THE 5–9 SECOND X–RAY PULSARS

L. Stella[1,⋆], G. L. Israel[2,⋆] and S. Mereghetti[3]

[1] *Osservatorio Astronomico di Roma, V. dell'Osservatorio 2, I–00040 Monteporzio Catone (Roma), Italy,* stella@coma.mporzio.astro.it
[2] *International School for Advanced Studies (SISSA–ISAS), Via Beirut, 3, I–34014, Trieste, Italy,* israel@sissa.it
[3] *Istituto di Fisica Cosmica, CNR, Via Bassini 15, I–20133 Milano, Italy,* sandro@ifctr.mi.cnr.it
⋆ *Affiliated to I.C.R.A.*

ABSTRACT

A new class of X–ray pulsars has been recently identified. Its members are characterised by: (i) similar spin periods in the 5–9 s range; (ii) secular spin down; (iii) very soft X–ray spectra; (iv) relatively low and constant X–ray luminosities of $\sim 10^{35} - 10^{36}$ erg s^{-1}; (v) association with regions of diffuse X–ray and radio emission, perhaps old supernova remnants. These pulsars contain neutron stars that derive their X–ray emission from matter accretion and are probably rotating close to their equilibrium period. The inferred magnetic field strengths are of a few$\times 10^{11}$ G. While at least one member of the class is in a binary system, it is yet unclear whether the other 5–9 s pulsars accrete from a very low mass companion or are isolated and posses a residual accretion disk. It has been proposed that these pulsars are young ($\sim 10^5$ yr) descendants of the evolution of massive binary systems, probably high mass X–ray binaries after common envelope and spiral in evolution.

INTRODUCTION

X–ray pulsations with periods ranging from $\sim$ 0.069 to $\sim$ 1450 s are present in a large number (about 50) of X–ray binaries. This signal originates from the beamed radiation which is produced close to the magnetic poles of an accreting neutron star with a surface field of $\sim 10^{12} - 10^{13}$ G. 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. Most of these pulsars (over 40) 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. Secular spin period changes arise because of the torque exerted on the neutron star magnetosphere by the accreting matter (see e.g. Henrichs 1983; White, Nagase & Parmar 1995). 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 early type mass donor (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. These 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 drastically enlarged the 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). Three of the LMXBs pulsars are peculiar systems: Her X–1 has a comparatively massive A–star companion (~ 2 $M_\odot$), while GX 1+4 and the hard transient GRO J1744–28 have evolved low–mass companions (see, e.g., Rappaport & Joss 1983 and Nagase 1989; Finger, Wilson & van Paradijs 1996). GRO J1744–28 in particular displays an unprecedented variety of bursting behaviours (Kouveliotou *et al.*1996; Strickman *et al.*1996; Stark *et al.*1996).
The remaining five X–ray pulsars which are not in HMXBs (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). Based also on several other similarities, we proposed that these 5–9 s X–ray pulsars belong to a homogeneous class of sources and suggest a possible explanation for their narrow spin period distribution (Mereghetti & Stella 1995). Whether or not the recently discovered 13 s X–ray pulsations from HD49798 originate in an accreting neutron star with similar characteristics is unclear at present (Israel *et al.*1995, 1996).

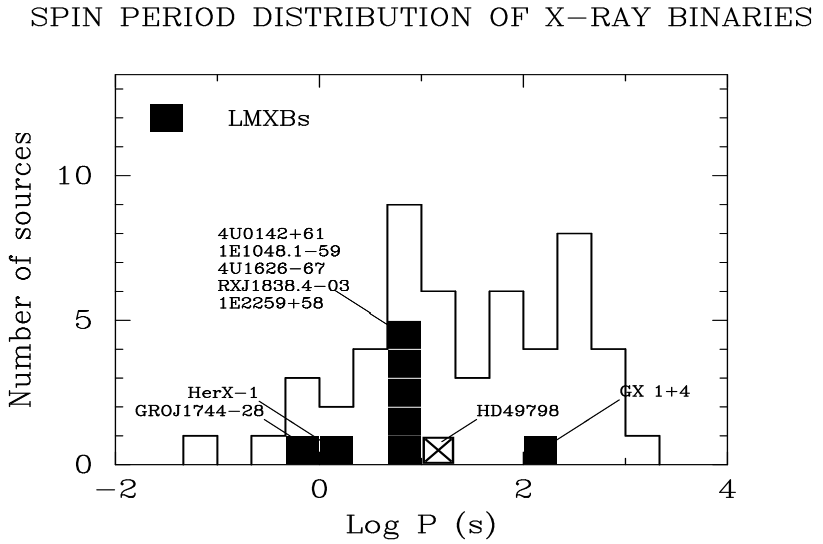

Figure 1: The observed period distribution of X–ray pulsars. The black squares indicate the X–ray pulsars that are not HMXBs.

OBSERVATIONAL CHARACTERISTICS OF THE 5–9 SECOND X–RAY PULSARS

a) 4U 0142+61

The properties of 4U 0142+61 (White *et al.*1987) remained puzzling for some 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 1–10 keV spectrum is extremely soft (power law photon index of ~ 4, White *et al.*1987) and led to the initial classification of this source as a possible black hole candidate. Recent ASCA spectra provide evidence for an additional ~ 0.4 keV blackbody component contributing some $\sim 40\%$ of the X–ray flux (White *et al.*1996). The X–ray luminosity of 4U 0142+61 did not show large secular variations around an average value of $\sim\ 2.5 \times 10^{35}$ erg s^{-1} (assuming a distance of 2 kpc).

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, Charles & Smale 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}.

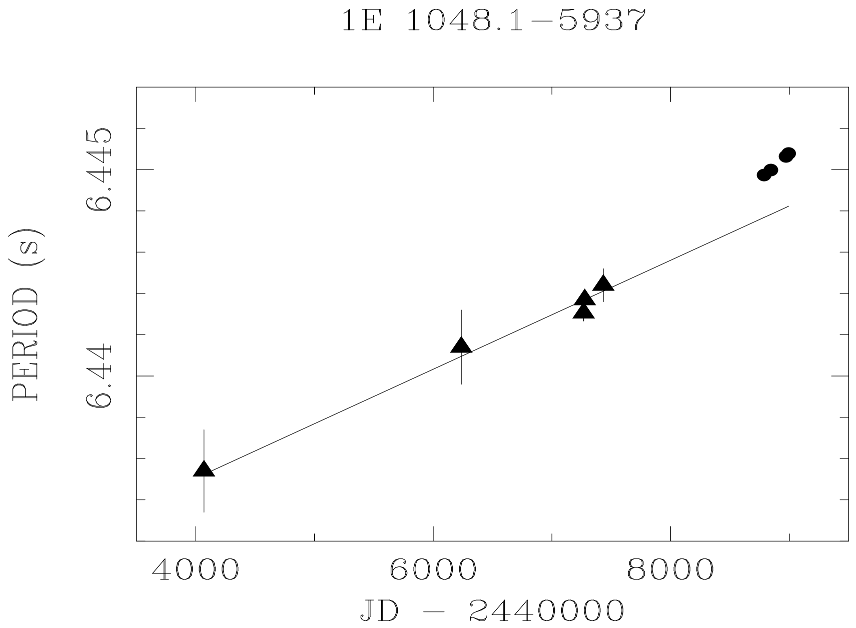

Figure 2: Spin period evolution of 1E 1048.1–5937 (from Mereghetti 1996).

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 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 $\sim$ 1000 s, little intensity variations are present in 4U 1626–67. The pulse averaged spectrum above a few keV, a flat power law (photon index $\sim$ 0.4) followed by an exponential cut–off at $\sim$ 20 keV (Pravdo *et al.*1979), is similar to that of HMXB pulsars (White, Swank & Holt 1983). An ASCA observation revealed the presence of a low energy excess (modelled with a 0.6 keV blackbody) and a complex feature around 1 keV, interpreted as emission from hydrogen–like Neon (Angelini *et al.*1995). The latter implies a large Ne overabundance in 4U 1626–67, testifying that the companion star, now probably a light Ne–rich He white dwarf, once burned He.

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 $\sim$ 32000 yr old supernova remnant at a distance of $\sim$ 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 $\sim$ 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

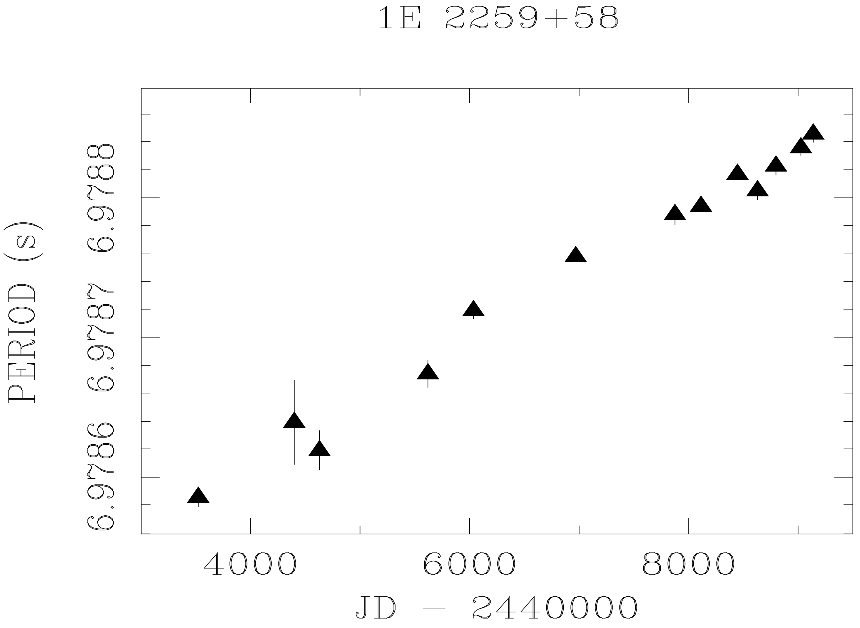

Figure 3: Spin period evolution of 1E 2259+58 (from Baykal & Swank 1996).

limit on $a_x \sin i$ is of 0.08 lt–s for 10^3 s $< P_{orb} < 10^4$ s (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 $\sim$2 has been reported. A distance of 3.6$\pm$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 $^{-1}$.

f) HD49798

HD49798 is a subdwarf O6 star in a single component spectroscopic binary (with P_{orb} = 1.55 d, $a \sin i$ = 3.60 $R_\odot$, f(m) = 0.263 $M_\odot$; Thackeray 1970; Stickland & Lloyd 1994). Despite extensive studies, the nature of the companion star remained unclear for decades. Being relatively massive ($M \sim 0.7 - 2.1$ $M_\odot$) very hot (T$\sim$ 47000 K) and luminous (Log $(L/L_\odot) \sim 3.9$) the sdO6 star outshines the flux emitted by the companion star (at least in the optical–UV). The level of H depletion together with the strong overabundance of N and underabundance of C, testify that the outer layers of HD49798 were processed through the CNO cycle and the envelope of the progenitor star was lost during a common envelope phase. Bisscheroux *et al.*(1996) argue that the sdO star has a degenerate CO core and is in the phase of shell helium burning. The recent discovery of strong 13 s pulsations in the soft X–ray flux from HD49798, proves that the system hosts an accreting degenerate companion either a white dwarf or, more likely, neutron star (Israel *et al.*1995, 1996). The source X–ray spectrum is extremely soft, with a power law photon index of $\alpha \sim 4$, corresponding to an unabsorbed 0.1–2 keV luminosity of a few $\times 10^{32}$ erg s^{-1} (distance of 650 pc; $\sim$210 pc above the galactic plane). A luminosity of up to $\sim 10^{35}$ erg s^{-1} might be hidden in the EUV. The relationship of HD49798 to the other 5–9 s X–ray pulsars hinges on the nature of its degenerate star, which remains to be firmly established as a neutron star. Therefore in the next three sections we exclude HD49798 from the sample of "5–9"s pulsars.

A NEW CLASS OF X–RAY PULSARS

The main properties of the 5–9 s X–ray pulsars described above are summarised 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 $\sim 4\times10^{-3}$ that the period distribution of these five sources and that of the HMXB pulsars are drawn from the same parent distribution. (b) With the exception of 4U 1626–67 (which, on the other hand, possess a low energy excess), 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. 4U 0142+61 and 1E 2259+586, in particular, have even softer spectra than 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$\times10^{36}$ erg s^{-1} can

Table 1: Properties of the VLMXB pulsars

Source	Period (s)	Spin–down (s yr^{-1})	X–ray Flux (erg cm^{-2} s^{-1})	α	L_{eq} (erg s^{-1})	d_{eq} (kpc)	z (pc)
4U 0142+61	8.69	7.2×10^{-5}	5.5×10^{-10}	4	1.4×10^{35}	1.5	–11
1E 1048.1–59	6.44	4.6×10^{-4}	2.2×10^{-11}	2.3	2.8×10^{35}	10.6	+93
4U 1626–67	7.66	1.4×10^{-3}	6.0×10^{-10} [a]	0.4	1.9×10^{35}	1.7	–385
RX J1838.4–03	5.45	...	5×10^{-12}–4×10^{-9}	$\sim$3	4.1×10^{35}	27–1	+135
1E 2259+58	6.98	2.3×10^{-5}	5.3×10^{-11}	4–5	2.3×10^{35}	6.2	–108

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

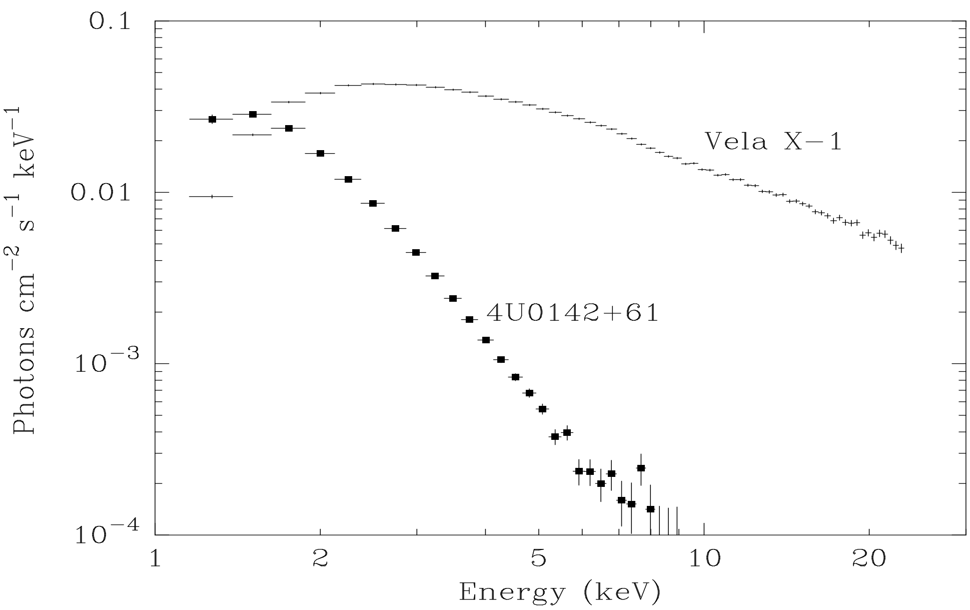

Figure 4: A comparison of the EXOSAT ME spectra of Vela X–1 and 4U 0142+61.

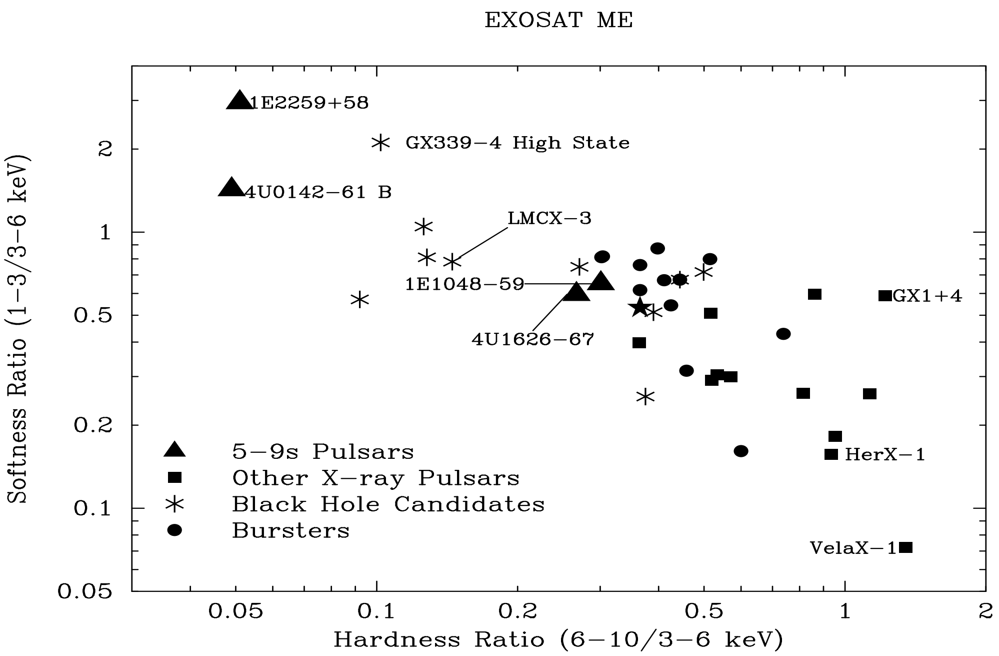

Figure 5: X–ray colour–colour diagram for a sample of X–ray binaries.

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, GX 1+4 and GRO J1744–28) for which large flux variations (encompassing transient activity) have been observed. (e) Two of these sources are likely associated to regions of diffuse X–ray and radio emission, which are likely 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.

Based on these similarities, Mereghetti & Stella (1995) proposed that these sources form a homogeneous subclass of accreting neutron stars, perhaps members of LMXBs, which are characterised by lower luminosities ($10^{35} - 10^{36}$ erg s^{-1}) and higher magnetic fields ($B \sim 10^{11}$ G) than classical LMXBs.

ENERGY PRODUCTION MECHANISMS

Models that have been proposed through the years for some of the X–ray pulsars of the new class (in particular for 1E2259+586) 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 the 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. 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 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 (1996) show that the spin period history of 1E 2259+586 consists of short term spin–up episodes superimposed on a secular spin–down and that its fluctuation level is similar to that of a number of accreting X–ray pulsars in HMXBs (see fig.3). More crucially Mereghetti (1996) discovered

an increased spin–down episode from 1E1048.1–5937 (see fig.2), which (contrary to the case of 1E 2259+585, Usov 1994) cannot be explained with a glitch, therefore ruling out the unconventional applications of the radio pulsar model described above.
Models based on matter accretion onto a magnetic rotating neutron star are clearly favoured. These models, in turn, envisage both possibilities that the neutron star is isolated or in a binary system.

EQUILIBRIUM SPIN PERIODS

The measured spin–down rate of three of the 5–9 s pulsars testifies that the neutron star is accreting close to its equilibrium spin period. We assume that also RX J1838.4–0301, and 4U 1626–67 are (nearly) equilibrium rotators. In the case of the latter source this is supported by the observed reversal from spin–up to spin–down. The equilibrium period 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). A measurement of the magnetic field strength based on cyclotron features has been obtained 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 be difficult to detect in the available spectra of 4U 0142+61, 1E 1048.1–5937 and 1E 2259+586 (note that the application of the standard X–ray pulsar spectral model to 4U0142+614 gives $E_{cut} \sim 1.4$ keV, although the fit is quite poor, see White *et al.*1996). We conclude that for the 5–9 s pulsars $E_{cut} <$ 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 luminosities and distances values are generally in good agreement with the X–ray and optical observational data 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 rate measured 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 Henrichs 1983) is used together with the period derivative observed during the spin–up phase ($\dot{P}/P \sim -2 \times 10^{-4}$ yr^{-1}) and a luminosity decrease of a factor $\sim$4 observed in correspondence to the $\dot{P}$ 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}.
In the interpretation above, the narrow spin period distribution of the 5–9 s pulsars should therefore reflect a relatively narrow range of neutron star magnetic field and accretion luminosity.

BINARY VS. ISOLATED ACCRETING NEUTRON STARS

Table 1 gives also the height z above the galactic plane of the 5–9 s X–ray pulsars as estimated from their equilibrium distances (cf. van Paradijs *et al.*1995). With the exception of 4U1626–67 and, perhaps, HD49798 (the only two known binary systems of the sample), the 5–9 s pulsars show a narrow z–distribution in the galaxy. This, together with the association (in two cases) with shell–like structures that appear to be $\sim 10^5$ year old supernova remnants, indicates that the 5–9 s

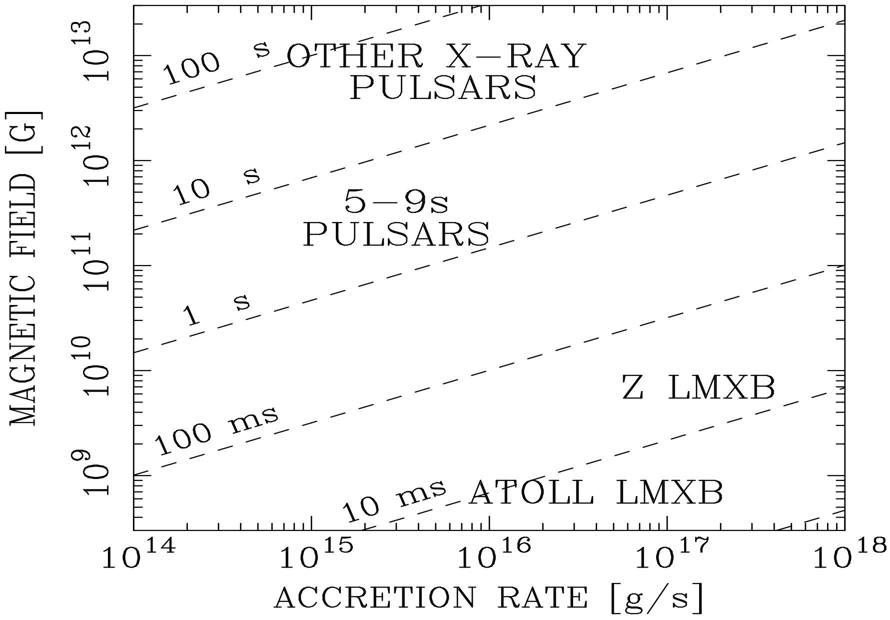

Figure 6: Schematic representation of the position occupied by different classes of X–ray binaries in the B, $\dot{M}$ diagram. Lines of different equilibrium spin periods are also plotted.

pulsars are young descedants (roughly 10^5 yr old) of the evolution of massive stars. Based on their current number and estimated distances Van Paradijs *et al.*(1995) suggest that our galaxy contains some 20–50 X–ray pulsars with similar characterstics, and therefore that their birth rate is in the $\sim 10^{-3}$ yr^{-1} range. However the combination of relatively low luminosities, very soft spectra and absorbing columns in the galactic plane likely introduces a bias against the detection of other 5–9 s X–ray pulsars. Therefore, the numbers quoted above should be regarded as lower limits.

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.

Mass accretion from a very low mass companion is perhaps the simplest explanation to account for the observed properties of the 5–9 s pulsars. The faintness of their optical counterpart and the absence of measurable Doppler modulations in the X–ray pulses, indicate that these systems have small orbital periods and/or companions of very low mass (clearly the case of HD49798 could be an important exception). 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 the 5–9 s X–ray 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 possibility that such very low mass X–ray binaries, VLMXBs, are formed through the accretion induced collapse of white dwarfs in AM Her–type cataclysmic variables (Mereghetti & Stella 1995) faces serious difficulties with their expected z–distribution ($z_{rms} \simeq 300$ pc for AM Hers) and birth rate ($\sim 10^{-5}$ yr^{-1}; cf. van Paradijs *et al.*1995).

Van Paradijs *et al.*(1995) propose that the 5–9 s pulsars are the result of the evolution of short orbital HMXRBs, following the expansion of the massive star and the onset of unstable Roche Lobe overflow, before central hydrogen is exhausted (see also Cannon *et al.*1992). The resulting common envelope phase should lead to the spiral–in of the neutron star and the complete disruption of the companion star after the so–called Thorne–Zytkov stage. Therefore, these sources (with the exception of 4U1626–67 and, possibly, HD49798) should consist of an isolated neutron star accreting matter from a residual disk with a mass in the $10^{-3} - 1$ $M_\odot$ range. A problem with this model, however, is that such a massive disk would be highly unstable to its own gravity. Perhaps the common envelope and spiral in stage could be halted before complete coalescence is reached, even in the absence of a dense helium core, leading to a very low mass, hydrogen depleted companion orbiting the neutron star.

In this context it is interesting to note that independent evidence supports the view that the binary X–ray pulsars 4U1626–67 and HD49798 were formed following a common envelope and spiral–in evolutionary phase (see Angelini *et al.*1995 and Israel *et al.*1996 and references therein). The different properties of the companion stars in these two cases may reflect the fact that unstable mass transfer set in at different phases in the nuclear evolution of their progenitors (in turn, reflecting different initial masses and orbital periods; see also Ghosh *et al.*1996). We note that a post common envelope evolutionary scenario for 4U0142+614 is also suggested by the recent inference that about half of the X–ray absorbing material is close to the source (White *et al.*1996).

CONCLUSIONS

The most likely interpretation is that the neutron stars in the 5–9 s pulsars derive their X–ray emission from accretion of matter close to the equilibrium rotator regime. Their magnetic fields are likely of the order of a few$\times 10^{11}$ G, i.e. lower than those of HMXB pulsars, but still much higher than those of classical LMXBs (see Fig. 6). That these pulsars are members of binary systems is proven only in one, or perhaps two, cases. Whether the other 5–9 s pulsars are in very low mass X–ray binary systems, or are isolated and accrete from a residual disk remains to be established. There is evidence, however, that the 5–9 s pulsars are young ($\sim 10^5$ yr) and originate in the common envelope evolution that follows the HMXB stage.

Future studies of this new class of X–ray pulsars should concentrate on: (a) obtaining more accurate X–ray pulse timing that could reveal unambiguously the presence of a companion; (b) searching for the optical counterparts with deeper observations; (c) searching for pulsations in low luminosity X–ray sources close to the galactic plane; (d) understanding the processes that lead to the formation of a much softer X–ray spectrum than that of standard X–ray pulsars.

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REFERENCES

Angelini, L. *et al.*, *ApJ* , 449, 41 (1995).
Baykal, A. and Swank, J.H., *ApJ* , in press (1996).
Bildsten, L. *et al.*, *AIP Conf. Proceedings*, 304, 290 (1994).
Bisscheroux, B.C. *et al.*, *A&A* , in press (1996).
Cannon, R.C. *et al.*, *ApJ* , 386, 206 (1992).
Coe, M.J. and Jones, L.R, *MNRAS* , 259, 191 (1992).
Coe, M.J., Jones, L.R., and Letho, H. 1994, *MNRAS* , in press (1994).
Corbet, R.H.D. and Day, C.S.R., *MNRAS* , 243, 553 (1990).
Corbet, R.H.D, Smale, A.P., Ozaki, M. *et al.*, *ApJ* , submitted (1995).
Davies, S.R. and Coe, M.J., *MNRAS* , 249, 313 (1991).
Thompson, C. and Duncan, R.C., *ApJ* , 408, 194 (1993).
Fahlman, G.G. and Gregory, P.C. 1981, *Nature* , 293, 202 (1981).
Fahlman, G.G. *et al.*, *ApJ* , 261, L1 (1982).
Finger, M.H., Wilson, R.B. & van Paradijs, J., *IAU Circular N.*6286 (1996).
Ghosh, P. and Lamb, F.K., *ApJ* , 232, 259 (1979).
Ghosh, P. *et al.*, *ApJ* , in press (1996).
Gregory, P.C. and Fahlman, G.G., *Nature* , 287, 805 (1980).
Hellier, C., *MNRAS* , 271, L21 (1994).
Henrichs, H.F., in "Accretion Driven Stellar X–ray Sources", ed. W.H.G. Lewin & E.P.J. van den

Heuvel (Cambridge University Press) (1983).
Hughes, V.A. *et al.*, *ApJ* , 283, 147 (1984).
Israel, G.L., Mereghetti, S., Stella L., *ApJ* , 433, L25 (1994).
Israel, G.L. *et al.*, *IAU Circular N.* 6277 (1995).
Israel, G.L. *et al.*, *ApJ* L, in press (1996).
Iwasawa, K., Koyama, K., and Halpern, J.P., *PASJ* , 44, 9 (1992).
Kouveliotou, C. *et al.*, *Nature* , 379, 799 (1996).
Koyama, K. *et al.*, *PASJ* , 41, 461 (1989).
Leisawitz, D., Bash, F.N. and Thaddeus, P., *ApJ Supp.* , 70, 731 (1989).
Levine, A. *et al.*, *ApJ* , 327, 732 (1988).
Lutovinov, A.A., Grebenev, S.A., Sunyaev, R.A., and Pavlinskii, M.N., *Astronomy Letters*, 20, 538 (1994).
Makishima, K. *et al.*, *PASJ* , 42, 295 (1990).
Makishima, K. *et al.*, in "Frontiers of X–ray Astronomy", ed. Y. Tanaka & K. Koyama, (Univ. Academy Press) 23 (1992).
McClintock, J.E. *et al.*, *Nature* , 270, 320 (1977).
Mereghetti, S., *ApJ* , 455, 598 (1996).
Mereghetti, S. and Stella, L., *ApJ* , 442, L17 (1995).
Mereghetti, S., Caraveo, P. and Bignami, G.F., *A&A* , 263, 172 (1992).
Mereghetti, S., Stella, L. and De Nile, F., *A&A* , 278, L23 (1993).
Middleditch, J., Mason, K.O., Nelson, J.E., White, N.E., *ApJ* , 244, 1001 (1981).
Morini, M., Robba, N.R., Smith, A., and van der Klis, M., *ApJ* , 333, 777 (1988).
Motch, C. *et al.*, *A&A* , 246, L24 (1991).
Nagase, F., *PASJ* , 41, 1 (1989).
Paczynski, B., *ApJ* , 365, L9 (1990).
Pravdo, S.H. *et al.*, *ApJ* , 231, 912 (1979).
Rappaport, S.A. and Joss, P.C., in "Accretion Driven Stellar X–ray Sources", ed. W.H.G.Lewin & E.P.J. van den Heuvel (Cambridge University Press) (1983).
Rappaport, S. A. *et al.*, *ApJ* , 217, L29 (1977).
Reynolds, A.P., Parmar, A.N., White, N.E., *ApJ* , 414, 302 (1993).
Schwentker, O., *A&A* , 286, L47 (1994).
Seward, F., Charles, P.A., Smale, A.P., *ApJ* , 305, 814 (1986).
Skinner, G.K. *et al.*, *Nature* , 297, 568 (1982).
Stark, M.J. *et al.*, *ApJ* , 470 L109 (1996).
Steinle, H., Pietsch, W., Gottwald, M. and Graser, U., *A&A* , 131, 687 (1987).
Stickland , D.F. & Lloyd, C., *The Observatory*, 114, 41 (1994).
Strickman, M.S. *et al.*, *ApJ* , 464, L131 (1996).
Thackeray, A.D., *MNRAS* , 150, 215 (1970).
Thompson, C. & Duncan, R.C., *ApJ* , 408, 194 (1993).
Usov, V.V., *ApJ* , 427, 984 (1994).
van Paradijs, J. and McClintock, J.E., *A&A* , 290, 133 (1994).
van Paradijs J., Taam R.E. and van den Heuvel E.P.J., *A&A* , 299, L41 (1995).
van Paradijs, J., van Amerongen, S., Damen, E. and van der Woerd, H., *A&A Supp.* , 63, 71 (1986).
White, N.E. *et al.*, *MNRAS* , 226, 645 (1987).
White, N.E., Swank, J.H. and Holt S.S., *ApJ* , 270, 711 (1983).
White, N.E., Stella, L., and Parmar, A.N., *ApJ* , 324, 363 (1988).
White, N.E., Nagase, F, and Parmar, A.N., in "X–ray Binaries", eds. W.H.G. Lewin, J. van Paradijs & E.P.J. van den Heuvel (Cambridge: Cambridge Univ. Press), 1 (1995).
White, N.E. *et al.*, *ApJ* , 463, L83 (1996).