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# DISCOVERY OF RADIO EMISSION FROM AE AQUARII

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## ABSTRACT

Using the VLA, we have searched for radiation at 1.4 and 4.9 GHz from six DQ Her–type cataclysmic variables: AE Aqr, FO Aqr (H2215−086), AO Psc (H2252−035), BG CMi (3A 0729+103), TV Col, and EX Hya. We report the discovery of variable radio emission from AE Aqr, with flux densities of 8–16 mJy at 4.9 GHz and 3–5 mJy at 1.4 GHz. The emission at both frequencies varied on time scales $\lesssim 5$ minutes; no circular polarization ($\lesssim 15\%$) was detected. We obtained upper limits of about 0.2 mJy (3 $\sigma$) at 1.4 and 4.9 GHz for the remaining five stars.

The radio emission from AE Aqr is best explained by synchrotron emission from mildly relativistic electrons. The magnetic field of the white dwarf primary is too small to confine the energetic electrons required to produce the observed radio emission, implying either that the secondary star has a substantial magnetic field or that the source is dynamic. The magnetohydrodynamic (MHD) torque coupling the magnetic white dwarf and the secondary star can power the radio emission only if the secondary has a substantial magnetic field. Alternatively, the MHD torque coupling the magnetic white dwarf and the accretion disk can power the radio emission in a dynamic model.

*Subject headings:* stars: binaries — stars: magnetic — stars: novae — stars: radio radiation

## I. INTRODUCTION

The study of radio emission from cataclysmic variables (CVs) is a new and rapidly developing field (see the excellent review by Chanmugam 1987). A number of CVs have been detected in outburst, but only AM Her has been detected in quiescence, at the relatively modest level of $\sim$0.4–0.7 mJy (Chanmugam and Dulk 1982; Dulk, Bastian, and Chanmugam 1983). Lamb *et al.* (1983) proposed that the synchronous rotation of the magnetic white dwarf in AM Her systems is brought about by a magnetohydrodynamic (MHD) torque. They noted that radio emission might be produced by electrons accelerated in the electric fields arising from distortion of the magnetic field lines linking the two stars due to asynchronous rotation (see also Chanmugam and Dulk 1983). Motivated by this possibility, we have searched for radio emission from six DQ Her stars. In § II, we present the results of our observations. In § III, we examine possible radio emission mechanisms, and in § IV we discuss the energy source of the observed radio emission.

## II. OBSERVATIONAL RESULTS

We searched for radio emission from six DQ Her systems at 1.4 and 4.9 GHz on 1984 July 21 using the VLA[4] in the C/D hybrid configuration with a 50 MHz bandwidth and 7 s time resolution. Table 1 lists our targets and the observed fluxes or 3 $\sigma$ upper limits. We maximized our coverage of both the white dwarf rotation period $P$ and the binary period $P_b$ of each system within the constraints of the scheduled observations. Our observations of AE Aqr at 4.9 GHz covered nearly 20 rotation periods; those of TV Col and EX Hya covered 4% and 20% of their rotation periods, respectively, while those of the remaining systems covered roughly half of their rotation periods. Each source (except TV Col and EX Hya) was also observed at least twice at 1.4 GHz.

We detected a radio source at $\alpha(1950) = 20^h37^m34^s.42$, $\delta(1950) = -1°2'55''.59$, offset from the optical position of AE Aqr by $+1''.9$ in R.A. and $+0''.8$ in decl. The optical position is accurate to about 1″ (Williams 1983), and we therefore identify the radio source with AE Aqr. Figure 1 shows the time variability of the observed flux density at 1.4 and 4.9 GHz. The flux density ranged from 3 to 5 mJy at 1.4 GHz and 8 to 16 mJy at 4.5 GHz over our 3.3 hr observation, with variability of up to a factor of 1.3 at 1.4 GHz and 1.6 at 4.5 GHz on a time scale of approximately 5 minutes. Although our observations at 1.4 and 4.9 GHz are not simultaneous (those at 1.4 GHz immediately preceded and followed those at 4.9 GHz), we estimate that the spectral index $\alpha$ ($f_\nu \approx \nu^\alpha$) varies from 0.3 to 1.5. The broad-band (1.4–4.9 GHz) radio luminosity is $L_{obs} \approx 1.7$–$3.0 \times 10^{26}(d/84\ \mathrm{pc})^2$ ergs s$^{-1}$, assuming a mean spectral index $\alpha \approx 1$ and scaling to the distance derived by Bailey (1981). We searched for circular polarization by comparing $R$ and $L$ maps of the entire observation as well as of subintervals, and by constructing a map of the Stokes parameter $V$ for the entire observation. We find no evidence of circular polarization to within the instrumental sensitivity ($\lesssim 15\%$).

The $B$ magnitude of AE Aqr was $11.3 \pm 0.3$ throughout 1984 July, according to data made available to us by the AAVSO (J. Mattei 1985, private communication). Thus AE Aqr was not in an unusual optical state nor was it flaring during our observations, and we infer that relatively strong, variable radio emission from this system is probably common.

We obtained upper limits of about 0.2 mJy (3 $\sigma$) at 1.4 and 4.9 GHz for radio emission from the remaining five stars, FO Aqr (H2215−086), BG CMi (3A 0729+103), TV Col, EX Hya and AO Psc (H2252−035) (see Table 1). Córdova, Mason, and Hjellming (1983) earlier reported upper limits of about 0.20 and 0.15 mJy at 4.9 GHz for EX Hya and AO Psc, respectively, using the VLA.

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TABLE 1

RADIO OBSERVATIONS OF DQ HERCULIS STARS

| Star | Orbital Period (hr) | Rotation Period (minutes) | Frequency (GHz) | Flux Density (mJy)[a] | Integration Time (minutes) |
|---|---|---|---|---|---|
| AE Aqr ........ | 9.9 | 0.55 | 1.4 | 3–5 | 26.8 |
| | | | 4.9 | 8–16 | 48.3 |
| FO Aqr ........ | 4.0 | 21 | 1.4 | <0.2 | 26.2 |
| | | | 4.9 | <0.14 | 49.3 |
| BG CMi ....... | (3.2) | 15 | 1.4 | <0.45 | 32.3 |
| | | | 4.9 | <0.14 | 56.1 |
| TV Col ......... | 5.5 | 32 | 4.9 | <0.18 | 42.6 |
| EX Hya ........ | 1.6 | 67 | 4.9 | <0.18 | 46.5 |
| AO Psc ........ | 3.6 | 13 | 1.4 | <0.2 | 27.3 |
| | | | 4.9 | <0.2 | 49.0 |

[a] Flux densities are for the detected sources; the upper limits are 3 $\sigma$ values.

### III. RADIO EMISSION

The semimajor axis of AE Aqr is $1.9 \times 10^{11}$ cm (Patterson 1979; Chincarini and Walker 1981). The brightness temperature of the source is $T_b \approx 4.7 \times 10^{10} S_{16}\, \nu_{4.9}^{-2} d_{84}^{2} r_{11}^{-2}$ K, scaling to the maximum observed flux density $S_{16} \equiv S/16$ mJy at the frequency $\nu_{4.9} \equiv \nu/4.9$ GHz, the distance $d_{84} \equiv d/84$ pc derived by Bailey (1981), and a source size $r_{11} \equiv r/10^{11}$ cm, corresponding roughly to the distance between the white dwarf and the surface of the secondary. This brightness temperature is too high to be explained by thermal bremsstrahlung, since the limit $r_{11} \lesssim 100$ on the size of the source imposed by the time variability and the emission measure inferred from the radio observations (see below) mean that AE Aqr should be an intense soft or hard X-ray source, which it is not ($L_X \approx 1 \times 10^{33}$ ergs s$^{-1}$; Lamb and Patterson 1983). The absence of very rapid time variability and strong circular polarization indicates that the emission is not coherent and favors synchrotron over gyrosynchrotron emission. We therefore consider synchrotron emission from mildly relativistic (Lorentz factors $\gamma \lesssim 3$) electrons.

Assuming that the field in the radio emitting region is dipolar, the equatorial magnetic field there is given by $B(r) = \mu_{33}/r_{11}^{3}$ G, where $\mu_{33} \equiv \mu/10^{33}$ G cm$^3$. Suppose that the observed radiation arises from a range of cyclotron harmonics centered on harmonic $s$. Then emission occurs near radius $r = 8.3 \times 10^9 (s\mu_{33}/\nu_{4.9})^{1/3}$ cm and

$$T_b = 6.8 \times 10^{12} s^{-2/3} S_{16}\, d_{84}^{2} \mu_{33}^{-2/3} \nu_{4.9}^{-4/3}\ \mathrm{K}\,. \quad (1)$$

We assume that the emitting electrons have a roughly isotropic pich-angle distribution and a power-law distribution in energy, $n(E) = KE^{-\delta}$, where $K$ is related to the electron number density $N$ by $K = (\delta - 1)E_0^{\delta-1}N$ and $E_0$ is a low-energy cutoff. Taking a viewing angle relative to the magnetic field of $\theta \approx 60°$, the effective temperature $T_{\rm eff}$ of the electrons is given by (Dulk 1985)

$$T_{\rm eff} = 2.8 \times 10^9 \times 2^{-\delta/2} s^{1/2}\ \mathrm{K}\,. \quad (2)$$

Assuming a homogeneous source, the smallest electron energies and number densities required to explain the observed radio emission occur when $T_b \approx T_{\rm eff}$ (Dulk 1985). The radio

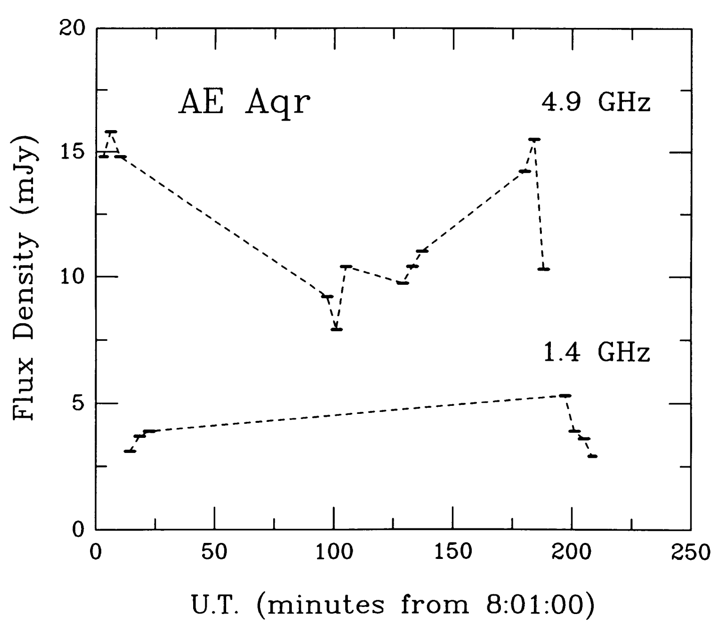


FIG. 1.—Time variability of the radio emission from AE Aqr. The RMS (1 $\sigma$) errors in the fluxes are $\pm 0.17$ and $\pm 0.11$ mJy at 1.4 and 4.9 GHz, respectively, and the systematic errors are still smaller. These errors are too small to be shown in the figure.

emission is centered on harmonic

$$s \approx 800 \times 2^{3\delta/7} S_{16}{}^{6/7} d_{84}{}^{12/7} \mu_{33}{}^{-4/7} \nu_{4.9}{}^{-8/7}\,, \quad (3)$$

and the magnetic field strength $B = 1.8 \times 10^3 \nu_{4.9}/s$.

The required number density of energetic electrons can be estimated by setting $\tau = \kappa_\nu r \approx 1$, where $r$ is the thickness of the absorbing region ($\sim$the radius of the emitting region) and the synchrotron absorption coefficient $\kappa_\nu$ is given by $\kappa_\nu = 1.0 \times 10^{-11}(\delta - 1)10^{(\delta+4)/2} s^{-(\delta+4)/2}(E_0/\mathrm{MeV})^{\delta-1} N/B$ (Dulk 1985). This gives

$$N \approx 210(\delta - 1)^{-1} 10^{-\delta/2} s^{(3\delta+4)/6} (E_0/\mathrm{MeV})^{1-\delta} \times \mu_{33}{}^{-1/3} \nu_{4.9}{}^{4/3}\ \mathrm{cm}^{-3}\,. \quad (4)$$

For $\mu = 3.4 \times 10^{34}$ G cm$^3$ (see below) and $\delta = 2.5$–$3.5$, the above expressions give $s = 2.2$–$3.0 \times 10^2$, $T_{\mathrm{eff}} = 1.8$–$1.4 \times 10^{10}$ K, $r = 1.6$–$1.8 \times 10^{11}$ cm, $N = 0.78$–$4.5 \times 10^5$ cm$^{-3}$, and $B = 7.9$–$5.9$ G.

In a "steady state" picture, the magnetic field must contain the energetic electrons, i.e., $B^2(r)/8\pi > NkT \equiv B_{\mathrm{eq}}{}^2(r)/8\pi$, where the average electron energy $kT = [(\delta - 1)/(\delta - 2)]E_0$ and $B_{\mathrm{eq}}(r)$ is the equipartition value of the magnetic field. $B_{\mathrm{eq}}(r) \propto E_0{}^{-(\delta-2)/2}$ and decreases as $E_0$ increases, since $N$ decreases without affecting $L_{\mathrm{radio}}$. However, $L_{\mathrm{radio}}$ *does* decrease if $E_0$ approaches $T_{\mathrm{eff}}$, and we therefore require $E_0 \lesssim T_{\mathrm{eff}}/3$. This condition and the requirement $B(r) \gtrsim B_{\mathrm{eq}}(r)$ gives a *minimum* required stellar magnetic moment.

$$\mu \gtrsim \mu_{\mathrm{eq}} = 9.0 \times 10^{32}(\delta - 2)^{-7/17} 10^{0.316\delta + 0.062\delta^2} \times S_{16}{}^{22/17} d_{84}{}^{44/17} \nu_{4.9}{}^{-2}\ \mathrm{G\ cm}^3\,. \quad (5)$$

The radio emission also must not be suppressed by the Razin-Tsytovich effect, requiring $\nu_{\mathrm{obs}} \gtrsim \nu_p{}^2/\nu_c$, where $\nu_{\mathrm{obs}}$, $\nu_p$, and $\nu_c$ are the observed, plasma, and cyclotron frequencies, respectively. In the case of AE Aqr, this requirement is less severe than equation (5).

Figure 2 shows the restriction on $\mu$ imposed by equation (5). The magnetic moment of the white dwarf primary in AE Aqr inferred from its spin behavior is $\mu_1 \approx 7.5 \times 10^{30}$ G cm$^3$, corresponding to a mean surface field $B_1 \approx 6 \times 10^4$ G for a 1 $M_\odot$ white dwarf with radius $R_1 = 5 \times 10^8$ cm (Lamb and Patterson 1983; Lamb and Melia 1988). This is *too small* to confine the energetic electrons needed to produce $L_{\mathrm{radio}}$.

Consider now a magnetic secondary star. Isolated emission line K and M dwarfs exhibit surface magnetic fields as large as $B_s \approx 3000$ G covering 70% of their stellar surface (see, e.g., Saar and Linsky 1985); the highest fields are thought to be concentrated in a band of limited width in latitude (see, e.g., Uchida and Sakurai 1983). A value for the magnetic moment of the secondary of $\mu_2 \approx 3.4 \times 10^{34}$ G cm$^3$ is thus not implausible, corresponding to a surface magnetic field $B_s \approx 100$ G or $\sim$1000 G in the case of a dipole or a quadrupole, respectively, for a somewhat evolved $\approx$0.7 $M_\odot$ K5 V secondary with radius $R_2 \approx 7 \times 10^{10}$ cm (see, e.g., Patterson 1984) and an emitting region a few stellar radii above its surface. Figure 2 shows that such a magnetic moment is sufficient to confine the energetic electrons provided $\delta \lesssim 3.5$. Thus emission by energetic electrons confined within the magnetosphere of the secondary star offers a viable model. The observed variability time scale $\tau_{\mathrm{var}}$ is shorter than the synchrotron cooling time scale $\tau_{\mathrm{syn}} \approx 6 \times 10^4 \gamma^{-1}[B_2(r)/100\ \mathrm{G}]^{-2}$ s for the energetic electrons. However, collisions with the accretion disk or the surface of the companion star may possibly remove the energetic electrons in a sufficiently short time.

An alternative possibility is that the source is dynamic, with the variable radio emission due to a superposition of flare events; such a model is currently being investigated by Bastian, Dulk, and Chanmugam (1988).

## IV. ENERGY SOURCE

The luminosity of AE Aqr at 4.9 GHz is $\gtrsim 10^4$ times that of ordinary K and M dwarfs (Bookbinder 1988), implying that its

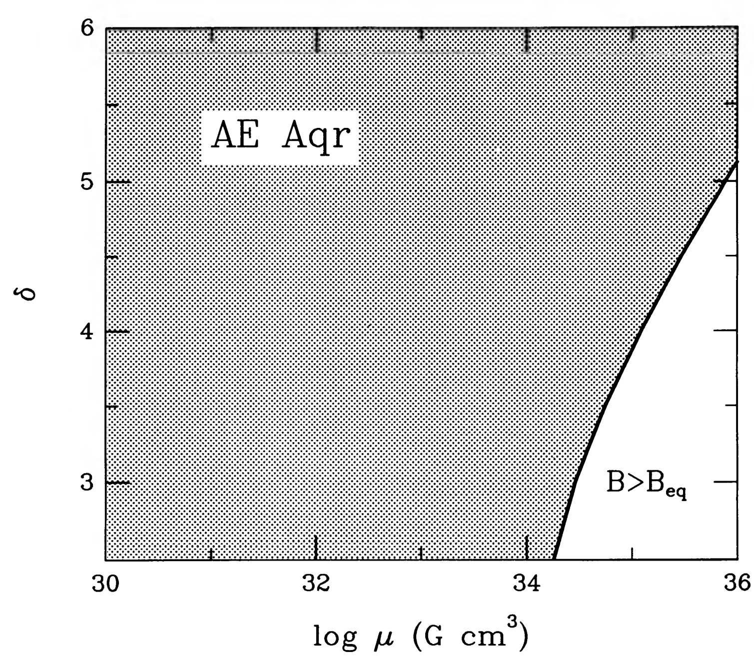


FIG. 2.—Constraint on the stellar magnetic moment $\mu$ from the requirement that the magnetic field energy density exceed the electron energy density in the radio emission region.

interacting magnetic binary nature plays a crucial role in producing the radio emission.

In the MHD torque model of Lamb *et al.* (1983), the picture of radio emission is as follows. If the secondary has no intrinsic magnetic field ($\mu_2 = 0$), the magnetic field of the white dwarf threads a portion of the secondary, due to turbulent transport by convection or to ordinary resistive diffusion, and links the two stars. If the secondary has an intrinsic magnetic field, it and the field of the white dwarf join, again linking the two stars. Asynchronous rotation of the white dwarf distorts the field lines linking the two stars, producing large electric fields. The accompanying magnetic field reconnection and large-scale MHD turbulence inject electrons, which are accelerated to high energies by the large electric fields and produce radio emission.

The greatest distortions of the field lines linking the two stars occur in regions where the combined magnetic field of the white dwarf and the secondary is small; however, the greatest dissipation occurs in the region between the two stars where the field strength, while a minimum, is large. According to the model, the energy dissipation rate $\dot{E} \approx N_{\rm MHD}{}^{\rm star}\xi$, where $\xi = \Omega - \Omega_b$ is the synodic frequency of the white dwarf relative to the binary, and $\Omega$ and $\Omega_b$ are the angular rotation frequencies of the white dwarf and the binary, respectively. The MHD torque itself is given by

$$N_{\rm MHD}{}^{\rm star} = \frac{1}{2}\,\alpha\gamma D R_2{}^2\left(\frac{\mu_1}{D^3}\right)^2 \quad (\mu_2 = 0)$$

$$= \gamma\left(\frac{\mu_1\mu_2}{D^3}\right), \qquad (\mu_2 \gtrsim \mu_1) \qquad (6)$$

where $\alpha$ is the fractional area of the secondary threaded by the magnetic field of the white dwarf, $\gamma$ is the pitch angle of the magnetic field lines linking the two stars, $D$ is the separation of the binary, and $R_2$ is the radius of the secondary.

The parameter $\alpha \gtrsim 0.9$ for a somewhat evolved 0.7 $M_\odot$ star (Lamb *et al.* 1983), and we expect large-scale MHD instabilities to occur when $\gamma$ reaches $\sim 1$. Using values $\alpha \approx 1$, $\gamma \approx 1$, $\mu_1 \approx 7.5 \times 10^{30}$ G cm$^3$, $\mu_2 = 0$, and $D \approx 1.9 \times 10^{11}$ cm (Patterson 1979; Chincarini and Walker 1981), we find $N_{\rm MHD}{}^{\rm star} \approx 5 \times 10^{26}$ dyn cm and $\dot{E} \approx 1 \times 10^{26}$ ergs s$^{-1}$. Defining $\epsilon$ to be the efficiency with which dissipated energy is converted to relativistic electrons, $L_{\rm radio} \approx \epsilon\dot{E} \approx 1 \times 10^{26}\epsilon$ ergs s$^{-1}$. Comparison with the observed radio luminosity $L_{\rm obs} \approx 1.7$–$3.0 \times 10^{26}(d/84\ {\rm pc})^2$ ergs s$^{-1}$ shows that an efficiency $\epsilon \approx 3$ is required! Thus the magnetic field of the white dwarf alone also cannot produce a large enough MHD torque, and therefore a large enough energy dissipation rate, to account for the observed radio power.

Consider now the possibility that the secondary has a substantial magnetic field. In this picture, the asynchronously rotating magnetic white dwarf acts like an "injector," accelerating electrons to relativistic energies in the region between the two stars, while the magnetosphere of the secondary acts like a "bottle," confining the electrons while they radiate. Using the parameter values adopted previously, except $\mu_2 \approx 3.4 \times 10^{34}$ G cm$^3$, we find $N_{\rm MHD}{}^{\rm star} \approx 4 \times 10^{31}$ dyn cm and $\dot{E} \approx 7 \times 10^{30}$ ergs s$^{-1}$. This value of $N_{\rm MHD}{}^{\rm star}$ is consistent with the upper bound $N_{\rm MHD}{}^{\rm star} < N_{\rm acc} \approx \dot{M} r_{\rm A}{}^2\Omega_{\rm K}(r_{\rm A}) \approx 8 \times 10^{32}$ dyn cm implied by the fact that the white dwarf in AE Aqr is not synchronously rotating. Here $N_{\rm acc}$ is the accretion torque, $r_{\rm A}$ is the Alfvén radius, and $\Omega_{\rm K}(r_{\rm A})$ is the Keplerian angular velocity at $r_{\rm A}$ (see Ghosh and Lamb 1979*a*, *b*). The required efficiency is then $\epsilon \approx 4 \times 10^{-5}$. Thus a "steady state" model in which the secondary has a substantial magnetic field can produce the observed radio power and confine the required number density of energetic electrons.

Consider alternatively a dynamical model in which the radio emission is powered by the MHD torque coupling the magnetic white dwarf and the inner edge of the accretion disk (Ghosh and Lamb 1979*a*, *b*). The greatest distortions of the field lines threading the disk occur at large radii where the field is small; however, the greatest dissipation occurs in the vicinity of $r_{\rm A}$, where the magnetic field strength is greatest. In analogy with equation (6), we can write a rough estimate of the MHD torque produced at $r_{\rm A}$ as

$$N_{\rm MHD}{}^{\rm disk} = \frac{1}{2}\,\alpha\gamma r_{\rm A}{}^3\left(\frac{\mu_1}{r_{\rm A}{}^3}\right)^2, \qquad (7)$$

where $\alpha \ll 1$ is the fractional area of the accretion disk to which the magnetic field of the white dwarf couples most strongly and $\gamma$ is the pitch angle of the field lines (cf. Ghosh and Lamb 1979*b*, eq. [3]). This model implies an energy dissipation rate $\dot{E}_{\rm disk} \approx N_{\rm MHD}{}^{\rm disk}\xi$, where $\xi = \Omega_{\rm K}(r_{\rm A}) - \Omega \equiv \omega\Omega$ is the synodic frequency of the white dwarf relative to the Keplerian angular velocity $\Omega_{\rm K}(r_{\rm A})$ at the inner edge of the disk.

Using values $\alpha \approx 10^{-2}$, $\gamma \approx 1$, $\omega \approx 1$, $r_{\rm A} \approx 3R \approx 1.5 \times 10^9$ cm, and $\mu_1 \approx 7.5 \times 10^{30}$ G cm$^3$, we find $N_{\rm MHD}{}^{\rm disk} \approx 8 \times 10^{31}$ dyn cm and $\dot{E}_{\rm disk} \approx 2 \times 10^{31}$ ergs s$^{-1}$. Thus $\epsilon \approx 2 \times 10^{-5}$, implying that the MHD coupling between the magnetic white dwarf and the accretion disk can power $L_{\rm obs}$. Since the magnetic field of the white dwarf is incapable of confining the number density of energetic electrons required to produce the observed synchrotron emission (recall § III), flare events like those postulated by Bastian, Dulk, and Chanmugam (1988) could well result. DQ Her stars with longer rotation periods would be expected to produce much weaker radio emission, as observed (see Table 1), since their $N_{\rm MHD}{}^{\rm disk}$ are roughly comparable while their $\xi$ are much smaller.

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