311**, 814.

KENNETH R. LANG and ROBERT F. WILLSON: Department of Physics and Astronomy, Robinson Hall, Tufts University, Medford, MA 02155