The Astrophysical Journal, 537:319–326, 2000 July 1

STUDY OF THE LONG-TERM STABILITY OF TWO ANOMALOUS X-RAY PULSARS, 4U 0142+61 AND 1E 1048.1−5937, WITH *ASCA*

B. Paul,[1] M. Kawasaki, T. Dotani, and F. Nagase
Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan; bpaul@astro.isas.ac.jp, kawasaki@astro.isas.ac.jp, dotani@astro.isas.ac.jp, nagase@astro.isas.ac.jp
Received 1999 November 26; accepted 2000 February 7

ABSTRACT

We present new observations of two anomalous X-ray pulsars (AXPs), 4U 0142+61 and 1E 1048.1−5937, made in 1998 with *ASCA*. The energy spectrum of each of these two AXPs is found to consist of two components, a power-law and a blackbody emission from the neutron star surface. These observations, when compared with earlier *ASCA* observations in 1994, show remarkable stability in the intensities, spectral shapes, and pulse profiles. However, we find that the spin-down rate in 1E 1048.1−5937 is not constant. In this source, we have clearly identified three epochs with spin-down rates different from each other and from the average value. This has very strong implications for the magnetar hypothesis for AXPs. We also note that the spin-down rate and its variations in 1E 1048.1−5937 are much larger than can normally be produced by an accretion disk with a very low mass accretion rate corresponding to its low X-ray luminosity.

Subject headings: pulsars: individual (4U 0142+61, 1E 1048.1−5937) — stars: neutron — X-rays: stars

1. INTRODUCTION

Some X-ray pulsars are known to have remarkable similarity in their properties, which are different from those of other binary or isolated X-ray pulsars (Mereghetti & Stella 1995). The properties common to most of these objects are (1) pulse period in a small range of 5–12 s, (2) monotonous spin-down with $P/\dot{P}$ in the range 5×10^{11}–1.3×10^{13} s, (3) identical X-ray spectrum consisting of steep power-law ($\Gamma = 3$–4) and blackbody components ($kT \sim 0.5$ keV), (4) stable X-ray luminosity (10^{34}–10^{36} ergs s^{-1}) for years, (5) faint or unidentified optical counterpart, and (6) no evidence of orbital motion. The sources also have a Galactic distribution; most of these are within $|b| \leq 0\overset{\circ}{.}5$, and all are probably young ($\sim 10^4$ yr) because of their association with supernova remnants (SNRs) or molecular clouds. The objects in which all the properties mentioned above have been observed are 4U 0142+61, 1E 2259+586, 1E 1048.1−5937, 1RXS J170849.0−400910, and 1E 1841−045 (Kes 73). Two more objects, AX J1845.0−0300 (Torii et al. 1998) and RX J0720.4−3125 (Haberl et al. 1996), also probably belong to the same class, but to establish their anomalous X-ray pulsar (AXP) candidacy, more X-ray observations are required to measure their pulse period variations, search for possible pulse arrival time delay, and investigate the flux stability. Classification of an object as an AXP because it has only some properties similar to the above is not very firm. 4U 1626−67, probably a binary system, shows both spin-up and spin-down (Chakrabarty et al. 1997) and also has an optically bright accretion disk (Middleditch et al. 1981). Another object, RX J1838.4−0301 (Schwentker 1994), does not have stable intensity, and pulsations are also not always detectable in it (Song et al. 1999). Therefore, these two objects are not AXPs.

Considering the strong similarity among this handful of sources, it has been proposed that they have the same physical nature, and different scenarios have been proposed to explain the observed properties. The prominent models are (1) accretion from a low-mass binary companion (Mereghetti & Stella 1995), (2) a single neutron star accreting from a molecular cloud or a product of common-envelope evolution (Thorne-Żytkow object) of close high-mass X-ray binaries in which a solitary neutron star accretes matter from a fossil disk (van Paradijs, Taam, & van den Heuvel 1995; Ghosh, Angelini, & White 1997), and (3) an extremely high magnetic field neutron star radiating X-rays because of magnetic field decay (Thompson & Duncan 1996). Unlike in radio pulsars and rotationally powered X-ray pulsars, in AXPs the spin-down rate is not large enough to power the observed X-ray emission.

Among the 90 or so known X-ray pulsars (Nagase 1999), direct evidence of binary nature is known for more than 35 sources (van Paradijs 1995). Including the indirect evidence, this number can be up to about 65, and seven pulsars are isolated stars in SNRs and are powered by rotational energy losses. In the rest of the pulsars, in which no binary signature is known, this is often a result of a lack of sufficient observation. However, in the seven objects that are either AXPs or candidate AXPs (or 10 if we include the three soft gamma-ray repeaters in which pulsations have been detected), no binary signature has been found in spite of extensive searches. The strong upper limit on pulse arrival time delay that has been obtained in some of these sources strongly suggests nonbinary nature for the AXPs. In addition, the spin change behavior of the AXPs is also remarkably different from that of accreting pulsars (Bildsten et al. 1997). In almost all the accreting X-ray pulsars, both spin-up and spin-down episodes have been seen; these may be randomly distributed (in persistent sources) or spin-downs in quiescence followed by rapid spin-ups during bright transient phases (in transient pulsars) or long monotonic spin-up and spin-down episodes accompanied by spectral and luminosity changes (e.g., 4U 1626−67; Yi & Vishniac 1999).

AXPs are in many respects also similar to the X-ray counterparts of the soft gamma-ray repeaters (SGRs). The

[1] On leave from the Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai, 400005, India.

X-ray spectral and timing properties of these two types of objects have strong similarities; one-half the AXPs and SGRs are associated with supernova remnants. This has led to the suggestion that AXPs are also magnetars in which the X-ray emission is due to magnetic field decay (Thompson & Duncan 1996). The main difference between these two types of objects is the nondetection of SGR bursts from the AXPs. However, considering the rarity of the SGR activity among the established SGRs (Kouveliotou et al. 1996), the absence of bursts from AXPs is not a serious issue. From a relatively young age of the AXP 1E 1841−045 in the supernova remnant Kes 73, Gotthelf, Vasisht, & Dotani (1999) proposed that, in the evolutionary track, AXPs are an early quiescent state of SGRs. Stability of the X-ray emission properties (spin-down rate, luminosity, spectral shape, and pulse shape and fraction) is usually mentioned as one important aspect of AXPs, though one has to compare observations made with different instruments for which the energy band, energy resolution, and sensitivity are not identical. To make a rigorous comparison of the stability of the X-ray emission properties we have made new observations of two AXPs with *ASCA*, 4 yr after two previous observations reported by White et al. (1996) and Corbet & Mihara (1997). The aim was to examine critically the stability of the X-ray emission pattern and obtain more pulse period measurements, which may provide support to either the accretion-powered or the magnetar hypothesis for these objects.

The source 4U 0142+61 is close to a long-period binary pulsar, RX J0146.9+6121, and, in the *EXOSAT* observations of this field in which pulsations were first discovered, pulsations from both the sources were observed simultaneously (Israel, Mereghetti, & Stella 1994). With *EXOSAT*, the 8.7 s pulsations in this source were detected only in the 1.0–4.0 keV range. A binary nature of the system was preferred despite the large X-ray to optical flux ratio and the absence of a pulse arrival time delay. The source was subsequently observed with *ROSAT*, and the pulse period was found to be very close to the *EXOSAT* measurement (Hellier 1994). *ASCA* observation in 1994 confirmed the steady spin-down trend and defined the spectral character clearly. A model consisting of a 0.4 keV blackbody and a power law with a photon index of 3.7 was found to describe the spectrum well. From a small radius of a few kilometers of the blackbody emission zone (which probably is on the surface of the neutron star), White et al. (1996) suggested that the blackbody component is more likely to be due to a spherical accretion rather than accretion from a disk. A small pulse fraction and energy-dependent pulse profile, double peaked at low energy and single peaked at high energy, is characteristic of this pulsar. From *RXTE* observations, the upper limit on the pulse arrival time delay was determined to be 260 ms in the 70 s to 2.5 days range thereby ruling out all types of binary companions except white dwarfs or low-mass He main-sequence stars (Wilson et al. 1999). *BeppoSAX* observations during 1997–1998 confirmed the spectral characteristics, pulse profiles, and spin-down trend (Israel et al. 1999b). Observations spanning 20 yr during 1979–1998, with *Einstein*, *EXOSAT*, *ROSAT*, *ASCA*, *BeppoSAX*, and *RXTE*, show an overall constant spin-down trend with $\dot{P} = 2.2 \times 10^{-12}$ s s^{-1}.

Pulsations in the source 1E 1048.1−5937 were discovered from observations with the *Einstein* observatory in 1979 and were confirmed by *EXOSAT* observation in 1985 (Seward, Charles, & Smale 1986). The energy spectrum was found to be a power-law type ($\Gamma = 2.26$) with low-energy absorption ($N_H = 1.6 \times 10^{22}$ atoms cm^{-2}). The relatively harder power-law spectrum and a candidate optical counterpart led to the speculation that this could be a Be star binary. Several *Ginga* observations established a secular spin-down trend with $\dot{P} = 1.5 \times 10^{-11}$ s s^{-1}, similar to a few other soft-spectrum pulsars (Corbet & Day 1990). Subsequent *ROSAT* observations, however, revealed an increase in the spin-down rate, which is remarkably different from other established AXPs (Mereghetti 1995). The low-energy part of the spectrum was first accurately measured with *ASCA* in 1994 (Corbet & Mihara 1997). However, it could not distinguish between power-law ($\Gamma = 3.34$) emission and a combination of power-law ($\Gamma = 2.0$) and blackbody ($kT = 0.55$ keV) emission. During the *ROSAT* and *ASCA* observations, the spin-down rate remained at the higher level of 3.3×10^{-11} s s^{-1}. A decrease in intensity by a factor of 3 compared to the *EXOSAT* observation was also noticed. *BeppoSAX* observation in 1997 showed that a combined blackbody and power-law model fits the data well. The size of the blackbody emission zone was found to be of the order of square kilometers, identical to other AXPs (Oosterbroek et al. 1998). Compared to other AXPs, the pulse fraction was found to be much larger (~65%) in 1E 1048.1−5937 and has little energy dependence. The power-law component is also relatively harder ($\Gamma = \sim 2$–2.5) compared with the other AXPs ($\Gamma = \sim 3$–4). *RXTE* observations in 1996–1997 showed yet another change in the spin-down rate, now close to that in the 1980s. Long *RXTE* observations established a small upper limit of 60 ms for any pulse arrival time delay for orbital periods in the range 200 s to 1.5 days. Based on this, any binary companion other than a low-mass helium-burning star in a face-on system has been ruled out (Mereghetti, Israel, & Stella 1998).

2. OBSERVATIONS AND DATA ANALYSIS

Both sources were observed twice with *ASCA*, in 1994 and in 1998, with about 4 yr time difference between the two observations. *ASCA* has two Solid-State Imaging Spectrometers (SISs) and Gas Imaging Spectrometers (GISs), each at the focal plane of four identical mirrors of typical photon-collecting area 250 cm^2 at 6 keV. The energy resolutions are 120 and 600 eV (FWHM) at 6 keV for the SIS and GIS detectors, respectively. For more details about *ASCA* please refer to Tanaka, Inoue, & Holt (1994). Details of the 1994 observations are given in Corbet & Mihara (1997) and White et al. (1996). In 1998, the GIS observations were made in normal PH mode, in which the time resolutions are 64 and 500 ms at high and medium bit rates, respectively. The SIS observations were made with one of the CCD chips and have a time resolution of 4 s. The standard data selection criteria of the *ASCA* guest observer facility, which comprise a cutoff rigidity of charged particles 6 GeV/c, maximum rms deviation from nominal pointing of 0°.01, minimum angle from Earth's limb 10°, satellite outside the South Atlantic Anomaly region, etc., were applied. Data were removed from the hot and flickering pixels of the SIS detectors, and also the charged particle events were removed from the GIS detectors based on rise-time discrimination. For the two observations of 4U 0142+61, the source photons were extracted from circular regions of radius 6′ and 4′ around the source for GIS and SIS, respectively. In the case of 1E 1048.1−5937, the source photons were extracted from relatively smaller regions of 5′ and 3′, respectively. For SIS, the background spectra were accumulated from the whole chip excluding a circular region around the source, and, for GIS, they were collected from regions diametrically opposite to the source location in the field of view.

2.1. *Period Analysis*

To calculate the pulse periods accurately, barycentric correction was applied to the arrival time of each photon and light curves were extracted from the pair of GIS detectors with a time resolution of 0.5 s in the energy band of 0.5–10.0 keV. An epoch-folding method was applied to obtain the approximate pulse periods, and templates for the pulse profiles were created by folding the light curves at the approximate pulse periods. Subsequently, the light curves were divided into eight segments of equal length, and pulse profiles were created from each of these segments by applying the same epoch and pulsation period. The relative phases of the pulses were then evaluated by cross-correlating the pulse profiles with the respective templates. A linear fit to the relative phases with their pulse numbers gave the correction necessary to obtain the accurate pulse period. The 1998 observations of the two AXPs resulted in new measurement of pulse periods at these epochs, and from the 1994 observations we obtained pulse periods similar to those reported earlier, with reduced uncertainty for 4U 0142+61. The pulse periods obtained for the two sources are given in Table 1. The pulse profiles of the two sources in three energy bands are shown in Figures 1 and 2. The pulse fraction, defined as the ratio of the pulsed to total flux, was calculated from background-subtracted pulse profiles in the 0.5–10.0 keV band. Pulse fractions were found to be identical in both the observations, ∼9% and ∼75% in 4U 0142+61 and 1E 1048.1−5937, respectively. In 4U 0142+61, the pulse profile shows energy dependence, from double peaked in low (0.5–1.5 keV) and medium (1.5–4.0 keV) energy to single peaked in high (4.0–8.0 keV) energy, associated with increase in the pulse fraction. In 1E 1048.1−5937, on the other hand, the pulse profile and pulse fraction are almost identical over the *ASCA* energy range. Light curves of the two sources did not show any intensity variations at minutes to days timescale.

2.2. *Spectral Analysis*

In 4U 0142+61, a simple absorbed power-law fit shows large residuals at low energy, and the addition of a blackbody component results in acceptable fit. For the 1998 observation, inclusion of the blackbody component improved the reduced χ^2 from 2.88 to 0.94 and from 1.23 to 0.76 for the GIS and SIS, respectively. Similar improvement in fitting was reported by White et al. (1996) for the 1994 observation. The photon indexes of the power-law component obtained from the SIS data for the two observations are identical, $\Gamma = 3.3$. The photon index from the GIS data is slightly different from the SIS value, $\Gamma = 3.9$, but it is

TABLE 1

PULSE PERIODS FROM THE *ASCA* OBSERVATIONS

Source Name	Date of Observation (MJD)	Pulse Period (s)
4U 0142+61	49614.1	8.687873 ± 0.000034
4U 0142+61	51046.7	8.688267 ± 0.000024
1E 1048.1−5937......	49416.5	6.446645 ± 0.000001
1E 1048.1−5937......	51021.1	6.450815 ± 0.000002

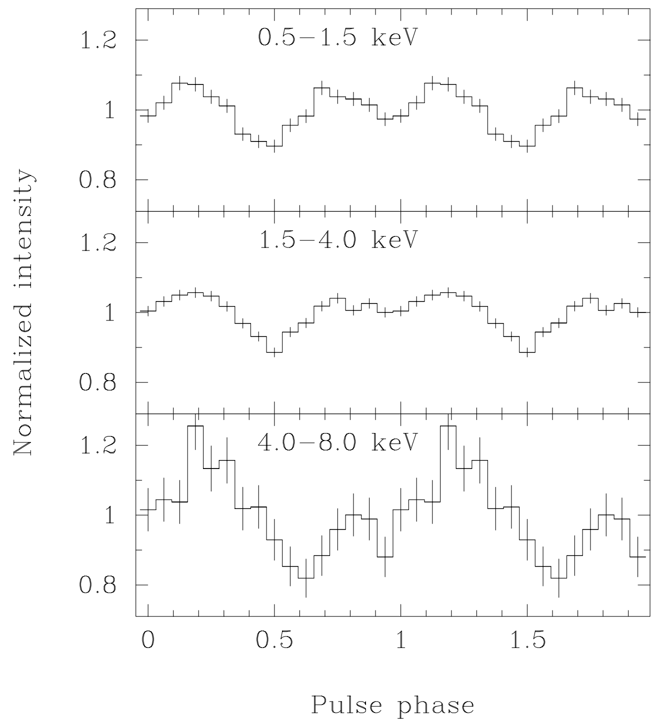

FIG. 1.—Background-subtracted pulse profiles of 4U 0142+61 obtained with the GIS in three energy bands are plotted for two cycles. A change in the pulse profile, from double peaked at low energies to single peaked at high energies, can be noticed.

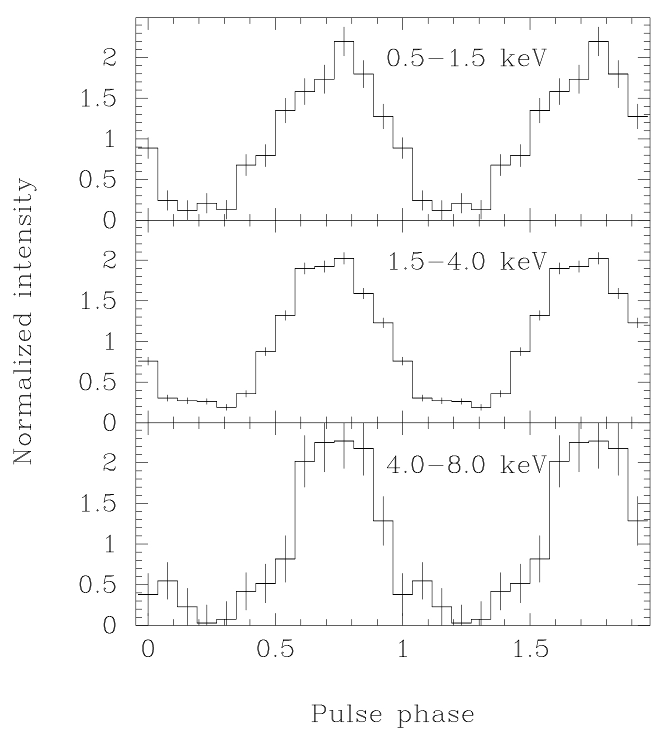

FIG. 2.—Same as Fig. 1 but for 1E 1048.1−5937. The pulse fraction of this source is ∼75%, highest among the AXPs.

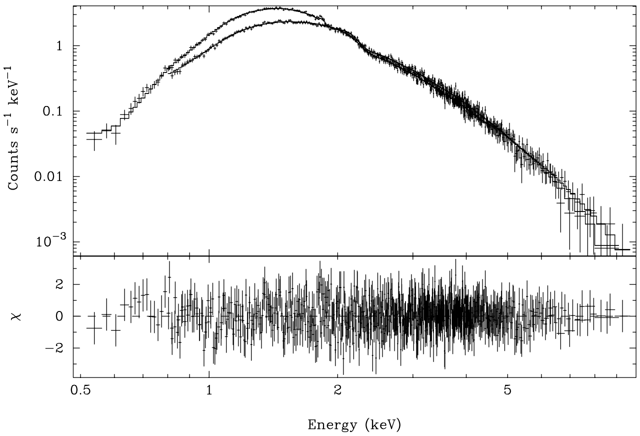

FIG. 3.—Observed SIS and GIS energy spectra of 4U 0142+61 shown with histograms for the model spectra folded through the responses matrices and the residuals.

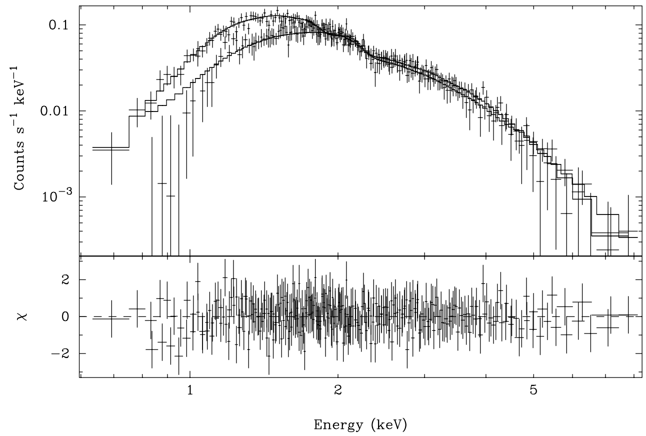

FIG. 4.—SIS and GIS energy spectra of 1E 1048.1−5937 along with the residuals. The histograms represent the best-fit model folded with the response matrices. A simultaneous fitting of the SIS and GIS spectra was performed.

identical for the two observations. The temperatures of the blackbody component obtained from both SIS and GIS are identical, 0.39 keV, in both the observations, and the fluxes in the two components are also identical. The difference in the photon index between the SIS and GIS can possibly be attributed to calibration uncertainty because the in-flight spectral calibration of the spectrometers is done with sources that have relatively harder spectra. The SIS and GIS spectra of the 1998 observation are shown in Figure 3 along with the best-fit models for the respective detectors and the residuals to the model spectra.

For the other source, 1E 1048.1−5937, Corbet & Mihara (1997) showed that the power-law and blackbody with power-law models could not be distinguished from spectral analysis of the *ASCA* data. We have found different and deeper minima in the χ^2 for the blackbody with power-law model. The improvement in χ^2 ($\Delta\chi^2$ of 41 for 292 degrees of freedom [dof] and 28 for 261 dof for the 1998 and 1994 observations, respectively, both indicating a probability of chance occurrence less than 10^{-3}), therefore, favors the inclusion of a blackbody component. The blackbody component has also been detected with *BeppoSAX* (Oosterbroek et al. 1998). The best-fit power-law plus blackbody model gives a photon index of ~ 3.0, blackbody temperature of ~ 0.56 keV, and column density of $\sim 1 \times 10^{22}$ atoms cm^{-1}. The spectral parameters are identical in both the *ASCA* observations and are given in Table 2. Because of the relative weakness of this source, simultaneous spectral fitting was carried out with the GIS and SIS data for the 1998 observation (Fig. 4). However, for the 1994 observation, the SISs were operated in FAST mode and spectra were available only from the two GIS detectors.

TABLE 2

SPECTRAL PARAMETERS

Parameter	GIS	SIS	SIS+GIS	GIS	SIS	SIS+GIS
			4U 0142+61			
		1998 Sep 18–19			1998 Aug 21	
N_H[a]	1.03 ± 0.08	0.92 ± 0.05	1.10 ± 0.04	1.08 ± 0.09	0.97 ± 0.08	1.17 ± 0.04
Photon index	3.9 ± 0.1	3.3 ± 0.1	3.84 ± 0.08	3.98 ± 0.15	3.3 ± 0.2	3.87 ± 0.09
Power-law normalization[b]	0.26 ± 0.05	0.12 ± 0.03	0.25 ± 0.03	0.30 ± 0.06	0.10 ± 0.03	0.24 ± 0.03
Blackbody temperature (keV)	0.39 ± 0.01	0.380 ± 0.006	0.382 ± 0.007	0.399 ± 0.014	0.384 ± 0.005	0.378 ± 0.009
Blackbody normalization[c]	1.4 ± 0.2	1.9 ± 0.1	1.5 ± 0.1	1.16 ± 0.18	1.97 ± 0.15	1.30 ± 0.12
Reduced χ^2 / dof	0.95 / 691	1.11 / 356	1.35 / 1030	0.76 / 354	0.94 / 287	1.76 / 645
Observed flux[d]	...	13.0	...	...	13.4	...
			1E 1048.1−5937			
		1994 Mar 2–5			1998 Jul 26–27	
N_H[a]	1.0 ± 0.2	...	...	...	...	1.21 ± 0.24
Photon index	2.9 ± 0.3	...	...	...	...	3.2 ± 0.5
Power-law normalization[b]	5 ± 310^{-3}	...	...	...	...	7 ± 410^{-3}
Blackbody temperature (keV)	0.57 ± 0.04	...	...	...	...	0.56 ± 0.06
Blackbody normalization[c]	0.05 ± 0.02	...	...	...	...	0.060 ± 0.015
Reduced χ^2 / dof	0.98 / 261	...	...	...	...	0.62 / 292
Unabsorbed flux[d]	0.58	...	...	...	...	0.60

[a] 10^{22} atoms cm^{-2}.
[b] photons cm^{-2} s^{-1} keV^{-1} at 1 keV.
[c] 10^{-3} photons cm^{-2} s^{-1}.
[d] 10^{-11} ergs cm^{-2} s^{-1}, 2–10 keV.

3. DISCUSSION

3.1. *Period Changes and Emission Stability*

The pulse period measurements of 4U 0142+61 are rather scarce except for the last 2 yr (Fig. 5). In spite of the source being very bright, with a flux of more than 10^{-10} ergs cm^{-2} in the 2.0–10.0 keV band, a pulse fraction of only about 10% has restricted the accuracy of the individual pulse period measurements to only about $\Delta P/P \sim 10^{-5}$. A linear fit to the pulse period history shows that, of the 10 measurements available, only during the 1994 *ASCA* observation was the pulse period measurement slightly different (2.5 σ) from the linear trend. If the reported errors of all the measurements are taken at their face values, the linear fit gives a reduced χ^2 of 1.7 for 8 dof. It therefore can be concluded that the recent *ASCA* measurement together with the previous results is consistent with a constant spin-down rate. The observations are not yet sufficient to clearly identify any significant variation from a constant spin-down rate.

In the source 1E 1048.1−5937, departure from a linear spin-down is already known (Mereghetti 1995; Oosterbroek et al. 1998). In this source, an order of magnitude larger spin-down rate and better pulse period measurements ($\Delta P/P \sim 10^{-6}$), owing to a high pulse fraction (∼75%), help us to identify three different epochs of spin-down history. Though the method adopted for calculating the errors in the pulse period is not known for all the observations and the uncertainty level is likely to be nonuniform, a constant spin-down trend can be ruled out without any doubt. A linear fit to the pulse period history with the reported errors gives a reduced χ^2 of 4500 for 11 dof. Including the 1998 *ASCA* observation (see Fig. 6) with the recent *BeppoSAX* and *RXTE* observations, we find that since 1996 the source has had a spin-down rate of $(1.67 \pm 0.02) \times 10^{-11}$ s s^{-1}. This is a factor of 2 smaller than the spin-down rate of $(3.29 \pm 0.03) \times 10^{-11}$ s s^{-1} during the 1994–1996 period. The present spin-down rate is closer to the value of $(1.5 \pm 0.5) \times 10^{-11}$ s s^{-1}, measured during the *Einstein*, *EXOSAT*, and *Ginga* observations made in the period 1979–1988. The spin-down rate is much closer to being constant during these three epochs, with reduced χ^2 of 0.8, 7.7, and 36 for 3, 3, and 1 dof, respectively.

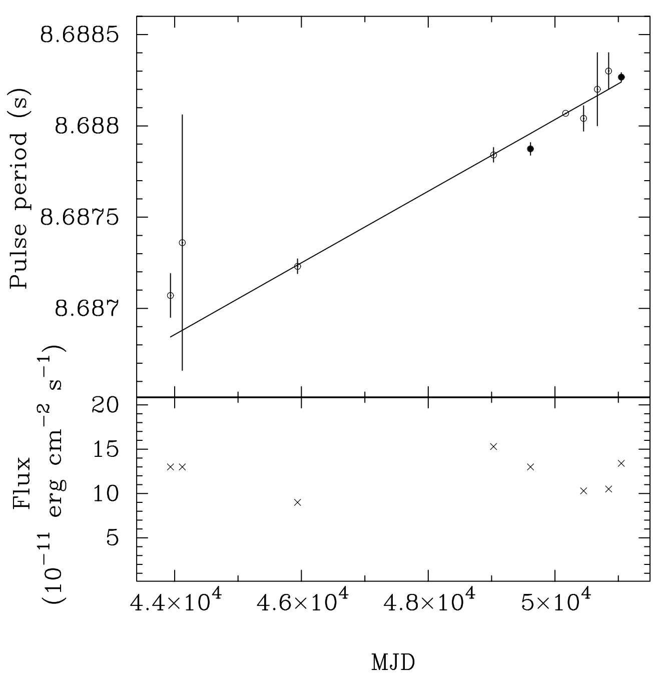

FIG. 5.—Pulse period and flux history of 4U 0142+61. The straight line shows the best fit for a constant spin-down. The pulse period measurements with *ASCA* are marked with filled circles, and the open circles are for all the other observations mentioned in the text.

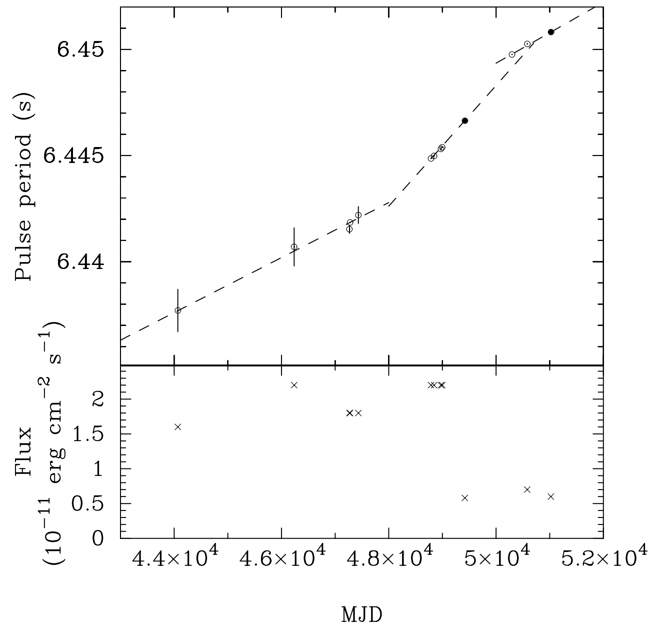

FIG. 6.—Pulse period and flux history of 1E 1048.1−5937. The lines are used to identify the different spin-down epochs. The pulse period measurements with *ASCA* are marked with filled circles, and other observations with open circles.

These two sources do not show flux variability on timescales from a few minutes to days. In the *ASCA* observations of both the sources separated by 4 yr we have found that the overall intensity and spectral parameters have remarkable stability. A difference between the GIS and SIS photon indexes that has been found in 4U 0142+61 is due to calibration uncertainties. The spectral parameters obtained from the 1998 GIS and SIS observations are identical to the 1994 values. The spectral parameters obtained from the simultaneous fitting of the GIS and SIS spectra are similar to the *BeppoSAX* values obtained during 1997–1998. In 4U 0142+61, the flux history shows an rms variation of 15% around the average value (Fig. 5), and multiple measurements with the same instruments (*ASCA* and *BeppoSAX*) gave almost identical flux. In 1E 1048.1−5937, the overall intensity during the two *ASCA* observations and one *BeppoSAX* observation in between is within 10% of the average value. The 2.0–10.0 keV fluxes during the *Einstein* and *ROSAT* observations are estimated by extrapolating the measurements in the low-energy bands of 0.2–4.0 keV and 0.5–2.5 keV, respectively, and using the rather low photon index of 2.26, obtained by *EXOSAT*. The flux during the *Ginga* observation is estimated by comparing the pulsed fluxes during the *Ginga* and *EXOSAT* observations and assuming that the pulse fraction remained same. The flux measurements from the previous observations as shown in the bottom panel of Figure 6 are about a factor of 3 higher than the recent measurements with *ASCA* and *BeppoSAX*. We note that there is some overestimation in extrapolation of the soft X-ray measurements with *Einstein* and *ROSAT* because a smaller photon index was used, and the flux estimates from *EXOSAT* and *Ginga* could be overestimated because of contribution from the nearby bright and variable source η Carina, which is only 0°.4 away and is about 15 times brighter than 1E 1048.1−5937 (Corcoran et al. 1998; Ishibashi et al. 1999). In view of the stability of the flux during 1994–1998, as obtained from the imaging instruments *ASCA* and *BeppoSAX*, it is possible that the overall intensity of this source does not vary at a few years timescale. The spectral parameters from the two *ASCA* observations are also identical and consistent with the values obtained with *BeppoSAX* in between. However, we note that, in 1E 1048.1−5937, the absorption column densities obtained from the two *ASCA* observations are identical and a factor of 1.5–2 larger than the *BeppoSAX* measurement in between. This difference is somewhat larger than the known calibration difference between the two instruments (Orr et al. 1998).

Some low-mass X-ray binaries (LMXBs) have also been detected at low luminosity levels ($\sim 10^{33}$ ergs s^{-1}; e.g., Cen X-4, Aql X-1; see Tanaka & Shibazaki 1996, and references therein), understood to be the quiescent phase of the soft X-ray transients (SXTs). Usually the LMXB sources show both short- and long-term irregular intensity variations, and many also show quasi-periodic oscillations, bursts, dips, or orbital modulation. Even though the AXPs do not show significant temporal variations other than the pulsations, which is somewhat different from the typical characteristics of low-luminosity LMXBs, this in itself is not a strong argument against the AXPs being LMXBs. One LMXB that has some properties similar to the AXPs is 4U 1626−67. The X-ray luminosity, magnitude of spin-change rate, pulse period, and flux stability over very short to years timescale of this source are similar to the AXPs. However, the presence of both spin-up and spin-down, quasi-periodic oscillations, an optically bright accretion disk, and a hard X-ray spectrum makes it different from the AXPs.

3.2. *Accretion Torque in the Common-Envelope Evolution Model*

It has been proposed that AXPs are recent remnants of common-envelope evolution of high-mass X-ray binaries (van Paradijs et al. 1995; Ghosh et al. 1997). In this model, the pulsar is rotating near its equilibrium period, close to the Keplerian period at the innermost part of the disk. If the pulsar is rotating at the equilibrium period, small changes in the mass accretion rate cause alternate spin-up and spin-down episodes. The overall spin-down is explained with the assumption that in the absence of a companion star as the source of mass accretion, the mass accretion rate from the disk decreases slowly on a viscous timescale. The equilibrium period of the pulsar is inversely related to the mass accretion rate and shows secular increase. For 1E 1048.1−5937, which has a pulse period of 6.5 s and luminosity of 6.3×10^{33} ergs s^{-1} for a distance of 3 kpc (or in a more favorable case, 7×10^{34} ergs s^{-1} if the source is at a distance of 10 kpc), the magnetic field strength inferred for an equilibrium rotator (Frank, King, & Raine 1992) is $B = 10^{11}(P/3)^{7/6}L_{35}^{1/2} = 6.2 \times 10^{10}$ (or 2.1×10^{11}) G. Here and in what follows we have assumed a neutron star with mass $M = 1.4\ M_{\odot}$, radius $R = 10^6$ cm, and moment of inertia $I = 10^{45}$ g cm^2. A pulse period of P implies that, if in equilibrium, the corotation radius, or in this case the radius of the inner disk, is $r_M = (GM)^{1/3}(P/2\pi)^{2/3}$. The infalling material from the disk carries a positive angular momentum of $\dot{M}(GMr_M)^{1/2}$. The torque can also be expressed in terms of the pulse period P and the X-ray luminosity L_X as $RL_X(P/2\pi GM)^{1/3}$. Even if we assume that all of the X-ray emission is a result of disk accretion, the accretion torque is only 1.1×10^{31} (or 1.2×10^{32}) g cm^2 s^{-2}. To achieve the observed spin-down rate for a neutron star with moment of inertia 10^{45} g cm^2, the negative torque required to be imparted onto the neutron star is $I\dot{\Omega} = 4.9 \times 10^{33}$ g cm^2 s^{-2}. This is a factor of 450 (or 40) larger than the accretion torque, and in the common-envelope evolution model, a negative dimensionless torque of this magnitude is required to spin down the pulsar at the observed rate. In other words, the spin-down rate of this source is much larger than what can be achieved with disk accretion onto a neutron star with a luminosity of less than 10^{35} ergs s^{-1}. 1E 1048.1−5937 does not fit in the classical picture of $\dot{P}$ versus $PL^{3/7}$ of the equilibrium rotators (Ghosh & Lamb 1979). In addition, the two *ASCA* observations made during the two epochs that have a factor of 2 different spin-down rates do not show significant difference in the luminosity or the spectral parameters.

Among the other AXPs, 1RXS J170849.0−400910 (Sugizaki et al. 1997; Israel et al. 1999a) and 1E 1841−045 (Kes 73; Vasisht & Gotthelf 1997; Gotthelf et al. 1999) have relatively large spin-down rates of 2.2×10^{-11} and 4.1×10^{-11} s s^{-1}, respectively, while the X-ray luminosity is in the range 10^{35}–10^{36} ergs s^{-1}. In the common-envelope evolution model of AXPs, a faster spin-down compared to the torque provided by the accreting matter can be a potential problem for these two sources also. For this model to be correct for the AXPs, a very fine tuning of the mass accretion rate is required. All the sources need to have a disk accretion rate a tiny fraction larger than the propeller regime. Li (1999) has identified several other problems in the context of applicability of this model to AXPs. Most notable is the limited lifetime of an accretion disk around a solitary neutron star compared with the response timescale of the neutron star to changes in the accretion torque. One possible alternative is that the spin-down is due to magnetically driven wind from an accretion disk, proposed also for SGR 1900+14 (Marsden, Rothschild, & Lingenfelter 1999), but this will require a harder X-ray spectrum than has been observed. Chatterjee, Hernquist, & Narayan (1999) proposed a scenario in which AXPs are formed as single neutron stars with fossil disks made from fallback material from the supernova explosions. In this model, the spin-down from an initial period of a few ms to ~ 6 s is due to strong propeller effect at some period when the accretion rate is very low. However, if accretion is the correct phenomenon in the AXPs, as high spin-down goes on in the presence of substantial accretion, spin-down due to wind outflow seems to be more plausible than accretion-induced angular momentum loss. However, it should be remembered that the classical equilibrium disk picture assumed here is often found not to be the most appropriate description for X-ray pulsars (Bildsten et al. 1997).

3.3. *Magnetar Model*

In view of a very narrow mass and type allowed for any binary companion and several arguments against the common-envelope evolution model, the magnetar model seems to be the most likely one for the AXPs. If the spin-down is due to magnetic braking, dipole field strength of the order of 10^{14} G is estimated for these sources. A nearly constant spin-down property was thought to favor the magnetar model over a binary scenario. In two AXPs, 1E 1841−045 (Gotthelf et al. 1999) and 1RXS J170849.0−400910 (Kaspi, Chakrabarty, & Steinberger 1999), there is very strong evidence for constant spin-down, whereas in 1E 1048.1−5937, deviation from a linear trend is clear. Recently, a deviation has also been detected from SGR 1900+14 (Woods et al. 1999). 1E 2259+586, the most frequently observed AXP, has provided an interesting pulse period history. Observations made for about 15 yr with many instruments preceding *RXTE* showed considerable variation in the spin-down rate (Baykal & Swank 1996). However, the pulse-coherent timing observations with *RXTE* proved it to be otherwise, at least for a period of last 2.6 yr (Kaspi et al. 1999).

Two scenarios have been proposed that can explain the changing spin-down rate even when the overall braking is due to the ultrastrong magnetic field. Melatos (1999) showed that for reasonable neutron star parameters, a radiative precession effect may take place that can give the observed spin-down variations with timescales of about 10 yr. It will be possible to verify this scenario when more pulse period measurements become available in the next few years. Woods et al. (1999) have identified a possible *braking glitch* in SGR 1900+14 close to the time when SGR activity was very strong. However, if the spin-down variation is related to the SGR activity, similar activities should have been observed from 1E 1048.1−5937 and 1E 2259+586. We have found that all the gamma-ray bursts observed with the BATSE for which the estimated positions are within 2 σ of these AXPs (about 30 GRBs around each AXP) have strong high-energy emission, unlike the SGR bursts. Heyl & Hernquist (1999) have proposed that the spin-down variations can be explained as glitches (similar to those in radio pulsars) superposed on constant spin-down. However, with recent pulse period measurements of 1E 1048.1−5937 and SGR 1900+14, this will require too many glitches, one before almost every observation unless there are *braking glitches*, never observed in radio pulsars.

In the magnetar model, the X-ray emission is due to decay of the magnetic field. The energy generated at the core is transported to the crust along the magnetic field direction. The blackbody component of the spectrum is thermal emission from the hot spots at the magnetic polar regions, and the power-law component is part of the thermal emission reprocessed by the magnetic field and the environment. Investigation about the expected pulse profile and its energy dependence is required. Time and/or energy dependence of the pulse profile as has been observed in SGR 1806−20 (Kouveliotou et al. 1998) and SGR 1900+14 (Hurley et al. 1999; Kouveliotou et al. 1999; Murakami et al. 1999) also must be addressed. A double-peaked pulse profile at low energy and single-peaked profile at high energy are observed in 4U 0142+61 (Fig. 1). The pulsation is very weak in some sources (only 5%–10% in SGR 1806−20 and 4U 0142+61) and 75% in 1E 1048.1−5937. If the pulsation is due to confinement of the heat in the magnetic polar regions by the magnetic field, a correlation between magnetic field strength and pulse fraction should be observed. However, it is likely to be smeared by the geometric effect of individual sources, i.e., the orientation of the spin and magnetic axes with respect to the line of sight. In the magnetar model, there are two mechanisms by which X-rays can be generated. If the X-ray emission is powered by decaying magnetic field, the luminosity is a very strong function of the magnetic field strength, $L_X \propto B^4$ (Thompson & Duncan 1996). An alternate process of X-ray generation is particle acceleration by Alfvén waves resulting from small-scale fracture of the crust, in this case $L_X \propto B^2$. The X-ray luminosities and pulse fractions of five confirmed AXPs and two SGR sources are shown in Figure 7 against the magnetic field strength. The latter is estimated from pulse period and the overall spin-down rate assuming $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G. Although there is uncertainty in the luminosity of some sources (see the legend of Fig. 7), a second- or fourth-power correlation between L_X and B does not seem to be present. There is also no correlation between pulse fraction and the magnetic field.

A clustering of the pulse periods of 10 sources (seven AXPs and three SGRs) in the 5–12 s range also needs to be addressed, because the magnetars are expected to be alive in X-ray until they have slowed down to a pulse period of about 70 s (Duncan & Thompson 1992). The magnetars are expected to be radio quiet because of suppression of pair creation at high magnetic field (Baring & Harding 1998), and this seems to be true for most sources.

Changes in luminosity or small changes in the spectral parameters can be a result of varying activities in the core, the heat generated from which is transported to the surface along the direction of the magnetic field at a timescale of a few years. Variability study of AXPs with very high sensitivity may rule out the magnetar model if significant change in column density is observed. This will indicate the pres-

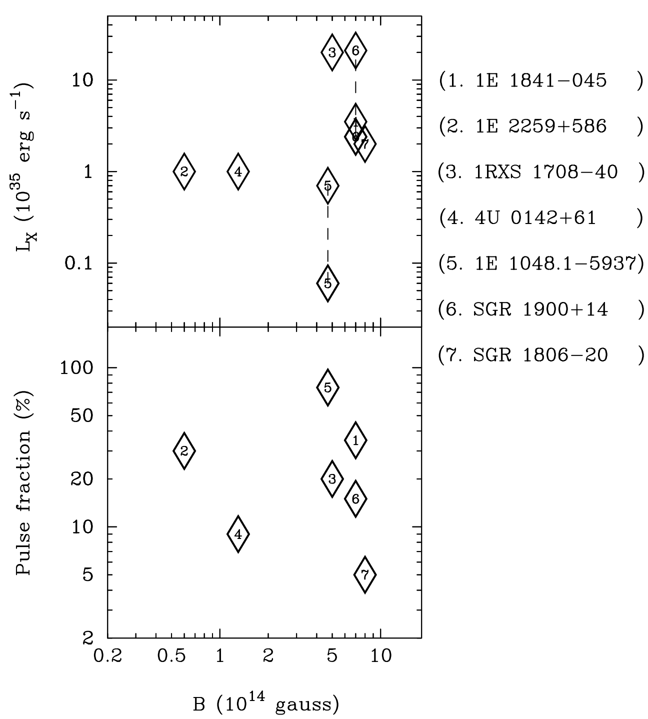

FIG. 7.—X-ray luminosity and pulse fraction of the AXPs and SGRs are plotted against magnetic field strength assuming that these objects are magnetars. Two values of the luminosity are plotted for 1E 1048.1−5937 to show the uncertainty in its distance, and the same has been done for SGR 1900+14 to show the variability in its X-ray emission. The distance of 1RXS J170849.0−400910 is taken to be 10 kpc, and those for other sources are the best available estimates.

ence of accretion disk and wind in the neighboring area. The *BeppoSAX* and *ASCA* observations give identical column density for 4U 0142+61 but slightly different column density in the case of 1E 1048.1−5937. However, multiple observation of the latter source with the same instrument is found to give identical values, indicating that the difference between the two instruments could also be a systematic effect.

4. CONCLUSION

Using multiple observations of two AXPs with *ASCA* we have found remarkable stability in their intensities, spectral shapes, and pulse profiles over a 4 yr period. For the source 1E 1048.1−5937, we have confirmed that, similar to other AXPs, the spectrum consists of a power-law component and a blackbody component. The spin-down trend of 4U 0142+61 is consistent with a constant rate, whereas in 1E 1048.1−5937 we have clearly identified three different spin-down epochs. We have shown that the fast spin-down of some of the AXPs is difficult to achieve with disk accretion. Hence, the common-envelope evolution scenario of AXPs is unlikely to be the case, unless the spin-down is due to wind outflow from the disk. In this case also, the stability of X-ray emission in spite of varying spin-down rate remains unexplained. The significantly different spin-down rates of 1E 1048.1−5937 in different epochs are also difficult to reconcile in the magnetar model, unless precession is at work. However, the flux stability and lack of variation of the spectral parameters appear to favor the magnetar model.

We thank an anonymous referee for many suggestions, which helped to improve a previous version of the manuscript. B. Paul was supported by the Japan Society for the Promotion of Science through a fellowship.

REFERENCES

Baring, M. G., & Harding, A. K. 1998, ApJ, 507, L55
Baykal, A., & Swank, J. 1996, ApJ, 460, 470
Bildsten, L., et al. 1997, ApJS, 113, 367
Chakrabarty, D., et al. 1997, ApJ, 474, 414
Chatterjee, P., Hernquist, L., & Narayan, R. 1999, preprint (astro-ph/9912137)
Corbet, R. D., & Mihara, T. 1997, ApJ, 475, L127
Corbet, R. H. D., & Day, C. S. R. 1990, MNRAS, 243, 553
Corcoran, M. F., et al. 1998, ApJ, 494, 381
Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (2d ed.; Cambridge: Cambridge Univ. Press)
Ghosh, P., Angelini, L., & White, N. E. 1997, ApJ, 478, 713
Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296
Gotthelf, E. V., Vasisht, G., & Dotani, T. 1999, ApJ, 522, L49
Haberl, F., Pietsch, W., Motch, C., & Buckley, D. A. H. 1996, IAU Circ. 6445
Hellier, C. 1994, MNRAS, 271, L21
Heyl, J. S., & Hernquist, L. 1999, MNRAS, 304, L37
Hurley, K., et al. 1999, ApJ, 510, L111
Ishibashi, K., et al. 1999, ApJ, 524, 983
Israel, G. L., Covino, S., Stella, L., Campana, S., Haberl, F., & Mereghetti, S. 1999a, ApJ, 518, L107
Israel, G. L., Mereghetti, S., & Stella, L. 1994, ApJ, 433, L25
Israel, G. L., et al. 1999b, A&A, 346, 929
Kaspi, V. M., Chakrabarty, D., & Steinberger, J. 1999, ApJ, 525, L33
Kouveliotou, C., et al. 1996, Nature, 379, 799
Kouveliotou, C., et al. 1998, Nature, 393, 235
Kouveliotou, C., et al. 1999, ApJ, 510, L115
Li, X. D. 1999, ApJ, 520, 271
Marsden, D., Rothschild, R. E., & Lingenfelter, R. E. 1999, ApJ, 520, L107
Melatos, A. 1999, ApJ, 519, L77
Mereghetti, S. 1995, ApJ, 455, 598
Mereghetti, S., Israel, G. L., & Stella, L. 1998, MNRAS, 296, 689
Mereghetti, S., & Stella, S. 1995, ApJ, 442, L17
Middleditch, J., Mason, K. O., Nelson, J. E., & White, N. E. 1981, ApJ, 244, 1001
Murakami, T., Kubo, S., Shibazaki, N., Takeshima, T., Yoshida, A., & Kawai, N. 1999, ApJ, 510, L119
Nagase, F. 1999, in Highlights in X-Ray Astronomy in Honour of Joachim Truemper's 65th birthday, ed. B. Aschenbach & M. J. Freyberg (MPE Rep. 272; Garching: MPE), 74
Oosterbroek, T., Parmar, A. N., Mereghetti, S., & Israel, G. L. 1998, A&A, 334, 925
Orr, A., Yaqoob, T., Parmar, A. N., Piro, L., White, N. E., & Grandi, P. 1998, A&A, 337, 685
Schwentker, O. 1994, A&A, 286, L47
Seward, F. D., Charles, P. A., & Smale, A. P. 1986, ApJ, 305, 814
Song, L., Mihara, T., Matsuoka, M., Negoro, H., & Corbet, R. 1999, PASJ, 52, 181
Sugizaki, M., Nagase, F., Torii, K., Kinugasa, K., Asanuma, T., Matsuzaki, K., Koyama, K., & Yamauchi, S. 1997, PASJ, 49, L25
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37
Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
Thompson, C. & Duncan, R. C. 1996, ApJ, 473, 322
Torii, K., Kinugasa, K., Katayama, K., Tsunemi, H., & Yamaguchi, S. 1998, ApJ, 503, 843
van Paradijs, J. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 536
van Paradijs, J., Taam, R. E., & van den Heuvel, E. P. J. 1995, A&A, 299, L41
Vasisht, G., & Gotthelf, E. V. 1997, ApJ, 486, L129
White, N. E., Angelini, L., Ebisawa, K., Tanaka, Y., & Ghosh, P. 1996, ApJ, 463, L83
Wilson, C. A., Dieters, S., Finger, M., Scott, D. M., & van Paradijs, J. 1999, ApJ, 513, 464
Woods, P. M., et al. 1999, ApJ, 524, L55
Yi, I., & Vishniac, E. T. 1999, ApJ, 516, L87