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SPIN-UP OF LOW-LUMINOSITY, LOW-MASS X-RAY BINARIES

INSU YI¹

Institute for Advanced Study, Princeton, NJ 08540; yi@ias.edu

AND

JONATHAN E. GRINDLAY

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; jgrindlay@cfa.harvard.edu

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ABSTRACT

We examine the spin-up of low-luminosity, low-mass X-ray binaries (LMXBs) to millisecond pulsars (MSPs). In the conventional spin-up model of the Ghosh & Lamb type, where the stellar magnetic field interacts with the Keplerian accretion disk, MSPs could be produced from LMXBs if the magnetic field $B_* \lesssim 10^8 (\dot{M}/10^{16} \text{ g s}^{-1}) \text{ G}$, where $\dot{M}$ is the mass accretion rate. However, for $\dot{M} < \dot{M}_c \sim 10^{16} \text{ g s}^{-1}$, accretion is likely to occur via a quasi-spherical flow with a sub-Keplerian rotation. The sub-Keplerian rotation rate is smaller than the Keplerian rate by a factor ~ 2 –10. As a consequence, the spin up of LMXBs produces pulsars with spin periods longer by a factor of ~ 2 –10 than those with a Keplerian accretion disk. The observed MSPs could be produced only for $B_* < 10^7 \text{ G}$ even when $\dot{M} \sim \dot{M}_c \sim 10^{16} \text{ g s}^{-1}$. This suggests that the low-luminosity LMXBs with $\dot{M} < \dot{M}_c$ would not be able to spin-up to the observed MSPs. This rules out any undetected populations of persistent, low-luminosity LMXBs and a potentially significant fraction of the atoll sources as a possible source population of the observed MSPs. If a large number of undetected, persistent, low-luminosity LMXBs do exist, they could produce MSPs near the pulsar death line with intrinsic electromagnetic luminosity $\lesssim 10^{30} \text{ ergs s}^{-1}$. The observed MSPs could possibly arise from a population of soft X-ray transients (SXTs) containing neutron stars, although this is not supported by current estimates of the outburst rate or numbers of such systems. Accretion-induced collapse of low magnetic field white dwarfs remains a possible channel for MSP formation.

Subject heading: accretion, accretion disks — pulsars: general — stars: magnetic fields — X-rays: stars

1. INTRODUCTION

The origin of millisecond pulsars (MSPs) remains an outstanding problem (see, e.g., Bhattacharya & van den Heuvel 1991). A number of channels of MSP formation have been discussed. In the standard model, magnetized, low-mass X-ray binaries (LMXBs) spin up to MSPs through mass accretion (see, e.g., Frank, King, & Raine 1992). Several statistical analyses, however, have questioned whether the known LMXB populations could produce the observed MSPs (Grindlay & Bailyn 1988; Kulkarni & Narayan 1988; Bailyn & Grindlay 1990; Kulkarni 1995).

The problem of MSP birthrate is briefly summarized as follows (see, e.g., Grindlay 1995). The MSP lifetime owing to the electromagnetic dipole emission (see, e.g., Shapiro & Teukolsky 1983) is $\tau_{\text{MSP}} \sim 10^{10} (B_*/5 \times 10^8 \text{ G})^{-2} (P_*/5 \text{ ms})^2 \text{ yr}$, where B_* is the pulsar magnetic field strength and P_* is the spin period. For the estimated total number of MSPs (Bailes & Lorimer 1995), $N_{\text{MSP}} \sim 10^5$, the observed MSPs require a birthrate of $\sim N_{\text{MSP}}/\tau_{\text{MSP}} \sim 10^{-5}$ on the MSP birthrate, $\sim 3 \times 10^{-6} \text{ yr}^{-1}$ above the luminosity limit of 1 mJy kpc^2 . The uncertainty in this estimate could be large owing to uncertainties in beaming of pulsar emission and the Galactic scale height of the pulsar distribution. For a high accretion rate $\dot{M}$ and a relatively low B_* , the accretion flow extends close to the neutron star surface. Then, the spin-up of a slowly rotating neutron star to the spin period of $P_* \sim 5 \text{ ms}$ would require mass accretion of at least $\gtrsim \Delta M \sim I_* \Omega_*/(GM_* R_*)^{1/2} \sim 0.1 M_\odot$, where the moment of inertia $I_* = 10^{45} \text{ g cm}^2$, the mass $M_* = 1.4 M_\odot$, the

radius of the neutron star $R_* = 10^6 \text{ cm}$, and $\Omega_* = 2\pi/P_*$ (see, e.g., Bhattacharya & van den Heuvel 1991). Luminous Z sources have luminosities $L_Z \sim 3 \times 10^{37}$ – $10^{38} \text{ ergs s}^{-1}$ close to the Eddington luminosity $L_{\text{Edd}} \sim 2 \times 10^{38} \text{ ergs s}^{-1}$, and their magnetic fields are estimated to be in the range $\sim 10^9$ – 10^{10} G . The typical spin-up timescale for Z sources is $\tau_Z \gtrsim GM_* \Delta M/L_Z R_* \sim 3 \times 10^7 \text{ yr}$. For the observed number of Z sources, $N_Z = 6$, and the MSP birthrate from Z sources is expected to be $\lesssim N_Z/\tau_Z \sim 2 \times 10^{-7} \text{ yr}^{-1}$. For less luminous, bursting atoll sources with luminosities $L_{\text{atoll}} \sim 10^{36}$ – $10^{37} \text{ ergs s}^{-1}$, the typical spin-up timescale is $\tau_{\text{atoll}} \gtrsim GM_* \Delta M/L_{\text{atoll}} R_* \sim 10^9 \text{ yr}$. For the total number of atoll sources $N_{\text{atoll}} \sim 10^2$, the estimated birthrate is $\lesssim N_{\text{atoll}}/\tau_{\text{atoll}} \sim 10^{-7} \text{ yr}^{-1}$, which is within a factor ~ 2 of the Z source rate. These rates fall short of the MSP formation rate by at least 1 order of magnitude (see, e.g., Kulkarni 1995).

Recent observations with *Rossi X-Ray Timing Explorer* (RXTE) (see, e.g., summary in White & Zhang 1997) have yielded the long-sought evidence that LMXBs (including both Z sources and burst sources) are spun up to a few millisecond spin periods as indicated by their kHz quasi-periodic oscillations (QPOs) and the direct detection in a few sources of what appear to be underlying spin periods. Some 10 sources now appear to have $\sim 300 \text{ Hz}$ pulsation frequencies, which certainly suggests that these sources have indeed spun up and could thus evolve to MSPs. Recently, the first direct detection of a true LMXB MSP (SAX J1808.4–3658) with a spin period of 2.49 ms was reported (Wijnands & van der Klis 1998) along with the value for its binary period ($\sim 2 \text{ h}$), probable companion mass ($\lesssim 0.1 M_\odot$), and likely evolution (Chakrabarty & Morgan 1998). However, even if all the known LMXBs are found to have

¹ Also at CAIS-RIBs and Department of Physics, Ewha University, Seoul, Korea.

FIG. 1a

FIG. 1.—(a) Spin-up lines in the B_* vs. P_* plane. Crosses are the observed pulsars adopted from the website of Taylor and coworkers (1995). The dashed line is the pulsar death line, $B_* \sim 2 \times 10^{11} P_*$. The solid lines are the spin-up lines for $\dot{M}$, 10^{18} g s^{-1} , $\dot{M}_c = 3.5 \times 10^{16} \text{ g s}^{-1}$, 10^{16} g s^{-1} , $6.3 \times 10^{15} \text{ g s}^{-1}$, and 10^{13} g s^{-1} from top to bottom, respectively. The thick solid lines are relevant for typical atoll sources. (b) Similar to (a), with the sub-Keplerian rotation ($\omega_a = 0.2$) for $\dot{M} < \dot{M}_c$. The spin-up line for a given $\dot{M} < \dot{M}_c$ moves down owing to the sub-Keplerian rotation. Top to bottom: $\dot{M} = 3.5 \times 10^{16} \text{ g s}^{-1}$, 10^{16} g s^{-1} , $6.3 \times 10^{15} \text{ g s}^{-1}$, and 10^{13} g s^{-1} . The box at bottom left indicates the location of the “typical” MSPs spun up by the sub-Keplerian accretion flows. The dotted line is a possible birth line from AIC for $\dot{M} = 3.2 \times 10^{18} \text{ g s}^{-1}$. The thick solid lines are relevant for typical atoll sources.

similar pulsation periods, the birthrate problem summarized above still remains to be resolved.

The MSP formation problem could be solved if a generally unseen population of LMXBs with low luminosities spin up to MSPs. Recent observations have measured low quiescent luminosities from recurrent transients as well as some usually bright persistent sources (Verbunt et al. 1994). The required number N_l of the low-luminosity LMXBs with the luminosity L_l is $N_l \sim 10N_{\text{atoll}}(L_{\text{atoll}}/L_l)$ if these sources are the solution to the MSP formation problem. Since the spin-up timescale for the low-luminosity population is $\tau_l \sim \tau_{\text{atoll}}(L_{\text{atoll}}/L_l)$, L_l must be at least $\sim 0.1L_{\text{atoll}}$ in order to avoid an excessively long spin-up timescale. $N_l \sim 100N_{\text{atoll}}$ is required with $L_l \sim 0.1L_{\text{atoll}}$. The low luminosities are

either a constant for persistent sources or a time-averaged value for recurrent transient sources. It is crucial whether low-luminosity sources with $L_l \sim 0.1L_{\text{atoll}}$, persistent or recurrent, are able to spin up to MSPs.

2. SPIN-UP OF LMXBS: STANDARD MODEL WITH LOW $\dot{M}$

The spin period of a neutron star evolves according to $\dot{P}_* = -NP_*^2/I_*$, where N is the torque exerted on the star by the accretion flow. In the conventional magnetized, Keplerian accretion disk mode (see, e.g., Wang 1995; Yi, Wheeler, & Vishniac 1997, and references therein), the accretion flow is truncated by the neutron star magnetosphere

FIG. 1b

at a radius R_o determined by

$$\left(\frac{R_o}{R_c}\right)^{7/2} \left[1 - \left(\frac{R_o}{R_c}\right)^{3/2}\right]^{-1} = \frac{2N_c}{\dot{M}(GM_* R_c)^{1/2}} \quad (1)$$

where $R_c = (GM_* P_*^2 / 4\pi^2)^{1/3}$ is the Keplerian corotation radius, $N_c = (\gamma/\alpha) B_*^2 R_o^6 R_c^{-3}$, α is the usual viscosity parameter (Frank et al. 1992), and γ is the parameter of order unity that determines the pitch of the magnetic field in the accretion disk (see, e.g., Wang 1995). For numerical values, we adopt $\alpha = 0.3$ and $\gamma = 1$ unless noted otherwise. The torque exerted on the star is

$$N = \left(\frac{7N_o}{6}\right) \frac{[1 - (8/7)(R_o/R_c)^{3/2}]}{[1 - (R_o/R_c)^{3/2}]}, \quad (2)$$

where $N_o = \dot{M}(GM_* R_o)^{1/2}$. The spin equilibrium $N = 0$ occurs when $R_o/R_c = x_{eq} = (7/8)^{2/3}$. This adopted magnetic torque model differs little from other phenomenological

models for the purpose of the present discussion (Wang 1995).

In the spin-up regime $N > 0$ or $R_o/R_c < x_{eq}$, we get from equation (2)

$$N \approx 1.3(GM_* R_*^2)^{3/7} \left(\frac{\gamma}{\alpha}\right)^{1/7} B_*^{2/7} \dot{M}^{6/7}. \quad (3)$$

In this regime, the spin period evolves simply as $\dot{P}_* \propto -(\gamma/\alpha)^{1/7} B_*^{2/7} \dot{M}^{6/7} P_*^2$. The spin-up line is determined by the equilibrium spin condition $\dot{N} = 0$,

$$P_* \approx [5 \text{ ms}] \gamma^{3/7} \alpha_{-1}^{-3/7} B_{*,8}^{6/7} \dot{M}_{16}^{-3/7} \quad (4)$$

where $\alpha_{-1} = \alpha/0.1$, $B_{*,8} = B_*/10^8 \text{ G}$, and $\dot{M}_{16} = \dot{M}/10^{16} \text{ g s}^{-1}$. Spin periods of $P_* \lesssim 5 \text{ ms}$ would be reached for $B_* < [3 \times 10^8 \text{ G}](\alpha/\gamma)^{1/2} \dot{M}_{16}^{1/2}$. The spin-up line corresponding to $\dot{M} = 10^{18} \text{ g s}^{-1}$, which is close to the Eddington rate, is $P_* \approx [0.4 \text{ ms}] B_{*,8}^{6/7}$, which obviously implies that MSPs with $P_* \sim 5 \text{ ms}$ could easily form from high-luminosity LMXBs such as Z sources with B_* as high as $\lesssim 3 \times 10^9 \text{ G}$.

For $\dot{M} = 10^{16} \text{ g s}^{-1}$, which is relevant for atoll sources, the spin-up line is $P_* \approx [3 \text{ ms}] B_{*,8}^{6/7}$. $P_* \sim 5 \text{ ms}$ requires $B_* \lesssim 2 \times 10^8 \text{ G}$. Given the dependence of $B_* \propto (\alpha/\gamma)^{1/2}$, it is gratifying that the uncertainties in α and γ are not critical unless $\alpha \ll 0.1$ and $\gamma \gg 1$, which is highly unlikely (see, e.g., Aly & Kuijpers 1990; Wang 1995).

In Figure 1a, we plot the spin-up lines in the P_* versus B_* plane. The crosses are the positions of the observed pulsars with their spin periods and estimated magnetic fields adopted from Taylor et al.² The magnetic fields have been estimated based on the assumption that their power is derived from the electromagnetic dipole emission at a rate $\dot{E} = 4\pi I_* \dot{P}_*/P_*^3$; i.e., $B_* = (3I_* c^3 P_* \dot{P}_*/8\pi^2 R_*^6)^{1/2}$. In Figure 1a, we show spin-up lines assuming that the accretion flow remains Keplerian for all $\dot{M}$ s. This plot shows that MSPs form only from LMXBs with weak magnetic fields less than 10^8 G if $\dot{M} < 6 \times 10^{15} \text{ g s}^{-1}$, or LMXBs with $B_* < 10^7 \text{ G}$ if $\dot{M} \sim 10^{13} \text{ g s}^{-1}$. A system with a lower $\dot{M}$ needs proportionally more time to spin up to an MSP than does a high- $\dot{M}$ system. The final spin period becomes the equilibrium period, which is fixed by both $\dot{M}$ and B_* only if the system arrives at the equilibrium period on timescales for the binary not to have evolved significantly. Otherwise, $\dot{M}$ would have changed significantly, in which case a new equilibrium spin period would be sought. For $\dot{M} \sim 10^{13} \text{ g s}^{-1}$, the spin-up timescale is prohibitively long, $\gg 10^{10} \text{ yr}$, and spin up to an MSP in a timescale less than the age of the Galaxy is impossible. Therefore, in the standard model, the MSP formation rate problem could be solved only if there are $\gtrsim 5 \times 10^2 N_{\text{atoll}} \sim 5 \times 10^4$ persistent, low-luminosity LMXBs with $\dot{M} \sim 10^{15} \text{ g s}^{-1}$ (i.e., luminosity $L \sim 5 \times 10^{-2} L_{\text{atoll}}$) and magnetic fields $\sim 5 \times 10^7 \text{ G}$ (see below for recurrent sources).

3. SPIN-UP BY SUB-KEPLERIAN FLOWS AT LOW MASS ACCRETION RATES

The conclusion we have derived above may get dramatically worse because of the possible transition in accretion flows (Grindlay 1995). This is because at low $\dot{M}$, the accretion flow is likely to take the form of a quasi-spherical, sub-Keplerian rotation (see, e.g., Narayan & Yi 1995). More specifically, when $\dot{M}$ falls below the critical accretion rate $\dot{M}_c$, the viscously dissipated energy in the accretion flow is not efficiently radiated but kept as internal heat energy of the accreted gas. As a result, the accretion flow is heated essentially to the virial temperature, and the accretion flow thickens because of the internal pressure support. The internal pressure support also causes the rotation of the quasi-spherical flow to deviate from Keplerian to sub-Keplerian.

The sub-Keplerian rotation of the accretion flow can be conveniently modeled as $\Omega = \omega_a \Omega_K$ where $\omega_a \leq 1$ and $\Omega_K = (GM_*/R^3)^{1/2}$ is the Keplerian rotation (Narayan & Yi 1995; Yi et al. 1997). The sub-Keplerian rotation parameter ω_a is determined essentially by the ratio of the internal pressures $\beta = P_{\text{gas}}/(P_{\text{gas}} + P_{\text{mag}})$, where P_{gas} is the gas pressure and P_{mag} is the magnetic pressure from the tangled, isotropic magnetic field in equipartition with the thermal energy of the accreted plasma; i.e., $\omega_a = [(10 - 6\gamma_s)/(9\gamma_s - 5)]^{1/2}$, where $\gamma_s = (8 - 3\beta)/(6 - 3\beta)$ is the ratio of specific heats in the assumed equipartition plasma (Esin

1997; Narayan & Yi 1995). A large $\beta \sim 1$ (i.e., small magnetic pressure) would give $\omega_a \ll 1$, whereas $\omega_a \sim 0.4$ for equipartition $\beta \sim 0.5$. The sub-Keplerian rotation parameter ω_a weakly depends on α as long as $\alpha = 0.01\text{--}0.3$. Recently, Yi et al. (1997) have suggested that the torque reversals seen in some X-ray pulsars could precisely be because of this accretion flow transition, which would also confirm that indeed sub-Keplerian flows form probably for $\dot{M}$ below a critical rate $\dot{M}_c$ for accretion onto neutron stars, since otherwise these advection-dominated accretion flows (ADAFs) have been derived originally only for accretion onto black holes (Narayan & Yi 1995). It has been demonstrated that observed reversal events are reproduced by $\omega_a \approx 0.1\text{--}0.4$ when the transition occurs at $\dot{M} = \dot{M}_c \sim 10^{16} \text{ g s}^{-1}$. This supports the existence of the plasma roughly with equipartition in accretion flows around LMXBs when $\dot{M} < \dot{M}_c$.

The critical accretion rate $\dot{M}_c \sim 0.1\alpha^2 \dot{M}_{\text{Edd}}$, where $\dot{M}_{\text{Edd}}$ is the Eddington accretion rate with 10% efficiency (Narayan & Yi 1995). For $\alpha = 0.3$, $\dot{M}_c \sim 10^{16} \text{ g s}^{-1}$ is expected. This rate could be somewhat lower than the critical rate for the ADAF black hole systems, since cooling of the accretion flow is more efficient in neutron star systems owing to the soft photons from the neutron star surface (Narayan & Yi 1995). The appearance of the quasi-spherical flow is accompanied by slight luminosity changes (Yi et al. 1997 and references therein), but the X-ray spectral changes appear to be significant (Vaughan & Kitamoto 1997).

When the accretion flow rotation becomes sub-Keplerian, the corotation radius is shifted to a new location, $R'_c = \omega_a^{2/3} R_c$ (Yi et al. 1997). The magnetospheric radius R_o is then shifted to the radius R'_o , which is determined by (see, e.g., eq. [1])

$$\left(\frac{R'_o}{R'_c}\right)^3 \left[1 - \left(\frac{R'_o}{R'_c}\right)^{3/2}\right]^{-1} = \frac{2N'_c}{\omega_a N'_o}, \quad (5)$$

where $N'_o = \omega_a \dot{M} (GM_* R'_o)^{1/2}$. The torque exerted on the star is modified as (Yi et al. 1997)

$$N' = \left(\frac{7N'_o}{6}\right) \frac{1 - (8/7)(R'_o/R'_c)^{3/2}}{1 - (R'_o/R'_c)^{3/2}}. \quad (6)$$

In the spin-up regime, the spin-up torque is given by

$$N' \approx 1.3\omega_a (GM_*)^{3/7} R_*^{6/7} (\gamma/\alpha)^{1/7} B_*^{2/7} \dot{M}^{6/7}, \quad (7)$$

and the spin-up line is given by

$$P_* = [49 \text{ ms}] \omega \gamma^{3/7} \alpha^{-3/7} B_{*,8}^{6/7} \dot{M}_{16}^{-3/7} \quad (8)$$

where $\omega_{a,-1} = \omega_a/0.1$. The equilibrium spin period for given $\dot{M}$ and B_* becomes longer by a factor of $\omega_a^{-1} > 1$. $P_* \lesssim 5 \text{ ms}$ would be reached for

$$B_* \lesssim [3 \times 10^8 \text{ G}] \omega_a^{7/6} \left(\frac{\alpha}{\gamma}\right)^{1/2} \dot{M}_{16}. \quad (9)$$

For $\omega_a = 0.2$ and $\dot{M} = 10^{16} \text{ g s}^{-1}$, $P_* \approx [15 \text{ ms}] B_{*,8}^{6/7}$, which suggests that a typical MSP with $P_* = 5 \text{ ms}$ would require $B_* \lesssim 3 \times 10^7 \text{ G}$. Any LMXBs with $\dot{M} < 10^{15} \text{ g s}^{-1}$ cannot produce the observed MSPs with $B_* > 5 \times 10^7 \text{ G}$.

It is usually thought that neutron stars are born with larger magnetic fields and that such low magnetic fields required ($B_* \lesssim 3 \times 10^7 \text{ G}$) for spin-up of low-luminosity LMXBs to MSPs must therefore result from field decay. Although the exact mechanism for field decay still remains uncertain, in a simple heuristic model the field decays as a

² J. H. Taylor, R. N. Manchester, A. G. Lyne, & F. Camilo, 1995, available at [ftp://pulsar.princeton.edu/pub/catalog](http://pulsar.princeton.edu/pub/catalog).

result of mass accretion, and the strength of the magnetic field is determined by the amount of mass accreted (see, e.g., Taam & van den Heuvel 1986; Romani 1990). In this model, $B_* \propto (\dot{M}\Delta t/\Delta M_d)^{-x}$, where Δt is the duration of accretion and ΔM_d is the characteristic mass scale for field decay. Assuming that neutron stars are typically produced with field strengths $\gtrsim 10^{12}$ G, the spin-up of atoll sources with $\dot{M} \sim 10^{17}$ g s⁻¹ to MSPs requires $\Delta t \sim 5 \times 10^7$ yr and $B_* \sim 3 \times 10^8$ G (and $\sim 6 \times 10^8$ yr for the subcritical accretion case with $\dot{M} \sim 10^{16}$ g s⁻¹ and $B_* \lesssim 3 \times 10^7$ G). Thus for the atoll source case (with $\dot{M} \sim 10^{17}$ g s⁻¹) the field decay model requires the characteristic mass $\Delta M_d \sim 3 \times 10^{-5} M_\odot$ for $x \sim 1$.

However, there is now evidence against field decay in LMXBs with values below $\sim 10^8$ G: the newly discovered LMXB MSP SAX J1808.4–3658 (Wijnands & van der Klis 1998) directly shows that this LMXB contains a neutron star with a likely magnetic field $B \sim (2\text{--}14) \times 10^8$ G (although these same authors speculate that perhaps the lack of detection of pulsations in other LMXBs suggests they may indeed have lower B fields). Additional evidence against field decay (to below 10^8 G) in even very old LMXB systems comes from the detection of kHz QPOs and possible pulsations (at the QPO difference frequency of 275 ± 8 Hz) in the relatively luminous atoll source 4U 1820–30 in the globular cluster NGC 6624 (Smale, Zhang, & White 1997; Zhang et al. 1998). Since the neutron star in this system is a Population II neutron star, and therefore likely to have an age $\sim 10^{10}$ yr, and yet the kHz QPOs (and possible pulsations) in this object with $\dot{M} \approx 10^{17}$ g s⁻¹ suggest a magnetic field $B \gtrsim 3 \times 10^8$ G, it appears that even continued accretion has not reduced the B field below this value.

Thus the required B field values of MSPs actually observed, the required spin-up timescales, and the lack of evidence that field decay continues below $\sim 10^8$ G combine to effectively rule out any persistent low-luminosity sources as a possible source of MSPs. In fact, spin-up of atoll sources to MSPs also becomes questionable. This rather radical conclusion can be avoided only when $\alpha/\gamma \gg 1$ or when $\dot{M}_c \ll 10^{16}$ g s⁻¹. The former possibility is not likely (Wang 1995; Aly & Kuijpers 1990) and the latter is not supported by recent work (see, e.g., Narayan & Yi 1995; Yi et al. 1997, and references therein).

In Figure 1b we show the spin-up lines assuming that the accretion flow becomes sub-Keplerian below the assumed critical accretion rate 3.5×10^{16} g s⁻¹ with $\omega_a = 0.2$ (Yi et al. 1997). This figure confirms our conclusion that even at a relatively high accretion rate, $\sim 10^{16}$ g s⁻¹, MSPs would be produced only when $B_* \lesssim 3 \times 10^7$ G. For such low values of B_* , most LMXBs with $\dot{M} < 6 \times 10^{15}$ g s⁻¹ would not emerge out of the so-called pulsar graveyard below the death line (see, e.g., Ritchings 1976) during spin-up. They would be detected as MSPs only after arriving at periods $P_* \lesssim 3 \times 10^{-2}$ s (i.e., solid lines above the death line). It is interesting to point out that in the P_* versus B_* plot, there could be a gap due to the accretion flow transition as implied by the spin-up line for the assumed $\dot{M}_c \sim 3.5 \times 10^{16}$ g s⁻¹. For $\dot{M} > \dot{M}_c$ the Keplerian spin-up line in Figure 1a applies, whereas for $\dot{M} < \dot{M}_c$ (Fig. 1b) the sub-Keplerian spin-up line would be shifted discontinuously downward, leaving a region between the two lines as a gap. If there is a significant population of low-luminosity LMXBs spun up with the sub-Keplerian rotation, they

could produce MSPs above the death line typically with $P_* \sim 5$ ms and $B_* \sim 10^7$ G. These MSPs would populate the region marked by the solid box in the bottom left corner in Figure 1b. Their intrinsic electromagnetic power is expected to be only $\sim B_*^2 R_*^6 \Omega_*^4 / 6c^3 \lesssim 2 \times 10^{30}$ ergs s⁻¹, which is roughly 2 orders of magnitude lower than that of typical MSPs and is therefore likely well below the ~ 1 mJy kpc² radio luminosity limit of MSPs detected by Lyne et al. (1997). It is not clear whether a significant number of such MSPs could be found in reality given the longer spin-up timescales ($\gtrsim 10^9$ yr) for lower $\dot{M}$ s.

4. MSPS FROM RECURRENT SOFT X-RAY TRANSIENTS

Some LMXBs show low luminosities (i.e., $\dot{M} < \dot{M}_c$) between recurrent outbursts (Verbunt et al. 1994), or during some periods as persistent sources (see, e.g., Tanaka & Shibazaki 1996). During high $\dot{M}$, the spin-up timescale and the equilibrium spin period could become considerably shorter than those of the low $\dot{M}$ period. If the high $\dot{M}$ and low $\dot{M}$ periods alternate, the LMXB systems would be constantly away from their equilibrium spin periods. The typical spin-up timescale $t_{\text{spin}} = P_*/\dot{P}_*$ depends on $\dot{M}$ as

$$t_{\text{spin}} = \frac{I_*}{P_* \dot{N}} \approx \frac{2(M_* R_*^2)^{4/7}}{(\gamma/\alpha)^{1/7} (GM^2)^{3/7} B_*^{2/7} P_*} \quad (10)$$

$$\approx (5 \times 10^7 \text{ yr})(\gamma/\alpha/10)^{1/7} M_{16}^{-6/7} \times B_{*8}^{-2/7} P_{*,1}^{-1}, \quad (11)$$

where $P_{*,1} = P_*/10$ ms. This timescale applies to both the Keplerian accretion disk and the sub-Keplerian flow. If recurrent outbursts have $\dot{M}$ as high as $\sim 10^{18}$ g s⁻¹, the short equilibrium spin period corresponding to this high $\dot{M}$ would be reached if the outburst phase cumulatively lasts for $\gtrsim 10^7$ yr while accreting a mass of $\sim 0.1 M_\odot$. Since the low $\dot{M} < 10^{15}$ g s⁻¹ phase would have a long spin-up timescale $> 10^9$ yr, the recurrent outbursts would determine the eventual spin period if the duration of the outburst is $\lesssim 10^{-3}$ of the quiescent duration. For instance, for an outburst recurrence timescale ~ 10 yr, the required duration of outbursts is ~ 1 month, which is typical of the “soft X-ray transients” (SXTs) containing black hole primaries (e.g., Tanaka & Shibazaki 1996).

SXT systems containing neutron star (NS) primaries (NS SXTs) could thus in principle solve the MSP formation problem. The plausibility of this channel of MSP formation critically depends on actual detections of NS SXTs in sufficient numbers. Presently, there is little evidence that indicates the existence of a large population of such transient sources, and in fact van Paradijs (1996) has shown that among the transients, black hole SXTs are likely to be favored over NS SXTs. Of the known NS SXTs, Aql X-1 has been found in recent *RXTE* observations (e.g., White & Zhang 1997) to have a ~ 500 Hz pulsation, which could make Aql X-1 a promising MSP progenitor. However, since it has a ~ 1 yr recurrence timescale and ~ 1 month outburst duration and so is more similar to the quasi-persistent source 4U 1608–52 and the atoll sources, for which the birthrate problem exists, it may not represent the required class of NS SXT progenitor. In fact, only one bona fide NS SXT system is known, Cen X-4, which shows deep quiescence between strong outbursts every $\sim 10\text{--}20$ yr. More detections of NS SXTs (as discussed below) are definitely required for them to be regarded as likely MSP progenitors.

Recently, Gotthelf & Kulkarni (1997) have reported the detection of an unusual burst source in the globular cluster M28. They attributed the unusually low burst luminosity to the low mass accretion rate onto a magnetized neutron star. The possible type I burst could occur in the magnetized accretion column that naturally increases the effective mass accretion rate and density on the stellar surface. Even if such sources eventually show up in great numbers as a potentially important new class of NS SXTs, the deduced magnetic field strength (based on the nondetection of pulsations and hence extremely slow spin) is much too large to be compatible with the typical field strength needed for MSP progenitors.

5. SUMMARY AND DISCUSSION

We have found that low-luminosity LMXBs are hard to spin up to MSPs unless they have magnetic fields substantially lower ($\lesssim 5 \times 10^7$ G) than those of the observed MSPs with $B \gtrsim 10^8$ G. Thus the LMXB phase would have to be followed by a phase of field amplification to produce the currently observed MSPs. Even when the magnetic fields are sufficiently weak, the long spin-up timescale $\sim 10^{10}$ yr for low mass accretion rates $\ll 10^{15}$ g s $^{-1}$ poses another problem. If, as is likely for ADAF models (Narayan & Yi 1995), the accretion flow becomes quasi-spherical and sub-Keplerian for $\dot{M} < 10^{16}$ g s $^{-1}$, it could rule out any low-luminosity populations and potentially a significant fraction of atoll sources as a possible source of the MSPs. Thus we conclude that the “standard model” for the formation of MSPs from LMXBs requires that they form from a larger population of normally quiescent SXT systems containing neutron stars with $B \gtrsim 10^8$ G. If these sources have a fractional duty cycle $f = 0.01$ (i.e., accrete at $\sim 10^{18}$ g s $^{-1}$ for ~ 1 month every ~ 10 yr), they could provide the observed MSP population if their parent population is ~ 10 times the observed persistent atoll source population (since, although only $\sim 10^7$ yr is needed for spin-up, the $\sim 1\%$ duty cycle means that an effective lifetime needed is 10^9 yr, or the same as that for the persistent sources). More generally, a population of quiescent NS SXTs with peak accretion rates $\dot{M}_{18}$ (in units of 10^{18} g s $^{-1}$) and an on-time duty cycle f_{-2} (in units of 0.01) could only solve the MSP birthrate problem if at any given time there are $N_{\text{NSXT}} \sim 10/(\dot{M}_{18} f_{-2})$ yr $^{-1}$ in outburst. Thus there would need to be ~ 10 NS SXTs like Cen X-4 (with $\dot{M}_{18} \sim 1$ and $f_{-2} \sim 1$) or ~ 100 like Aql X-1 (with $\dot{M}_{17} \sim 1$ and $f_{-2} \sim 10$) in their “on” state at any given time, which is clearly not consistent with observations. Although the discovery of SAX J1808.4–3658 may point to a larger population of Aql X-1 type NS SXTs, the apparent rate of these new bursters discovered by *RXTE* or *BeppoSAX* thus far appears much too low: perhaps there are at most ~ 3 “new” (recurrent) bursters that are “on” at any given time. A recent example is the *RXTE* rediscovery of the burster XTE J1806–246 (Marshall & Strohmayer 1998), which is very likely the burster 2S 1803–245 originally detected with *SAS 3*. Thus the required large population of NS SXTs are simply not seen (it would be comparable in number to the known number of persistent atoll sources), and so we conclude there is as yet no compelling evidence for MSP formation from NS SXTs.

A new class of MSPs could possibly form from an as yet undetected population of persistent, low-luminosity LMXBs. These would produce a low magnetic field ($< 10^7$

G), and radio-weak MSPs with typical radio luminosities $\sim 10^{28}$ ergs s $^{-1}$ if the radio efficiency is $\sim 1\%$. If the magnetic field is much weaker than $\sim 10^7$ G, the MSPs would reside in the region below the pulsar death line, which makes the detection of these pulsars virtually impossible. If a significant number of low-luminosity LMXBs spin up to MSPs, they could appear as a group of radio-weak MSPs distinct from the known MSPs.

Given the difficulties of the standard model, even for NS SXTs, we consider finally the accretion-induced collapse (AIC) model for “direct” production of MSPs without the LMXB progenitor phase (Michel 1987; Grindlay & Bailyn 1988; Bailyn & Grindlay 1990). In the AIC scenario, white dwarfs (WDs) collapse to neutron stars after reaching the critical Chandrasekhar limit $\sim 1.4 M_{\odot}$ through accretion. It is believed that AIC occurs for high mass accretion rates $\gtrsim 2.5 \times 10^{18}$ g s $^{-1}$ (see, e.g., Nomoto & Kondo 1991; Livio & Truran 1992). The pre-AIC magnetic field on the WD will play an important (and poorly determined) role in the formation of MSPs. For magnetic WDs ($B \gtrsim 10^6$ G) and initially slowly rotating WDs accreting at a rate in the range $\sim (1-7) \times 10^{18}$ g s $^{-1}$, and assuming that the magnetic fields are flux frozen and amplified by compression during collapse, Yi & Blackman (1997) have found that the magnetic field of AIC-produced pulsars would be correlated with the pulsar spin as $\Omega_{*,4} \sim \eta B_{*,11}^{-4/5}$ (see, e.g., Narayan & Popham 1989), where $\Omega_{*,4} = \Omega_*/10^4$ s $^{-1}$, $B_{*,11} = B_*/10^{11}$ G, and η is a constant of order unity. In Figure 1b the dotted line is the hypothetical birth line of strongly magnetized pulsars from AIC. This correlation indicates that the field strength of pulsars with $\Omega_* \sim 10^3$ s $^{-1}$ would be typically close to $\sim 10^{13}$ G, which are many orders of magnitude larger than the observed MSPs. Unless these fields decay rapidly, or if magnetic flux is not conserved during collapse in AIC (e.g., if instead the field is annihilated), the AIC-produced MSPs would be very bright and lose their rotational kinetic energy at a rate of $L_{*,\text{EM}} \sim 10^{44} \Omega_{*,4}^{3/2}$ ergs s $^{-1}$ with the characteristic emission timescale $\sim I_* \Omega_{*,4}^2 / 2L_{*,\text{EM}} \sim 2 \times 10^8 \Omega_{*,4}^{1/2}$ s. Such a short timescale indicates that the pulsars could evolve almost instantaneously to long P_s . They could be an abundant source of LMXBs if accretion resumes after ~ 10 yr of intense electromagnetic activity. These AIC-produced LMXBs would produce MSPs similar to the observed ones only when the magnetic field somehow decays by several orders of magnitude during the LMXB phase. However, by requiring a subsequent LMXB phase, they obviously do not solve the observed LMXB versus MSP birthrate problem, and so we do not consider this further (for MSP production).

For the case of weakly magnetized ($\lesssim 10^{4-5}$ G) WDs, AIC could directly produce low field MSPs, but only if the collapse itself is not halted by rotation. To produce the observed ~ 2 ms spin periods, the pre-AIC WD must have a spin period of ~ 20 s (assuming conservation of angular momentum in the collapse from a $1.4 M_{\odot}$ WD of radius $\sim 10^3$ km to a 10 km radius neutron star). However, these stars are not braked by low magnetic fields and so the spin period of the precollapse WD could instead be spun up to the minimum $[(4\pi^2 R_{\text{WD}}^3 / GM_{\text{WD}})^{1/2} \sim 1$ s] period where collapse would be halted unless the excess angular momentum is first removed. Thus for AIC to be completed without producing the so-called rotationally supported “fizzlers,” angular momentum must be efficiently removed during or before collapse (see, e.g., Tohlin 1984). This implies that AIC

would produce the MSPs only if WDs stop spinning up despite continued accretion. Thus the possibility of spin-down near the breakup period, despite continuous accretion (Popham & Narayan 1991; Paczyński 1991; Bisnovatyi-Kogan 1993), is an intriguing possible solution to the MSP birthrate problem.

We conclude that if an AIC process produces the bulk of the observed MSPs, it is necessary to shed angular momentum (low B field WD) or magnetic field (high B field WD) either prior to or during the collapse. Since only the former

process directly produces an MSP without an LMXB, it is preferred. Both processes may occur, however, and in fact may relate the problems of MSP formation to that of the origin of gamma-ray bursts, as we discuss in a forthcoming paper (in preparation).

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