SPIN-UP AND MAGNETIC FIELDS IN DQ HER STARS

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ABSTRACT

We have carried out a detailed comparison of the spin-up behavior of the recently discovered faint long-period X-ray sources, using the accretion torque theory of Ghosh and Lamb. We confirm that these sources are degenerate dwarfs. We find that they have magnetic fields $B \sim 1 \times 10^6$ G, an order of magnitude smaller than those of AM Her stars. On this basis, we predict that they will show significant polarization in the infrared.

1. INTRODUCTION

Recently, several faint galactic X-ray sources have been found to pulse in both X-rays and optical light with periods $\gtrsim$ 1000 seconds. Table 1 lists six of these sources, together with the three previously known DQ Her stars with rotation periods < 100 seconds, and summarizes some of their properties. Figure 1 shows the distribution of rotation period versus binary period for these nine stars. Also shown are the ten AM Her stars and the nine pulsing neutron stars for which the binary period is known. There has been controversy about whether the long-period sources are degenerate dwarfs, like the AM Her stars, or are neutron stars. Their optical appearance and their X-ray to optical luminosity ratio of order unity suggest that they are degenerate dwarfs (Patterson and Price 1981), however their properties are otherwise indistinguishable from the long-period neutron star sources (White and Marshall 1981).

We have carried out a detailed comparison of the spin-up rate of these stars and that expected from the classic accretion torque theory of Ghosh and Lamb (1978, 1979a,b). In this paper we summarize our findings. The full details of our analysis and a more complete discussion of our results will be published elsewhere (Lamb and Patterson 1982).

2. SPIN-UP BEHAVIOR

Ghosh and Lamb (1978, 1979a,b; hereafter GL) have developed a magnetohyrodynamic theory of disk accretion onto magnetic stars. According to this theory (see also Lamb, Pethick, and Pines 1973), the accretion torque is the sum of a matter torque and a torque arising from stressed magnetic field lines that thread the disk. If the star is a slow rotator (in the sense $\omega_s \equiv \Omega_K(r_o)/\Omega \ll 1$, where $\Omega_K(r_o)$ is the Keplerian angular velocity at the

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TABLE 1

DQ Her Stars

STAR	P_b (Hours)	d (pc)[a]	P (s)	$\lvert\dot{P}\rvert^{-1}$	L_s (10^{30} ergs s^{-1})[b]	T_{bb} (eV)	L_h (10^{30} ergs s^{-1})[b]	T_{br} (keV)	REFERENCES
AE Aqr	9.88	84	33.076737	$> 2 \times 10^{13}$	5.4	...	...	...	1, 10, 11, 13
V533 Her	$\simeq 7$	1000-1500	63.63307	$> 3 \times 10^{12}$	< 20-40	...	...	...	3, 9, 11
DQ Her	4.65	420	71.0653	1.2×10^{12}	< 2.4	...	...	...	3, 15
V1223 Sgr		400	794.380	$> 2 \times 10^{10}$	...	...	1600	$\gtrsim 10$	17, 18
H2252-035	3.59	250	805.21	$> 5 \times 10^{9}$	...	...	500	> 20	12, 13, 20, 21
3A0729+103	3.75	[200]	913.48	$> 5 \times 10^{9}$			160	[10]	7
H2215-086	4.03	[200]	1254.5	$> 5 \times 10^{9}$	20	...	48 120	$\gtrsim 10$ $\gtrsim 10$	16
Ex Hya	1.64	100	4021.62	2.2×10^{10}	14	570	60 100	$\simeq 5$ $\simeq 4.5$	4, 5, 19
TV Col (= 3A0526-328)	5.49	[200]	18690.	$> 2 \times 10^{6}$			140	[10]	2, 6, 8

[a] Distances in brackets are assumed.

[b] Luminosities assume a distance of 200 pc if distance is unknown and include only observed flux.

(1) Bailey (1981)
(2) Charles et al. (1979)
(3) Cordova, Mason, and Nelson (1981)
(4) Cordova and Riegler (1979)
(5) Gilliland (1982)
(6) Hutchings et al. (1981)
(7) McHardy et al. (1982)
(8) Motch (1981)
(9) Patterson (1979a)
(10) Patterson (1979b)
(11) Patterson (1982a)
(12) Patterson (1982b)
(13) Patterson et al. (1980)
(14) Patterson and Price (1981)
(15) Patterson, Robinson, and Nather (1978)
(16) Patterson and Steiner (1982)
(17) Steiner (1981)
(18) Steiner et al. (1981)
(19) Swank (1980)
(20) Warner, O'Donoghue, and Fairall (1981)
(21) White and Marshall (1981)

inner radius r_o of the disk and Ω is the angular velocity of the star), the matter torque dominates and the star is spun up. On the other hand, if the star is a fast rotator ($\omega_s \simeq 1$), the torque due to the stressed magnetic field lines dominates and the star is spun down. The spin-up rate is given in general by

$$-\dot{P} = 4.09 \times 10^{-11}\, n(\omega_s)\, (P_3 L_{34}{}^{3/7})^2\, B_6{}^{2/7} (M/M_\odot)^{-3/7}\, (R/5 \times 10^8 \text{ cm})^{12/7} I_{50}{}^{-1} \text{ s s}^{-1}, \quad (1)$$

where P_3 is the rotation period in units of 10^3 seconds, L_{34} is the luminosity in units of 10^{34} ergs s^{-1}, and M, R and I_{50} are mass, radius, and moment of inertia of the star, the last in units of 10^{50} g cm^2. In the remainder of this paper, we use the values of M, R, and I_{50} for a 1 $M_\odot$ degenerate dwarf. The dimensionless torque function $n(\omega_s)$ is given by GL (1979b; eq. 10), while the fastness parameter ω_s is given by

$$\omega_s = 0.114\, (P_3 L_{34}{}^{3/7})^{-1} B_6{}^{6/7}\, (M/M_\odot)^{-2/7} (R/5 \times 10^8 \text{ cm})^{15/7}. \quad (2)$$

Letting the constants in the theory take their standard values, the accretion torque vanishes for $\omega_s = 0.35$. This defines an equilibrium state for the accreting star. Assuming that the accreting star is near this equilibrium state, the spin-up rate is

$$-\dot{P}_{eq} = 5.96 \times 10^{-11}\, (\omega_s/0.35)^{1/3}\, (P_3 L_{34}{}^{3/7})^{7/3}\, (M/M_\odot)^{-1/3}\, (R/5 \times 10^8 \text{ cm}) I_{50}{}^{-1} \text{ s s}^{-1} \quad (3)$$

For somewhat larger values of ω_s, the centrifugal force exceeds the gravitational force at r_o and steady accretion is not possible; thus $\omega_s \sim 1$ also represents an upper limit to the fastness of the star. This translates into an upper bound on the stellar magnetic field,

$$B \lesssim 3.71 \times 10^6\, (\omega_s/0.35)^{7/6}\, (P_3 L_{34}{}^{3/7})^{7/6}\, (M/M_\odot)^{1/3}\, (R/5 \times 10^8)^{-5/2} \text{ G}, \quad (4)$$

and on the inner radius of the disk,

$$r_o/R \lesssim 14.9\, (\omega_s/0.35)^{2/3}\, P_3{}^{2/3}\, (M/M_\odot)^{1/3} (R/5 \times 10^8 \text{ cm})^{-1}. \quad (5)$$

All the sources display large amplitude X-ray and/or optical pulsations, indicating that the magnetic field is strong enough to disrupt the disk and channel the flow of accreting matter toward the magnetic pole(s). This implies a lower bound on the stellar magnetic field,

$$B \gtrsim 2.24 \times 10^5\, (r_o/3R)^{7/4}\, L_{34}{}^{1/2}\, (M/M_\odot)^{-1/4} (R/5 \times 10^8 \text{ cm})^{-3/4} \text{ G}. \quad (6)$$

Lower bounds on B and r_o/R can also be derived from the observed upper limit or measured value of $\dot{P}$, but are generally not very stringent because $\dot{P}$ depends so weakly on B (see eq. 1 above). Similar expressions hold for the pulsing neutron star X-ray sources, and when they are needed in the remainder of the paper, we use the values of M, R, and I for a 1.3 $M_\odot$ PPS star (Pandharipande, Pines, and Smith 1976).

In order to compare theory and observation, we need estimates of the accretion rates and luminosities of the sources. We have derived the accretion rates using the techniques described in Patterson (1982b) and Lamb and Patterson (1982), and have converted them to luminosities assuming a 1 $M_\odot$ star. The results are listed in the second and third columns of Table 2.

3. DISCUSSION

3.1. Nature of Long-Period Sources

Figure 2 shows the spin-up rates given by the theory of GL for degenerate dwarfs with magnetic fields $B = 10^4$-10^8 G (solid curves) and neutron stars with $B = 10^{10}$-10^{14} G (dashed curves). Also plotted are the observed upper limits or measured value of the spin-up rates for the nine stars listed in Table 1 and the nine pulsing neutron star sources for which $\dot{P}$'s have been measured (cf. Rappaport and Joss 1977; GL 1979b, Table 2). The region of Figure 2 accessible to degenerate dwarfs lies inside the region accessible to neutron stars. Therefore, there is always a neutron star spin-up curve that passes through any given degenerate dwarf spin-up rate. However, these solutions always require that the star be an extremely fast rotator. Even Her X-1, for which $\omega_s \simeq 0.35$ and for which the accretion torque is 30 times less than the slow rotator value, is not nearly fast enough, as can be seen from Figure 2. Furthermore, the seven upper limits and two measured values of the spin-up rate for the nine stars listed in Table 1 are all consistent with the spin-up behavior expected for degenerate dwarfs that are not particularly fast rotators. This agreement supports the accretion torque theory of GL. We also conclude the the nine stars listed in Table 1 are indeed all degenerate dwarfs. Henceforth we shall refer to them as DQ Her stars.

Throughout the remainder of this paper we shall assume the validity of the GL accretion torque theory for the DQ Her stars. If we further assume that the stars lie near the equilibrium state corresponding to $\omega_s = 0.35$ described earlier, we can derive the equilibrium spin-up rate $-\dot{P}_{eq}$, the range of allowed stellar magnetic field, and an upper bound to the ratio of the inner radius of the disk and the stellar radius r_o/R, for each of the DQ Her stars listed in Table 1, using equations (3), (4) and (6), and (5), respectively. The results are given in Table 2.

The values of $-\dot{P}_{eq}$ agree well with the observed spin-up rates of DQ Her and EX Hya (compare column 5 of Table 1 and column 4 of Table 2). The values of $-\dot{P}_{eq}$ for the remaining sources constitute predictions, provided that the stars are near equilibrium. They suggest that the spin-up rates of most of the sources will soon be measurable, but that those of AE Aqr and TV Col may not be measurable for some time to come. On the other hand, if the stars are not near equilibrium, they must have experienced episodes of spin-down as well as spin-up in the past, since their spin-up time scales ($T_s \equiv P\,|\dot{P}|^{-1}$) are all much less than the evolutionary time scales of their binary systems (cf. the discussions by GL 1979b and Elsner, Ghosh, and Lamb 1980 of the analogous situation in the long period neutron star X-ray sources).

3.2. Magnetic Field Strengths

The range of stellar magnetic field strengths allowed by the spin-up and pulsing behavior of the DQ Her stars is given in column 5 of Table 2. In the cases of the three short-period sources, the maximum and minimum allowed field strengths coincide (in the cases of DQ Her and V533 Her, they are even slightly inconsistent). Assuming the stars to be very slowly rotating, rather than nearly in equilibrium, would make the minimum and maximum field strengths more inconsistent. We conclude that these stars are moderately fast rotators near equilibrium, and predict that they have magnetic fields $B \sim 6 \times 10^5$ G. For the long-period sources, a range of magnetic fields is consistent with their spin-up and pulsing behavior. The allowed magnetic fields are $B \sim 1 \times 10^6$ G, an order of magnitude smaller than those of AM Her stars. On this basis, we predict that the long-period sources will show significant polarization in the infrared, while the short-period ones will show

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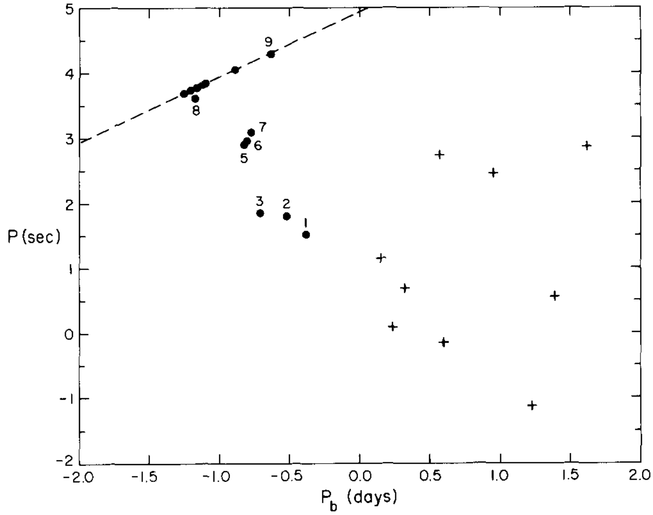

Fig. 1--Distribution of rotation period P versus binary period P_b for the nine stars in Table 1 (the numbers label them by their position in the table). Also shown are the ten AM Her stars and the nine pulsing neutron star X-ray sources for which the binary period is known.

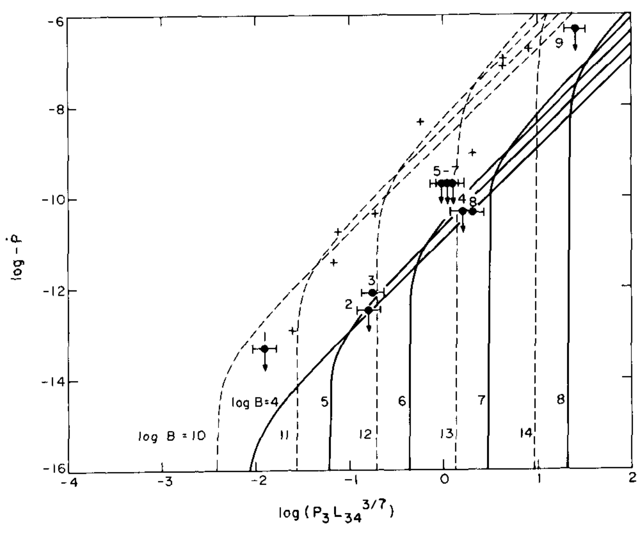

Fig. 2--Curves of the spin-up rate for degenerate dwarfs (solid lines) and for neutron stars (dashed lines). Also plotted are the observed upper limits or measured values of $\dot{P}$ for the nine stars in Table 1 (again labeled by their position in the table) and the nine pulsing neutron star sources for which $\dot{P}$'s have been measured.

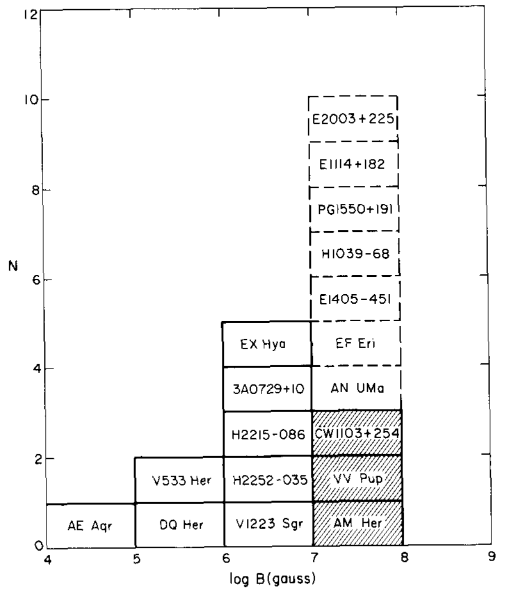

Fig. 3--Histogram of the stellar magnetic field strengths of the known magnetic cataclysmic variables. The shaded boxes are AM Her stars for which the magnetic field has been directly measured; the dashed boxes are the remaining AM Her stars (assumed to have similar fields). The unshaded boxes are DQ Her stars; their fields have been inferred from their spin-up and pulsing behavior.

TABLE 2

Derived Properties of DQ Her Stars

STAR	$\dot{M}$ ($10^{-9} M_\odot$ yr^{-1})	L (10^{34} erg s^{-1})	$\lvert\dot{P}_{eq}\rvert^{-1}$	B (gauss)[a]	r_o/R[a]
AE Aqr	0.06	0.1	7×10^{14}	$\simeq 6 \times 10^4$	$\simeq 3$
V533 Her	5	8	2×10^{12}	$\simeq 6 \times 10^5$	$\simeq 3$
DQ Her	5	8	1×10^{12}	$\simeq 6 \times 10^5$	$\simeq 3$
V1223 Sgr	3	5	8×10^9	$5 \times 10^5 - 5 \times 10^6$	$\lesssim 10$
H2252-035	2	2	2×10^{10}	$3 \times 10^5 - 3 \times 10^6$	$\lesssim 10$
3A0729+103	1	2	1×10^{10}	$3 \times 10^5 - 4 \times 10^6$	$\lesssim 10$
H2215-086	0.3	0.5	3×10^{10}	$1 \times 10^5 - 3 \times 10^6$	$\lesssim 20$
EX Hya	0.1	0.2	4×10^9	$9 \times 10^4 - 6 \times 10^6$	$\lesssim 30$
TV Col	1	2	1×10^7	$3 \times 10^5 - 1 \times 10^8$	$\lesssim 90$

[a]The larger value or the equality applies if the star is near equilibrium, i.e., if the accretion torque is nearly zero.

polarization only at longer wavelengths. Finally, we note that the fact that EX Hya does not rotate sychronously with its binary period, although the period is shorter than those of many AM Her stars, is now easily understood as due to the fact that it has a magnetic field at least an order of magnitude smaller than the fields in AM Her stars.

The upper bound on the ratio r_o/R is given in column 6 of Table 2. It is a function only of the rotation period of the star (see eq. 5) and increases as the period increases. If the star is near equilibrium, the equality applies; otherwise, the ratio must be smaller. The ratio is only ~ 3 for the three short-period sources, indicating that the disk extends down nearly to the stellar surface (note, however, that $r_o/R \propto L^{-2/7}$, so that an increase in luminosity of a factor of ~ 50 is still required to crush the magnetosphere to the stellar surface). For the long-period sources, the ratio is larger, although not as large as the value ~ 200 typical of pulsing neutron star X-ray sources. In fact, the emission lines from the disks in these sources should all be rather broad (velocity profiles $\gtrsim 1000$ km s^{-1}. However, if the emission line widths seen in TV Col (Hutchings et al. 1981) are due to Keplerian velocity broadening, the large inferred velocity ($\simeq 3000$ km s^{-1}) suggests that r_o/R is not very large and that this source is far from equilibrium. This result and the lack of observed optical polarization (Charles et al. 1979) indicates that the magnetic field in TV Col is closer to the minimum value $\simeq 3 \times 10^5$ G than to the maximum of $\simeq 1 \times 10^8$ G.

Figure 3 shows a histogram of the stellar magnetic field strengths of the known magnetic cataclysmic variables (AM Her stars and DQ Her stars). The stars in the interval 10^7-10^8 G are all AM Her stars; the shaded stars are those in which the magnetic field has been directly measured, while the remainder have been assumed to have similar field strengths on the basis of their similar X-ray, UV, and optical spectra, and the fact that they are all phase-locked to their binary periods. The stars in the unshaded boxes drawn with solid lines are all DQ Her stars; their magnetic fields have been inferred from their spin-up and pulsing behavior, as described above. The observational selection effects affecting this histogram are obviously severe; for example, the identification of AM Her stars is relatively easier. Thus, it is not clear at present what to make of the distribution of magnetic fields; however, the situation may inprove as an X-ray-selected sample of stars becomes possible.

4. CONCLUSIONS

We have carried out a detailed comparison of the spin-up rate of the recently discovered faint long-period X-ray sources and that expected from the classic accretion torque theory of Ghosh and Lamb (1978, 1979a,b). Our analysis supports the theory and confirms that the long-period sources are indeed degenerate dwarfs. These stars have rotation periods appropriate to their luminosities and magnetic fields. We therefore believe that they and the DQ Her stars should be regarded as members of a single class, as are the short- and long-period pulsing neutron star X-ray sources.

Our analysis also shows that the long-period sources have magnetic fields $B \sim 1 \times 10^6$ G, an order of magnitude smaller than those of AM Her stars, and that the three previously known short-period DQ Her stars have still smaller fields. On this basis, we predict that the long-period sources will show significant polarization in the infrared, while the short-period ones will show polarization only at longer wavelengths.

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DISCUSSION FOLLOWING D. LAMB'S TALK

CHANMUGAM: I have a comment regarding the distribution of magnetic fields. These isolated white dwarfs have no magnetic fields less than $3x10^6$ Gauss or something like that and I think there are upper limits, down to 10^4 Gauss in isolated magnetic white dwarfs. This means that the field distribution here, since you are seeing a lot of systems with fields in between is quite different.

LAMB: I think it is premature to conclude that. To my knowledge the most careful work that has been done on the distribution of magnetic fields in isolated degenerate dwarfs is by Liebert, Borra, and Handstreet. Their results are consistent with a uniform distribution of magnetic field strengths.

CHANMUGAM: According to Angel et al., that is between $3x10^6$ and $3x10^8$, there is a cut off at about 10^6.

ROBINSON: AE Aqr has a very low accretion rate and its Alfven radius is still relatively close to the white dwarf, how much could you increase that accretion rate before the Alfven radius got squashed right down to the white dwarf?

LAMB: It goes like $L^{-2/7}$ so if you want to change this by a factor of 2 it would be a factor of 10 in accretion rate.

ROBINSON: So, as the star evolves and its accretion rate goes up or down, I am talking about secular variations, the magnetic field of the white dwarf can be important or absolutely negligible depending on the accretion rate.

LAMB: That's correct. But this is true only for low field strengths.

WILLIAMS: I find it curious that several of the intermediate polar objects are active novae whereas non of the AM Her type are novae and I wonder what the possible effects of magnetic fields on the nova phenomenon are.

LAMB: It could have effects, but they are poorly understood and I don't wish to try to address them here.

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