A NEW CLASS OF X–RAY PULSARS ?

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ABSTRACT.
While the distribution of spin periods of High Mass X–ray Binaries (HMXBs) spans more than four orders of magnitude (69 ms – 25 min), the few known X–ray pulsars accreting from very low mass companions (< 1 M$_\odot$) have very similar periods between 5.4 and 8.7 s. These pulsars display also several other similarities and they are probably members of a subclass of Low Mass X–ray Binaries (LMXBs) with similar magnetic field (a few 10^{11} G), companion stars and, possibly, evolutionary histories. If they are rotating at, or close to, the equilibrium period, their properties are consistent with luminosities of the order of a few 10^{35} erg s^{-1}. These pulsars might represent the closest members of a subclass of LMXBs characterized by lower luminosities, higher magnetic fields and smaller ages than non–pulsating LMXBs.

1. Introduction

X–ray pulsations with periods ranging from ~ 0.069 to ~ 1450 s are present in a large number (about 45) of X–ray binaries. This signal originates from the beamed radiation which is produced close to the magnetic poles of a young accreting neutron star with a surface field of $\sim 10^{12} - 10^{-13}$ Gauss. Due to the misalignement of the magnetic and rotation axes, the neutron star rotation modulates the X–ray intensity observed at the earth in a light–house fashion. Period (or phase) changes, introduced by the binary motion, allow to measure some of the orbital parameters of these systems. Together with the duration of the X–ray eclipse (which is observed in several systems) and the Doppler velocity and photometric modulations of the optical companion, these measurements provide the absolute orbital solution and the masses of the two components.

Most of these pulsars (over 35) are found in high mass X–ray binaries (HMXRB), containing an early type (OB) star with a mass of > 5 M$_\odot$. Mass transfer usually takes place because part of the intense stellar wind emitted by the OB star is captured by the gravitational field of the collapsed object. In some cases the OB star fills up its Roche lobe and mass transfer, towards the neutron star, takes place also through the first Lagrangian point, leading to the formation of an accretion disk around the neutron star. Secular spin period changes arise because of the torque exerted on the neutron star magnetosphere by the accreting matter (Henrichs 1983 and references therein). Disk–fed systems are characterised by a pronounced spin–up with a timescale that can be as short as $\sim$ 100 yr. Alternating spin–up and spin–down intervals are instead frequent among wind fed–systems; these likely result from the variable wind characteristics of the mass donor early type star (especially if a Be star), which can cause the angular momentum of the captured material to reverse its sign relative to the neutron star. Even in these cases, however, an average spin–up trend is ensued.

The spectra of X–ray pulsars in HMXBs are quite hard. They are usually characterised in terms of a power–law extending up to energies of several tens of keV, followed by a steep nearly exponential decay, beyond which cyclotron absorption features are sometimes detected.

The number of X–ray pulsars that are not in HMXBs is very small, but recent observations have virtually doubled this sample. This has also resulted from the finding that a few optically unidentified sources have X–ray to optical flux ratios incompatible with the presence of massive companions. Several of these systems have low mass donor stars and, therefore, are Low Mass X–ray Binaries (LMXBs). Two of the LMXBs pulsars, Her X–1, which has a comparatively massive companion of ~ 2 $M_{\odot}$, and GX 1+4, whose companion is an M giant, are peculiar systems (see, e.g., Rappaport & Joss 1983, Nagase 1989). The remaining five LMXBs pulsars (4U 0142+61, 1E 1048.1–5937, 4U 1626–67, RX J1838.4–0301 and 1E 2259+589) have very similar spin periods in the 5 to 9 s range (see Fig. 1). This narrow period distribution is remarkable, when one considers that the X–ray pulsars in HMXBs have spin periods ranging from 69 ms (A 0538–66, Skinner et al. 1982) to 25 min (RX J0146.9+6121, Mereghetti, Stella & De Nile 1993). We proposed that these LMXB pulsars belong to a homogeneous class of sources and suggest a possible explanation for their narrow spin period distribution (Mereghetti & Stella 1995).

2. Observational characteristics of the Very Low Mass X–ray Binary Pulsars

a) 4U 0142+61

The properties of 4U 0142+61 (White et al. 1987) remained puzzling for a long time, owing to confusion problems with a nearby pulsating and transient Be/neutron star system (Motch et al. 1991, Mereghetti, Stella & De Nile 1993). Despite the small error box (5" radius), no optical counterpart has yet been identified, down to V$>$ 24 (Steinle et al. 1987), thus excluding the presence of a massive companion. Using data from the EXOSAT archive, Israel, Mereghetti & Stella (1994) discovered periodic pulsations at 8.7 s, which were later confirmed with ROSAT (Hellier 1994). No delays in the pulse arrival times caused by orbital motion were found, with upper limits on $a_x \sin i$ of about ~ 0.37 lt–s for orbital periods between 7 min and 12 hr (Israel, Mereghetti & Stella 1994). The EXOSAT and ROSAT period measurements, obtained in 1984 and 1993, provide a spin–down rate of $\sim 7 \times 10^{-5}$ s yr^{-1}. The 2–10 keV spectrum, a power law with photon index of ~ 4, is extremely soft (White et al. 1987) and led to the initial classification of this source as a possible black hole candidate. The X–ray luminosity of 4U 0142+61 did not show large secular variations around an average value of $\sim$ 2.5×10^{35} erg s^{-1} (assuming a distance of 2 kpc).

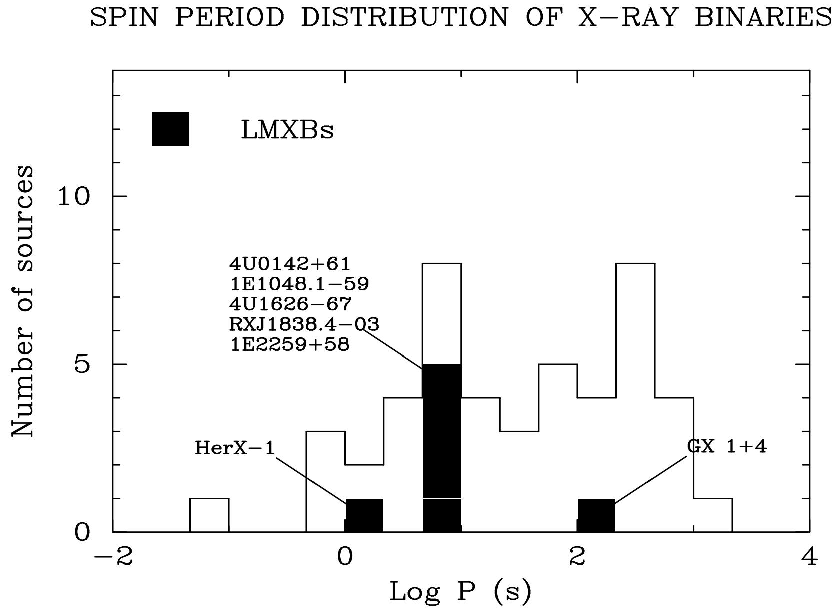

Fig. 1. The observed period distribution of X–ray pulsars. The black squares indicate the X–ray pulsars that are not HMXBs.

b) 1E 1048.1–5937

This source was serendipitously discovered with the Einstein Observatory in 1979, and found to pulsate at 6.44 s (Seward, Charles & Smale 1986). The brightest candidate counterparts in the small error box have V> 20 (Mereghetti, Caraveo & Bignami 1992) indicating that also 1E 1048.1–5937 is a LMXB. 1E 1048.1–5937 was repeatedly observed with ROSAT in 1992 and 1993. While all the previous observations with EXOSAT and GINGA (Corbet & Day 1990) were consistent with a constant spin-down at a rate of $\sim 5 \times 10^{-4}$ s yr^{-1}, the ROSAT data (Mereghetti 1996) indicate a doubling of the spin-down rate (Fig. 2) . The power law photon index derived with EXOSAT (2.3, Seward et al. 1986) implies also for this source a spectrum somewhat softer than the "canonical" spectrum of X–ray pulsars. The high column density suggests that 1E 1048.1–5937 lies behind the Carina nebula, i.e. at more than 2.8 kpc. The luminosity corresponding to this distance is $\sim 2 \times 10^{34}$ erg s^{-1}.

c) 4U 1626–67

This LMXBs is optically identified with the V$\simeq$ 18.5, blue star KZ TrA (Mc Clintock et al. 1977). In addition to the X–ray periodicity at 7.7 s (Rappaport et al. 1977), a pulsation at a slightly lower frequency is present in the optical band (Middleditch et al. 1981). This is probably due to reprocessing of the X–ray pulses occurring near the companion star, and the difference of the two periodicities can be explained with an orbital period of 41.4 min. The high X–ray to optical flux ratio, as well as the very strong

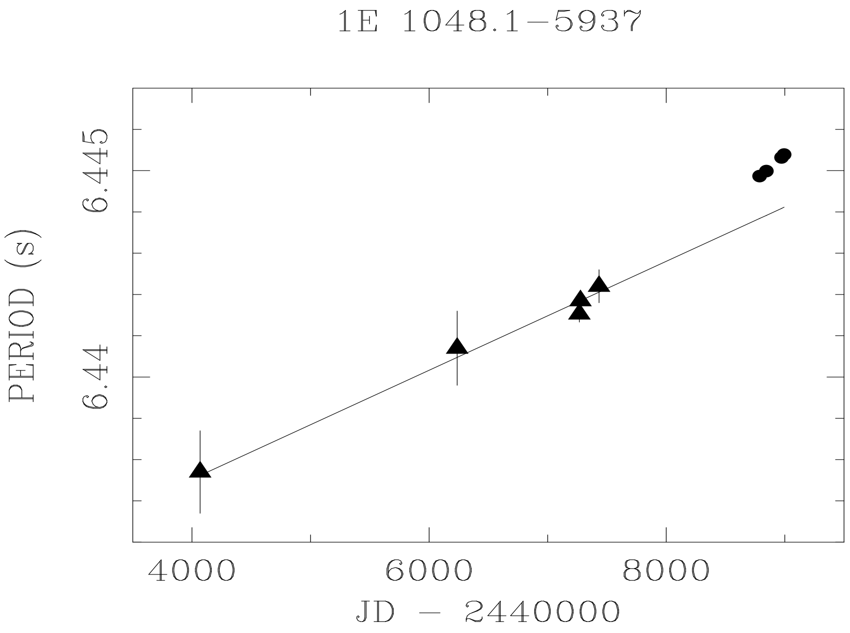

Fig. 2. Spin period evolution of 1E 1048.1–5937 (from Mereghetti 1995).

limits on the optical mass function ($a_x \sin i < 0.013$ lt–s for 10 min $< P_{orb} <$ 10 hr, Levine et al. 1988), clearly indicate that 4U 1626–67 is a LMXB. The period measurements obtained before 1990 were consistent with a constant spin–up rate of -1.6×10^{-3} s yr^{-1} (Nagase 1989), but in 1991 the period derivative changed sign (Lutovinov et al. 1994, Bildsten et al. 1994). On the basis of the luminosity required to explain the spin–up torque ($L_x \sim 2 \times 10^{36}$–$10^{37}$ $erg\ s^{-1}$) Levine et al. (1988) estimated a distance of 3 to 6 kpc. With the exception of quasi–periodic flares with a characteristic timescale of ~ 1000 s, little intensity variations are present in 4U 1626–67. The pulse averaged spectrum, a flat power law (photon index ~ 0.4) followed by an exponential cut–off at ~ 20 keV (Pravdo et al. 1979), is similar to that of HMXB pulsars (White, Swank & Holt 1983). A recent ASCA observation revealed the presence of spectral features around 1 keV, interpreted as emission lines of hydrogen–like Neon (Angelini et al. 1995). This indicates an overabundance of Ne in 4U 1626–67, which might give interesting constraints on the nature and evolution of its companion star.

d) RX J1838.4–0301

This pulsar, recently discovered with ROSAT, is embedded in a region of diffuse X–ray and radio emission, which is interpreted as a supernova remnant ~ 32000 years old at a distance of ~ 4 kpc (Schwentker 1994). The brightest optical object in its 10" radius error box has V=14. The spectrum in the 0.1–2.4 keV band, and therefore the unabsorbed flux, are not well constrained by the data (Schwentker 1994), but there is evidence that also this source is quite soft (best fit power law photon index of ~ 3).

Also RX J1838.4–0301 is likely a LMXB.

e) 1E 2259+586

The source 1E 2259+586 was discovered with the Einstein Observatory at the center of the X–ray and radio supernova remnant G109.1–1.0 (Fahlman & Gregory 1981). Extensive searches for optical, IR and radio counterparts were carried out without success (Fahlman et al. 1982; Coe & Jones 1992; Coe, Jones & Letho 1994), but they definitely exclude the presence of a massive companion (Davies & Coe 1991). The spin period of 1E 2259+586 has been increasing at $\sim 2 \times 10^{-5}$ s yr^{-1} until 1992 (Koyama et al. 1989, Iwasawa, Koyama & Halpern 1992). Recent ROSAT data revealed the first spin–up episode for this source. A detailed analysis of all the period measurement over the last 15 years (Baykal & Swank 1996) showed that 1E 2259+586 undergoes random angular velocity variations similar to those observed in other accreting binary neutron stars (Fig. 3). The upper limit on $a_x \sin i$ is of 0.08 lt–s for 10^3 s $< P_{orb} < 10^4$ s

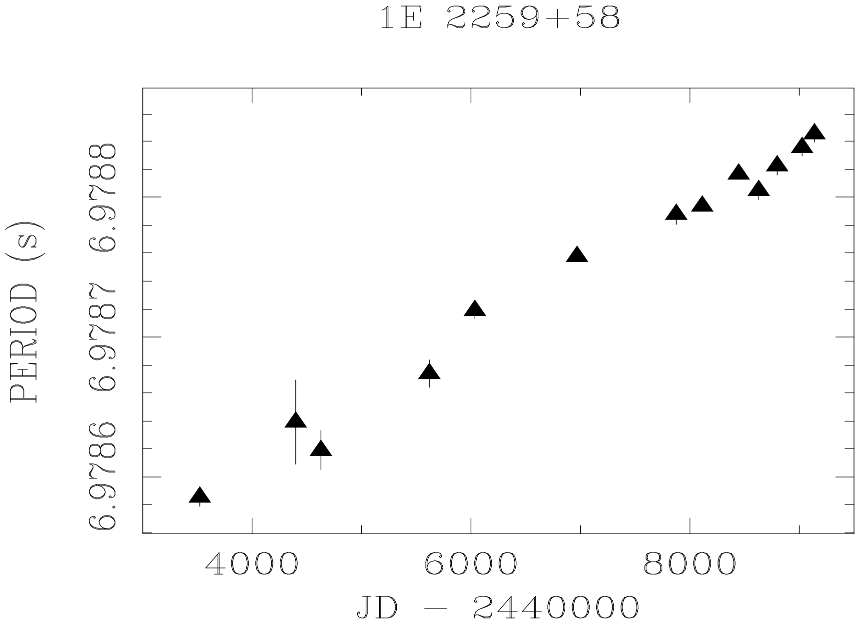

Fig. 3. Spin period evolution of 1E 2259+58.

(Koyama et al. 1989). 1E 2259+586 has a very soft spectrum, as recently confirmed by BBXRT and ASCA observations (Corbet et al. 1995). Also in this source, no long term variability greater than a factor ~2 has been reported. A distance of 3.6±0.4 kpc for the supernova remnant G109.1–1.0 was estimated by using the classical relation between distance and radio surface brightness (Gregory & Fahlman 1980). Based on improved radio observations, Hughes et al. (1984) have subsequently derived a value of 5.6 kpc. For this distance the average X–ray luminosity of 1E 2259+586 is $\sim 2 \times 10^{35}$ erg s $^{-1}$.

3. A new class of X–ray Pulsars ?

The main properties of the sources considered above are summarized in Table 1. Their most important similarities are the following. (a) When compared to the other X–ray pulsars, the most striking property of these objects is their narrow spin period distribution (Fig. 1). A Kolmogorov–Smirnov test yields a probability of 4 $\times10^{-3}$ that the period distribution of these five sources and that of the HMXBs pulsars are drawn from the same parent distribution. (b) With the exception of 4U 1626–67, their spectra are much softer than those of the other X–ray pulsars (White, Swank & Holt 1983). Figure 4 shows a comparison of the EXOSAT spectra of Vela X–1 and 4U 0142+61. The steep power law spectra of 4U 0142+61 and 1E 2259+586 are even softer than those of most LMXBs (White, Stella & Parmar 1988). This is also apparent from the position occupied by these source in the X–ray colour–colour diagram of Fig. 5. (c) These sources are probably less luminous than most persistent LMXBs. Indeed, for 1E 2259+586, 1E 1048.1–5937 and 4U 0142+61 firm upper limits of a few 10^{36} erg s^{-1} can be derived by requiring that they lie within the Galaxy. The best estimates for the distances of 4U 1626–67 and RX J1838.4–0301 also imply luminosities of this order of magnitude or smaller. (d) Their flux appears to be relatively constant on timescales from months to years. This is unlike most of the other X–ray pulsars (including Her X–1 and GX 1+4) for which large flux variations (encompassing transient activity) have been observed. (e) Two of these sources are likely associated to supernova remnants. Another source, 1E 1048.1–5937, lies in the direction of the Carina Nebula, a complex region of radio, optical and X–ray diffuse emission, clearly associated with recent star formation activity.

TABLE I
Properties of the VLMXB pulsars

Source	Period (s)	Spin–down (s yr^{-1})	X–ray Flux (erg cm^{-2} s^{-1})	Pow.–Law Ph.In.	L$_{eq}$ (erg s^{-1})	d$_{eq}$ (kpc)
4U 0142+61	8.69	7.2×10^{-5}	5.5×10^{-10}	4	1.4×10^{35}	1.5
1E 1048.1–59	6.44	4.6×10^{-4}	2.2×10^{-11}	2.3	2.8×10^{35}	10.6
4U 1626–67	7.66	1.4×10^{-3}	6.0×10^{-10} a	0.4	1.9×10^{35}	1.7
RX J1838.4–03	5.45	...	5×10^{-12}–4×10^{-9}	3	4.1×10^{35}	27–1
1E 2259+58	6.98	2.3×10^{-5}	5.3×10^{-11}	4–5	2.3×10^{35}	6.2

NOTE - L_{eq} and d_{eq} have been computed assuming $B = 5 \times 10^{11}$ G for all the sources.
[a] flux during spin–down; when 4U 1626–67 was spinning–up at –1.6 $\times10^{-3}$ s yr^{-1} its flux was $\sim$4 times higher.

Based on these similarities, Mereghetti & Stella (1995) proposed that these pulsars belong to a homogeneous subclass of LMXBs characterized by lower luminosities (10^{35} –

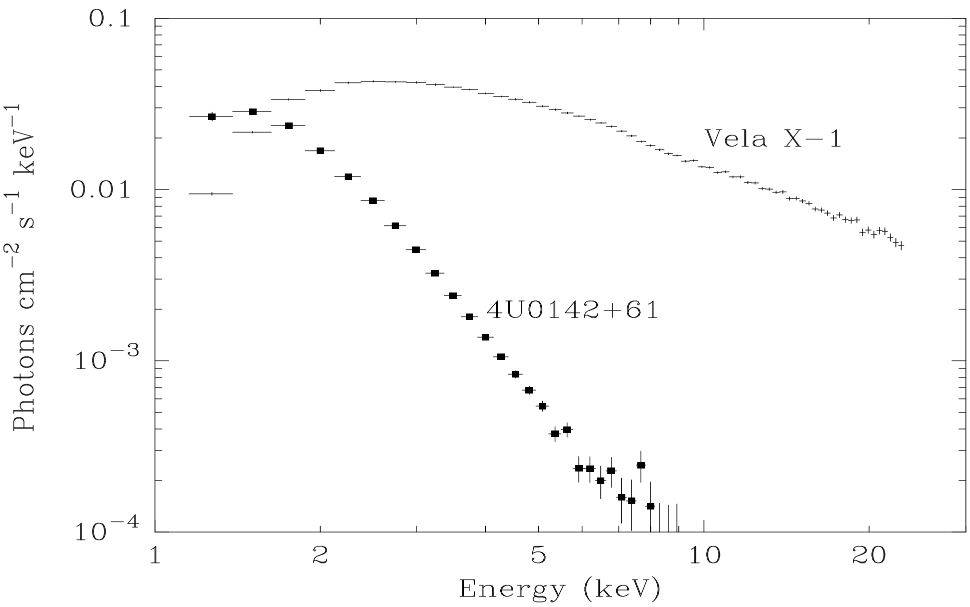

Fig. 4. A comparison of the EXOSAT ME spectra of Vela X–1 and 4U 0142+61.

10^{36} erg s^{-1}) and higher magnetic fields ($B \sim 10^{11}$ G) than classical, non-pulsating LMXBs.

4. Models

Models that have been proposed through the years for some of the X–ray pulsars of the new class differ with respect to the energy production mechanism as well as binary versus single nature of the magnetic degenerate star. Among models based on rotational energy dissipation, simple radio pulsar models can be ruled out based on the fact that measured spin–down rates correspond to a rotational energy loss by a magnetic neutron star which is more than two orders of magnitude lower than the inferred X–ray luminosities. Carlini and Treves (1989) suggest a modified radio pulsar scenario in which the emission beam of a freely precessing neutron star sweeps the earth from different angles, depending on the precession phase. In their model, the observed X–ray periodicity reflects the precession period of a weakly magnetized (B $\sim 10^{10}$ G), neutron star with mass 0.3 $M_{\odot}$ and with a spin period of only a few milliseconds. Morini et al. (1988) and Paczynski (1990) propose instead a white dwarf equivalent of the standard radio pulsar model. Due to the factor of $\sim 10^5$ larger moment of inertia, the white dwarf rotational energy loss implied by the measured $\dot{P}$ is considerably larger than the measured X–ray luminosity. Within this framework, the spin–down rate changes of 1E 2259+586 observed by Iwasawa, Koyama & Halpern (1992) have been interpreted by Usov (1994) in terms of white dwarf glitches. In

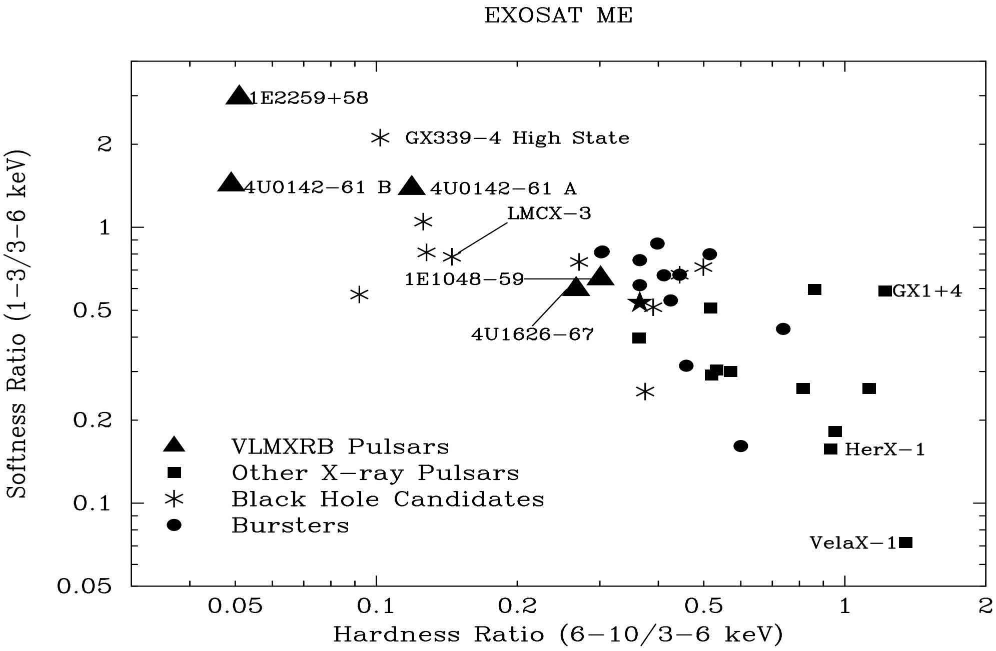

Fig. 5. X–ray colour–colour diagram for a sample of X–ray binaries.

a different vein, Thompson & Duncan (1993) suggest that 1E 2559+586 spins down like a standard radio pulsar, while the emitted radiation results from the gradual dissipation of the intense magnetic field ($> 10^{14}$ G) of the neutron star.

All the models outlined above are virtually ruled out by two recent studies. Baykal & Swank (1995) show that the spin period history of 1E 2259+586 consists of short term spin–up episodes superposed on a secular spin–down and that its fluctuation level is similar to that of a number of accreting X–ray pulsars in HMXBs. More crucially Mereghetti (1996) revealed an increased spin–down episode from 1E1048.1–5937, which is clearly incompatible with the spin–down rate expected in the unconventional applications of the radio pulsar model described above.

Models based on matter accretion onto a magnetic rotating neutron star are clearly favored. These models, in turn, envisage both possibilities that the neutron star is isolated or in a binary system. Israel, Mereghetti & Stella (1994) and Corbet et al. (1995) suggest that the neutron stars in 4U 0142+614 and 1E 2259+586, respectively, might be accreting matter from a dense region of a molecular cloud. The problem with this scenario is that the highest expected mass capture rates are in the 10^{13}g s^{-1} range, therefore giving rise to an accretion luminosity of $\sim 10^{33}$ erg s^{-1}. This is well below the inferred X–ray luminosities.

Based on the galactic distribution of four of the X–ray pulsars in the sample (4U1626–67 is excluded because of its binary nature), van Paradijs et al. (1995) propose that they are the result of the evolution of a neutron star spiralling in a massive star, after the so–called Thorne–Zytkov stage. Therefore, these sources should consist of isolated neutron stars accreting matter from a residual disk. While clearly viable, this model faces difficulties with the stability of such a self–gravitating disk (van Paradijs et al. predict a disk mass in the $10^{-3} - 1$ $M_\odot$ range).

Mass accretion from a companion star is the simplest explanation to account for the observed X–ray emission. In this framework, the peculiar period distribution of these sources can be explained by assuming that these neutron stars are rotating close to their equilibrium period (see Mereghetti & Stella 1995 for details). Due to the high angular momentum content, mass transfer in LMXBs is mediated by an accretion disk, resulting in a secular spin–up, unless the corotation radius is close to the size of the neutron star magnetosphere. In this "equilibrium rotator" regime (cf. Ghosh & Lamb 1979) a spin–down may result from the torques exerted by the magnetic field lines threading the accretion disk. The equilibrium rotator condition is given by :

$$L_{eq} \sim 8.6 \times 10^{35} (B/10^{11} G)^2 P^{-7/3} erg\ s^{-1},$$

where L_{eq} is the accretion luminosity at equilibrium and B the surface magnetic field of the neutron star (see, e.g., Henrichs 1983; we use a neutron star mass of 1.4 $M_\odot$ and radius of 10^6 cm). The measured spin–down rate of three of these sources testifies that the neutron star is close to equilibrium. We assume that also RX J1838.4–0301 and 4U 1626–67 are (nearly) equlibrium rotators. In the case of the latter source this is supported by the recent reversal from spin–up to spin–down. A measurement of the magnetic field strength based on cyclotron features is available only for 1E 2259+586, giving $B \sim 5 \times 10^{11}$ G (Iwasawa, Koyama & Halpern 1992, see, however, Corbet et al. 1995 for a different interpretation). The magnetic field of the other systems can be constrained by using the properties of their X–ray continuum. The spectrum of most X–ray pulsars is characterised by a relatively flat power law (photon index 0.5–1.8), with a cut–off around 10–30 keV above which the spectrum is much steeper (White, Swank & Holt 1983). This high energy cutoff is interpreted in terms of resonant cyclotron absorption in the vicinity of the polar caps. In those X–ray pulsars in which cyclotron line features are observed, the cutoff energy, E_{cut}, was empirically determined to be related to the cyclotron line energy through $E_{cyc} \sim (1.2 - 2.5)E_{cut}$ (Makishima et al. 1990, 1992). Therefore, E_{cut} can be used to approximately estimate the magnetic field strength (see however the case of EXO 2030+375; Reynolds, Parmar & White 1993). With the exception of 4U 1626–67, the photon indeces of the spectra in our sample (measured shortwards of 10 keV) are higher than the range measured in other X–ray pulsars. It is therefore likely that the part of the spectrum above E_{cut} is predominantly observed in the X–ray pulsars in our sample. Due to the combined effects of poor statistics and photoelectric absorption, a cutoff below 2–3 keV would remain undetected in the available spectra of 4U 0142+61, 1E 1048.1–5937 and 1E 2259+586. We conclude that for the pulsars in our sample $E_{cut} <$ 2–3 keV and therefore $B < 8 \times 10^{11}$ G. These values are substantially lower than those measured (or inferred) from most other X–ray pulsars ($10^{12} - 10^{13}$ G). Assuming $B = 5 \times 10^{11}$ G (based on the analogy with 1E 2259+586), Eq. 1 yields for the sources in our sample luminosities of 1–4 $\times$ 10^{35} erg s^{-1}. The corresponding distances, d_{eq}, are reported in Table 1. These distance and luminosity values are generally in good agreement with the X–ray and optical observational data

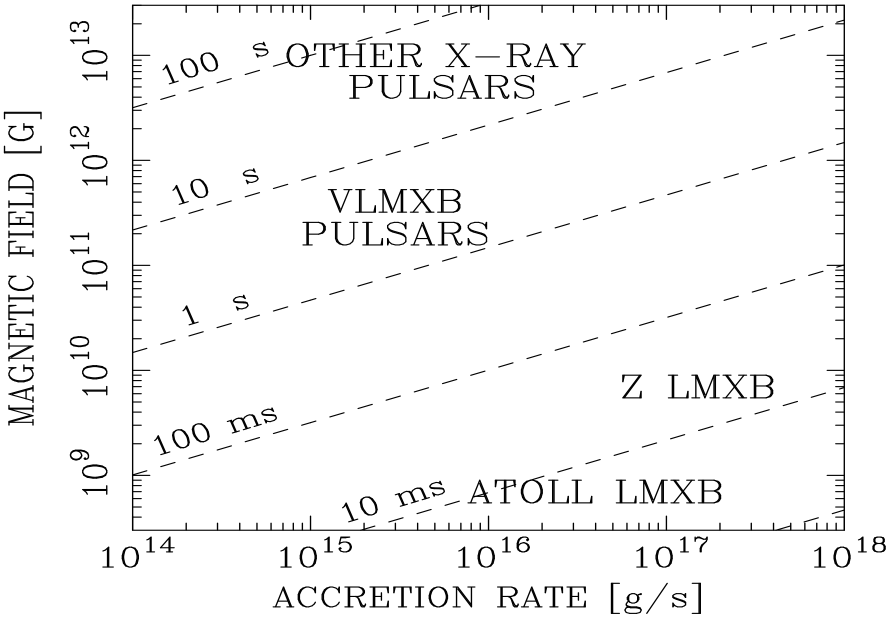

Fig. 6. Schematic representation of the position occupied by different classes of X–ray binaries in the B, $\dot{\rm M}$ diagram. Lines of different equilibrium spin periods are also plotted.

described in Section 2. The only exception is 4U 1626–67, for which $d_{eq} \sim 1.7$ kpc is outside the range of 3–6 kpc derived by Levine et al. (1988) based on the spin–up observed before 1990. This indicates that 4U 1626–67 has a somewhat higher magnetic field (d_{eq} scales linearly with B), as also suggested by its hard spectrum. A similar conclusion is reached if, in addition to Eq. 1, the equation for the accretion torque (cf. eq. 28 in Henrics 1983) is used together with the period derivative observed during the spin–up phase ($\dot{\rm P}$/P$\sim$–2 $\times 10^{-4}$ yr^{-1}) and a luminosity decrease of a factor $\sim$4 observed in correspondence to the $\dot{\rm P}$ reversal (Bildsten et al. 1994). This provides an independent rough estimate of $B \sim 1.1 \times 10^{12}$ G and $L_{eq} \sim 9\times 10^{35}$ erg s^{-1}.

5. Conclusions

The most likely interpretation is that the X–ray pulsars 4U 0142+61, 1E 1048.1–5937, 4U 1626–67, RX J1838.4–0301 and 1E 2259+589 are rotating close to their equilibrium spin periods and accreting from similar low mass companions. Their magnetic fields are likely of the order of a few 10^{11} G, i.e. lower than in HMXB pulsars, but still much higher than those of non–pulsating LMXBs (see Fig. 6).

Though the orbital period is (possibly) known only for 4U 1626–67, the faintness of the optical counterpart and the absence of Doppler modulations in the X–ray pulses, indicate that these systems have small orbital periods and/or companions of very low mass. The main contribution to the optical emission is thus expected to come from the X–ray heated accretion disk. An empirical relation between absolute magnitude, X–ray luminosity and orbital period for LMXBs has been derived by van Paradijs & McClintock (1994). For $L_x \sim 1-4 \times 10^{35}$ erg s^{-1} it predicts $M_v \sim 5-1.5 Log(P_{orb}/1\mathrm{hr})$. Therefore, we would expect to detect the optical counterparts only for the closest and least absorbed of our LMXB pulsars, as indeed is the case (the optical absorption of 4U 1626–67 is only $A_v < 0.3$; van Paradijs et al. 1986). The relatively low luminosities imply that only the closest members of this class of LMXBs have so far been discovered. It is also possible that some of the already known, but poorly studied, LMXBs contain a pulsar with a spin period in the 5–10 s range.

Future studies of this new class of X–ray pulsars should concentrate on: (a) more accurate X–ray pulse timing studies that could reveal unambiguously the presence of a companion star; (b) deeper searches for the optical counterparts; (c) periodicity searches in low luminosity X–ray sources close to the galactic plane.

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