BROADBAND X-RAY SPECTROSCOPY OF A0535+262 WITH SUZAKU

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ABSTRACT

The transient X-ray binary pulsar A0535+262 was observed with Suzaku on 2005 September 14 when the source was in the declining phase of the August–September minor outburst. The ~103 s X-ray pulse profile was strongly energy dependent, with a double-peaked profile in the soft X-ray energy band (<3 keV) and a single-peaked smooth profile in hard X-rays. The width of the primary dip is found to increase with energy. The broadband energy spectrum of the pulsar is well described with a negative and positive power law with exponential (NPEx) continuum model, along with a blackbody component for soft excess. A weak iron Kα emission line with an equivalent width ~25 eV was detected in the source spectrum. The blackbody component is found to be pulsating over the pulse phase, implying that the accretion column and/or the inner edge of the accretion disk may be the possible emission site of the soft excess in A0535+262. The higher value of the column density is believed to be the cause of the secondary dip in the soft X-ray energy band. The iron line equivalent width is found to be constant (within errors) over the pulse phase. However, a sinusoidal type of flux variation of the iron emission line, in phase with the hard X-ray flux, suggests that the inner accretion disk is the possible emission region of the iron fluorescent line.

Subject headings: pulsars: individual (A0535+262) — stars: neutron — X-rays: stars

1. INTRODUCTION

Be X-ray binaries consist of a neutron star in an eccentric orbit around a Be star companion. The orbit of Be X-ray binaries is generally wide and eccentric with orbital periods in the range 16–400 days (Coe 2000). Mass transfer from the Be companion to the neutron star takes place through the circumstellar disk. When the neutron star passes through the disk or during the periastron passage, it shows strong outbursts with an increase in X-ray luminosity by a factor ≥100 (Negueruela 1998).

A0535+262 is a 103 s Be/X-ray binary pulsar discovered by Ariel 5 during a large outburst in 1975 (Coe et al. 1975). The binary companion HDE 245770 is an O9.7–B0 IIIe star in a relativistic wide eccentric orbit (e = 0.47) with an orbital period of ~111 days and at a distance of ~2 kpc (Finger et al. 1996; Steele et al. 1998). The pulsar shows regular outbursts with the orbital periodicity.Occasional giant X-ray outbursts are also observed when the object becomes even brighter than the Crab. The pulsar shows three typical intensity states, quiescence with a flux level of below 10 mcrab, normal outbursts with flux level in the range 10–100 mcrab, and giant outbursts during which the object becomes even brighter than the Crab. The pulsar was observed by Suzaku on 2005 September 14 when the source was in the declining phase of the August–September minor outburst. The ~103 s X-ray pulse profile was strongly energy dependent, with a double-peaked profile in the soft X-ray energy band (<3 keV) and a single-peaked smooth profile in hard X-rays. The width of the primary dip is found to increase with energy. The broadband energy spectrum of the pulsar is well described with a negative and positive power law with exponential (NPEx) continuum model, along with a blackbody component for soft excess. A weak iron Kα emission line with an equivalent width ~25 eV was detected in the source spectrum. The blackbody component is found to be pulsating over the pulse phase, implying that the accretion column and/or the inner edge of the accretion disk may be the possible emission site of the soft excess in A0535+262. The higher value of the column density is believed to be the cause of the secondary dip in the soft X-ray energy band. The iron line equivalent width is found to be constant (within errors) over the pulse phase. However, a sinusoidal type of flux variation of the iron emission line, in phase with the hard X-ray flux, suggests that the inner accretion disk is the possible emission region of the iron fluorescent line.

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During past X-ray observations of A0535+262 in quiescence, outburst, and giant outbursts, 103 s pulsations were detected. The pulse profile was single-peaked in quiescence (in the 1–10 keV range, see Mukherjee & Paul 2005; in the 3–20 keV range, see Negueruela et al. 2000), and double-peaked with a clearly asymmetric “main” and a more symmetric “secondary” pulse during the X-ray outbursts (Mihara 1995; Kretschmar et al. 1996; Maisack et al. 1997). The X-ray spectrum of the pulsar has been studied at soft and hard X-rays with various instruments at different luminosity levels. The spectrum of the object, during outbursts, shows cyclotron resonant scattering features at higher energies than those of the other pulsars. Two harmonic features at around 50 and 100 keV were detected in its 1989 outburst with the HEXE/TTM instrument on Mir-Kvant (Kendziorska et al. 1994). The CGRO/SSE observations of the 1994 outburst of the pulsar showed a significant absorption feature at 110 keV (Grove et al. 1995). These detections did not resolve whether the magnetic field of the pulsar is ~5 × 10^{12} G (when the fundamental occurs at 55 keV) or ~10^{13} G (for the 110 keV fundamental).

The most recent major X-ray outburst was detected in 2005 May–June with the BAT instrument on Swift when the 15–195 keV count rate was greater than 3 times that of the Crab Nebula (Tsuenger et al. 2005). Following the detection of the recent outburst, the pulsar was observed by INTEGRAL, RXTE, and the recently launched Suzaku. A cyclotron resonance feature at ~45 keV was detected in the Hard X-ray Detector (HXD) spectrum of Suzaku, with the estimated magnetic field of the pulsar at ~4 × 10^{12} G (Terada et al. 2006). The detection of the absorption feature at ~45 keV and its first harmonic at ~100 keV is reported from the INTEGRAL and RXTE observations of the pulsar during the 2005 August–September outburst (Caballero et al. 2007). Using the same Suzaku observation used for the analysis of the cyclotron resonance feature (Terada et al. 2006), we study the broadband spectral properties of the pulsar in the present paper.

2. OBSERVATION

The detection of the recent outburst of A0535+262 on 2005 May 16 with the BAT instrument on Swift prompted many observatories to observe the pulsar during this period. The RXTE ASM monitoring of the pulsar showed one major outburst of the pulsar, which lasted from 2005 May 6 to June 24. During this outburst,
The XIS was operated with the "1/4 window" option, which gives effective exposures of 22.3 ks with XIS and 21.7 ks with HXD. The XRD/DGSO detectors, silicon PIN diodes (450 cm$^2$, $E_{FWHM} = 180$ eV at 6 keV) and GSO crystal scintillators (<70 keV energy band) and GSO crystal scintillators (>30 keV). The effective areas of the PIN and GSO detectors are $180$ cm$^2$ at 15 keV and $390$ cm$^2$ at 100 keV, respectively. For a detailed description of the XIS and HXD detectors, refer to Koyama et al. (2007) and Takahashi et al. (2007).

One of the four CCDs is back-illuminated (BI), whereas the other three are front-illuminated (FI). The field of view of XIS is 1024$^2$ pixel X-ray-sensitive silicon PIN diodes and 30–600 keV with GSO scintillators. There are four sets of XIS, each with a 1024$^2$ pixel X-ray-sensitive CCD detector at the focus of each of the four X-ray telescopes. One of the four CCDs is back-illuminated (BI), whereas the other three are front-illuminated (FI). The field of view of XIS is 18$\times$18$\times$18 in full window mode, with an effective area of 340 cm$^2$ (FI) and 390 cm$^2$ (BI) at 1.5 keV. The energy resolution was 130 eV (FWHM) at 6 keV just after the launch. The HXD is a nonimaging instrument that is designed to detect high-energy X-rays. The HXD has 16 identical units made up of two types of detectors, silicon PIN diodes (<70 keV) and GSO crystal scintillators (>30 keV). The effective areas of the PIN and GSO detectors are $\sim 145$ cm$^2$ at 15 keV and $315$ cm$^2$ at 100 keV, respectively. The XRD/DGSO detectors are $\sim 145$ cm$^2$ at 15 keV and $315$ cm$^2$ at 100 keV, respectively. For detailed information on the XIS and HXD detectors, see Koyama et al. (2007) and Takahashi et al. (2007).

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3. Analysis and Results

The HXD data of the Suzaku observation of A0535+262 has already been presented by Terada et al. (2006). The same procedure was followed for the HXD/GSO data reduction to obtain the GSO source and background spectra. For HXD/PIN and XIS data reduction, we used the cleaned event data (ver. 1.2 products) to obtain the PIN and XIS light curves and source spectra. The simulated background events (bgd_a) were used to estimate the HXD/PIN background (Kokubun et al. 2007) for the A0535+262 observation. The response files released in 2006 March and August were used for HXD/GSO and HXD/PIN spectra, respectively. The accumulated events of the XIS data were discarded when the telemetry was saturated, the data rate was low, the satellite was in the South Atlantic Anomaly, and the source elevation above the Earth’s limb was below 5° for night-Earth and below 20° for day-Earth. Applying these conditions, the source spectra were accumulated from the XIS cleaned event data by selecting a circular region of 4.3 around the image centroid. Because this extraction circle is larger than the optional window, the effective extraction region is the intersection of the window and this circle. The XIS background spectra were accumulated from the same observation by selecting rectangular regions away from the source. The response files and effective area files for XIS were generated by using the xissimarfgen and xismarfgen tasks of FTOOLS (ver. 6.2). X-ray light curves of 2 s time resolution were extracted from the XIS and PIN event data. In the version 1.2 products of Suzaku observations, it is known that the XIS time assignment contains an error of 6 s compared to HXD when the 1/4 window option is applied.6 The HXD absolute time assignment was verified to be correct to better than 360 μs with the observation of the Crab pulsar (Terada et al. 2007). Although the time assignment error in XIS was much smaller than the pulse period of A0535+262, we corrected it before the analysis of the XIS data.

3.1. Timing Analysis

Barycentric correction was applied to the light curves of A0535+262 for the measurement of the pulse period. Pulse folding and a χ$^2$ maximization method were applied to the light curves, yielding the pulse period of the pulsar to be 103.375 ± 0.09 s (as reported in Terada et al. 2006). The pulse profiles obtained from the XIS and PIN light curves of the Suzaku observation of the pulsar are shown in Figure 2. From the figure, it is observed that the shape of the pulse profile in the XIS energy band (0.2–12 keV) is different from that in the HXD/PIN energy band (8–70 keV). The dip in the pulse profile in the pulse phase range 0.17–0.35, hereafter referred to as a primary dip, is narrow at soft X-rays (XIS energy band) and broad in the hard X-ray energy band. Apart from the variable width of the dip, a diplate structure is present in the soft X-ray pulse profile in the 0.65–0.80 pulse phase range which is absent in the hard X-ray profile. To investigate the energy dependence of the pulse profile of A0535+262, we generated light curves in different energy bands from XIS and PIN event data. The light curves are folded with the pulse period, and the corresponding pulse profiles are shown in Figure 3. The energy-resolved pulse profiles of the pulsar obtained from the Suzaku observation are found to be different from those of the previous observations (Mukherjee & Paul 2005; Negueruela et al. 2000; Kretschmar et al. 1996; Mihara 1995). The diplate structure (in the pulse phase range 0.65–0.80) is found to be very prominent below 1 keV. The width and depth of this structure decrease gradually with energy up to ~8 keV, beyond which it becomes

6 See http://www.astro.isas.jaxa.jp/suzaku/analysis/xis/timing/.
indistinguishable from the fine structures in the pulse profile. A gradual decrease in the normalized intensity in the 0.0–0.17 pulse phase range (as shown in the figure) is found at soft X-ray profiles, which finally merged with the primary dip, making the hard X-ray pulse profiles smooth and single-peaked. Pulse phase resolved spectroscopy would help in understanding the nature of the diplike structure and the gradual decrease of normalized intensity with energy prior to the primary dip in the pulse profile of A0535+262.

3.2. Spectral Analysis

3.2.1. Pulse Phase Averaged Spectroscopy

We calculated the energy spectrum from the events selected in the energy ranges of 0.3–10.0 keV for the back-illuminated CCD (XIS-1), 0.5–10.0 keV for the front-illuminated CCDs (XIS-0, XIS-2, and XIS-3), 10–70 keV for HXD/PIN, and 45–135 keV for HXD/GSO. After appropriate background subtraction, simultaneous spectral fitting was done using the XIS, PIN, and GSO spectra. All the spectral parameters other than the relative normalization were tied together for all the detectors. We tried to fit the broadband energy spectra with a model consisting of a blackbody component, a power law with exponential cutoff, a Gaussian function for the iron fluorescence line at 6.4 keV, and the cyclotron resonance factor (CYAB) at ~45 keV (as detected by Caballero et al. 2007). The analytical form of the CYAB is

\[
\text{CYAB}(E) = \exp \left[ -\frac{\tau (W/E_a)^2}{(E - E_a)^2 + W^2} \right],
\]

where \( E_a \) is the resonance energy, \( W \) is the width of the absorption structure, and \( \tau \) is the depth of the resonance.

This model gave a reduced \( \chi^2 \) of 1.41 (for 804 dof). The parameters of the cyclotron resonance feature are found to be consistent with those reported in Terada et al. (2006). It is found that the residual structures below 1 keV contribute significantly to the statistics of the spectral fitting. Because the spectral shape in this energy range is determined mainly by the low-energy absorption,
detailed modeling of the absorber (in terms of abundance, uniformity, etc.) may be necessary to improve fitting. However, we are interested in the global shape of the energy spectrum, not in the local structures, so we simply ignored the data below 1 keV for the subsequent spectral fitting. Simultaneous spectral fitting to the XIS and HXD spectra in 1.0–135.0 keV with the above model improved the fitting result, with a reduced $\chi^2$ of 1.33 (for 733 dof). However, a blackbody temperature of 1.36 keV is unusual in accretion-powered X-ray pulsars. This does not directly mean that the model is unacceptable, but it is worth pursuing another model. We have also tried to fit the continuum spectrum using a power law with a Fermi-Dirac cutoff, as described by Coburn et al. (2002), along with a blackbody component, Gaussian function, and cyclotron resonance factor. The spectral fitting, however, was very poor, with a reduced $\chi^2$ of 2.2 (for 736 dof).

We then tried to fit the broadband spectrum of A0535+262 using the negative and positive power law with exponential (NPEX) continuum component, along with the cyclotron resonance factor (CYAB) and interstellar absorption. The analytical form of the NPEX model is

$$\text{NPEX}(E) = (N_1E^{-\alpha_1} + N_2E^{-\alpha_2}) \exp \left(-\frac{E}{kT}\right),$$

where $E$ is the X-ray energy (in keV), $N_1$ and $\alpha_1$ are the normalization and photon index of the negative power law, respectively, $N_2$ and $\alpha_2$ are those of the positive power law, and $kT$ is the cutoff energy in units of keV. All five parameters of the NPEX continuum component were kept free. However, as in the case of Terada et al. (2006), we could not constrain the positive power law index ($\alpha_2$) very well. Terada et al. fixed $\alpha_2$ to 2, but we found that a slightly larger value of $\alpha_2$ improved the overall fit to the data. The value of $\chi^2$ found by fixing the value of $\alpha_2$ to 2 and 3 are 1029 and 933 for 730 dof, respectively. Therefore, we fixed the second index ($\alpha_2$) to 3 in the subsequent analysis. The relative instrument normalizations of the four XISs and the PIN and GSO detectors were kept free, and the values are found to be

1.0, 1.0, 0.92, 1.0, 1.1, and 1.04 for XIS3, XIS0, XIS1, XIS2, PIN, and GSO, with a clear agreement with the detector calibration.

The CYAB parameters were initially set around the value quoted in Terada et al. (2006) and then allowed to find the corresponding best-fit values. The NPEX continuum model showed significant improvement over the Fermi-Dirac cutoff and cutoff power-law models in the spectral fitting, with a reduced $\chi^2$ of 1.28 for 730 dof. It was found that the NPEX continuum model fits the Suzaku 1.0–135 keV spectrum better than the cutoff power-law continuum model which was used to describe the RXTE and INTEGRAL spectra of the pulsar (Caballero et al. 2007). The spectral parameters of the best-fit model obtained from the simultaneous spectral fitting to the XIS, PIN, and GSO data of the Suzaku observation of A0535+262 are given in Table 1. The count-rate spectra of the Suzaku observation are shown in Figure 4, along with the model components (top) and residuals to the cutoff power-law continuum model (middle) and the best-fit NPEX continuum model (bottom). We need to note that the iron line width could be an artifact, because no degradation of the energy resolution is included in the response files. In such a case, an artificial line width of 20 eV (1 $\sigma$, at 5.9 keV) may be obtained even at the time of the A0535+262 observation (Koyama et al. 2007).

### 3.2.2. Pulse Phase Resolved Spectroscopy

The presence of significant energy-dependent dips in the pulse profile of A0535+262 prompted us to make a detailed study of the spectral properties at different pulse phases of the pulsar. To investigate the changes in the spectral parameters at soft X-rays at different pulse phases of the pulsar, we used data from the XIS (both BI and FI) and HXD/PIN detectors. The XIS and PIN spectra were accumulated into 10 pulse phase bins by applying phase filtering in the FTOOLS task xselect. The XIS and PIN background spectra and response matrices used for the phase-averaged spectroscopy were also used for the phase-resolved spectroscopy. Simultaneous spectral fitting was done in the 1.0–70.0 keV energy band.
respectively, whereas the NPEX flux in the 1–50 keV energy band is plotted in units of $10^{24} \text{ atoms cm}^{-2}$.

For phase 0.2–0.3, we found that the (99%) upper limit of the absorption column density toward the pulsar ($N_{\text{H}}$) is lower than the Galactic hydrogen column density ($N_{\text{H}}$). How- ever, because the interstellar medium can be highly nonuniform, we consider that this $N_{\text{H}}$ value is within the acceptable range.

Minimum values for the blackbody flux, absorption column density, and photon index $\alpha$ occur at phase 0.2–0.3. Although the minimum looks significant, we should be careful about the correlation among the parameters.

In Figure 6 we plot confidence contours between $N_{\text{H}}$ and the blackbody normalization ($N_{\text{BB}}$) to check the acceptable ranges of these parameters, taking two extreme phases, namely, the 0.3–0.4 (left) and 0.2–0.3 (right) pulse phases. For phase 0.2–0.3, we found that the (99%) upper limits to $N_{\text{H}}$ and the blackbody normalization ($N_{\text{BB}}$) are $3.8 \times 10^{21}$ atoms cm$^{-2}$ and $2.4 \times 10^{-3}$, respectively. However, for phase 0.3–0.4, the acceptable ranges of $N_{\text{H}}$ and $N_{\text{BB}}$ are found to be $(1.56-1.94) \times 10^{22}$ atoms cm$^{-2}$ and $(4.5-9.5) \times 10^{-3}$, respectively (for 99% confidence level). The confidence contours for the above two phases show that the absorption column density and the blackbody flux are low at pulse phase 0.2–0.3 and high at the 0.3–0.4 phase. During the diplike structure, a hint of decrease in the blackbody flux and a higher value of $N_{\text{H}}$ can be seen in the figure. This implies that the diplike structure at soft X-rays in the pulse profile is due to the increase in the absorption column density, resulting in the reduction of the apparent blackbody flux. The iron line equivalent width does not show any systematic variation over pulse phases. On the other hand, the modulation is a little larger in the line intensity, whose profile is similar to that of the NPEX flux. However, if we exclude the 0.2–0.3 phase bin, the $\chi^2$ value of the line intensity is reduced to 3.4 (8 dof). If we apply the $F$-test, the reduction corresponds to $F^2_{8,1} = 13.3$ and a probability of 6.55 $\times 10^{-3}$. This means that the line intensity at phase 0.2–0.3 is significantly different from that of the other phases.

4. DISCUSSION

Apart from two RXTE observations and three BeppoSAX observations during quiescence, all other observations reported before
2005 August were made during the giant outbursts when the source flux was about equal to or more than that of the Crab Nebula. The RXTE and INTEGRAL observations of the pulsar, during the 2005 August–September minor outburst, confirmed the earlier discovery of a cyclotron feature at \( \sim 45 \) keV, along with the detection of its first harmonic at \( \sim 100 \) keV (Caballero et al. 2007). The Suzaku observation of A0535+262 during the declining phase of the 2005 August–September normal outburst provided new data on spectral properties of the pulsar up to \( \sim 100 \) keV and how they might evolve throughout the outburst.

4.1. Pulse Profile

During the present observation of the minor outburst, the pulse profile of A0535+262 is different from that in the quiescence or during the earlier reported outbursts. The pulse profile in the hard energy band is known to show energy and luminosity dependence in outbursts, which is described in Bildsten et al. (1997) based on the BATSE observations. The profile tends to be double-peaked when the luminosity is high, e.g., \( > 10^{37} \) ergs s\(^{-1}\) (20–100 keV), whereas it becomes a single peak at \( 4 \times 10^{36} \) ergs s\(^{-1}\). The current Suzaku observation had even lower luminosity (2 \( \times 10^{35} \) ergs s\(^{-1}\) in the 20–100 keV band), and showed an almost sinusoidal profile above 25 keV. The Suzaku hard-band observation found a single-peaked profile, as was seen by BATSE.

Hard X-ray pulse profiles of A0535+262, obtained from the RXTE and INTEGRAL observations of the same 2005 outburst with a peak luminosity of \( \sim 10^{37} \) ergs s\(^{-1}\), appear to be double-peaked (Caballero et al. 2007). The two peaks with a shallow valley constitute a trapezoid-like profile above 35 keV separated by a wide trough. Although the observations were carried out during the peak and the decay of the outburst, the added pulse profile may be dominated by the profile during the peak of the outburst. Therefore, the profile presented by Caballero et al. (2007) probably reflects that at the higher luminosity outburst (at the peak of the outburst). The double-peaked hard X-ray profiles at a source luminosity of \( \sim 10^{37} \) ergs s\(^{-1}\) agrees with the luminosity dependence of pulse profiles observed with BATSE. The profiles obtained from the Suzaku observation, however, appear to be different from those of the RXTE and INTEGRAL observations. This is interpreted as being due to luminosity-dependent effects, as the Suzaku observation was at a luminosity level 2 orders of magnitude less that peak luminosity.

On the other hand, the Suzaku pulse profile in the soft energy band (<10 keV) is found to be similar to that obtained from the Ginga observation of the 1989 outburst (Mihara 1995). The dip-like structure, prominent only at soft X-rays, is also recognized in the Ginga profile. Because the Ginga observation was made during the outburst when the source was \( \sim 80 \) times brighter than the present observation, the profile may be interpreted such that A0535+262 in outbursts generally contains a dip-like structure at soft X-rays as seen in the 2005 Suzaku observation. This type of structure is also seen in the RXTE observation of the pulsar during the same minor outburst in 2005 August–September (Caballero et al. 2007). This dip-like structure is absent in the pulse profiles when the pulsar was in quiescence (Mukherjee \\& Paul 2005). As other observations of A0535+262 in giant outbursts focused on the hard X-ray energy ranges, the dip-like structure could have been missed in the pulse profiles.

4.2. Phase-Averaged Spectroscopy

The X-ray spectrum of A0535+262 has been described by different continuum models at different energy ranges. Hard X-ray observations during outbursts, meant for the study of cyclotron absorption features and hence the pulsar magnetic field, were fitted by different continuum models such as optically thin thermal bremsstrahlung, power law, power law with an exponential cutoff, Wien’s law, or different combinations of the above components (dal Fiume et al. 1988; Kendziorra et al. 1994; Grove et al. 1995), whereas the 2–37 keV spectrum, obtained from the Ginga observation of the 1989 outburst, was well fitted with the NPEX continuum model (Mihara 1995). Current analysis of the Suzaku data showed that the NPEX continuum model fits well to the source spectrum.

Selection of an appropriate continuum model may be crucial to investigate the broad features in the spectrum, such as the soft excess represented by a blackbody component. The spectral fitting to the 0.3–10 keV BeppoSAX spectra, during quiescence, yielded a blackbody component of temperature \( \sim 1.3 \) keV, along with a power-law component of index \( \sim 1.8 \) (Mukherjee \\& Paul 2005). On the other hand, the Suzaku data when fitted with NPEX continuum model yielded a much lower temperature of \( \sim 0.16 \) keV, which is common for most of the X-ray pulsars. We suspect that the difference arises from the different selection of the continuum model. In fact, when the Suzaku wide-band spectra were fitted...
by a power law with an exponential cutoff, we did indeed obtain a blackbody temperature of 1.36 keV. This demonstrates the importance of the continuum selection to quantify the blackbody component. However, the selection criteria for the continuum choice have yet to be rigorously defined.

Most of the transient Be/X-ray binary pulsars undergo periodic outbursts due to the enhanced mass accretion when the neutron star passes through the dense regions of the circumstellar disk. During the passage, there is every possibility of an increase in the absorption column density. In the case of A0535+262, we found that the absorption column density was higher than the Galactic column density toward A0535+262 (5.9 × 10^{21} atoms cm\(^{-2}\)) during the minor outburst in 2005 August–September. Note that the Suzaku observation was made near the apastron at the orbital phase of 0.42–0.43. From BeppoSAX observations of the pulsar in quiescence (orbital phases 0.77, 0.05, and 0.42), however, the estimated value of the absorption column density was found to be similar to that of the Galactic column density (Mukherjee & Paul 2005). During the 1998 RXTE PCA observations (in quiescence, orbital phases of 0.0 and 0.77), the value of the absorption column density was found to be a factor of about 10 higher than that of the Galactic column density (Negueruela et al. 2000). During the Ginga observation of the pulsar in the 1989 outburst (orbital phase of 0.96), the estimated absorption column density was found to be 4.8 ± 1.2 × 10^{21} atoms cm\(^{-2}\) (Mihara 1995), which is compatible with the Galactic value. These are only three instances where the absorption column density of the pulsar is reported so far. Although the available data are scarce, the absorption column density does not show clear correlation with the source intensity or the orbital phase. In this sense, it is noteworthy that the observations of the large absorption column with RXTE PCA were made when the circumstellar disk around the Be companion (Be disk) was absent (Negueruela et al. 2000).

Haigh et al. (2004) suggest that the X-ray activity of the pulsar is correlated with the change of the truncation radius of the Be disk. The truncation of the disk by the tidal interaction with the neutron star, which defines the truncation radius, could explain the observed X-ray outbursts in Be/X-ray binary systems. When the truncation radius reduces, the material from the outer portions of the disk are expelled and may be found elsewhere in the binary system. This may trigger the giant X-ray outburst. When the Be disk disappears, as in the case of RXTE PCA observations, all the disk material is considered to be accreted and/or ejected throughout the binary system. The presence of the expelled material in the line of sight may have caused a moderately large absorption column. Haigh et al. (2004) argue that the reduction of the Be disk continues for several orbital periods before/ap the giant outburst. Because the Suzaku observation was made around an orbital period after the giant outburst in 2005 May–June, the reduced Be disk may have caused moderately large absorption column.

Broadband spectroscopy of A0535+262 shows the presence of a weak iron K\(_α\) emission line with ~25 eV equivalent width. Other than the 1989 Ginga observation and recent RXTE and INTEGRAL observations of the same minor outburst, none of the previous observations of the pulsar could detect the weak emission line at ~6.4 keV. The emission line is interpreted as being due to the fluorescent line from the cold ambient matter in the vicinity of the neutron star. If the cold matter is distributed spherically symmetric around the neutron star, the excess column density over the Galactic value, ~5 × 10^{21} atoms cm\(^{-2}\), would produce an iron emission line with an equivalent width of only a few eV (Makishima 1986). The larger equivalent width we detected may be interpreted as the cold matter having an asymmetric distribution, and more matter is distributed outside the line of sight.

The fluorescence of the atmosphere of the binary companion could be a possible source of the iron emission line. However, we consider that it does not make a major contribution to the observed equivalent width, because the solid angle subtended by the companion, which is estimated as \(\Omega/4\pi \leq 10^{-4}\) at apastron, is very small due to the long orbital period of A0535+262. Instead, we conjecture that the accretion disk is the probable reprocessing site producing the iron fluorescent line. Because the pulse phase with higher line flux covers more than a half of the pulse period, the reprocessing site should subtend a large solid angle against the neutron star. The accretion disk conforms to this condition.

4.3. Pulse Phase Resolved Spectroscopy

Pulse phase resolved spectroscopy of A0535+262 showed that the blackbody component, used to describe the soft excess, is pulsating as seen in some other accreting X-ray pulsars, such as LMC X-4 and SMC X-1 (Naik & Paul 2004a, 2004b; Paul et al. 2002 and references therein). The pulsation is found to be in phase with that of the middle-band X-ray emission (e.g., 2.5–5.0 keV band; see Fig. 3). However, in the case of Her X-1, the pulsating soft component is found to be shifted by about 230° in phase from the power-law continuum component (Endo et al. 2000). A systematic and detailed study of the accreting X-ray pulsars which show soft excess revealed that the soft excess is a common feature in the X-ray pulsars (Hickox et al. 2004). Both the pulsating and nonpulsating natures of the soft excess seen in various X-ray pulsars suggest a different origin of emission of the soft components. The possible origins of the soft excess in accretion-powered X-ray pulsars are (1) emission from accretion column, (2) emission by a collisionally energized cloud, (3) reprocessing by a diffuse cloud, and (4) reprocessing by optically thick material in the accretion disk (Hickox et al. 2004). The soft excess emission from the accretion column and the reprocessing of harder X-rays by optically thick material in the accretion disk are expected to show pulsations, whereas in other cases it is nonpulsating in nature. The pulsation of the soft component (blackbody component) in phase with the middle-band X-ray emission in A0535+262 suggests that the most probable region of soft X-ray emission is the accretion column and/or the inner accretion disk.

The absorption column seems to make a significant contribution to produce the diplike structure at soft X-rays at phases 0.65–0.80 in the count rate profile (Fig. 5, top left). Column density takes large values, ~1.2 × 10^{22} atoms cm\(^{-2}\), at phase 0.7–0.8. This may contribute to produce the diplike structure in the profiles below 1 keV which disappears from the profiles at higher energies. On the other hand, the primary dip exists at all energies. The observed primary dip in the pulse profile can be understood by the change in the NPEx model parameters over pulse phase. The NPEx continuum model is an approximation of the saturated thermal Comptonization in hot plasma (Makishima et al. 1999). At low energies, it reduces to the ordinary power law with negative slope. The lower value of the power-law index (\(\alpha_1\)) at the primary dip phase implies a large optical depth to the Compton scattering. This means that many photons are scattered out from the line of sight. It explains the presence of the primary dip in the soft and hard X-ray pulse profiles at same phase. In addition to the primary dip, the deepening of the dip at the phases 0.0–0.17 (Fig. 3) can also be understood by the changes of the parameters of the Comptonizing plasma. The power-law index (\(\alpha_1\)) tends to be larger and the exponential cutoff energy is smaller in this phase range. This means that the Comptonizing plasma has a relatively smaller optical depth and a lower temperature. This reduces the efficiency of Compton upscatter.
of hard photons, which causes the deepening of the dip at phases 0.0–0.17 above 5 keV.

5. SUMMARY

Using the Suzaku observation of A0535+262, we performed the timing and spectral analysis in the broadband energy range. The \( \approx 103 \) s pulsation is detected both in HXD/PIN and XIS light curves of the pulsar. Apart from the primary dip, the pulse profile at soft X-rays shows a diplike structure which disappears at higher energies. When the source spectrum was modeled by a cutoff power-law continuum model with a blackbody component for the soft excess, it yielded a blackbody temperature of \( \approx 1.36 \) keV. However, the NPEX continuum model provided a blackbody component of \( \approx 0.16 \) keV temperature, which is common in the case of accretion-powered X-ray pulsars, along with a weak iron emission line of equivalent width of about 25 eV. The value of the absorption column density \( N_H \) is found to be higher than that of the Galactic value toward the pulsar. The pulsating nature of the blackbody component, as seen from the phase-resolved spectroscopy, suggests that the accretion column and/or inner part of the accretion disk is the possible source of soft excess emission in A0535+262. The iron line equivalent width remains more or less constant over the pulse phase with an average value of about 25 eV. This value of equivalent width is found to be high for a symmetric distribution of circumstellar matter corresponding to a \( N_H \) of \( 5 \times 10^{21} \) atoms cm\(^{-2}\). This rules out the fluorescence from the atmosphere of the companion and fluorescence by the surrounding material in the line of sight as the dominant source of iron line emission. The pulsating nature of the iron line flux in phase with the hard X-ray (NPEX) flux suggests that the inner part of the accretion disk is the probable site of iron fluorescence emission.

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REFERENCES

Bildsten, L., et al. 1997, ApJS, 113, 367
Caballero, I., et al. 2007, A&A, 465, L21
Coburn, W., et al. 2002, ApJ, 580, 394
Coe, M. J. 2000, in IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith & H. F. Henrichs (ASP Conf. Ser. 214; San Francisco: ASP), 656
Coe, M. J., Carpenter, G. F., Engel, A. R., & Quenby, J. J. 1975, Nature, 256, 630
d’Al Fiume, D., Frontera, F., & Morelli, E. 1988, ApJ, 331, 313
Endo, T., Nagase, F., & Mihara, T. 2000, PASJ, 52, 223
Finger, M. H., Wilson, R. B., & Harmon, B. A. 1996, ApJ, 459, 288
Finger, M. H., et al. 1994, in The Evolution of X-Ray Binaries, ed. S. Holt & C. S. Day (New York: AIP), 459
Grove, J. E., et al. 1995, ApJ, 438, L25
Haigh, N. J., Coe, M. J., & Fabregat, J. 2004, MNRAS, 350, 1457
Hickox, R. C., Narayan, R., & Kallman, T. R. 2004, ApJ, 614, 881
Kendziorra, E., et al. 1994, A&A, 291, L31
Kokubun, M., et al. 2007, PASJ, 59, 53
Koyama, K., et al. 2007, PASJ, 59, 23
Kretschmar, P., et al. 1996, A&AS, 120, 175
Maisack, M., et al. 1997, A&A, 325, 212
Makishima, K. 1986, in Physics of Accretion onto Compact Objects, ed. K. O. Mason, M. G. Watson, & N. E. White (Berlin: Springer), 249
Makishima, K., Mihara, T., Nagase, F., & Tanaka, Y. 1999, ApJ, 525, 978
Mihara, T. 1995, Ph.D. thesis, Univ. Tokyo
Mitsuda, K., et al. 2007, PASJ, 59, 1
Mukherjee, U., & Paul, B. 2005, A&A, 431, 667
Naik, S., & Paul, B. 2004a, ApJ, 600, 351
———. 2004b, A&A, 418, 655
Negueruela, I, 1998, A&A, 338, 505
Negueruela, I., Reig, P., Finger, M., & Roche, P. 2000, A&A, 356, 1003
Paul, B., et al. 2002, ApJ, 579, 411
Steele, I. A., Negueruela, I., Coe, M. J., & Roche, P. 1998, MNRAS, 297, L5
Takahashi, T., et al. 2007, PASJ, 59, 35
Terada, Y., et al. 2006, ApJ, 648, L139
———. 2007, PASJ, submitted
Tueller, J., et al. 2005, Astron. Telegram 504