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SYNCHRONIZATION OF MAGNETIC STARS IN BINARY SYSTEMS

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ABSTRACT

Asynchronous rotation of magnetic stars in close binary systems drives substantial field-aligned electrical currents between the magnetic star and its companion. The resulting magnetohydrodynamic torque is able to account for the heretofore unexplained synchronous rotation of the strongly magnetic degenerate dwarf component in systems like AM Her, VV Pup, AN UMa, and EF Eri as well as the magnetic A type component in systems like HD 98088 and 41 Tauri. The electric fields produced by even a small asynchronism are large and may accelerate some electrons to high energies, producing radio emission. The total energy dissipation rate in systems with degenerate dwarf spin periods as short as 1 minute may reach 10^{33} ergs s^{-1}. Total luminosities of this order may be a characteristic feature of such systems.

Subject headings: hydromagnetics — stars: binaries — stars: magnetic — stars: radio radiation — stars: rotation — stars: white dwarfs — X-rays: binaries

I. INTRODUCTION

Many magnetic stars in close binary systems are observed to be spinning synchronously with their orbital motion. These include the strongly magnetic degenerate dwarf components in systems like AM Her, VV Pup, AN UMa, and EF Eri (see Liebert and Stockman 1983, and references therein) and magnetic A type stars in systems like HD 98088 (Abt *et al.* 1968) and 41 Tauri (Wolf 1973). Synchronous rotation of the degenerate dwarfs is surprising because (1) evolution of these systems leads naturally to asynchronism, (2) the viscous coupling between the degenerate dwarf and its companion is expected to be negligible, (3) the accretion torque tending to spin up the degenerate dwarf is typically strong, while (4) the moment of inertia of the degenerate dwarf is small. Synchronous rotation of magnetic A type stars in binary systems with periods longer than 4 days is also surprising, since normal A type stars in such wide systems are observed to be asynchronous (Floquet 1979).

A common conjecture is that synchronism in these systems is somehow the result of magnetic coupling. The first detailed calculation of magnetic coupling in stellar systems was the pioneering study by Joss, Katz, and Rappaport (1979, hereafter JKR), who assumed a vacuum dipole-dipole (VDD) interaction between the magnetic star and its companion and carefully worked out the resulting torques. However, this model does not appear capable of explaining the observations, for two reasons. First, for any plausible plasma density (i.e., $n \gtrsim 10^{-2}$ cm^{-3}), the volume between the two stars is electrodynamically not a vacuum. As a result, asynchronous rotation of the magnetic star drives large electrical currents between the two stars, qualitatively changing the nature of their interaction. Second, even if the VDD interaction were relevant, it would probably be too weak to explain the data. In the absence of accretion, the VDD torque would require more than 10^{10} yr to change the spin period of the degenerate dwarf in systems like AM Her and VV Pup even by a factor of 2. This is almost certainly much longer than the evolutionary time available for synchronization.[2] The VDD synchronization torque would also be too weak to explain the synchronism observed in magnetic A star systems with orbital periods less than approximately 7 days, a fact noted by JKR. This suggests that some other mechanism is operating in binaries containing magnetic A type stars, a mechanism that may also be effective in magnetic white dwarf systems.

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[2]The extreme weakness of the VDD synchronization torque was not as apparent in 1979 because at that time the magnetic field strength in AM Her stars was believed to be a factor of approximately 5 larger than the value, approximately 2×10^7 gauss, that has since been measured (Schmidt, Stockman, and Margon 1981; Latham, Liebert, and Steiner 1981).

An alternative possibility is that synchronism is due to the magnetohydrodynamic (MHD) torque resulting from currents flowing between the two stars. A preliminary estimate of the likely size of the MHD torque showed it to be approximately 10^4 times stronger than the VDD synchronization torque (Lamb and Lamb 1979). We have now carried out a detailed study of MHD spin-orbit coupling in binary stellar systems. The purpose of this *Letter* is to summarize our results. The full details of our analysis and a more complete discussion of the implications for magnetic stars in binary systems will be published elsewhere.

II. PHYSICS OF THE MHD TORQUE

The quantity of magnetic flux linking the magnetic star to its companion depends on the outcome of several physical processes acting over the entire evolutionary history of the system. These processes include flux linkage at the time the two stars are formed, diffusion of flux into the companion star due to Coulomb collisions and turbulence, pumping of flux into the companion by convection, and reconnection (if the companion has its own intrinsic magnetic field). In order to simplify the discussion in this *Letter*, we assume that there is initially *no* flux linking the two stars. The torque that we calculate is therefore a lower bound on the torque at any later time. We assume that the spin axis of the magnetic star is parallel to the orbital angular momentum of the system. We further assume that the magnetic star has an axisymmetric magnetic field aligned with its spin axis and that the companion star has no intrinsic magnetic field. Some of the effects of relaxing the latter assumptions are discussed briefly at the end of this section.

The physics of the MHD coupling is as follows. The spinning motion of the magnetic star creates a $\boldsymbol{v} \times \boldsymbol{B}$ electric field within it, which produces a potential difference between points on its surface that are at different magnetic latitudes. To the extent that the electric potential is constant along a given field line, field lines threading the plasma outside the star impress a potential drop across it. If the magnetic star is spinning asynchronously, the potential drop between the field lines threading the companion star drives cross-field electrical currents inside the companion. The circuit is closed primarily by field-aligned currents flowing between the two stars and by cross-field currents inside the magnetic star. The resulting $\boldsymbol{j} \times \boldsymbol{B}$ forces within the two stars produce torques that alter their angular velocities and that of the system, eventually leading to synchronous rotation of the magnetic star. Electrical currents will persist for some time after synchronism has been achieved, due to the large self-inductance of the current loop. The resulting torque leads to damped oscillations of the magnetic star about a preferred orientation with respect to the companion. Some of these phenomena are similar to those that are thought to occur in the Jupiter-Io system (see Scarf *et al.* 1982, and references therein).

An alternative, but equivalent, and perhaps more easily visualized description is that the field-aligned currents produce a toroidal component of the magnetic field between the two stars, as seen from the magnetic star (see Fig. 1). The resulting magnetic stresses, when integrated over the surfaces of the two stars, give the torques on them and the system.

We have estimated the MHD torque on the magnetic star by integrating the magnetic stresses over a surface enclosing it. An expression for the torque that explicitly

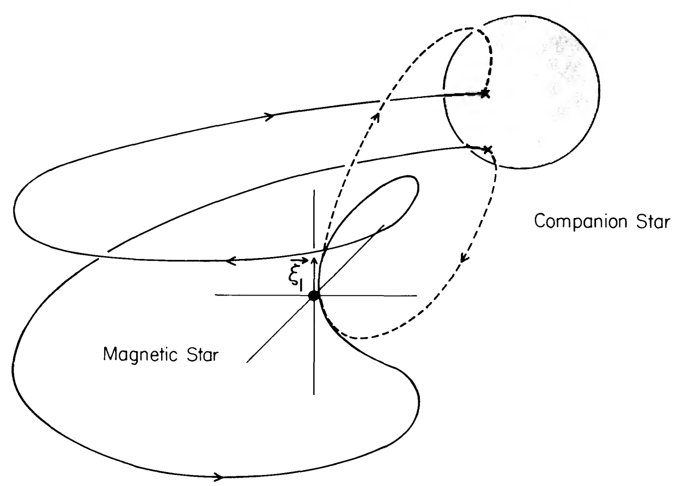

FIG. 1.—Perspective view of the binary system illustrating how a given flux tube is twisted as the magnetic star rotates with respect to its companion. *Dashed curve*, initial shape; *solid curve*, shape at a later time. The resulting Maxwell stress on the magnetic star produces a torque that opposes the rotation. For simplicity, slippage of field lines through the plasma has been neglected in this figure. In reality, the twist of the flux tube will not increase indefinitely but will be limited by the processes described in the text.

displays its dimensions is

$$N_{\rm MHD} \approx \alpha\gamma D R_2^2 \left(\mu_1/D^3\right)^2, \qquad (1)$$

where α is the fractional area of the companion star threaded by magnetic flux, γ is the pitch of the magnetic field linking the two stars, D is the binary separation, R_2 is the radius of the companion star, and μ_1 is the magnetic moment of the magnetic star. The results of our detailed numerical calculations are contained in the nondimensional factors α and γ and are discussed below. The remaining factors set the scale of the MHD torque: the magnetic stress at the companion is scaled in units of $(\mu_1/D^3)^2$, where μ_1/D^3 is the magnetic field at the companion, the area on which the stress acts is scaled in units of R_2^2, and the moment arm with respect to the magnetic star is scaled in units of D.

The pitch of the magnetic field linking the two stars is limited by dissipation of the field-aligned currents that maintain it, by magnetic flux reconnection, and by large-scale MHD instability of the field configuration. Our calculations indicate that dissipation within the magnetosphere by current-driven plasma instabilities there is less important in limiting the pitch than other effects if the particle density there exceeds 10–50 $\rm cm^{-3}$. We assume that this is the case and that, when the magnetic star is asynchronous, the pitch is limited by large-scale MHD instabilities. Numerical solutions of the two-dimensional partial differential equations that describe axisymmetric sheared-field configurations similar to those that arise in this system as well as analytical studies of the stability of such configurations (see Low 1982; Aly 1983) indicate that γ is limited to a value of approximately 1. This corresponds to approximately one turn in the magnetic field between the magnetic star and its companion. Once synchronism is achieved, γ becomes a function of the orientation of the magnetic star with respect to its companion, and the MHD torque tends to orient the magnetic star so that $\gamma = 0$.

The fractional area α of the companion star threaded by flux depends principally on the extent of convection in the companion star. We have computed the evolution of α with time for companion stars in the mass range 0.1–2.9 $M_\odot$ using 11 zero-age main-sequence (ZAMS) stellar models constructed by R. Webbink (private communication). This complex physical process was approximated by a scalar diffusion equation. Where present, turbulent transport by convective motions was modeled by an effective magnetic diffusivity $\eta_m = 0.15\, u_t l_t$. Here u_t and l_t are the convective velocity and the mixing length. The models with masses less than 0.3 $M_\odot$ are fully convective. In these models, α grows rapidly as a result of flux pumping and turbulent diffusion, reaching approximately 1 in a time much shorter than 10^5 yr. The models with masses in the range from 0.43 to 1.0 $M_\odot$ have substantial surface convection zones; here α initially grows to approximately 0.4–0.8 in much less than 10^5 yr and then grows more slowly as flux continues to diffuse inward by ordinary resistive diffusion. The 1.5, 2.0, and 2.9 $M_\odot$ models are radiative outside a small convective core. In these models, α grows slowly by resistive diffusion, reaching approximately 0.2 after about 10^8 yr (the flux does not reach the convective core until much later). The results for the stars that are not fully convective are shown in Figure 2. A more detailed discussion of the threading of the companion star will be given elsewhere.

The time to reach synchronism is plotted on the right-hand vertical axis of Figure 2, in units of the characteristic synchronization time:

$$\tau_s \equiv \frac{I_1 \xi_0}{N_{\rm MHD}}$$
$$= 1.76 \times 10^5 \gamma^{-1} \left(\frac{\xi_0}{5 \times 10^{-4}\ {\rm rad\ s^{-1}}}\right) \times \left(\frac{\mu_1}{2 \times 10^{34}\ {\rm gauss\ cm^3}}\right)^{-2} \times \left(\frac{I_1}{10^{50}\ {\rm g\ cm^2}}\right)\left(\frac{R_2}{3 \times 10^{10}\ {\rm cm}}\right)^{-2}\left(\frac{D}{10^{11}\ {\rm cm}}\right)^5 {\rm yr}. \qquad (2)$$

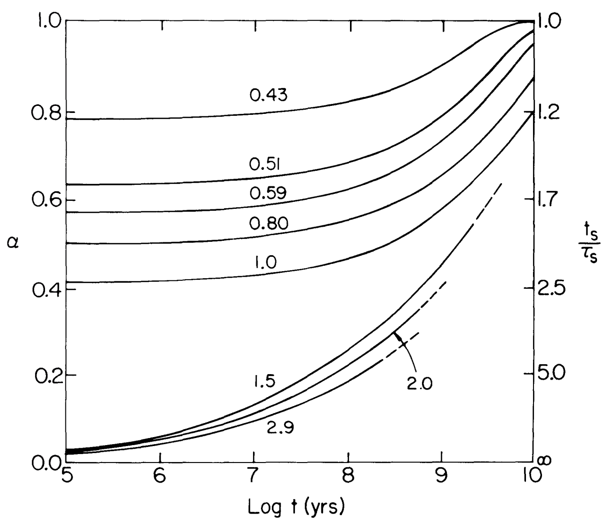

FIG. 2.—Increase in the strength of the MHD spin-orbit coupling with time for eight models of companion stars, assuming no flux threads the companion star initially. The vertical scale on the left shows the fractional area α of the companion threaded by magnetic flux, while that on the right shows the synchronization time t_s in units of the characteristic synchronization time τ_s, assuming that the torque is constant. The curves are labeled with the mass of the star in solar masses. Those for the three most massive stars end at approximately 10^9 yr because the ZAMS models used in the calculations are inaccurate representations of these stars at such late times.

Here I_1 is the inertial moment of the magnetic star, and $\xi_0 = \Omega_1(0) - \Omega_b(0)$ is its initial synodic frequency, where $\Omega_1(0)$ and $\Omega_b(0)$ are the initial angular frequencies of the magnetic star and the binary system. Equation (2) assumes that the synchronization torque is constant, an assumption that is approximately correct for the time scales of interest. The second expression on the right is scaled in units appropriate to systems like AM Her.

We have also considered the size of the MHD torque on magnetic stars with magnetic field configurations more general than the aligned rotator described above. We find that the torque produced by the aligned component $\mu_{\|}$ of the magnetic moment is comparable to the expression for $N_{\rm MHD}$ given above, with μ replaced by $\mu_{\|}$. In contrast, the torque produced by the perpendicular component $\mu_{\perp}$ is much less, except for synodic periods longer than approximately 10^3 yr, because α for this component is limited by the fact that the magnetic field associated with $\mu_{\perp}$ varies with the synodic frequency. If the companion star also has an intrinsic magnetic field, flux linkage between the two stars will occur via reconnection in the volume between the two stars. The magnetic pitch will be limited by precisely the same physical processes discussed above, and we expect the resulting torque to be comparable to $N_{\rm MHD}$. In this case, α will depend on the strength and orientation of the companion star's magnetic field as well as the evolutionary history of the system.

III. APPLICATIONS TO MAGNETIC STARS IN BINARY SYSTEMS

Consider first systems containing a strongly magnetic degenerate dwarf. When mass transfer is absent, equation (1) shows that the MHD torque can synchronize the degenerate star in AM Her type systems in as little as 10^5 yr. Even degenerate dwarfs with initial synodic periods as short as approximately 1 minute can be synchronized in approximately 10^8 yr in close systems. For white dwarfs with periods as short as this, the resulting energy dissipation rate $N_{\rm MHD}\xi$ is approximately 10^{33} ergs s^{-1} for about 10^3 yr. If they exist, such systems would be an interesting new class of relatively bright but short-lived, low-mass binaries. We expect most of the energy to be dissipated in regions of low plasma density between the two stars. Thus, luminosities of this order from low-density plasma may be a characteristic feature of such systems.

When mass transfer is present, the MHD torque can dominate the accretion torque on the degenerate dwarf for typical system parameters. Thus, for a system like AM Her, with $M_1 = 0.39\ M_\odot$, $R_1 = 1.1 \times 10^9$ cm, $B_1 \approx 2 \times 10^7$ gauss, $M_2 = 0.26\ M_\odot$, and $D = 6.4 \times 10^{10}$ cm (Young, Schneider, and Shectman 1981), one has $\mu_1 \approx 10^{34}$ gauss cm^3 and $I_1 \approx 2.7 \times 10^{50}$ g cm^2. The resulting MHD torque is approximately 8×10^{34} dyne cm, whereas the accretion torque is only approximately 10^{34} dyne cm for an accretion luminosity (Patterson 1984) of approximately 10^{33} ergs s^{-1}.

The AM Her stars appear to have very similar magnetic fields. For a given field strength, the strength of the MHD torque increases rapidly as the binary separation decreases and the companion star becomes more fully convective. This dependence offers a natural explanation for the fact that most systems with orbital periods longer than 4 hr, which are wider and contain companions with radiative cores (see Rappaport, Joss, and Webbink 1982), are synchronous (see Lamb and Patterson 1983 and references therein), whereas most systems with orbital periods shorter than approximately 4 hr, which are closer and contain fully convective companions, are synchronized.

The electric fields produced by asynchronous rotation are large and may accelerate electrons in some regions to high energies, exciting current-driven instabilities and radio emission. In AM Her, an efficiency of approximately 10^{-2} and a temporary synodic frequency as small as 10^{-4} of the orbital frequency would be sufficient to account for the radio luminosity reported by Chanmugam and Dulk (1982). Even in the absence of asynchronism, radio emission may persist for some time due to the large self-inductance of the current loop connecting the two stars.

The MHD torque is also strong enough to account for the observed synchronous rotation of magnetic A type stars in binary systems with periods as long as 7 days. Thus, for a system like HD 98088, with $M_1 = 2.2\ M_\odot$, $R_1 = 2.1\ R_\odot$, $B_1 = 1.8 \times 10^3$ gauss, $M_2 = 1.6\ M_\odot$, $R_2 = 1.5\ R_\odot$, and $D = 1.5 \times 10^{12}$ cm (Abt *et al.* 1968), one has $\mu_1 \approx 7 \times 10^{36}$ gauss cm^3, $I_1 \approx 8 \times 10^{54}$ g cm^2, and hence a characteristic synchronization time $\lesssim 1.4 \times 10^8$ yr. For comparison, the main-sequence evolutionary lifetime is 5.3×10^8 yr for a 2.2 $M_\odot$ A type star (Iben 1967, Table III). The fact that the orbit in HD 98088 is elliptical means that the relative phase of the magnetic star and its companion varies with orbital phase, even though the mean synodic frequency is zero. *Variable radio emission may therefore be present, if MHD spin-orbit coupling occurs.*

In neutron star systems, the MHD synchronization torque is too small to counter even a weak accretion torque, in agreement with the observed asynchronism of these systems.

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