Discovery of 101-s Pulsations from AX J0057.4—7325 in the SMC with ASCA

Jun YOKOGAWA,1 Ken’ichi TORII,2 Takayoshi KOHMURA,3 Kensuke IMANISHI,1 and Katsuji KOYAMA1*

1Department of Physics, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502
E-mail (JY): jun@cr.scphys.kyoto-u.ac.jp
2National Space Development Agency of Japan, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505
3Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043

(Received 2000 August 11; accepted 2000 September 11)

Abstract

The results from two ASCA observations of AX J0057.4—7325 = RX J0057.3—7325 are presented. Coherent pulsations with a barycentric period of 101.45 ± 0.07 s were discovered in the second observation. The X-ray spectrum was found to be hard (photon index ~ 0.9) and unchanged through these observations, except for the flux. The ROSAT archival data show that AX J0057.4—7325 exhibits a flux variation with a factor ≥ 10. A discussion on a possible optical counterpart is given.

Key words: pulsars: individual (AX J0057.4—7325) — stars: neutron — X-rays: stars

1. Introduction

Recently, many X-ray pulsars have been discovered in the Small Magellanic Cloud (SMC), and now ~ 20 X-ray pulsars are known in this galaxy. Most of them are interpreted as being X-ray binary pulsars (XBPs), because of their hard X-ray spectrum, long pulse period (> 1 s), large flux variability, and/or the existence of a massive star counterpart (Yokogawa et al. 2000 and references therein). Massive star counterparts have been mostly revealed to be a Be star by detailed optical observations on individual objects (Hughes, Smith 1994; Southwell, Charles 1996; Buckley et al. 1997; Cowley et al. 1997; Israel et al. 1997; Coe et al. 1998; Lamb et al. 1999; Stevens et al. 1999; Coe, Orosz 2000; Cole et al. 2000), except for SMC X-1 with a B (not Be) supergiant star companion (Bildsten et al. 1997).

Haberl and Sasaki (2000) investigated the spatial correlation between SMC X-ray sources and emission-line objects (hereafter ELOs) cataloged by Meyssonnier and Azzopardi (1993; MA93) as well as Murphy and Bessell (2000). They found that most of the already established Be/X-ray binaries have a counterpart in these ELO catalogs, and thus proposed that other X-ray sources having an ELO counterpart are also likely to be Be/X-ray binaries. They concluded that the number ratio of Be/X-ray binaries to OB supergiant X-ray binaries in the SMC is extremely higher than that in our Galaxy. They also pointed out that the main body of the SMC contains no OB supergiant X-ray binary, suggesting a different star-formation history between the main body and the eastern wing. In this context, it would be important to search for pulsations from X-ray sources with no ELO counterpart.

In this letter, we report on the discovery of coherent pulsations with ASCA from AX J0057.4—7325 (Torii et al. 2000), for which neither a Be star nor an ELO counterpart has been known. We also investigated several catalogs of optical stars to find a possible optical counterpart.

2. Observations and Data Reduction

Two ASCA observations pointed at the edge of the SMC main body have covered AX J0057.4—7325. The observation dates were 51309.583–51310.698 (hereafter, obs. A1) and 51659.506–51660.598 (obs. A2), in unit of Modified Julian Day (MJD).

ASCA carries four XRTs (X-ray Telescopes, Serlemitsos et al. 1995) with two GISs (Gas Imaging Spectrometers, Ohashi et al. 1996) and two SISs (Solid-state Imaging Spectrometers, Burke et al. 1994) on each focal plane. In both observations, the GIS was operated in the normal PH mode with a time resolution of 0.0625/0.5 s, while the SIS was operated in the complementary 2-CCD mode with a time resolution of 8 s. The SIS data format in each observation was Faint/Faint with a level discrimination of 0.7 keV (A1) and Faint/Bright with a level discrimination of 0.55 keV (A2).
We first rejected any data obtained in the South Atlantic Anomaly, or in low cut-off rigidity regions (< 4 GV), or when the elevation angle of the target from the earth's rim was less than 5°. We also rejected the SIS data obtained when the elevation angle from the bright earth was lower than 25°. Particle events for GIS were removed by a rise-time discrimination method. Hot and flickering pixels of SIS were rejected. After screening, the total available exposure times were ~ 41 ks (A1; GIS), ~ 37 ks (A1; SIS), ~ 26 ks (A2; GIS), and ~ 17 ks (A2; SIS). Since SIS has been severely damaged by particle radiation, the pixel-to-pixel fluctuation of the zero level has become significantly large. To compensate for the degradation, we made an RDD correction for obs. A1 (Dotani et al. 1997, ASCA News 5, 14), which is reliably applicable only to the Faint mode data. We did not apply any RDD correction for obs. A2, because we simultaneously used the Faint and Bright data to obtain better statistics.

3. Results

3.1. Source Identification

In obs. A2, a source was detected at the center of the SIS chip, S1C1. Using the SIS image, we determined the source position using a method described by Ueda et al. (1999) to be (00°57'29".4, -73°25'19") for equinox 2000, with an error radius of 30". We thus designate this source as AX J0057.4—7325. Positions determined with GIS in both observations or SIS in obs. A1 were consistent with the above coordinates. We investigated several X-ray and optical catalogs to find counterparts of AX J0057.4—7325. A ROSAT source, RX J0057.3-7325 (Haberl et al. 2000), and an optical star, MACS J0057-734#010 (Tucholke et al. 1996), were found within the ASCA error circle.

3.2. Timing Analyses

In each observation, we collected source photons from a circle with a radius of ~ 3.5 centered on AX J0057.4—7325. We made a barycentric correction on the photon arrival times and performed an FFT (Fast Fourier Transformation) on the event lists in each observation. From the power spectrum of the GIS data in obs. A2, we detected a significant peak at a frequency of ~ 0.0099 Hz (figure 1), which was also confirmed with the SIS data. The maximum power of 49.6 was obtained with photons in the energy band of 1.1-7.6 keV. Because random fluctuation can cause such a large power with a very low probability of $2 \times 10^{-6}$, pulse detection is highly significant. We performed epoch folding on the GIS + SIS data, and determined the barycentric period to be $P = 101.45 \pm 0.07$ s.

We also detected weak evidence for coherent pulsations from obs. A1. A maximum power of 34.1 was detected at ~ 0.0098 Hz with the GIS+SIS data. The probability to obtain such a power at any frequency from random events is not very small, 0.03%, but this is a rather conservative estimation because the period search could be restricted to a narrow range of around ~ 101 s. We thus performed an epoch folding search on the data, and determined the barycentric period to be $P = 101.47 \pm 0.06$ s.

Figure 2 shows the pulse profiles of GIS+SIS in the energy bands 0.7-2.0 keV and 2.0-7.0 keV for both observations. The pulse shape is broad, and there may be an additional sub-peak in the low-energy band. The pulsed fraction, defined as (pulsed flux)/(total flux) after removing the background, is ~ 46% (A1) or ~ 35% (A2) in the 2.0-7.0 keV band.

We also searched for any aperiodic intensity variation during each observation, but neither a burst nor a large flux variation was detected.

3.3. Spectral Analyses

Source photons were collected from the same regions used in the timing analyses, while background photons were from off-source areas near the source. We used the GIS and SIS spectra of obs. A1 and only the GIS spectrum of obs. A2. The SIS spectrum of obs. A2 was not used because we do not have a reliable response matrix for the Bright mode data, which is severely affected by radiation damage.

At first, we separately fitted each spectrum to a simple power-law model with the interstellar absorption. The derived parameters (photon index $\Gamma$ and column density $N_H$) were found to be consistent in both observations and in both detectors. Therefore, to further constrain

© Astronomical Society of Japan • Provided by the NASA Astrophysics Data System
the parameters, we assumed that $F$ and $N_H$ were the same for both observations, and simultaneously fitted the three spectra to the same model. We obtained the best-fit parameters as $\Gamma = 0.9$ (0.7–1.0) and $N_H = 2 \times 10^{21}$ cm$^{-2}$, with a reduced $\chi^2$ of 1.00 for 96 degrees of freedom (the values in parentheses indicate 90% confidence limits). X-ray fluxes were derived to be $1.2 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ (for obs. A1) and $2.4 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ (for obs. A2). Figure 3 shows the phase-averaged spectrum of GIS in obs. A2, which had the best statistics, and the best-fit model.

We also extracted phase-resolved spectra from phases 0–0.5 and 0.5–1 (see figure 2) and fitted them with the same model. No significant difference was found for $\Gamma$ and $N_H$ within the statistical errors, which is consistent with the energy-resolved pulse shapes (figure 2).

4. Discussion

Six ROSAT observations and no Einstein observation have covered the position of AX J0057.4–7325. To investigate the long-term flux variation of this source, we used the ROSAT archival data as follows. We derived the count rate from AX J0057.4–7325 ($= \text{RX J0057.3–7325}$) in each observation, after background subtraction. We assumed that $\Gamma$ and $N_H$ were the same as those derived from the ASCA observations ($\Gamma = 0.9$ and $N_H = 2 \times 10^{21}$ cm$^{-2}$), and converted the count rate to flux with the PIMMS software. We also made a vignetting correction according to the source's off-axis angle in each observation. The results are given in table 1: AX J0057.4–7325 was detected in obs. R1 and R2 with a signal-to-noise ratio of 2 and 10, respectively. By comparing the fluxes in obs. R4 and A2, we conclude that the flux has changed by a factor of $\geq 10$. The flux variability, the hard X-ray spectrum, and the long pulse period are all consistent with a scenario that AX J0057.4–7325 is an XBP with a companion of either a Be, an OB supergiant, or a low-
Table 1. Flux variability of AX J0057.4–7325.

<table>
<thead>
<tr>
<th>Observation ID</th>
<th>Date (MJD)</th>
<th>Instrument</th>
<th>Flux (erg s$^{-1}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>48550.301</td>
<td>ROSAT/PSPC</td>
<td>1.1 x 10$^{-12}$</td>
</tr>
<tr>
<td>R2</td>
<td>48732.665</td>
<td>ROSAT/PSPC</td>
<td>1.3 x 10$^{-12}$</td>
</tr>
<tr>
<td>R3</td>
<td>49118.070</td>
<td>ROSAT/PSPC</td>
<td>&lt; 3.5 x 10$^{-13}$</td>
</tr>
<tr>
<td>R4</td>
<td>49298.538</td>
<td>ROSAT/PSPC</td>
<td>2.4 x 10$^{-13}$</td>
</tr>
<tr>
<td>R5</td>
<td>49321.271</td>
<td>ROSAT/PSPC</td>
<td>&lt; 3.9 x 10$^{-13}$</td>
</tr>
<tr>
<td>R6</td>
<td>49470.832</td>
<td>ROSAT/HRI</td>
<td>&lt; 1.1 x 10$^{-12}$</td>
</tr>
<tr>
<td>A1</td>
<td>51310.141</td>
<td>ASCA/GIS+SIS</td>
<td>1.2 x 10$^{-12}$</td>
</tr>
<tr>
<td>A2</td>
<td>51660.052</td>
<td>ASCA/GIS</td>
<td>2.4 x 10$^{-12}$</td>
</tr>
</tbody>
</table>

*Middle of the observations.
†In the 0.7–10.0 keV band, after vignetting correction.

mass star.

As far as we have investigated, we found only one optical source, MACS J0057–734#010, in the ASCA error circle. It is interesting that there exists no ELO, i.e., a Be star candidate, in the ASCA error circle. Because the nearest ELO, No. 986 in MA93, is located 1′4 away from AX J0057.4–7325, a possibility for the optical counterpart would be ruled out. This is a rare case where an X-ray pulsar in the SMC is not associated with a Be star or an ELO. We note that AX J0057.4–7325 is located at the edge of the main body, fronting to the eastern wing. The fact that OB supergiant X-ray binaries in the SMC (only SMC X-1 and EXO 0114.6–7361) are both located in the eastern wing may lead us to suspect that AX J0057.4–7325 would be the third example. Because the discovery of a true optical counterpart would provide essential information, we strongly encourage deep and detailed optical observations on this field.

We thank Dr. M. J. Coe for his valuable suggestions about MACS J0057–734#010 and optical counterparts of the SMC sources. We also thank Dr. F. Haberl for useful comments on the SMC PSPC catalog. The ROSAT data were obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. J.Y. and T.K. are supported by JSPS Research Fellow-

References

Lamb R.C., Prince T.A., Macomb D.J., Finger M.H. 1999, IAU Circ. 7081
Murphy M.T., Hessell M.S. 2000, MNRAS 311, 714
Torii K., Kohmura T., Yokogawa J., Koyama K. 2000, IAU Circ. 7441
Ueda Y., Inoue H., Ogawara Y., Fujimoto R., Yamaoka K., Kii T., Gotthelf E.V. 1999, ISAS research Note 688