THE DECREASE IN X-RAY FLUX OF THE ACCRETION-POWERED MILLISECOND PULSAR
SAX J1808.4−3658 IN QUIESCENCE DETECTED BY ASCA

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Received 2000 June 20; accepted 2000 September 11; published 2000 October 27

ABSTRACT

The accretion-powered millisecond X-ray pulsar SAX J1808.4−3658 was observed in quiescence with ASCA in 1999 September. We detected a dim X-ray source in the Solid-State Imaging Spectrometer (SIS) data at the position consistent with SAX J1808.4−3658. The source count rate was (1.1 ± 0.4) × 10^-3 counts s^-1 (0.5−5 keV) for a single SIS, which corresponds to (3 ± 1) × 10^-14 ergs s^-1 cm^-2 if a power-law energy spectrum of photon index 2 with low-energy absorption corresponding to a hydrogen column density of 1.3 × 10^{22} cm^-2 is assumed. The statistical quality of the data was insufficient to constrain the energy spectrum or to detect the 401 Hz coherent pulsation. We compare the data with the BeppoSAX observation also made during the quiescent state and find that the X-ray flux measured by ASCA is at least a factor of 4 smaller than that measured by BeppoSAX. We discuss the possible X-ray emission mechanisms that could explain the flux change, including the radio pulsar and the radio pulsar shock emission.

Subject headings: pulsars: general — stars: individual (SAX J1808.4−3658) — stars: neutron —
X-rays: general — X-rays: stars

1. INTRODUCTION

SAX J1808.4−3658 is a unique transient X-ray source that displays both type I X-ray bursts and millisecond X-ray pulsations. The source is thought to be the formerly missing link between the neutron star low-mass X-ray binaries and the millisecond radio pulsars. SAX J1808.4−3658 was discovered in 1996 September using the Wide Field Camera aboard BeppoSAX (in 't Zand et al. 1998). It reached a peak intensity of 0.1 crab and lasted between 6 and 40 days. Detection of two bright type I X-ray bursts demonstrated that the compact object is a neutron star. Recently, a third burst was found approximately 30 days after the first two bursts through reanalysis of a more extended set of data. An improved distance estimate of 2.5 ± 0.1 kpc resulted (in 't Zand et al. 2000).

The source was detected again in 1998 April with the Proportional Counter Array aboard the Rossi X-Ray Timing Explorer (Marshall 1998). The observation led to the discovery of a coherent X-ray pulsation at 401 Hz (Wijnands & van der Klis 1998). The pulse profile was sinusoidal and had a low fractional rms amplitude of ~4% (2−60 keV). Because mass accretion onto the neutron star was considered to power the X-ray emission, a major part of the accreted mass may be channeled to the magnetic poles without being expelled by the so-called propeller effect. This sets an upper limit to the surface magnetic field of the neutron star of (2−6) × 10^8 G, which is comparable to that of the millisecond radio pulsars (Wijnands & van der Klis 1998). Subsequent analysis showed the presence of a binary period of 2.0 hr (Chakrabarty & Morgan 1998). This confirmed the low-mass nature of the companion.

Several transient X-ray binaries have been detected in quiescence, and their X-ray properties were found to be quite different, depending on the nature of the compact object in the system. Soft X-ray transients containing a neutron star (NS SXTs) generally have a bottom luminosity around 10^{32}−10^{33} ergs s^-1 in quiescence, whereas those containing a black hole (BH SXTs) can be as dim as or even dimmer than 10^{33} ergs s^-1 (Asai et al. 1998). The former has a characteristic energy spectrum consisting of a soft component and a hard tail. Quiescent X-ray emission from SAX J1808.4−3658 was discovered with BeppoSAX on 1999 March 17−19 (Stella et al. 2000). The observed Medium-Energy Concentrator/Spectrometer (MECS) count rate was very low, ~3 × 10^{-3} counts s^-1, and may convert to a luminosity of ~(0.7−1.5) × 10^{32} ergs s^-1 (0.5−10 keV) for an assumed distance of 2.5 kpc. This is in the range of quiescent luminosities in other NS SXTs. In this Letter, we report the results of the 1999 September ASCA observation of SAX J1808.4−3658 made in the quiescent state.

2. OBSERVATION AND RESULTS

SAX J1808.4−3658 was observed with ASCA from 1999 September 17 (18:10 UT) through September 20 (4:40 UT) for a net exposure time of 63 ks. ASCA utilizes grazing-incidence, thin-foil mirrors with two kinds of focal-plane detectors: the Gas Imaging Spectrometer (GIS) and the Solid-State Imaging Spectrometer (SIS; Tanaka, Inoue, & Holt 1994). The GIS has a wider field of view and a higher time resolution, but it has poorer spatial resolution and low-energy efficiency (Ohashi et al. 1995). On the other hand, the SIS has a higher spatial resolution, a higher energy resolution, and better low-energy efficiency.

For our quiescence observation of SAX J1808.4−3658, we set the GIS to the highest time resolution mode in order to search for the 401 Hz pulsation, thus sacrificing the rise-time information and a part of the spectral and spatial information. The time resolution was 61 μs at a high-telemetry bit rate and 0.5 ns at a medium bit rate. The image resolution was reduced to 64 × 64 pixels, and the total number of spectral bins was 256. The SIS was operated in 1-CCD faint mode, which is appropriate for the observations of dim sources. The
SIS data have a time resolution of 4 s and cover a field of view of 11′ × 11′ area.

Both the SIS and the GIS data were screened with the standard data screening criteria. However, we could not apply the task GISCLEAN, which rejects background data using the combination of pulse height and rise-time information, because of the lack of the rise-time data. This resulted in a relatively high internal background in the GIS data. Using the screened data, we calculated an image for each sensor. We applied a temperature-dependent attitude correction to the SIS data, which reduced the systematic error of the source position to 0.5 (Gotthelf 1996; Ueda et al. 1999a). We found that the images of SIS-0 and SIS-1 were consistent and that both showed slight excess flux at the position consistent with that of SAX J1808.4—3658. However, the images of GIS-2 and GIS-3 look very different. In Figure 1, we show the images calculated from GIS-2, GIS-3, and summed SIS data. The images are slightly smoothed with a Gaussian kernel appropriate for each image. As seen in the GIS images, the difference in the diffuse emission pattern is apparent, especially at the position of SAX J1808.4—3658; a pointlike emission is seen in only GIS-3. Because the image difference (∼1 × 10⁻³ counts s⁻¹ cm⁻² keV⁻¹) is comparable to the local fluctuation of the internal background of the GIS (Makishima et al. 1996), we tried several different screening criteria using the GIS monitor data and the satellite’s orbit-related parameters. However, the difference did not disappear. Careful inspection of the GIS-3 image showed that the pointlike emission at the position of SAX J1808.4—3658 actually consisted of a single bright pixel. Smoothing by a Gaussian kernel mimicked a pointlike source. Because the raw image does not contain such a bright pixel, the coordinate transformation to the sky image, which includes a position randomization process, may have produced such a bright pixel. We confirmed that the bright pixel is not produced if we use a difference sequence of random number. Based on these analyses, we consider that the coarse image binning (1′ × 1′ bin) and high internal background make the GIS data inadequate to search for the faint point source. A search for the 401 Hz coherent pulsations also demonstrated that the statistics of the GIS data were not enough to detect the pulsations, even if the relative pulse modulation equals 100%.

Because the GIS data proved to be inadequate, we used the SIS data to evaluate the X-ray flux from SAX J1808.4—3658. We calculated a radial profile of the source from the summed SIS image (Fig. 2). The center of the profile was taken at the local peak of the (smoothed) image, which coincided with the position of SAX J1808.4—3658 within the accuracy of position determination (0.5 in radius). The radial profile was fitted with the model radial profile of a point source plus a constant background to determine the source flux. Precisely speaking, the model radial profile depends slightly on the X-ray energy, although the dependence is completely negligible compared with the statistical errors of the present data. The source flux was estimated to be (1.1 ± 0.4) × 10⁻³ counts s⁻¹ (the average of SIS-0 and SIS-1) for the energy range of 0.5–5 keV. The poor statistics of the data did not allow us to extract the spectral information. If we assume a power-law spectrum (with a photon index of 2) with an absorption column of 1.3 × 10²¹ cm⁻², which corresponds to the neutral hydrogen column of the source.

Fig. 1.—X-ray images calculated from the ASCA data: (a) GIS-2, (b) GIS-3, and (c) sum of SIS-0 and SIS-1. The expected position of SAX J1808.4—3658 is indicated by the encircled cross. GIS images are smoothed with a Gaussian kernel of σ = 1′. Contours are plotted in linear scale from 13.7 counts arcmin⁻¹ with an increment of 1.37 counts arcmin⁻¹. The SIS image (the sum of SIS-0 and SIS-1) is smoothed with a Gaussian kernel (σ = 0′42) after rebinning by a factor of 8. Contours are plotted in linear scale from 63.3 counts arcmin⁻¹ with an increment of 4.87 counts arcmin⁻¹. Note that the field of view is different between GIS and SIS.

Fig. 2.—Radial profile of the X-ray image calculated from the sum of the SIS-0 and SIS-1 data. The local peak of the image was taken as the center of the radial profile. Data points are plotted as crosses, and the best-fitting model profile for a point source (plus a constant background) is plotted as a solid line. No background is subtracted from the data.

3 See http://heasarc.gsfc.nasa.gov/docs/asca/newsletters/source_position4.html.
direction (Dickey & Lockman 1990), then the X-ray flux would be \((3 \pm 1) \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}\) in 0.5–5 keV. This flux converts to a luminosity of \((1.5–3) \times 10^{33} \text{ ergs s}^{-1}\) for the source distance of 2.5 kpc.

3. DISCUSSION

We observed the accretion-driven millisecond X-ray pulsar SAX J1808.4–3658 in quiescence with ASCA. We detected a faint X-ray source at the sky position consistent with that of the pulsar. However, the source was so dim that we could not study its spectral or timing properties. We first elaborate on the identification of the source and then on the nature of the source.

Because the surface density of X-ray sources as dim as SAX J1808.4–3658 is relatively high, an X-ray source may happen to coincide with SAX J1808.4–3658 by chance. The chance probability may be estimated using the log N–log S relation of the X-ray sources. ASCA survey data were used to investigate the log N–log S relation for both the cosmic X-ray background and the Galactic ridge emission (Sugizaki et al. 1999b) and the Galactic ridge emission (Sugizaki 1999c). The relation for both the cosmic X-ray background and the Galactic ridge emission (Sugizaki et al. 1999b) and the Galactic ridge emission (Sugizaki 1999c).

The X-ray sources brighter than \(3 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}\) are about 10^{11} deg^{-2}. Because the ASCA position determination error of SAX J1808.4–3658 is about 0.5 arcmin, the probability of finding a source of \(3 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}\) by chance at the position consistent with SAX J1808.4–3658 is estimated to be \(\approx 2\%\). Although this probability is not very low, the source that we detected is most probably SAX J1808.4–3658. If it were a chance coincidence of an unrelated source, the luminosity that we calculated for SAX J1808.4–3658 would be regarded as an upper limit.

The quiescent luminosity of SAX J1808.4–3658 that we obtained may be significantly lower than that obtained using BeppoSAX (Stella et al. 2000). In general, it is necessary that we assume an energy spectrum in order to convert the flux between different instruments. We assume that the spectral shape (e.g., the photon index and absorption column) of SAX J1808.4–3658 did not change between the ASCA and BeppoSAX observations and that the normalization did. We have tried two cases for the energy spectrum, a power law \((\Gamma = 2.0)\) and a blackbody \((kT = 0.3 \text{ keV})\), which may be appropriate for NS SXTs in quiescence. Because the column density of SAX J1808.4–3658 is not well constrained, we have tried a range of the column densities, from \(1.3 \times 10^{21}\) through \(6 \times 10^{21} \text{ cm}^{-2}\). Under these assumptions, the MECS count rate \((3.1 \times 10^{-3} \text{ counts s}^{-1} \text{ in 1.3–10 keV})\) is converted to the SIS count rate using the Portable, Interactive Multi-Mission Simulator, which is developed and maintained by HEASARC. \(^4\) Corresponding SIS count rates are found to be \((0.7–1.1) \times 10^{-2} \text{ counts s}^{-1} \text{ (0.5–5 keV)}\) for a power law and \((1.9–2.9) \times 10^{-2} \text{ counts s}^{-1} \text{ (0.5–5 keV)}\) for a blackbody. From this estimation, we conclude that the observed SIS count rate \((1.1 \pm 0.4) \times 10^{-3} \text{ counts s}^{-1}\) is at least a factor of 4 smaller than the MECS count rate, even if the statistical errors are considered. This means that the X-ray emission from SAX J1808.4–3658 is time variable.

The radio pulsar shock emission, which is preferred by Stella et al. (2000), may explain the time variation between the BeppoSAX and ASCA observations. X-ray emission from the shocked pulsar wind has been observed from the PSR B1259–63/SS 2883 system, which consists of a 48 ms radio pulsar and a Be star (Hirayama et al. 1999). ASCA observations of the PSR B1259–63/SS 2883 system were made near periastron and apastron of the highly elliptical orbit \((e = 0.86)\) of the pulsar. X-ray emission was detected at both periastron and apastron, but the X-ray intensity was different by an order of magnitude. Because the intensity change is well correlated to the binary phase, the difference of the stellar wind density may cause the intensity change. If the same or a similar mechanism works for the X-ray emission from SAX J1808.4–3658, the flux decrease between the BeppoSAX and ASCA observations may be understood as the density decrease of the ambient matter around SAX J1808.4–3658. However, it is not clear what would cause the density decrease of the ambient matter. Another emission mechanism, neutron star cooling, is also discussed by Stella et al. (2000). Although thermal emission from the cooling neutron star cannot explain the time variation, the mechanism may still be valid if the X-ray emission observed by BeppoSAX were dominated by another emission mechanism, such as residual accretion or radio pulsar shock emission.

Although the BeppoSAX observation favors the radio pulsar shock emission for the quiescence emission from SAX J1808.4–3658 (Stella et al. 2000), another possibility can be considered for the X-ray emission detected during the ASCA observation. ASCA may have observed the X-ray emission directly from the radio pulsar. ROSAT and ASCA observations of rotation-powered pulsars show that there is a very good correlation between the X-ray luminosity and the spin-down energy loss rate \(L_X = 10^{-2}E_{\text{spin}}^2\) (Becker & Trümper 1997). Here the X-ray luminosity \(L_X\) is defined in the range of 0.1–5 keV. The observed flux may be converted to the unabsorbed luminosity \((0.1–2.4 \text{ keV})\) as \(3.5 \times 10^{36} d_{14}^3 d_{a}^{-1} \text{ ergs s}^{-1}\), where \(d_{14}\) is the source distance normalized by 2.5 kpc (a power law with \(T = 2\) and \(N_H = 1.3 \times 10^{21} \text{ cm}^{-2}\) is assumed). By substituting \(L_X = 3.5 \times 10^{36} d_{14}^3 d_{a}^{-1}\), we obtain the spin-down energy-loss rate as \(E_{\text{spin}} = 3.5 \times 10^{34} d_{14}^2 \text{ ergs s}^{-1}\). This leads to a surface magnetic field of \(3.8 \times 10^{4} \text{ G}\). Although the distance to SAX J1808.4–3658 is not accurately known, this estimation of the surface magnetic field is consistent with the limits obtained from the outburst observation (Wijnands & van der Klis 1998; Psaltis & Chakrabarty 1999). This is also consistent with the surface magnetic field of millisecond radio pulsars. Therefore, we consider it possible that SAX J1808.4–3658 might have been a radio pulsar during the ASCA observation.

The very low X-ray luminosity of SAX J1808.4–3658 measured by ASCA may not fit in a scenario in which NS SXTs generally have a bottom luminosity of around \(10^{32}–10^{33} \text{ ergs s}^{-1}\) in quiescence while BH SXTs do not (Asai et al. 1998). We argue that this scenario may still be valid but that some unique feature of SAX J1808.4–3658 makes it an exception. Because the propeller effect might play an important role in NS SXTs in quiescence (Menou et al. 1999), one may suspect that the spin period and the magnetic field strength of the neutron star in SAX J1808.4–3658 have very different values than those of other neutron stars in low-mass X-ray binaries (LMXBs). However, this is not the case. Spin frequencies of the neutron star may be estimated from the observations of nearly coherent oscillations during type I X-ray bursts, as observed in some neutron star X-ray binaries or from the kilohertz quasi-periodic oscillations, and are mostly found in the range of \(200–600\) Hz (van der Klis 2000). According to the recycle scenario (Bhattacharya & van den Heuvel 1991), the surface magnetic field of the neutron stars in LMXBs may be comparable to those of the millisecond radio pulsars. Observations of the spectral transition of nonsupernovar NS SXTs actually give magnetic field

\(^4\) See http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html.
strengths comparable to those of the millisecond radio pulsars (Zhang, Yu, & Zhang 1998). Therefore, the spin frequency and the magnetic field strength of SAX J1808.4−3658 are not exceptional. It is noteworthy that the outburst luminosity of SAX J1808.4−3658 was only \(~10^{36}\) ergs s\(^{-1}\). If the quiescent and long-term average outburst luminosities are related, as is the case if the quiescent emission is dominated by thermal emission from the neutron star surface (Brown, Bildsten, & Rutledge 1998; Rutledge et al. 2000), the low quiescent luminosity may result from the low outburst luminosity. However, it is not clear why the outburst luminosity of SAX J1808.4−3658 is low (but see King 2000). Although we do not know what makes SAX J1808.4−3658 unique, its uniqueness may be responsible for both the detectable spin modulation during the outburst and the very low luminosities in quiescence.

R. W. was supported by NASA through Chandra Postdoctoral Fellowship grant PF9-10010 awarded by CXC, which is operated by SAO for NASA under contract NAS8-39073.

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