Discovery of an X-Ray Pulsar in the SMC: AX J0058–7203

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Abstract
We report on the discovery and analysis of an X-ray pulsar, AX J0058–7203, in the Small Magellanic Cloud. This pulsar exhibits coherent pulsations at $P = 280.3$ s with a double-peak structure. The X-ray spectrum is well fitted with a simple power-law model of photon index $\Gamma \sim 0.7$. No significant change of the pulsation period over the observation was found. A comparison with ROSAT observations in the same field reveals that AX J0058–7203 is highly variable, and is most likely a Be star binary pulsar.

Key words: Magellanic Clouds — Pulsars: individual (AX J0058–7203) — X-rays: binaries

1. Introduction
X-ray binary pulsars (here XBPs) constitute a bright class of X-ray sources in the sky, and have been major objects for X-ray astronomy. Sporadic mass accretion from a companion star onto a spinning neutron star makes this class to be variable X-ray sources. X-ray binaries with a Be star companion (here Be-XBPs) are the most variable subclass; occasional outbursts may be caused by mass-ejection episodes of a companion Be star or by encounters with a dense stellar wind region along with a highly eccentric orbit of a neutron star. The average luminosity is generally lower than ordinal XBPs, and is typically in the range of $10^{34} - 10^{35}$ erg s$^{-1}$. This moderate luminosity together with a limited duty ratio of the outbursts has prevented us to perform a complete survey of this class with the conventional non-imaging instruments. The imaging instruments on-board the Einstein and ROSAT satellites greatly improved the detection threshold. Since XBPs (also Be-XBPs) generally exhibit a hard X-ray spectrum, contemporary hard X-ray satellites, ASCA (Advanced Satellite for Cosmology and Astrophysics), RXTE (Rossi X-ray Timing Explorer), and Beppo-SAX, further enhance the detection probability for this class of X-ray sources (XBPs and Be-XBPs).

In fact, multiple observations of the Small Magellanic Cloud (SMC) caused a rush of X-ray pulsar discoveries (Yokogawa et al. 1999). Among the known 16 X-ray pulsars in the SMC at present (Bildsten et al. 1997; Kahabka et al. 1999; Lamb et al. 1999; Macomb et al. 1999), 13 have been discovered within 1.5 years: from the end of 1997 to the middle of 1999. Most are considered to be Be-XBPs based on their transient nature and/or an optical Be counterpart.

We report here on the discovery and analysis of AX J0058–7203, one of the newly discovered pulsars during the pulsar rush episode (Yokogawa, Koyama 1998). We also examine the flux variability using the archives of ASCA and ROSAT, and propose to classify this source as a Be star binary system in the SMC.

2. Observations
ASCA observed a SMC region centered at R.A. = 00$^h$59$^m$26.3$^s$, Dec. = $-72^\circ$10’12’’12’’ (equinox 2000) on 1997 November 14 to 15, during the AO-6 cycle. The primary target of this observation was N66, one of SNRs in the SMC region. Details concerning the ASCA satellite as well as its instruments (GIS: Gas Imaging Spectrometer, SIS: Solid-state Imaging Spectrometer) and X-ray telescope (XRT) can be found in Tanaka et al. (1994), Ohashi et al. (1996), Makishima et al. (1996), Burke et al. (1991) and Serlemitsos et al. (1995). As is the nominal case, two GISs (GIS 2, 3) and SISs (SIS 0, 1) were operated in parallel.

AX J0058–7203 was in the field of view of the GISs and SISs at $\sim 13'$ off-axis positions. We excluded the data taken during the South Atlantic Anomaly or at an elevation angle less than 5$^\circ$ or the passage through a region where cut-off rigidity is lower than 6 GeV. In addition, we employed a rise-time discrimination technique to reduce particle events for the GIS data. After these filterings, the net exposure times were $\sim 35$ ks for GIS and $\sim 31$ ks for SIS.

3. Results and Analysis
3.1. X-Ray Image and Source Identification

A combined GIS image (GIS 2 + GIS 3) is shown in figure 1. The accurate position of this source was determined using two SIS images (SIS 0 and 1) to be R.A. = 00\h 57\,m 53\,s, Dec. = -72\,\degree 02\,\arcmin 46\,\arcsec with an error circle of \(\sim 40\)\,\arcsec in radius (Gotthelf 1996; ASCA News 4, 31), hence, we designate this source as AX J0058−7203. Two other X-ray pulsars are serendipitously located in the GIS field: 1SAX J0054.9−7226 with a pulsation period of 58.969 s (Santangelo et al. 1998) at the top left and 1SAX J0103.2−7209 with a pulsation period of 345.2 s (Israel et al. 1998) at the bottom right of figure 1. This demonstrates an extremely high density of X-ray pulsars of the central region of the SMC.

For source identification, we checked two comprehensive SMC source catalogs provided by Wang and Wu (1992) with Einstein observatory, and by Kahabka et al. (1999) with ROSAT observatory. Source No. 41 (SMC 0056.2−7219) in the former catalog and source No. 124 (RX J0057.8−7202) in the latter one are found to be located within the error circle of AX J0058−7203.

3.2. Temporal Analysis

The X-ray photons of AX J0058−7203 were extracted from the elliptical regions, as is indicated by the solid line in figure 1 for both the GIS and SIS data. We first confirmed that there was no flaring event nor any trend of flux variation during the observation. After a barycentric correction of the photon-arrival times, we conducted a Fast Fourier Transform (FFT), in order to search for any coherent periodicity. Figure 2 shows the power spectrum for the GIS data in the 0.7−7.0 keV band. We found two significant peaks at 3.6 \times 10^{-3}\,Hz and 7.2 \times 10^{-3}\,Hz. The chance probabilities to obtain these two peaks are estimated to be 9 \times 10^{-10} and 1 \times 10^{-11}, respectively. Since the frequency ratio between the two peaks is exactly double, we infer the lower frequency peak to be the fundamental period of \(P = 280.3\) s and the higher to be the second harmonics.

We then employed a folding technique to the GIS and SIS data around a trial period of \(P = 280.3\) s, and found the most likely period to be 280.4 ± 0.3 s. The folded pulse profile of 280.4 s period is given in figure 3. In the pulse profile, we can see two peaks, as was already expected from the power spectrum. Since the intensity of the main peak is about twice larger than that of the sub-peak, we conclude that 280.4 s is really the fundamental pulse period. The two-peak pulse profile does not change with the X-ray energy. The pulse fraction, defined as \((I_{\text{max}}-I_{\text{min}})/(I_{\text{max}}+I_{\text{min}})\), where \(I_{\text{max}}\) and \(I_{\text{min}}\) are the maximum and the minimum count rate including background photons, is 61% in the soft band (0.7−2.0 keV) and 48% in the hard band (2.0−7.0 keV). We also divided the full observation data into two data sets, the former half and the latter half, then separately applied the folding technic, but found no significant changes of the pulsation period over the observation period.

3.3. Spectral Analysis

Using the same source data as in the timing analysis (solid line in figure 1) and subtracting the background data in the dotted-line region in figure 1, we constructed the GIS and SIS X-ray spectra separately, showing the
3. Discussion

A long pulse period and a rather flat spectrum indicate this source to be an accretion-powered binary pulsar with a high-mass companion (Nagase 1989). Among high-mass binary pulsars with various types of optical companion, binary systems of an X-ray pulsar with a Be star share the transient nature which is exclusively found in this subclass (Stella et al. 1986).

Thus, information concerning the long-term flux variability of this source is critical to reveal its nature. We therefore used ROSAT and Einstein archival data which cover the region of AX J0058–7203 to search for its history of variability. The count rate, or upper limit, from this source are summarized in table 2 together with the ASCA result.

From table 2, we find that AX J0058–7203 shows a variation of more than 10 times in flux, which favors AX J0058–7203 to be a Be star binary pulsar. Due to limited data from this source the Be star interpretation still remains preliminary; hence, follow-up observations involving long-term pulsation monitoring and optical identification of a companion star are encouraged.

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Table 1. Best-fit parameters of the spectrum.

| Detector  | Photon index $^\dagger$ | Absorption $^\dagger$ | Reduced $\chi^2$ (d.o.f.) |
|-----------|------------------------|----------------------|---------------------------|
| GIS       | $0.86 \pm 0.23$        | $4.8 \pm 3.7$        | $0.60 (26)$               |
| SIS       | $0.61 \pm 0.22$        | $2.6 \pm 2.4$        | $1.08 (14)$               |
| GIS+SIS   | $0.75 \pm 0.19$        | $3.6 \pm 1.9$        | $0.72 (40)$               |

$^\dagger$ Errors are for 90% confidence level.

Table 2. Flux history of AX J0058−7203.

| Satellite | Detector | Date       | Count rate $^\dagger$ | Predicted X-ray flux $^\dagger$ $^\ddagger$ |
|-----------|----------|------------|------------------------|-----------------------------------------------|
|           |          |            | cnts s$^{-1}$          | erg cm$^{-2}$ s$^{-1}$                        |
| Einstein  | IPC      | 1979/11/13 | $(1.0 \pm 0.1) \times 10^{-4}$ | $(5.4 \pm 0.5) \times 10^{-14}$             |
|           |          | 1980/03/15 | $< 1.9 \times 10^{-4}$    | $< 1.0 \times 10^{-13}$                      |
| ROSAT     | PSPC     | 1991/10/08 | $(3.3 \pm 0.9) \times 10^{-3}$ | $(6.4 \pm 1.8) \times 10^{-13}$             |
|           |          | 1992/04/17 | $< 1.7 \times 10^{-3}$    | $< 3.3 \times 10^{-13}$                      |
|           |          | 1993/03/29 | $< 1.2 \times 10^{-4}$    | $< 2.4 \times 10^{-14}$                      |
|           |          | 1993/05/12 | $(8.4 \pm 11.5) \times 10^{-4}$ | $(1.6 \pm 2.2) \times 10^{-13}$             |
|           |          | 1993/10/01 | $(1.9 \pm 1.0) \times 10^{-3}$ | $(3.7 \pm 2.0) \times 10^{-13}$             |
|           |          | 1994/05/05 | $(2.8 \pm 1.5) \times 10^{-3}$ | $(5.4 \pm 2.9) \times 10^{-13}$             |
|           | HRI      | 1994/04/18 | $< 5.7 \times 10^{-3}$    | $< 3.1 \times 10^{-12}$                      |
|           |          | 1994/04/19 | $< 1.7 \times 10^{-3}$    | $< 9.2 \times 10^{-13}$                      |
|           |          | 1994/10/05 | $< 4.9 \times 10^{-3}$    | $< 2.6 \times 10^{-12}$                      |
|           |          | 1995/04/12 | $(2.6 \pm 2.9) \times 10^{-3}$ | $(1.4 \pm 1.6) \times 10^{-12}$             |
|           |          | 1995/04/13 | $< 8.5 \times 10^{-4}$    | $< 4.6 \times 10^{-13}$                      |
|           |          | 1995/04/14 | $< 1.0 \times 10^{-3}$    | $< 5.4 \times 10^{-13}$                      |
| ASCA      | GIS      | 1997/11/14 | $1.4 \times 10^{-2}$     | $3.2 \times 10^{-12}$                        |

$^\dagger$ Count rate with 1-$\sigma$ error in a circle of 1′ radius around the source position, after subtracting the background count rate taken in a neighboring off-source region. Upper limits for 1-$\sigma$ significance level are given for observations in which the source was not detected.

$^\ddagger$ X-ray flux 1-$\sigma$ error in the 0.7–10.0 keV is simulated from the count rate by the pimms software, assuming no change from the ASCA spectrum. For those not detected, the upper limit is given. The ASCA result, together with the count rate, is also shown at the last row.