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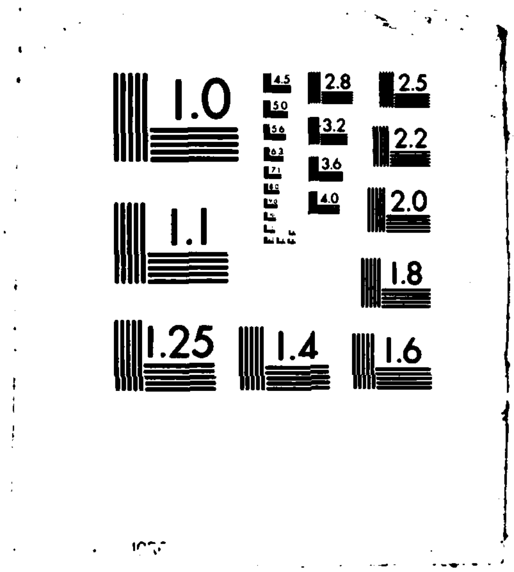

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RADIO WAVELENGTH OBSERVATIONS OF MAGNETIC FIELDS ON ACTIVE DWARF-M, RS CVN AND MAGNETIC STARS*

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ABSTRACT

The dwarf M stars YZ Canis Minoris and AD Leonis exhibit narrow-band, slowly varying (hours) microwave emission that cannot be explained by conventional thermal radiation mechanisms. The dwarf M stars AD Leonis and Wolf 424 emit rapid spikes whose high brightness temperatures similarly require a nonthermal radiation process, ~~We attribute them to~~ which coherent mechanisms such as an electron-cyclotron maser or coherent plasma radiation. If the electron-cyclotron maser emits at the second or third harmonic of the gyrofrequency, the coronal magnetic field strength H = 250 G or 167 G and constraints on the plasma frequency imply an electron density of $N_e = 6 \times 10^9$ cm^{-3}. Coherent plasma radiation requires similar values of electron density but much weaker magnetic fields. Radio spikes from AD Leonis and Wolf 424 have rise times $\tau_R < 5$ ms, indicating a linear size of $L < 1.5 \times 10^8$ cm, or less than 0.005 of the stellar radius. Although Ap magnetic stars have strong dipole magnetic fields, they exhibit no detectable gyroresonant radiation, suggesting that these stars do not have hot, dense coronae. The binary RS CVn star UX Arietis exhibits variable emission at 6 cm wavelength on time scales ranging from 30 s to more than one hour. The shortest variation implies a linear size much less than that of the halo observed by VLBI techniques, and most probably sizes smaller than those of the component stars. The observed variations might be due to absorption by a thermal plasma located between the stars.

DWARF M FLARE STARS

The dwarf M flare stars exhibit relatively weak microwave bursts (a few tenths of one Jy) with a rate comparable to that of optically visible flares from the same stars. Quiescent, or nonflaring, microwave emission has also now been detected from several dwarf M stars using the Very Large Array (VLA). These stars exhibit quiescent X-ray emission whose absolute luminosity may be as much as 100 times that of the Sun. Both the microwave and the X-ray emission suggest that dwarf M stars have hot stellar coronae and large-scale coronal loops with strong magnetic fields. In this section we will demonstrate that both the quiescent microwave emission and the microwave bursts from dwarf M stars cannot be attributed to thermal radiation mechanisms. The required non-thermal emission processes can provide stringent constraints on the electron density and magnetic field strength in the stellar coronae.

What accounts for the slowly varying microwave emission from dwarf M stars? 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 flux density is at least two orders of magnitude below the detection threshold of the VLA. Thermal electrons gyrating about large-scale magnetic fields might emit detectable gyroresonant, or cyclotron, radiation. The radiation will be emitted in gyroresonant layers that lie outside the visible star at a radius, R, given by the Rayleigh-Jeans law /1/

$$R^2 = 10^{13} \frac{SD^2}{\nu^2} \text{ cm}^2 , \qquad (1)$$

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

$$\nu = 2.8 \times 10^6 \; nH \; Hz \qquad (2)$$

where n is the maximum harmonic for which the stellar corona still remains optically thick.

Gyroresonance radiation of thermal electrons in extensive coronae was once believed to be the most likely explanation for the slowly varying quiescent emission of dwarf M flare stars. Values of R amounting to a few stellar radii were obtained following detection of low flux densities at 6 cm wavelength, and gigantic coronal loops of about three times larger than the visible star were envisaged. However, we have now detected stronger slowly-varying emission at longer wavelengths (20 cm) from YZ Canis Minoris /2/. Substituting the relevant data ($S = 0.02$ Jy, $D = 5.99$ pc $= 1.8 \times 10^{19}$ cm, $\nu = 1.5 \times 10^9$ Hz and $T = 10^6$ K) into equation 1, we obtain $R = 5.4 \times 10^{12}$ cm, which is 200 times larger than the visible star's radius. Strong, large-scale magnetic fields extending out to 200 stellar radii are inconceivable.

Our observations of narrow-band structure from YZ Canis Minoris additionally rule out a thermal radiation mechanism for its slowly-varying microwave emission /2/. Moreover, other observers subsequently found narrow-band structure in hour-long variations from AD Leonis and shorter bursts from UV Ceti /3/. The narrow-band radiation has bandwidth $\Delta\nu < 0.1\ \nu$. Continuum emission processes like thermal bremsstrahlung, thermal gyroresonant radiation or gyrosynchrotron radiation will not normally exhibit such spectral features. Coherent radiation processes like electron-cyclotron masers can give rise to the observed narrow-band structure, but before explaining these processes we will provide additional evidence for coherent burst emission from dwarf M stars.

After several hours of observation at the Arecibo Observatory, a stellar eruption was detected from AD Leonis at 20 cm wavelength with a maximum flux density of 30 mJy. The burst was composed of highly left-handed circularly polarized (100%) spikes with rise times of $\tau_R < 200$ ms. An upper limit to the linear size $L < 6 \times 10^9$ cm, and a brightness temperature of $T_B < 10^{13}$ K (symmetric emitter) were inferred from these rise times /4/.

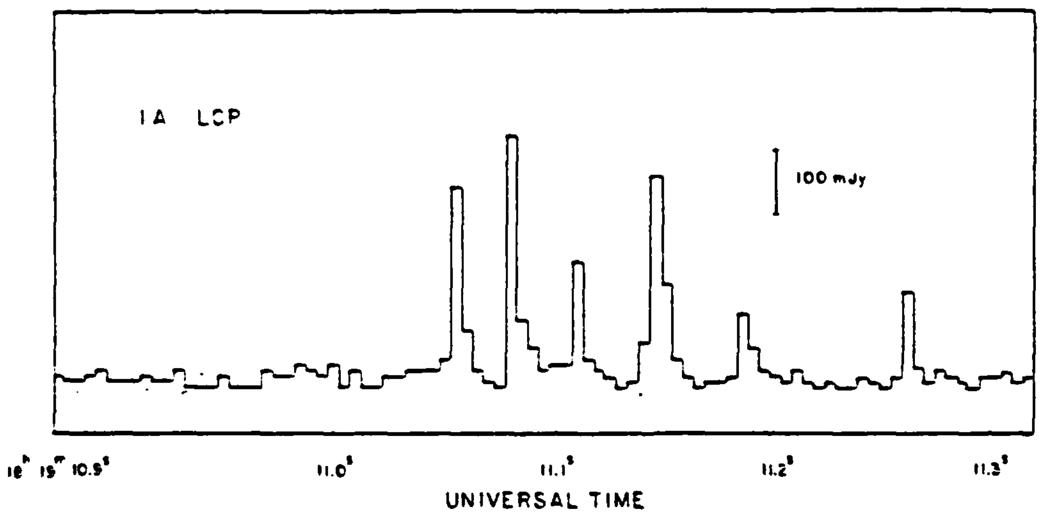

Fig. 1. The total power detected at a frequency of 1415 MHz (21.2 cm) while tracking the dwarf M star AD Leonis. The left-hand circularly polarized (LCP) signal has been displayed with a 5 ms integration time. There are five quasi-periodic spikes with a mean periodicity of $\tau_P = 32 \pm 5$ ms and a total duration of $\tau_D = 150$ ms. Each of these spikes had a rise time of $\tau_R < 5$ ms, leading to an upper limit to the linear size $L < 1.5 \times 10^8$ cm for the spike emitter. A symmetric source of this size would have a brightness temperature of $T_B > 10^{16}$ K, requiring a coherent radiation mechanism.

As illustrated in Figure 1, subsequent Arecibo observations resulted in the detection of quasi-periodic, highly polarized spikes at 20 cm wavelength from AD Leonis /5/. The spikes had rise times of $\tau_R < 5$ ms. An upper limit to the linear size of the spike emitting region is $L < 1.5 \times 10^8$ cm, the distance that light travels in 5 milliseconds. This size is only five hundredths of the estimated radius of AD Leonis. Provided that the emitter is symmetric, it has a brightness temperature greater than 10^{16} K.

We have subsequently detected spikes of shorter rise time $\tau_R = 0.1$ s from AD Leonis that are 100% right-hand circularly polarized, as well as spikes from Wolf 424 with rise times $\tau_R < 5$ ms. All of these spikes require high brightness temperatures in excess of 10^{13} K. The high degrees of circular polarization (up to 100%) indicate an intimate connection with the star's magnetic field, and the high brightness temperatures suggest a coherent radiation mechanism such as an electron-cyclotron maser or coherent plasma radiation. The coherent process provides constraints on the electron density, N_e, and the magnetic field strength, H, in the stellar coronae /6/. If the electron-cyclotron maser emits at the second or third harmonic of the gyrofrequency, the longitudinal magnetic field H = 250 G or 167 G and constraints on the plasma frequency imply an electron density of $N_e = 6 \times 10^9$ cm^{-3}. Although we do not know the harmonic with certainty, the high circular polarization requires a strong magnetic field, and high harmonics provide slow growth and insufficient optical depth. Coherent plasma radiation at the first or second harmonic of the plasma frequency respectively require $N_e = 2 \times 10^{10}$ cm^{-3} and H << 500 G or $N_e = 6 \times 10^9$ cm^{-3} and H << 250 G.

MAGNETIC STARS

Although we have ruled out thermal gyroresonant radiation from dwarf M stars, such radiation might be detected from the magnetic stars that have large, strong magnetic fields /7/. These stars have magnetic field strengths of a few hundred to a few thousand gauss. The observed field strengths vary in a roughly sinusoidal fashion with periods in the range of 1 to 10 days. Most of these magnetic stars also vary in brightness and have spectral lines that vary in strength; the period of variation is always the same as the magnetic period. The magnetic variations are explained by a dipolar magnetic field that is frozen into the rotating star. As the star rotates, the observer sees different aspects of the magnetic geometry. It is typically dipolar with two magnetic poles of opposite sign and unequal strength.

Detailed calculations indicate that the gyroresonant layers lie fully outside the star and form closed surfaces around it /8/. The degree of circular polarization depends on the angle between the line of sight and the axis of the magnetic dipole. The magnetic field strength can be inferred from the harmonic of the gyrofrequency. As an example, the magnetic stars ε Ursae Majoris and α^2 Canum Venaticorum have maximum magnetic field strengths of 960 and 3.500 gauss respectively, and respective distances of 20.0 and 43.5 parsecs. For these parameters and assuming an electron temperature $T_e = 10^7$ K, and electron density $N_e = 10^9$ cm^{-3}, the computed flux density for gyroresonant emission at $\nu = 10$ GHz is 0.8 mJy.

We have observed the 11 magnetic stars listed in Table 1 with the VLA for at least one hour each at 6 cm wavelength. No emission was detected from these stars at a 3 sigma level of about 0.2 mJy (see Table). The results indicate that strong surface magnetic fields are not sufficient to produce detectable radio emission. The magnetic Ap stars probably do not have the hot, dense coronae and stellar winds required to produce significant radio luminosity. In contrast, radio emission has been detected from at least two helium-rich, magnetic variable Bp stars with kilogauss photospheric fields (σ Ori E and HR 1890) /8/.

THE RS CVN STAR UX ARIETIS

As illustrated in Figure 2, the binary RS CVn star UX Arietis exhibits variable emission at 6 cm wavelength on time scales ranging from 30 s to more than one hour /8/. In contrast, the flux at 20 cm wavelength had a nearly constant value of about 30 mJy. From the shortest variations of 30 s, we place an upper limit of $L < 9 \times 10^{11}$ cm for the size of the emitting region under the assumption that the source cannot move faster than the velocity of light. This size is four times smaller than that of the halo component obtained from 6 cm VLBI observations, but comparable to the upper limit given by VLBI for the core component.

Velocities considerably below the velocity of light are most likely. For example, plausible magnetic field strengths of H = 10-100 gauss and electron densities of $N_e = 10^7$-10^8 cm^{-3}, result in an Alfven velocity of 2×10^8 cm s^{-1} $< V_A < 7 \times 10^9$ cm s^{-1}. This implies a source size of $L = 6 \times 10^9$ cm to 2×10^{11} cm and a brightness temperature of $T_B > 10^{11}$ K to $T_B > 10^{13}$ K for the rapid 30 s variations. These sizes are small compared to the separation between the two stars ($L = 1.4 \times 10^{12}$ cm) and to the sizes of the stars themselves ($L = 1.4 \times 10^{11}$ cm and 4.2×10^{11} cm).

A model that might explain the relatively abrupt variations of less than 10-20 minutes is one in which the variable emission is absorbed by a thermal plasma lying between the two stars. High temperature plasma may reside in coronal loops which are comparable in size to the binary system. Absorption of radio emission from one component of UX Arietis by the thermal plasma in coronal loops lying along the line of sight might then explain both the variations at 6 cm and the absence of variations at 20 cm wavelength /9/.

Table 1. Upper limits at the 3 sigma level to the 6 cm flux density, S, of magnetic stars that exhibit no detectable radiation at this wavelength.

STAR NAME	m_v	P (days)	H (gauss)	D (pc)	S (mJy)
α Andromedae	2.1	0.9636	500	41.6	0.23
ι Cassiopeiae	4.5	1.7405	1030	47.6	0.35
53 Camelopardi	6.0	8.0278	17000	7.0	0.21
30H Ursae Majoris	5.0	11.58	1200	25.0	0.20
γ Virginis	3.0	—	436	9.9	0.15
ε Ursae Majoris	1.8	50.0887	960	20.0	0.25
α^2 Canum Venaticorum	2.9	5.4694	3500	43.5	0.20
ι Librae	4.5	—	300	43.5	0.20
β Coronae Borealis	3.7	18.4870	6100	32.3	0.18
χ Serpentis	5.3	1.5958	1840	33.3	0.20
γ Equulei	4.7	—	3500	47.6	0.23

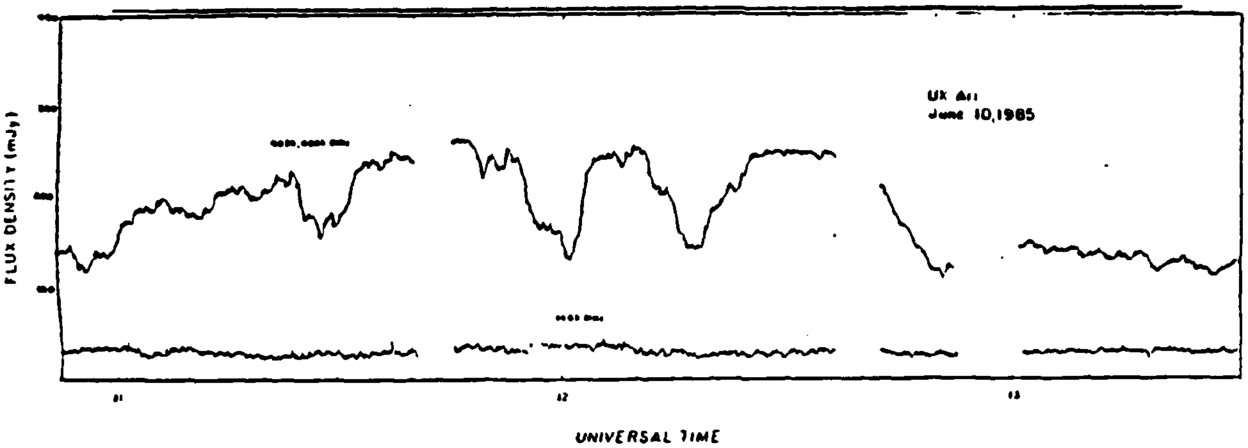

Fig. 2. A plot of the total intensity, I, observed at 1465 MHz, 4835 MHz, and 4885 MHz from the RS CVn star UX Arietis on June 10, 1985. The visibility data were phase shifted to the source center and then vector averaged, baseline by baseline, over a 6.67 s interval to produce these time profiles.

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