ULTRAHIGH TIME RESOLUTION OBSERVATIONS OF RADIO BURSTS ON AD LEONIS

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ABSTRACT

We report observations of a radio burst that occurred on the flare star AD Leonis over a frequency range of 1120–1620 MHz (\(\lambda \approx 18–27\) cm). These observations, made by the 305 m telescope of the Arecibo Observatory, are unique in providing the highest time resolution (1 ms) and broadest spectral coverage (\(\Delta \nu/\nu = 0.36\)) of a stellar radio burst yet obtained. The burst was observed on 2005 April 9. It produced a peak flux density of \(~500\) mJy, and it was essentially 100% right-circularly polarized. The dynamic spectrum shows a rich variety of structure: patchy emission, diffuse bands, and narrowband, fast-drift striae. Focusing our attention on the fast-drift striae, we consider the possible role of dispersion, and find that it requires rather special conditions in the source to be a significant factor. We suggest that the emission may be due to the cyclotron maser instability, a mechanism known to occur in planetary magnetospheres. We briefly explore possible implications of this possibility.

Subject headings: radio continuum: stars — stars: activity — stars: coronae — stars: late-type

1. INTRODUCTION

The use of radio dynamic spectra has played a central role in identifying and clarifying the physical mechanisms at work in the solar corona (see McLean & Labrum 1985 for reviews). The application of similar techniques to active stars has long been an important goal, but it has been hampered by limitations in available instrumentation. Past studies of radio emission from M dwarf flare stars led to the discovery of extreme stellar radio bursts, characterized by close to 100% circularly polarized emission with brightness temperatures in excess of \(10^{14}\) K and durations less than a few tens of milliseconds (Güdel et al. 1989; Bastian et al. 1990). However, these spectroscopic investigations of the coherent radio bursts on flare stars have typically been limited by relatively long integration times (Bastian & Bookbinder 1987; Güdel et al. 1989) and/or limited frequency bandwidth ratios \(\Delta \nu/\nu\) (usually just a few percent; e.g., Bastian et al. 1990; Abada-Simon et al. 1997). The necessary combination of high time resolution and a large frequency bandwidth ratio has only been available infrequently (Stepanov et al. 2001; Zaitsev et al. 2004), precluding measurements of key parameters such as the intrinsic bandwidth of the radio bursts, and making the interpretation of these puzzling events difficult. It is only with the recent advent of radio spectrometers capable of simultaneously supporting both a large bandwidth ratio and high time resolution that progress in understanding the physics of radio bursts in the coronas of other stars has become possible.

AD Leonis, a young disk star at a distance of 4.9 pc from the Sun, is one of the most active flare stars known, producing intense, quasi-steady chromospheric and coronal emissions (Hawley et al. 2003; Hüensch et al. 1999; Jackson et al. 1989) seen at UV, X-ray, and radio wavelengths. The star is also highly variable, producing flares from radio to X-ray wavelengths (e.g., Bastian et al. 1990; Hawley & Pettersen 1991; Hawley et al. 2003, 1995; Favata et al. 2000). Its propensity for frequent and extreme radio bursts (with intensities peaking at >500 times the quiescent radio luminosity of \(5.5 \times 10^{13}\) erg s\(^{-1}\) Hz\(^{-1}\); Jackson et al. 1989) makes it a frequent target for radio investigations of stellar flares. In a previous paper (Osten & Bastian 2006, hereafter Paper I), we described the initiative of a pilot program to observe active M dwarfs with the Arecibo Observatory’s Wideband Arecibo Pulsar Processor (WAPP), and first results from that program. Here we describe the next phase, which increased the time resolution by a factor of 10 to 1 ms.

2. OBSERVATIONS

We observed AD Leo with the 305 m telescope at Arecibo Observatory\(^2\) on each of four days from 2005 April 8 to April 11, during which approximately 4 × 4 hr of data were collected. The observations were made using the “L-band wide” dual-linear feed and receiver (1100–1700 MHz) with the WAPP back end. The WAPP was selected because it provides the means of observing a large instantaneous bandwidth with excellent spectral and temporal resolution. The WAPP provides four data channels, each of 100 MHz bandwidth. These were deployed across the L-band wide receiver as follows: 1120–1220 MHz, 1320–1420 MHz, 1420–1520 MHz, and 1520–1620 MHz. A gap was deliberately left between 1220 and 1320 MHz to avoid the strong radio frequency interference (RFI) present in this frequency range. Nevertheless, the effects of other sources of RFI could not be entirely avoided in the frequency bands observed. We employed a data acquisition mode in which data were sampled with a time resolution of 1 ms; 128 spectral channels were sampled across each 100 MHz channel, yielding a spectral resolution of 0.78 MHz. All four correlation products were recorded within the native linear X and Y feed elements (XX, YY, XY, and YX) with three-level sampling. Our observing strategy was to observe the target, 2 The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.
A spectacular radio burst occurred on 2005 April 9 at approximately 01:15:40 UT. An overview of the event is shown in Figure 1 with a time resolution of 100 ms. Note the data gap between 1220 and 1320 MHz, and the horizontal features due to RFI. The radio burst is essentially 100% right-circularly polarized (RCP; Fig. 1a). The emission is bounded in frequency from above, the upper limit ranging from ≈1200 to 1600 MHz. The low-frequency limit of the emission is unknown because of a lower limit imposed by the spectrometer. The emission presumably extends well below 1120 MHz.

While the burst was only ≈45 s in duration, it was observed with a time resolution of 1 ms. In the following, we confine our attention to only a small part of the data, which nevertheless shows a rich variety of spectral signatures. The horizontal bar shown in Figure 1, spanning the most intense RCP emission, indicates the 10 s interval shown in Figure 2 with a time resolution of 10 ms. The four consecutive 2 s time intervals labeled A–D in Figure 2 are, in turn, shown with 1 ms time resolution in Figure 3. It is readily apparent that the radio emission is spectrally and temporally complex. Details of time intervals a–d are shown in Figures 4–8 over restricted bands, but with 1 ms time resolution.

Figure 4 is of particular interest. It shows a 0.75 s interval of the spectrum corresponding to time interval “a” in Figure 3a. The frequency interval shown is 1120–1220 MHz. An intense series of striae are visible, drifting from high to low frequencies with time.

It is difficult to determine whether an underlying diffuse component exists or whether the striae recur so fast that they overlap and merge. It is therefore difficult to isolate and characterize the bandwidths and durations of single striae. Nevertheless, their durations have been constrained in aggregate as follows: first, the spectrum was smoothed in the time channel by channel using a 50 ms running mean. Second, the smoothed spectrum was subtracted from the observed spectrum, yielding a residual spectrum containing the rapidly varying striae. Third, to improve the signal-to-noise ratio (S/N), the residual spectrum was then “corrected” for the frequency drift of the striae by progressively shifting each channel in time to yield vertical striae. Note that if the drift rate were due to group delay, this operation would be referred to as de-dispersion; however, see § 4.1. It is found that a range of drift rates is present in the striae, corresponding to delays of 43–48 ms.
per 100 MHz. The mean delay is 45 ms per 100 MHz. Therefore, the mean drift rate is $-2.2 \, \text{GHz s}^{-1}$, with an observed range of $-2.33$ to $-2.08 \, \text{GHz s}^{-1}$. Finally, the drift-corrected residual spectrum was frequency averaged over the central 70 (RFI-free) channels. All striae with a S/N > 4 were accumulated, totaling 32 in all. These have a mean FWHM duration of $t \approx 2 \, \text{ms}$. A limit on the intrinsic source size $d$ follows by noting that $d < c t \approx 600 \, \text{km}$. Coupled with the frequency drift rate of the striae, the mean duration implies a mean instantaneous bandwidth of $4.4 \, \text{MHz}$, or $\frac{1}{1000}$: $5\%$. The recurrence rate of the striae is $>40 \, \text{s}^{-1}$ in this example.

Turning to other examples, Figure 5 also shows 0.75 s of data (interval “b” in Fig. 3b) from 1120 to 1220 MHz. The emission at this time, only 2 s after interval “a”, is far more diffuse than that shown in Figure 4, although fast-drift structure is still visible. Figure 6 shows 0.5 s of data (interval “c” in Fig. 3c). Here, a frequency range of 1320 to 1620 MHz is shown. The emission is relatively diffuse; no striae are obviously present. The emission is frequency bounded from above and below throughout the interval. The instantaneous frequency bandwidth varies from $\frac{1}{1000}$ to $180 \, \text{MHz}$ ($\frac{1}{1000}$: $5\%$ to $14\%$). Figure 7 also shows a 0.5 s interval and a frequency range of 1120 to 1220 MHz (interval “d1” in Fig. 3d). This interval is striking in the abrupt onset and cessation of each patch of emission, and the crisply defined lower boundary to the frequency of emission. At least two patches are resolved in frequency, near 01:15:47.37 and 01:15:47.56 UT. These have bandwidths of 25 and $\frac{1}{1000}$: $2.2\%$, respectively), the latter patch showing signs of band-limited striae. The other patches may likewise be composed of overlapping striae drifting from high to low frequency in the same sense as displayed in interval “a”. The upper frequency boundary is not known for the other patches because of the presence of the data gap between 1220 and 1320 MHz, but it is less than 1320 MHz.

Finally, Figure 8 again shows 0.5 s of data, but from 1320 to 1520 MHz, which corresponds to the interval “d2” in Figure 3d. Here, the emission is patchy and diffuse, with some striae superposed, again with the same sense of drift as noted in prior intervals. Apparent frequency bandwidths range from $\sim 5 \, \text{MHz}$ to $\sim 200 \, \text{MHz}$ ($\Delta \nu/\nu \sim 0.5\%$–14\%).

While these observations exploited the largest frequency-bandwidth ratio currently available (36%), the bandwidth is still insufficient to detect possible low-order harmonics of the emission because the ratio of the highest to the lowest frequency

![Fig. 3.—Details of the RCP spectrum shown in Fig. 2. Each panel A–D shows 2 s of data with the full time resolution of 1 ms.](image1)

![Fig. 4.—Detail of the RCP spectrum indicated by the bar (“a”) in Fig. 3a. The frequency range is 1120–1220 MHz, the time interval is 0.75 s, and the time resolution is 1 ms. The upper panel shows the time variation of flux density at the frequencies indicated. Note the fast-drift striations.](image2)

![Fig. 5.—Detail of the RCP spectrum as indicated by the bar (“b”) in Fig. 3b. The frequency range is 1120–1220 MHz, the time interval is 0.75 s, and the time resolution is 1 ms. Here the emission is relatively diffuse.](image3)
sampled is only 1.45:1. While higher harmonic ratios, e.g. 4:3, could in principle be detected, there is no evidence for such harmonic relations in the data. Therefore, no constraints on the emission mechanism are possible on the basis of harmonic structure.

To summarize, a variety of spectral structures—fast-drift striae, discrete patches, and diffuse emission—are seen in the few seconds of data presented here. The striae show a remarkably uniform drift rate of 2.2 GHz s\(^{-1}\). The durations of the striae, typically \(\approx 2\) ms, imply dynamical source sizes \(\approx 0.2\%\) of the stellar radius. The spectral features are resolved in frequency, showing bandwidths ranging from \(\leq 0.5\%\) to as much as 14\%. Where drifting structures appear to be present, the sense of the drift is the same: the emission starts at high frequencies and proceeds to lower frequencies. The signatures appear only in RCP emission, indicating a high degree of circular polarization.

4. DISCUSSION

In this section, we focus our attention on the striae shown in Figure 4, since their properties—flux density, drift rate, mean duration, and mean bandwidth—are well constrained. We first consider whether the observed spectral features, notably the rapid frequency drift with time, could result from dispersion of the signal in the plasma due to group delay. We also consider propagation effects such as scintillation. We conclude that it is unlikely that propagation effects play a significant role. We then consider the relevant emission mechanism. We argue that, in contrast to the fast-drift bursts presented in Paper I, the striae bursts in the present case are unlikely to be the result of plasma radiation from electron beams, and suggest that they may be due to the action of the cyclotron maser instability (CMI). We comment on the other burst phenomena at the end of the section.

4.1. Propagation Effects

As a radio wave traverses a plasma medium, it propagates at the group velocity \(v_g = \mu c\), where \(\mu = (1 - \nu_{pe}^2/v^2)^{1/2}\) is the refractive index, \(\nu_{pe} = e^2n_e/m_e c\) is the electron plasma frequency, \(n_e\) is the electron number density in the plasma medium, \(e\) is the electron charge, and \(m_e\) is the electron mass. If a radio signal emitted at a frequency \(\nu\) is received at a distance \(d\) from the source, the delay in reception relative to a signal traversing the same distance in vacuo is

\[
\Delta t = \frac{1}{c} \int_0^d \left( \frac{1}{\mu} - 1 \right) \, dr.
\]
We first consider the stellar corona, and assume that the variation in electron number density can be described by a barometric model: $n_e(r) = n_0 \exp(-r/\lambda_n)$, where $\lambda_n$ is the number density scale height. If we assume that the observed emission is fundamental plasma radiation emitted at $r = R$, then the group delay equation can be recast (Wild et al. 1959), integrating from the location of the source emission to $\infty$, as

$$\Delta t = \frac{2\lambda_n}{c} \int_0^1 \frac{d\mu}{1 + \mu} = \frac{2\lambda_n}{c} \log 2 - \frac{2\lambda_n}{c}.$$  

(2)

Under these circumstances, the delay is frequency independent, and an observed frequency drift can be attributed to source motion (Paper I).

On the other hand, if the emission occurs at frequencies well above the local plasma frequency ($\nu \gg \nu_{pe}$), then $1/\mu \approx 1 + \nu_{pe}^2/2\nu^2$, and the relative delay between two frequencies can be written as

$$\Delta t = \frac{1}{c} \int \frac{1}{\mu(\nu_1) - \mu(\nu_2)} d\nu = \frac{e^2}{2\pi m_e c} \left[ \frac{1}{\nu_1^2} - \frac{1}{\nu_2^2} \right] \int \frac{n_e(r) dr}{\mu(\nu)},$$  

(3)

where the integral quantity is commonly referred to as the dispersion measure. Supposing the source is intrinsically broadband and located at least 3$\lambda$ above the plasma level where $n_0 = n_0 \approx 1.7 \times 10^{10} \text{ cm}^{-3}$, which corresponds to a plasma frequency of 1170 MHz, $\Delta t < 1.3 \times 10^{-13} \text{ s}$. Taking $\lambda_n \approx 10^{10} \text{ cm}$, $\Delta t < 1.3 \text{ ms}$ across the 100 MHz bandwidth, which is far less than the 45 ms observed in the straia described above. It is also worth considering the additional delay introduced by the interstellar medium (ISM). With a mean density of 0.1 cm$^{-3}$ (Cox & Reynolds 1987) and a distance to AD Leo of 4.9 pc, we find that the incremental delay resulting from propagation through the ISM is only 0.25 ms across the 100 MHz band.

In fact, rather special conditions are required to account for the observed frequency drift in terms of impulsive broadband signals and group delay. The relative delay between two frequencies $\nu_1$ and $\nu_2$ within a source at a height $r$ is

$$\Delta t = \frac{2\lambda_n}{c} \int \frac{\mu(r)}{1 + \mu} d\mu = \frac{2\lambda_n}{c} \log \left[ \frac{1 + \mu_2}{1 + \mu_1} \right].$$  

(4)

where $\mu_1$ and $\mu_2$ are the refractive index at $r$ for frequencies $\nu_1$ and $\nu_2$. We find that the observed delay of 45 ms between 1120 and 1220 MHz can occur if the mean frequency of the band is $\approx 20\%$ above the plasma frequency $\nu_{pe} \approx 0.97 \text{ GHz}$, where $\mu \approx 0.55$.

For completeness, we mention that the presence of a magnetic field renders a plasma birefringent and causes radiation at a fixed frequency to show a differential delay between the ordinary and extraordinary modes, which corresponds to a delay between RCP and LCP emissions. At frequencies where $\nu \gg \nu_{pe}$ and $\nu_{Ba}$, the differential group delay between RCP and LCP over a path from the region of source emission to observation is (Benz & Pianezzi 1997; Fleishman et al. 2002a, 2002b)

$$\Delta t = \int \left[ \frac{1}{\nu_1} - \frac{1}{\nu_o} \right] d\nu = \frac{2\lambda_n}{c} \frac{\nu_{pe}^2 \nu_{Ba} \cos \theta}{\nu^3},$$  

(5)

where $\nu_{Ba} = eB/2\pi m_e c$ is the electron gyrofrequency, and $\theta$ is the angle between the magnetic field and the line of sight. For the observations under consideration, the emission is essentially 100% RCP, discrete LCP features being indistinguishable from background. Hence, any differential delay between RCP and LCP is unmeasurable. Future observations of moderately polarized bursts with sufficient time resolution and frequency coverage may be able to exploit this technique.

We now briefly consider additional propagation effects that may influence the observed dynamic spectra. Turbulent interstellar plasma can produce scattering of radio waves propagating from pointlike sources; for objects with sufficiently high transverse velocity and/or sufficiently long path length through the scattering medium, amplitude modulations, pulse broadening, and frequency smearing can occur. The slow amplitude variations of pulsars, maser sources, and compact cores of active galactic nuclei, among other sources, have been identified as examples of refractive interstellar scintillation (RISS; see discussion in Rickett 1990). Diffractions interstellar scintillation (DISS) occurs in the limit of strong scattering from small-scale irregularities in interstellar plasma, and corresponds to deep modulations in time and frequency. Dynamic spectra of pulsars reveal bands drifting in frequency and time, as well as csscrisscrossed and periodic bands of emission, which qualitatively resemble some of the features seen in AD Leo’s dynamic spectrum; these features have been explained qualitatively by refractive steering of a DISS pattern (Rickett 1990).

Could the observed spectral structure be due to scintillation as a result of propagation through the stellar corona and/or the ISM? Sources must be compact for either phenomenon (RISS or DISS) to occur. The small intrinsic source size implied by the extremely short durations of the observed emissions ($d < 600 \text{ km}$) suggests an angular size $\theta \sim d/D \lesssim 1 \mu\text{as}$. The intensity of RISS varies relatively (temporally) slowly, and its polarization should not change (Rickett 1990); it is thus inconsistent with the emission properties described earlier. DISS is usually seen in two-dimensional dynamic spectra; analysis of the two-dimensional Fourier transform of dynamic spectra reveals discrete structures that are typically explained as interference between two or more scattered images. Scintillation arcs due to DISS in pulsar dynamic spectra are a broadband phenomenon, having been observed over a factor of $\approx 5$ in frequency (Pulse broadening due to multi-path scattering in the ISM can be estimated using equation (6) in Cordes & McLaughlin (2003) and Cordes & Lazio (2001) which, for a dispersion measure of 0.5 pc cm$^{-3}$, is $\approx 10^{-10}$ s, and therefore negligible. The scintillation bandwidth is inversely related to the pulse broadening time and can be estimated as $\Delta t_d \approx 1600 \text{ MHz}$. In addition, the scintillation timescale can be estimated from the transverse velocity of the star, and is $\approx 5000 \text{ s}$. The timescale of the phenomena seen in pulsar dynamic spectra is typically much longer than that of the emission seen here, and is broadband as well. Thus, the characteristics of the observed emission are incompatible with both RISS and DISS.

Alternatively, the density inhomogeneities in the stellar corona may yield scintillation phenomena. This possibility has been investigated in the case of solar radio emission and coronal turbulence (Bastian 1994; Uralov 1998). However, it can be dismissed by the following argument: to observe diffractive scintillation requires enough temporal and spectral resolution to resolve the decorrelation time and bandwidth, respectively. The decorrelation time for a point source embedded in the corona of AD Leo is $\tau_d \sim d^2 D^2/2cz$, $d$ is the distance to AD Leo, $\theta_c \sim d^2 D^2$ is the (angular) source size, $D$ is the (linear) source size estimated in § 2, and $z$ is the distance from the source to the effective scattering plane. Bastian (1994) showed that $z \sim 0.1 R_\odot$ for solar coronal conditions; we assume that it is of similar magnitude here in relation to AD Leo’s radius and find that
The small instantaneous bandwidth of the striae observed here implies that if fundamental plasma radiation is the relevant emission mechanism, Langmuir waves are excited over a small range of densities at any given time. In particular, $\Delta n_e/n_e = 2\Delta\nu/\nu \lesssim 1\%$; then if $n_e = n_0 \exp(-r/\lambda_e)$, we have $\Delta n_e/n_e \approx \delta s/\lambda_e$, or $\delta s \lesssim 0.01\lambda_e$, where $\delta s$ is the extent of the exciter along its trajectory. Again, with $\lambda_e \sim 10^{16}$ cm, $\delta s \lesssim 1000$ km, which is consistent with previous estimates of the source size. Moreover, if the duration of discrete striae is determined by collisional damping, a relatively cool source, only 1.5 MK for fundamental plasma radiation, is implied. While relatively cool plasma does exist in the corona of AD Leo (van den Besselaar et al. 2003), the assumption that the emission is fundamental plasma radiation implies a relatively dense source, with $n_0 \sim 2$. The picture to emerge is one in which the striae are excited by a succession of tiny blobs, each a few hundred km in size, in a relatively cool, dense plasma. A significant problem with this idea is that if the source were in such a cool, dense plasma, the optical depth $\tau$ of the overlying plasma due to collisional absorption would be extremely large, with $\tau \sim 300(\lambda_e/10^{10})$ (e.g., Benz 2002). In this case, it would be difficult to understand the escape of the radiation at all, let alone the extremely high brightness temperature of the bursts, unless $\lambda_e$ is at least 2 orders of magnitude smaller than assumed, as perhaps might be possible in a highly inhomogeneous corona. This idea cannot be correct, however. The striae are observed to drift in frequency at a rate of 2.2 GHz s$^{-1}$. The drift rate is $\nu = \nu_{pe}\nu_{th}/2\lambda_e \approx \nu_{th}/2\lambda_e$, where $\nu_{th}$ is the speed of the blobs presumed to excite Langmuir waves, and $\nu \approx \nu_{pe}$. Then, if $\lambda_e \sim 10^8$ cm, we infer that $\nu_{th} \sim 3800$ km s$^{-1}$, which is comparable to the thermal speed of the ambient electrons with $T \sim 1.5$ MK, and an instability that produces the necessary Langmuir waves is not expected.

On these grounds, therefore, we question the relevance of plasma radiation to the stria described here. What is the alternative? One possibility is clearly the cyclotron maser instability (CMI), a mechanism widely believed to play a significant role in planetary magnetospheres (see the recent review by Treumann 2006 and references therein) and long suspected of playing a role in the radio emission from the Sun (Melrose & Dulk 1982), stellar coronae (e.g., Bastian & Bookbinder 1987; Güdel et al. 1989; Bastian et al. 1990; Abada-Simon et al. 1994; Bingham et al. 2001), and, more recently, in the coronae of extremely late-type stellar and substellar objects (e.g., Hallinan et al. 2007). The CMI is a resonant wave-particle phenomenon, the resonance being between electromagnetic waves and magnetized electrons. The source of free energy for the process is an anisotropy in the electron distribution function that produces a positive gradient with respect to the perpendicular momentum: $d\phi/dP_{\perp} > 0$. In its simplest form, the anisotropy is assumed to take the form of a loss-cone distribution, as might be set up in closed coronal magnetic loops. However, work over many years in the context of terrestrial and planetary radio emissions has greatly extended and refined our knowledge about the conditions under which the CMI is operative. Treumann (2006) reviews the extensive in situ observations that have been made in the terrestrial magnetosphere over the past two decades. These demonstrate that loss cone anisotropies are not the dominant driver of the CMI; instead “shell” or “horseshoe” distributions are relevant, with magnetic field–aligned electric fields playing a central role in setting up the distribution that provides the free energy to the CMI (e.g., Ergun et al. 2000). Moreover, the CMI occurs in density cavities where $\nu_{pe} \ll \nu_{Be}$. Here, $\nu_{Be} = eB/2\pi m_e c \approx 2.8B_1$ GHz, and $B_1$ is the magnitude of the magnetic field in kG. We note that if the CMI is the relevant mechanism, with $\nu_{pe} \ll \nu_{Be}$, group delay is insignificant, and the observed drifts are intrinsic to the source.
The CMI leads to direct amplification of electromagnetic waves, producing intense, coherent radiation at the fundamental, or possibly the harmonic, of the (relativistic) electron gyrofrequency $v_{ce}/\gamma$. The radiation is emitted in a narrow angular range perpendicular to the magnetic field for horseshoe distributions. The extraordinary ($X$) mode is generally favored over the ordinary ($O$) mode for growth by the CMI, thereby explaining the high degree of circular polarization. Its frequency bandwidth is expected to be on the order of 1% or less, although broader frequency bandwidths can be accommodated with higher energy electrons. It is expected to achieve brightness temperatures in excess of $10^{18}$ K. These attributes are collectively consistent with the observations of the striae.

What about the drift rate of the striae? In recent years, there has been great interest in the fine structure seen in CMI emission in the terrestrial case, driving speculation concerning the role of "elementary radiation sources." Perhaps analogous to the striae seen on AD Leo is the so-called striped or striated terrestrial auroral kilometric radiation (AKR; see, e.g., examples presented by Menietti et al. 1996, 2000; Pottelette et al. 2001; Mutel et al. 2006, 2007). Pottelette et al. argue that such fine structure may be due to localized solititary structures such as electron phase space holes. Recently, Mutel et al. (2007) challenged the relevance of electron holes, showing that ion holes may be the more likely cause of AKR fine structure. The steep gradients set up in the local distribution function by these holes may contribute intense, elementary sources of radiation (see Teo et al. 2006 for a detailed discussion).

The frequency drift of AKR fine structures is interpreted as the propagation speed of these elementary radiation sources along the magnetic field in the source. Speeds on the order of 500 km s$^{-1}$ are inferred for the case of AKR fine structures. Applying this to the case of the striae on AD Leo, the drift rate is presumed to be intrinsic to the source, and therefore represents motion of the source along the magnetic field gradient: $\nu \propto \dot{B} = \dot{v} \mathbf{B}$. If the magnetic field can be described as dipolar, $\dot{B} = B_0 (\lambda_B/r)^2$, where $\lambda_B$ is the characteristic scale of the dipole field, and the observed frequency is the local electron gyrofrequency, the speed of the exciter can be written $\nu \approx 47 B_0^{1/3} \nu v^{4/3}$. With $\nu$ and $\dot{v}$ known, this becomes $\nu \approx 0.084 B_0^{1/3}$. Assuming that each stria represents an elementary radiation source, capping the speed of these sources to be less than that of the emitting electrons ($\sim 10$ keV) suggests that $v < 6 \times 10^{5}$ km s$^{-1}$, and so ($\lambda_B/r_*) B_0^{1/3} < 2.4$, where $r_*$ is the radius of AD Leo ($4.4 R_\odot$). For $B_0 = 500$–$2000$ G, we find that $\lambda_B \lesssim (0.2$–$0.3) r_*$. We conclude that the fast-drift striae may be compatible with the CMI mechanism if the magnetic field in the source is described by a magnetic field with scale comparable to a large "active region" rather than a global dipole field.

If the CMI mechanism is indeed relevant, the problem first pointed out by Melrose & Dulk (1982) and reiterated in Paper I remains: How does the radiation escape from the source to a distant observer? CMI radiation emitted near the fundamental of the electron gyrofrequency suffers catastrophic absorption at the second gyroresonant harmonic layer of the atmosphere. Ergun et al. (2000) argue, however, that because the CMI operates in a density cavity in the terrestrial case, the surrounding plasma acts as a duct. Rapid refraction and scattering of CMI radiation cause it to emerge more nearly parallel to the magnetic field. Alternatively, Robinson (1989) has suggested that conditions may be favorable for partial mode conversion in CMI sources. In particular, fundamental $X$-mode radiation amplified by the CMI undergoes partial conversion to fundamental $O$-mode. The optical depth to $O$-mode radiation can be several hundred times less than that to $X$-mode. This process does not require significant scattering or refraction of the emitted radiation. Whether either of these processes in fact occurs in the corona of AD Leo cannot be answered by the observations in the present case.

5. CONCLUDING REMARKS

We have described observations of a unique set of stellar radio bursts that take advantage of the wide bandwidth and high time resolution capabilities of the WAPP at the Arecibo Observatory. These ultrahigh time resolution observations reveal phenomena that differ from those previously described using a similar observational setup, which points out the complexity and diversity of processes likely occurring in stellar coronal plasmas. Whereas in Paper I we concluded that a plasma emission process appeared to be producing the two types of radio bursts observed in 2003 June, in the current paper we prefer a different explanation, a cyclotron maser instability, for the fast-drift striae observed in 2005 April. While all sets of phenomena show drifting structures of highly circularly polarized radiation, key discriminants between them are the durations and bandwidths of spectral features, as well as the magnitude and sign of the drift rates.

In Paper I and here, we have demonstrated that the analysis of dynamic spectra of stellar radio bursts provides observational constraints that can be used as a measure to gauge the likelihood that a particular emission process is operative. Extensions of the current observational setup can look for dynamics at even higher time resolution, search for harmonic emissions over larger frequency bandwidths, expand the observational program to other dMe flare stars, and search for high time resolution behavior on other classes of active stars. Given the complexity of solar radio emissions at meter wavelengths compared with the already rich variation of decimetric phenomena, the observational results presented here for the dMe flare star AD Leo suggest that the next generation of radio instrumentation, particularly at metric wavelengths, promises to reveal a wealth of new phenomena that can diagnose plasma processes occurring in stellar coronae. As highly circularly polarized radio emission appears to be a common phenomenon on active stars, these spectacular radio bursts on dMe flare stars apparently represent the tip of the iceberg of stellar coronal plasma physics soon to be available for study.

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REFERENCES

Abada-Simon, M., Lecacheux, A., Aubier, M., & Bookbinder, J. A. 1997, A&A, 321, 841
Abada-Simon, M., Lecacheux, A., Louarn, P., Dulk, G. A., Belkora, L., Bookbinder, J. A., & Rosolen, C. 1994, A&A, 288, 219
Bastian, T. S. 1994, ApJ, 426, 774
Bastian, T. S., & Bookbinder, J. A. 1987, Nature, 326, 678
Bastian, T. S., Bookbinder, J. A., Dulk, G. A., & Davis, M. 1990, ApJ, 353, 265
Benz, A. O., 2002, Plasma Astrophysics: Kinetic Processes in Solar and Stellar Coronae (2nd ed.; Dordrecht: Kluwer)
Benz, A. O., & Pianezzi, P. 1997, A&A, 323, 250
Bingham, R., Cairns, R. A., & Kellett, B. J. 2001, A&A, 370, 1000
Cordes, J. M., & Lazio, T. J. W. 2001, ApJ, 549, 997
Cordes, J. M., & McLaughlin, M. A. 2003, ApJ, 596, 1142
Cox, D. P., & Reynolds, R. J. 1987, ARA&A, 25, 303

Cordes, J. M., & Lazio, T. J. W. 2001, ApJ, 549, 997
Cordes, J. M., & McLaughlin, M. A. 2003, ApJ, 596, 1142
Cox, D. P., & Reynolds, R. J. 1987, ARA&A, 25, 303
Ergun, R. E., Carlson, C. W., McFadden, J. P., Delory, G. T., Strangeway, R. J., & Pritchett, P. L. 2000, ApJ, 538, 456
Favata, F., Micela, G., & Reale, F. 2000, A&A, 354, 1021
Fleishman, G. D., Fu, Q. J., Huang, G.-L., Melnikov, V. F., & Wang, M. 2002a, A&A, 385, 671
Fleishman, G. D., Fu, Q. J., Wang, M., Huang, G.-L., & Melnikov, V. F. 2002b, Phys. Rev. Lett., 88, 1101
Güdel, M., & Benz, A. O. 1990, A&A, 231, 202
Güdel, M., Benz, A. O., Bastian, T. S., Furst, E., Sinnett, G. M., & Davis, R. J. 1989, A&A, 220, L5
Hallinan, G., et al. 2007, ApJ, 663, L25
Hawley, S. L., & Pettersen, B. R. 1991, ApJ, 378, 725
Hawley, S. L., et al. 1995, ApJ, 453, 464
———. 2003, ApJ, 597, 535
Hill, A. S., Stinebring, D. R., Barnor, H. A., Berwick, D. E., & Webber, A. B. 2003, ApJ, 599, 457
Hünsch, M., Schmitt, J. H. M. M., Sterzik, M. F., & Voges, W. 1999, A&AS, 135, 319
Jackson, P. D., Kundu, M. R., & White, S. M. 1989, A&A, 210, 284
Lee, L. C. 1977, ApJ, 218, 468
Maggio, A., Drake, J. J., Kashyap, V., Hardeen, F. R., Jr., Micela, G., Peres, G., & Sciortino, S. 2004, ApJ, 613, 548
McLean, D. J., & Labrum, N. R. 1985, Solar Radiophysics: Studies of Emission from the Sun at Metre Wavelengths (Cambridge: Cambridge Univ. Press)
Melrose, D. B., & Dulk, G. A. 1982, ApJ, 259, 844
Menietti, J. D., Pizzuto, A., Pickett, J., & Gurnett, D. 2000, J. Geophys. Res., 105, 18857
Menietti, J. D., Wong, H. K., Kurth, W. S., Gurnett, D. A., Granroth, L. J., & Groene, J. B. 1996, J. Geophys. Res., 101, 10673
Mutel, R. L., Menietti, J. D., Christopher, I. W., Gurnett, D. A., & Cook, J. M. 2006, J. Geophys. Res. Space Phys., 111, 10203
Mutel, R. L., Peterson, W. M., Jaeger, T. R., & Scudder, J. D. 2007, J. Geophys. Res. Space Phys., 112, 7211
Osten, R. A., & Bastian, T. S. 2006, ApJ, 637, 1016 (Paper 1)
Pottelette, R., Treumann, R. A., & Berthomier, M. 2001, J. Geophys. Res., 106, 8465
Rickett, B. J. 1990, ARA&A, 28, 561
Robinson, P. A. 1989, ApJ, 341, L99
Seiradakis, J. H., Avgoloupis, S., Mavridis, L. N., Varvoglis, P., & Fuerst, E. 1995, A&A, 295, 123
Stepanov, A. V., Kliem, B., Zaitsev, V. V., Fürst, E., Jessner, A., Krüger, A., Hildebrandt, J., & Schmitt, J. H. M. M. 2001, A&A, 374, 1072
Treumann, R. A. 2006, Astron. Astrophys. Rev., 13, 229
Uralov, A. M. 1998, Sol. Phys., 183, 133
van den Besselaar, E. J. M., Raassen, A. J. J., Mewe, R., van der Meer, R. L. J., Güdel, M., & Audard, M. 2003, A&A, 411, 587
Wild, J. P., Sheridan, K. V., & Neylan, A. A. 1959, Australian J. Phys., 12, 369
Zaitsev, V. V., Kislyakov, A. G., Stepanov, A. V., Kliem, B., & Fürst, E. 2004, Astron. Lett., 30, 319