RADIO EMISSION FROM CATACLYSMIC VARIABLES

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Abstract

The study of radio emission from cataclysmic variables (CVs) is a new and developing field. Radio emission from novae, recurrent novae, dwarf novae and each of the subclasses (AM Her and DQ Her) of magnetic CVs have now been reported and are reviewed here. These observations are shown to provide, in general, a probe of the structure of the CV on length scales typically $\gtrsim 10^{11}$cm. Radiation mechanisms, both incoherent and coherent, relevant to the observed radio emission are also discussed. These suggest that the red dwarf in AM Her and DQ Her is also magnetized and provides support for theories for the evolution of CVs which require a magnetized secondary star.

1. *Introduction*

Radio emission from the sun and other stars is, in general, several orders of magnitude weaker than their optical emission. The sun, in particular, is a weak radio emitter and its quiescent radio emission would not be detectable if it were a few parsecs away although its radio emission in flares, which are a factor $\backsim 10^2$ larger than the quiescent emission, would be detectable. It is therefore not surprising that radio observations of stars have

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developed only recently, with significant progress begun only after the opening of the Very Large Array (VLA), in New Mexico in 1981, which has sensitivities up to a 100 times greater than previous radio telescopes and has substantially improved angular resolution. A recent conference on "Radio Stars" (Hjellming and Gibson 1985) and timely review articles (Zheleznyakov 1983, Dulk 1985a, Kuijpers 1985) show that this is now a maturing subject.

Cataclysmic variables are binary star systems in which a white dwarf star accretes matter from a companion star. They have been subdivided into several classes: novae, recurrent novae, nova like variables and dwarf novae (Robinson 1976). An additional subclass consists of the magnetic CVs in which the white dwarf has a sufficiently strong magnetic field ($\gtrsim 10^5$gauss) which channels the flow of material near its surface. As is the case for stars in general, CVs are, if at all, weak emitters of radio emission. Although nova outbursts have been recorded with the naked eye for centuries, the first detection of radio emission from CVs was made, for novae in outburst, only relatively recently (Hjellming and Wade 1970). Subsequently several other CVs have been observed to be radio emitters and although the number of such systems detected is small (~ 10), each of the subclasses of CVs with the exception of nova-like variables has at least one reported radio emitter. This radio emission, for which a variety of emission mechanisms have been proposed, provides, in general, a probe of the large scale structure of the binary on scales $\gtrsim 10^{11}$cm. This length scale $\sim 10^{11}$cm is comparable to the orbital separation a of the two stars for typical orbital periods $P_{orb} \sim$ few hr and to the size of companion star. Similar emission mechanisms have also been suggested for other radio emitting binary star systems such as symbiotic stars (e.g. Michalitsianos 1984) and RS CVn stars (e.g. Brown and Crane 1978), but those binaries will not be discussed here.

2. *Radio Emission Mechanisms*

An important parameter for understanding radio emission is the brightness temperature T_b, the temperature of a black body which emits radio emission with the same specific intensity I_ν as observed at frequency ν. Thus in the Rayleigh-Jeans approximation, $h\nu \ll kT_b$, it follows that $I_\nu = kT_b \nu^2/c^2$. The flux density S_ν, per polarization, is given by

$$S_\nu = k(\nu^2/c^2) \int T_b \, d\Omega \qquad (1a)$$

where $d\Omega$ is the differential solid angle and the integral is over the projected area of the source. Hence for a source of radius ℓ at a distance d emitting radiation with a flux density S_ν:

$$\ell = 1\cdot 9\times10^{11} \left[\frac{d}{100pc}\right] \left[\frac{5GHz}{\nu}\right] \left[\frac{S_\nu}{mJy}\right]^{½} \left[\frac{10^9K}{T_b}\right]^{½} \text{ cm,} \qquad (1b)$$

where 1 mJy = 10^{-26} erg cm^{-2} s^{-1} Hz^{-1}. Since the minimum flux densities detectable with VLA are ~1mJy, for $T_b \lesssim 10^9$ K and d ~ 100 pc it follows that ℓ must be $\gtrsim 10^{11}$ cm in order for the source to be detectable.

If the effective temperature of the radiating electrons is T_{eff}, for a homogeneous and isolated source, it follows that (Kraus 1986, Dulk 1985a)

$$T_b = T_{eff} [1 - \exp(-\tau_\nu)] \qquad (2)$$

where τ_ν is the optical depth. Hence the maximum brightness temperature that can be achieved is $T_b=T_{eff}$ which occurs for $\tau_\nu \gg 1$. This result is not valid for plasmas which are not in equilibrium (Kuijpers 1985).

The optical depth is $\tau_\nu=\alpha_\nu L$, where $L \sim \ell$ is the path length through *the plasma and* α_ν *is the absorption coefficient. The principal processes* responsible for absorption, and hence emission, are in general due to bremsstrahlung absorption and if magnetic fields are present due to cyclotron or gyrosynchrotron absorption. If the emission at frequency ν is due to gyrosynchrotron emission at harmonic number s in a magnetic field B it follows that

$$s = 17.9 \left[\frac{\nu}{5GHz}\right] \left[\frac{100gauss}{B}\right]. \qquad (3)$$

Since bremsstrahlung absorption is a collisional process it is more important in dense plasmas whereas gyrosynchrotron emission is more important in *dilute and more energetic plasmas (Kuijpers 1985).* Furthermore, bremsstrahlung may be important at low viewing angles θ with the magnetic field and high frequencies (Barrett and Chanmugam 1985) since cyclotron opacities decrease drastically at high frequencies and as $\theta \to 0$.

If $T_b \gtrsim 10^{12}$K, the inverse Compton limit, the emission must be coherent. Similarly if $T_b \gtrsim 10^{10}$K and the radiation has a high degree of circular polarization the emission must be coherent (Dulk 1985b). A high degree of circular polarization also implies that the emission is at low cyclotron harmonics (s~1).

TABLE 1. Cataclysmic Variable Radio Sources

Name	Type	Frequency (GHz)	Maximum Flux Density (mJy)	Mechanism	References
Nova Per 1901	N	4.835	8.4	S	1
		1.465	18.6		
HR Del 1967	N	31.6	230	B	2,3
		8.085	73		
		2.695	23		
FH Ser 1970	N	90	550	B	2,3
		31.6	250		
		8.085	53		
		2.695	13		
V 1500 Cyg 1975	N	90.0	260	B	3,4
		22.5	67		
		8.085	36		
		4.995	17		
		2.695	9		
Nova Aql 1982	N	2.5	17	B	5
RS Oph 1985	RN	22.46	75	B or G	6
		14.94	68		
		4.85	61		
		1.49	63		
T Cor Bor	RN	2.5	22	B or G	5
SU UMa	DN	4.75	1.3	G	7 cf. 8,9
TY Psc	DN	2.5	10	B or G	5
UZ Boo	DN	2.5	2.4	B or G	5 cf. 9
AM Her	M	14.85	0.5	G	10
		4.9	10	CM	11
AE Aqr	M	14.85	18	G	12
		4.9	16	G	13
		1.4	5	G	13

N – nova, RN – recurrent nova, DN – dwarf nova, M – magnetic CV,
B – bremsstrahlung, CM – cyclotron maser, G – gyrosynchrotron,
S – synchrotron.

1	Reynolds and Chevalier 1984	8	Fürst et al. 1986
2	Wade and Hjellming 1971	9	Echevarria et al. 1986
3	Hjellming et al. 1979	10	Bastian et al. 1985
4	Seaquist et al. 1980	11	Dulk et al. 1983
5	Turner 1985	12	Bastian et al. 1986
6	Hjellming et al. 1986	13	Bookbinder and Lamb 1986
7	Benz et al. 1983		

3. *Novae*

The discovery of radio emission from CVs was made when Hjellming and Wade (1970) detected radio emission from the novae FH Serpentis 1970 and HR Delphini 1967 during 1970 with the NRAO three-element interferometer. These and subsequent observations showed that the radio fluxes of novae in outburst increased and then decreased with time (Hjellming et al. 1979). The maximum flux densities recorded at radiofrequencies are typically ~10-100 mJy (Table 1) and occur ~1yr after the optical outburst.

An interesting feature of the radio emission is that the spectral index β, where $S_\nu \propto \nu^\beta$, evolves with time from a value close to +2 to $\beta \sim 1$ and then to $\beta \sim 0$ (Kwok 1985). This may be understood qualitatively by assuming that the emission arises as a result of thermal bremsstrahlung from the expanding nova envelope. If the nova envelope expands with a speed ~1000 km s^{-1} for ~1yr the radius of the source is $\ell \sim 3\times10^{15}$cm. Hence if $d \sim 500$pc, $S_\nu \sim 50$mJy it follows that $T_b \sim 5000^\circ$K consistent with a thermal bremsstrahlung interpretation.

If the radio emission is optically thick, as is likely during the early phases after the outburst, it follows from Eq.(2)) that $T_b = T_{eff}$ and $I_\nu \propto \nu^2$. Eventually the emission must become optically thin ($\tau_\nu \ll 1$) so that $T_b = T_{eff}\tau_\nu$ and $I_\nu \propto \nu^2 \tau_\nu$. Now, the bremsstrahlung absorption coefficient for an ionized H-He plasma is given at radio frequencies roughly by (Dulk 1985a)

$$\alpha_\nu \approx 0.2\ n_e^2\ T_{eff}^{-3/2}\ \nu^{-2}\ cm^{-1}. \qquad (4)$$

Hence the spectral index $\beta \approx 0$. In between the optically thick and thin cases $\beta \sim 1$ and detailed models assuming a density gradient in the envelope have been presented for this case (Seaquist et al. 1980). Note that for gyrosynchrotron emission in the optically thin case $\beta < 0$ and $|\beta| \gg 1$ (Dulk 1985a).

The post-maximum visible light curves of novae have been understood qualitatively by assuming an optically thick wind (Bath and Shaviv 1976, Bath 1978) and quantitative fits were made by Hartwick and Hutchings (1978). Improved fits to both the optical and radio light curves have been obtained by Kwok (1983) who assumed that the mass-loss rate is not constant but decreases according to a power law:

$$\dot{M}(t) = \dot{M}_0 (t_0/t)^\alpha. \qquad (5)$$

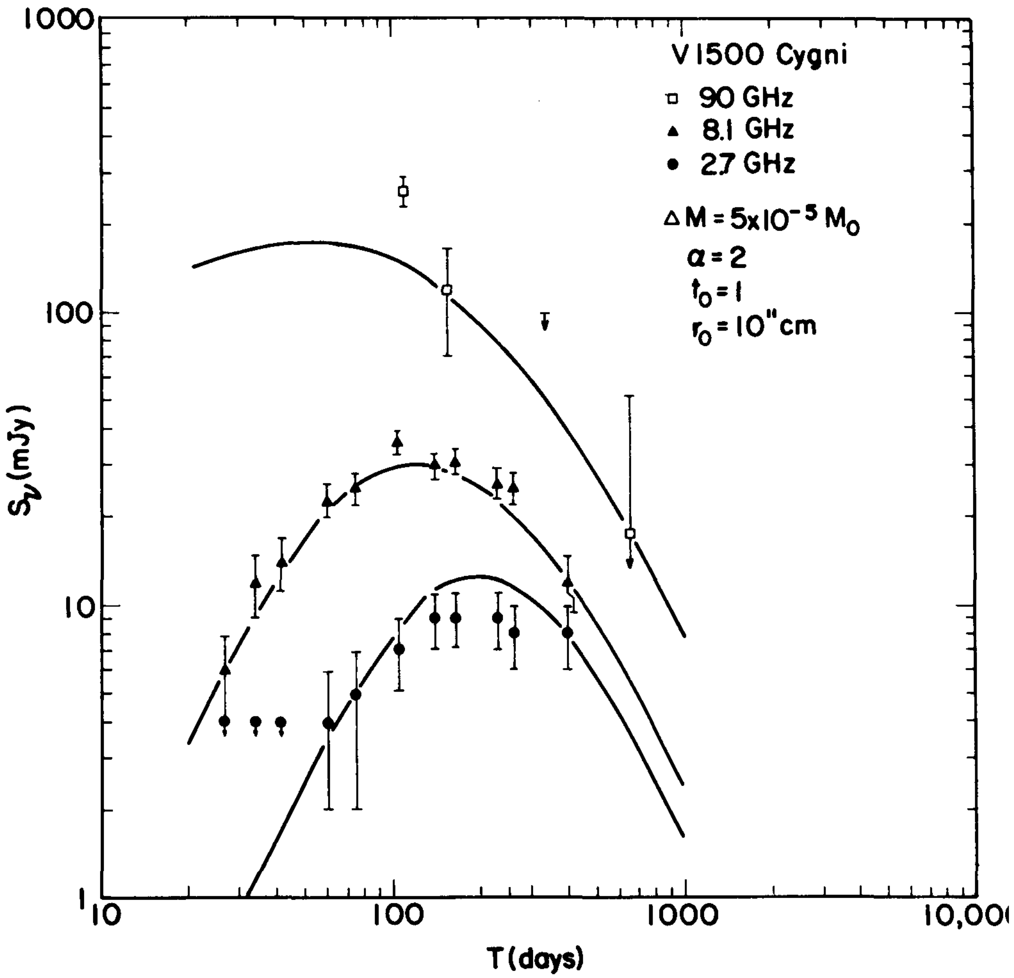

Fig. 1: Theoretical fits to the radio light curves of the nova V1500 Cygni due to Kwok (1983).

The visible light curves for V1500 Cygni, FH Ser and HR Del can be well fitted in this case with $\alpha=2$ and $t_0=0.05$yr, 0.1yr and 0.1yr respectively. For the radio light curves $\alpha=1.7$ and $t_0=1$yr for FH Ser, and $\alpha=2$, $t_0=1$ yr for V1500 Cygni (see Fig. 1). Thus, although the optical and radio light curves may be fitted separately they may not be both fitted with the same parameters. This suggests that the nova ejection occurs in two phases characterized by different timescales $t_0 \sim 0.1$yr and $t_0 \sim 1$yr, but how one can understand both the optical and radio light curves consistently is unclear.

The possibility that a nova shell interacting with the surrounding medium could give rise to turbulence with the generation of relativistic electrons, as in young supernova remnants, and leading to radio emission has been suggested by Chevalier (1977). The detection (Reynolds and Chevalier 1984) of radio emission from the old nova GK Persei (Nova Persei 1901) (see Table 1) seems to confirm this idea. The dominant mechanism is probably synchrotron emission from a shell of radius 3×10^{17} cm and requires the conversion of ∽1% of the initial kinetic energy (∽10^{45} erg) in the nova explosion into energy in relativistic electrons and magnetic field (∽6×10^{-5} gauss).

4. Recurrent Novae

Radio emission from a recurrent nova was first discovered, during an outburst, by Padin et al. (1985). The observations of RS Ophiuchi were made only about 18 days after the optical outburst and indicate that the radio emission turned on about 10 days after the outburst. By comparison, radio emission from classical novae are usually detected at least 50 days after the optical maximum. An interesting feature of the observations of RS Oph is that about 24 days after the optical maximum, the flux density has a classical light curve $S_\nu \propto (t-t_0)$ where t_0 is the time of the optical maximum (Fig. 2). Recently, detailed observations at several wavelengths have been obtained by

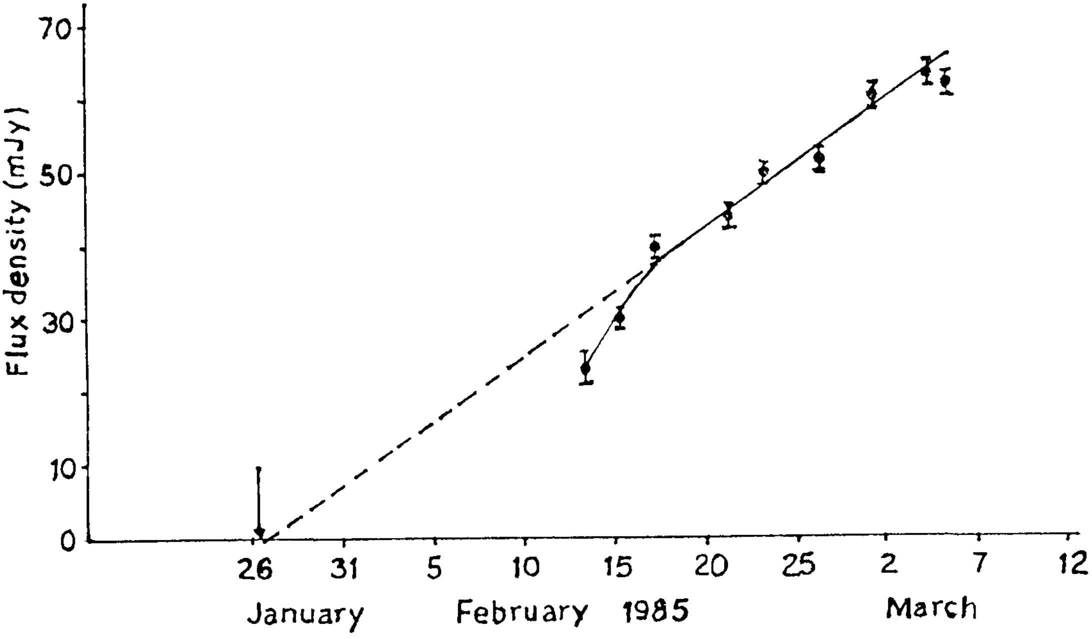

Fig. 2: Radio light curve for the recurrent nova RS Ophiuchi at 5 GHz with left-hand circular polarization due to Padin et al. (1985). The arrow indicates time of optical outburst.

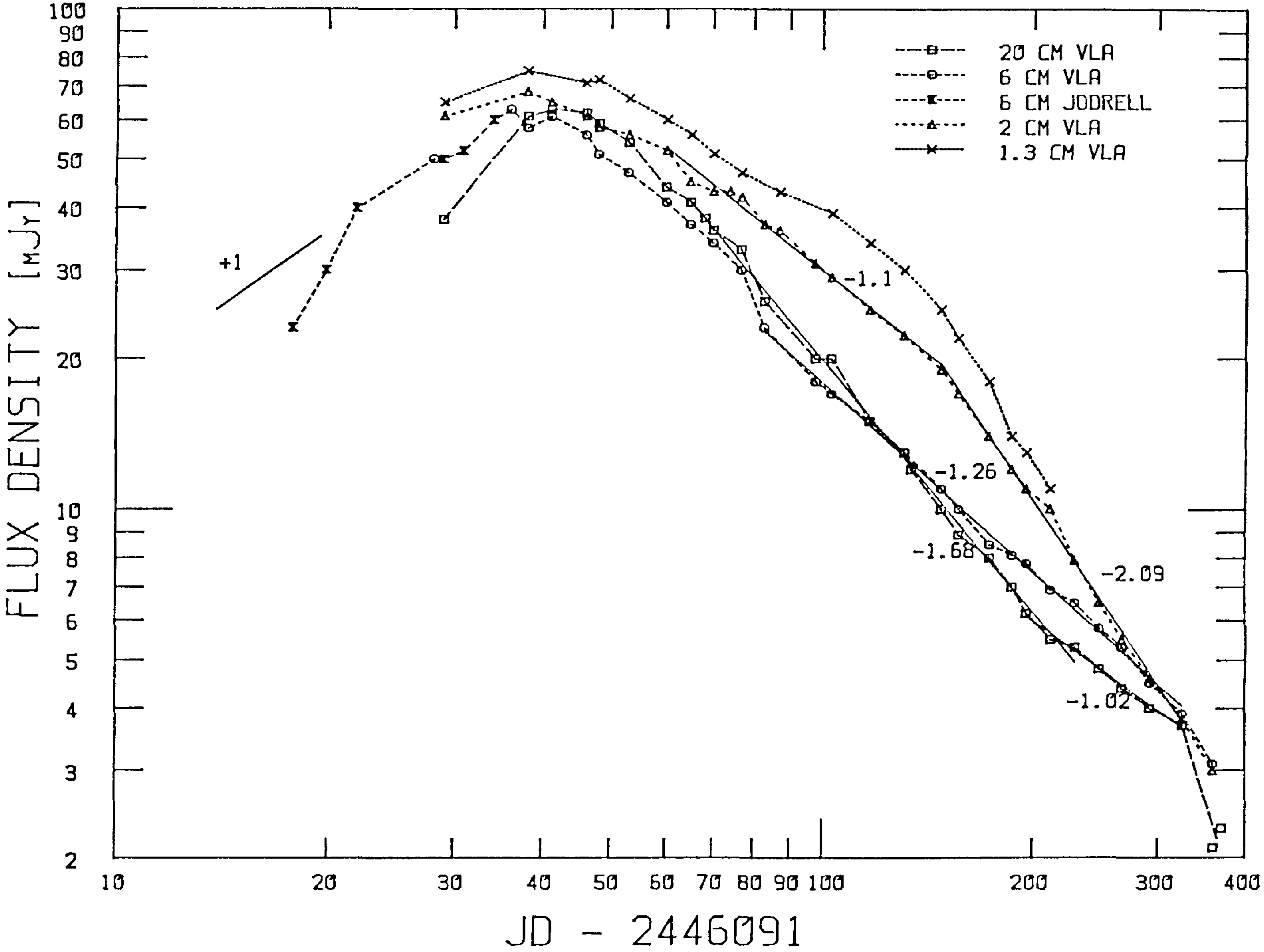

Fig. 3: Radio light curves of the recurrent nova RS Ophiuchi at several wavelengths obtained by Hjellming et al: (1986) with the VLA and at Jodrell Bank.

Hjellming et al. (1986) (Fig. 3). They find that the brightness temperature $T_b \sim 10^5 - 10^7$K and depends on the frequency $\nu = 1.5$ to 15 GHZ. Thus T_b is substantially higher than the value $\sim 10^4$K typically found for classical novae. Other important differences from classical novae are that the light curves have timescales <1yr instead of ~1yr, decay power indices ~-1 to -2 instead of -2.3 to -2.5, and spectra not corresponding to that of an optically thin source with $\alpha \approx 0$ as for classical novae. These differences probably arise because the companion star in a recurrent nova is a red giant star which has a stellar wind. Thus the material ejected in a recurrent nova outburst starts off with velocities ~4000 km s^{-1} but is then decelerated to <300 km s^{-1} after ~100 days because of the ram pressure effects when the ejected material encounters the wind from the red giant (Pottasch 1967). No quantitative models for the radio light curves have yet been presented.

Padin et al. (1985) have shown that thermal models with $T_{eff} \sim 10^4$K fail to account for the radio emission. This, together with the high brightness temperatures have led Hjellming et al. (1986) to suggest that the principal emission mechanism is gyrosynchrotron emission. However, intense soft X-rays from RS Ophiuchi during the 1985 outburst have been detected by Mason et al. (1985). These authors argue that the X-rays originate in gas shock-heated by the nova outburst to temperatures $\sim 10^6$ to 10^7 K. These values are roughly comparable to the brightness temperature so that thermal models cannot be ruled out.

5. *Dwarf Novae*

The first report of radio emission from a dwarf nova was that of SU UMa and made by Benz et al. (1983) with the 100 m telescope at Effelsburg. A flux density of 1.3 mJy was detected at 4.75 GHZ (Table 1). However, subsequent observation at 4.9 GHZ with the VLA by some members of the same group (Fürst et al. 1986) and by Echevarria et al. (1986) only revealed upper limits ~0.1 to 0.5 mJy. It is difficult to say whether the detection was spurious or not since the radio emission may not take place at optical maximum but a few days later. Note that, as we have seen above, nova and recurrent nova radio outbursts occur at least 50 to 10 days, respectively, after the optical maximum.

Radio emission from TY Psc and UZ Boo at 2.5 GHZ have been reported by Turner (1985) with flux densities of 10 and 2.4 MJy (Table 1) but at 4.9 GHZ only an upper limit of 0.7 mJy has been reported for UZ Boo (Echevarria et al. 1986).

6. *Magnetic Cataclysmic Variables*

The magnetic CVs may be divided into two subclasses the AM Her and DQ Her binaries (e.g. Lamb 1985). In the former the white dwarf has a magnetic field which is sufficiently large ($\sim$ few x 10^7 gauss) that its magnetosphere extends to the companion star. No accretion disk is formed and the white dwarf is believed to rotate asynchronously. In the DQ Her binaries the magnetosphere does not extend to the companion, either because the white dwarf has a weak magnetic field $\sim 10^5 - 10^6$ gauss (Lamb 1985) and/or because its orbital separation is larger than in the AM Her binaries (Chanmugam and Ray 1984).

Radio emission from AM Her was discovered with the VLA by Chanmugam and Dulk (1982) with a flux density of 0.67 mJy at 4.9 GHZ. The brightness temperature of the emission was found to be $T_b \sim 3 \times 10^9$K for a source radius $\sim 10^{11}$ cm, assuming a distance $\sim$100pc. Such high values for T_b imply that non-thermal processes must be responsible for the emission. Gyrosynchrotron emission by electrons with average energies $\approx$0.5MeV in a magnetic field $\approx$40 gauss and harmonic number $\sim$40 (see Eq. (3)) is a plausible explanation of the radio emission. AM Her was also detected later at 2 cm (Bastian et al. 1985) and upper limits were set at 20 cm (Table I).

Long term variations of the emission at 4.9 GHZ reveal some remarkable features (see Fig.4, Bastian et al. 1985, 1986). The early observations showed relatively strong emission which was unpolarized. In 1983 the flux decreased and the source was undetectable. When it reappeared in 1984 strong circular polarization ($\sim$25%) was detected.

The decline in the radio flux in mid-1983 coincided with a remarkable change in the X-ray emission from AM Her indicating that the second magnetic pole also began to accrete (Heise et al. 1985). It is possible that this might have caused an opening of the region of the magnetosphere containing the energetic electrons responsible for the radio emission. The depletion of energetic electrons may have resulted in a reduction in the radio emission. Later when the energetic electrons were

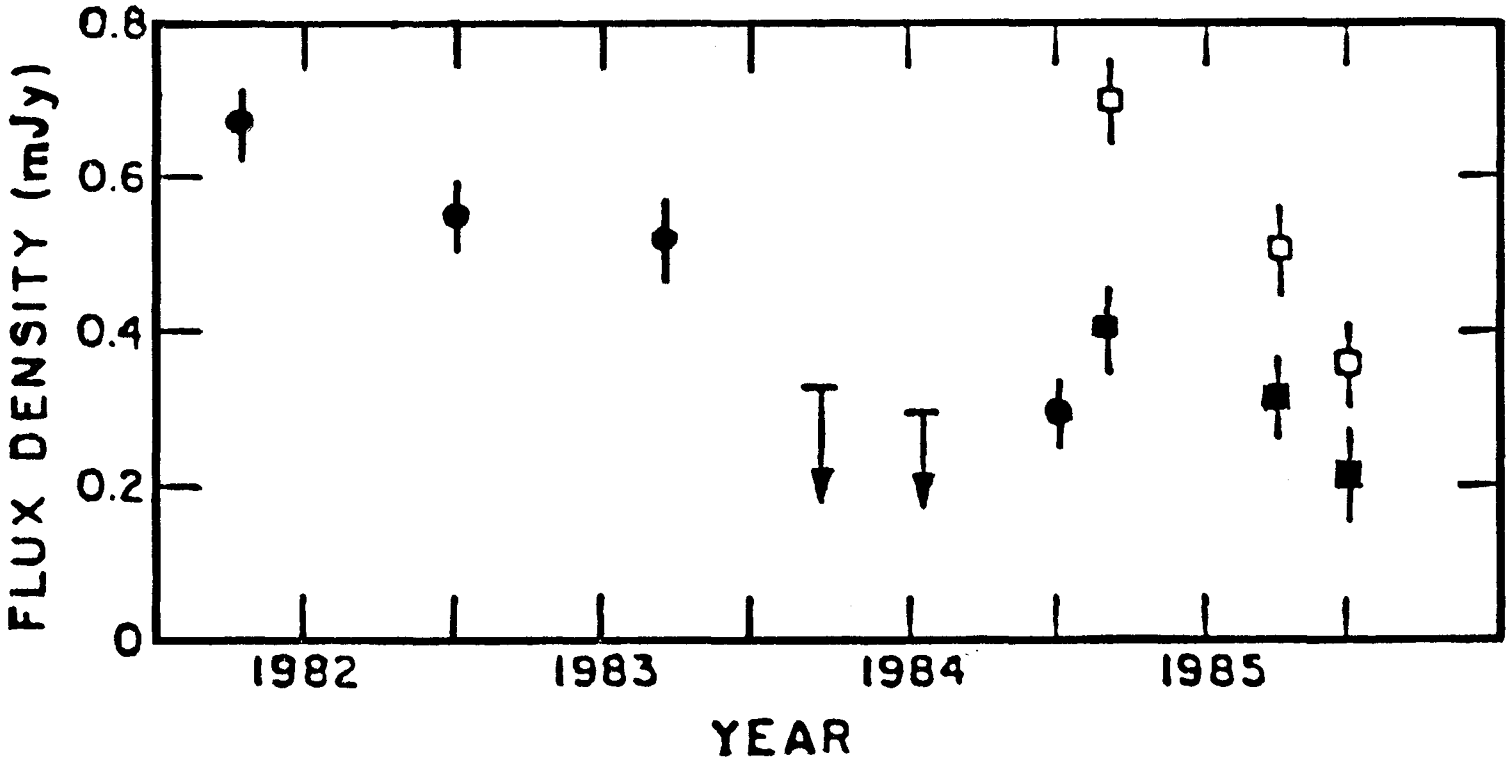

Fig. 4: Long term variations of the 4.9 GHz flux from the magnetic CV AM Herculis (from Bastian et al. 1985, 1986). The solid circles give the total intensity I. The solid, open squares correspond to the left and right hand circular polarization intensities I_{LH}, I_{RH} where $I = (I_{LH}+I_{RH})/2$.

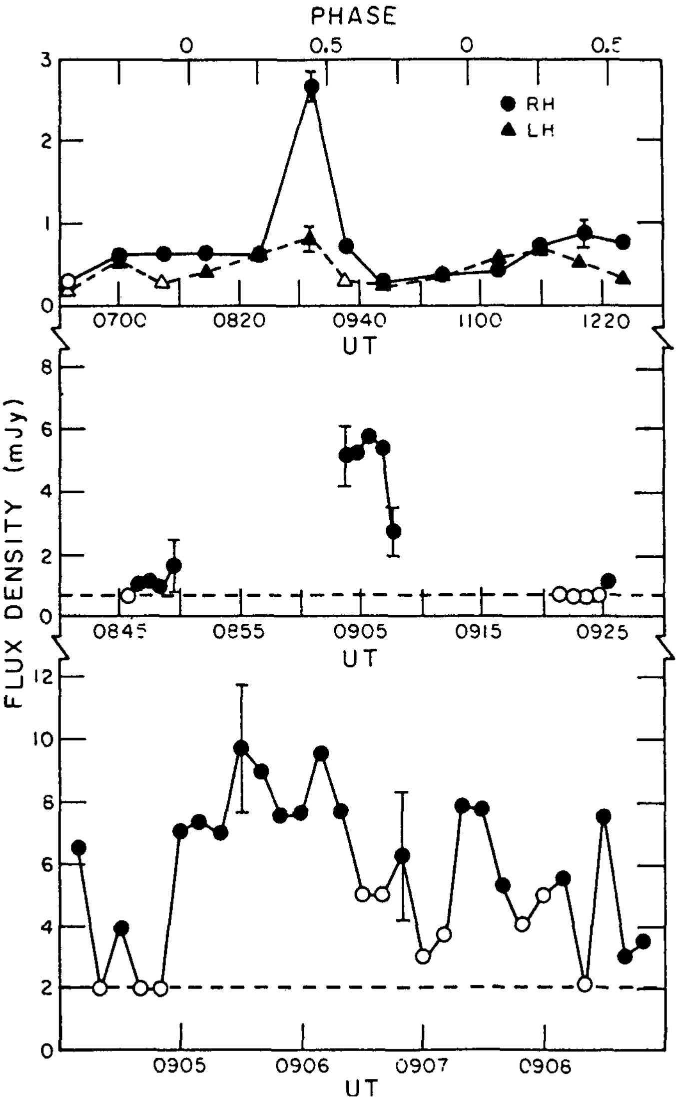

Fig. 5: Time intensity plots of the 4.9 GHz emission from AM Her (Dulk et al. 1983). The top panel shows 30 min. averages, the middle panel 5 min. averages and bottom panel shows the central five minute scan at 10s resolution.

replenished the radio emission increased. The lower intensities compared to 1981 suggests lower optical depths in the ordinary and extra-ordinary modes ($\tau_\nu \lesssim 1$) and hence the high circular polarization. Thus if the τ_ν and hence the intensity increase in the future the circular polarization should decrease.

A remarkable radioflare with a peak flux of 9.7 mJy (see Table 1) has also been detected from AM Her (Dulk et al. 1983). The high brightness temperature $\gtrsim 10^{10}$K and high circular polarization ($\approx$100%, see Fig.5) imply that a coherent mechanism such as plasma oscillations (Kuijpers 1985) or cyclotron masing (Melrose and Dulk 1982) was responsible. The former requires a high electron number density in which case the emitted radiation would undergo free-free absorption in the overlying layers. Cyclotron emission at the fundamental cyclotron harmonic is similarly likely to undergo second harmonic absorption in an overlying layer where the field has half the value. Thus it is more likely that the emission arises at the second harmonic since this is less likely to be absorbed. Hence, from Eq.3, a field of $\approx 10^3$ gauss may be deduced for the emission region. The latter is probably near the red dwarf suggesting that the flare is either due entirely to the red dwarf or as a result of the interaction and reconnection of the fields of the two stars. The latter type of mechanism has been proposed for the flaring observed from RS CVn stars where also 100% circularly polarized radiation has been observed (Brown and Crane 1978).

The first detection of radio emission from a DQ Her binary has recently been reported by Bookbinder and Lamb (1986) who detected a flux density $\approx$15 mJy from AE Aquarii (see Table I). AE Aqr contains a magnetized white dwarf which spins with a period of 33s and has an orbital period of 9.8hr. The magnetic field of the white dwarf is probably weak ($\sim 10^5$ gauss) and its magnetosphere does not extend to its companion. Thus mechanisms involving the unipolar inductor (Chanmugam and Dulk 1983) or MHD torques (Lamb et al. 1983) which had been suggested, for producing the energetic electrons needed to explain the radio emission from AM Her, do not apply. Instead Bookbinder and Lamb (1986) suggest that the emission implies a magnetic field $\gtrsim 10^3$ gauss on the red dwarf. They suggest that in the emission region, near the red dwarf, the field is $\sim$10 gauss and that the emission is due to electrons, with a power law $N(E)=N_0E^{-\delta}$ where $\delta \lesssim 2.5$, at harmonic number $\sim$80. Thus it is quite likely that flaring on or near the red dwarf produces the energetic electrons responsible for the quiescent radio emission from both AM Her and AE Aqr. Although no flaring has been detected on AE Aqr it would be valuable to search for such flaring in the future.

The radio observations of AM Her and AE Aqr have important implications for understanding the evolution of CVs. It has been suggested that CVs, with orbital periods >3hr, evolve primarily as a result of magnetic braking due to a stellar wind from the tidally synchronized secondary

(Rappaport et al. 1985, Spruit and Ritter 1983). These theories require that the secondary star be magnetized, for which no direct evidence has been previously presented. The radio observations of AM Her and AE Aqr provide the first evidence for a magnetized secondary and hence supports these theories.

If the red dwarf is magnetized why doesn't one observe radio emission from other CVs? Perhaps both the white dwarf and the secondary must be magnetized and it is the interaction between the fields of the two stars involving reconnection of field lines which gives rise to the flaring. But then why has no radio emission been detected from all the other magnetic CVs which have been observed? Perhaps, these systems are marginally below the threshold for detection. Clearly, various technical improvements in radio telescopes now underway could lead to detections of many more sources.

7. *Summary*

Radio emission from novae, recurrent novae, dwarf novae and each of the two types (AM Her and DQ Her type) of magnetic CVs have now been reported. The radio emission in these systems arises by various mechanisms such as thermal bremsstrahlung emission and coherent or incoherent non-thermal gyrosynchrotron emission. The radio emission from these binaries probes, in general, length scales $\ell \gtrsim 10^{11}$cm. For novae and recurrent novae $\ell \sim 10^{14}$-10^{15}cm and corresponds to the nova envelope. Future observations of such systems in outburst should in many instances be resolvable at radiofrequencies enabling one to have a better understanding of these systems.

The radio emission which has been detected from AM Her and AE Aqr, which belong to the AM Her and DQ Her subclasses of magnetic CVs, suggest strongly, but not conclusively, that the secondary star in these systems is magnetized. If this is true, it provides strong support to theories for the evolution of CVs which suggest that the secondary stars in CVs with orbital periods >3hr are magnetized.

In conclusion we note that although the number of radio emitting CVs known is small (~10), radio surveys of CVs have only recently begun. Completion of these surveys and improvements in radio telescopes currently underway are likely to reveal a larger number of sources in the near future.

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