AN UNUSUAL MICROWAVE FLARE WITH 56 SECOND OSCILLATIONS ON THE M DWARF L726-8 A

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ABSTRACT

Using the VLA, we have observed an unusual flare event on L726-8 A (dM5.5e), the primary star in the M dwarf system containing the prototype flare star UV Cet. This flare had a peak flux of 8 mJy at 6 cm and a corresponding brightness temperature \( \gtrsim 10^{10} \) K, was almost entirely right-hand circularly polarized, showed large flux variations on the 10 s time resolution of the VLA, and exhibited quasi-periodic oscillations with a period of about 56 ± 5 s. While periodic flux variations have been detected during solar flares and RS CVn type stellar flares, this is the first detection to our knowledge of periodicity in microwaves from M dwarf stars. We propose that the observed radiation was due to maser action, probably an electron-cyclotron maser, and that the energy release mechanism was modulated.

Subject headings: radio sources: variable — stars: coronae — stars: flare — stars: late-type — stars: radio radiation — Sun: radio radiation

I. INTRODUCTION

The binary system L726-8 is 2.6 pc distant and consists of a dM5.5e primary star (L726-8 A) and a dM6e secondary star (UV Cet) now separated by 1.29 (Worley and Behall 1973; Fisher 1982). UV Cet was the first flare star discovered, and numerous optical, radio, and X-ray flares have been reported. Four radio flares were observed on the primary star (L726-8 A) at 6 and 20 cm by Fisher (1982). Quiescent emission from UV Cet was discovered by Gary and Linsky (1981) and confirmed by Fisher (1982), but no quiescent emission above the 0.2 mJy detection limit has been reported for L726-8 A. In § II, we present observations of an unusual flare from the L726-8 system that shows quasi-periodic variations in flux with time. In § III, we discuss some of the possible interpretations of the observations and examine what they tell us about the physical conditions in the source region.

II. OBSERVATIONS

On 1981 October 16, we observed the L726-8 system at a frequency of 4.9 GHz (6 cm wavelength) from 0420 to 1040 UT with the Very Large Array (VLA) of the National Radio Astronomy Observatory near Socorro, New Mexico (Thompson et al. 1980). The VLA was in the C configuration with a maximum baseline of 3.37 km and a synthesized beamwidth of 3\'8 at 4.9 GHz. The observations were made using 21 antennas and were calibrated in phase and flux by observing nearby calibration sources every 30 minutes throughout the observing period.

Synthesized maps using 5 minute integrations were made in both right and left circular polarizations with the aim of monitoring slow variations in the flux and polarization of the quiescent emission from UV Cet. We will discuss these observations of quiescent emission in a subsequent paper, but report in this Letter on an unusual radio flare that occurred during the time of our observations. This flare appeared on three of the 5 minute maps (Fig. 1a) as an increase in flux from the base level of about 4 mJy (1 mJy = 10^{-29} W m^{-2} Hz^{-1}) up to a peak of 8 mJy, with the source being strongly right-hand circularly polarized. To obtain better information on the temporal structure of the flare, we then made separate maps for each 10 s of data.

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**Fig. 1.**—(a) 4.9 GHz flux of L726-8 in right-hand (RH) and left-hand (LH) circular polarization taken from VLA maps of 5 minute integration time. Most of the emission is from UV Cet, but the flare emission from 0650 to 0703 UT is mainly from the primary star, L726-8 A (see text). (b) Flare flux profiles as in (a) but taken from VLA maps of 10 s integration time. Error bars indicate the typical 1σ rms noise level. For maps on which no source was visible, the 3σ noise level has been plotted as a plus sign. In the LH flux curve, fluxes denoted by dots were taken from 1 minute integrated maps. Dots with arrows denote upper limits.

— the smallest time segment possible. The resulting flux curves, for righthand (RH) and left-hand (LH) flux are shown in Figure 1b. Here we use the convention

\[ S' = \frac{S_R + S_L}{2} = \frac{k}{\lambda^2} \left( \int d\Omega R_T^R + \int d\Omega L_T^L \right), \]

where \( k \) is Boltzmann’s constant, \( d\Omega \) is the differential solid angle, \( T_b \) is the brightness temperature, and the superscripts \( I, R, \) and \( L \) denote total intensity and RH and LH polarizations, respectively. The RH curve exhibits quasi-periodic variations that are significantly greater than the rms noise level, shown as error bars in the figure. The period of these variations is about 56 ± 5 s, and each peak exhibits roughly equal rise and fall times of 20 s. The degree of circular polarization during the entire event remained greater than 40% and was higher than 82% during the two brightest peaks.

The phase center for the maps was R.A. = 01°36′32.6″, decl. = −18°12′24″3″, which was the observed position of UV Cet on a previous observing run (1981 June 19). The synthesized beamwidth was about twice the separation of the two components of L726-8, and the maps were gridded such that there were three cells per beamwidth (1.25 per cell). We noticed that the peak of the quiescent emission was located in the center of the maps before and after the flare, but that the flare source itself appeared to be shifted to the southwest. Providing that the signal-to-noise ratio is large, the relative position of a source can be determined to within about a tenth of a beamwidth (about a third of a cell) by measuring the centroid of the source. We did this for each map and found a definite shift in position, when the flare was present, of 173 ± 074 at position angle 240° ± 20°. The small amount of scatter in the centroid positions from map to map, especially for the flare maps, convincingly showed the shift to be real. The orbit of Worley and Behall (1973) was used by Fisher (1982) to find the relative positions of L726-8 A and B and produced an excellent fit to his VLA observations, which were made with ~1′0 resolution. He found that L726-8 A is 1″9 from UV Cet at a position angle of 243°. Comparison of the magnitude of our observed shift (1.6 ± 074 when one takes into account the continuing quiescent emission from UV Cet) and position angle demonstrates that the flare occurred on L726-8 A.

**III. DISCUSSION**

A flare with quasi-periodic variations in the 2.7 GHz radio flux was reported by Brown and Crane (1978) for the RS CVn system HR 1099. Its characteristics were similar to those of the present flare despite the differences between the short-period RS CVn systems, where interaction between stars is of prime importance (cf. Simon, Linsky, and Schiffer 1980), and the widely spaced L726-8 system, where no interactions are likely. The HR 1099 flare exhibited intensity fluctuations of 120–240 mJy which were highly circularly polarized and had a well-defined period of about 4 minutes. The number of events such as that and the present one is difficult to assess since most other observations of radio flares are not easily compared to ours. Until the VLA became available, the noise level of most of the radio observations was greater than about 20 mJy, so that flares with flux levels like we report here would not be detected, much less any quasi-periodic fluctuations.

The literature contains many reports of quasi-periodic variations in emission from solar flares at wavelengths from gamma-rays to decametric waves. The period of variation of most events is typically a few seconds in the solar case compared with about 1 minute in our case.
Below, we consider two possible explanations of the variations in this flare: (a) that they result from a modulation of the source emissivity caused by an external agent, and (b) that they are due to a modulation of the energy release mechanism.

**a) Modulation of Source**

Large solar flares generally consist of two phases—the initial (impulsive) phase and the second (gradual) phase. The impulsive part of a solar flare frequently exhibits spikes and strong fluctuations with time (e.g., Dennis, Frost, and Orwig 1981) but seldom with any periodicity. (Chupp et al. 1981 reported one example of an 8 s duration, quasi-periodic pulses in an impulsive flare observed in gamma-rays, X-rays, and microwaves.) However, numerous cases of quasi-periodic fluctuations have been reported in the gradual phase of solar flares, especially in decimeter and meter radio waves (Boisshot, Fokker, and Simon 1959; Abrami 1970; Rosenberg 1970; McLean et al. 1971), but occasionally in hard X-rays and microwaves (Hoying, Brown, and van Beek 1976; Karpen 1982). Klein et al. (1983) have attempted to link fluctuations in both X-ray and radio observations for the same flare.

The quasi-periodic fluctuations observed in solar decimeter and meter radio waves show a very small range of periods (1–3 s), continue for many cycles, and exhibit intensity variations both above and below the background intensity (see Wild and Smerd 1972 for a short review). This led Rosenberg (1970) to propose a mechanism whereby emission by particles in a radially oscillating magnetic loop is modulated at the oscillation frequency of the loop. McLean et al. (1971) proposed that shock waves excite these oscillations because type II bursts are usually observed together with continuum radiation. As Rosenberg (1970) showed, an ideal circular cross section magnetic flux tube will oscillate radially due to fast magnetosonic modes with a frequency given by the maxima of the first-order Bessel function $J_1(r\omega/u)$, where $r$ is the radius of cross section of the flux tube, $u$ is the characteristic speed of the excited wave (essentially the Alfvén speed, $v_A = B/\sqrt{4\pi\rho}$), and $\omega$ is the angular frequency of oscillation. The lowest frequency mode will occur for $r\omega/u \sim 1.8$, which, for solar parameters, gives a period of a few seconds in agreement with solar observations.

If a similar mechanism is to account for our observed period of $\sim 56$ s, we must have a loop of cross sectional radius $r = 16.0_{-0.1}^{+0.2}$ cm, where $v_A$ is the Alfvén speed expressed in cm/s. Assuming an Alfvén speed similar to that for the Sun ($\sim 10^8$ km s$^{-1}$), we find that the loop must have a cross sectional radius of $\sim 0.2$ solar radii. Remembering that the stars of the L726-8 system have radii of only $\sim 0.25$ solar radii and that magnetic field strengths of dMe stars are likely much larger than that of the Sun (Mullan 1974) so that the Alfvén speed is also likely to be larger, we conclude that radial oscillations of a flux tube via fast mode waves cannot account for our observed oscillation period.

Zaitsev and Stepánov (1975) and Meerson, Sasorov, and Stepánov (1978) pointed out a difficulty in Rosenberg's (1970) model. The latter authors noted that fast mode MHD waves are radiatively damped to such an extent that they cannot account for the long-lasting solar pulsations. They also pointed out that no similar damping exists for Alfvén and slow magnetoacoustic waves, and further that these waves can excite oscillations with periods defined not by the radius of a magnetic flux tube, but rather by its length $L \gg R$. Thus, a shock wave interacting with a magnetic loop of $L \approx 0.2$ solar radii could induce the loop to oscillate with a 56 s period via these waves. Brown and Hoying (1975) proposed a similar model that may successfully explain the quasi-periodic oscillations in hard X-rays from the large solar flare of 1972 August 4. In that case, the period was about 120 s, even longer than in the present case, and some characteristics of the radiation suggested that betatron acceleration was indeed occurring. Karpen, Crannell, and Frost (1979) found two other examples of long-lasting, quasi-periodic microwave and hard X-ray bursts that could be explained in a similar fashion.

We conclude that such oscillations of a flux tube are a possible candidate to explain the 56 s periodicity of the present event.

Another possible way to explain the oscillations is that a burst of particles is released into a closed magnetic structure, with a bounce time $\tau = L/v_p$, where $v_p$ is the speed of the particles ($\sim c/3$). This mechanism is attractive for the solar examples with $\tau \approx 1$ s, and Meerson et al. (1978) proposed a “bounce-resonance” to initiate the fast mode MHD waves in Rosenberg’s (1970) theory. Also, Brown and Crane (1978), trying to account for the $\sim 4$ minute oscillation period observed from HR 1099, suggested that particles bounce in a magnetic trap extending from one star of the RS CVn system to the other. However, this mechanism appears to be untenable in our case since the 56 s period would require a magnetic trap of dimension $L \approx 8$ solar radii.

**b) Modulation of Energy Release Mechanism**

A major disadvantage of the models above, which invoke modulation of incoherent gyrosynchrotron emission, is that they do not readily explain the high brightness temperature and circular polarization measured for the present flare. Brightness temperature is inversely proportional to source area, so even with a flux tube covering 0.12 of the stellar disk, the brightness temperature would still be $10^{10}$ K, implying an average energy for the emitting particles of greater than 1 MeV. How much greater depends on $\tau$, the optical thickness of the presumed gyrosynchrotron source, and is 1 MeV only if $\tau \sim 1$. Further, the magnetic field would have to be
relatively weak so that the presumed larger number of less energetic particles do not dominate the radiation. However, these characteristics are not compatible with the observed high degree of circular polarization, which requires low-energy particles and high magnetic field strengths (Dulk and Marsh 1982). Another difficulty is that the degree of polarization at the intensity peaks, where the particle energy is larger, should be less than in the valleys for the source modulation models, but no such effect was observed.

As an alternative we suggest that the radiation was due to maser action, in particular an electron-cyclotron maser. As was demonstrated by Melrose and Dulk (1982), a maser operating at the second harmonic of the cyclotron frequency is a favorable mechanism to explain those solar and stellar bursts having rapid variations, high brightness temperatures, and high degrees of circular polarization. Examples are the microwave spike bursts observed by Dröge (1977) and Slottje (1978, 1980), and the burst from the RS CVn binary observed by Brown and Crane (1978). In a wider context, this maser mechanism (but at the fundamental of the cyclotron frequency) can account for the bursts of terrestrial kilometric radiation and the decametric harmonic, the observed radiation at 4.9 GHz requires the harmonic will only be reabsorbed at the third harmonic, below. However, maser emission just above the second harmonic cannot be reabsorbed, and some or all of the radiation will escape provided that a loss cone anisotropy develops when the electrons with small pitch angles precipitate into high-density regions at the footpoints. The third condition is unlikely to be satisfied for maser emission at the fundamental of the cyclotron frequency, the required magnetic field would be 1750 gauss. The main difficulty here is that resonance absorption at the second harmonic level is likely to be severe; for the Sun, Melrose and Bulk (1982) estimated that when $\omega_p/\Omega_e > 0.3$, the radiation would be in the $p$-mode because the $x$-mode is suppressed (Wu and Lee 1979). If the radiation were at the fundamental of the cyclotron frequency, the required magnetic field would be 1750 gauss. The main difficulty here is that resonance absorption at the second harmonic level is likely to be severe; for the Sun, Melrose and Bulk (1982) estimated that when $\omega_p/\Omega_e > 0.3$, the radiation would be in the $p$-mode because the $x$-mode is suppressed (Wu and Lee 1979).

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To conclude, we have observed an unusual flare from the primary of the L726-8 binary system that exhibits quasi-periodic flux variations of a period of about 56 ± 5 s. The emission was highly RH circularly polarized with a brightness temperature estimated to be greater than $10^{14}$ K. We suggest that the polarization and high brightness temperature are most likely due to maser emission within a magnetic flux tube, which requires only a source of energetic particles elsewhere in the loop and a magnetic field strength in the source region of 875 gauss. The quasi-periodic nature of the flux variations remains unexplained but may be due to flux tube oscillations that modulate the maser action. This observation points out the capability of the VLA for making high sensitivity, high time resolution observations of stellar flares, with exciting new results.

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