THE ANOMALOUS X-RAY PULSARS

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1. Introduction

In the last few years it has been recognized that a few X–ray pulsars, which
are not rotation powered, have peculiar properties that sets them apart from
the majority of accreting pulsars in X–ray binaries. These objects, initially
suggested as a homogeneous new class of pulsators in 1995 (Mereghetti &
Stella 1995), have been named in different ways, reflecting our ignorance
on their true nature: Very Low Mass X–ray Pulsars, Braking Pulsars, 6-
sec Pulsars, Anomalous X–ray Pulsars. The latter designation (AXP) has
become the most popular and will be used here.

Though we can be reasonably confident that the AXP are rotating neu-
tron stars without massive companions, it is unclear whether they are soli-
dary objects or are in binary systems with very low mass stars. As a conse-
quence, different mechanisms for powering their X–ray emission have been
proposed, involving either accretion or other less standard processes such
as, e.g., the decay of magnetic energy.

The properties that distinguish the AXP from the more common pulsars
found in High Mass X–Ray Binaries (HMXRB) are the following:

   a) spin periods in a narrow range (∼6-12 s), compared to the much
broader one (0.069 - ∼10^4 s) observed in HMXRB pulsars (see Fig. 1)

   b) no identified optical counterparts, with upper limits excluding the
presence of normal massive companions, like OB (super)giants and/or Be
stars

   c) very soft X–ray spectra (characteristic temperature ∼ 1 keV and/or
power-law photon index ∼ 3)
| SOURCE         | $P$ (s) | $\dot{P}$ (s$^{-1}$) | SNR        | SPECTRUM         |
|----------------|---------|----------------------|------------|------------------|
|                |         |                      | d (kpc)/age (kyr) | $kT_{BB}/\alpha_{ph}$ |
| **Anomalous X-ray Pulsars (AXP)** |         |                      |            |                  |
| 1E 1048.1–5937 | 6.45    | $[1.5-4] \times 10^{-11}$ | – | BB+PL [3] |
| [1]            |         |                      |            |                  |
| 1E 2259+586    | 6.98    | $\sim 5 \times 10^{-13}$ | G109.1–0.1 [7,8,9] | BB+PL [9] |
| [4]            |         |                      | 4-5.6 / 3-20 |                  |
| 4U 0142+61     | 8.69    | $\sim 2 \times 10^{-12}$ | – | BB+PL [11,12] |
| [10]           |         |                      |            |                  |
| RXSJ170849–4009| 11.00   | $2 \times 10^{-11}$   | – | BB+PL [13] |
| [13]           |         |                      |            |                  |
| 1E 1841–045    | 11.77   | $4.1 \times 10^{-11}$ | Kes 73 [17,18] | PL [19] |
| [15]           |         |                      | 6-7.5 / $\lesssim 3$ | $\sim 3.4$ |
| AX J1845.0–0300| 6.97    | –                     | G29.6+0.1 [21] | BB [20] |
| [20]           |         |                      | $<20 / <8$ |                  |
| **Pulsed Soft Gamma-ray Repeaters (SGR)** |         |                      |            |                  |
| SGR 0526–66    | 8.1     | –                     | N49 in LMC [23] | uncertain [24] |
| [22]           |         |                      |            |                  |
| SGR 1806–20    | 7.48    | $\sim 8.3 \times 10^{-11}$ | G10.0–0.3 [26] | PL [27] |
| [25]           |         |                      |            | $\sim 2.2$ |
| SGR 1900+14    | 5.16    | $\sim [5-4] \times 10^{-11}$ | G42.8+0.6 [31] | BB+PL [32] |
| [28]           |         |                      |            | $\sim 0.5$ keV / 1.1 |
| **(Candidate) Radio-Quiet Neutron Stars** |         |                      |            |                  |
| 1E 1207–5209   | –       | –                     | G296.5+10 | BB [33] |
| [33]           |         |                      |            | $\sim 0.25$ keV |
| 1E 1614–5055   | –       | –                     | RCW 103   | BB [35] |
| [34]           |         |                      |            | $\sim 0.6$ keV |
| 1E 0820–4247   | 0.075?  | $1.5 \times 10^{-13}$ ? | Puppis A  | BB [35] |
| [37]           |         |                      |            | $\sim 0.3$ keV |
| RX J0720.4–3125| 8.39    | –                     | –         | BB [38] |
| [38]           |         |                      |            | $\sim 0.08$ keV |
| RXJ1856.5–3754 | –       | –                     | –         | BB [39] |
| [39]           |         |                      |            | $\sim 0.06$ 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] Vasish et al. & Gotthelf 1997; [16] Gotthelf et al. 1999; [17] Sanbomatsu & Helfand 1992; [18] Helfand et al. 1994; [19] Gotthelf & Vasish 1997; [20] Torii et al. 1998; [21] Gaensler et al. 1999; [22] Mazets et al. 1979; [23] Clinic et al. 1982; [24] Marsden et al. 1996; [25] Kouveliotou et al. 1998; [26] Kulkarni et al. 1994; [27] Sonobe et al. 1994; [28] Hurley et al. 1999; [29] Kouveliotou et al. 1999; [30] Woods et al. 1999b; [31] Vasish et al. 1994; [32] Woods et al. 1999a; [33] Mereghetti et al. 1996; [34] Tuohy & Garmire 1980; [35] Gotthelf et al. 1997; [36] Petre et al. 1996; [37] Pavlov et al. 1999; [38] Haberl et al. 1997; [39] Walter et al. 1996;

Table 1 - AXP and related objects
d) relatively low X-ray luminosity ($\sim 10^{34} - 10^{36}$ erg s$^{-1}$) compared to that of HMXRB pulsars (see Fig. 1)

e) little or no variability (on timescales from hours to years)

f) relatively stable spin period evolution, with long term spin-down trend

g) a few of them are associated with supernova remnants.

There are now six members of the AXP class (section 2). This review is mainly focused on their observational properties (section 3), while the models are briefly discussed in section 4.

2. The AXP sample

Table 1 lists the 6 pulsars that share the above characteristics and form the current AXP sample. For comparison, also the properties of other objects that might be related to the AXP are reported in Table 1. The soft gamma-ray repeaters (SGR) have $P$ and $\dot{P}$ values very similar to those of the AXP. As discussed below, the magnetar model, originally developed to explain the SGR, has also been applied to the AXP. A few other (candidate) isolated
neutron stars have some similarities with the AXP (see Fig. 2), but more observations are needed to establish their nature.

On the basis of a better understanding of the AXP properties and/or of new observational results, we exclude from the AXP group a few sources that have been previously considered as part of this class of objects. 4U 1626–67 was originally included in the AXP class (Mereghetti & Stella 1995), but several authors pointed out its different nature: it has a harder spectrum, an optical identification, there is clear evidence for a binary nature, and showed an extended period of spin-up (van Paradijs et al. 1995, Ghosh et al. 1997).

The presence of pulsations at 5.45 s in the ROSAT source RXJ 1838.4–0301 (Schwentker 1994) has not been confirmed by more sensitive ASCA observations. Furthermore, optical observations of its possible counterparts revealed the presence of a main sequence K5 star with $V \sim 14.5$ (Mereghetti, Belloni & Nasuti 1997). This star could be responsible for the observed X-ray flux, since the implied X-ray to optical flux ratio ($f_x/f_{opt}$) is compatible with the level of coronal emission expected in late type stars. Thus it seems very likely that RXJ 1838.4–0301 is not a pulsar – i.e. the statistical significance of the periodicity was overestimated (Schwentker 1994).

The 8.4 s pulsar RX J0720.4–3125 (Haberl et al. 1997) has also been sometimes included in the AXP group, on the basis of its period value, high $f_x/f_{opt}$, and soft spectrum. Indeed its spectrum is even softer than that of AXP and it can only be detected thanks to the very low interstellar absorption ($N_H \sim 10^{20}$ cm$^{-2}$). Since this is taken as evidence for a very small distance ($d\sim 100$ pc), the implied luminosity of $\sim 3\times 10^{31}$ erg s$^{-1}$ is much smaller than that of the AXP. It has been suggested that RX J0720.4–3125 is an old neutron star accreting from the interstellar medium, but the possibility of a medium age neutron star, still emitting through dissipation of its internal heat, cannot be excluded.

3. Observational Properties of the AXP

3.1. SPECTRA

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 (i.e. power law photon index $\alpha_{ph} \sim 1$) that steepen with an exponential cut-off above $\sim 20$ keV. On the contrary, since their first observations, AXP showed very soft power law spectra, with $\alpha_{ph} \gtrsim 3-4$. Reports of possible cyclotron features at low energy ($\sim 5-10$ keV) in 1E 2259+586 (Iwasawa et al. 1992) have not been confirmed.

Recent observations with ASCA and BeppoSAX, 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 observation 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 $kT \sim 0.5$ and a steep power law ($\alpha_{ph} \sim 3-4$). A single power law is adequate to describe the spectrum of 1E 1841−045 (Gotthelf & Vasisht 1998), but the analysis is complicated by the presence of the underlying emission from the SNR that might hamper the detection of the blackbody component. In AX J1845.0−0300 a blackbody with $kT \sim 0.7$ keV gives a good fit without the need for an additional power law component (Gotthelf & Vasisht 1997).

The spectral parameters for all the AXP are summarized in Table 2. The emitting area inferred from the blackbody components, that account up to $\sim 40$-50% of the observed luminosity, is compatible with a large fraction of a neutron star surface.

Some evidence for spectral variations as a function of the spin-period phase has been reported for several AXP: 1E 2259+586 (Iwasawa et al. 1992, Corbet et al. 1995, Parmar et al. 1988), 4U 0142+61 (Israel et al. 1999a), 1E 1048.1−5937 (Corbet & Mihara 1997, Oosterbroek et al. 1988) and 1RXS J170849−400910 (Sugizaki et al. 1997). Unfortunately, the relatively poor energy resolution, and the limited statistics, do not allow to unambiguously characterize the spectral variations in the two separate components.

It is possible that this two component model be an oversimplified description of the true underlying spectra resulting from the current instrumental limitations. Future observations with XMM should resolve this issue, possibly leading to the discovery of narrow spectral features that so far escaped detection. Note in particular that the energy of cyclotron lines from ions lies in the 0.1 - 10 keV range for the high values of the magnetic field ($B \sim 10^{14}$) expected for the magnetar model (see section 4.2).

3.2. DISTANCES AND LUMINOSITIES

Due to the lack of optical identifications, the distances of AXP are quite uncertain (with the exception of the two in SNR, section 3.8). However, some constraints can be derived from their location in the Galaxy.

The low distribution on the galactic plane ($<|b|>=0.35^\circ$), indicates that, as a population, they are unlikely to be nearby ($\lesssim 1$ kpc) objects. Such a conclusion is also consistent with the relatively high column density derived from the X-ray spectral fits (Table 2).

1E 1048.1−5937 lies in the direction of the Carina Nebula, which is thought to contribute to the high absorption measured in its spectrum, giving a lower limit to the distance of 2.8 kpc (Seward et al. 1986). A similar argument can be made for 4U 0142+61 that probably lies behind
a local (d < 1 kpc) molecular cloud clearly visible in absorption on the Palomar Sky Survey plate (Israel, Mereghetti & Stella 1994). On the other hand, a distance much in excess of ∼5 kpc, would place this source outside the Galaxy.

The two AXP associated with SNR have better distance estimates: 6-7.5 kpc for 1E 1841−045 in Kes 73 (Sanbonmatsu & Helfand 1992) and 5.6 kpc for 1E 2259+586 in G109.1−0.1 (Hughes et al. 1984).

1RXS J170849−400910 is in the general direction of the galactic center region and has a highly absorbed X–ray spectrum, which suggests a distance of the order of 8 kpc or more.

According to Torii et al. (1998), AX J1845.0−0300 could be located in the Scutum arm, at d~8.5 kpc. Also this source is very absorbed and its distance could be larger. More information will be obtained if its association with the new radio SNR found by Gaensler et al. (1999) is confirmed.

Based on these distances and the observed fluxes, luminosities in the ∼10^{34}–10^{36} erg s^{-1} range are obtained for the AXP (see Table 2).

Another uncertainty affecting the AXP luminosity estimates is the correction for the (model dependent) X–ray absorption. In principle, this could...
be a relevant factor, due to the steepness of the observed spectra. Note in fact that for a power law spectrum that extends down to low energy with, e.g., $\alpha_{ph} \sim 4$, the flux in the 0.5-2 keV range is $\sim$15 times the 2-10 keV one. However, for the blackbody plus power law spectra discussed in section 3.1 this correction is much smaller. It seems therefore well established that AXP have X–ray luminosities smaller than those typically observed in persistent HMXRB pulsars.

| SOURCE            | $L_x^{(a)}$ $d^{(b)}$ | $kT_{BB}^{(c)}$ | $R_{BB}^{(d)}$ | $N_H^{(e)}$ | $L_{BB}/L_{tot}$ Pulsed Fraction |
|-------------------|------------------------|-----------------|----------------|-------------|----------------------------------|
| 1E 1048.1–5937    | $2 \times 10^{34}$ ergs$^{-1}$ | 0.64 keV | 1 km | $5 \times 10^{21}$ cm$^{-2}$ | 0.55
| 1E 2259+586       | $5 \times 10^{34}$ ergs$^{-1}$ | 0.44 keV | 4 km | $9 \times 10^{21}$ cm$^{-2}$ | $\sim$70%
| 4U 0142+61        | $8 \times 10^{34}$ ergs$^{-1}$ | 0.4 keV | 3.2 km | $1.4 \times 10^{22}$ cm$^{-2}$ | $\sim$10%
| 1RXSJ170849–4009  | $9 \times 10^{35}$ ergs$^{-1}$ | 0.41 keV | 3.4 km | $3 \times 10^{22}$ cm$^{-2}$ | $\sim$35%
| 1E 1841–045       | $3 \times 10^{35}$ ergs$^{-1}$ | 0.7 keV | 4.6 km | $4 \times 10^{22}$ cm$^{-2}$ | $\sim$50%
| AX J1845.0–0300   | $5 \times 10^{34}$ ergs$^{-1}$ | 0.4 keV | 3.2 km | $3 \times 10^{22}$ cm$^{-2}$ | $\sim$30%
|                   | $8 \times 10^{34}$ ergs$^{-1}$ | 0.7 keV | 3.4 km | $4 \times 10^{22}$ cm$^{-2}$ | $\sim$35%

(a) corrected for interstellar absorption  
(b) assumed values, see section 3.2 for the uncertainties  
(c) temperature of blackbody component  
(d) equivalent radius of blackbody component  
(e) photon index of power law component

Table 2 - Spectral properties of AXP

3.3. VARIABILITY

In general, AXP have relatively steady X–ray fluxes, compared with the kind of variability displayed by other classes of accreting compact objects. Most AXP have been detected at similar flux levels by all the satellites that looked at them. There are, however, some interesting exceptions.

The best evidence for flux variability has been so far obtained for AX J1845.0–0300. This source was discovered at a flux level of $4.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (2-10 keV) in an ASCA pointing performed in December 1993, but it was not visible 3.5 years later, implying a flux decrease greater than a factor 14 (Torii et al. 1998). A further ASCA observation revealed only a weak source at a position consistent with that of the AXP (Gaensler et al. 1999). Though a search for pulsations could not be performed, due to the
small number of counts, it is likely that this source is AX J1845.0−0300 in a low state, a factor $\sim$10 fainter than the 1993 level.

In a GINGA observation performed in 1990 (Iwasawa et al. 1992), 1E 2259+586 was a factor $\sim$2 brighter than in previous measurements with the same instrument. During the higher intensity state a change in the double-peaked pulse profile (a larger difference in the relative intensity of the two pulses) was also observed, as well as a variation in the spin-down rate. Most of the other observations of 1E 2259+586, obtained with different satellites, yielded flux measurements of $\sim$2-3 $\times$ 10$^{-11}$ erg cm$^{-2}$ s$^{-1}$, consistent with the lower intensity state (see Corbet et al. 1995, Parmar et al. 1998 and references therein).

The flux measurements available for 1E 1048.1−5937 have been summarized by Oosterbroek et al. (1998). They show long term variations within a factor $\sim$5 (possibly more if a rather uncertain upper limit obtained with the Einstein Observatory is also considered, Seward et al. 1986). However, the comparison of these flux measurements is affected by the uncertainties deriving from the use of different instruments.

No evidence for significant variability has been reported for the three remaining AXP: 4U 0142+61, 1E 1841−045 and 1RXS J170849−400910. However, since most of the relevant observations have been obtained with different instruments (sometimes also in different energy ranges) the limits that one can infer on the absence of variability are subject to considerable uncertainties. Several measurements were obtained with non-imaging instruments, and the fluxes must be corrected for the (poorly known) contribution from other components in the field of view (e.g. SNRs, diffuse galactic ridge emission, other sources, etc..), which introduce further uncertainties.

The level of variability in AXP is of interest since it is expected that some emission processes (e.g. thermal emission from the neutron star surface), produce less variability than other models (e.g. those involving mass accretion, which is in general subject to intensity fluctuations). More detailed searches for correlations between luminosity changes and spin-down variations can support accretion models, in which fluctuations in the mass accretion rate produce different torques on the rotating neutron star. Finally, the possible existence of many transient AXP with low quiescent luminosities, similar to AX J1845.0−0300, has important implications for the total number of AXP in the Galaxy and their inferred birthrate.

3.4. SPIN PERIOD DISTRIBUTION

As shown in Fig. 1, X-ray pulsars in massive binaries have spin periods spanning several orders of magnitude, from 69 ms (A 0538–67) to about
3 hr (2S 0114+65). The concentration of periods in the narrow \( \sim 6-12 \) s interval was one of the properties that led to the identification of the AXP as a possibly distinct class of objects. It is clear, however, that a period in this range is not enough to qualify a pulsar as an AXP (in fact there are several HMXRB with periods similar to those of the AXP). If we define the AXP as “pulsars with a very soft spectrum, that are neither HMXRB nor rotationally powered neutron stars, and have luminosity \( \sim 10^{34} \text{ to } 10^{36} \text{ erg s}^{-1} \)”, it turns out remarkably that all the known objects satisfying this definition have periods of a few seconds and a secular spin-down (when measured).

Why no AXP are seen with much longer, or much shorter, periods? There are no obvious selection effects explaining this narrow period distribution. Though a chance result due to the statistics of small numbers cannot be ruled out, this could be a real effect related to the particular characteristics and evolution of these objects. If this period clustering reflects the fact that the AXP are (close to) equilibrium rotators, one has to invoke similar magnetic fields and accretion rates in all the AXP.

3.5. PERIOD EVOLUTION

One of the distinctive peculiarities of AXP is their long term period evolution. In general, accreting neutron stars are expected to spin-up, due to the angular momentum transferred from the accreting material, often forming an accretion disk (see, e.g. Henrichs 1983). Indeed this is observed in many HMXRB pulsars in which there is evidence for an accretion disk. Other pulsars show alternating episodes of spin-up and spin-down, the origin of which is not completely understood. On the contrary, the spin periods of AXP are increasing at a nearly constant rate (on timescales ranging from \( \sim 2,000 \) to \( \sim 4 \times 10^5 \) yrs). This behaviour has now been observed in a few AXP for an extended period, spanning more than two decades.

It can immediately be seen that for these values of \( P \) and \( \dot{P} \), and assuming the canonical value for the momentum of inertia of a neutron star \( I=10^{45} \text{ g cm}^2 \), the rotational energy loss is orders of magnitude too small to power the observed luminosity of AXP.

Accurate timing measurements have shown that the spin-down of AXP is not constant, but is subject to small fluctuations (see, e.g., Iwasawa et al. 1992, Mereghetti 1995). Baykal & Swank (1996) showed that the level of \( \dot{P} \) fluctuations in 1E 2259+586, the AXP with the largest number of period measurements, is similar to that typically observed in neutron stars accreting in X-ray binaries, which is several orders of magnitude greater than that of radio pulsars. More recently, Kaspi et al. (1999) have been able to obtain a phase-coherent timing solution for RXTE observations of
1E 2259+586 spanning 2.6 years. These data show a very low level of timing noise, contrary to the previous results that were based on sparse (not phase-coherent) observations spanning ∼20 years. Also 1RXS J170849—400910, monitored with RXTE for 1.4 yrs, was found to have a similar level of timing noise (Kaspi et al. 1999), while an even more stable rotator is 1E 1841—045 (Gotthelf et al. 1999). It seems therefore that, at least on timescales of a few years, some AXP can be very stable rotators, with a timing noise similar to that of radio pulsars – a finding that supports the magnetar interpretation (see section 4.2).

3.6. SEARCHES FOR ORBITAL PERIODS

No periodic intensity variations, like eclipses or dips, that might indicate the presence of a binary system, have been detected in AXP. Another clear signature of binarity, that has been of extreme importance in the study of HMXRB pulsars, is the presence of orbital Doppler shifts in the pulse frequency. The most sensitive searches for orbital Doppler shifts in AXP have been carried out with the RXTE satellite. Searches for orbital periods between a few minutes and one day gave negative results, yielding upper limits on the projected semi-major axis $a \sin i$ of ∼30 and ∼60 light-days for 1E 2259+586 and 1E 1048.1—5937 respectively (Mereghetti, Israel & Stella 1998). Similar results were obtained by Wilson et al. (1998) for 4U 0142+61.

For any assumed value of the inclination angle $i$, these limit constrain the possible values of the companion mass $M_c$ and orbital period (Fig. 3). As discussed by Mereghetti, Israel & Stella (1998), except for the unlikely possibility that all these system are seen nearly face-on, main sequence companion stars can be ruled out. Helium burning stars with mass $M \lesssim 0.8 \, M_\odot$ cannot be excluded, but the accretion rate produced by Roche lobe overflow would give a luminosity much greater than observed. A possibility is that of a He-burning companion, underfilling the Roche lobe and providing a low rate of accretion through a stellar wind, as suggested by Angelini et al. (1995) for 4U 1626-67. Another possibility that cannot be ruled out by the current limits on $a \sin i$, and on the inferred mass accretion rates, is that of a white dwarf companion. For example, a white dwarf with $M \sim 0.02 \, M_\odot$, filling its Roche lobe for an orbital period of the order of ∼30 min, would give an $\dot{M}$ of a few ×10$^{-11} \, M_\odot$ year$^{-1}$, consistent with the observed luminosities. Mainly due to the lack of suitable observations, no similar searches for orbital Doppler shifts have been performed for the three remaining AXP: 1RXS J170849—400910, AX J1845.0—0300 and 1E 1841—045.
3.7. OPTICAL AND INFRARED COUNTERPARTS

The error box of 1E 1048.1−5937 has a radius of 15′′ and contains several stars (Mereghetti, Caraveo & Bignami 1992). Spectroscopy of the 3 brightest objects \((V \gtrsim 19)\) did not yield a plausible counterpart showing the classical emission lines considered a signature of accreting objects. More objects were studied by Corbet & Mihara (1997), again with negative results. These studies are complicated by the presence of diffuse \(\text{H} \alpha\) emission from the Carina nebula, which affects the sky subtraction from the stellar spectra.

1E 2259+586 is the AXP for which more extensive searches for counterparts have been carried out (Davies & Coe 1991, Coe & Jones 1992, Coe et al. 1994), sometime leading to possible identifications later disclaimed by better observations. The latest error box (5′′ radius), reported by Coe & Pightling (1998) contains only three faint objects with K-band magnitudes of \(\sim 18\) and \(V > 24\).

A different situation is found for 4U 0142+61, since in this case no objects are present within the small error box (\(\sim 3′′\) radius). The current best limits are \(V > 24\) (Steinle et al. 1987) and \(K > 17\) (Coe & Pightling 1998).
Optical observations of the field of 1RXS J170849−400910 have been reported by Israel et al. (1999b). These authors found that the possible counterparts cannot be massive early type stars, being too faint and blue (very distant and/or absorbed OB stars should appear more reddened by the interstellar dust absorption). No detailed reports on optical/IR observations of 1E 1841−045 and AX J1845.0−0300 have been published so far.

Though in general the limits on the possible optical/IR counterparts of AXP allow to rule out the presence of massive companion stars, more work is needed to explore different possibilities, especially because it is not clear which kind of properties one should expect from the AXP counterparts. Due to the crowding of these low galactic latitude fields, more precise localizations are also needed.

3.8. ASSOCIATION WITH SUPERNOVA REMNANTS (SNR)

The fact that two (possibly three) AXP are found at the center of SNR is very important, since it gives informations on their origin, age and distance.

1E 2259+586 is located close to the geometrical center of G109.1−0.1 (also known as CTB 109), a partial radio/X-ray shell with an angular diameter of ∼30′ (see, e.g., Rho & Petre 1997). As discussed in Parmar et al. (1998), the estimated age for this SNR is subject to a considerable uncertainty, ranging from ∼3,000 yrs to 20,000 yrs. The other AXP clearly associated to a SNR is 1E 1841−045. It was discovered as an unresolved source at the center of Kes 73, a young (∼2000 yr) SNR at a distance of ∼7 kpc (Helfand et al. 1994). Gaensler et al. (1999) have recently reported the discovery of a radio SNR around AX J1845.0−0300. These three AXP are found close to the geometrical center of the respective SNR, implying relatively small transverse velocities for these objects.

One should not forget that three AXP (4U 0142+61, 1E 1048.1−5937 and 1RXS J170849−400910) lack visible SNRs. This might indicate that the lifetime of AXP is much longer than several 10^4 years.

There are also a few unresolved X-ray sources within SNRs that, apart for the lack of pulsations, share the same properties of the AXP (see Table 1). The sources in RCW 103 (Gotthelf, Petre & Hwank 1997), G296.5+10.0 (Mereghetti et al. 1996), and Puppis A (Petre et al. 1996) have high f_x/f_opt, soft spectra (characteristic blackbody temperatures kT ≲ 0.6 keV), and low luminosity, similar to the AXP (see Fig. 2). More sensitive searches for pulsations in these sources (so far hampered by the poor statistics) might reveal in the future new AXP (this does not apply to the source in Puppis A if the possible periodicity at 75 ms reported by Pavlov et al. (1999) is confirmed by better data).
4. Models

Though the absence of a massive companion and the presence of a neutron star are observationally well established, the AXP remain one of the more enigmatic classes of galactic high energy sources. Also the main mechanism responsible for the observed X–ray luminosity is still unclear. Having excluded models powered by the rotational energy loss of isolated neutron stars (see section 3.5), the remaining explanations advanced for the AXP fall into two main classes: models based on accretion (with or without a binary companion of very low mass) and those invoking highly magnetized neutron stars powered by the decay of the magnetic field and/or internal heat dissipation.

Binary models have the advantage of naturally providing accretion as a source of energy. However, the tight limits on the possible companion stars (sections 3.6, 3.7) have also led to interpretations based on accretion unto isolated neutron stars.

4.1. ACCRETION-BASED MODELS

In general, accretion from the interstellar medium (ISM) cannot provide the required luminosity under typical ISM parameters and neutron star velocities. In fact, the accretion luminosity is given by $L_{\text{acc}} \sim 10^{32} v_{50}^{-3} n_{100} \text{ erg s}^{-1}$ 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 (~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.

van Paradijs et al. (1995) proposed a more efficient scenario, in which isolated neutron stars are fed from residual accretion disks, formed after the complete spiral-in of a neutron star in the envelope of a giant companion star (a Thorne-Zytkow object, TZO, Thorne & Zytkow 1977). Thus the AXP could be one possible outcome of the common envelope evolutionary phase of close HMXRB 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 sometimes found associated with SNR. According to van Paradijs et al. (1995), the estimated birthrate of AXP is consistent with that of TZO.

The idea that AXP are isolated neutron star accreting from a residual disk has been further developed by Ghosh et al. (1997), who put this model in the broader context of the evolution of close massive binaries. In this scenario, a HMXRB undergoing common envelope evolution can produce two kinds of objects, depending on the efficiency with which the massive star envelope is lost. Relatively wide systems have enough orbital
energy to led to the complete expulsion of the envelope before the settling of the neutron star at the center. This would result 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, would produce TZO due to the complete spiral in of the neutron star in the common envelope phase. These systems would subsequently evolve into AXP: isolated neutron stars undergoing accretion from two distinct flows: a disk and a spherically symmetric component, resulting from the part of the envelope with less angular momentum. According to Ghosh et al. (1997), this model would also explain the two component spectra observed in most AXP, as well as their secular spin-down: the accretion from the disk is responsible for the power-law and the long term spin-down due to the decreasing mass accretion rate, while the spherically symmetric flow gives rise to the blackbody emission from a large fraction of the neutron star surface.

Though this is certainly an interesting model, several uncertainties exist. In particular very little is known on the evolution during the common envelope phase and on the efficiency of conversion of the orbital binding energy to that of the dynamical outflow of the envelope. According to Li (1999), other problems of this model are the short lifetime of the accretion disk and the fact that in any case it would be unable to reproduce the spin-down behaviour observed in AXP.

Binary models for AXP have not been developed in detail, although we note that they cannot be completely ruled out in the case very low mass companions and/or unfavourable inclination angles (furthermore, sensitive searches for Doppler modulations have only been done for three out of six AXP). In a certain sense, this is the most conservative explanation since it does not involve new kinds of objects with relatively uncertain properties. In the context of binary systems with very low mass companions, Mereghetti & Stella (1995) proposed that the AXP are weakly magnetized neutron stars ($B \sim 10^{11} \text{ G}$) rotating close to the equilibrium period. This requires accretion rates of the order of a few $10^{15} \text{ g s}^{-1}$, consistent with the AXP luminosities.

4.2. MAGNETARS

Models based on strongly magnetized ($B \sim 10^{14}–10^{15} \text{ G}$) neutron stars, or "magnetars", were originally developed to explain the peculiar properties of SGR (Duncan & Thompson 1992; Thompson & Duncan 1995,1996) and received a substantial support with the discovery of pulsations and spin-down in these sources (Kouveliotou et al. 1998, 1999, Hurley et al. 1999). If one assumes that the AXP spin-down is due to magnetic dipole radiation losses, values of $B = 3.2 \times 10^{19} \ (PP)^{1/2} > 10^{14} \text{ G}$ are obtained, suggest-
ing that also the X-ray emission from these objects could be powered by magnetic field decay (see Thompson, these proceedings).

Different authors discussed the kind of spin-down irregularities expected in the magnetar model. Heyl & Hernquist (1999) fitted the period histories of 1E 2259+586 and 1E 1048.1−5937 with glitches similar to those observed in radio pulsars. The same data were interpreted by Melatos (1999) in terms of a periodic (~5-10 yrs) oscillation in $\dot{P}$ caused by radiative precession, an effect due to the star asphericity induced by the very strong magnetic field. Unfortunately, the sparse period measurements available for AXP do not allow for the moment to discriminate among the different possibilities.

5. Conclusions

Though the nature of the AXP is still unknown, after more than 20 years since the discovery of the prototype of this class (1E 2259+586), it is clear that these objects represent an important manifestation of neutron stars. There is growing evidence that a large fraction of neutron stars are born with properties very different from that of the Crab and Vela pulsars. This might explain why only very few energetic, rapidly spinning radio pulsars have a firm association with a SNR.

Due to their relatively low luminosity and soft spectrum (critically affected by the interstellar absorption) AXP are not easy to find. Several of the known X-ray sources, too faint for sensitive pulsations searches, could be AXP and we can expect that, thanks to the coming X-ray satellites, many more will be discovered in the near future. Furthermore, if AX J1845.0−0300 is confirmed as a "transient" AXP, the overall population of this class of objects would be even larger than assumed so far. It might well be that the "Anomalous" pulsars are indeed one of the most "normal" manifestations of young neutron stars.

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