A Suzaku View of Accretion-powered X-Ray Pulsar GX 1+4

Yuki Yoshida1,2, Shunji Kitamoto1,2, Hiroo Suzuki1, Akio Hoshino1,2, Sachindra Naik3, and Gaurava K. Jaisawal3

1 Department of Physics, College of Science, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan; yy@rikkyo.ac.jp
2 Research Center for Measurement in Advanced Science, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
3 Astronomy and Astrophysics Division, Physical Research Laboratory, Navrangpura, Ahmedabad-380009, Gujarat, India

Received 2016 August 29; revised 2016 December 24; accepted 2017 February 22; published 2017 March 21

Abstract

We present results obtained from a Suzaku observation of the accretion-powered X-ray pulsar GX 1+4. A broadband continuum spectrum of the pulsar was found to be better described by a simple model consisting of a blackbody component and an exponential cutoff power law than the previously used compTT continuum model. Though the pulse profile had a sharp dip in soft X-rays (<10 keV), phase-resolved spectroscopy confirmed that the dimming was not due to an increase in photoelectric absorption. Phase-sliced spectral analysis showed the presence of a significant spectral modulation beyond 10 keV except for the dip phase. A search for the presence of a cyclotron resonance scattering feature in the Suzaku spectra yielded a negative result. Iron K-shell ($K_{\alpha}$ and $K_{\beta}$) emission lines from nearly neutral iron ions (<Fe III>) were clearly detected in the source spectrum. A significant $K_{\alpha}$ emission line from almost neutral Ni atoms was detected for the first time in this source. We estimated an iron abundance of $\sim$80% of the solar value and an Ni/Fe abundance ratio of about two times the solar value. We searched for an iron Ly-$\alpha$ emission line and found a significant improvement in the spectral fitting by inclusion of this line. We found a clear intensity modulation of the iron $K_{\alpha}$ line with the pulse phase with an amplitude of 7%. This finding favored an inhomogeneous fluorescent region with a radius much smaller than the size ($\sim$3 $\times$ 10$^{12}$ cm) estimated by an assumption of homogeneous matter.

Key words: accretion, accretion disks – pulsars: individual (GX 1+4) – stars: neutron

1. Introduction

GX 1+4 is a peculiar accretion-powered X-ray pulsar with a long pulse period of about 150 s (Doty 1976). Early observations in the 1970s showed the pulsar to be very bright in X-rays and exhibiting regular spin-up ($\dot{\nu}/\nu = 0.02$ yr$^{-1}$) (Nagase 1989), which is in good agreement with the standard accretion torque model (e.g., Ghosh & Lamb 1979a, 1979b). However, in the 1980s, the luminosity of the pulsar decreased by at least two orders of magnitude, during which it remained undetectable (Hall & Davelaar 1983). When the pulsar reappeared, it showed a spindown activity (Makishima et al. 1988), suggesting the occurrence of a torque reversal event. According to the standard accretion torque model (Ghosh & Lamb 1979b), the observed torque reversal in GX 1+4 indicates that the surface magnetic field of the neutron star should be $\sim$10$^{14}$ G (Makishima et al. 1988; Dotani et al. 1989; Mony et al. 1991). As this value is extremely high, an alternative model, e.g., a retrograde disk model, was also discussed by Makishima et al. (1988) and Dotani et al. (1989). Chakrabarty et al. (1997) suggested that the formation of a retrograde disk denied the need for an unusually strong magnetic field and naturally explained the anticorrelation between torque and luminosity in the 20–60 keV band as observed with BATSE. A marginal detection of cyclotron resonance scattering features at $\sim$34 keV (Naik et al. 2005; Rea et al. 2005; Ferrigno et al. 2007) indicated that the magnetic field of the neutron star should be of the order of 10$^{12}$ G. Therefore, the question of the magnetic field strength of GX 1+4 is still open. The companion star of GX 1+4 is a late-type giant star (Glass & Feast 1973; Davidsen et al. 1976). An optical counterpart of the neutron star was classified as an M5 III spectral type giant star in a rare type of symbiotic system (Shahbaz et al. 1996; Chakrabarty & Roche 1997). Based on variations of the pulse period of the neutron star during spinup
The energy spectrum of accretion-powered X-ray pulsars is often represented by a model consisting of a power law with a high-energy cutoff, known to be the signature of unsaturated Comptonization, and Gaussian functions for the iron emission lines. In intermediate- and high-luminosity states of GX 1+4 ($F_{10-100\text{keV}} = 10^{-10} - 10^{-9}$ erg s$^{-1}$ cm$^{-2}$), the source spectrum has been described by either a cutoff power-law (CPL) model or an analytical model based on thermal Comptonization of hot plasma close to the source (compTT in XSPEC; Galloway et al. 2000, 2001; Naik et al. 2005; Ferrigno et al. 2007). Galloway et al. (2000) proposed that the compTT model reproduced the observed spectrum of GX 1+4 with scattering taking place in the accretion column. Phase-sliced spectroscopy of GX 1+4 using the compTT model provided us with insight into the accretion flow and the accretion column geometry (Galloway et al. 2000, 2001; Naik et al. 2005; Ferrigno et al. 2007).

It is well known that GX 1+4 exhibits bright iron K-shell emission lines (Dotani et al. 1989; Kotani et al. 1999; Naik et al. 2005; Paul et al. 2005). The long pulsation period of the pulsar makes it appropriate to investigate the phase dependence of emission-line properties. Kotani et al. (1999) analyzed K-shell emission lines from lowly ionized iron ions by using Ginga and ASCA observations of the pulsar and found a positive correlation between the equivalent width and the absorption column density of the circumstellar matter. Using parameters such as the ionization state of the iron ions (Fe I–IV), absorption column density, and estimated X-ray luminosity, Kotani et al. (1999) suggested that the line-emitting region in GX 1+4 consisted of lowly ionized plasma and extended up to $10^{12}$ cm from the neutron star.

Along with the iron K$\alpha$ line, a strong K$\beta$ emission line with an equivalent width of $\sim$550 eV was also detected during an extended low state of the pulsar in 2000 (Naik et al. 2005). On the other hand, Paul et al. (2005) reported a discovery of an Ly$\alpha$ emission line in the absence of a K$\beta$ line in the pulsar spectrum. They suggested that the diffuse gas in the Alfvén sphere and/or accretion curtains to magnetic poles are the possible iron Ly$\alpha$ line emitting regions in GX 1+4. The distance and size of the line-emitting region can be determined by examining the intensity modulation of emission lines with respect to the neutron star rotation. Considering the detection of emission lines corresponding to different ionization states at different luminosity levels, it is important to carry out detailed spectral investigation of the pulsar by using data from detectors with good energy resolution to have a clear understanding of the matter distribution in the binary system.

Suzaku observation of GX 1+4 provided us with an opportunity to analyze the phase-sliced broadband spectra and emission-line diagnostics because of its highly sensitive detectors with very good energy resolution, as well as the long spin period of the pulsar. In this paper, we report mainly the results obtained from the detailed spectral analysis of Suzaku observation of the pulsar. These results will help in understanding the emission mechanism around the neutron star and the origin of the emission lines.

2. Observation and Data Reduction

2.1. Suzaku Observation

Suzaku observation of the pulsar GX 1+4 (ObsID = 405077010) was carried out from 2010 October 02 06:43 (UT) to October 04 12:20 (UT). During the observation, the X-ray Imaging Spectrometers (XISs; Koyama et al. 2007) were operated in normal mode incorporating a 1/4 window option, which ensures a time resolution of 2 s. Spaced-row Charge Injection (SCI) was also performed with 2 keV equivalent electrons for XIS 0 and XIS 3 (front-illuminated or FI CCDs) and 6 keV equivalent electrons for XIS 1 (back-illuminated or BI CCD). The Hard X-ray Detector (HXD; Takahashi et al. 2007) was operated in the standard mode wherein individual events were recorded with a time resolution of 61 $\mu$s. The target was placed at the HXD nominal position. Though the total on-source duration during the observation was $\sim$192 ks, the effective exposures with XIS-0, XIS-1, XIS-3, HXD/PIN, and HXD/GSO were 97.3, 99.7, 99.7, 88.3, and 82.2 ks, respectively.

2.2. Data Reduction

Suzaku archival data of GX 1+4 were analyzed by using HEASARC software version 6.16–6.18. On-source events of the XISs were extracted from a circular region of 3$'$ radius with center at the source position. Background events were extracted from the XIS data by selecting an annulus region (from 4$'$ to 5$'$) away from the source with the pulsar coordinates as the center. A pileup estimation following Yamada et al. (2012) showed a maximum pileup of 1% around the source position. Therefore, we neglected the effect of the pileup. A quick-look analysis of the XIS 1 data showed an apparently inconsistent energy scale compared to those of XIS 0 and XIS 3. This inconsistency has been interpreted as the self charge filling (SCF) effect (Todoroki et al. 2012). Events for XIS 0 and XIS 3 were well recovered from the degradation of the charge transfer efficiency with the SCI, though it was insufficient for XIS 1. We corrected XIS 1 data from the SCF effect by applying the method proposed by Todoroki et al. (2012) (see the Appendix). The redistribution matrix files and ancillary response files for XISs were generated by using xisrmfgen and xissimarfgen routines (Ishisaki et al. 2007), respectively. In our analysis, the response file released in 2010 July was used for HXD/PIN data, whereas response and effective area files released in 2010 May were used for HXD/GSO data.

Background-subtracted spectra obtained from the Suzaku observation of GX 1+4 are shown in Figure 1. In the same figure, expected background spectra for the HXD/PIN and HXD/GSO are also plotted. We used tuned (LCFITDT) non-X-ray background (NXB) models (Fukazawa et al. 2009) to get the NXB events for HXD/PIN and the HXD/GSO. Repeatability of the NXB for HXD/PIN is about 5%. Therefore, it is at most 5% of the signal from GX 1+4 even in the energy range around 50 keV. After NXB subtraction from the HXD/PIN data, we also subtracted an expected contribution of cosmic X-ray background (CBX) by using a typical model by Boldt (1987). Since CBX amounts to only 5% of NXB, its ambiguity due to the sky-to-sky fluctuation ($\sim$11% at $1\sigma$) corresponds to at most 0.6% of NXB and is negligibly small.

As GX 1+4 is located at Galactic coordinates of ($l$, $b$) = (1°9, 4°28), Galactic ridge X-ray emission (GRXE) may contaminate the data as well. INTEGRAL/IBIS mapping observations showed that the typical 17–60 keV GRXE flux is less than $2 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$ FOV$^{-1}$ in the Galactic bulge region $l|l| < 10^\circ$ (Figure 13 of Krivonos et al. 2007). However, within the HXD/PIN field of view (FOV), we expected a contribution of GRXE flux of $<2 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, and it
...during Suzaku observation of GX 1+4. The expected NXB spectra and their repeatability are plotted in blue, and the CXB and GRXE are shown in orange and purple, respectively.

The expected NXB contribution of contamination for the source. Since all the contaminating sources were near the edge of the FOV of HXD/GSO, with a small effective area of HXD, we neglected them. For timing analysis, we applied barycentric correction to the arrival times of individual photons using the aebarycen task of FTOOLS. Light curves with time resolutions of 2 and 1 s were extracted from XIS (2–10 keV) and HXD/PIN (15–60 keV) event data, respectively. Figure 2 shows the background-subtracted light curves with a bin time of 160 s, i.e., at the pulsar spin period, in soft (top panel) and hard X-rays (bottom panel). Although there are several data points with a low count rate, there is no trend of any gradual intensity change during the Suzaku observation of the pulsar.

3. Analysis and Results

3.1. Timing Analysis

For timing analysis, we applied barycentric correction to the arrival times of individual photons using the aebarycen task of FTOOLS. Light curves with time resolutions of 2 and 1 s were extracted from XIS (2–10 keV) and HXD/PIN (15–60 keV) event data, respectively. Figure 2 shows the background-subtracted light curves with a bin time of 160 s, i.e., at the pulsar spin period, in soft (top panel) and hard X-rays (bottom panel). Although there are several data points with a low count rate, there is no trend of any gradual intensity change during the Suzaku observation of the pulsar.

3.1.1. Pulse Profile

We searched for pulsations in the light curves obtained from XISs (2–10 keV range), HXD/PIN (15–60 keV range), and HXD/GSO (60–114 keV range) by using the standard epoch-folding technique (Leahy et al. 1983). Our analysis revealed a consistent barycentric pulsation period of $P = 159.9445 \pm 0.0002$ s at an epoch of 55,471.3 MJD, in all the light curves. Our estimated pulse period agrees well with the expected value derived by considering the earlier measurements of period and period derivative of the pulsar (González-Galán et al. 2012). Using the estimated pulse period and time of intensity minimum (55,471.2796 MJD) as the epoch, we generated pulse profiles of the pulsar by applying the efold task of FTOOLS. Pulse profiles obtained from background-subtracted light curves in 2.0–4.0 keV, 4.0–7.0 keV, 7.0–10.0 keV, 15.0–25.0 keV, 25.0–60.0 keV, and 60.0–114 keV energy ranges (top to bottom panels). For phase-resolved spectroscopy, the data in each panel are divided into eight pulse phase intervals as indicated by quoted numbers and different colors.
corrected for dead time. A gradual change in the shape of the energy-resolved pulse profiles can be clearly seen in the figure. The sharp dip in the soft X-ray pulse profiles was prominent, although there was no spike-like feature in the dip as reported by Dotani et al. (1989). The width of the dip was found to be increasing with energy as pointed out by Naik et al. (2005). Apart from the dip, a small hump was also seen at phase $\sim 0.1$ in the 15.0–25.0 keV range pulse profile.

3.2. Phase-averaged Spectroscopy

3.2.1. Continuum of Broadband Spectrum

In this section, we describe phase-averaged spectroscopy of GX 1+4 by using XIS, HXD/PIN, and HXD/GSO data obtained from the Suzaku observation of the pulsar. As shown in Figure 1, prominent iron K-shell emission lines and significant absorption in the low-energy band are evident even without any spectral model fitting. Since the XIS spectra show strong absorption, the detected events below 2 keV are dominated by the “low-energy tail” component (Matsumoto et al. 2006), which is characteristic of the instruments. Suchy et al. (2012) reported that this “low-energy tail” component had not been well calibrated, due to which there is a small mismatch between the FI and BI CCDs. Therefore, we used data from FI CCDs in the 2–10 keV range in our broadband spectral fitting.

Broadband (2–120 keV range) spectra of GX 1+4 were simultaneously fitted with the earlier reported comppTT continuum model along with the photoelectric absorption (TBabs in XSPEC) by matter along the line of sight (Galloway et al. 2000). We applied both the geometries, e.g., a disk and a sphere, by using the analytical approximation at a fixed redshift of 0. The residuals obtained from the spectral fitting by assuming disk and spherical geometries are shown in panels (a) and (b) of Figure 4, respectively. The best-fit parameters obtained from these fittings are column density of photoelectric absorption $N_H = 1.1 \times 10^{23}$ atoms cm$^{-2}$, photon source temperature $T_\gamma = 1.4$ keV, hot electron temperature $T_e = 11$ keV, and optical depths for disk geometry $\tau_{\text{disk}} = 4.4$ and spherical geometry $\tau_{\text{sphere}} = 9.6$. These values are nearly consistent with those of earlier reported values obtained from RXTE (Galloway et al. 2000), BeppoSAX (Naik et al. 2005), and INTEGRAL (Ferrigno et al. 2007) observations. However, the presence of global wavy structures in the residuals can be clearly seen in panels (a) and (b) of Figure 4, yielding poor values of reduced $\chi^2$ ($\chi^2_\nu = 4.4$ for 261 dof) for both geometries.

As an alternative representation of the continuum, we attempted our spectral fitting by using an empirical model consisting of an exponential CPL continuum along with photoelectric absorption (TBabs). This simple model fitted the 2–120 keV range spectrum better than the comppTT model, yielding a reduced $\chi^2$ of 2.9 (dof = 262). However, the residuals obtained from this fitting still showed wavy structures (panel (c) of Figure 4). The addition of a blackbody (BB) component to the exponential CPL continuum model improved the spectral fitting further. The reason for better spectral fitting with the addition of a blackbody component is as follows. The BB+CPL model has an additional free parameter compared to the comppTT model and can determine the slope of the high-energy part (index of the CPL) and the cutoff energy independently from the low-energy range of the spectrum. On the other hand, the slope and the cutoff energy of the comppTT model are not independent at low-energy range. Though the value of the reduced $\chi^2$ obtained from fitting the data with the BB+CPL model is still poor ($\chi^2_\nu/dof = 2.1/260$), the wavy structures are now absent in the residuals (panel (d) of Figure 4). Therefore, we used the BB+CPL model as the most suitable model to describe the broadband (2–120 keV range) spectrum of GX 1+4. A possible reason for the poor value of reduced $\chi^2$ can be due to the spectral variations at different pulse phases as shown in Figure 3. The values of parameters obtained from spectral fitting with the BB+CPL model are column density of photoelectric absorption $N_H = (1.30 \pm 0.02) \times 10^{23}$ H atoms cm$^{-2}$, blackbody temperature $kT_{BB} = 1.66 \pm 0.03$ keV, radius of blackbody emitting region $R = 0.63^{+0.16}_{-0.20}$ km (assuming a distance of 4.3 kpc), photon index $\Gamma = 0.46^{+0.03}_{-0.04}$ and cutoff energy $E_{\text{cutoff}} = 22.1 \pm 0.6$ keV. Using this model, the unabsorbed source flux in the 1–120 keV range was estimated to be $F_{1–120 \text{ keV}} = 4.1 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$.

3.2.2. Emission Lines and Related Features

As discussed in the previous section, the broadband continuum spectrum of GX 1+4 can be better described by a model consisting of a blackbody component and a cutoff power-law component (BB+CPL) along with interstellar absorption. As seen in Figure 1, several emission lines and other features are distinctly visible even without spectral fitting. For a detailed analysis of emission lines and related features in GX 1+4, we restricted our spectral fitting to the 5.8–7.8 keV energy range. In this restricted region, the continuum can be fitted by a simple power-law (PL) model with an absorption edge so that we can deduce the edge parameter independently from the low-energy absorption. However, the large value of photoelectric absorption with $N_H = 1.30 \times 10^{23}$ H atoms cm$^{-2}$ affects the intensities of the emission lines. Thus, we applied the photoelectric absorption (TBabs) to only the Gaussian functions used for emission lines by fixing it at the above value. Note that, for our broadband spectroscopy, we used only the FI CCDs because of a discrepancy between the FI and BI CCDs in the low-energy region (below 3 keV). However, in the above-restricted narrow energy range, the...
Since the intense emission line feature at around 6.4 keV is known to be the iron Kα line, the iron Kβ line should appear at around 7.1 keV. As the iron Kβ line contaminates the absorption edge feature, it is difficult to determine the parameters corresponding to these structures. As the ionization state of the iron is low for the 6.4 keV line, we fixed the ratio of the energy of the iron Kβ to that of the Kα lines to be 0.6.

Therefore, we used data from all three CCDs for the analysis of emission lines and related features in GX 1+4.

Table 1
Best-fit Spectral Parameters for Emission Lines and Related Structures Obtained by Fitting the Phase-averaged Spectrum of GX 1+4

| Parameter | Model A<sup>a</sup> | Model A<sup>b</sup> | Model B<sup>c</sup> | Model C<sup>d</sup> |
|-----------|---------------------|---------------------|---------------------|---------------------|
| $N_{\text{Fe}}$ (10<sup>15</sup> cm<sup>−2</sup>) | 1.30(fixed) | 1.30(fixed) | 1.30(fixed) | 1.30(fixed) |
| $E_{\text{Edge}}$ (keV) | 7.190±0.012 | 7.190(fixed) | 7.190(fixed) | 7.190(fixed) |
| $E_{\text{Fe Kα}}$ (keV) | 6.424±0.001 | 6.425±0.001 | 6.425±0.002 | 6.424±0.001 |
| $E_{\text{Fe Kβ}}$ (keV) | 1.119±0.002 | 1.119±0.002 | 1.119±0.002 | 1.119±0.002 |
| $N_{\text{Fe Kα}}$ (10<sup>−3</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | 1.39±0.02 | 1.40±0.02 | 1.29±0.02 | 1.28±0.02 |
| $N_{\text{Fe Kβ}}$ (10<sup>−3</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | 153±3 | 153±3 | 152±3 | 152±3 |
| $E_{\text{Fe Kα}}$ (keV)<sup>e</sup> | 7.086 | 7.086 | 7.087 | 7.085 |
| $E_{\text{Fe Kβ}}$ (keV) | 0.10±0.04 | 0.10±0.04 | 0.10±0.04 | 0.10±0.04 |
| $N_{\text{Fe Kα}}$ (10<sup>−4</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | 1.5±0.2 | 1.3±0.3 | 1.4±0.2 | 1.4±0.2 |
| $N_{\text{Fe Kβ}}$ (10<sup>−4</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | 0.11±0.02 | 0.16±0.03 | 0.10±0.02 | 0.11±0.01 |
| $E_{\text{Fe Kα}}$ (eV) | 18.5<sup>f</sup> | 25.4<sup>f</sup> | 15±3 | 17±3 |
| $E_{\text{Fe Kβ}}$ (eV) | 7.49±0.02 | 7.50±0.02 | 7.49±0.02 | 7.48±0.01 |
| $N_{\text{Fe Kα}}$ (10<sup>−4</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | 1.7±0.3 | 1.7±0.3 | 1.3±0.2 | 1.5±0.2 |
| $E_{\text{Fe Kα}}$ (eV) | 17±5 | 18±3 | 16<sup>g</sup> | 17±3 |
| $N_{\text{Fe Kβ}}$ (10<sup>−4</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | ... | ... | 6.98±0.06 | ... |
| $N_{\text{Fe Kα}}$ (10<sup>−4</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | ... | ... | 0.6±0.3 | ... |
| $E_{\text{Fe Kα}}$ (eV) | ... | ... | 8±3 | ... |
| $E_{\text{Fe Kβ}}$ (eV) | ... | ... | 6.70(fixed) | ... |
| $N_{\text{Fe Kα}}$ (10<sup>−4</sup> photons s<sup>−1</sup> cm<sup>−2</sup>) | ... | ... | <0.1 | ... |
| $E_{\text{Fe Kβ}}$ (eV) | ... | ... | <3.2 | ... |
| $\chi^2$/dof<sup>h</sup> | 1.10(966) | 1.09(965) | 1.09(965) | 1.11(965) |

Notes. Widths of iron Kα, Ni Kα, iron Lyα, and iron Heα were fixed to 0 eV. The errors given here are for 90% confidence limits.

<sup>a</sup> Model A: a power-law continuum multiplied by an absorption edge model along with three Gaussians for iron Kα and Kβ lines and Ni Kα line.

<sup>b</sup> Model A*: similar spectral components to Model A, but the line width of iron Kβ remained a free parameter.

<sup>c</sup> Models B, C: spectral models that are like model A but with an additional Gaussian component. Model B includes an additional Gaussian for the iron Lyα line, and model C includes an additional Gaussian for the iron Heα line. In any model, the photoelectric absorption is multiplied by only the Gaussian components.

<sup>d</sup> Energies of the iron Kβ line were set to be 1.103 times that of the iron Kα line.

Discrepancy between the FI and BI CCDs is negligibly small. Therefore, we used data from all three CCDs for the analysis of emission lines and related features in GX 1+4.
with the High Energy Transmission Grating Spectrometer (HETGS) on board Chandra. We also searched for an iron Lγ line in the XIS spectra of the pulsar. Before adding the iron Lγ line component to our model, we fitted the phase-averaged spectra by keeping the width of the Kα line as a free parameter. The values obtained are summarized in Table 1 (model A'). We found a significant broadening of the Kβ line with 100 ± 30 eV, in the standard deviation of the Gaussian function with a 90% confidence level. The null hypothesis probability of increasing freedom as being free of the width was 1.2 × 10⁻³ using the F-test. This broadening of the Kβ line suggests that the emission-line feature is contaminated with other features, such as an Lγ line. We added another line component at around 6.9 keV as the iron Lγ line to the model consisting of a PL continuum, an absorption edge, and three Gaussian functions for emission lines and taking into account a photoelectric absorption (TBabs).

The fitting was conducted by scanning the center energy of the iron Lγ line from 6.9 to 7.06 keV with a step of 5 eV. Then the energy of the edge was fixed at 7.190 keV, which was obtained in the analysis of emission lines and related features without an iron Lγ component. In the fitting, the lines were assumed to be sufficiently narrow.

Figure 5(b) shows the resultant χ² values as a function of the center energy of the iron Lγ line emission line. Addition of an iron Lγ line component to the model significantly improved the fitting, with the value of χ² decreased from 1066.89 (dof = 966) to 1054.14 (dof = 965). The null hypothesis probability of the inclusion of this line component was estimated to be 6.9 × 10⁻⁴. The results obtained from our analysis are listed in Table 1 (model B). The line center energy and intensity, estimated from Suzaku observation of the pulsar, were found to be 6.98 ± 0.06 keV and (0.8 ± 0.1) × 10⁻⁴ photons s⁻¹ cm⁻², respectively, which are consistent with those reported by Paul et al. (2005). If the iron Lγ line component was included in the model, the resultant intensity ratio of iron Kα and Kβ emission lines was 0.10 ± 0.02, which is still consistent with that of Fe I–Ⅲ within their errors.

We also searched for an He-like iron Kα emission by fixing its center energy to be 6.70 keV, which is expected from the best-fit value of the iron Lγ emission line. We did not find any improvement in the value of χ² with the addition of the Gaussian function. The 90% upper limit of the line intensity
Further, we searched for a cyclotron absorption line at \( \sim 34 \text{ keV} \) as reported earlier from BeppoSAX (Naik et al. 2005; Rea et al. 2005) and INTEGRAL (Ferrigno et al. 2007) observations of the pulsar, although there was no visual indication of any such feature in the residuals obtained from HXD/PIN and HXD/GSO were fitted with the addition of an absorption component—a multiplicative absorption edge or Gaussian absorption line (\( g_{\text{abs}} \) in XSPEC; \( \exp\left(-\tau_a/\sqrt{2\pi}\sigma_a\right)\exp\left(-(E-E_{\text{abs}})^2/2\sigma_a^2\right) \)), where the width of the Gaussian absorption line, \( \sigma_a \), was fixed at 4 keV as in Ferrigno et al. (2007). The absorption feature at \( \sim 34 \text{ keV} \) could not be detected, as its significance was less than 3\( \sigma \). The 90\% confidence upper limit for maximum absorption depth \( \tau_a \) of the line was \(<0.7\). Further, we searched for an absorption feature between 30 and 110 keV by using a Gaussian absorption line model, the width of which was fixed at 5, 10, and 15 keV. Consequently, we conclude the absence of any detectable absorption feature in the above energy range.

### 3.2.3. Search for an Absorption Feature at \( \sim 34 \text{ keV} \)

We searched for a cyclotron absorption line at \( \sim 34 \text{ keV} \) as reported earlier from BeppoSAX (Naik et al. 2005; Rea et al. 2005) and INTEGRAL (Ferrigno et al. 2007) observations of the pulsar, although there was no visual indication of any such feature in the residuals obtained from HXD/PIN and HXD/GSO were fitted with the addition of an absorption component—a multiplicative absorption edge or Gaussian absorption line (\( g_{\text{abs}} \) in XSPEC; \( \exp\left(-\tau_a/\sqrt{2\pi}\sigma_a\right)\exp\left(-(E-E_{\text{abs}})^2/2\sigma_a^2\right) \)), where the width of the Gaussian absorption line, \( \sigma_a \), was fixed at 4 keV as in Ferrigno et al. (2007). The absorption feature at \( \sim 34 \text{ keV} \) could not be detected, as its significance was less than 3\( \sigma \). The 90\% confidence upper limit for maximum absorption depth \( \tau_a \) of the line was \(<0.7\). Further, we searched for an absorption feature between 30 and 110 keV by using a Gaussian absorption line model, the width of which was fixed at 5, 10, and 15 keV. Consequently, we conclude the absence of any detectable absorption feature in the above energy range.

### 3.3. Phase-sliced Spectroscopy

The pulse profile of the pulsar, as shown in Figure 3, was found to be characterized by several energy-dependent features, such as the sharp and prominent dip with variable width, the hump-like feature, etc. This prompted us to carry out phase-sliced spectral analysis of the Suzaku observation of GX 1+4. For this, we divided data into eight pulse phase bins as shown in Figure 3 with different colors. Phase intervals 1 and 3 (marked in red in the figure) were combined into one. Phase interval 2 (marked in black in the figure) is around the intensity minimum phase, and we call this phase the “dip interval.”

In order to grasp the basic properties of the pulsar among all the phase-sliced spectra in a model-independent way, we first calculated spectral ratios, e.g., dividing the phase-sliced spectra by the phase-averaged spectrum. The resultant spectral ratios are shown in Figure 7. The modulation below \( \sim 7 \text{ keV} \) was found to be small for all the phase-sliced spectra except the dip interval. The spectral ratio for the dip interval not only showed a simple absorption feature but also implied the absence of a spectral component that mainly contributes in the energy range below 10 keV. In hard X-ray ranges, an increase in the amplitude of spectral modulation with energy suggested a change in power-law photon index for different phase bins. Apart from the spectral changes with pulse phase of the pulsar, a large equivalent width of the iron K\( \alpha \) emission line can be clearly seen in the dip interval.

We fitted the phase-sliced spectra in the 2–120 keV ranges with the model consisting of BB + (continuum + gaussFeK ++ , gaussFeK ++ + gaussFeK NiK ++ ). As in the case of phase-averaged spectroscopy, we used the BB + CPL continuum model to fit all the phase-sliced spectra. It was found that the above model fitted all seven spectra very well, and the residuals obtained from our fitting are shown in the left panels of Figure 8. The reduced \( \chi^2 \) values obtained were in the range of 1.15–1.37. The best-fit parameters derived from phase-sliced spectral fitting by using the BB + CPL continuum model are listed in Table 2 and plotted as a function of pulse phase in Figure 9. The column density (\( N_{\text{H}} \)) of photoelectric absorption was found to be constant (within errors) over pulse phases, while the value of the photon index and cutoff energy showed variations over pulse phase. One notable result of this fitting is that the \( kT_{\text{BB}} \) and \( \Gamma \) at the dip interval are significantly larger and flatter than those at other phases as shown in Figures 9(b) and (d).

As an alternative representation of the BB + CPL continuum, we adopted the compTT model to the phase-sliced spectra as was used to reproduce the source spectrum in previous works. The residuals obtained from the fitting by the compTT continuum model are shown in Figure 8, and parameters obtained from spectral fitting are compiled in Table 2. The values of reduced \( \chi^2 \) obtained from each of the phase-sliced spectral fittings with the compTT model were \(<2\). The
equivalent hydrogen column density did not show any significant variation over pulse phases of the pulsar. While the optical depth of hot plasma $\tau$ and the photon source temperature $T_e$ during the dip interval resulted in larger values than those of other phases, the hot electron temperature $T_e$ and the normalization $A_e$ were minimum at the dip interval. However, as in the case of phase-averaged spectroscopy, the residuals show wavy structures above $20\,\text{keV}$, which yielded larger values of reduced $\chi^2$ than those obtained from the BB+CPL model.

To investigate the variation of emission lines and related features with pulse phase, we used the same model as in the case of phase-averaged spectroscopy, e.g., power-law continuum multiplied by an absorption edge and the emission lines (iron K$_\alpha$, iron K$_\beta$, and Ni K$_\alpha$ lines) multiplied by the photoelectric absorption ($\text{TBabs}$) to fit the phase-sliced spectra. Then, we fixed the ratios of the energies of the iron K$_\beta$ line and the edge to that of the iron K$_\alpha$ line at 1.03 and 1.119 times, respectively, and the widths of the three lines were fixed to be narrow enough according to the results of the phase-averaged spectroscopy. The values of equivalent hydrogen column density $N_H$ were fixed at $(1.29-1.38) \times 10^{23}$ H atoms cm$^{-2}$ for each phase-sliced spectrum (see Table 2).

The iron Ly$\alpha$ line was not included in this analysis.

Parameters obtained from our spectral fitting are plotted in Figure 9 and summarized in Table 2. The center energies of the iron ($E_{\text{Fe K}_\alpha}$) and Ni lines ($E_{\text{Ni K}_\alpha}$) were found to remain constant. Enhancement of the equivalent width of the iron K$_\alpha$ line at the dip interval was notable, and the same was seen for iron K$_\beta$ and Ni lines. The intensity ratio of the iron K$_\beta$ to the K$_\alpha$ lines was consistent with a constant value (within errors) at 0.12 of the neutral case (Yamaguchi et al. 2014). An intensity modulation of the iron K$_\alpha$ line can be seen in the figure. The line became intense in the phase between 0.7 and 1.1. Intensities of iron K$_\beta$ and the Ni K$_\alpha$ lines also showed similar behavior. We performed a $\chi^2$ test to investigate the presence/absence of modulation in the line intensity with pulse phase, which yielded $\chi^2$/dof = 29.84/7. This value indicated that the modulation of line intensity with pulse phase is statistically significant with a null hypothesis probability of $1.0 \times 10^{-4}$. The depth of the edge was slightly shallow at around phase 0.5, although the errors are large.

4. Discussion

4.1. Pulse Profile and Dip

Pulse profiles of GX 1+4 have been studied by several authors to understand the cause of the presence of a peculiar sharp dip. Detailed investigation of the source properties during the dip can provide important information about the accretion flow and geometry of the emission region. Dips in pulse profiles can originate from various mechanisms, which were discussed in previous studies. Dotani et al. (1989) interpreted that the dip structure in the pulse profile is due to the cyclotron resonant scattering of photons at the accretion column above the magnetic pole. Recently it has been reported that the cyclotron resonance scattering can affect the pulse profile of accretion-powered X-ray pulsars at energies closer to the cyclotron absorption line energy, as seen in the case of Be/X-ray binary pulsar GX 304-1 (Jaisawal et al. 2016, and references therein). However, the cyclotron absorption line has not yet been detected in the broadband spectra of GX 1+4.

Therefore, the cyclotron resonance scattering feature may not be the cause of the sharp dip seen in the pulse profile of GX 1+4. In phase-resolved spectroscopy of the RXTE observations, Galloway et al. (2001) found an increase in optical depth at the dip phase of the pulsar. They interpreted the sharp and prominent dip in the pulse profile as being due to the obscuration or eclipse of a hot spot by the accretion column. A similar explanation was also proposed by Giles et al. (2000) during a faint state of GX 1+4.

We carried out phase-averaged and phase-sliced spectroscopy to investigate the changes in spectral parameters during the dip and nondip phases of the pulsar by using high-quality data from Suzaku observation. Spectral hardening was observed during the dip interval compared to the nondip phases. However, the value of equivalent hydrogen column density did not show any significant variation within the 90% confidence level. Moreover, the spectral ratio for the dip interval (Figure 7) showed the dimming of the source over a wide energy band, especially below 10 keV. These results indicate that the dip in the pulse profile of GX 1+4 is not due to the increase in the photoelectric absorption, but rather due to the scattering of photons by hot electrons in the optically thick region compared to other phase intervals. This supports the earlier interpretation of alignment of the accretion column containing hot plasma with the line of sight as the cause of the sharp dip in the pulse profile of GX 1+4.

Naik et al. (2005) pointed out the widening of the dip at higher energies and speculated that the high-energy photons escape from the column preferentially at large angle, whereas the low-energy photons are more isotropic. In other words, the emission geometry might have changed from a pencil beam at low energy to a fan beam at high energy. The energy-resolved pulse profiles of GX 1+4 obtained from Suzaku observation also indicated a similar shape change with energy. The idea by Naik et al. (2005), therefore, can qualitatively explain the observed behavior. A similar idea had been proposed by Galloway & Wu (1999), where photons emitted from the polar caps get Compton-scattered by the plasma in the accretion column before escaping toward the observer.

4.2. Broadband Spectroscopy of GX 1+4

4.2.1. X-Ray Spectrum with Suzaku Observation

In intermediate- and high-luminosity states, the spectra of GX 1+4 have been described by the compTT model (Galloway et al. 2000; Naik et al. 2005; Ferrigno et al. 2007). The luminosity during Suzaku observation of the pulsar was comparable to those observations. Considering earlier results, we also attempted to have the compTT continuum model fit the observed phase-averaged broadband spectrum. The results obtained from our spectral fitting were found to be consistent with those reported earlier. However, the presence of wavy structures in the residuals obtained from fitting the source spectra with the compTT continuum model allowed us to try another empirical model, e.g., the blackbody and cutoff power-law (BB+CPL) model in spectral fitting. This model improved the spectral fitting without showing any such features in the residuals.

The compTT continuum model provides meaningful physical parameters compared to other empirical models. In our phase-sliced spectroscopy with the compTT continuum model, the optical depth $\tau$, photon source temperature $T_e$, and normalization $A_e$ were found to be
Table 2
Best-fit Spectral Parameters Obtained by Fitting the Phase-sliced Spectra of *Suzaku* Observation of GX 1+4

| Interval | 1 and 3 | 2 | 4 | 5 | 6 | 7 | 8 |
|---------|---------|---|---|---|---|---|---|
| \(N_{\text{BH}}(10^{23} \text{ cm}^{-2})\) | 1.13±0.04 | 1.06±0.04 | 1.16±0.05 | 1.14±0.04 | 1.04±0.03 | 1.09±0.03 | 1.09±0.02 | 1.07±0.03 |
| \(T_0\) (keV) | 1.30±0.04 | 1.66±0.05 | 1.91±0.05 | 1.40±0.03 | 1.44±0.02 | 1.38±0.05 | 1.33±0.05 | 1.33±0.04 |
| \(T_e\) (keV) | 9.1±0.3 | 8.6±0.3 | 11.3±0.3 | 11.2±0.2 | 11.3±0.2 | 11.3±0.2 | 10.8±0.2 | 10.8±0.2 |
| \(\tau\) | 4.3±0.1 | 5.2±0.2 | 3.8±0.1 | 4.4±0.1 | 4.6±0.0 | 4.8±0.0 | 4.3±0.3 | 4.3±0.3 |
| \(A_{1}\) | 1.82±0.07 | 1.17±0.04 | 1.53±0.06 | 1.75±0.03 | 2.01±0.02 | 1.98±0.02 | 1.86±0.04 | 1.86±0.04 |
| \(\chi^2_{\nu}\) ( dof) | 1.17(261) | 1.23(261) | 1.30(261) | 1.86(261) | 1.82(261) | 1.50(261) | 1.41(261) |

| Interval | 1 and 3 | 2 | 4 | 5 | 6 | 7 | 8 |
|---------|---------|---|---|---|---|---|---|
| \(N_{\text{BH}}(10^{23} \text{ cm}^{-2})\) | 1.12±0.04 | 1.07±0.05 | 1.17±0.05 | 1.06±0.03 | 1.09±0.03 | 1.09±0.02 | 1.06±0.04 | 1.06±0.03 |
| \(T_0\) (keV) | 1.31±0.05 | 1.63±0.08 | 1.19±0.02 | 1.41±0.04 | 1.44±0.02 | 1.38±0.04 | 1.34±0.05 | 1.34±0.05 |
| \(T_e\) (keV) | 9.4±0.3 | 8.6±0.3 | 11.3±0.3 | 11.2±0.2 | 11.3±0.2 | 11.3±0.2 | 10.9±0.3 | 10.9±0.3 |
| \(\tau\) | 9.3±0.2 | 12.2±0.5 | 8.4±0.1 | 9.5±0.1 | 9.9±0.1 | 10.4±0.1 | 9.3±0.2 | 9.3±0.2 |
| \(A_{1}\) | 1.83±0.05 | 1.20±0.05 | 1.55±0.04 | 1.83±0.04 | 2.04±0.03 | 2.01±0.02 | 1.87±0.06 | 1.87±0.06 |
| \(\chi^2_{\nu}\) ( dof) | 1.17(261) | 1.24(261) | 1.30(261) | 1.86(261) | 1.82(261) | 1.50(261) | 1.41(261) |

### Notes
- The errors given here are for 90% confidence limits.
- Intervals 1–3 correspond to 0.90–0.95, 0.95–0.99, 0.99–1.00, 1.00–1.10, 1.25–1.50, 1.50–1.75, 1.75–2.00, and 2.00–2.25 phase ranges, respectively.
- Normalization parameter for the $\text{comptT}$ model component ($\times 10^{-2}$).
- BB and CPL represent blackbody and exponential cutoff power law, respectively.
- Blackbody radius assuming a distance of 4.3 kpc.
- The model is represented by a power-law continuum multiplied by an absorption edge model along with three Gaussians for iron Kα, Kβ lines and the Ni Kα line.
- Widths of iron Kα, iron Kβ, and Ni Kα are fixed to 0 eV in the fitting. Energies of the iron Kα line and the edge are set to 1.108 and 1.119 times that of the iron Kα line, respectively.
- In units of 10^{-3} photons s^{-1} cm^{-2}.

significantly modulated with the pulse phase of the pulsar. In particular, the increasing value of \(\tau\) and decreasing values of \(T_e\) and \(A_{1}\) at the dip interval were also reported by Galloway et al. (2000).

In the $\text{comptT}$ model, the seed photons undergo scattering by thermal hot plasma through an escape probability distribution that depends on optical depth and geometry (either sphere or disk). Therefore, this model is insufficient to describe Comptonization in the accretion column, where the hot plasma has a cylindrical geometry with the base as the source of seed photons. Additional parameters should be introduced that affect the energy spectra, such as the ratio of height and radius of the cylinder and the angle between the line of sight and the cylinder axis. For example, only scattered photons are expected to be observed from the column if it is viewed at a right angle with respect to the cylinder axis, even if the optical depth is \(\leq 1\). On the other hand, the number of scattered photons gets reduced when viewed along the cylinder axis. Therefore, the viewing angle of the accretion column plays a crucial role in shaping the energy continuum. Better fitting of *Suzaku* data with the BB+CPL continuum model suggested that cylindrical geometry is most preferred in GX 1+4. In this geometry, the observed spectrum can be separated into two components, e.g., a seed photon component described by the blackbody (BB) and the scattered photon component expressed as CPL. We also tried to fit the phase-averaged broadband spectra of GX 1+4...
with two-component models such as compTT+compTT (used to describe the hard X-ray spectrum of Be/X-ray binary pulsar X Per by Doroshenko et al. 2012) and compTT+BB. These models also fitted the energy spectra well with comparable values of reduced χ² as in the case of the BB+CPL model. Although these empirical models fit the data better, the correspondence between the obtained parameters and actual physical ones is not clear. For this purpose, more sophisticated modeling is required by considering the scattering cross section in the strong magnetic field and realistic geometry of the accretion column.

4.2.2. X-Ray Spectra of Previous Observations

In an effort to confirm our interpretation, we analyzed archival data from the BeppoSAX and Rossi X-ray Timing Explorer (RXTE) observations of the pulsar and then compare the results obtained from the Suzaku observation of GX 1+4. The log of these observations is given in Table 3. We have used two BeppoSAX observations of the pulsar GX 1+4 when the source was at a flux level of ~10⁻⁹ erg s⁻¹ cm⁻² in the 2–100 keV energy range. These two observations are the same as used by Naik et al. (2005). The data were obtained with three major instruments: the Low-Energy Concentrator Spectrometer (LECS; 0.1–5 keV), Medium-Energy Concentrator Spectrometers (MECS; 1–10 keV), and hard X-ray Phoswich Detector System (PDS; 15–300 keV), covering a broad energy range from soft to hard X-rays (Boella et al. 1997). During the observation in 1996, LECS was not operated and the effective exposures for MECS and PDS were 38.6 and 17.6 ks, respectively. The 1997 observation was carried out for effective exposures of 13.0, 31.5, and 13.5 ks for LECS, MECS, and PDS, respectively. Standard procedures were followed for data reduction for both the BeppoSAX observations of GX 1+4. Spectra from LECS and MECS were extracted from CCD chips by selecting circular regions of 4′ around the source center. Background spectra for these observations were also extracted by selecting circular regions away from the source. The PDS spectra were retrieved from the standard products of both the observations. Using appropriate spectra, background, and response files as provided by instruments teams, spectral fitting was carried out in the ~1–150 keV range.

We also analyzed archival data of the pulsar obtained from the Proportional Counter Array (PCA; Jahoda et al. 1996) and High Energy X-ray Timing Experiment (HEXTE; Rothschild et al. 1998) on board the RXTE satellite to obtain a suitable continuum model. For this purpose, four RXTE observations of the pulsar with long exposures (>15 ks) during intermediate- and high-luminosity phases were chosen to examine the properties of the pulsar. One of these observations (X-III) is the same RXTE observation, the results of which are published in Galloway et al. (2001). The HEAsoft analysis package (version 6.16) and up-to-date calibration database (CALDB) files were used during reduction of RXTE data. For our study, we extracted source and background spectra from Standard-2 mode PCA data following the standard procedure. Data from all available PCUs were used in our analysis. Using data from HEXTE Cluster-A, source and background spectra were obtained using standard tasks of FTOOLS. The dead-time correction was also applied to the HEXTE spectra. The response files for PCA and HEXTE detectors were created by using pcarsp and hxdrsp commands, respectively. In the spectral fitting, data in the range of 3–150 keV were used from the RXTE observations.

We fitted all the phase-averaged broadband spectra obtained from the BeppoSAX and RXTE observations (Table 3) by using four continuum models: compTT with the geometry of a disk, compTT with the geometry of a sphere, CPL, and BB+CPL. In all the models, a component for photoelectric absorption (TBabs) and Gaussian functions for iron emission lines were included. We added 0.5% systematic errors to the RXTE spectra. In BeppoSAX data analyses, we did not include the edge component at 34 keV that was reported by Naik et al.
The Astrophysical Journal, 838:30 (15pp), 2017 March 20

Yoshida et al.

Table 3

Log of BeppoSAX and RXTE Observations of GX 1+4 and Spectral Parameters Obtained from Fitting Data with Three Different Models

| Observatory | BeppoSAX | BeppoSAX | RXTE | RXTE | RXTE | RXTE |
|-------------|----------|----------|------|------|------|------|
| ID          | 2020500100 | 2020500200 | 10133-02-01-000 | 10133-02-01-001 | 10104-02-01-00 | 70065-01-01-00 |
| Date (yyyy mm dd) | 1996 Aug 18 | 1997 May 25 | 1996 Feb 12 | 1996 Feb 12 | 1996 Feb 17 | 2002 Apr 26 |
| Exposure (ks) | 77.2 | 62.6 | 26.5 | 21.0 | 18.0 | 20.6 |

| Model compTT Assuming Disk Geometry |
|-------------------------------------|
| $N_0$ (10^{22} \text{ cm}^{-2}) | 18.8^{+1.0}_{-1.0} | 0.9^{+0.1}_{-0.1} | 5.7 \pm 0.1 | 6.3 \pm 0.1 | 5.4 \pm 0.1 | 0.6 \pm 0.2 |
| $T_e$ (keV) | 2.0^{+0.05}_{-0.05} | 1.35^{+0.03}_{-0.03} | 1.54 \pm 0.01 | 1.62 \pm 0.01 | 1.61 \pm 0.01 | 1.46 \pm 0.01 |
| $T_e$ (keV) | 3.4^{+0.4}_{-0.4} | 14.1^{+1.1}_{-1.1} | 11.0 \pm 0.1 | 9.5 \pm 0.1 | 10.2 \pm 0.1 | 11.8 \pm 0.1 |
| $\tau$ | 2.8^{+0.1}_{-0.1} | 2.5^{+0.3}_{-0.3} | 4.05 \pm 0.02 | 4.33 \pm 0.03 | 4.74 \pm 0.02 | 3.58 \pm 0.03 |
| $A_e$ | 7.7^{+0.4}_{-0.4} | 4.5^{+0.6}_{-0.6} | 24.2 \pm 0.2 | 21.7 \pm 0.2 | 39.3 \pm 0.2 | 27.4 \pm 0.3 |
| $\chi^2$ (dof) | 1.10(261) | 1.09(363) | 3.11(191) | 5.00(191) | 5.02(126) | 1.85(174) |

| Model compTT Assuming Sphere Geometry |
|-------------------------------------|
| $N_0$ (10^{22} \text{ cm}^{-2}) | 18.8^{+1.4}_{-1.0} | 0.9^{+0.1}_{-0.1} | 5.7 \pm 0.1 | 6.3 \pm 0.1 | 5.4 \pm 0.1 | 0.6 \pm 0.2 |
| $T_e$ (keV) | 2.0^{+0.05}_{-0.05} | 1.35^{+0.03}_{-0.03} | 1.54 \pm 0.01 | 1.62 \pm 0.01 | 1.61 \pm 0.01 | 1.46 \pm 0.01 |
| $T_e$ (keV) | 3.4^{+0.4}_{-0.4} | 14.1^{+1.1}_{-1.1} | 11.0 \pm 0.1 | 9.5 \pm 0.1 | 10.2 \pm 0.1 | 11.8 \pm 0.1 |
| $\tau$ | 6.3^{+0.6}_{-0.2} | 5.7^{+0.6}_{-0.6} | 4.05 \pm 0.02 | 4.33 \pm 0.03 | 4.74 \pm 0.02 | 3.58 \pm 0.03 |
| $A_e$ | 7.7^{+0.4}_{-0.4} | 4.5^{+0.6}_{-0.6} | 24.2 \pm 0.2 | 21.7 \pm 0.2 | 39.3 \pm 0.2 | 27.4 \pm 0.3 |
| $\chi^2$ (dof) | 1.10(261) | 1.09(363) | 3.11(191) | 5.00(191) | 5.02(126) | 1.85(174) |

| BB+CPL^{b} |
|-------------|
| $N_0$ (10^{22} \text{ cm}^{-2}) | 23.46^{+1.40}_{-1.45} | 2.39^{+0.20}_{-0.23} | 8.7 \pm 0.2 | 10.5 \pm 0.2 | 8.2 \pm 0.2 | 3.6 \pm 0.2 |
| $kT_{BB}$ (keV) | 2.4^{+0.1}_{-0.1} | 2.0^{+0.1}_{-0.1} | 2.09 \pm 0.03 | 3.18 \pm 0.09 | 2.00 \pm 0.03 | 2.01 \pm 0.03 |
| $r_{BB}$ (km)^{c} | 0.23^{+0.22}_{-0.24} | 2.16^{+0.72}_{-0.44} | 0.5 \pm 0.2 | 0.2 \pm 0.1 | 0.6 \pm 0.2 | 0.7 \pm 0.2 |
| $\Gamma$ | 0.80^{+0.09}_{-0.11} | 0.89^{+0.09}_{-0.11} | 0.60 \pm 0.03 | 0.79 \pm 0.03 | 0.33 \pm 0.03 | 0.77 \pm 0.03 |
| $E_{\text{cutoff}}$ (keV) | 24.5^{+2.6}_{-2.6} | 25.3^{+3.2}_{-3.2} | 23.6 \pm 0.5 | 27.8 \pm 1.1 | 19.6 \pm 0.4 | 26.4 \pm 0.9 |
| $\chi^2$ (dof) | 1.00(260) | 1.00(362) | 1.51(190) | 1.90(190) | 1.49(125) | 1.06(173) |

Notes. The errors given here are for 90% confidence limits in BeppoSAX data and 1σ confidence limits in RXTE data.

* Normalization parameter for the compTT model component ($\times 10^{-3}$).

* BB and CPL represent blackbody and exponential cutoff power law, respectively.

* Blackbody radius assuming a distance of 4.3 kpc.

While fitting the data from the 1996 BeppoSAX observation, we added a bremsstrahlung component to the spectral model representing the soft X-ray excess as reported by Naik et al. (2005). In the simultaneous spectral fitting, we found that the BB+CPL model described the continuum spectra of the pulsar obtained from both the observatories better than other models, as in the case of Suzaku data. The broadband spectra, along with the best-fit BB+CPL model for six epochs of observations, are shown in the top panels of Figure 10. Residuals of the data from the model obtained from fitting the phase-averaged spectra for six epochs with the compTT continuum model for a disk geometry, compTT for a spherical geometry, the CPL continuum model, and a blackbody and CPL model are shown in panels (b)–(e) of Figure 10, respectively. Best-fit parameters obtained for the compTT model (for disk and sphere geometries) and the BB+CPL model are given in Table 3.

4.3. Origin and Region of Line Emission

4.3.1. Line Center Energy

Using Suzaku observation, we detected iron K\alpha and K\beta emission lines and a K absorption edge in GX 1+4. The ratio of the energy of the K absorption edge to that of the K\beta emission line strongly restricts the ionization state of the iron ion to be less than 2 ($<$Fe III). However, the absolute energy of the iron K\alpha emission line, e.g., 6.425 ± 0.001 keV, as observed in the present study, is not consistent with the energy of neutral iron in a laboratory frame and is higher by approximately 30 eV. Similar values of line energy were also reported by Naik et al. (2005) from BeppoSAX observations of the pulsar. However, using Chandra/HETGS observation of GX 1+4, Paul et al. (2005) reported 6.400 ± 0.005 keV as the energy corresponding to the Fe K\alpha emission line. Although we applied the correction for the SCF effect, the absolute energy determination with a CCD is extremely difficult. The observed discrepancy in the line energy of the iron K\alpha emission line is comparable to the energy calibration ambiguity. Therefore, future observations with high spectral capability instruments are required to understand this energy shift.

4.3.2. Homogeneous Matter

The emission region of the fluorescent iron line has been discussed by Kotani et al. (1999), where the matter is assumed to be homogeneously distributed. They showed a positive correlation between the iron emission line equivalent width and absorption column density that was consistent with the expected results from isotropic distribution of absorbing matter around the pulsar (Makishima 1986). The values of
The Astrophysical Journal, 838:30 (15 pp), 2017 March 20

Yoshida et al.

Figure 10. Broadband phase-averaged spectra of GX 1+4 obtained from the BeppoSAX and RXTE observations, along with the best-fit BB+CPL model, are shown in the top panels (a). Residuals divided by its errors, obtained from fitting the source spectra with the compTT model and assuming disk and spherical geometry, are shown in panels (b) and (c), whereas those obtained from fitting data with CPL and BB+CPL models are shown in panels (d) and (e), respectively. Each of the six plots show the results that were obtained from fitting with different continuum models for six epochs (two epochs of BeppoSAX and four epochs of RXTE) of observations in the sequence of S-I, S-II, X-I, X-II, X-III, and X-IV as given in Table 3. The sequences are quoted above each individual plot.

The size of the line-emitting region, as discussed in the previous subsection, was derived by assuming homogeneous distribution of matter and the observed ionization state.

4.3.3. Inhomogeneous Matter

The size of the line-emitting region, as discussed in the previous subsection, was derived by assuming homogeneous distribution of matter and the observed ionization state.

equivalent width (\( \sim 150 \text{ eV} \)) and absorption column density (1.30 \( \times 10^{23} \text{ H atoms cm}^{-2} \)) obtained from Suzaku observation of the pulsar are also consistent with the relation. During the Suzaku observation, the ionization state of iron atoms was determined to be \( \leq \text{Fe}^{3+} \). This corresponds to a value of the ionization parameter \( \xi (=L/nr^2) \) of less than 22.4 (log \( \xi < 1.35 \)) (Kallman & McCray 1982) for an ionizing source of \( 10^{37} \text{ erg s}^{-1} \) with a 10 keV bremsstrahlung in optically thick plasma. Luminosity of GX 1+4 during the Suzaku observation was estimated to be \( 10^{37} \text{ erg s}^{-1} \) (assuming a distance from the source of 4.3 kpc), and the value of equivalent hydrogen column density was 1.30 \( \times 10^{23} \text{ H atoms cm}^{-2} \). Using these values and assuming that the distance from the X-ray source is comparable to the size of the plasma, the distance of the fluorescent line emitting region from the X-ray source is estimated to be more than \( 3.4 \times 10^{12} \text{ cm} \), which is consistent with the value reported by Kotani et al. (1999). This value is comparable to the size of the orbit (\( \sim 10^{13} \text{ cm} \)) for the earlier reported period of 300 days (Cutler et al. 1986; Pereira et al. 1999). If the fluorescent lines are emitted from such a large region, the observed time variation should be smeared with the light-crossing time of the region, which is more than 100 s for the size of \( 3.4 \times 10^{12} \text{ cm} \). One of our new findings is the intensity modulation of the fluorescent line with the neutron star rotation. The line was intense in the pulse phase range of 0.7–1.1 with an amplitude of 7%. As the modulation amplitude is not large and the spin period of the pulsar is \( \sim 150 \text{ s} \), observed intensity modulation might be possible as long as the plasma size is not significantly larger than \( 3.4 \times 10^{12} \text{ cm} \). If it is caused by nonsymmetric circumstellar matter with the size of the binary orbit, we can expect a progressing of the line-intense phase according to the orbital motion, and we may examine this idea by using future observations.

There are only a few sources that show pulse phase dependence of emission-line flux, namely, flux of the O VI line in 4U 1626-67 (Beri et al. 2015) and the fluorescent iron emission line in Her X-1 (Vasco et al. 2013) and GX 301-2 (Suchy et al. 2012). In the case of 4U 1626-67 \( (P_{\text{spin}} \sim 7.7 \text{ s}) \), an intensity modulation by a factor of about 4 over pulse phases was reported (Beri et al. 2015). This was interpreted in terms of a warped accretion disk being illuminated by the X-rays from the neutron star. In the case of Her X-1 \( (P_{\text{spin}} \sim 1.24 \text{ s}) \), the fluorescent iron line intensity shows a sharp and deep minimum (close to zero) at the peak of the pulse profile (Vasco et al. 2013). Based on these results, Vasco et al. (2013) discussed the possibility of the accretion column being the line-emitting region in Her X-1. For these fast rotators, the emission regions are considered to exist at the vicinity of the neutron star. However, GX 301-2 is a slow rotator with a spin period \( P_{\text{spin}} \sim 700 \text{ s} \), and sinusoidal intensity modulation of the iron fluorescent line was reported with a modulation amplitude of 10% (Suchy et al. 2012). In this case, the line-emitting region is considered to be very large. In GX 1+4, we found sinusoidal modulation of the iron line intensity at an amplitude of \( \sim 7\% \). The maximum of the line intensity does not coincide with either the minimum or maximum of the continuum emission over pulse phases. These characteristics are similar to those seen in GX 301-2.
However, if we introduce a volume filling factor $f$, the result becomes completely different, though this is just one possibility. Assuming $n$ as the density of the highly dense region and negligible (close to zero) density for a thin region, the observed column density can be written as $N_{\text{H}} \sim nfr$, where $r$ is the size of the fluorescent region. This $r$ can also be assumed as the distance of the region. The ionization parameter of the dense region, $\xi$, can be expressed as $\frac{L}{n^2r^2}$. For $\xi = 22.4$, $L = 10^{37}$ erg s$^{-1}$ and $N_{\text{H}} = 1.30 \times 10^{23}$ H atoms cm$^{-2}$, we obtained the distance $r > (3.3f) \times 10^{12}$ cm. For $f \sim 0.03$, the size of the fluorescent region can be reduced to $\sim 10^{14}$ cm, which is comparable to the size of an accretion disk.

Paul et al. (2005) reported the detection of the Ly$\alpha$ emission line from iron ions in GX 1+4 and suggested the diffused gas in the Alfvén sphere or the accretion curtains to the magnetic poles as the line-emitting regions. During the Suzaku observation of the pulsar, we also detected the Ly$\alpha$ emission line in the pulsar spectrum with comparable intensity as reported by Paul et al. (2005). If we consider the inhomogeneous matter as the fluorescent line emitting gas, then the thin region should be highly ionized and may be the possible origin of the Ly$\alpha$ emission line. Another possible reason for the smaller size of the fluorescent region can be the presence of local dense matter. Rea et al. (2005) discussed the prospect of the existence of a thick torus-like accretion disk. If we introduce such a thick region surrounding the magnetosphere with a radius of $\sim 8.2 \times 10^9$ cm as a fluorescent region (assuming that the magnetospheric radius is equal to the co-rotation radius based on the torque reversal scenario), the density of the torus should be $6.5 \times 10^{15}$ cm$^{-3}$ for $\xi = 22.4$.

4.4. Elemental Abundance

For the first time, we detected an emission line at 7.49 ± 0.02 keV in the spectrum of GX 1+4. This line was identified as the K$\alpha$ emission line from neutral Ni atoms that is expected at 7.47 keV in the laboratory frame. As this line is expected from neutral atoms, we can assume that Ni K$\alpha$ emission also originated from the same fluorescent matter that is attributed to the iron K$\alpha$ emission. The abundance ratio [Ni/Fe] of the fluorescent matter can also be investigated by studying the properties of these lines. By assuming a small optical depth for the absorption, the expression for the ratio of line intensities can be written as

$$\frac{I_{\text{Fe line}}}{I_{\text{Ni line}}} \sim \frac{\eta_{\text{Fe}} \int_{E_{\text{Fe}}}^{\infty} I(E) \sigma_{\text{Fe}}(E) N_{\text{H}} A_{\text{Fe}} dE}{\eta_{\text{Ni}} \int_{E_{\text{Ni}}}^{\infty} I(E) \sigma_{\text{Ni}}(E) N_{\text{H}} A_{\text{Ni}} dE},$$  \tag{1}

where $I_{\text{M line}}$, $\sigma_{\text{M}}(E)$, $\eta_{\text{M}}$, $A_{\text{M}}$, and $E_{\text{M line}}$ are the intensity, photoelectric absorption cross section, fluorescence yield, elemental abundance, and binding energy of the K-shell electrons for the neutral atom $M$. $I(E)$ is the continuum emission, which is a function of the X-ray energy $E$, and $N_{\text{H}}$ is the hydrogen column density. By setting appropriate parameters, Equation (1) can be reduced to

$$\frac{I_{\text{Ni line}}}{I_{\text{Fe line}}} \sim 1.15 \frac{A_{\text{Ni}}}{A_{\text{Fe}}}. \tag{2}$$

By inserting the observed value of the intensity ratio of the emission lines of 0.12 ± 0.02, we obtained $\frac{A_{\text{Ni}}}{A_{\text{Fe}}}$, i.e., $[\text{Ni/Fe}] = 0.10 \pm 0.02$, which is approximately two times larger than that of the solar abundance (Anders & Grevesse 1989). Iron abundance can also be estimated by considering the depth of the iron K-shell edge at around 7.1 keV. The maximum optical depth of the absorption edge was determined to be 0.31 ± 0.02. If we assume the solar abundance of iron, $3.4 \times 10^{-5}$, and the absorption cross section of $9.2 \times 10^{-20}$ cm$^2$, the expected optical depth is 0.4. Since the maximum optical depth was 0.31 ± 0.02, the iron abundance of the fluorescent matter is $\sim 80\%$ of the solar value.

5. Conclusion

We carried out a detailed spectroscopic study of the X-ray emission from GX 1+4 by using Suzaku observation of the pulsar. Results obtained from the timing analysis, broadband phase-averaged and phase-sliced spectroscopy, and detailed investigation of the fluorescence emission lines and line-emitting regions are summarized as follows:

1. Using Suzaku observation, the spin period of the pulsar was estimated to be $\sim 159.94$ s. This indicates that the pulsar is spinning down. In addition, a peculiar sharp and prominent dip was also seen in the soft X-ray pulse profiles.
2. The continuum spectrum of the pulsar can be described better by a two-component model consisting of a blackbody and an exponential cutoff power law (BB + CPL) than by the previously used compTT continuum model. This was supported by the spectral fitting of BeppoSAX and RXTE observations carried out in high- and intermediate-luminosity states of the pulsar.
3. We identified iron K$\alpha$ and K$\beta$ emission lines and a newly detected K$\alpha$ emission line at 7.49 keV from lowly ionized Ni atoms.
4. Detection of iron K$\alpha$, K$\beta$, and K absorption edges indicated that the degree of ionization of iron is less than 2 (Fe III).
5. The iron Ly$\alpha$ line was clearly detected with an intensity comparable to that obtained from the Chandra/HETGS observation of the pulsar (Paul et al. 2005).
6. No cyclotron resonance scattering feature was detected in the 30–110 keV range spectrum of the pulsar.
7. The phase-sliced spectra can be well fitted by the BB + CPL continuum model. Parameters such as the power-law photon index and cutoff energy obtained from the phase-resolved spectroscopy showed a significant variation with pulse phase of the pulsar. However, the photoelectric absorption did not show any significant variation with pulse phase, including the dip interval.
8. Clear spin phase modulation of the intensity of the iron K$\alpha$ emission line was detected with an amplitude of 7%, peaking at around the 0.7–1.1 phase.

From the above results, we draw the following conclusions: Although the compTT model can describe the broadband spectra of GX 1+4, the parameters in the model are not sufficient to reproduce the emission spectrum, due to Comptonization in the accretion column. A combination of blackbody and an exponential CPL can add another freedom in the model and can fit the observed broadband spectrum better than the compTT model.
We derived the iron abundance in GX 1+4 to be \(~80\%\) of the solar value as compared with the photoelectric absorption \(N_{\text{H}}\). Assuming both the iron and Ni fluorescent lines to have originated from the same region, the abundance ratio \([\text{Ni}/\text{Fe}]\) is calculated to be approximately two times larger than the solar value.

If the iron fluorescent line emitting region is homogeneous, the size of the emission region is expected to be large in order to explain the observed low ionization state. However, a fine-tuning is required to produce the line intensity modulation over pulsar phases. If we introduce an inhomogeneity in the matter distribution, a smaller size of the fluorescent line emitting region can be accepted. This can also explain the line intensity modulation observed during \textit{Suzaku} observation of the pulsar.

This work was partially supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Grant-in-Aid for Science Research 25400237, and the MEXT Supported Program for the Strategic Research Foundation at Private Universities, 2014-2018. This research was carried out by using data obtained from the Data Archive and Transmission System (DARTS), provided by the Center for Science-satellite Operation and Data Archive (C-SODA) at ISAS/JAXA.

Appendix

Correction for SCF Effect

The SCF effect of \textit{Suzaku} data was first pointed out by Todoroki et al. (2012), and consequently they proposed a method to correct the data for this effect. As suggested, we divided the source extraction region of \(3\)’ radius into six regions. The energy spectrum was extracted from each of the regions. The prominent iron \(K_{\alpha}\) emission line in each spectrum was fitted by a Gaussian function, and the line energy was derived from fitting. The central energies obtained from XIS 0, XIS 1, and XIS 3 data were plotted as a function of the event density (in units of \(\text{events exposure}^{-1} \text{pixel}^{-1}\)) and shown in Figure 11. A clear dependence of the central energy on the event density was found for XIS-1 data, but no apparent dependency was found in data obtained from XIS-0 and XIS-3.

Then we fitted the central energy of XIS 1 with the function of

\[
E = E_0 + (E_1 - E_0)[1 - \exp(-\epsilon x)] = E_1[1 - C \exp(-\epsilon x)],
\]

where \(x\) is the event density, \(E_1\) is the expected true energy, \(\epsilon\) is the amount of the SCF effect, \(E_0\) is the energy in the low event density limit, and \(C = (E_1 - E_0)/E_1\). The best-fit curve is shown in Figure 11 with the dotted line, and the best-fit parameters are listed in Table 4.

The energy scale of the spectra obtained from the six regions of XIS 1 was corrected according to the parameters obtained (shown in Table 4). The central energy of the iron \(K_{\alpha}\) emission line obtained from the corrected spectra of XIS is plotted in Figure 11, as well as the data of XIS 0 and XIS 3.

Table 4

| Parameter | Unit | Value |
|-----------|------|-------|
| \(E_1\)   | keV  | 6.42  |
| \(E_0\)   | keV  | 6.39 ± 0.01 |
| \(\epsilon\) | \(\text{...}\) | \(1800^-1800^+\) |

References

Anders, E., & Grevesse, N. 1989, GeCoA, 53, 197
Beri, A., Paul, B., & Dewangan, G. C. 2015, MNRAS, 451, 508
Boella, G., Butler, R. C., Perola, G. C., et al. 1997, A&AS, 122, 229
Boldt, E. A. 1987, in NASA Conf. Publication 2464, in Essays in Space Science, ed. R. Ramaty, T. L. Cline, & J. F. Ormes (Greenbelt, MD: NASA), 339
Chakrabarty, D., Bildsten, L., Finger, M. H., et al. 1997, ApJL, 481, L101
Chakrabarty, D., & Roche, P. 1997, ApJ, 489, 254
Corbet, R. H. D., Sokoloski, J. L., Mukai, K., Markwardt, C. B., & Tueller, J. 2008, ApJ, 675, 1424
Cutler, E. P., Dennis, B. R., & Dolan, J. F. 1986, ApJ, 300, 551
Davidson, A., Malina, R., & Bowyer, S. 1976, PASP, 88, 606
Doroshenko, V., Santangelo, A., Kreykenbohm, I., & Doroshenko, R. 2012, A&A, 540, L1
Dotani, T., Kii, T., Nagase, F., et al. 1989, PASJ, 41, 427
Doty, J. 1976, IAUC, 2910, 2
Ferrigno, C., Segreto, A., Santangelo, A., et al. 2007, A&A, 462, 995
Fukazawa, Y., Mizuno, T., Watanabe, S., et al. 2009, PASJ, 61, S17

Figure 11. Central energy of the iron \(K_{\alpha}\) emission line as a function of event density, (a) before correction of the SCF effect of XIS 1 data and (b) after the correction.
Erratum: “A Suzaku View of Accretion-powered X-Ray Pulsar GX 1+4” (2017, ApJ, 838, 30)

Yuki Yoshida¹², Shunji Kitamoto¹², Hiroo Suzuki¹, Akio Hoshino¹², Sachindra Naik³, and Gaurava K. Jaisawal³

¹Department of Physics, College of Science, Rikkyo University 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan; kitamoto@rikkyo.ac.jp
²Research Center for Measurement in Advanced Science, Rikkyo University 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
³Astronomy and Astrophysics Division, Physical Research Laboratory, Navrangapura, Ahmedabad-380009, Gujarat, India

Received 2018 October 29; published 2018 December 4

An erroneous evaluation of the iron abundance was reported in Section 4.4 of the published article because an incorrect absorption cross section was used. The correct absorption cross section is $3.765 \times 10^{-20}$ cm$^2$ just above the absorption edge (Berger et al. 2010). The last two sentences in Section 4.4 should be corrected as follows: “If we assume the solar abundance of iron of $3.4 \times 10^{-5}$, and the absorption cross section of $3.765 \times 10^{-20}$ cm$^2$, the expected optical depth is 0.17. Since the maximum optical depth was $0.31 \pm 0.02$, the iron abundance of the fluorescent matter is $\sim 1.8$ times of the solar value.”

Because of this correction, a statement in the abstract should be changed to “We estimated an iron abundance of $\sim 1.8$ times of the solar value.” Furthermore, a statement in the conclusion (first sentence in page 15) should be changed to “We derived the iron abundance in GX1+4 to be $\sim 1.8$ times of the solar value as compared with the photoelectric absorption, $N_H$.” The other values and the discussion are not affected by this correction.

ORCID iDs

Yuki Yoshida © https://orcid.org/0000-0003-2462-198X
Shunji Kitamoto © https://orcid.org/0000-0001-8948-7983
Gaurava K. Jaisawal © https://orcid.org/0000-0002-6789-2723

References

Berger, M. J., Hubbell, J. H., Seltzer, S. M., et al. 2010, XCOM: Photon Cross Section Database (version 1.5; Gaithersburg, MD: NIST), https://www.nist.gov/pml/xcom-photon-cross-sections-database