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An Investigation of Radio Emission in Magnetic Cataclysmic Variables

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Abstract. The origin of radio emission in magnetic CVs is a long standing problem without a satisfactory solution. We review the radio observations of both non-magnetic and magnetic CVs and discuss possible emission mechanisms. We pose the following questions: Is the presence of a magnetic white dwarf a necessary condition for radio emission? Is there a single cause for the radio emission or are there several radio emission mechanisms? We revisit the suggestion that asynchronism or at least the lack of strict magnetic locking might be a necessary condition for radio emission.

1. Introduction

Surveys of cataclysmic variables (CVs) suggest that non-magnetic CVs (outside of outburst) are not radio emitters (Cordova, Mason & Hjellming, 1983 and Fuerst et al. 1986). Radio upper limits obtained by these surveys are given in Table 1. There is a single unconfirmed detection of a non-magnetic CV during outburst. Benz et al. (1983) reported radio emission, with a peak flux of 1.3 mJy, during an outburst the dwarf nova SU UMa which correlated with optical phase. However, at least some magnetic CVs (MCVs) are radio sources. These include three polars, three IPs, and the first radio selected CV and probable IP, FIRST J1023+0038 (Bond et al. 2002). The lack of radio detected non-magnetic CVs suggests that that the presence of a magnetic white dwarf is a necessary condition for radio emission. It does not appear to be a sufficient condition, since some MCVs are apparently radio quiet.

The radio polars are AM Her, V834 Cen, and ST LMi. AM Her exhibits quiescent non-thermal emission (0.67 mJy) and a 100% circularly polarized flare (9.7 mJy), both detected at 4.9 GHz (Chanmugam & Dulk 1982). V834 Cen has strongly variable emission at 8.4 GHz (2 mJy) with multiple flare events (up to 35 mJy) (Wright et al. 1988). There is marginal evidence that the emission from V834 Cen is a function of orbital phase (Wright et al. 1988). ST LMi was detected (2.0 ± 0.3 mJy at 5 GHz) on 2 out of 3 occasions. This is a 6σ detection, but the authors warn that confusion may have occurred, so confirmation is required (Pavelin et al. 1994).

The radio IPs are AE Aqr, DQ Her, and BG CMi. AE Aqr has variable non-thermal emission (1-12 mJy at 15 GHz) with multiple flare events (up to 35 mJy) (e.g. Bastian, Dulk & Chanmugam 1988). It is a strong variable source across the spectrum, including γ-rays at TeV energies (Meintjes et al. 1992, Abada-Simon et al. 1993, de Jager et al. 1994). DQ Her was detected (1-4 mJy at 5 GHz) on 3 out of 4 occasions, with one flaring event (Pavelin et al. 1994). An exciting new result is the probable IP, J102347.6+003841, a radio selected CV with highly variable emission including a 6.6 mJy flare at 1.4 GHz (Bond et al., 2002). Radio detections and upper-limits of IPs are listed in Table 2.

Table 1. Radio Observations of Non-Magnetic CVs

Object Name	Reference	Detection or Upper Limits Flux Density (mJy)	Frequency (GHz)
TT Ari	Cordova et al. (1983)	< 0.44	4.9
U Gem	Cordova et al. (1983)	< 0.15	4.9
RW Sex	Cordova et al. (1983)	< 0.15	4.9
SS Cyg	Cordova et al. (1983)	< 0.1	4.9
CN Ori	Fuerst et al. (1986)	< 0.3	4.9
SS Aur	Fuerst et al. (1986)	< 0.1	4.9
YZ Cnc	Fuerst et al. (1986)	< 0.1	4.9
SU UMa	Fuerst et al. (1986)	< 0.11	4.9
Z Cam	Fuerst et al. (1986)	< 0.1	4.9
EM Cyg	Fuerst et al. (1986)	< 0.12	4.9
RZ Sge	Fuerst et al. (1986)	< 0.3	4.9

2. Radio Emission Mechanisms

Since non-magnetic CVs do not appear to be radio emitters, it is logical to assume that the presence of a magnetic white dwarf is a necessary condition for radio emission. This assumption is, however tentative, as additional surveys of non-magnetic CVs are required. There are two questions to consider.

Question 1: What emission mechanisms are responsible? The quiescent emission of AM Her is probably due to gyrosynchrotron emission from 500 keV electrons trapped in the magnetosphere of the white dwarf or the red dwarf. Flaring emission of AM Her is likely a cyclotron maser operating at the surface of the white dwarf or plasma oscillations, since the emission is 100% circularly polarized and has a high brightness temperature (10^{10}K) implying a highly coherent mechanism. Bastian, Dulk & Chanmugam (1988) argue that the radio flares in AE Aqr result as a superposition of expanding plasma clouds, emitting synchotron radiation, which change from being optically thick to optically thin upon expansion. This model is supported by the propeller model for AE Aqr (e.g. Wynn, King & Horne, 1997) where most of the matter is ejected out of the system by the rapidly rotating ($P_{spin} = 33$s) white dwarf.

Question 2: How can electrons be accelerated to the required high energies? Chanmugam & Dulk (1982) suggest that small departures from synchronous rotation may accelerate electrons to MeV energies, as a type of unipolar inductor. A strong upper limit on the radio emission from BY Cam obtained by Mason, Fisher & Chanmugam (1996) brings this model into question. If the secondary has a field of a few thousand Gauss then interaction between the field lines of the two stars similar to the RS CVn systems (Uchida & Sakurai 1983) may accelerate electrons.

Table 2. Radio Observations of IPs

Object Name	Reference	Detection or Upper Limits Flux Density (mJy)	Frequency (GHz)
EX Hya	Cordova et al. (1983)	< 0.2	4.9
BG CMi	Pavelin et al. (1994)	2.2 ± 0.7	5
SW UMa	Pavelin et al. (1994)	< 1.06	5
V795 Her	Pavelin et al. (1994)	< 0.77	5
DQ Her	Pavelin et al. (1994)	$1 - 4$	5
AE Aqr	Bastian et al. (1988)	$1 - 12$	4.9
FO Aqr	Pavelin et al. (1994)	< 1.41	5
AO Psc	Cordova et al. (1983)	< 0.15	4.9
J1023+0038	Bond et al. (2002)	6.6	1.4

3. Synchronization Parameter

In order to address the possibility that those polars that are only marginally magnetically locked might be radio emitters, we derive a degree of synchronization parameter for polars and stream-fed IPs. The parameter S is defined by

$$S = N_{mag}/N_{acc}$$

where N_{mag} and N_{acc} are the magnetic and accretion torques respectively. If $S < 1$ then the system is not synchronized. If $S > 1$ then the white dwarf's rotation period will be synchronized (or will become synchronized if currently not in equilibrium) with the binary. The parameter S may be written in terms of the accretion rate, $\dot{M}$, in gs^{-1}, the white dwarf mass, M_{wd}, in solar units, the binary mass ratio, q, the orbital period, P_{orb}, in hours, and the primary's magnetic field strength, B_{dip}, in MG, and γ is the pitch angle of the connecting field lines. Following Warner (1996) equation (36),

$$S = 0.389 \times 10^{-17}\ \gamma \dot{M}^{-1} P_{orb}^{-1/12} (1+q)^{6/7} q^{0.213} M_{wd}^{1/2} B_{dip}$$

Where the mass radius relationship for the white dwarf,

$$R = 0.73 \times 10^{9} M_{wd}^{-1/3}$$

(Warner 1996) is used, where R is measured in cm and M_{wd} is measured in solar masses.

Table 3 lists the polars with known periods and magnetic field strengths. For the sake of consistency, white dwarf masses are assumed to be $0.6 M_{\odot}$ and accretion rates are assumed to be $6 \times 10^{16} \mathrm{gs}^{-1}$, γ is taken to be unity. Binary mass ratios are calculated using the relationship for Roche-Lobe filling secondaries (Warner 1996), namely,

$$M_2 = 0.065 P_{orb}^{5/4}(\mathrm{h}) \quad P_{orb}(\mathrm{h}) < 9\mathrm{h}$$

For polars with low S parameters, accretion rate fluctuations may result in the loss of strict synchronism and hence may provide conditions for acceleration of electrons required for radio emission. From Table 3, it appears that the radio emitting MCVs are those with a low synchronization parameter, however nearly all of the quoted upper limits are greater than the quiescent emission of AM Her. Only BY Cam has a meaningful upper limit comparable to the upper limits obtained for the non-magnetic CVs. Therefore the existing data fail to shed any light on which MCV properties correlate with radio emission.

4. Discussion

The only non-magnetic CV to be detected as a radio source is the dwarf nova SU UMa (Benz et al. 1983). That detection was made during outburst, but a later outburst of SU UMa was not accompanied by a radio detection (Fuerst et al 1986). Upper-limits for radio emission of other non-magnetic CVs are up to a factor of six lower than the quiescent emission of AM Her. These upper-limits are sufficiently strong as to place meaningful constraints on radio emission mechanisms. It suggests that a magnetized primary enhances, or is possibly required for, radio emission from CVs.

Both polars and IPs have be been detected at radio wavelengths. For the most part, published radio upper-limits for polars and IPs are not strongly constraining. Most of the upper-limits listed in Tables 2 and 3 are at or above the quiescent level of emission of AM Her. Considering that these binaries are in general more distant than AM Her and strong flares might by relatively rare, upper-limits near 1 mJy are not very useful.

Flaring events have been observed for most of the detected sources and often sources that were detected at one or more epochs were not detected at other epochs. It is possible that the quiescent emission is the result of the superposition of many faint flares, at least for some systems, and that some systems with detected flare emission have quiescent emission too faint to have been observed.

Theoretical efforts suggest that departures from binary synchronism and/or the presence of a significant magnetic field on the secondary may be required for the acceleration of electrons to the energies necessary for synchrotron radiation at the observed wavelengths.

5. Conclusions

Following Warner(1996) a synchronization parameter, which gauges the degree of magnetic locking by comparing the magnetic torque to the accretion torque, is calculated. The only radio detections among polars are those with low S values. In such binaries a decrease in accretion rate, especially during low states,

Table 3. Radio Observations of Polars

OBJECT NAME	S	Distance (pc)	Detection or Upper Limits: Flux Density (mJy)	Detection or Upper Limits: Frequency (GHz)
V2301 Oph	1.06	150		
EF Eri	2.23	90	< 1.1	5
RXJ1846.9+5538	2.72			
AM Her	2.75	85	0.67 ± 0.053	4.9
ST LMi	2.90	180	2.0 ± 0.7	5
RX J0704.2+6203	3.16			
V834 Cen	3.21	80	1.2 ± 0.45	8.4
MR Ser	3.80	200	< 0.67	5
RX J2157.5+0855	3.97			
MN Hya	3.98	500		
HY Eri	4.56			
BL Hyi	4.57	180		
VV Pup	4.65	80		
RS Cae	5.26	440		
RX J1554.2+2721	5.37			
AN UMa	5.50	120	< 1.08	5
DP Leo	6.14	380	< 0.72	5
RX J0803.4-4748	6.41			
EK UMa	7.18		< 0.82	5
BY Cam	8.12	210	< 0.023	4.9
UZ For	8.43		< 2.4	5
AI Tri	9.05	600		
WX LMi	12.2	140		
RX J1313.2-3259	12.6	200		
HS 0922+1333	17.0	190		
V 1309 Ori	21.7	500		
V884 Her	22.8			
AR UMa	35.3	90		

results in an angular acceleration of the white dwarf. For a period of time the binary will rotate slightly asynchronously as the binary seeks an equilibrium orientation. During this period there will be relative motion between the primary and secondary star's magnetic field lines, providing an acceleration mechanism for electrons.

In polars with high S parameters, the magnetic torque overwhelms the accretion torque to the extent that changes in accretion rate are not expected to cause a change in the equilibrium magnetic field configuration. A first look at Table 3 suggests only low S polars are radio emitters. However, a closer look at the upper-limits reveals that such a relationship is poorly constrained. It is therefore important to observe MCVs more deeply to provide more detections and more useful upper-limits in order to determine which binary characteristics correlate with radio emission. The current state of the data provides few meaningful constrains on theories of radio emission. With the possible exception that non-magnetic CVs appear not to be radio sources, at least outside of outburst.

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