THE ZOO OF X-RAY PULSARS

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Abstract

I review some recent developments in the field of X-ray pulsars: the discovery of millisecond pulsations in the Low Mass Binary System SAX J1808.4-3658, the large number of transient Be systems discovered in the Magellanic Clouds and the enigmatic class of objects known as Anomalous X-ray Pulsars.

1 Introduction

Accretion powered X-ray pulsars were among the first sources observed in X-ray astronomy and, thanks to their characteristic timing signatures, could be quite soon correctly interpreted as rotating, magnetized neutron stars (Pringle & Rees 1972, Davidson & Ostriker 1973). Since then, the observation and study of X-ray pulsars has provided a wealth of important information on the physics of neutron stars and on the evolution of stars in binary systems.

The designation of “X-ray” pulsars has traditionally been used to indicate the objects powered by accretion of matter from a companion star in a close, interacting binary (such as, e.g., Her X-1 and Cen X-3), in contrast to the “radio” pulsars, consisting of (in general) isolated neutron stars, the emission of which is powered by the loss of rotational energy. In fact only a few of the youngest and more powerful (in terms of $E_{\text{rot}}$) radio pulsars were observed at X-ray energies (e.g. the Crab and Vela pulsars). Nowadays it appears more appropriate to distinguish between accretion powered and rotation powered pulsars, since the better sensitivity of current satellites has allowed the detection of X-rays from ~40 of the more than 1000 radio pulsars.

Here we concentrate only on accretion powered pulsars (see Becker 2000 for a review of the X-ray properties of rotation powered pulsars).
The current census of accretion powered X-ray pulsars lists ~95 objects. 28 of them are located in the Magellanic Clouds (see Table 1) and three possible pulsars have also been reported in more distant galaxies (M31 and M33, Israel et al. 1995, Dubus et al. 1999). The observed spin periods are in the range from 2.5 ms to about 3 hours, but most of them are between ~1 and 1000 s. This is shown in Figure 1, where also the maximum observed luminosities are plotted. The X-ray pulsars are generally divided into different classes, based on the spectral type classification of the mass donor companion star. Several excellent reviews describe the properties of accretion powered pulsars (Nagase 1989, White et al. 1995, Bildsten et al. 1997). Here I will only comment on a few recent developments in this field.

2 SAX J1808.4−3658 : The Missing Link

Most X-ray pulsars have massive companions, either OB supergiants or Be stars. On the other hand the more numerous X-ray sources in Low Mass binary systems, display a variety of interesting phenomena indicating the presence of an accreting neutron star, but are characterized by the lack of periodic coherent signals identifiable as the neutron star spin. Numerous searches for periodicities have been carried out in Low Mass X-ray
Binaries (LMXRB) without success for more than 15 years, until the recent discovery of pulsations at 2.5 ms in the transient source SAX J1808.4−3658 (Wijnands & van der Klis 1998).

This finding is of extreme importance, since the LMXRB are thought to be the progenitors of the millisecond radio pulsars (see, e.g., Bhattacharya 1995). It is believed that the weakly magnetized neutron stars in LMXRB are spun-up to rotation periods of a few millisecond due to their interaction with the rapidly rotating inner part of the accretion disk. Once accretion terminates, the X-ray emission stops and the neutron star can shine again in the radio band as a recycled rotation powered pulsar. The detection of a very rapidly rotating neutron star in SAX J1808.4−3658 finally provided a clear evidence supporting this evolutionary scenario.

However, this finding also raises the puzzling question of why coherent pulsations have been seen only in one system, out of several tens of objects in which a similar signal could have been detected. It is possible that this is due to an orientation effect that makes the periodic modulation visible in SAX J1808.4−3658. In fact, pulse arrival time measurements in this source yielded an orbital period of \( \sim 2 \) hours, a projected semimajor axis of 63 light-ms and a very small mass function of \( \sim 3.8 \times 10^{-5} \) \( M_\odot \) (Chakrabarty & Morgan 1988). This indicates that SAX J1808.4−3658 has a light companion \( (< 0.2 \ M_\odot) \) and probably a very low inclination \( (<20^\circ) \).

Interestingly, SAX J1808.4−3658 is a transient system, i.e. a source that spends most of the time in a state of low luminosity. Although the mechanism responsible for the mass accretion variations that cause the transient behavior of these systems is still unclear, transient X-ray binaries give the possibility to study the physics of the accretion and of the interaction of the matter with the neutron star magnetosphere over a wide interval of accretion rates (Campana et al. 1998). A recent observation, carried out with the BeppoSAX satellite, has provided a measurement of the quiescent emission from SAX J1808.4−3658 at a luminosity level of only \( \sim 2-3 \times 10^{32} \) erg s\(^{-1}\) (Stella et al. 2000). This luminosity is too high to be due to the coronal emission from the companion star. Different possibilities to explain the observed X-ray flux have been considered, but the observational data, at the limit of the BeppoSAX capabilities, did not provide enough statistics for a spectral study that could discriminate among the different models. It is possible that, as observed in other soft X-ray transients, the quiescent spectrum of SAX J1808.4−3658 contain also a power law tail, in addition to the softer component due to the thermal emission from the neutron star atmosphere. Stella et al. (2000) discussed the constraints that can be derived on two possible models for the power law spectral component: accretion stopped at the magnetospheric radius or shock emission from the interaction between the relativistic wind of the neutron star and the wind from the companion.

Detailed spectral and timing studies of SAX J1808.4−3658 will be possible with the new, more sensitive X-ray satellites, such as XMM Newton. Thus, future observations of the “missing link” SAX J1808.4−3658, exploiting the knowledge of a well determined spin period (so far not available for other soft X-ray transients), will greatly help to understand the nature of the quiescent emission from X-ray transient sources.
3 X-ray Pulsars in the Magellanic Clouds

With an angular size of a few square degrees, the Magellanic Clouds are ideal targets for imaging X-ray telescopes. They offer the advantage of providing a population of sources at the same, known distance (respectively $\sim 54$ and $\sim 60$ kpc, for the Large and Small Magellanic Cloud).

The current list of all the known Magellanic Clouds X-ray pulsars is reported in Table 1. Most of the X-ray pulsars in the Magellanic Clouds have been discovered only in the last few years, thanks to observations with the ASCA and BeppoSAX satellites.

It seems that such a large number of newly discovered sources cannot simply be due to the fact that these satellites have devoted much more time to observe our satellite galaxies than previous X-ray missions. Especially in the Small Cloud, the pulsars in neutron star/Be systems seem to be more abundant than in our Galaxy. The total mass of the Small Magellanic Cloud is about 100 times smaller than that of our Galaxy. Scaling the observed number of SMC Be pulsars by this factor we should see $\sim 2000$ such objects in our Galaxy, compared to the $\sim 40$ actually observed.

In reality the discrepancy is not as large as these numbers would suggest, due to the presence of selection effects that make more difficult to observe X-ray sources in our Galaxy. In fact, the galactic Be/neutron star pulsars have a rather flat distribution in galactic longitude. This indicates that their average distance is only a few kiloparsecs, i.e. we are not sampling the whole galactic volume: we can only see the closest systems. Another selection effect is related to the transient nature of the majority of these systems. Dim transients in the galactic plane are difficult to discover, due to the limited coverage with sensitive instrument (all sky monitors have relatively high flux thresholds and are often confusion limited at low galactic latitudes) and to the effect of interstellar absorption.

However, although these selection effects are difficult to quantify, they are probably not large enough to completely explain the overabundance of massive X-ray binaries in the Small Magellanic Cloud, that is probably related to the different star formation history in our satellite galaxies. In fact another related evidence is the paucity of Low Mass X-ray binaries in the Magellanic Clouds. Despite all the recent observations only a few bright LMXB are known, in striking difference with the corresponding galactic population.

4 The Anomalous X-ray Pulsars

In the last few years it has been recognized (Mereghetti & Stella 1995, van Paradijs et al. 1995) that there is a class of X-ray pulsars with properties clearly different from those of the more common pulsars accreting from high mass companions. These objects have been called Anomalous X-ray Pulsars (AXP, see Mereghetti (2000) for a detailed review of their properties). Six AXP are currently known, three of which are clearly associated with Supernova Remnants (see Table 2).

AXP have spin periods in a narrow range ($\sim 6-12$ s), compared to the much broader one ($0.069 - \sim 10^4$ s) observed in HMXRBB pulsars (see Fig. 1). Their periods are monotonically increasing, on timescales of $\sim 10^4 - 4 \times 10^5$ years, again at variance with the typical behavior of the majority of accreting pulsars that are either spinning-up
Table 1 - X-ray Pulsars in the Magellanic Clouds

| NAME            | P (s) | Class(s) | References                          |
|-----------------|-------|----------|-------------------------------------|
| A 0538–66       | 0.069 | Be       | Skinner et al. 1982                 |
| RX J0502.9–6626 | 4.06  | Be       | Schmidtke et al. 1995               |
| LMC X-4         | 13.5  | S        | Kelley et al. 1983, Vrtilek et al. 1997 |
| EXO 053109–6609.2 | 13.67 | Be?     | Dennerl et al. 1996                 |
| RX J0529.8–6556 | 69.5  | Be?      | Haberl et al. 1997                  |
| SAX J0544.1–710 | 96.08 | Be       | Cusumano et al. 1998                |

| NAME            | P (s) | Class(s) | References                          |
|-----------------|-------|----------|-------------------------------------|
| AX J0043–737    | 0.0876| ?        | Yokogawa & Koyama 2000               |
| SMC X-1         | 0.717 | S        | Lucke et al. 1976                   |
| SMC X-2         | 2.37  | Be       | Corbet & Marshall 2000              |
| RX J0059.2–7138 | 2.763 | Be       | Hughes 1994                         |
| AX J0105–722    | 3.34  | Be?      | Yokogawa & Koyama 1998              |
| XTE J0052–723   | 4.782 | Be?      | Corbet et al. 2001                  |
| 2E 0050.1–7247  | 8.9   | Be       | Israel et al. 1997                  |
| AX J0049–732    | 9.13  | Be?      | Imanishi et al. 1998                |
| RX J0052.1–7319 | 15.3  | Be       | Lamb et al. 1999                    |
| RX J0117.6–7330 | 22.07 | Be       | Macomb et al. 1999                  |
| XTE J0111.2–7317 | 30.95 | Be      | Yokogawa et al. 2000a               |
| 1WGA J0053.8–7226 | 46.63 | Be      | Corbet et al. 1998                  |
| 1SAX J0054.9–7226 | 59    | Be      | Marshall & Lochner 1998             |
| RX J0049.1–7250 | 74.67 | Be      | Yokogawa et al. 1999                |
| AX J0051–722    | 91.12 | Be       | Corbet et al. 1998                  |
| AX J0057.4–7325 | 101.42| Be?     | Torii et al. 2000                   |
| XTE J0054–720   | 169   | Be?      | Lochner et al. 1998                 |
| AX J0051.6–7311 | 172.4 | Be      | Yokogawa et al. 2000b               |
| AX J0058–7203   | 280.3 | Be?     | Tsujimoto et al. 1999               |
| AX J0051–733    | 323.2 | Be      | Imanishi et al. 1999                |
| 2E 0101.5–7225  | 343.5 | Be      | Israel et al. 2000                  |
| AX J0049.5–7233 | 755.5 | Be      | Yokogawa et al. 2000c               |

Notes: (a) S = Supergiant companion; Be = Companion of Be spectral type; A question mark indicates that the optical counterpart has not yet been identified and the source is classified only on the basis of its X-ray properties.
### Table 2 - The Anomalous X–ray Pulsars

| SOURCE          | P (s)   | $\dot{P}$ (s s$^{-1}$) | SNR d (kpc)/age (kyr) | SPECTRUM $kT_{BB}/\alpha_{ph}$ |
|-----------------|---------|-------------------------|-----------------------|---------------------------------|
| 1E 1048.1–5937 | 6.45    | $[1.5-4] \times 10^{-11}$ | –                     | BB+PL [3]                       |
| 1E 2259+586    | 6.98    | $\sim 5 \times 10^{-13}$ | G109.1–0.1 [7,8,9]    | $\sim 0.64$ keV / $\sim 2.5$   |
| 4U 0142+61     | 8.69    | $\sim 2 \times 10^{-12}$ | –                     | BB+PL [11,12]                   |
| RXSJ170849–4009| 11.00   | $2 \times 10^{-11}$     | –                     | $\sim 0.4$ keV / ~4             |
| 1E 1841–045    | 11.77   | $4.1 \times 10^{-11}$   | Kes 73 [17,18]        | $\sim 0.41$ keV/ 2.92           |
| AX J1845.0–0300| 6.97    | –                       | G29.6+0.1 [21]        | PL [19]                         |
|                 |         |                         | $<20 / <8$            | BB [20]                         |
|                 |         |                         |                       | $\sim 0.7$ keV / –              |

[1] Seward et al. 1986; [2] Mereghetti 1995; [3] Oosterbroek et al. 1998; [4] Fahlman & Gregory 1981; [5] Baykal & Swank 1996; [6] Kaspi et al. 1999; [7] Hughes et al. 1984; [8] Rho & Petre 1997; [9] Parmar et al. 1998; [10] Israel et al. 1994; [11] Israel et al. 1999a; [12] White et al. 1996; [13] Sugizaki et al. 1997; [14] Israel et al. 1999b; [15] Vasisht & Gotthelf 1997; [16] Gotthelf et al. 1999; [17] Sanbonmatsu & Helfand 1992; [18] Helfand et al. 1994; [19] Gotthelf & Vasisht 1997; [20] Torii et al. 1998; [21] Gaensler et al. 1999;

or display an erratic period evolution. While their P and $\dot{P}$ values strongly suggest that AXP are neutron stars, it is clear that the corresponding rotational energy loss ($\sim 10^{45} \Omega \dot{\Omega} \text{erg s}^{-1}$) is not sufficient to power the luminosities of these objects, that are typically in the range $10^{34} - 10^{36}$ erg s$^{-1}$.

The optical counterparts of AXP are not known (with the possible exception of 4U 0142+61, see below). On the basis of the limits in the optical and IR bands, the presence of a massive companion star (OB super giants and/or Be stars) can be excluded in most AXP. Furthermore, there are no signatures of orbital motion in their X-ray light curves (i.e. no periodic modulations/eclipses nor Doppler shifts in the spin frequency induced by an orbital motion of the source).

The AXP are characterized by soft X-ray spectra, clearly different from those of the pulsars in HMXRB. The latter have relatively hard spectra in the 2-10 keV range (power law photon index $\alpha_{ph} \sim 1$) that steepen with an exponential cut-off above $\sim 20$ keV. Observations with the ASCA and BeppoSAX satellites, have shown that in most cases a single power law is not sufficient to describe the spectra of AXP. All the AXP for which good quality observations are available (White et al. 1996, Parmar et al. 1998, Oosterbroek et al. 1998, Israel et al. 1999a) require the combination of a blackbody-like component with $kT \sim 0.5$ keV, accounting up to ~40-50% of the observed luminosity, and a steep ($\alpha_{ph} \sim 3–4$) power law (see Table 2). The emitting area inferred from the blackbody components ($R_{BB} \sim 1-4$ km) corresponds to a large fraction of the neutron star surface.
Though the absence of a massive companion and the presence of a neutron star are well established, the AXP remain one of the more enigmatic classes of galactic X-ray sources: the mechanism responsible for the observed X-ray luminosity is still unclear. As mentioned above, models powered by the rotational energy loss of isolated neutron stars can be excluded on energetic grounds. The models based on neutron stars proposed for the AXP involve either accretion (with or without a binary companion of very low mass) or the decay of a very strong magnetic field. Also more exotic possibilities involving quark stars have been discussed (Dar & De Rujula 2000).

4.1 Accretion based models for the AXP

Binary models have the advantage of naturally providing accretion as a source of energy. However, the tight limits on the possible companion stars have also led to interpretations based on accretion on isolated neutron stars.

Mereghetti & Stella (1995) originally proposed that the AXP are weakly magnetized neutron stars (B \( \sim \) 10^{11} G) rotating close to their equilibrium period. This requires accretion rates of the order of a few 10^{15} g s^{-1}, consistent with the AXP luminosities.

The possible nature of the companion stars is constrained directly by the optical/IR limits on the AXP counterparts and indirectly by the absence of orbital Doppler modulations of the pulses. The first method allows to exclude bright massive companions, while the limits on the Doppler modulations are now beginning to exclude also main sequence stars for large regions of the orbital parameter space. Except for the unlikely possibility that these systems are seen face-on, main sequence companions can be ruled out in the three best studied AXP (1E 2259+586 , 1E 1048.1−5937 , 4U 0142+61 ; Mereghetti, Israel & Stella 1998, Wilson et al. 1998). Helium burning stars with M \( \lesssim \) 0.8 M\(_\odot\) cannot be excluded, but the accretion rate resulting from Roche lobe overflow would produce a much greater luminosity than the observed one. A possibility is that the He companion underfill its Roche lobe thus giving a smaller accretion rate by a stellar wind. White dwarf companion stars are compatible with the a\(_*\) sin i limits and yield consistent values of accretion. For example, a white dwarf of 0.02 M\(_\odot\) and P\(_{\text{orb}}\) \sim 30 min would give the M of a few \times 10^{-11} M\(_\odot\) yr^{-1} required by the observed luminosity of 1E 2259+586.

Accretion from the interstellar medium (ISM) cannot provide the luminosities observed in AXP for typical ISM parameters and neutron star velocities. The accretion luminosity is given by \( L_{\text{acc}} \sim v_{50}^{-3} n_{100} \) erg s^{-1}, where v\(_{50}\) is the relative velocity between the neutron star and the ISM in units of 50 km s^{-1} and n\(_{100}\) is the gas density in units of 100 atoms cm^{-3}. Unless all the AXP lie within nearby (\sim 100 pc) molecular clouds, which seems very unlikely considered their distribution in the galactic plane, the accretion rate is clearly insufficient to produce the observed luminosities.

An alternative possibility involving isolated neutron stars fed from a residual accretion disk was first advanced by Corbet et al. (1995) for 1E 2259+586 , and developed in more detail by van Paradijs et al. (1995) and Ghosh et al. (1997). These authors proposed that AXP result from the common envelope evolution of close massive X-ray binary systems. The connection with massive binaries is supported by the fact that the AXP seem to be relatively young objects, being located at small distances from the galactic plane and, in at least 50% of the cases, at the center of SNRs. A residual accretion disk could be formed after the complete spiral-in of a neutron star in
the envelope of a giant companion (a Thorne-Zytkow object, TZO, Thorne & Zytkow 1977). According to Ghosh et al. (1997), a massive binary undergoing common envelope evolution can produce two kinds of objects, depending on the (poorly known) efficiency with which the envelope of the massive star is lost. Relatively wide systems have enough orbital energy to lead to the complete expulsion of the envelope before the settling of the neutron star at the center of the massive companion. This results in the formation of binaries composed of a neutron star and a helium star, like 4U 1626–67 and Cyg X–3. Closer HMXRB, on the other hand, produce TZO, due to the complete spiral in of the neutron star in the common envelope phase, and then evolve into AXP.

According to Ghosh et al. (1997), this model can also explain the two component X–ray spectra of AXP, as well as their secular spin-down. The accretion flow is supposed to consist of two distinct components: one forming a disk and one spherically symmetric, resulting from the part of the envelope with less angular momentum. The hot (kT~1 keV) and ionized spherically symmetric flow forms a shock at the magnetospheric boundary, cools, and enters into the magnetosphere through a Rayleigh-Taylor instability. This results in accretion over a large fraction of the neutron star surface, producing the observed blackbody emission. The power law spectral component is instead produced by the conventional, field-aligned accretion onto the polar caps resulting from the disk component. The AXP are supposed to rotate close to their equilibrium periods, which increase due to the decreasing mass accretion rate (see, however, Li (1999) for a criticism to this model).

Another possibility for the formation of a disk around an isolated neutron star is through fallback of some material from the progenitor star after the supernova explosion (Chatterjee et al. 2000). For appropriate values of the neutron star magnetic field, initial spin period, and mass of the residual disk, these systems can evolve into AXP with luminosities, periods and lifetimes consistent with the observed values. Due to the steadily declining mass accretion rate, the rotating neutron star evolves through different states. During an initial “propeller” phase, lasting a few thousand years, the spin period increases up to values close to those observed in AXP. In this phase, the AXP progenitors are very faint, undetectable X–ray sources, since accretion down to the neutron star surface is inhibited (or greatly reduced) by the magnetospheric centrifugal barrier. In the following phase, the spin frequency approaches the Keplerian frequency at the inner edge of the disk \( \Omega(r_m) \), most of the mass flow is accreted, and the star becomes visible as an AXP. During this quasi-equilibrium phase, the neutron star spins down trying to match \( \Omega(r_m) \), which decreases with the declining mass accretion rate in the disk. To explain the narrow range of spin periods observed in AXP, Chatterjee et al. (2000) propose that an advection-dominated accretion flow (ADAF) ensues when the accretion rate further decreases. This causes a very small X–ray luminosity, thus explaining the lack of old AXP (\( \gtrsim 5 \times 10^4 \) yrs) with long spin periods.

4.2 Strongly magnetized neutron stars (Magnetars)

Models based on strongly magnetized (B~10^{14–10^{15}} G) neutron stars, or “magnetars” (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996), were originally developed to explain the Soft Gamma-ray Repeaters (SGR). SGRs are remarkable transient events characterized by brief (< 1 s) and relatively soft (peak photon energy ~20-30 keV) bursts of super-Eddington luminosity. Only four (or possibly five) SGRs are
currently known (see Hurley 2000 for a review). Several authors pointed out some analogies between the prototype AXP 1E 2259+586 and the soft repeater SGR 0526–66, located in the Large Magellanic Cloud SNR N49 and for which pulsations at 8 s were reported during the famous super-burst of March 5, 1979.

The possible connection between AXP and SGR, received renewed attention after the discovery of periodicities also in SGR 1806–20 (Kouveliotou et al. 1998) and SGR 1900+14 (Hurley et al. 1999, Kouveliotou et al. 1999). The values of $P$ and $\dot{P}$ ($\sim (5-15) \times 10^{-11} \text{s s}^{-1}$) observed in SGRs are very similar to those of AXP. Other similarities with the AXP are the luminosity of their quiescent counterparts, ($L_X \sim 10^{34}-10^{35} \text{erg s}^{-1}$) and the fact that all of them appear to be associated with SNRs.

If the spin-down in AXP and SGR is interpreted as due to magnetic dipole radiation losses, the neutron star magnetic field can be estimated as $B \sim 3.2 \times 10^{19} \left(\frac{\dot{P}}{P}\right)^{1/2} \text{G}$. The observed values of $P$ and $\dot{P}$ lead to values of $B \gtrsim 10^{14}-10^{15} \text{G}$. In the magnetar model the magnetic field is the main energy source, powering both the persistent X–ray (and particle) emission and the soft gamma-ray bursting activity. This involves internal heating, due to the magnetic field dissipation, and the generation of seismic activity. The latter is responsible for the soft $\gamma$-ray bursts, when the magnetic stresses in the neutron star crust shake the magnetosphere and accelerate particles.

Heyl & Hernquist (1997) showed that, if the magnetic fields in AXP are $\gtrsim 10^{15} \text{G}$, their residual thermal energy can be sufficient to power for a few thousand years the observed X–ray luminosity. This requires the presence of an envelope of hydrogen and helium (an iron envelope is much more efficient in insulating the core, resulting in a lower luminosity and effective temperature at the neutron star surface). The envelope of light elements, with a required mass of $\sim 10^{-11}-10^{-8} \text{M}_\odot$, could be due to fallback material after the supernova explosion and/or to accretion from the interstellar medium if the neutron star is born in a sufficiently dense environment ($\gtrsim 10^4 \text{cm}^{-3}$).

Actually, the AXP magnetic fields derived through the dipole radiation formula are very likely overestimated. In fact, the particle wind outflow, either continuous or in the form of strong episodic outbursts, also contributes significantly to the spin-down (Thompson & Blaes 1998). Harding et al. (2000) estimated magnetic field and spin-down age as a function of the particle wind duty cycle and luminosity. They found that, in the case of continuous particle outflows, the AXP and SGR magnetic fields can be in the same range as those of conventional radio pulsars.

Colpi et al. (2000) noted that, in the context of the magnetar scenario, the period clustering of AXP can be explained only if the magnetic field decays on a timescale of $\sim 10^4$ years. Models without a significant field decay would lead to the presence of AXP with longer periods, which have not been observed.

### 4.3 Discriminating between AXP models

Different authors discussed the kind of spin-down irregularities expected in the magnetar model. Melatos (1999) described the oscillation in $\dot{P}$ caused by radiative precession, an effect due to the star asphericity induced by the very strong magnetic field. He fitted the observed evolution of rotation frequency of the AXP 1E 2259+586 and 1E 1048.1–5937 in terms of the periodic ($\sim 5-10 \text{ yrs}$) behavior of $\dot{P}$ resulting from this effect. Unfortunately, the sparse period measurements available for AXP do not allow, for the moment, to discriminate against alternative possibilities.
For instance, Heyl & Hernquist (1999) fitted the same data with a constant spin-down interrupted by a few glitches. The magnitude of these glitches is similar to that observed in radio pulsars. Earlier analysis of the same 1E 2259+586 data showed that the level of $\dot{P}$ fluctuations was similar to that of accreting X–ray pulsars (Baykal & Swank 1996), and was therefore taken as support to accretion based models. More recently, Kaspi et al. (1999) could obtain for 1E 2259+586 a phase-coherent timing solution, thanks to RXTE observations spanning 2.6 years. These data show a very low level of timing noise, contrary to the previous results based on sparse observations that could not be phase related. Also 1RXS J170849−400910, monitored with RXTE for 1.4 yrs, was found to have a low level of timing noise (Kaspi et al. 1999), until the detection of a sudden spin-up event with all the characterestics of a glitch (Kaspi et al. 2000).

In conclusion it seems that timing studies can certainly help to understand AXP, but the emerging picture is still unclear. The low level of timing noise observed in the pulsars mentioned above (and in 1E 1841−045, Gotthelf et al. 1999) contrasts with the more irregular behavior of 1E 1048.1−5937 (Paul et al. 2000).

The other promising way to discriminate between different AXP models is through deep optical observations. Recently Hulleman et al. (2000) reported the discovery of a faint (R~25) blue object in the error box of 4U 0142+61. According to these authors, the faintness of the proposed optical counterpart rules out the presence of an accretion disk, thus favoring the magnetar interpretation. Unfortunately, detailed estimates of the expected optical brightness from disks around isolated neutron stars are very uncertain and depends on several factors, like the disk inclination, dimensions, amount of X–ray reprocessing, etc... (Perna et al. 2000). It seems therefore premature to draw firm conclusions based on the single case of 4U 0142+61. The search for the optical/IR counterparts of other AXP is complicated by the large reddening and by the fact that their error boxes are not small enough to search for counterparts at such faint magnitude levels (see, e.g. the case of 1E 1841−045, Mereghetti et al. (2001)). In this respect, more accurate positions for the AXP are expected from the on-going program of observations with the Chandra and XMM Newton satellites, which will also provide high quality spectral information, possibly allowing to discriminate between different X–ray emission mechanisms.

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