AM HERCULIS BINARIES: PARTICLE ACCELERATION, RADIO EMISSION AND SYNCHRONIZATION*

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ABSTRACT

It has been suggested that the recently discovered radio emission from AM Her arises as a result of gyrosynchrotron radiation from electrons at energies ≈400 keV in the magnetosphere of the white dwarf. However, no mechanism for producing such energetic electrons was discussed. In this paper, we argue that small departures from synchronous rotation can cause the companion star to act as a unipolar inductor. This leads to high voltages being produced across the companion star, which provides the necessary acceleration mechanism. This also implies that if the magnetic white dwarf was formed with a rapid rotation, synchronization would be achieved on a time scale ~10^4 yr.

1. INTRODUCTION

The AM Herculis binaries are a subclass of cataclysmic variables and are distinguished by the strong magnetic field $\gtrsim$ few x 10^7 gauss of the white dwarf (Schmidt et al 1981, Chanmugam and Dulk 1981). The field is sufficiently strong to prevent formation of an accretion disk and the companion is likely to be inside the magnetosphere of the white dwarf. Furthermore all of these systems are believed to be rotating synchronously. The prototype of these systems AM Her, in addition to emitting soft and hard X-rays, UV radiation, infrared radiation and polarized light (see the review by Chiappetti et al 1980) has recently been discovered to be a radio source (Chanmugam and Dulk 1982). The observed flux density of 0.67±.052 mJy at 4.9 GHz implies a radio luminosity ~ 10^{25} erg s^{-1}, assuming a distance of 100 pc. If the projected area of the emitting region is πr^2 the brightness temperature of the radio emission is $T_b \approx 2.7 \times 10^9$ r_{11}^{-2} K where $r_{11} = r/10^{11}$ cm. This is probably too high to be explained by thermal bremsstrahlung. Instead a self-consistent model in which the radio emission arises as a result of gyro-synchrotron emission at a cyclotron number $\gtrsim$ 30 to 50 has been proposed (Chanmugam and Dulk 1982). The emission probably occurs in the magnetosphere of the white dwarf at a radial distance ≈7-9 x 10^{10} cm from the white dwarf, with the average

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energy of the electrons $\approx$ 400 - 300 keV. However, the source of the energetic electrons is unknown.

The purpose of this paper is to show that departures from synchronous rotation (or nutations) could lead to the companion star acting as an unipolar inductor. This could lead to large potential differences being set up across the companion star, which can provide the necessary acceleration mechanism. We also show that if the white dwarf is formed spinning rapidly and the system acts as a unipolar inductor, synchronization can take place on a timescale ~ 10^4 yr. This is much shorter than the timescale ~ 10^{10} yr obtained if ohmic dissipation from the magnetic interaction of the two stars brings about synchronization (Joss et al 1979).

2. ACCELERATION MECHANISM

AM Her is analogous to the Jupiter-Io system in that the companion star (which corresponds to Io) is inside the magnetosphere of the white dwarf (shich corresponds to Jupiter). However, there is an important difference: the AM Her system rotates synchronously whereas the Jupiter-Io system does not. As the magnetic flux tubes of Jupiter sweep by Io, large potential differences are set up across the flux tube connecting Io to Jupiter, leading to acceleration of electrons (Goldreich and Lynden-Bell 1969). Here we consider the possibility that there are small departures from synchronous rotation in AM Her which gives rise to large potential differences being set up across the companion star.

The surface magnetic field of the white dwarf is $B_{WD} \simeq 2 \times 10^7$ gauss (Schmidt et al 1981). If this field is dipolar the magnetic field at the companion is $B = 2 \times 10^7 \, d_9^{-3}$ gauss, assuming the radius of the white dwarf to be 10^9 cm, and the distance between the two stars to be d. The induced electric field seen by the companion is then (Goldreich and Lynden-Bell 1969, Michel 1979) $\underset{\sim}{E} = -\underset{\sim}{V} \times \underset{\sim}{B}/c$, where $\underset{\sim}{V} = \underset{\sim}{V}_{orb} - \underset{\sim}{V}_{corot}$, with $\underset{\sim}{V}_{orb}$ the orbital velocity of the companion star and $\underset{\sim}{V}_{corot}$ the velocity of the plasma corotating with the white dwarf as it passes the companion. Let $\underset{\sim}{\xi}$ be the angular velocity characterizing the departure from synchronism. Hence

$$E \simeq 2 \times 10^8 \, \xi \, d_9^{-2} \text{ Volt cm}^{-1}.$$

If the companion has a diameter D ($\approx 6 \times 10^{10}$ cm), the potential difference across it is

$$\Phi \simeq 2 \times 10^{18} \, \xi \, d_9^{-2} \, D_{10} \text{ Volts.}$$

Thus with d_9=70 to obtain Φ~1MeV only a very small departure from synchronism is needed, i.e. $\xi \sim 10^{-9}$ rad s^{-1}. This potential difference acts across the flux tube from the white dwarf which encompasses the companion and drives an electric current from the companion to the white dwarf along half the surface of the flux tube. The current then crosses the flux tube in the atmosphere of the white dwarf near the polar cap and returns to the companion along the other half surface of the flux tube.

The circuit is completed across the companion.

In order to ensure that the large potential differences could be set up, it is necessary to show that a d.c. circuit can be established. This requires estimates of the electrical conductivities in the circuit. The most important of these is the Pedersen conductivity in the atmosphere of the white dwarf at the polar cap: $\sigma_p \approx 1.3\times10^8$ s^{-1}, since the temperature is ~ 10^5 K (Chiappetti et al 1980) and the electron number density is ~10^{17} cm $^{-3}$. Hence the height integrated resistance of the atomosphere is $R_{WD} \approx 8\times10^{-14}$ in Gaussian cgs units or ≈ 0.1 ohm. This is much higher than the resistance of the portion of the circuit through the atmosphere of the companion or the flux tube. Hence if $\xi \lesssim 10^{-3}$ rad s^{-1}, the electric current flowing in the circuit is not large enough to create a magnetic field which would perturb the flow past the companion and hence reduce the electric field substantially (Dessler and Hill 1979). Another requirement for the d.c. circuit model to be valid, is that the flux tube cannot slip by more than D during the time T_A it takes for an Alfven wave to travel from the companion to the white dwarf and back. We estimate T_A to be ~10^3 s. This condition is satisfied because of the lower resistance of the companion (Dermott 1970). Hence, although there are uncertainties in our estimates of the resistance it is very likely that a d.c. circuit can be established. If so, electrons can be accelerated to energies ~1MeV provided ξ ~10^{-9} rad s^{-1}; upon diffusing into the magnetosphere they are a possible source of the observed radio emission.

3. SYNCHRONIZATION

During the formation of the white dwarf, mass loss can result in magnetic braking which would reduce ξ to a value ~ 10^{-3} rad s^{-1} in about 10^4 yr (Brecher and Chanmugam 1978). The unipolar inductor model should then be applicable and since the power loss rate is Φ^2/R_{WD} the equation for ξ is given by

$$I\, d\xi/dt = -\,(dBD/c)^2\, \xi/R_{WD},$$

where I~10^{50} gm cm^2 is the moment of inertia of the white dwarf. Hence ξ decays exponentially on a timescale ~10^4 yr. Once the value of ξ is reduced to ~ 10^{-8} rad s^{-1}, the ohmic dissipation mechanism becomes more efficient in synchronizing the rotation. This is because $d\,\xi/dt \propto \xi^{-\frac{1}{2}}$ for that mechanism whereas $d\xi/dt \propto \xi$ for the unipolar inductor. It is noteworthy that Joss et al (1979) mentioned that the unipolar inductor may be more important than the ohmic dissipation mechanism but did not give any details (see also Lamb and Lamb (1979)).

4. CONCLUSIONS

Observations indicate that AM Her undergoes synchronous rotation. However, accretion torques would tend to change the rotation period of the white dwarf, and nutations could exist if the orbit is slightly eccentric. A small departure from synchronous rotation with ξ~10^{-9} rad s^{-1} is adequate to create large potential differences which could accelerate the electrons to energies $\gtrsim$ 400 keV, as required for the gyrosynchrotron radio-emission. Note that ξ is much less than the orbital angular velocity of 5.6 x 10^{-4} rad s^{-1} and hence not easily detectable. Departures from synchronism will tend to be damped either as a result of electromagnetic torques due to the current flowing through the companion or as a result of ohmic dissipation in the atmosphere of the companion; further investigation is needed to determine what value of ξ is necessary.

A consequence of our analysis is that if the white dwarf was formed spinning rapidly, extremely high potential differences would be set up and could result in ultra-high energy synchrotron emission. A possibly more significant consequence is that the large electromagnetic torque acting on the white dwarf can synchronize its rotation on a timescale which is much shorter than given by the ohmic dissipation model of Joss et al (1979).

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DISCUSSION FOLLOWING G. CHANMUGAM'S TALK

ROBINSON: Is either the current flow or the electric field that you set up large enough to affect the accretion?

CHANMUGAN: This current I presume will flow on the surface of the flux tube, it is a skin effect so you can have accretion through the middle of the flux tube. So I don't think it will affect the mass flow because the energetics involved are much lower.

MEYER: Do you know how strongly the fields are swept back near the secondary when you couple with this resistance?

CHANMUGAN: I have not estimated that.

MEYER: It is an interesting question because you would not expect magnetic fields in this configuration to be swept back by much more than 45°, because usually then you get MHD instabilities which break the whole configuration, so you have there a hole in the strength for the coupling of magnetic fields. What determines the resistance in the polar cap?

CHANMUGAN: It is the ordinary conductivity of an ionized gas, but you have to divide it by $\omega_c^2\tau^2$, where ω_c is the cyclotron frequency and τ is the collision time.

KING: When you got it in synchronism, it is held there by the Joss, Rappaport mechanism. The dissipation required, where does that go, is it in the secondary?

CHANMUGAN: In that mechanism it is in the outer part, in the skin of the secondary.

KING: Your mechanism gets it into synchronism and Joss and Rappaport's is supposed to keep it there.

LAMB: Joss, Katz, Rappaport (1979) discuss two torques. One is a dipole-induced dipole torque which is dissipative, and which acts to synchronize the system. With the smaller magnetic fields now known to occur in the AM Her stars, this dissipative torque is too small to bring about synchronous rotation on the timescale required. Dr. Chanmugam and I are talking about new dissipative torques which can act to synchronize the system. Once the system is cynchronized, a second torque, due to the magnetostatic interaction between the stars, acts to maintain synchronous rotation. This torque is much stronger than the kind of torques we are talking about right now, and does not dissipate anything anywhere.

CHANMUGAN: I would like to make the comment that we have not detected radio emission from EF Eri, VV Pup, AN UMa.

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