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On the nature of the 'anomalous' 6-s X-ray pulsars

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Abstract. Recently it has become clear that there is a group of X-ray pulsars, with pulse periods close to 6 seconds which are distinct from accreting strongly magnetized neutron stars in X-ray binary systems. Here we argue that these objects are the recent products of the evolution of massive stars. They are unlikely to be neutron stars that formed through accretion induced collapse of a white dwarf. We propose that they are single neutron stars accreting from a disk, the recent remnants of the common-envelope evolution of a high-mass X-ray binary.

Key words: X-ray sources - neutron stars - accretion - Thorne-Zytkow objects

1. Introduction

There are currently seven X-ray pulsars known which are neither high-mass X-ray binaries, nor rotation powered neutron stars like the Crab pulsar. Two of them are accretion powered neutron stars with a low-mass (near) main-sequence or giant companion (Her X-1 and GX 1+4, respectively). In an important recent paper Mereghetti & Stella (1995) pointed out that the remaining five X-ray pulsars are distinguished by having pulse periods in a very narrow range (5.5 - 8.8 s) compared to that of the several dozen other X-ray pulsars (cf. Van Paradijs 1995). These authors also pointed out that with respect to other properties these objects are different from 'normal' binary X-ray pulsars as well [see Table 1; cf. Mereghetti & Stella (1995)].

(i) Except for 1626–67, their X-ray spectra are much softer than those of 'normal' X-ray pulsars; 1626–67 is also the only source for which there is evidence (from Doppler shift measurements of optical pulsations; see Middleditch et al. 1981) that it is a member of a binary. (ii) Their X-ray luminosities are in the range 10^{35} to 10^{36} erg/s, and tend to be quite constant on time scales of days to $\sim$ 10 years; (iii) Two of them (2259+587 and J1838.4–0301) have been associated with shells that have the appearance of supernova remnants (Fahlman & Gregory 1981; Schwentker 1994). (iv) Their pulse periods tend to increase with time, while accreting binary X-ray pulsars with periods this short tend to decrease with time.

Two models have been proposed for these peculiar X-ray pulsars. (i) Mereghetti & Stella (1995) suggested that they are accreting neutron stars with a very-low-mass companion; (ii) Paczynski (1990) proposed that they are the result of a merger of two $\sim 0.6\ M_\odot$ white dwarfs forming a rapidly rotating massive white dwarf with a magnetic field of order 10^8 G, which radiates through the loss of rotational energy. (Of course, this model does not apply to 1626–67, the only known binary among the sample.)

Apart from binarity, 1626–67 differs from the 4 remaining X-ray pulsars in other respects. As mentioned already, it has a much harder X-ray spectrum. Also its distance to the galactic plane (0.4 kpc) is much higher than that of the others (100 pc r.m.s.; see also Table 1). In our opinion, these differences indicate that the remaining four pulsars are different types of object from 1626–67; the properties of the four are sufficiently similar, and different from those of other X-ray pulsars to consider them a distinct group of sources. In the following discusssion 1626–67 is therefore not included.

2. Constraints on the formation mechanism

These systems appear to be very young. Two of the four (2259+586 and J1838.4–0301) are associated with what apparently is a supernova remnant, which would limit their ages to several 10^5 years. The system SS433 shows us, however, that shells of similar appearance may be produced by mass ejection that is not caused by a supernova explosion (Begelman et al. 1980; cf. Van den Heuvel 1981). We will take 10^5 years as a reasonable estimate of the ages of these systems, consistent with their small distances from the galactic plane.

The lack of substantial Doppler shifts of the X-ray pulse arrival times (Koyama et al. 1989; Corbet & Day 1989; Israel et al. 1994), and the absence of optical counterparts indicates that if these X-ray pulsars are in binaries their companion star masses could be at most a few tenths of a solar mass.

Table 1.

Source	P (sec)	$P/\dot{P}$ (year)	l^{II}	b^{II}	d (kpc)	z (pc)
4U 0142+61	8.69	1.2 10^5	129.4°	−0.4°	1.5	−11
1E 1048.1-5937	6.44	1.4 10^4	288.3°	−0.5°	10.6	+93
4U 1626-67	7.66	5.5 10^3	321.8°	−13.1°	1.7	−385
RX J1838.4-0301	5.45	–	28.8°	+1.5°	5.2 [a]	+135
1E 2259+586	6.98	3.0 10^5	109.1°	−1.0°	6.2	−108

[a] harmonic average of range given by Mereghetti & Stella (1995)

If these four X-ray pulsars are neutron stars it is very unlikely that they were formed by accretion induced collapse (AIC) of a magnetic white dwarf in a cataclysmic variable, as proposed by Mereghetti & Stella (1995). Cataclysmic variables have a much wider z distribution in the Galaxy ($z_{\rm rms} \sim 300$ pc, Duerbeck 1984; Augusteijn et al. 1995); the same is true for the polars (Beuermann 1995), which were suggested as progenitor systems by Mereghetti & Stella (1995), following Lipunov & Postnov (1985). It is difficult to see how their descendants could have a much narrower z distribution.

From the distances given by Mereghetti & Stella (1995) one can estimate that the total number of these sources in the Galaxy is between 20 and 50. With our above estimate of their typical age, the corresponding birth rate in the Galaxy is of order 1 per 3000 years. Based on observational estimates and on theoretical considerations of their evolution, the birth rate of CVs has been estimated at (0.5-2) 10^{-14} pc^{-3} yr^{-1} (Ritter & Burkert 1986; De Kool 1992); with a galactic volume occupied by CVs of 10^{11} pc^3 this corresponds to a total galactic birth rate of $\sim$ 1 per 10^3 years. Since according to our current theoretical understanding of the mechanism, AIC requires fairly special circumstances (mass accretion rate in a relatively narrow interval, or an initial white-dwarf mass in the range 1.2-1.3 $M_\odot$), the fraction of CVs that are expected to undergo AIC is very small. Webbink (1992) estimated the formation rate of neutron stars through AIC at $\sim 10^{-5}$ yr^{-1}. The substantial discrepancy in birth rates further strengthens the argument against CVs as the progenitors of the 6-s X-ray pulsars.

On the basis of the above we conclude that if they are neutron stars, the 6-s pulsars are the recent descendants of the evolution of massive stars. Since the white-dwarf merger proposed by Paczynski (1990) also is the result of the evolution of massive binary stars (Iben & Tutukov 1984) this conclusion appears to be a fairly general one.

In the case of 1E 2259+586 the rate of spin down has been observed to change (Koyama et al. 1989; Iwasawa et al. 1992). This is difficult to reconcile with the merged white-dwarf model of Paczynski (1990). Furthermore, the small distances to the galactic plane of the anomalous X-ray pulsars provide rather strong contraints on the this model. The corresponding velocity dispersion in the z direction, $<$ 10 km/s using galactic acceleration models (Kuijken & Gilmore 1989), requires these systems to be younger than $\sim 2\ 10^9$ years (a population of older systems has a higher velocity dispersion because of interactions with molecular clouds, see e.g., Mihalas and Binney 1981). This would imply that the progenitor white-dwarf binaries would be driven together by gravitational radiation within $\sim 2\ 10^9$ years (corresponding to orbital periods less than about 3 hours), but not after longer time intervals. There is no evidence that double-degenerate binaries have periods preferentially this short (see, e.g., Bragaglia et al. 1990).

3. Neutron star models for the anomalous X-ray pulsars

In principle, there are several mechanisms by which a rotating neutron star can generate pulsed X-ray emission.

(i) Loss of rotational energy by a solitary neutron star. This mechanism does not apply to the anomalous pulsars, since the rate of rotational energy loss, as estimated from the observed periods and spin-down rates, is insufficient to account for the observed X-ray luminosities by several orders of magnitude.

(ii) Loss of magnetic energy of a solitary, very strongly magnetized neutron star. If we assume that the usual relation between (dipolar) magnetic field strength B, spin period P, and spin-down rate $\dot{P}$ (i.e., $B^2 = 10^{39}\ P\dot{P}$) applies, the required B fields are in the range $10^{13.3}$ to $10^{14.7}$ G for the anomalous X-ray pulsars; if the magnetic field configuration is not dipolar, the field strengths may be much higher. This mechanism was suggested by Thompson & Duncan (1992; see also Thompson & Duncan 1993, 1994) as an energy source for soft gamma repeaters [see Norris et al. (1990) for a recent review of these objects]; its application to the anomalous X-ray pulsars as suggested by Duncan & Thompson (1995) would provide a possible connection between these pulsars and soft gamma repeaters. Note that in this model the rather soft X-ray spectra of the pulsars do not imply that the magnetic fields are of order 10^{11} G, as is the case for accretion models.

(iii) Accretion

Strong support for the idea that the X-rays are powered by accretion is the fact that the anomalous pulsars are spinning near the equilibrium period, corresponding to their X-ray luminosity and magnetic field strengths (Mereghetti & Stella 1995; see below). Furthermore, Baykal & Ögelman (1994) found that 2259+586 follows the relation between pulsar noise and X-ray luminosity observed for normal binary X-ray pulsars (see also Baykal & Swank 1995).

As mentioned in Section 2, the small values of the Doppler shifts in the pulse arrival times (upper limits typically a few tenths of a second) and the absence of luminous optical counterparts strongly argue against a high-mass companion.

Low-mass companion stars are not excluded by these considerations. However, the recent formation of such a low-mass X-ray binary as the end result of the spiral-in evolution of a binary consisting of a massive star and a low-mass companion, is very unlikely. The spiral-in of such a low-mass companion star does not provide enough energy to unbind the envelope (however, it has been suggested that a low-mass star may form in a disk around a neutron star, e.g. as the aftermath of the evolution of a Thorne-Zytkow object). In addition, it is difficult to envision how the low-mass star can fill its Roche lobe (either by orbital shrinkage or evolutionary swelling) and initiate mass transfer within 10^{4-5} years.

We therefore propose that the anomalous X-ray pulsars are single neutron stars, accreting from a circumstellar disk. Such X-ray sources, formed in globular clusters by the disuption of a star in close passage to a neutron star, were first suggested by Krolik (1982) as a possible model for some globular-cluster X-ray sources. The possibility of such X-ray sources was mentioned in passing by Thompson & Duncan (1994).

4. Accretion onto a solitary neutron star

The possibility that an accretion disk can exist around a solitary neutron star has gained support from the discovery of a planetary system in nearly circular orbits around the radio pulsar PSR 1257+12 (Wolszczan & Frail 1992). Such a disk may be the remnant of a common-envelope evolution (e.g. a phase in which the neutron star spiraled into the center of a massive star to become the core of a Thorne-Zytkow object (TZO), see Thorne & Zytkow 1977; Taam et al. 1978; Biehle 1991; Cannon et al. 1992; Podsiadlowski 1995; Taam 1995), may be formed during some supernova events, or may be formed in other ways (cf. Van den Heuvel 1992).

TZO can be formed from massive binaries as the result of neutron star formation with a kick directing the newly formed neutron star into its companion (Leonard et al. 1994), and as a result of common-envelope evolution of a high-mass X-ray binary (HMXB) with a massive evolved companion (Taam et al. 1978). Podsiadlowski (1995) estimates that the birth rate corresponding to the first formation process is $\sim 10^{-4}$ yr^{-1}; with an estimated 50 HMXB with evolved companions in the Galaxy (Van Paradijs & McClintock 1995) the birth rate for the second process is $\sim$ 1 per 2000 yr. Thus, TZO are produced at a sufficient rate to be good candidate progenitors for the anomalous X-ray pulsars. With a velocity dispersion similar to that of HMXB, and ages of order several times 10^5 years (Podsiadlowski 1995) the confinement of the 6-s pulsars to within $\sim$ 100 pc from the galactic plane follows naturally in this model.

TZO generate their luminosity by accretion onto the neutron core and non-standard thermonuclear reactions (rapid proton captures; see Biehle 1991, Cannon et al. 1992). According to Podsiadlowski (1993), after exhaustion of the fuel the envelope of the TZO will deflate on a thermal time scale; if the angular momentum of the envelope is sufficiently high a massive ($\sim$ $M_\odot$ disk may form around the neutron star.

A disk with a mass in the range 10^{-3} to 0.1 $M_\odot$ may be formed by backfalling matter from the envelope of the collapsing core following the initial collapse which started the supernova event (Lin et al. 1991; Chevalier 1989; Woosley 1988). Also, neutron stars with a high ("kick") velocity may accumulate a disk (with mass up to $10^{-4} M_\odot$) from the part of the expanding envelope that is (nearly) comoving with the neutron star. (Note, that even at a velocity of 10^3 km/s the neutron star moves at most 100 pc from the galactic plane in 10^5 yr.)

With an estimated lifetime of 10^5 years, and $\dot{M}$ (estimated from the X-ray luminosities, see Mereghetti & Stella 1995) of $\sim 10^{-11}$ $M_\odot$ yr^{-1} the mass in the disk would have to be at least 10^{-6} $M_\odot$, which is comfortably accomodated by the above models.

Unless there are major short-term variations in the mass accretion rate, the neutron star is likely to be found near the equilibrium period $P_{\rm eq}$, which is equal to the Kepler period at the inner disk (bounded by the magnetosphere of the neutron star), and is given by (see e.g. Henrichs 1983; we use nominal values for the neutron star mass and radius of 1.4 $M_\odot$, and 10 km, respectively):

$$P_{\rm eq} \sim (3\ {\rm s})\ B_{11}^{6/7}\ L_{35}^{-3/7}$$

The magnetic fields inferred from the observed luminosities and X-ray pulse periods are a few 10^{11} G, similar to the values inferred from the soft X-ray spectra, using the relation between the magnetic field and the high-energy cut off in the spectra of X-ray pulsars (Makishima & Mihara 1992)

Although the tail of the B field distribution of young neutron stars can cover fields of a few 10^{11} G (Bhattacharya et al. 1992), it is not obvious why the magnetic fields of the 6-s pulsars are systematically low. However, in the TZ scenario they formed before the spiral-in, and they may be as old as 10^{6-7} years. Perhaps, in this case the shells around two of the pulsars are not supernova remnants, but the remnants of the TZ object. According to current ideas, decay of neutron star magnetic fields does not occur spontaneously, but is related to the accretion of matter and, perhaps, to the rotational history of the neutron star (see, e.g., Bhattacharya 1995). According to the relation between the magnetic field and the amount of accreted matter given by Bitzaraki & Van den Heuvel (1995) a field of several times 10^{11} G requires a few 10^{-2} $M_\odot$ to be accreted on the neutron star. If the accretion rate is Eddington limited this amount of mass can be accreted within the lifetime of TZ objects (Podsiadlowski 1995). A contribution may have also come from a previous HMXB stage; Taam & Van den Heuvel (1986) calculated that a neutron star in a Be/X-ray binary may accrete a few times 10^{-2} $M_\odot$ during its lifetime. The accretion stage can be drastically shortened in TZ objects if the accretion energy is predominantly carried away by neutrinos, as suggested by Bisnovatyi-Kogan & Lamzin (1984) and Chevalier (1993).

As the neutron star field decays to $10^{11.5}$ G, the neutron star is expected to be spun up to a period of order $P_{eq} \sim 0.4$ s, as long as it is in the Eddington-limited stage of accretion. Spin down to the much longer observed X-ray pulse period range should then have occurred during a subsequent interval of low mass accretion rate, in which the neutron star was in the 'propeller stage'. This downspin can have taken place in a very short time ($< 10^3$ years according to Ghosh & Lamb 1979).

It is possible that there has been a delay between the field decay and the accretion that induced it. This would have kept the spin period during the accretion stage relatively long (several seconds for a field of $10^{12.5}$ G), and would make the required spin-down time scale much shorter.

As is clear from the above remarks, the observed X-ray pulse periods, and the inferred relatively low magnetic field strengths do not follow smoothly from this accreting single neutron star scenario (neither do they in the low-mass companion model). Nevertheless, the proposed single descendants of HMXBs, accreting from a leftover disk following a TZ phase, appear to provide a self-consistent picture, in which the presence of SNR-like shells around two systems as well as the low galactic latitudes of the sources, their birth rates and their tendency to spin down, all follow naturally. This makes it, in our opinion, a promising model for the formation of these objects.

Our model would be falsified if Doppler shifts in the arrival times of the X-ray pulsations were measured; the upcoming launch of the *X-ray Timing Explorer* will soon provide the means for this.

Note After submission of this paper we became aware of a paper by Corbet et al. in which the possibility that 1E 2259+586 is a single neutron star accreting from a circumstellar disk is also mentioned.

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