Suzaku observation of the symbiotic X-ray binary IGR J16194−2810

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Abstract

We observed IGR J16194−2810 in the low/hard state with the Suzaku X-ray satellite in 2009. The source is a Symbiotic X-ray Binary (SyXB) classified as a category of a Low-Mass X-ray Binary (LMXB), since the system is composed of an M-type giant and probably a neutron star (NS). We detected the 0.8–50 keV signal with the XIS and HXD-PIN. The 2–10 keV luminosity was \( L \sim 7 \times 10^{34} \text{ erg s}^{-1} \) corresponding to \( \sim 10^{-3}L_{\text{Edd}} \), where \( L_{\text{Edd}} \) is the Eddington luminosity of a 1.4 \( M_\odot \) NS and a source distance of 3.7 kpc is assumed. The luminosity is similar to those of past observations. The spectral analysis showed that there are two emission components below and above \( \sim 2 \text{ keV} \). The hard emission component is represented by a Comptonized blackbody emission model with seed-photon temperature \( \sim 1.0 \text{ keV} \) and emission radius \( \sim 700 \text{ m} \). The seed photon is considered to come from a small fraction of the NS surface. The soft component is reproduced by either a raw blackbody (\( \sim 0.4 \text{ keV}, \sim 1.7 \text{ km} \)) or a Comptonized emission (\( \sim 0.1 \text{ keV}, \sim 75 \text{ km} \)). We think that the origin is the emission from another part of the NS surface or the accreting stream. The physical parameters of the hard emission component of IGR J16194−2810 are compared with those of an SyXB (4U 1700+24) and two LMXBs (Aql X-1 and 4U 0614+091). This comparison reveals that these SyXBs in the low/hard state have a smaller radiation region (\(< 1 \text{ km}\)) on the NS surface with a higher seed-photon temperature (\( \sim 1 \text{ keV} \)) than the comparison LMXBs.

Key words: binaries: symbiotic — stars: individual: (IGR J16194−2810) — stars: neutron — X-rays: binaries

1 Introduction

X-ray binaries are classified into Low-Mass X-ray binaries (LMXBs) and High-Mass X-ray binaries (HMXBs). 187 LMXBs have been discovered in our Galaxy (Liu et al. 2007). LMXBs are binaries consisting of a low-mass companion star and a main compact star [a black hole or a weakly magnetized neutron star (NS)], and thus they are old systems. HMXBs are binaries whose companion is a high-mass star.

A symbiotic X-ray binary (SyXB) is a system of a compact star with a red giant, and was previously defined as an LMXB (Masetti et al. 2006). Masetti et al. (2007) and Smith et al. (2012) detected six SyXBs. In addition, Lü et al. (2012) newly listed five candidate SyXB systems, although 1RXJ 180431.1−273932 and 2XMM J174016.0−290337 were reported as cataclysmic variables in Masetti et al. (2012a, 2012b), and IGR J16393−4643 was identified as an HMXB (Corbet et al. 2010; Bodaghee et al. 2012). Comparing SyXBs with general LMXBs, one of the remarkable features is a long NS spin period; for example, GX 1+4 and GX 1954+31 have 110–157 s (e.g., Chakrabarty et al. 1997; González-Galán et al. 2012) and \( \sim 5 \text{ h} \) (Corbet et al.
2 Observation and data reduction

IGR J16194–2810 was observed with Suzaku on 2009 February 5–6. The net exposure time was about 46 ks. Suzaku has four X-ray CCD cameras called X-ray Imaging Spectrometers (XIS-0, XIS-1, XIS-2, and XIS-3) which are sensitive in 0.2–12 keV. XIS-0, XIS-2, and XIS-3 are front-illumination (FI) CCDs, while XIS-1 uses back illumination (BI; Koyama et al. 2007). Due to damage, XIS-2 has not been operated since 2006 November 9. Suzaku has a non-imaging instrument called the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007). The HXD has two types of detector: Si-PIN photodiodes (PIN) and GSO scintillators, which are sensitive in 10–600 keV.

IGR J16194–2810 was observed at the HXD nominal position. The XIS was operated in the 3 × 3 and 5 × 5 editing modes and the normal clocking mode. The signal was detected in 0.8–50 keV with the XIS and HXD-PIN. For the spectral analysis, we chose Good Time Intervals (GTIs) when both XIS and HXD-PIN were active, and obtained an exposure of 36 ks. The observed source count rates after subtracting the background were 1.44 and 1.51 counts s\(^{-1}\) in 0.8–10 keV by XIS-FI and XIS-BI, respectively, and 0.03 counts s\(^{-1}\) in 20–50 keV by HXD-PIN.

2.1 XIS reduction

We analyzed the cleaned event file version 2.3 by using the analysis software package HEASOFT 6.10 and the most recent calibration database CALDB of 2011 April 1. We defined the source region as a circle with a radius of 2.7 from the source position, which we determined by looking at the XIS image. The background region was taken as an annulus with a radius of 3′3–5′0 from the source position. We generated the redistribution matrix files (RMFs) and ancillary response files (ARFs) using xisrmfgen and xissimarfgen from FTOOLS. We added the XIS-0 and XIS-3 spectra using mathpha from FTOOLS. Also, we multiplied the RMF and ARF by using marxarf from FTOOLS per each detector and we used these files as the RSP file. We added the XIS-0 and XIS-3 RSP files using addrmf from FTOOLS.

2.2 HXD reduction

We extracted the HXD-PIN spectrum from the cleaned event file version 2.3 by using hxdpinxtpi from FTOOLS, where the contribution of the cosmic X-ray background is subtracted assuming the spectral shape of the exponential cut-off power law (photon index = 1.29, cut-off energy = 40 keV, flux at 1 keV = 9.412 × 10\(^{-3}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) FOV\(^{-1}\); Boldt 1987). For the...
non-X-ray background (NXB), we used the tuned NXB file (Fukazawa et al. 2009), and the response file ae_hxd_pinhxnome5_20080716.rsp was used.

During this observation, the HXD temperature was high and the lower energy band of the HXD-PIN suffered from noise events. Therefore, we analyzed the HXD-PIN data above 20 keV when we fitted the spectra. A cross-normalization factor of 1.18 was introduced to explain the absolute flux difference from the XIS.1

### 3 Analysis

#### 3.1 Analysis of the time-averaged spectra

We analyzed the XIS-FI, BI, and HXD-PIN spectra by using XSPEC version 12.7.0. Hereafter, the error is estimated as a 90% confidence range ($\Delta \chi^2 = 2.7$) for one parameter. First of all, we tried to fit the spectra with Model 1, “phabs × power-law.” In this model, “phabs” represents the Galactic interstellar absorption with the cross-section data of Balucinska-Church and McCammon (1992). Free parameters are the absorption column density $N_{\text{H}}^\text{Gal}$, the photon index $\Gamma$, and the normalization of the power-law. We show the fitting result of Model 1 in table 1 and figure 1. This model does not reproduce the observed spectra with a reduced $\chi^2_r$ of 5.35 (d.o.f. = 591). Positive residuals are seen below 1 keV and at 2–6 keV, and a large negative residual appears above 6 keV. To represent the high-energy negative residual, we applied “phabs × compTT,” which is the model used by Masetti et al. (2007). The “compTT” component models Comptonized radiation of BB seed photons (Titarchuk 1994). As a result, the model can reproduce the spectra above 10 keV with the parameters of the seed-photon BB temperature of 0.74 keV and the optical depth of the Compton cloud of $\sim 0.1$. However, the low-energy residual still remains, and $\chi^2_r$ is 1.48 (d.o.f. = 589) and thus not formally acceptable.

Second, we fitted the spectra with a conventional model for the low/hard state of LMXBs: “phabs[diskbb + compPS (seed = BB)]” (Model 2). The “diskbb” (DBB) model represents a Multi-Color Disk blackbody (e.g., Mitsuda et al. 1984; Makishima et al. 1986). Parameters are the inner-radius temperature of the accretion disk $T_{\text{DBB}}$ and Normalization$_{\text{DBB}}$. In the DBB [and the following “compPS (seed = DBB)”] model, the obtained Normalization$_{\text{DBB}}$ can be converted into the physical value of the disk inner radius $R_{\text{DBB}}$ with Normalization$_{\text{DBB}} = \left[ R_{\text{DBB}} \right] / \left[ 0.37 \right] (\text{10 kpc})^{2} \cos \theta$, where $\theta$ is the inclination angle of the disk and a source distance of 3.7 kpc is assumed. Since $\theta$ for this source is uncertain, we assume 60°, considering the fact that the eclipse has not been observed for this object. If $\theta$ is measured as 0° or 85°, the $R_{\text{DBB}}$ value in this paper should be multiplied by a factor of 0.5 or 5.7 [other parameters such as the temperature and optical depth of the Compton cloud are independent of $\theta$ in the DBB and “compPS (seed = DBB)” models]. The “compPS” model (Poutanen & Svensson 1996) is physically the same as the above “compTT,” and it can estimate the radiation radius of the seed photon. Free parameters are BB temperature $T_{\text{BB}}$, the optical depth of the Compton cloud $\tau_{\text{BB}}$, and Normalization$_{\text{BB}}$. Since the Comptonizing electron temperature $T_{\text{e}}$ cannot be determined from the observed spectra, it is fixed at 100 keV; in fact, this value represents the lower limit of $> 90$ keV. As summarized in table 2, Model 2 reproduced well the observed spectra with a reduced $\chi^2_r$ of 1.13 (d.o.f. = 588). The improvement from Model 1 (the $\chi^2_r$ difference with an F-statistic value of 183) is significant at more than the 3σ level. However, the inner radius of the accretion disk becomes $R_{\text{DBB}} \sim 0.9 \pm 1.5$ km, assuming the distance of 3.7 kpc and the inclination angle of 60°. This is not likely since it is smaller than the NS radius.

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**Table 1. Fitting results with Model 1.**

| Model   | Parameter               | Value  |
|---------|-------------------------|--------|
| phabs   | $N_{\text{H}}^\text{Gal}$ (×10$^{22}$ cm$^{-2}$) | 0.97   |
| power-law | $\Gamma$              | 1.75   |
|         | Normalization*         | 1.22 × 10$^{-2}$ |
|         | $\chi^2_r$ (d.o.f.)    | 5.35 (591) |

* Normalization = photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

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1. (http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/abc.html).
Instead of the DBB model, we next tried the Astrophysical Plasma Emission Code (APEC) model which represents the emission from collisionally ionized diffuse gas, since the accreting stream originally from the stellar wind of the red giant may keep the diffuse gas hot rather than forming an optically thick disk. As shown in table 3, this model, “phabs[APEC + compPS (seed = BB)],” can also represent the spectral shape with a reduced $\chi^2$ of 1.14 (d.o.f. = 588).

However, due to the lack of Fe-L emission features around 1 keV, the spectral continuum below 2 keV requires too low an abundance of < 0.004 solar value, or too high a temperature $\sim$ 40 keV when the abundance is fixed at 0.3 solar value. Therefore, we think that Model 2 with either the DBB or APEC model cannot be accepted physically.

Since the unrealistically small emission radius of the DBB model may suggest that the soft emission component comes from the NS surface, we applied Model 2, “phabs[BB + compPS (seed = BB)].” As summarized in table 2 and figure 2, the

### Table 2. Fitting results with Model 2 using diskbb (DBB) and BB.

| Model       | Parameter | Diskbb | BB         |
|-------------|-----------|--------|------------|
| phabs       | $N_H^{\text{Gal}} \times 10^{22}$ cm$^{-2}$ | 0.40$^{\pm 0.07}$ | 0.33$^{\pm 0.03}$ |
|             | $T_{\text{DBB}}$ (keV) | 0.60$^{\pm 0.13}$ |             |
|             | $R_{\text{DBB}}$ (km) | 0.9$^{\pm 1.5}$ |             |
| BB          | $T_{\text{BB}}$ (keV) | 0.36$^{\pm 0.04}$ |             |
|             | $R_{\text{BB}}$ (km) | 1.7$^{\pm 0.4}$ |             |
| compPS (seed = BB) | $T_{\text{BB}}$ (keV) | 1.05$^{\pm 0.07}$ | 1.02$^{\pm 0.04}$ |
|             | $\tau_{\text{BB}}$ | 0.56$^{\pm 0.05}$ | 0.58$^{\pm 0.04}$ |
|             | $R_{\text{BB}}$ (m) | 680$^{\pm 40}$ | 730$^{\pm 30}$ |
|             | $\chi^2$ (d.o.f.) | 1.13 (588) | 1.14 (588) |

| Model       | Parameter | APEC | 0.3 (fix) |
|-------------|-----------|------|-----------|
| phabs       | $N_H^{\text{Gal}} \times 10^{22}$ cm$^{-2}$ | 0.49$^{\pm 0.04}$ | 0.38$^{\pm 0.02}$ |
| APEC        | $kT$ (keV) | 1.75$^{\pm 0.18}$ | 39$^{\pm 6}$ |
|             | Abundance* | 0 ($< 0.004$) | 0.3 (fix) |
|             | Normalization | (1.54$^{\pm 0.05}$) to $\times 10^{-2}$ | (1.56$^{\pm 0.04}$) to $\times 10^{-2}$ |
| compPS (seed = BB) | $T_{\text{BB}}$ (keV) | 1.05$^{\pm 0.04}$ | 1.06$^{\pm 0.01}$ |
|             | $\tau_{\text{BB}}$ | 0.6$^{\pm 0.02}$ | $< 0.1$ |
|             | Normalization | 3.22$^{\pm 0.32}$ | 1.94$^{\pm 0.11}$ |
|             | $R_{\text{BB}}$ (m) | 664$^{\pm 29}$ | 515$^{\pm 3}$ |
|             | $\chi^2$ (d.o.f.) | 1.14 (587) | 1.15 (587) |
|             | $F_{2-10}$ | 4.08 | 4.09 |
|             | $L_{2-10}$ | 6.98 | 6.93 |

* Abundance with respect to the solar value of Anders and Grevesse (1989).

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(2 http://atomdb.org/)
Fig. 2. (Top) As figure 1, but with Model 2 “phabs[BB + compPS (seed = BB)].” Dashed lines represent each model component. (Bottom) The deconvolved energy spectrum of Model 2 (BB). (Color online)

model can reproduce the spectra with a reduced $\chi^2_\nu$ of 1.14 (d.o.f. = 588), and the obtained parameters are physically reasonable; the BB radius is $\sim 1.7$ km with a temperature of $\sim 0.4$ keV.

Overestimation of the disk temperature may be another possibility for producing the too-small disk inner radius; the disk temperature would be much lower and the DBB photons would be upscattered by Comptonization into the soft X-ray band. Therefore, we also fitted the spectra with Model 3, “phabs[compPS (seed = DBB) + compPS (seed = BB)],” where the DBB in Model 2 is replaced by “compPS (seed = DBB).” The shape of the Compton cloud and the electron temperature $T_e$ are assumed to be spherical and 100 keV, respectively, the same as for “compPS (seed = BB).” Model 3 can reproduce the observed model as well as Model 2, with a reduced $\chi^2_\nu$ of 1.14 (d.o.f. = 587), as shown in table 4 and figure 3. In this model, the parameters of the seed DBB cannot be well constrained. When $T_{\text{DBB}} \sim 0.1$ keV, $T_{\text{DBB}}$ could be constrained from the spectral curvature below 1 keV, but the interstellar absorption

Table 4. As table 2, but with Model 3.

| Model          | Parameter                  | Value          |
|----------------|----------------------------|----------------|
| phabs          | $N_H^\text{Gal} (\times 10^{22} \text{cm}^{-2})$ | $0.65 \pm 0.15$ |
| compPS (seed = DBB) | $T_{\text{DBB}}$ (keV)     | $0.11 \pm 0.02$ |
|                | $\tau_{\text{DBB}}$       | $0.2 (\leq 0.4)$ |
|                | Normalization$_{\text{DBB}}$ | $\left(2.07_{-1.62}^{+5.12}\right) \times 10^4$ |
|                | $R_{\text{DBB}}$ (km)      | $75_{-65}^{+65}$ |
| compPS (seed = BB) | $T_{\text{BB}}$ (keV)     | $1.05 \pm 0.05$ |
|                | $\tau_{\text{BB}}$        | $0.6 \pm 0.1$ |
|                | Normalization$_{\text{BB}}$ | $3.36_{-0.36}^{+0.34}$ |
|                | $R_{\text{BB}}$ (m)       | $680_{-40}^{+30}$ |
|                | $\chi^2_\nu$ (d.o.f.)     | $1.14 (587)$ |
|                | $F_{2-10}$                 | $4.09$         |
|                | $L_{2-10}$                 | $7.11$         |

*Normalization = $[R_{\text{DBB}} (\text{km})]^2 / [0.37 (10 \text{kpc})^2 \cos \theta]$, where $R_{\text{DBB}}$ is the inner radius of the disk seed-photon emission in units of km; $\theta$ is the inclination angle and 60° is assumed.
prevents us constraining it. Nevertheless, the error region contains the parameter set that the disk temperature is low, the optical depth of the Compton cloud is large, and the disk inner radius is reasonable at > 10 km. Therefore, this model gives a possible solution of the spectral modeling. Note that the origin of seed photons with a temperature of ∼ 0.1 keV is not necessarily the multi-color disk blackbody emission, since the spectral shape of the seed-photon emission is not well determined. On the other hand, the BB temperature for “compPS (seed = BB)” is determined by the apparent concave shape of the spectra around 10 keV. Therefore, the uncertainty of $T_{BB}$ and $R_{BB}$ is smaller, unlike the case of “compPS (seed = DBB).”

We concluded that either Model 2 (BB) or Model 3 is physically able to reproduce the time-averaged spectra. The observed 2–10 keV flux and luminosity described in tables 2, 3, and 4 are $4 \times 10^{-11}$ erg s$^{-1}$ and $7 \times 10^{34}$ erg s$^{-1}$, respectively, which are comparable to those of the previous observations (Masetti et al. 2007).

### 3.2 Analysis of time variation

We made the source light curve by using FTOOLS lccurve 1.0 and studied the time variation. Figure 4 shows light curves for XIS-0 0.5–2 keV, 2–10 keV, and HXD-PIN 10–50 keV, and their color–color diagram is plotted in figure 5, where the bin size is 250 s. The count rate varies by a factor of 1.5–4 with a timescale of ∼ few 100 s for 0.5–2 keV and 2–10 keV, as also reported by Masetti et al. (2007).

In order to investigate whether the color also changes with the source intensity, we defined a “high”-luminosity period as > 1.65 counts s$^{-1}$ and a “low”-luminosity period as < 1.05 counts s$^{-1}$ in the XIS-0 0.5–10 keV band. Then, we made spectra of XIS-0, 1, 3, and HXD-PIN for both the “high”- and “low”-luminosity periods. To examine the changes in these spectra, we fitted them with Model 2 (BB). First, we fixed the spectral parameters representing the spectral shape to the best-fit parameters in subsection 3.1, and fitted the spectra with only the total normalization left free. (Color online)
and $0.54 \pm 0.01$, with $\chi^2$ values of 1.31 (d.o.f. = 341) and 1.96 (d.o.f. = 146), respectively. The “low” spectra have a worse $\chi^2$ value due to the relatively lower flux in the soft energy band. We next fitted the spectra by setting the normalizations of the soft and hard components of Model 2 (BB) as the free parameters. The normalization values obtained and their ratio are summarized in Table 5. The same analysis for Model 3 is shown in Table 6. Since the “low” spectra show the flux of the soft component at a lower level than that of the hard “compPS (seed = BB)” (i.e., a lower ratio by 40%–50%) in both models, it is indicated that the spectrum becomes harder when the source flux decreases.

In Figure 5, there are four data points with a high count ratio (> 5) between 2–10 keV and 0.5–2 keV; namely, the color becomes hard. These correspond to the period around the time of 65 ks in Figure 4, where the XIS count rate is low in both energy bands. We created the spectra for this period, and compared them with the time-averaged spectra in Figure 7. Since the difference between them appears only below 2 keV, and the “hard-color” spectra cannot be represented by changing only the total normalization of Model 2 (BB) [$\chi^2 = 3.80$ (d.o.f. = 101)], we again fitted the spectra by changing the normalizations of Models 2 (BB) or

![Figure 7](https://example.com/fig7.png)

Fig. 7. As figure 6, but for the time-averaged spectra (black) and those of the “hard-color” period (red). (Color online)
model is “pcfabs × phabs [BB + compPS (seed = BB)],” where “pcfabs” has a covering fraction from 0 to 1. Then, as shown in table 7, $N_{\text{H}}$ is obtained as $\sim 4 \times 10^{22} \text{ cm}^{-2}$ and about one order of magnitude larger than that of the “phabs” value [0.33 and $0.65 \times 10^{22} \text{ cm}^{-2}$ for Models 2 (BB) and 3] with the large covering fraction $\sim 0.75$. Therefore, there is a possibility that some material additionally covered the source in this period $\sim 1000 \text{s}$.

Since some SyXBs exhibit an X-ray pulse (e.g., GX 1+4, 4U 1954+31), we searched the X-ray pulse for IGR J16194–2810. Figure 8 shows the power spectrum created by FTOOLS powspec 1.0 for the XIS light curve, where the XIS 0, XIS 1, and XIS 3 light curves of the source region were combined into one to increase the statistic; this was done with barycentric correction using aebarycen of FTOOLS. The minimum time resolution is 8 s, determined by the XIS exposure period, and we calculated the power spectrum using 4096 s data segments and averaged them.

In figure 8, the power is proportional to $1/f^{1.04 \pm 0.02}$, where $f$ is the frequency, and resembles “very-low-frequency noise” observed in LMXBs (Hasinger & van der Klis 1989). There are no significant periodic features in the timescale from 0.0002 to 0.06 Hz (i.e., from 16 to 4096 s), as in the previous report (Masetti et al. 2007). Since the total number of X-ray events in the XIS light curve is $N_{\text{ph}} = 212806$, the upper limit of the amplitude $A_{\text{UL}}$ of the sinusoidal modulation is $A_{\text{UL}} \sim [2.6 \text{ Power}/(0.773N_{\text{ph}})]^{1/2}$ (van der Klis 1989), resulting in $A_{\text{UL}} \sim$ a few to 15% over $0.06 \text{ Hz}$ to 0.0002 Hz.

If there is any lag between the light curves of the soft and hard energy bands, such information is useful for identifying the origin of the soft emission component from either the NS surface (BB) or the accretion disk ("compPS (seed = DDB)"), since the disk region presumably becomes brighter before the NS surface. Then, using all XIS events in the source region with FTOOLS crosscor 1.0, we calculated the cross correlation of the light curves in 0.8–1.5 keV and 1.5–10 keV with a time resolution of 8 s, where the data were divided into 256 s segments and averaged. However, as shown in figure 8, the peak is consistent at a 0 s delay and has a symmetric shape, and no significant lags are detected between them.

### 4 Discussion

We observed the SyXB IGR J16194–2810 in the low/hard state with Suzaku. The source signal was detected in the 0.8–50 keV wide-energy band simultaneously, and the luminosity was $L \sim 7 \times 10^{34} \text{ erg s}^{-1}$ in 2–10 keV. The X-ray spectrum can be described by Model 2 (BB) “phabs[BB + compPS (seed = BB)]” or Model 3 “phabs[compPS (seed = DBB) + compPS (seed = BB)].” The hard “compPS (seed = BB)” component represents the energy band above 2 keV and gives the seed-photon parameters of $T_{\text{BB}} \sim 1.0 \text{ keV}$, $\tau_{\text{BB}} \sim 0.6$, and $R_{\text{BB}} \sim 700 \text{ m}$. The soft energy band is reproduced by either the raw BB ($T_{\text{BB}} \sim 0.4 \text{ keV}$, $R_{\text{BB}} \sim 1.7 \text{ km}$) or “compPS (seed = DBB)” ($T_{\text{DBB}} \sim 0.1 \text{ keV}$, $\tau_{\text{DBB}} \sim 0.1$, $R_{\text{DBB}} \sim 75 \text{ km}$ but with large uncertainties). During the net exposure of 46 ks, the flux varied by a factor of four in the XIS band, and the spectral shape

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**Table 7. Parameters of the additional absorber ("pcfabs") observed in the “hard-color” spectra.”**

| Parameter | Value |
|-----------|-------|
| $N_{\text{H}} \times 10^{22} \text{ cm}^{-2}$ | $3.8^{+0.9}_{-0.7}$ |
| Covering fraction | $0.75^{+0.05}_{-0.04}$ |
| $\chi^2$ (d.o.f.) | 1.06 (100) |

*The continuum emission of “phabs[BB + compPS (seed = BB)]] is fixed at the time-averaged values of Model 2 (BB) in table 2.*

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**Fig. 8.** (Top) A power spectrum of IGR J16194–2810 from the XIS light curve. The dotted line shows the best-fit power-law model of $1/f^{1.04 \pm 0.02}$. (Bottom) A cross-correlation function calculated from the XIS light curve between the 0.8–1.5 keV and 1.5–10 keV energy bands.
became harder when the flux decreased. There was also a time when the only count rate below 2 keV decreased for \( \sim 1000 \text{s} \) (the “hard-color” period). The power spectrum of the light curve shows a power-law shape without any significant periodic features.

As described in subsection 3.1, \( R_{\text{BB}} \) and \( T_{\text{BB}} \) of the hard “compPS (seed = BB)” component are well constrained by the spectral analysis, and thus we discuss these parameters. We obtained \( R_{\text{BB}} \) of IGR J16194−2810 to be \( \sim 700 \text{ m} \). This value is smaller than the NS radius of \( \sim 10 \text{ km} \), indicating that the BB emission comes from a part of the NS surface. We compare this issue with an SyXB 4U 1700+24 and typical transient and persistent LMXBs, Aql X-1 and 4U 0614+091 (Sakurai et al. 2012; Singh & Apparao 1994). Table 8 summarizes the X-ray luminosity, \( T_{\text{BB}} \), and \( R_{\text{BB}} \) of these objects together with those of IGR J16194−2810. Since the parameters of the hard “compPS (seed = BB)” component are almost independent of the modeling, we listed those of Model 3. Note that the spectrum of Aql X-1 in the high/soft state, that in the low/hard state, and that of 4U 0614+091 in the low/hard state are fitted with “diskbb + nthcomp,” “diskbb + compPS (seed = BB),” and “BB + compST,” respectively, where the “nthcomp” and “compST” models also calculate the Comptonized emission by Zycki, Done, and Smith (1999) and Sunyaev and Titarchuk (1980). In the case of 4U 0614+091, the Comptonized emission of “compST” is treated separately from the BB model, and the BB radius is considered as the lower limit without including the contribution of the seed photons. Considering the spectral features of the SyXBs and LMXBs, we suggested that the hard energy band of X-ray spectra of the NS-LMXB in the low/hard state can be explained commonly by the hard Comptonized BB emission from the NS surface.

From table 8, it can be seen that the \( R_{\text{BB}} \) of IGR J16194−2810 and 4U 1700+24 is smaller than 1 km, while that of Aql X-1 and 4U 0614+091 is larger and consistent with the emission coming from most of the NS surface. The temperature value \( T_{\text{BB}} \) of the SyXBs is \( \sim 1 \text{ keV} \) and higher than that of the LMXBs, although that of Aql X-1 in the high/soft state is even higher. Therefore, to irradiate the observed luminosity in the low/hard state, the SyXBs have a smaller radiation region on the NS surface with a higher seed-photon temperature compared with the LMXBs. We suggest that the difference in the luminosity dependence of \( R_{\text{BB}} \) and \( T_{\text{BB}} \) is due to the different magnetic field strength \( B \) between LMXBs and SyXBs.

We speculate that the magnetic field of SyXBs is stronger than that of LMXBs, and thus matter from the donor star is caught by the magnetic field and accreted to both poles along a line of magnetic force when the accreted rate is low. This hypothesis is also described in Masetti et al. (2007). For LMXBs, the magnetic field is generally believed to be weak, and thus the accreting stream falls onto the NS boundary layer without effects from the magnetic field.

In order to discuss this possibility, it is important to consider the Alfvén radius \( R_A = 2.9 \times 10^6 M_1^{1/7} R_9^{-6/7} L_{37}^{-2/7} \mu_{30}^{-1/7} \text{ cm} \), where \( M_1 \) is the mass of the compact star in units of 1\( M_\odot \), \( R_9 \) is the radius of the compact star in units of 10\(^6 \) cm, \( L_{37} \) is the luminosity in units of 10\(^{37} \) erg s\(^{-1} \), and \( \mu_{30} \) is the magnetic moment of the compact star in units of 10\(^{30} \) G cm\(^3 \). An NS with \( B \equiv 10^{12} \text{ G} \), \( R \equiv 10^6 \text{ cm} \) has \( \mu_{30} \equiv 1 \) (Frank et al. 1985). When \( L = 10^{34}, 10^{36}, \) and \( 10^{38} \) erg s\(^{-1}, R_A \) becomes 30 km, 8 km, and 2 km, respectively, for \( B \sim 10^7 \text{ G} \), 400 km, 110 km, and 30 km, respectively, for \( B \sim 10^9 \text{ G} \). Within the Alfvén radius, the accreting matter flows along a magnetic field line and finally falls on the magnetic poles of the compact star. In the case of a low luminosity and/or a strong magnetic field for an SyXB, \( R_A \) could be larger than the NS radius such that the accreting stream falls on the magnetic pole region, which is a small area, leading to a small \( R_{\text{BB}} \). The accreting matter is shocked on the NS surface and then heated up to \( \sim 1 \text{ keV} \). In the case of a high luminosity and/or a weak magnetic field typical of LMXBs, \( R_A \) is similar to or smaller than the NS radius and the accreting matter falls on a large portion of the NS surface.
of the Stefan–Boltzmann law, the temperature \( T_{\text{BB}} \) is not as high as 1 keV.

Lamb, Pethick, and Pines (1973) estimated the size and radius of the hotspot, where the matter accretes on the NS surface and emits X-rays, as \( \pi R^2 (R/R_A) \) and \( R \sqrt{G M/R_A} \), respectively. The value of \( R \) is the NS radius of 10 km. When we assume that the observed \( R_{\text{DBB}} \) of \( \sim 700 \) m corresponds to the hotspot radius, \( R_A \) is calculated as \( \sim 2000 \) km and \( B \) becomes \( \sim 4 \times 10^{10} \) G with a luminosity of \( 7 \times 10^{33} \) erg s\(^{-1}\). The strength of the magnetic field is actually higher than that of typical LMXBs (< \( 10^9 \) G).

If the accreting matter falls on the magnetic poles, the X-ray emission should show pulsation as HMXBs. However, we could detect no pulse from IGR J16194–2810, or from 4U 1700+24 (O. Nagae 2013 private communication). Lü et al. (2012) listed 10 SyXBs and candidates. The X-ray pulse has been detected from several objects; for example, GX 1+4 and 4U 1954+31. Their spin was \( P_s \sim \) a few 100 s (e.g., Chakrabarty et al. 1997; González-Galán et al. 2012) and \( \sim 5 \) h (Corbet et al. 2008), which is longer than the typical spin periods of LMXBs. Therefore, we speculate that the spin period of IGR J16194–2810 may be too long (\( \gtrsim 1 \) h) to be detected during this observation. There are also other possibilities to explain the absence of the pulsation: that the spin axis just coincides with the magnetic one, that it can be wiped out through Comptonization by a very hot Compton cloud (Torrejón et al. 2004), or that the compact star might be a black hole without a solid surface.

To accrete matter smoothly from \( R_A \) to the NS surface, the NS needs to spin more slowly (i.e., have a longer spin period) than the equilibrium spin period \( P_{\text{eq}} \geq 2\pi\sqrt{R_A^3/GM} \), where \( G \) is the gravitational constant and \( M \) is the NS mass. Otherwise, the matter is likely to be ejected due to the “propeller” effect (e.g., Illarionov & Sunyaev 1975). Assuming \( P_{\text{eq}} = 1 \) h from the above discussion, \( R_A \) becomes \( \lesssim 4 \times 10^3 \) km. Then, the magnetic field is estimated as \( B \lesssim 4 \times 10^{14} \) G with the observed luminosity \( L = 7 \times 10^{34} \) erg s\(^{-1}\). This upper limit is as large as that of magnetars and is also consistent with the value estimated above from the radius of the hotspot.

From the analysis of the time-averaged spectrum, the origin of the soft energy component below 2 keV is considered as the emission from the NS surface [Model 2 (BB)] or the accreting stream (Model 3). The timing analysis does not show significant lags and it is difficult to constrain the geometry further. If the emission comes from the NS surface, the region of \( \sim 1.7 \) km is larger than that of the hard component (\( \sim 700 \) m), but still smaller than the NS radius. Additionally, the temperature of \( \sim 0.4 \) keV is lower than the hard one \( \sim 1.0 \) keV, and this component may arise from thermalized matter after accretion at the magnetic poles.

On the other hand, there are also several predictions about matter accreting onto magnetic compact objects—whether it forms an accretion disk or a shell structure (Mitumoto et al. 2005; Shakura et al. 2012). However, the disk inner radius \( R_{\text{DBB}} \) of Model 3 is obtained as \( 75^{+65}_{-40} \) km, and is one or two orders of magnitude smaller than the estimated Alfvén radius \( R_A \sim 2000 \) km. This might imply that there exists a disk or shell structure around \( R_A \) but that the \( R_{\text{DBB}} \) obtained by the spectral fitting is underestimated. In fact, we cannot constrain \( R_{\text{DBB}} \) and \( T_{\text{DBB}} \) well or detect any large fraction of the un-Comptonized raw emission (i.e., a small portion of the emission might be injected into the Compton cloud and observed) due to interstellar absorption as described in subsection 3.1. In terms of the incompatibility between \( R_{\text{DBB}} \) and \( R_A \), Model 2 (BB) reproduces the data better physically than Model 3.

During the “hard-color” period of \( \sim 1000 \) s, the source flux decreased only below 2 keV. The spectrum is well represented by an additional absorber with a column density of \( \sim 4 \times 10^{22} \) cm\(^{-2}\) and a covering fraction of \( \sim 0.75 \). Such behavior is also observed in other X-ray binaries due to clumpy stellar wind (e.g., dips in Cyg X-1; Feng & Cui 2002). The red giant of IGR J16194–2810 might also have clumpy stellar wind (Crowley 2006).

5 Summary

In this paper, we analyzed the Suzaku data of SyXB IGR J16194–2810 in the energy range of \( 0.8–50 \) keV, and obtained the results described below.

1. The time-averaged spectrum at a luminosity of \( \sim 7 \times 10^{34} \) erg s\(^{-1}\) was physically represented by Model 2 (BB) (blackbody plus Comptonization model) or Model 3 (two-Comptonizations model). In both models, there were two emission components: the hard component of a Comptonized BB emission, and the soft one of either a raw BB or a Comptonized emission.

2. Compared with other SyXBs and typical transient and persistent LMXBs in the low/hard state, the hard emission component of SyXBs has a smaller \( R_{\text{BB}} \) < 1 km and a higher \( T_{\text{BB}} \sim 1 \) keV. We propose that this behavior is due to the stronger magnetic field of SyXBs than that of LMXBs, such that the accreting stream falls on the magnetic poles of the NS.

3. The emission region of the soft component is still unclear, since the lower energy band has uncertainties due to interstellar absorption, and no time lags were observed between soft and hard energy bands. One possibility [Model 2 (BB)] is that the raw BB emission may arise from thermalized matter after accretion at the magnetic poles. The other (Model 3) is that the seed
photon of the Comptonized emission might be injected from a small fraction of the accreting stream.

4. The light curve showed time variation during the 1 d observation, and it was suggested that the spectrum becomes harder when the source flux decreases. There was a $\sim 1000$ s period when the flux decreased only below 2 keV. The spectrum was reproduced with an absorber additional to the time-averaged one. The power spectrum did not have any significant periodic features in the timescale from 0.0002 to 0.06 Hz.

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