Spectral properties of anomalous X-ray pulsars

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Abstract In this paper, we concern on the spectra of the persistent emission from anomalous X-ray pulsars (AXPs) and their variation with spin-down rate $\dot{\Omega}$. Based on accretion model, the influences of both magnetic fields and mass accretion rate on the spectra properties of AXPs are addressed. We derive the relations between spectral properties of AXPs and accretion rate $\dot{M}$. Our results shows that accretion-based model demonstrates the linear correlation between the photon index and spin-down rate. The spectral hardness increases with increasing $\dot{M}$. A possible emission mechanism for the explanation of the spectral properties of AXPs is discussed as well.

Key words: pulsars: general – stars: neutron – X-rays: stars – accretion, accretion disks

1 INTRODUCTION

Anomalous X-ray pulsars (AXPs) are one of the enigmatic class of Galactic high energy sources. These sources differ from known magnetic accreting X-ray pulsars found in high and low mass X-ray binaries (HMXBs and LMXBs) (Mereghetti & Stella 1995; Van Paradijs et al. 1995). AXPs are sources of pulsed X-ray emission with spin periods in the 6-12s range, very soft X-ray spectra, secular spin down on time scales of $\sim 10^3 – 10^5$, and lack of bright optical counterparts. Two or possible three of AXPs are close associated with supernova remnants (SNRs). Additionally, AXPs share some similarities with the Soft Gamma-ray Repeters (SGRs) (Hurley 2000).

Two broad classes of models have been proposed to understand the X-ray emission from AXPs. The first class of models assumes that the source of AXPs are isolated neutron stars with ultra-magnetic filed strengths in the range $10^{14} – 10^{15}$Gauss - i.e. “magnetars” (Thompson & Duncan 1996; Hely & Hernquist 1997). The spin-down of the pulsars is primarily due to magnetic dipole radiation, then the AXPs have enormous surface magnetic dipolar fields. The
second class of model suggested to explain AXP emission is that they are accreting from a disk of material leftover from the supernova explosion that created the neutron star (Chatterjee et al. 2000, hereafter CHN). Such model doesn’t require neutron stars with unusually strong magnetic field. In this case, the spin-down torque is external and, supposedly, a neutral consequence of accretion braking (Francischell & Wijers 2003). A very different scenario for AXPs (and soft gamma-ray repeaters, hereafter SGRs), based on strange matter stars, has been proposed by Dar & DeRujula (2000). They argued that the AXPs are either strange stars or quark stars in which the X-rays are powered by gravitational contraction and the spin-down is due to the emission of relativistic jets.

AXPs could be magnetars, but valid alternative models cannot be ruled out with a decisive proof (Mereghetti et al. 2002). In the magnetar model, a more stable luminosity, spectrum and $\dot{P}$ noise can be expected than in accretion-powered pulsars. The spectra and light curves expected from the surface of highly magnetized neutron stars have been computed by several authors (Özel 2001; Zane et al. 2001; Ho & Lai 2001). The spin-down of magnetars is due to a combination of standard magnetic dipole radiation torque and torque from the wind (Harding et al. 1999). Both of these torques increase strongly with magnetic field strength, and therefore the hardening of the power-law spectral component with $\dot{\Omega}$ implies a similar hardening of the underlying Alfven wave spectrum with increasing magnetic field $B$. Therefore, the spectral hardness (photon index $\Gamma$) and the spin-down rate ($\dot{\Omega}$) correlation in AXPs predicted by magnetar model, depending on the magnetic field alone, is inconsistent with the data. The observation of AXPs shows that the spectral hardness decreases with increasing spin-down rate (Marsden & White 2001).

Based on the above investigations, alternatively, we relate accreting neutron star depending on both the magnetic field and the accretion rate $\dot{M}$ to model the spectral properties and spin-down rates of AXPs. The purpose of the present paper is twofold. Firstly, based on the observation, the relation between the photon index $\Gamma$ of AXPs/SGRs and the accretion rate $\dot{M}$ is investigated. Secondly, a possible emission mechanism is suggested to model the spectral properties of AXPs/SGRs. Finally, some predictions based on the relations between $\Gamma - \dot{M}$ are discussed.

## 2 PARAMETER AND OBSERVATION DATA FOR AXPS

For AXPs, the spin period ($P$) is important in describing it. Moreover, the AXPs slowly brakes: the time derivative of the period, $\dot{P}$, is another important parameter of the pulsar. On the basis
of these two observation, other useful pulsar parameters can be defined: the “characteristic age”
\[ \tau = \frac{P}{2\dot{P}} \]
and the magnetic field
\[ B = \left( \frac{3Ic^3}{8\pi^2r^6} \right)^{1/2} \left( \frac{P\dot{P}}{P^2} \right)^{1/2}, \]
where \( I \sim 10^{45} \text{g cm}^2 \), and \( r \sim 10^6 \text{cm} \).

The role of period derivatives \( \dot{P} \) is confirmed when observing the AXPs spectral index
variation. In this paper, we follow the data analysis of Marsden & White (2001) for the phase-
averaged spectra of the AXPs and SGRs in the range of 0.5 – 10.0 keV. Table 1 summarizes the
basic data of all the SGRs and AXPs with known spin periods and period derivatives detected
by ASCA. The period derivative of one object AXP 1048-59 cannot be determined definitely,
so we take two values throughout the following analysis. And the photon indexes here are
derived in terms of two-component black-body plus power law spectral models. Figure 1 shows
the variation of the photon index \( \Gamma \) vs. spin-down rate \( \dot{\Omega} \) for such AXPs and SGRs.

In another way, we can fit the relation of the photon index \( \Gamma \) and \( P, \dot{P} \) in terms of the
linear equation \( \Gamma = \alpha \log P + \beta \log \dot{P} + \gamma \), we find that \( \Gamma(P, \dot{P}) \) of 5 AXPs and 2 SGRs is given
as
\[ \Gamma(P, \dot{P}) = 2\log P - \log \dot{P}_{12} + 2.5, \]
where \( \dot{P}_{12} \) denotes \( \dot{P}/10^{-12} \text{ss}^{-1} \). Substituting \( \Omega = 2\pi/P \) and \( \dot{\Omega} = 2\pi\dot{P}/P^2 \) into Eq. 2, the
correlation between \( \Gamma \) and \( \dot{\Omega} \) can be yielded. \( \Gamma \) is a linear function of \( \dot{\Omega} \). The photon index \( \Gamma \)
decreases with increasing spin-down-rate \( \dot{\Omega} \). (see Fig. 1).

At present, this correlation have not be given a well explanation by the magnetar model
(Marsden & White 2001). Furthermore, we study the relation between the photon index of
AXPs/SGRs and magnetic field strength: \( \Gamma - B \), which have been displayed in Figure 2. It
seems to show the relation of the harder spectra with stronger magnetic field in AXPs and
SGRs. The present magnetar model cannot give this result yet, so it may require the further
theoretical considerations. Our following study shows an accretion-based model (CHN) could
give a possible explanation to the observed correlation between the photon index and spin-down
rate in AXPs and SGRs.

3 THE SPECTRAL PROPERTIES OF AXPS AND POSSIBLE MODEL

3.1 The diagram of spectral photon index and the accretion rate (\( \Gamma - \dot{M} \))

In accretion-based models, the neutron star can be observed as an X-ray pulsar during a tracking
phase. AXPs are supposed to rotate at a quasi-equilibrium period. And it is proposed that a
spin-down torque $\dot{J}$ is needed during this period. CHN suggest $\dot{J}$ as the following (Menou et al. 1999).

$$\dot{J} = I \dot{\Omega} = 2 \dot{m} R_m^2 \Omega_K(R_m) \left[ 1 - \frac{\Omega(t)}{\Omega_K(R_m)} \right], \quad (3)$$

where $\Omega_K(R_m)$ is the Keplerian rotation rate at radius $R_m$, and $R_m$ is the magnetospheric radius which is determined to be

$$R_m \approx 6.6 \times 10^7 B_{12}^{1/7} \dot{m}^{-2/7} \text{ cm} \quad (4)$$

In Eq. 4, $\dot{m} = \dot{M}/\dot{M}_{Edd}$, where $\dot{M}_{Edd} \approx 9.46 \times 10^{17} \text{ g s}^{-1}$ is the Eddington accretion rate, $B_{12} = B/10^{12}$ Gauss.

Following the arguments of Cannizzo et al. (1990), CHN suggest that after a dynamical time $T$ the fossil disk loses mass self-similarly,

$$\dot{m} = \begin{cases} \dot{m}_0, & 0 < t < T; \\ \dot{m}_0 \left(\frac{t}{T}\right)^{-\alpha}, & t \geq T; \end{cases} \quad (5)$$

where $T \sim 10^{-3} \text{s}$, is the local dynamical time, and $\dot{m}_0$ is a constant, which is normalized to the total initial disk mass, $M_d = \int_0^8 \dot{M}_d \, dt$, by $\dot{m}_0 = [(\alpha - 1) M_d]/(\alpha \dot{M}_{Edd} T)$. $\alpha > 1$ is a constant that directly depends on the disk opacity (Francischell & Wijers 2003). For a strong propeller ($\Omega(t) \gg \Omega_K(R_m)$), Eq. 3 can be written in the form

$$\dot{J} = I \dot{\Omega} = -2 \dot{m} R_m^2 \Omega(t). \quad (6)$$

Assuming an arbitrary value for $\alpha$, Eq. 5 and 6 can be combined to yield an analytic formula for $\Omega(t)$, in terms of incomplete gamma functions (CHN). For $\alpha = 7/6$, the solution of Eq. 6 is

$$\Omega \approx C_1 B_{12}^{-6/7} \dot{m}^{3/7}, \quad (7)$$

$$\dot{\Omega} \approx C_2 B_{12}^{2/7} \dot{m}^{6/7}, \quad (8)$$

where $C_1$ and $C_2$ are constants, $C_1 = 25.48$, $C_2 = 2.164 \times 10^{-10}$. Combining Equation 7 and 8, instead of using $\Omega = 2\pi/P$ and $\dot{\Omega} = 2\pi \dot{P}/P^2$, we obtain the accretion rate as function of $\dot{P}$ and $P$

$$\log \dot{m}(P, \dot{P}) = -\frac{7}{3} \log P + \log \dot{P} + 10.26. \quad (9)$$

If comparing Eq.s 9 and 2, we can find there exist the inverse relation between the photon index $\Gamma$ and the accretion rate $\dot{m}$. To further check this relation, we firstly calculated $\dot{m}$ in 5 AXPs and 2 SGRs according to Eq. 9, and plotted the diagram of $\Gamma$-$\dot{m}$ in Fig. 3. It shows a
good correlation between $\Gamma$ and $\dot{m}$, the line in the figure is fitted to the data points with the following equation

$$\log \dot{m} = 0.23 - 0.99\Gamma.$$  \hspace{1cm} (10)

### 3.2 Possible mechanism for the emission of AXPs

Figure 3 tells us that larger accretion rate produces the harder spectra (high-energy tail) in the accretion model. The origin of this high-energy tail is unexplained very well at present. However, this high-energy tail could be due to thermal Comptonization by a hot coronal plasma, or it could be due to non-thermal emission (Tavani & Liang 1996). Based on the energetics of particle acceleration and cooling near the Alfvén radius, Böttcher & Liang (2001) simulate the thermal-nonthermal radiation from a weakly magnetized neutron star magnetospheric accretion shell. As a natural consequence, they derived the anti-correlation of the hardness of the hard X-ray emission with the soft X-ray luminosity. Interestingly, in the case of very low accretion rates ($\dot{m} \sim 0.01$) and rather high magnetic turbulence levels, a similar anti-correlation of the hard X-ray spectral hardness with the soft X-ray luminosity exits for high surface magnetic fields. The hard X-ray spectral index resulting from the simulation of Böttcher & Liang (2001) are in excellent agreement with the values of $\Gamma \sim 3 - 4$ generally observed in AXPs. From this context, the fitting of $\Gamma - \dot{m}$ shows that the accretion rate is range from $10^{-2}$ to $10^{-4}$, which is satisfied with the model conditions suggested by Böttcher & Liang (2001). Therefore, we can apply the emission mechanism of Böttcher & Liang (2001) to construct the accretion-powered emission model for AXPs, which can well explain the relation between the accretion rate and spectral properties derived above.

### 4 DISCUSSIONS AND CONCLUSIONS

The correlations between the spectra and the spin-down rates of AXPs/SGRs shows that the photon index decreases with increasing spin-down rate for each AXPs and SGRs (see Fig. 1). This fact has not so far been given a good explanation. If the increasing power-law emission with spin-down rate is consistent with the magnetar model, the spectra of AXPs/SGRs is expected to extend into the far-UV band (Marsden & White (2001). This implies that observation of spectral breaks in the non-thermal persistent emission in the far-UV would be important evidence in support of the magnetar model. With respect to the accretion model (CHN), we calculate the spectral photon index and the accretion rate $\dot{m}$ (see Fig. 3). Our analysis shows that the correct spectral shape for the values of $B$ and $\dot{m}$ can produce the rapid spin-down of AXPs and SGRs.
The relation \( \log m = 0.23 - 0.99 \Gamma \) is derived, which shows the hardness of the spectra increases with increasing accretion rate. This resulting is consistent with the model prediction given by Böttcher & Liang (2001). Consequently, it is possible that high magnetic-field accreting neutron stars with low-mass accretion rate may be consistent with the data of AXPs/SGRs.

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Table 1  SGR AND AXP TIMING PARAMETERS

| Object       | Start date   | \(P(s)\)^a | \(P(10^{-12}\text{ss}^{-1})\)^b | \(\Gamma (BB + PL)^c\) | References^d |
|--------------|--------------|-------------|-------------------------------|-------------------------|-------------|
| SGR 1900+14  | 1998 Apr 30  | 5.158971(7) | 61.0±1.5                      | 2.1                     | 1, 2        |
|              | 1998 Sep 16  | 5.16025(2)  | 61.0±1.5                      | 2.1                     | 2, 3        |
| SGR 1806-20  | 1993 Oct 10  | 7.468514(3) | 115.7±0.2                     | 2.2                     | 4, 5        |
|              | 1995 Oct 16  | 7.46445(3)  | 115.7±0.2                     | 2.2                     | 4, 5        |
| AXP 1048-59  | 1994 Mar 03  | 6.446646(1) | 32.9±0.3                      | 2.5                     | 6, 7        |
|              | 1998 Jul 26  | 6.45082(1)  | 16.7±0.2                      | 2.5                     | 7           |
| AXP 1841-05  | 1993 Oct 11  | 11.76668(6) | 41.3±0.1                      | 3.4                     | 8, 9        |
|              | 1998, Mar 27 | 11.77243(7) | 41.3±0.1                      | 3.4                     | 9           |
| AXP 2259+59  | 1993 May 30  | 6.97884(2)  | 0.4883±0.0003                 | 3.9                     | 10, 11      |
|              | 1995, Aug 11 | 6.9788793(8)| 0.4883±0.0003                 | 3.9                     | 10          |
| AXP 0142+62  | 1994 Sep 18  | 8.68794(7)  | 2.2±0.2                       | 4.0                     | 12          |
|              | 1998 Aug 21  | 8.68828(4)  | 2.2±0.2                       | 4.0                     | 7           |
| AXP 1709-40  | 1996 Sep 03  | 10.99758(6) | 22±6                          | 2.9                     | 13, 14      |

^a Measured period (1 σ error in last digit).
^b Assumed period derivative (from references).
^c BB+PL stands for black-body plus power-law spectral fit
^d References.- (1)Hurely et al. 1999; (2)Woods et al. 1999; (3)Murakami et al. 1999; (4)Sonobe et al. 1994; (5)Woods et al. 2000; (6)Corbet & Mihara 1997; (7)Paul et al. 2000; (8)Gotthelf & Vasisht 1997; (9)Gotthelf, Vasisht, & Dotani 1999; (10)Kaspi, Chakrabarty, & Steinberger 1999; (11)Corbet et al. 1995; (12)White et al. 1996; (13)Sugizaki et al. 1997; (14)Israel et al. 1999
Figure 1  The $\Gamma - \dot{\Omega}$ diagram of AXPs and SGRs. The triangles denote the AXPs and the circles are SGRs, and the symbols are all same in the following figures.
Figure 2  The $\Gamma - B$ diagram of AXPs and SGRs.
Figure 3  The $\Gamma - \dot{M}$ diagram of AXPs and SGRs in the accretion model. The line denotes the best fitting relation of all the data points.