Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 6, 543–550
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

Spectral Properties of Anomalous X-ray Pulsars [*]

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Received 2003 April 17; accepted 2003 September 3

Abstract We examine the spectra of the persistent emission from anomalous X-ray pulsars (AXPs) and their variation with the spin-down rate $\dot{\Omega}$. Based on an accretion-powered model, the influences of both the magnetic field and the mass accretion rate on the spectral properties of AXPs are addressed. We then investigate the relation between the spectral property of AXPs and mass accretion rate $\dot{M}$. The result shows that there exists a linear correlation between the photon index and the mass accretion rate: the spectral hardness increases with increasing $\dot{M}$. A possible emission mechanism for the explanation of the spectral properties of AXPs is also discussed.

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 6–12 s range, very soft X-ray spectra, and secular spin down on time scales of $\sim 10^3 - 10^5$ yr, with a lack of bright optical counterparts. Two or possibly three of AXPs are closely associated with supernova remnants (SNRs). Additionally, AXPs share some similarities with the Soft Gamma-ray Repeaters (SGRs) (Hurley 2000).

Two broad classes of models have been proposed to understand the X-ray emission from AXPs. The first class assumes that the sources of AXPs are isolated neutron stars with ultra-magnetic field strengths in the range of $10^{14} - 10^{15}$ 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 was suggested to explain AXP emissions that they are accreting from a disk of material left over from the supernova explosion that created the neutron star (Chatterjee et al.

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[*] Supported by the National Natural Science Foundation of China.

2000, hereafter CHN; Alpar 2001; Lu & Cheng 2002; and Marsden et al. 2001). Such models do not require neutron stars with unusually strong magnetic fields. In these cases, the spin-down torque is external and, supposedly, a natural consequence of accretion braking (Francischell & Wijers 2003). In addition, a very different scenario, based on strange matter stars, has been proposed by Dar & DeRujula (2000). They argued that AXPs are either strange stars or quark stars in which 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 have not been decisively ruled out (Mereghetti et al. 2002). In the magnetar model, we can expect a more stable luminosity, spectrum and $\dot{P}$ noise 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 the 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 Alfvén wave spectrum with increasing magnetic field $\boldsymbol{B}$. It is known that the observation of AXPs shows that the spectral hardness decreases with increasing spin-down rate (Marsden & White 2001). Therefore, the correlation of the spectral hardness (photon index Γ) and the spin-down rate ($\dot{\Omega}$) predicted by magnetar model is inconsistent with the data. Based on the above investigations, we consider an alternative model which depends on both the magnetic field and the accretion rate $\dot{M}$ for the spectral properties and spin-down rates of AXPs. The purpose of the present paper is twofold. First, based on the observations, the relation between the photon index Γ 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 in terms of the relation between Γ and $\dot{M}$ are discussed.

2 PARAMETERS AND OBSERVATIONAL DATA FOR AXPs

An important parameter in describing an AXP is its spin period (P). It is known that the AXPs brake slowly, so the time derivative of the period, $\dot{P}$, is another key parameter. From these two parameters, two further useful parameters can be defined: the "characteristic age" $\tau = P/2\dot{P}$, and the magnetic field

$$B = \left(\frac{3Ic^3}{8\pi^2 r^6}\right)^{1/2} (P\dot{P})^{1/2} \ , \qquad (1)$$

where $I \sim 10^{45}\,\mathrm{g\,cm^2}$, and $r \sim 10^6\,\mathrm{cm}$.

The role of period derivatives $\dot{P}$ is confirmed when observing the AXPs spectral index variation. Following the data analysis of Marsden & White (2001) for the phase-averaged spectra of the AXPs and SGRs in the range of $0.5 - 10.0\,\mathrm{keV}$, we obtain the basic data of all SGRs and AXPs with known spin periods and period derivatives detected with ASCA which is summarized in Table 1. The period derivative of one object AXP 1048–59 cannot be determined definitely, so we take two values throughout the following analysis. 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 Γ vs. spin-down rate $\dot{\Omega}$ for such AXPs and SGRs.

The relation of the photon index Γ and $P, \dot{P}$ is fitted with a linear equation of the form $\Gamma = \alpha \log P + \beta \log \dot{P} + \gamma$. For five AXPs and two SGRs listed in Table 1, the fitting of $\Gamma(P, \dot{P})$

is

$$\Gamma(P,\dot{P}) = 2\log P - \log \dot{P}_{12} + 2.5 \ , \qquad (2)$$

where $\dot{P}_{12}$ denotes $\dot{P}/10^{-12}\mathrm{ss}^{-1}$. Substituting $\Omega = 2\pi/P$ and $\dot{\Omega} = 2\pi\dot{P}/P^2$ into Eq. (2), the correlation between Γ and $\dot{\Omega}$ can be obtained. Γ is a linear function of $\dot{\Omega}$. The photon index Γ decreases with increasing spin-down-rate $\dot{\Omega}$. (see Fig. 1).

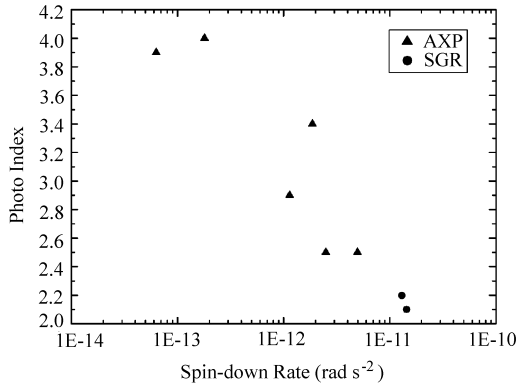

Fig. 1 $\Gamma - \dot{\Omega}$ diagram of AXPs and SGRs. The triangles denote the AXPs and the circles are SGRs, and the symbols are all the same in the following figures.

Table 1 SGR and AXP Timing Parameters

Object	Start date	$P(s)^{a}$	$\dot{P}(10^{-12}\mathrm{ss}^{-1})^{b}$	$\Gamma\,(BB+PL)^{c}$	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, 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		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		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		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		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		7
AXP 1709-40......	1996 Sep 03	10.99758(6)	22 ±6	2.9	13, 14

[a] Measured period (1 σ error in the 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) Cobet et al. 1995; (12) White et al. 1996; (13) Sugizaki et al. 1997; (14) Israel et al. 1999

Furthermore, we studied the relation ($\Gamma - B$) between the photon index and magnetic field strengths for these AXPs/SGRs. We plot the relation in Fig. 2 which shows that the harder the spectrum of AXPs/SGRs, the stronger the magnetic field. It seems that the present magnetar model cannot give this result yet, so it may require further theoretical considerations. The 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.

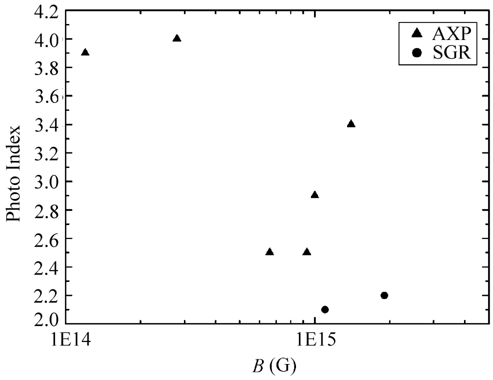

Fig. 2 $\Gamma - B$ diagram of AXPs and SGRs.

3 THE SPECTRAL PROPERTIES OF AXPs AND A POSSIBLE MODEL

3.1 The Diagram of Spectral Photon Index versus the Accretion Rate ($\Gamma - \dot{M}$)

In accretion-based models, a 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 a spin-down torque $\dot{J}$ is needed during this period. CHN suggests $\dot{J}$ changes with time according to the following formula (Menou et al. 1999)

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

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

$$R_m \approx 6.6 \times 10^7 B_{12}^{4/7}\dot{m}^{-2/7} \ \text{cm}. \tag{4}$$

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

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

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

where $T \sim 10^{-3}$ 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 $\dot{m}_0 = [(\alpha - 1)M_d]/(\alpha \dot{M}_{\rm Edd} T)$, $\alpha > 1$ is a constant that depends directly on the disk opacity (Francischell & Wijers 2003). Assuming an arbitrary value for α, Eqs. (5) and (3) 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. (3) is

$$\Omega(t) = \begin{cases} \Omega_k(R_m, 0)\dot{m}_0^{3/7} . & 0 < t < T \\ \Omega_k(R_m, 0)\left(\frac{\dot{m}}{\dot{m}_0}\right)^{3/7} . & t \geq T \end{cases} \tag{6}$$

Since $\Omega_k(R_m, 0) = GM_{ns}/R_m^3$, then for $t \geq T$

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

where C_1 is a constant and $C_1 = 25.48$. If $\Omega(t)$ evolves according to Eq. (7), then the spin period of the star nearly equals the evolving equilibrium period; this is the tracking phase (CHN). It is worth noting that the spin period of SGRs and AXPs implied by Eq. (7) depends on both the magnetic field and mass accretion accretion rate.

A strong propeller torque is needed to determine the spin evolution of the neutron star + fossil disk system (CHN). However, the way in which a propelling neutron star loses angular momentum is not well understood (Francischell & Wijers 2003). In the most general form, the exact mode in which angular momentum transfers between an accretion disk and a neutron star is a complex magneto-hydrodynamical process, so there is a no simple analytic solution for the variation of $\dot{\Omega}$ with $\dot{m}$ and B. It is thought that most of the captured matter is ejected before reaching the neutron stars surface, i.e., in the strong propeller phase. However, after a sharp propeller cycle, the system reaches a tracking phase which is argued as to be an "AXP-producing" phase (CHN). Clearly, employing different propeller torques (Francischell & Wijers 2003; Fabian 1975; and CHN) will produce different results in the determination of a general evolution of the system. The way that the propeller torques affect the time variation of the period was illustrated by Francischell & Wijers (2003). Based on the above discussion, it is safe to assume that some kinds of propeller torque do act on the neutron star between the strong propeller phase and tracking phase in order to spin it down with time. So, for simplicity, in this paper, we assume that the propeller torque is given by,

$$\dot{J} = I\dot{\Omega} = -2\xi \dot{m} R_m^2 \Omega(t) \;, \tag{8}$$

where ξ is a constant, which is in the range $0 < \xi \leq 1$, $\xi = 1$ is for the strong propeller limit (Francischell & Wijers 2003), and $\xi \sim 0$ is for the quasi-equilibrium phase, i.e., tracking phase. Then, from Eq. (8), we obtain

$$\dot{\Omega} \;\approx\; C_2 B_{12}^{2/7} \dot{m}^{6/7} \;, \tag{9}$$

where $C_2 = 2.164 \times 10^{-10}\xi$ is a constant.

Combining Eqs. (7) and (9), and taking into account of $\Omega = 2\pi/P$ and $\dot{\Omega} = 2\pi\dot{P}/P^2$, we obtain the mass accretion rate as function of $\dot{P}$ and P,

$$\log \dot{m}(P, \dot{P}) = -\frac{7}{3}\log P + \log \dot{P} + [10.26 - \log \xi] \;. \tag{10}$$

Comparing Eqs. (10) with (2), an inverse relation between the photon index Γ and the mass accretion rate $\dot{m}$ is inferred. Fitting the mass accretion rates $\dot{m}$ of five AXPs and two SGRs estimated according to Eq. (10) for the values $\xi = 1$, 0.5, and 0.05, we obtain

$$\log \dot{m} = A - 0.99\Gamma \ , \tag{11}$$

with $A = 0.23, 0.53$ and 1.53 for $\xi = 1, 0.5$ and 0.05, respectively. Equation (11) shows a good correlation between Γ and $\dot{m}$. The Γ-$\dot{m}$ diagram for $\xi = 0.5$ is plotted in Fig. 3.

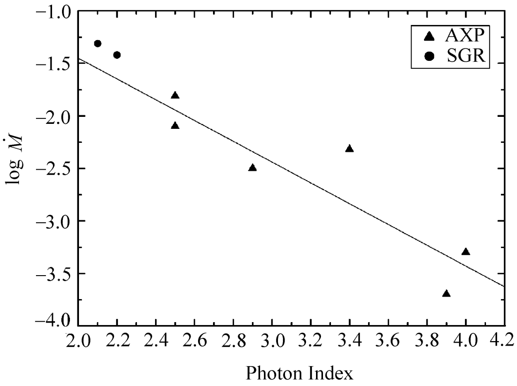

Fig. 3 $\Gamma - \dot{M}$ diagram of AXPs and SGRs in the accretion model. The line represents the best fitting relation for all the data points.

3.2 A Possible Mechanism for the Emission of AXPs

Figure 3 implies that a larger accretion rate produces harder spectra (high-energy tail) in the accretion-based model. The origin of this high-energy tail has not been well explained at present. However, Tavani & Liang (1996) have argued that this high-energy tail could be due to thermal Comptonization by a hot coronal plasma, or it could be due to non-thermal emission. Based on the energetics of particle acceleration and cooling near the Alfvén radius, Böttcher & Liang (2001) simulated the thermal-nonthermal radiation from a neutron star with both a weakly magnetized ($\sim 10^9$G) magnetospheric accretion shell and a normal one ($\sim 10^{12}$G). The basic conclusion of Böttcher & Liang (2001) is that there is a positive correlation between the spectral index and the accretion rate, i.e., a negative correlation between the spectral hardness and the accretion rate. It should be noted that this conclusion was reached in the situation of a neutron star with a weak magnetic field, i.e., $\sim 10^9$ G. The results for the normal magnetic case ($\sim 10^{12}$G) were shown in figs. 3 and 5 in Böttcher & Liang (2001). These two figures show that harder photon spectra are produced for higher accretion rates, particularly around energy 10 keV (2–10 keV, ASCA energy bands) with which we are concerned in this paper. As a natural consequence, in the case of a neutron star with a normal magnetic field, the photon index decreases with increasing accretion rates. In other words, there is a negative correlation between the spectral index and the accretion rate as was observed in AXPs/SGRs. Furthermore, the hard X-ray spectral index resulting from the simulation of Böttcher & Liang (2001) is in good agreement with the values of $\Gamma \sim 3 - 4$ generally observed in AXPs. The fitting of $\Gamma - \dot{m}$

shows that the accretion rate is in the range from 10^{-2} to 10^{-4}, which is consistent with the model conditions suggested by Böttcher & Liang (2001). Therefore, we can apply the emission mechanism of Böttcher & Liang (2001) for the normal magnetic case to construct an accretion-powered emission model for AXPs, which can explain the relation between the accretion rate and spectral properties.

4 DISCUSSION AND CONCLUSIONS

For the AXPs/SGRs, the spectral index decreases with increasing spin-down rate. So far this fact has not 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 are expected to extend into the far-UV band (Marsden & White 2001). This implies that observations 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), the spectral photon index and the accretion rate $\dot{m}$ is investigated. To simplify the calculation, we introduce an alternative propeller torque to limit the spin-down rate at the boundary when the system goes from the propeller phase to a "tracking" phase. The analysis demonstrates that the correct spectral shape for the values of B and $\dot{m}$ can produce a rapid spin-down in AXPs and SGRs. A relation of $\log \dot{m} = 0.53 - 0.99\Gamma$ is derived for the case of $\xi = 0.5$. The relation plotted in Figure 3 shows that the hardness of the spectra increases with increasing mass accretion rate. The same conclusion holds for different values of ξ, only the slope of fitting line is changed because ξ modifies the values of $\dot{m}$. In principle, the result shown in this paper is consistent with the model prediction given by Böttcher & Liang (2001) in the normal magnetic situation. Consequently, it is possible that even stronger magnetic-field accreting neutron stars with low-mass accretion rate may be consistent with the data of AXPs/SGRs.

Unlike the case for normal accretion onto neutron stars , the observed relationship between the absolute X-ray luminosity and the photon index Γ in AXPs/SGRs cannot be inferred from the relation of $\dot{m} - \Gamma$. This is because the X-ray luminosity of the system is determined by the mass accretion rate onto the surface of the star, which could be different from the mass accretion rate through the disk (CHN). Two reasons may be involved for this. First, in the propeller phase it is not clear how much material eventually reaches the neutron star surface, and what the radiation efficiency is of the matter stopped at the neutron star surface. Secondly, the X-ray luminosity may not account for the total luminosity.

Acknowledgements We are particularly grateful to the anonymous referee for insightful comments and suggestions. We would like to thank Ling J.R. and Zhang W.M. from Tsinghua University for useful discussions. This work was supported by the National Natural Science Foundation of China under grant no.10273011, the National 973 Project (NKBRSF G19990754), and the Special Funds for Major State Basic Research Projects.

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