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**Radiation-Driven Evolution of Low-Mass
Binaries and the Formation of Millisecond Pulsars**

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Cyg X-3 fits the evolutionary scenario for a RD-LMXB containing a very low mass white dwarf companion [12, 9]. A strong wind is indeed observed in Cyg X-3 [32] and the

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**RADIATION-DRIVEN EVOLUTION OF LOW-MASS X-RAY BINARIES
AND THE FORMATION OF MILLISECOND PULSARS**

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ABSTRACT. Recent data on low-mass X-ray binaries (LMXBs) and millisecond pulsars (MSPs) pose a challenge to evolutionary theories which neglect the effects of disk and companion irradiation. Here we discuss the main features of a radiation-driven (RD) evolutionary model that may be applicable to several LMXBs. According to this model, radiation from the accreting compact star in LMXBs ‘vaporizes’ the accretion disk and the companion star by driving a self-sustained mass loss until a sudden accretion-turn off occurs. The main characteristics of the RD-evolution are: (1) the lifetime of RD-LMXB’s is of order 10^7 years or less; (2) both the orbital period gap and the X-ray luminosity may be consequences of RD-evolution of LMXB’s containing lower main sequence and degenerate companion stars; (3) the companion star may transfer mass to the primary even if it underfills its Roche lobe; (4) a class of recycled MSPs can continue to vaporize the low-mass companions by a strong pulsar wind even after the accretion turn-off; (5) the RD-evolutionary model resolves the apparent statistical discrepancy between the number of MSPs and their LMXB progenitors in the Galaxy. We discuss the implications of the discovery of single MSPs in low-density globular clusters and the recent measurements of short orbital timescales of four LMXBs.

1. Introduction

Although there are approximately 100 known low-mass X-ray binaries (LMXB’s) in the Galaxy (and ~ 10 in globular clusters), in many cases the nature of the primary and companion stars, the mass transfer mechanism, and the lifetimes remain elusive. Evolutionary scenarios neglecting the effect of radiation from the primary star have been guiding the study of LMXB’s, and have accounted for the properties of several LMXB’s studied *individually* (e.g., [1]). Depending on the nature of the Roche lobe-filling companion star, mass transfer may be driven by angular momentum loss caused by gravitational radiation (GR), magnetic braking (MB), or core expansion for sub-giant companions. In the ‘standard model’ the mechanism of mass transfer is independent of the nature of the primary star, and works in the same way for binaries containing black holes, neutron stars and white dwarfs (cataclysmic variables, CVs). However, several questions arise both from the *statistical* features of LMXB’s, and from new data on orbital timescales: (1) *Why are most of the LMXB luminosities close to the Eddington limit of one solar mass primary?* The luminos-

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ity distribution of LMXBs with steady emission is peaked near the maximum possible value rather than toward the lower end of the luminosity range. The observed distribution is the opposite of what expected in the standard model which predicts that the X-ray sources spend most of their time at low values of the luminosity [1]. (2) *Why have there been no observed steady LMXB's with persistent emission in the range $L_X \sim 10^{36} - 10^{34.5}$ erg s $^{-1}$?* In what follows we will refer to this luminosity range as the 'luminosity gap'. (3) *Why is the orbital period distribution of LMXB's different from the corresponding distribution of CV's?* Fig. 1 gives the orbital period distributions for LMXBs and CVs. The CV 'period gap' is between 2 hrs and 3 hrs with a significant peak near $P_{orb} \simeq 2$ hrs. The LMXB period gap is wider than the CV gap with no galactic binary between 1 hr and ~ 3 hrs. (4) *Is the birthrate of millisecond pulsars in the Galaxy and globular clusters the same as the birthrate of their LMXB progenitors?* A statistical analysis of galactic MSPs and LMXBs gives an apparent discrepancy by a factor ~ 100 if the standard model is applied to the LMXB progenitors [2]. The same apparent discrepancy may exist in globular clusters ([3]; see, however, [4]).

Here we address these questions by showing that radiation from the primary star (operating effectively only for a primary with mass-energy conversion efficiency of order 10 %) can influence binary evolution so as to produce the observed luminosity and orbital period 'gaps' of the LMXB distributions, as well as to reconcile the LMXB/MSP birthrates. We discuss in Sect. 2 several issues of the RD-evolution such as lifetimes, orbital evolution and LMXB period gap, and recycled pulsars in binaries with main sequence companions. In Sect. 3 we briefly address some remarkable features of the binaries containing MSPs in the process of vaporizing their companion stars. In Sect. 4 we discuss the apparent statistical discrepancy between the estimated number of galactic MSPs and their LMXB progenitors evolved according to the standard model. It is shown that the RD-model can possibly resolve the statistical discrepancy of the MSP/LMXB birthrates. Finally, we present in Sect. 5 data concerning the orbital evolution of a very interesting class of short-lived LMXBs. Recent observations of $\dot{P}_{orb}/P_{orb}$ for the sources Cyg X-3, X 1822-371, EXO 0748-676 and 4U 1820-30 are interpreted in terms of the RD-evolution model.

2. Radiation-Driven Evolution of LMXB's

Irradiating photons in the energy band between 0.3 - 10 keV as well as soft γ -rays of energy $\sim 1/2$ MeV are the most efficient in driving an evaporative wind from an illuminated atmosphere [5,6,7]. In the presence of an external irradiating flux the ionization-recombination and heating-cooling balance conditions are satisfied at a relatively large depth (photosphere) but they cannot be maintained for low values of both density and temperature in the outer and more dilute atmospheric layers. As the density in the outer layers decreases, only a rapid rise in temperature can keep the gas medium in balance with the radiation field. A RD-wind is a consequence of a thermal instability of the irradiated atmosphere which develops a high temperature corona. Complex radiative, hydrodynamic and atomic physics effects make it difficult to compute the many features of the RD-wind mechanism. However, the progress obtained in twenty years of investigations of this subject (e.g. [8] and references therein) together with more recent results concerning the case of LMXBs [5, 6, 7, 9, 10] provide a firm basis of discussion of RD-winds².

²The reader is referred to Refs. [7, 9, 11] for further details of the RD-wind formation mechanism. A detailed and comprehensive calculation of atomic physics processes affecting the formation of RD-winds

The RD-mass loss rate can be written as $|\dot{m}_{rad}| = 10^{-17} f \dot{L} \text{ g s}^{-1}$ [5,6], where the dimensionless quantity f depends on the details of energy deposition, radiation transport and hydrodynamics at the base of the corona [7, 10], and $\dot{L} = \chi \Delta\Omega L$, where $\Delta\Omega$ is the effective solid angle subtended by the companion star to its primary, L the compact star's luminosity (in erg s^{-1}) and χ an attenuation factor which takes into account possible absorption/screening and scattering/reprocessing effects in the disk or corona surrounding the compact star (typically $\chi \lesssim 0.1$ for X-rays). Results of detailed hydrodynamical calculations of mass outflows in typical LMXBs show that both the irradiating fluxes and 'quality' of the spectra make possible the self-sustaining of the mass transfer [10]. In the simplest model of self-sustained evolution described here, the radiation-driven mass loss (corresponding to a luminosity $L^* \propto \beta |\dot{m}_{rad}|$, with β the fraction of the mass loss rate which is accreted by the primary star) can be either of order of $10^{18} - 10^{19} \text{ g s}^{-1}$ or zero. The transition occurs at a value of the companion's mass m_c (hereafter, *the critical mass*) which corresponds to a sudden decrease of the accretion rate or even a permanent accretion turn-off if a msec pulsar has been produced [5, 7].

2.1. LIFETIME OF RD-LMXBs

Two features of the self-sustained evolutionary phase make the lifetime of a RD-LMXB substantially shorter than in standard models: (1) the mass loss is driven at a relatively large rate, and one which is weakly dependent on orbital evolution; and (2) the companion may contract inside its Roche lobe and still transfer mass. This last possibility depends crucially upon the quantity β , the amount of mass lost from the binary during the RD-evolutionary phase and upon the specific angular momentum of the mass loss.

The RD-LMXB lifetime is comprised of two phases, i.e., where the companion fills and underfills its Roche lobe. We have $\tau = \Delta t_{RL} + \Delta t_{NRL}$, where the time the Roche lobe is filled is $\Delta t_{RL} = (m_1 / \langle \dot{m}_{rad} \rangle_{RL}) (1 - m^*/m_1)$; and the time the Roche lobe is underfilled is $\Delta t_{NRL} = (m^* / \langle \dot{m}_{rad} \rangle_{NRL}) (1 - m_2/m^*)$, with m_1 and m_2 respectively the initial and final companion's masses for $m_2 < m^* \lesssim m_1$, and $\langle \dot{m}_{rad} \rangle$ the corresponding average mass loss rate [7, 9]. Although the value of the RD-mass loss rate may depend upon the orbital evolution, here we will adopt the following numerical estimates: $\langle \dot{m}_{rad} \rangle_{RL} = \langle \dot{m}_{rad} \rangle_{NRL} \simeq 10^{-8} M_\odot \text{ yr}^{-1} \equiv \dot{m}_8$. For LMXB's with degenerate companions, m_1 can be larger (for an initial $\beta \sim 1/3$) or even equal to m^* (for $\beta \simeq 1$). Where mass transfer is self-sustained and the companion always fills its Roche lobe, $m_2 = m_{c,RL}$, the critical mass being given by $m_{c,RL} \simeq (0.1M/\Sigma)/(1 - 0.1/\Sigma)$, with $\Sigma = (\xi_{-1} f_{-1} \beta \chi)^{3/2}$, where $\xi_{-1} = \xi/0.1$ (ξ is the conversion of accreted matter into energy), and $f_{-1} = f/(0.1 \Upsilon)$ with Υ is a dimensionless quantity depending on the 'quality' of the irradiating spectrum (typically $\Upsilon \sim 1/2$ for soft gamma-rays and $\Upsilon \sim 10 - 100$ for X-rays) [7, 9, 10]. Alternately, after a Roche lobe underfilling evolutionary phase, $m_2 = m_{c,NRL} \simeq 0.6 m^* [\xi_{-1} f \chi (m^*/0.04 M_\odot)^{2/3}]^{-3/8} [1 + m^*/M]^{3/8}$, where we used $f \sim \Upsilon$ and $m^* \sim 0.04 M_\odot$ appropriate to the evolution of the binary progenitor of PSR 1957+20 [7]. Applying the relevant formulae given above to LMXB's with degenerate companions, we find the lifetime of a RD-LMXB containing a companion with, say, $m_1 \sim 0.1 M_\odot$ is $\tau_d \lesssim 10^7$ years for $\Upsilon \chi \sim 1$. In the case of LMXB's with degenerate companions underfilling their Roche lobe (as in the case of the progenitor of PSR 1957+20), $\Delta t_{NRL} \sim 10^6$ years;

(e.g., line cooling due to heavy elements) is in progress [London R. *et al.*, in preparation] as well as the calculation of RD-LMXB wind hydrodynamics [Tavani M. and Brookshaw L., in preparation].

for example, Cyg X-3 may be in this intermediate phase [12]. For the numerical estimate of the birthrate of very rapid LMXB's containing white dwarfs (see Sect. 4) we will use the lifetime $\tau_{vr,\tau} = \dot{m}_g^{-1} \tau_{vr} / (10^7 \text{ yrs})$.

Analogously, the inferred lifetime of an LMXB containing a lower main sequence companion whose outer layers are represented by a polytrope of index 3/2 is $\sim 10^7 \text{ yrs}$ [9]. For $\beta = 1$ we obtain $m_c/m^* \simeq 0.33(\xi_{-1} f \chi)^{-3/8} \cdot [(1 + m^*/M)/(m^*/0.4 M_\odot)]^{1/4}$, and for $\beta = 2/3$ we have $m_c/m^* \simeq 0.11(\xi_{-1} f \chi)^{-3/4} \cdot [(1 + m^*/M)(m^*/0.4 M_\odot)]^{1/2}$. In Sect. 4, for the lifetime of rapid LMXB's we will use $\tau'_r = \dot{m}_g^{-1} \tau_r / (3 \cdot 10^7 \text{ yrs})$.

2.2 ORBITAL EVOLUTION

The orbital evolution of an LMXB is determined by angular momentum loss (driven by gravitational radiation or a wind), as well as by mass loss from the companion star. For masses and orbital parameters of typical observed LMXBs, mass transfer mechanisms neglecting irradiation effects yield effective lifetimes and orbital timescales of order $10^8 - 10^9 \text{ yrs}$ [1]. For Roche lobe filling companions, the equation of the orbital evolution is particularly simple

$$\frac{\dot{P}_{orb}}{P_{orb}} = \frac{1}{2}(1 - 3n) \frac{|\dot{m}|_s}{m} \quad (1)$$

with $\dot{m}_s$ the mass loss rate of the standard evolutionary model driven by GR and MB [1], and n the effective stellar index of the companion which gives the stellar response to mass loss defined by $d \ln R = n d \ln m$, with R the companion radius. In the standard model $\dot{P}_{orb}/P_{orb} < 0$ for LMXBs with main sequence companions in thermal equilibrium with $n \simeq 1$, whereas $\dot{P}_{orb}/P_{orb} > 0$ for LMXBs with degenerate or subgiant companions with $n \simeq -1/3$. Evolution driven by the combined effects of GR and MB accounts successfully for the luminosity distribution of CVs.

Alternately, a self-sustained RD-mass loss from the companion (or from the outer edge of the disk) leads to an orbital evolution quite different from the standard model. The irradiated companion can transfer mass even if it does not fill its Roche lobe exactly. We obtain [9, 13]

$$\frac{\dot{P}_{orb}}{P_{orb}} = -3 \left[1 - [(1 - \beta_1)\tilde{\alpha}_1 + (1 - \beta_2)\tilde{\alpha}_2](1 + q) - \beta q - \frac{1}{3}(1 - \beta) \frac{q}{1 + q} \right] \frac{\dot{m}_{rad}}{m} + 3 \left(\frac{\dot{J}}{J} \right) \quad (2)$$

where m is the mass of the companion star, $\dot{m}_{rad}$ the RD-mass transfer rate, $\dot{J}/J = (\dot{J}/J)_{GR} + (\dot{J}/J)_{MB}$ the fractional change of the orbital angular momentum J from gravitational radiation (GR) and magnetic braking (MB), $q = m/M$ the ratio of the companion mass to primary mass M , and $\tilde{\alpha}$ the specific angular momentum parameter defined by $\delta J = \tilde{\alpha} \delta m (1 - \beta) a^2 2\pi / P_{orb}$, where P_{orb} is the orbital period. The lower-indices '1' and '2' indicate two different possible contributions to the mass loss from the binary (e.g., from the inner edge of the accretion disk with $\tilde{\alpha}_1 \lesssim 0.1$ and from the orbital radius with $\tilde{\alpha}_2 \sim 1$). The dimensionless parameter $\tilde{\alpha}$ gives the effective angular momentum loss caused mass loss from the binary. For example, if mass is lost from the binary at the orbital distance a and if the the outflowing gas does not acquire any additional specific angular momentum, then $\tilde{\alpha} = 1$. For a self-sustained value of the mass loss rate the first term of Eq. (2) proportional to $\dot{m}_{rad}/m$ is the dominant one. Note that the quantity $\dot{P}_{orb}/P_{orb}$ is expected to be $\sim +10^{-6} \text{ yr}^{-1}$ for RD-LMXBs with very low mass degenerate companions and $\beta \sim 1$

(possibly the case of Cyg X-3 [12]). In general, the time derivative of the orbital period of a RD-LMXB (Eq. (2)) can be either positive or negative depending primarily on the value of β and $\tilde{\alpha}$. The associated lifetime turns out to be $\sim 10^7$ years or less. The RD-orbital evolution can be very different from the evolution of the standard scenario as given by Eq. (1).

2.3 ORBITAL PERIOD ‘GAP’ OF LMXB’s

If the radiation-enhanced mass loss and RD-response of the companion are neglected, Eq. (1) applies and binaries with main sequence companions and, say, $P_{orb} \sim 5$ hrs, have an irresistible tendency to evolve toward the ‘period gap’ with $\dot{P}_{orb} < 0$. If the mechanism producing the CV period gap (probably due to Roche lobe underfilling of the companion star evolved out of thermal equilibrium because of magnetic braking [1]) were applicable to the LMXB case then we would expect the CV and LMXB distributions to be similar. Fig. 1 shows that this is not the case, with a lack of LMXBs in the range $1 \text{ hr} \lesssim P_{orb} \lesssim 3 \text{ hrs}$.

The orbital period gap can be ‘crossed’ relatively rapidly ($\tau \sim 10^6$ yrs) by RD-LMXBs containing degenerate companions [7], or never crossed and ‘repelled’ by RD-LMXBs with main sequence companions [9]. Preliminary calculations of the RD-orbital evolution with companion stars represented by polytropes of index 3/2 confirms that the main sequence companion can be repelled in correspondence with a broad range of P_{orb} [9]. Fig. 1 shows the schematic orbital behavior expected in the RD-evolution.

FIGURE 1 Distribution of orbital periods of CVs and LMXBs. Solid curves give the schematic behavior of the orbital RD-evolution [9]. *Line A* represents the rapid expansion of an LMXB with a degenerate companion for β in the range $1/3 \lesssim \beta \lesssim 1$; the timescale may be $\sim 10^6$ yrs. *Line B* and *line C* give the orbital evolution according to Eq. (1) of LMXBs with main sequence companions.

2.4 ORBITAL PERIODS OF BINARIES WITH RECYCLED PULSARS

If the mechanism of mass transfer is *not* driven by radiation during the evolution of LMXB’s above the period gap (for $P_{orb} \gtrsim 3$ hours), the sudden quenching of mass transfer occurring at $P_{orb} \sim 3$ hours may yield a millisecond pulsar whose radiation pressure could

be large enough to stop any further accretion. In this case we expect all of the recycled pulsars with main sequence companions to be concentrated at $P_{orb} \sim 3$ hrs. Alternately, the expected orbital period distribution of RD-LMXBs after accretion turn-off is broad and expected to be in the range $3 \text{ hrs} \lesssim P_{orb} \lesssim 10 \text{ hrs}$ for LMXBs with main sequence companions. Future observations in the Galaxy of recycled pulsars with main sequence companions can in principle test the two evolutionary models. Doppler-induced spread caused by orbital motion in binaries with P_{orb} of order of a few hours and the possible presence of vaporized material (see sect. 3.2) make difficult the detection of this important class of binary millisecond pulsars. Pulsar searches to be performed with acceleration-algorithms are therefore strongly urged.

We note that the existence of one binary MSP with a very low mass remnant star in an orbit with $P_{orb} \simeq 9$ hrs (PSR 1957+20 [14]) already excludes the application of the standard evolutionary model to such a system³.

3. Star-Vaporizing Pulsars

Even in the post-accretion phase, radiation produced by the relativistic wind emanating from millisecond pulsars can continue to vaporize and drive mass loss from their low-mass companions [5, 7, 9] leading to partial or even total evaporation of the companion star. Two binaries containing star-vaporizing pulsars (SVPs) are currently known.

Table 1

PSR	P_{spin} (msec)	P_{orb} (hours)	m_c ($M_\odot$)	L_P (erg s ⁻¹)	$\Delta L/L$	eclipse characteristics	Ref.
1957+20	1.60	9.2	~ 0.02	$1.5 \cdot 10^{35}$	$\sim 1/10$	stable	14
1744-24A	11.56	1.8	~ 0.1	?	$1/3 - 1/2 - 1$	highly variable	15

Table 1 gives the pulsar names, spin periods, orbital periods, companion masses, the inferred pulsar spindown luminosity L_P by assuming a neutron star moment of inertia 10^{45} g cm^2 , the ratio of the average eclipse size ΔL over the total orbital circumference L , the eclipse characteristics and references. The ratio of the evaporation time scale $\tau_{evap} = m_c/|\dot{m}|_{rad}$ and the spin-down time scale defined as $\tau_s = P/\dot{P}$ with P the pulsar spin period and $\dot{P}$ its time derivative can be written as

$$\frac{\tau_{evap}}{\tau_s} \simeq 0.8 \frac{P_{-3}^2}{(f/0.1)I_{45}} \left(\frac{m_c}{0.2 M_\odot} \right)^{1/3} \frac{1}{\Psi_c^2} \quad (3)$$

where P_{-3} is the spin period in milliseconds, I_{45} the neutron star's moment of inertia in units of 10^{45} g cm^2 , Ψ_c the value of $\Psi = R/R_L$ at the accretion turn-off with R_L the Roche lobe radius. In Eq. (3) the total mass has been assumed to be $\sim 1.8 M_\odot$. Energy deposition in the irradiated companion's atmosphere by secondary radiation produced by the pulsar relativistic wind⁴ gives $f \simeq 0.01 \Upsilon$ [7]. The quality factor Υ depends on the details of the spectrum irradiating the companion star. The physics of radiative processes near the

³The orbital parameters of the other MSP in the process of vaporizing its companion PSR 1744-24A [15] have been probably influenced by star encounters in the core of the globular cluster Ter 5 where the binary system was formed.

⁴In the case of PSR 1957+20, whether the ratio τ_{evap}/τ_s is less than unity depends upon currently

contact discontinuity where the pulsar wind and electromagnetic radiation interact with the mass outflow is particularly interesting. The shape of the irradiating spectrum ultimately depends on the pulsar wind composition ($e^\pm$'s, ions) as well as on plasma effects due to the relativistic shock, synchrotron radiation of $e^\pm$ -pairs and inverse Compton scattering against the soft background photons emitted by the irradiated face of the companion.

Even though complete evaporation of low-mass companions is a possible outcome of RD-evolution, only a subclass of MSPs are capable of producing a sufficiently large evaporative wind [9]. The RD-evolution of LMXB's makes plausible the existence of a relatively large number of MSP's in detached binaries containing lower main sequence stars heated and probably slightly evaporated by the pulsar wind. For $f \sim 0.1$, $m_c \sim 0.3 M_\odot$ and $P_{-3} \sim 10$ as expected by standard binary evolution at the upper edge of the period gap, Eq. (3) shows that these main sequence companions cannot be *completely* vaporized⁵. However, complete vaporization of the main sequence companion is possible if $P_{-3}/\Psi_c \sim 1$.

3.1 WIND HYDRODYNAMICS OF PSR 1957+20

The properties of the mass outflow of the eclipsing millisecond pulsar PSR 1957+20 have been studied with the help of a Smoothed Particle Hydrodynamics (SPH) code [18].

FIGURE 2 Example of a hydrodynamical calculation of the mass outflow in PSR 1957+20 in the corotating frame (from [18]). The mass loss rate from the half irradiated surface of the companion is $\dot{m} = 5 \cdot 10^{14} \text{ g s}^{-1}$, the gas temperature at the injection surface $T = 5 \cdot 10^6 \text{ }^\circ \text{K}$, and the Mach number $\mathcal{M} = 1.5$

unknown details of the irradiating spectrum; we obtain $\tau_{\text{evap}}/\tau_s \simeq 0.8 f^{-1} I_{45}^{-1}$. For a synchrotron spectrum at fixed electron energy, $\Upsilon \simeq 10$, and for a time integrated synchrotron spectrum of $e^\pm$ -pairs which lose most of their energy, $\Upsilon \simeq 100$ [7]. It is therefore plausible that the companion of 1957+20 would be completely evaporated even if $\Psi_c \simeq 1/3$. However, for the eclipsing pulsar in Ter 5 PSR 1744-24A we have $\tau_{\text{evap}}/\tau_s \gg 1$ [16]. We note that the discovery probability of binary pulsars not able to *completely* vaporize their companion is much larger than the probability of discovering systems with $\tau_{\text{evap}}/\tau_s < 1$.

⁵For a different view see [17]

In order to obtain physically meaningful results, pressure forces need to be considered in addition to gravitational and radiative forces. Fig. 2 shows an example of these calculations for a given set of initial conditions appropriate to a mass outflow which is thick to pulsar radiation except for the external leading particles near the bow shock region.

Note the initial unperturbed expansion of the gas followed by the formation of a strong shock at 2 - 3 companion star radii. The density profile as a function of orbital phase obtained for a given set of initial conditions can be compared with the density inferred from the eclipse properties at different frequencies [19]. An SPH calculation of the mass outflow [18] allows a sensible comparison among different input models, a selection of a range of plausible input quantities such as $\dot{m}_{rad}$, temperature, Mach number, and a detailed estimation of the effects yielding the remarkable timescale for orbital decay measured to be ~ 30 Myrs [19].

3.2 'HIDDEN' MILLISECOND PULSARS

The two currently known millisecond pulsars vaporizing their companion stars confirm the relevance of binary evolution driven by radiation from the primary relativistic star. The eclipse characteristics of the two systems are sufficiently different to make possible a classification of SVPs in terms of the properties of their radio-emission. PSR 1957+20 is the prototype of SVPs with stable eclipse properties (type I) whereas PSR 1744-24A shows a more erratic and sometimes intermittent behavior of radio-eclipses characteristics of a second class of SVPs (type II). In addition to these two SVP-classes, a third class of SVPs is expected on theoretical grounds (type III) [20]. The SVPs of type III are completely engulfed in the material provided by a Roche lobe underfilling companion star irradiated by the pulsar wind, and they are therefore 'hidden' pulsars because their radio-emission may be completely blocked by the evaporated material. In type III SVPs a steady state is reached and pulsar radiation pressure and the centrifugal barrier prevent accretion on the rapidly spinning neutron star. Binaries containing powerful MSPs and main sequence or white dwarf companions underfilling their Roche lobes are the most likely candidates for this class of type III SVPs. Particles in the pulsar wind irradiate most of their energy near the inner edge of the 'bubble' surrounding a hidden MSP. Depending on the characteristics of the pulsar wind and magnetic fields reflected at the inner bubble boundary, the radiation spectrum may range from soft X-rays to MeV-GeV γ -rays [20]. Some of the unidentified COS-B sources, soft X-ray transients and 'blue stragglers' may contain a SVP [20] and radio observations combined with ROSAT and GRO observations might provide evidence for the existence of SVPs of different types. Hidden MSPs may contribute to the resolution of the apparent discrepancy between the orbital period distribution of binary millisecond pulsars vs. their LMXB progenitors [20]. No MSP is currently known to be in a binary system containing a main sequence companion of mass $0.3 M_{\odot} \lesssim m \lesssim 1 M_{\odot}$, even though most of the LMXBs have companion stars in this range.

3.3 SINGLE PULSARS IN GLOBULAR CLUSTERS

Several single pulsars are known in globular clusters in addition to PSR 1937+21 and PSR 1257+12 [e.g., 21]. Given the variety of stellar encounters in the cluster cores, it is not surprising that a relatively large fraction of 'recycled' pulsars are found without companions. We summarize here the main mechanisms for producing single recycled pulsars.

3.3.1 Disruptive Coalescence after tidal capture. Catastrophic collisions of neutron stars with passing cluster stars are possible in dense cluster cores. In one-third of all collisions the normal star is disrupted and a massive disk ($m_d \sim 0.1 M_\odot$) is formed around the neutron star. However, not all of the disk material can be accreted because the accretion rate resulting from a massive disk is probably much larger than the Eddington limit [22]. The spin period of a spun-up neutron star depends of the total accreted mass m_a as follows $P_{-3} \simeq I_{45}^{3/4} (m_a/0.17 M_\odot)^{-3/4} (M/(1.4 M_\odot))^{-1/2}$, with M the mass of the neutron star. Since $m_a \ll m_d$ [22], the spin period of the resulting pulsar is likely to be in the range 0.1 - 1 sec if only $\sim 10^{-3} m_d$ is accreted. Remarkably, at least three relatively slow pulsars in dense clusters have periods in this range⁶ without any evidence of a pulsar population of possible progenitors between 10 and 100 msec [21]. The pulsars that might have been formed by disruptive star coalescence are PSR 1754-20 ($P = 288.6$ msec) in NGC 6440, PSR 1820-30B ($P = 378.6$ msec) in NGC 6624, and PSR 1744-24B ($P = 442$ msec) possibly in Ter 5, which are all single and belong to clusters which have either dense or collapsed cores.

3.3.2 Binary Ionization. Stellar encounters resulting from 2-body and 3-body interactions are likely to produce single pulsars in dense cluster cores. The resulting timescale for binary ionization in the densest cores of globular clusters is $\sim 10^9$ years and the single pulsars found in M 15, 47 Tuc might have been formed by ionization of wide binaries with orbital periods $P_{orb} \gtrsim 100$ days [23]. However, the four single millisecond pulsars found in clusters with low-density cores cannot be produced by 3-body interactions.

3.3.3 Companion Vaporization. The existence of a single 3 msec pulsar in the cluster M 28 (PSR 1821-24) motivated both the study of star-vaporization driven by pulsar winds [5] and the evaluation of the binary ionization mechanism in globular clusters [23]. Binary ionization in the low-density cluster M 28 is unlikely, especially in view of the relatively small pulsar spin-down rate of PSR 1821-24 ($\tau \sim 3 \cdot 10^7$ years) [23]. Vaporization of the companion star by the pulsar wind is therefore a viable possibility for PSR 1821-24 as well as for PSR 1908+00 ($P = 3.6$ msec) in NGC 6760, PSR 1516+02A ($P = 5.44$ msec) in M 5, and PSR 1640+36 ($P = 10.3$ msec) in M 13, which are all MSPs in low-density clusters.

4. Statistics of Millisecond Pulsars and LMXB's

A statistical analysis of galactic MSP's gives a birthrate $BR(MSPs) \simeq 2 \cdot 10^{-5} \text{ yr}^{-1}$ after taking into account the selection effects associated with radiopulsar surveys [2]. This birthrate is about 1000 times smaller than the galactic supernova formation rate and is too large by a factor $\sim 10 - 100$ to be in agreement with standard evolutionary models of LMXB's. This discrepancy is even more pronounced for the subgroup of 'rapid' low-mass binary pulsar systems (LMBP's), where the orbital period is $P_{orb} \lesssim 10$ days, and the birthrate $BR(\text{rapid LMBPs}) \simeq 1.5 \cdot 10^{-5} \text{ yr}^{-1}$. It is appropriate to consider separately binaries defined as 'very rapid' ($P_i \lesssim 0.5$ days), 'rapid' ($0.5 \text{ days} \lesssim P_i \lesssim 3 \text{ days}$), and 'slow'

⁶The pulsar PSR 2127+11A in M 15 ($P = 110.6$ msec) might have been formed by accretion following star coalescence. Alternately, it might have been first spun-up in a binary subsequently ionized in the high-density core of M 15 and later spun-down by loss of electromagnetic radiation. This last possibility is suggested by the existence in M 15 of pulsars of intermediate spin periods such as PSR 2127+11B ($P = 56.1$ msec) and PSR 2127+11C ($P = 30.5$ msec).

($P_i \gtrsim 3$ days), with P_i the initial orbital period. From the estimates of section 2.1 we can calculate the birthrates of rapid LMXB's evolving due to the radiation-driven mechanism of mass transfer. We obtain [24] $BR(\text{very rapid LMXB's}) \simeq (7 \cdot 10^{-6} \text{ yr}^{-1}) f_w \tau_{vr,7}^{-1}$ and $BR(\text{rapid LMXB's}) \simeq (6 \cdot 10^{-7} \text{ yr}^{-1}) f_r \tau_r'^{-1}$, with $f_w \simeq 1/2$ the fraction of very rapid LMXB's with white dwarf and main sequence companions, and f_r the fraction of LMXB's with $P_{orb} \gtrsim 0.5$ days containing sub-giant companions as defined in Ref. [2]. If we compare the birthrate of very rapid LMXB's driven by radiation and of rapid MSP's we find that they are approximately equal. Given the current statistical uncertainties of pulsar surveys and LMXB number estimations the statistical MSP/LMXB discrepancy may therefore be resolved by very rapid RD-LMXB's [24]. We note that since the 'prompt' formation of MSP's after the AIC of white dwarf primaries possibly affects only a fraction of slow binaries, the AIC mechanism is not applicable in this context.

At present it is uncertain whether the MSP/LMXB discrepancy in globular clusters is the same as in the Galaxy [3] or smaller by a factor of ~ 10 [4]. The inferred MSP birthrate is $BR(\text{cluster MSPs}) \simeq (0.2 - 1.7) \cdot 10^{-6} \text{ yr}^{-1}$. From the measured value of $\dot{P}_{orb}/P_{orb}$ for 4U 1820-30 (see Table 2) and the large value of the mass loss rate of AC211 in the globular cluster M 15 [25], we obtain $BR(\text{HML} - \text{LMXBs}) \simeq 1 \cdot 10^{-6} \text{ yr}^{-1}$, if we consider only the two high-mass-loss (HML) binaries 4U 1820-30 and AC211. We note that despite their apparent low X-ray luminosities, LMXB's in globular clusters may have radiation-driven orbital timescales of order 10^7 yrs, similarly to the X-ray burster EXO 0748-676 (see Table 2). The RD-LMXB birthrate in globular clusters may well be $\gtrsim$ a few 10^{-6} yr^{-1} .

Table 2

LMXB	P_{orb} (hours)	$\dot{P}_{orb}/P_{orb}$ (yr^{-1})	timescale (years)	Ref.
Cyg X-3	4.82	$+(2.20 \pm 0.22) \cdot 10^{-6}$	$5 \cdot 10^5$	26
X 1822-371	5.57	$+(3.40 \pm 0.94) \cdot 10^{-7}$	$2.9 \cdot 10^6$	27
EXO 0748-676	3.82	$-(2.02 \pm 0.28) \cdot 10^{-7}$	$5 \cdot 10^6$	28
4U 1820-30	0.18	$-(1.08 \pm 0.19) \cdot 10^{-7}$	10^7	29

5. Observations vs. Theory of LMXB Orbital Evolution

Measuring $\dot{P}_{orb}$ for an LMXB requires a stable fiducial point in the X-ray light curve. Such a measurement is often difficult because the majority of LMXBs do not have any dips, eclipses or pulsations. Furthermore, LMXBs have been observed for about 20 years and the lower limit for the measurable $\dot{P}_{orb}/P_{orb}$ is of order 10^{-7} yr^{-1} . Therefore, no LMXB with measurable $\dot{P}_{orb}/P_{orb}$ is expected if the standard model applies to all LMXBs. However, non-zero measurements of $\dot{P}_{orb}$ for a relatively large number of LMXBs have recently become available. The quantity $\dot{P}_{orb}$ has now been measured for Cyg X-3 [26], X 1822-371 [27], EXO 0748-676 [28], and 4U 1820-30 [29], all of which have $P_{orb} \lesssim 5.6$ hours (see Table 2 and [30]). None of the measured values agrees with the predictions of the standard GR and MB models for the $\dot{P}_{orb}/P_{orb}$'s assumed to represent secular changes of orbital evolution. The inferred timescale for orbital evolution is about 100 times shorter than expected in all systems except 4U 1820-30. In the case of 4U 1820-30 with $P_{orb} \simeq 11$ minutes [31], the measured $\dot{P}_{orb}/P_{orb}$ has a sign opposite to what expected by binary evolution driven by GR with a degenerate and Roche lobe filling companion (cf. Eq.

(1) and [32]).

An interpretation of the measured $\dot{P}_{orb}/P_{orb}$ in terms of the RD-model of LMXB evolution has been proposed in [13]. The existence of a class of LMXBs with orbital timescales of order 10^7 years was indeed predicted on theoretical grounds when only the measurement of $\dot{P}_{orb}$ for Cyg X-3 was known [7]. Fig. 3 gives the main characteristics of the RD-model applied to the sources of Table 2.

FIGURE 3 The quantity $\dot{P}_{orb}/P_{orb}$ computed for the RD-evolutionary model as a function of the mass of the companion for $\tilde{\alpha} = 1.1$. The upper part of the diagram has a positive $\dot{P}_{orb}/P_{orb}$. The three upper curves are computed for $\dot{m}_8 = 3$ and $\beta = 1$ (solid line), $\beta = 2/3$ (dotted line), and $\beta = 1/3$ (dashed line), respectively. The lower part of the diagram has a negative $\dot{P}_{orb}/P_{orb}$. The two shadowed areas give the allowed range for $\dot{P}_{orb}/P_{orb}$ with $\dot{m}_8 = 10$ and 20, respectively. Their boundaries are defined by the curves for $\beta = 1/10$ (short-dashed curves) and for $\beta = 1/20$ (dot-dashed curves). The horizontal thick marks in correspondence with the measured $\dot{P}_{orb}/P_{orb}$'s give the mass range for the companion stars.

Cyg X-3 fits the evolutionary scenario for a RD-LMXB containing a very low mass white dwarf companion [12, 9]. A strong wind is indeed observed in Cyg X-3 [33] and the observed orbital period change is in agreement with the inferred large wind mass loss rate. Even the source X 1822-371 has a positive and large rate of change of the orbital period [27]. This is in contradiction with the standard model if the LMXB contains a MS companion. Both the sign and the magnitude of $\dot{P}_{orb}/P_{orb}$ are different from the expected values (see Eq. (1)). However, as shown in Fig. 3, RD-LMXB's with lower main sequence companions may be characterized by a large positive value of $\dot{P}_{orb}/P_{orb}$ if $\dot{m}_8 \gtrsim 3$. Alternately, the X 1822-371 may contain a white dwarf companion [13], and Fig. 3 shows that in this case the likely mass is of order $m = (0.1 M_\odot)\dot{m}_8$. If both Cyg X-3 and X 1822-371 contain a very low-mass white dwarf, these systems can be naturally considered progenitors of binaries similar to the eclipsing pulsar PSR 1957+20. We note that both the sign and magnitude of $\dot{P}_{orb}/P_{orb}$ for Cyg X-3 and X 1822-371 suggest a stable RD-mass transfer with $1/3 \lesssim \beta \lesssim 1$ and $\Psi \lesssim 1$.

By contrast, EXO 0748-676 and 4U 1820-30 may belong to a class of RD-LMXB's in which a large mass loss from the binary plays a crucial role in determining the orbital evolution [13]. According to the RD-model, EXO 0748-676 and 4U 1820-30 are characterized by a relatively large mass loss from the binary with $\beta \sim 1/10$ and $\Psi \gtrsim 1$. For both EXO 0748-676 and 4U 1820-30 the RD-mass transfer is expected to be unstable ($\Psi \gtrsim 1$), in agreement with the large intensity fluctuations (by a factor of ~ 5) observed in EXO 0748-676 and 4U 1820-30. The RD-model allows two classes of RD-LMXBs characterized by different values of β [13]. Cyg X-3 and X 1822-371 belong to the high- β class, whereas EXO 0748-676 and 4U 1820-30 belong to the low- β class.

At present four out of fifteen LMXBs with $P_{orb} \lesssim 5.5$ hrs have measured $\dot{P}_{orb}/P_{orb}$'s. Of the total sample of ~ 100 LMXBs only ~ 36 binaries have well established orbital periods [e.g., 34]. A complete analysis of the selection effects affecting the measurements of $\dot{P}_{orb}/P_{orb}$ would be very useful in order to obtain an estimate of the true number of RD-LMXBs. As we have shown in Sect. 4 the existence of a class of short-lived LMXBs can be crucial for the resolution of the apparent statistical discrepancy between the MSP/LMXB birthrates. The discrepancy is resolved if more than a third of LMXBs are radiation-driven [24].

The detection of ionized mass outflow from LMXBs at the level of 10^{18} g s^{-1} and with temperature $T \gtrsim 10^7 \text{ K}$ from the companion star and possibly the outer disk depends on complex details of both the geometry of the gas flow and the heating/cooling mechanism in the expanding corona. No clear indication of ionized mass loss has been obtained from known LMXBs thus far, with the possible and notable exceptions of Cyg X-3 [33] (a favorable case with $\beta \simeq 1$) and the source AC211 in the globular cluster M 15 [25]. AC211, a good candidate for a RD-LMXB, is probably characterized by a large mass outflow of order $10^{-7} M_\odot \text{ yr}^{-1}$ [25] which simplifies the detection of emission/absorption lines Doppler-shifted by gas motion. We note here that line detection depends crucially on the geometry of the mass outflow as well as the total mass loss from the companion. In general for typical orbital parameters and wind velocities expected in RD-LMXBs, we can expect a relation of the type $\dot{m}_8 \simeq 10(L_{l,14})^{1/2}$, with $L_{l,14}$ the line luminosity in units of $10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ (which corresponds to the current sensitivity limit for most LMXBs). Detection of Doppler-shifted lines from LMXBs with $\dot{m}_8$ between 1 and 10 may be particularly difficult, and this problem deserves a more detailed theoretical and observational analysis of known LMXBs.

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