XTE AND SAX OBSERVATIONS OF THE ANOMALOUS X–RAY PULSARS

Sandro MEREGHETTI
IFCTR, v.Bassini 15, Milano, ITALY, sandro@ifctr.mi.cnr.it
Gian Luca ISRAEL & Luigi STELLA
Oss. Astrononico di Roma, Monteporzio Catone, ITALY
Paper presented at the International Conference on Neutron Stars and Pulsars, Tokyo, November 17-20, 1997

1. The Anomalous X–ray Pulsars

The majority of the $\gtrsim$ 50 known accreting X–ray pulsars are in High Mass X–ray Binaries (HMXRB). In most cases this is inferred from the observation of their optical counterparts: ten X–ray pulsars are optically identified with OB supergiants, and ~20 with Be stars. Many of the unidentified X–ray pulsars are believed to be HMXRB because they share the properties of the Be/neutron star systems (hard spectrum, transient behaviour, often with a recurrence equal to the orbital period). In the last few years there has been growing evidence that a group of pulsars, clearly not belonging to the HMXRB class, possess the following prominent common properties (Mereghetti & Stella 1995):

- their optical counterparts are very faint, implying that they cannot have massive companions

- their spin periods are distributed in a narrow range (~5-10 s), contrary to those of HMXRB that cover a much larger interval

- they have very soft X–ray spectra (with the exception of 4U 1626–67)

- their X–ray luminosity is relatively low (10^{35}-10^{36} erg s^{-1}) compared to that of HMXRB pulsars

- their X–ray flux shows little variability on timescales from months to years (they are not transient systems)

- they have a relatively stable spin period evolution, with long intervals of nearly constant spin-down

- a few of them are possibly associated to supernova remnants.

The 5 sources originally included in this group of "Anomalous X–ray Pulsars" (AXP) are : 1E 2259+586, 1E 1048.1–5937, 4U 1626–67, 4U 0142+61, and RXJ 1838.4–0301. Thanks to recent ASCA discoveries, two new possible members have been proposed. An 11 s periodicity has been found (Sugizaki et al. 1997) in the soft spectrum source 1RXS J170849.0-400910. The second possible AXP is the unresolved source 1E 1841–045 located at the center of the young ($\sim$ 2000 yr) supernova remnant Kes 73 and recently found to pulsate at 11.8 s (Vasisht & Gotthelf 1997).

Though 4U 1626–67 was originally included in the AXP group, various authors (van Paradijs et al. 1995, Ghosh et al. 1997) pointed out its different nature: it has a hard spectrum and it is the only source of this group with an identified optical counterpart and a well established binary nature. Also the inclusion of RXJ 1838.4–0301 appears now in doubt (Mereghetti et al. 1997), in the lack of an independent confirmation of the reported 5.45 s pulsations (Schwentker 1994).

2. Recent observational results

Recent ASCA (White et al. 1996) and BeppoSAX (Parmar et al. 1998, Oosterbroek et al. 1998) observations have shown that the spectra of 1E 2259+586, 1E 1048.1-5937 and 4U 0142+61 cannot be described by single power laws, but require the combination of a blackbody-like component (kT $\sim$ 0.5 keV) and a steep power law (photon index α $\sim$3-4). The same two-component spectrum is compatible with the ASCA data for 1RXS J170849.0-400910, although a simple power law gives a formally acceptable fit (Sugizaki et al. 1997). The spectrum of 1E 1841–045 (Vasisht & Gotthelf 1997) can be fit with a highly absorbed, soft power law ($\alpha \sim 3$). A blackbody component would be difficult to detect due to the high column density ($N_H \sim 2\ 10^{22}$ cm^{-2}). The spectrum of 4U 1626–67, a flat power law with a cut-off at $\sim$ 20 keV (Pravdo et al. 1979), is more typical of accreting pulsars in HMXRB. However, the presence of a soft blackbody component has been reported by several authors. A complex spectral feature around 1 keV, interpreted as emission from hydrogen-like neon (Angelini et al. 1995), might indicate that the companion of 4U 1626–67 is a He-burning star.

No periodic X–ray flux modulations such as dips or eclipses have been detected in AXP. 4U 1626–67 is the only object for which there is an (indirect) evidence for an orbital period. In this source, in addition to the X–ray periodicity at 7.7 s, a pulsation at a slightly lower frequency is present in the optical band (Middleditch et al. 1981). This has been interpreted as reprocessing of the X–ray pulses occurring near the companion star, and the difference of the two periodicities implies an orbital period of 41.4 min.

In the lack of optical identifications, the search for Doppler delays in the pulse arrival times is the only way to assess the possible binary nature of AXP.

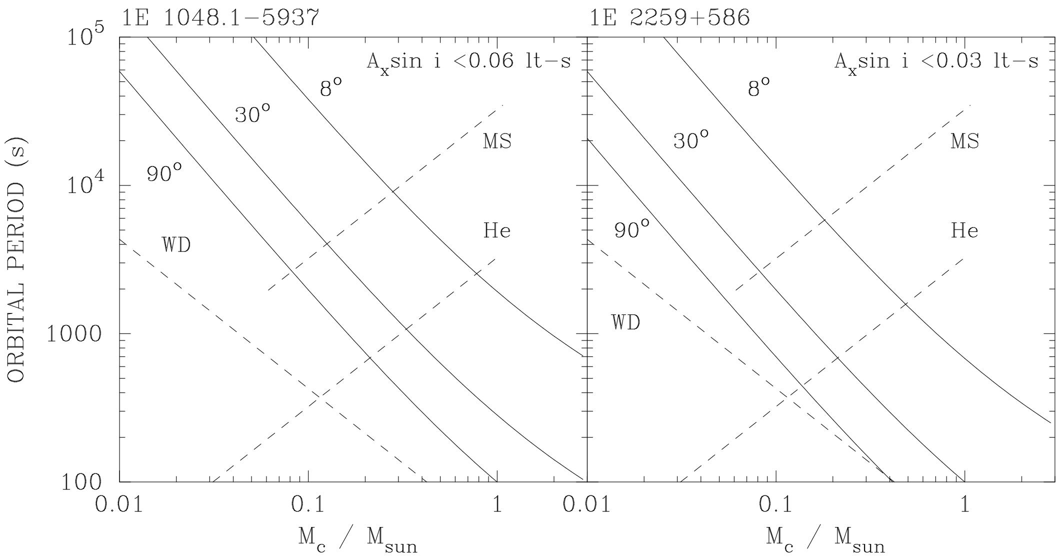

Fig. 1. Limits on $a_x \sin i$ derived with RossiXTE (Mereghetti et al. 1998)

Up to now, such searches have been unsuccessful. The most constraining limits have been recently obtained with the RossiXTE satellite for 1E 1048.1-5937 and 1E 2259+586 (Mereghetti et al. 1998). These limits and their implications for the possible companions are illustrated in figure 1.

3. Discussion

The P and $\dot{P}$ values measured in AXP imply rotational energy losses of $\sim 10^{32} - 10^{33}$ erg s^{-1} (for neutron stars, $I = 10^{45}$ g cm^2), too small to power the observed luminosities. A spinning down, isolated white dwarf would provide a larger rotational energy loss thanks to its higher momentum of inertia. Such a model was originally proposed for 1E 2259+586 (Morini 1988, Paczynski 1990), but later ruled out. Indeed, the observed variations in $\dot{P}$, sometimes correlated with luminosity changes and occasionally implying short spin-up intervals, are a strong indication that accretion is occurring in these systems (Mereghetti 1996, Baykal & Swank 1996).

It has been proposed (van Paradijs et al. 1995) that the AXP (with the exception of 4U 1626–67) are the descendant of Thorne-Zytkow objects and consist of isolated neutron stars accreting from residual disks. The blackbody component observed in some AXP has been interpreted as evidence for quasi-spherical accretion onto an isolated neutron star formed after common envelope evolution and spiral-in of a massive X-ray binary (White et al. 1996, Ghosh et al. 1997). In this case, the accretion flow results from the remaining part of the massive star envelope and is thought to consist of two components: a low-angular momentum component, giving rise to the blackbody emission from a considerable fraction of the neutron star surface, and a high-angular momentum one, forming a disk responsible for the power-law emission and for the long term spin-down.

Though this is certainly an interesting interpretation to be investigated with future observations, a more standard binary scenario is also possible. In fact, the presence of very low mass white dwarfs or He-burning companions cannot be ruled out, despite the limits on $a_x \sin i$. This is illustrated in figure 1, where the limits on orbital period, P_{orb}, versus mass of the companion, M_c, are plotted assuming three different values of $\sin i$. The dashed lines indicate the positions of Roche-lobe filling companions under the assumption of conservative mass transfer driven by angular momentum losses due only to gravitational radiation (see, e.g., Verbunt & van den Heuvel 1995). They refer to the cases of a main sequence, a He burning star and a fully degenerate hydrogen white dwarf. Values of P_{orb} and M_c below the corresponding dashed line are excluded, while those above the lines require accretion through stellar wind.

It is clear that, unless all these systems are nearly face-on, the most likely mass donors are white dwarfs and helium stars with masses below a few tenths of solar masses. In the latter case, the mass transfer is most likely through a stellar wind, since the accretion rates expected from a Roche-lobe filling He-star would produce a far greater luminosity than the observed ones.

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