X-ray and Near-Infrared Observations of the Black Hole Candidate GX 339–4

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Abstract

We present our latest X-ray and near-infrared results of the Galactic black hole candidate GX 339–4 observed with *Suzaku* and *IRSF* (*Infra-Red Survey Facility*) in 2009 March during the low/hard state. The X-ray spectral analysis suggests that the accretion disk is likely truncated at a radius larger than the innermost stable circular orbit (ISCO for a non-spinning black hole), and that its inner part is almost fully covered by hot corona with an electron temperature of approximately 170 keV. The Comptonized corona has at least two optical depths, $\tau = 0.9$ and 0.3. The one-day averaged near-infrared light curves are found to be correlated with hard X-ray flux. The radio to near infrared spectral energy distribution suggests that the optically thin synchrotron radiation from the compact jets dominates the near-infrared flux. We estimate that the magnetic field and size of the jet base are $\sim 10^4$ G and $\sim 10^9$ cm, respectively, and that the synchrotron self Compton component contributes less than 0.4% of the total X-ray flux. Finally, we also report results from the long term monitoring of GX 339–4 with *MAXI*/GSC and discuss the spectral evolution during the outburst.

Key words: accretion, accretion disks — black hole physics — infrared: stars — stars: individual (GX 339–4) — X-rays: binaries — X-rays: stars

1. Introduction

GX 339–4 is a transient Galactic black hole binary (BHB), discovered in the early 1970s. This object has been observed many times at various X-ray luminosities ($L_{\rm X}$) to investigate the accretion disk geometry. In the bright low/hard state at $L_{\rm X} \sim 0.01 L_{\rm Edd}$, where $L_{\rm Edd}$ is the Eddington luminosity, Miller et al. (2006) detected a smeared iron-K line and suggested that the standard disk of GX 339–4 is extending down to $\approx 4R_{\rm g}$ ($R_{\rm g} \equiv GM/c^2$ is the gravitational radius, where G, M, and c are the gravitational constant, black hole mass, and light velocity, respectively.) This is questioned by Done & Diaz Trigo (2010), however, who re-analyze the Miller et al.

(2006) data and find that the spectrum is consistent with a truncated disk well above the ISCO for a non-spinning black hole. Thus, while there is a consensus that an optically thick disk is truncated before reaching the ISCO at low mass accretion rates (e.g., Esin et al. 1997), discussion at what Eddington fraction the disk becomes truncated is still controversial.

To establish the inner disk structure and the origin of the continuum emission of BHBs in the low/hard state, we observed GX 339–4 using the X-ray satellite *Suzaku* in 2009 March, when it became active and stayed in the low/hard state. Quasi-simultaneous near-infrared observations were performed with the *Infrared Survey Facility* (*IRSF*) 1.4 m telescope to reveal the jet activity. The reader is referred to Shidatsu et al. (2011) for the details of these observations and results.

GX 339–4 underwent an outburst and made a hard-to-soft transition in 2010. This is almost continually observed with the Monitor of All-sky X-ray Image (*MAXI*: Matsuoka et al. 2009). In this paper, we also reports the results from the analysis of the spectra obtained with Gas Slit Camera (GSC) onboard *MAXI* during the outburst, and discuss the spectral evolution of GX 339–4.

2. Suzaku Results in the Low/hard State

We performed three sequential ToO (Target of Opportunity) observations of the Galactic black hole candidate GX 339–4 with Suzaku on 2009 March 18, 25–26, and 30–31, each for a net exposure of $\sim$ 40ksec. The ToO observations were triggered after the X-ray flux of the source began to increase (Markwardt et al. 2009). It stayed in the low/hard state during our observations and the observed 1–100 keV flux was 3.4×10^{-9} ergs cm^{-2} sec^{-1}, which corresponds to a luminosity of $\approx 0.02 L_{\rm Edd}$ by assuming its distance and black hole mass to be 8 kpc and 10 $M_\odot$, respectively.

From these observations, we achieved the best quality broad-band (0.5–310 keV) spectra that have ever obtained in the low/hard state of GX 339–4. As shown in Figure 1, the time-averaged spectrum in each epoch exhibits almost the same shape, and therefore we co-added the data of the three observations to use for the analysis.

We find that the overall continuum in the 2–100 keV band can be roughly approximated by a power law of a photon index of $\sim$1.5. This confirms that GX 339–4 stayed in the low/hard state throughout our observations. Thus, following the previous studies of BHBs in the low/hard state with *Suzaku*, we adopt a thermal Comptonization model as the basic description of the hard X-ray continuum. The broad-band spectrum is fitted with a model of emission from a standard accretion disk and its thermal Comptonization by a hot corona. The disk emission is assumed to be the multi-color blackbody radiation modeled by `diskbb` (Mitsuda et al. 1984). For the Comptonization component, we employ the `compPS` model (Poutanen & Svensson 1996), which is able to include a reflection component from the disk. We assume that the Comptonization cloud has a spherical shape and that seed photons are entirely originated in the standard disk.

In Figure 2, the best-fit model spectrum in the νF_ν form (where F_ν is the energy flux) is plotted, with contribution of each component, corrected for the interstellar absorption. We find that the time-averaged X-ray spectrum is dominated by thermal Comptonization component with an electron temperature of $\approx$170 keV. The direct disk flux is very small ($\leq$1% of the total at 0.5 keV), indicating that the inner part of the optically thick disk is almost fully covered by the corona. The strength of the reflection component (in terms of the solid angle, $\Omega/2\pi \approx 0.4$) and the ionization parameter of the reflector ($\xi \approx 0.6$) are consistent with the result from a previous *Ginga* study in the similar intensity state (in 1989 September) analyzed with a power law continuum Ueda et al. (1994), but are now determined with much smaller uncertainties thanks to the better energy resolution and wider coverage of *Suzaku*. The Comptonized corona has at least two optical depths ($\tau \approx 0.9$ and 0.3). This suggest that the Comptonizing corona has a more complex geometry than that assumed in a single zone, spherical model. Similar conclusions have been obtained from Cyg X-1 (Makishima et al. 2008) and GRO J1655–40 (Takahashi et al. 2008) in the low/hard state with *Suzaku*. Thus, we suggest that such physical properties of the corona may be a common feature in the low/hard state of BHBs.

The analysis of the iron-Kα and Kβ lines with a relativistic disk emission-line model yields an inner radius of $(13.3^{+6.4}_{-6.0}) R_{\rm g}$, with an estimated inclination of $\approx 50^\circ$. This radius is consistent with that estimated from the continuum fit by assuming the conservation of photon numbers in Comptonization. Our results suggest that the standard disk of GX 339–4 is extended near the ISCO for a non-spinning black hole but likely truncated in the bright low/hard state at $\approx$2% of Eddington luminosity. Comparing this $R_{\rm in}$ value with those obtained in previous observations, we can study how the inner edge of the accretion disk evolves during the low/hard state as a function of luminosity. We derive the radius by re-analyzing the iron line profile of the Tomsick et al. (2009) data obtained with *Suzaku* in 2008 September, assuming an inclination angle as 50° and emissivity index as -2.3, which are adopted from the best-fit value of our 2009 data. The 3–8 keV spectra, best-fit models, and residuals are plotted in Figure 3. It is seen that the iron-K line observed in the 2008, when the 1–100 keV flux was approximately 14 times fainter than that in our *Suzaku* observations, is significantly narrower than that obtained

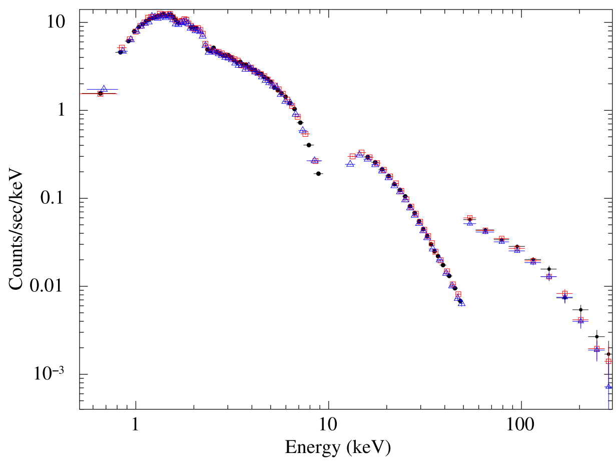

Fig. 1. The time-averaged *Suzaku* spectra obtained in Epoch-1 (black, filled circle), -2 (red, open square) and -3 (blue, open triangle).

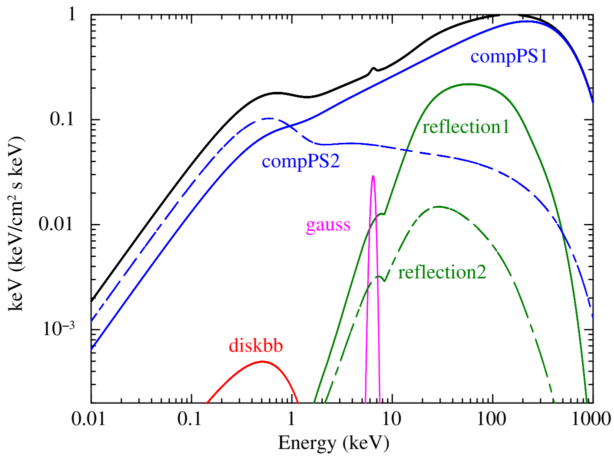

Fig. 2. The best-fit double compPS model in the νF_ν form, corrected for the interstellar absorption. Each component is separately plotted.

in 2009. The resulting inner disk radius is $R_{\rm in} = 480^{+770}_{-330}$, which is approximately 40 times larger than in our observations. These results indicate that the inner edge moved inward as the luminosity increased from 2008 to 2009.

3. IRSF Observations and Results

We carried out $JHKs$-band near-infrared photometric observations of GX 339–4 on 11 nights over a period from 2009 Feb 27 to 2009 March 23, using IRSF (InfraRed Survey Facility) 1.4m telescope at the South African Astronomical Observatory (SAAO).

We examine the origin of the multi-wavelength SED of GX 339–4 in the low/hard state with different emission components, utilizing our quasi-simultaneous near-infrared (*IRSF*) and X-ray (*Suzaku*) spectra combined with previous data (Figure 4). In this figure, the interstellar absorption is corrected in the X-ray spectrum, and all the near infrared data are deredenned by assuming $A_V = 3.7$ (Corbel & Fender 2002). We plot the estimated contribution of the "intrinsic" MCD component including photons that are Compton-scattered in the corona, through the photon number conservation, assuming that the disk is extending to infinity (for illustrative purpose) with the temperature proportional to $r^{-3/4}$, where r is the radius from the black hole. The results are based on the broad-band fit of the *Suzaku* data, which gives the innermost disk temperature of 0.22 keV. We also plot the upper limit of the contribution from the companion star, assuming a blackbody of 4000 K. Here we refer to the r-band magnitude of > 21.4 by Zdziarski et al. (2004), which is then corrected for extinction corresponding to $A_V = 3.7$. As noticed from the figure, the blackbody component of the multi-color disk (MCD) and companion star contributes only $\leq 0.5\%$ and $\leq 1\%$ of the total flux in the near-infrared range, respectively.

Our averaged *IRSF* spectrum shows a somewhat steeper slope than the radio spectrum, $\alpha = -0.1$; the corresponding $J - K_{\rm s}$ color is similar to that of the 1981 observations compiled by Corbel & Fender (2002). As shown by them, this color is consistent with a superposition of two different components with $\alpha = -0.6$ and $\alpha = 2.1$, which can be explained by the optically *thin* synchrotron radiation from the jets and the reprocessed, thermal emission by X-ray irradiation from outer parts of the disk, respectively (see also Markoff et al. 2003, and Gandhi et al. 2010). It is thus indicated that the transition point from optically thick to thin regime of the synchrotron emission, defined as $\nu_{\rm t}$, must appear at frequencies just below or around the near-infrared band, $\sim 10^{14}$ Hz. Based on a simple analysis, we estimate the magnetic field and size of the jet base to be 5×10^4 G and 6×10^8 cm, respectively, and the synchrotron self Compton component to be approximately 0.4% of the total X-ray flux. This justifies our assumption that the X-rays spectrum is described as Comptonization of the emission from the accretion disk.

To examine the correlation between the $K_{\rm s}$ and hard X-ray light curves, we plot the one-day averaged 15–50 keV flux ($F_{\rm X}$) versus $K_{\rm s}$ band flux ($F_{\rm Ks}$) in Figure 5. The data point taken from the 1981 dataset Corbel & Fender (2002) is also plotted. By fitting *IRSF* and *Swift* points with a power law of $F_{\rm Ks} \propto F_{\rm X}^{\Gamma}$, we obtain $\Gamma = 0.45 \pm 0.06$. Similar correlation is reported between the radio and X-ray fluxes with a steeper slope of 0.7–0.9 in the low/hard state (Corbel et al. 2003). These correlations confirm the strong link between the jet formation and

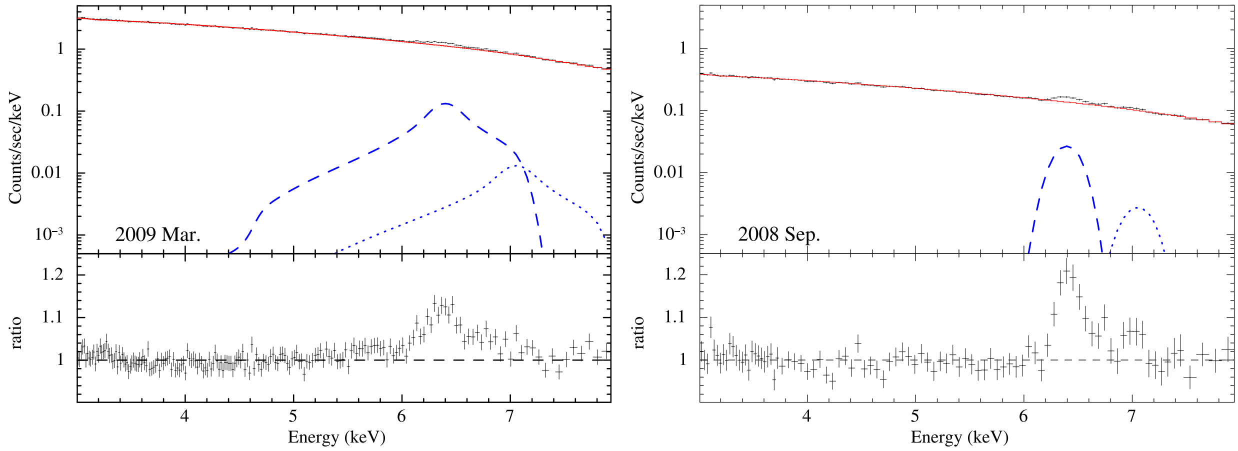

Fig. 3. *Suzaku* 3–8 keV spectra of GX 339–4 obtained in 2009 March (our data, left) and in 2008 September (Tomsick et al. 2009, right), fitted with the `diskline` model for the iron-K emission line. The Kα and Kβ line components are plotted in dashed and dotted lines, respectively. The bottom panels show the ratio between the data and continuum model of 2009 and 2008 data, respectively.

accretion flow, as directly indicated by the strong cross correlation between the optical and X-ray bands on much shorter ($<$ 1 sec) time scale for this source. The slope of the correlation and its dependence on the wavelength and luminosity give us important clues to understand the origin of the SED.

4. Observations of GX 339–4 with MAXI

Since 2009, *MAXI* has been continuously monitoring GX 339–4 with the Gas Slit Camera (GSC) at energies of 2–30 keV, including its outburst and state transition from the low/hard to high/soft states occurred in 2010. We extracted one-day averaged spectra on 2010 March 25 (Epoch-1), May 4 (Epoch-2), and June 3 (Epoch-3). As shown in Figure 6 plotting the one-day *MAXI*/GSC light curves of GX 339–4 in different energy bands, these three dates correspond to the onset of the outburst, the peak of the total band flux, and the period after the decrease of hard X-ray (10–20 keV) flux, respectively.

The Epoch-1 spectrum can be well fit with a simple absorbed power law model within statistics, yielding an photon index of 1.7 ± 0.1. This indicates that GX 339–4 was in the low/hard state in Epoch-1. The best-fit model is shown in Figure 7. Next, we analyze the Epoch-2 and -3 spectra, which are dominated by the soft X-ray ($<$ 10 keV) flux. Fitting with a MCD model (`diskbb`) results in significant positive residuals in the $>$ 8 keV band. The discrepancy can be attributed to the presence of a "hard tail" often observed in the high/soft state, which is most probably a Comptonized component by non-thermal electrons. Hence, we re-fit the spectrum by including a Comptonized spectrum with seed photons from the MCD component. As for the Comptoniza-

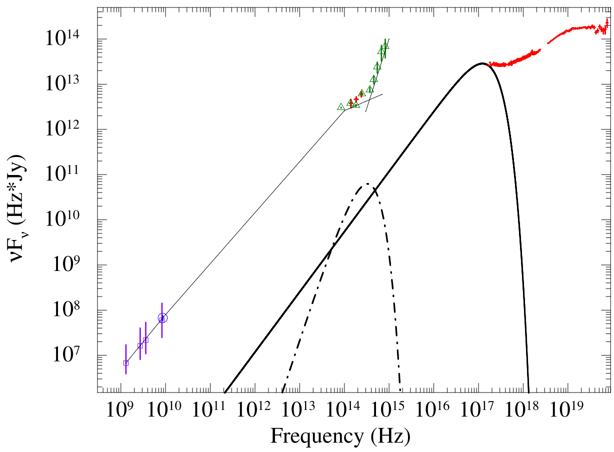

Fig. 4. Multi-wavelength SED of GX 339–4 in the νF_ν form, corrected for the interstellar absorption/extinction by assuming $A_{\rm V} = 3.7$. The *Suzaku* spectra and the radio data in 1992–1999 (Fender 2001) and are displayed in red (cross), purple (open square), respectively. The point at 8.64×10^9 Hz is an estimated flux from the empirical relation with the 20–100 keV flux (Corbel et al. 2003). The green triangles correspond to the infrared/optical data obtained in 1981 (Corbel & Fender 2002), which are adjusted to fit the $K_{\rm S}$ band flux of our *IRSF* data shown in red (cross). The solid curve shows the estimated contribution of intrinsic multicolor disk emission, including the Compton scattered photons. The dash-dotted curve represents the upper limit of the contribution from the companion star, assuming a blackbody with an effective temperature of 4000 K (Zdziarski et al. 2004). The broken power law represents an estimated contribution from the compact jet, while the steepest power law component correspond to the reprocessing of X-ray emission in the outer disk.

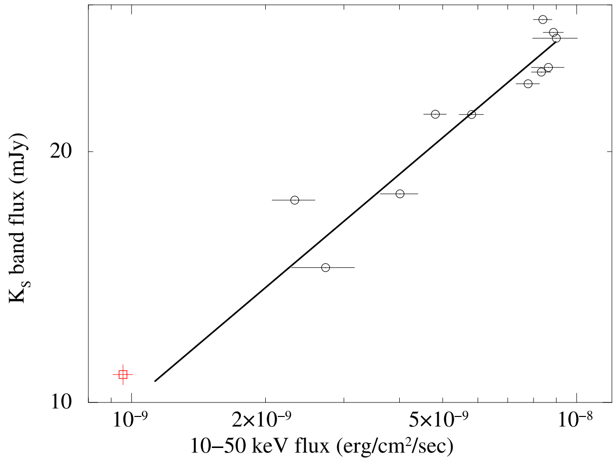

Fig. 5. The relation between the X-ray (15–50 keV) and IR (K_S) fluxes of GX 339–4 with *Swift*/BAT and *IRSF*/SIRIUS in 2009 March. The result of the 1997 observation (Corbel & Fender 2002) is also included (red, open square). Each K_S band flux is calculated by averaging all the magnitudes obtained on the same day. The data points except for the 1997 data are fitted by a power law with $F_{\rm Ks} \propto F_{\rm X}^{\Gamma}$. The best-fit result ($\Gamma = 0.45$) is shown as a solid line in this figure.

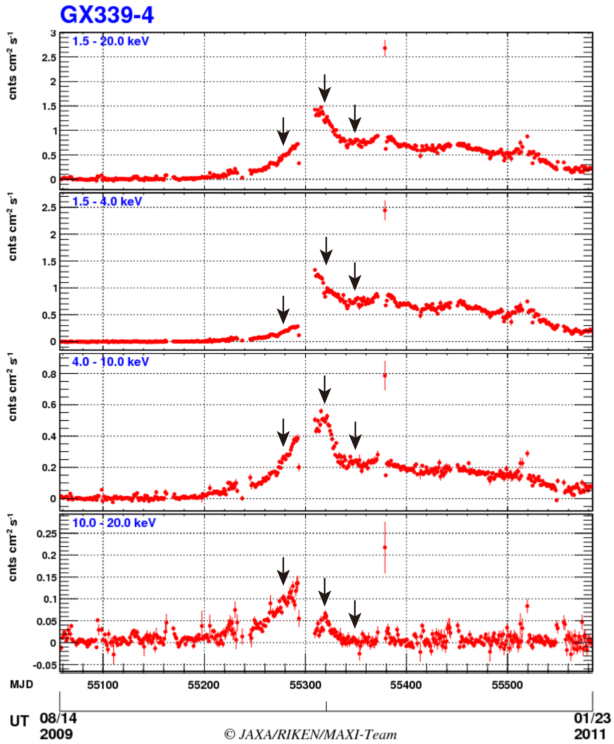

Fig. 6. *MAXI*/GSC light curves of GX 339–4 provided by the *MAXI* team (http://maxi.riken.jp). From top to bottom, those in the 1.5–20 keV, 1.5–4.0 keV, 4.0–10 keV, and 10–20 keV bands. The arrows in each panel show the three epochs (MJD 55280, 55320, 55350) where we extracted the one-day averaged spectra.

tion model, we employ an empirical convolution model, `simpl`, which converts a given fraction of the incident spectrum to a power law component (Steiner et al. 2009). Because of the poor statistics in the hard X-ray (> 10 keV) band, we cannot constrain the photon index of the `simpl` model in Epoch-3, which is thus fixed at 2.0. The fit is found to be acceptable and the best-fit models are plotted in Figure 8.

We calculate the inner disk radii in Epoch-2 and -3 from the normalization of the MCD component, correcting for the boundary condition and ratio of the color/effective temperature (see e.g., Kubota et al. 1998). The resulting inner radii are found to be 58^{+8}_{-7} (Epoch-2) and 64^{+12}_{-10} km (Epoch-3). These are consistent with the Makishima et al. (1986) result obtained in the high/soft state, $R_{\rm in} \approx 55$ km, when the distance and inclination angle of the source is assumed to be 8 kpc and 50°, respectively, by applying the same corrections as above. Hence, we can estimate the black hole mass of GX 339–4 to be 6–7 $M_{\odot}$ from the inner radius of the spectra obtained in Epoch-2 and -3, assuming that the standard disk is extending to the ISCO of a non-spinning black hole. This is consistent with the value obtained from the mass function and other constraints as summarized in Shidatsu et al. (2011).

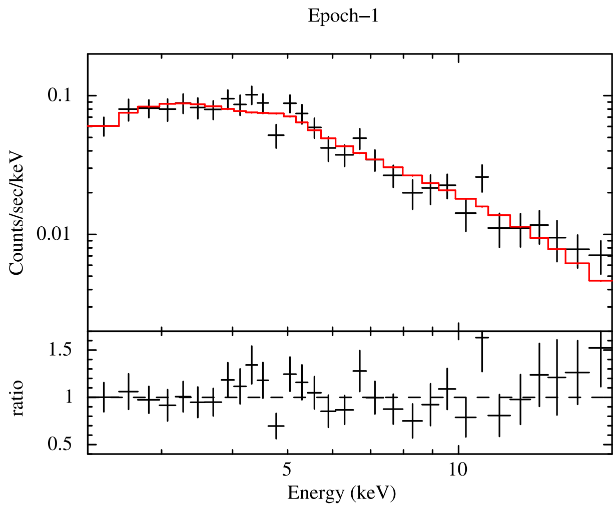

Fig. 7. *MAXI*/GSC spectrum of GX 339–4 in Epoch-1 with the energy response (upper panel). The best-fit absorbed power law model is overplotted. The ratios between the data and best-fit model are shown in the lower panel.

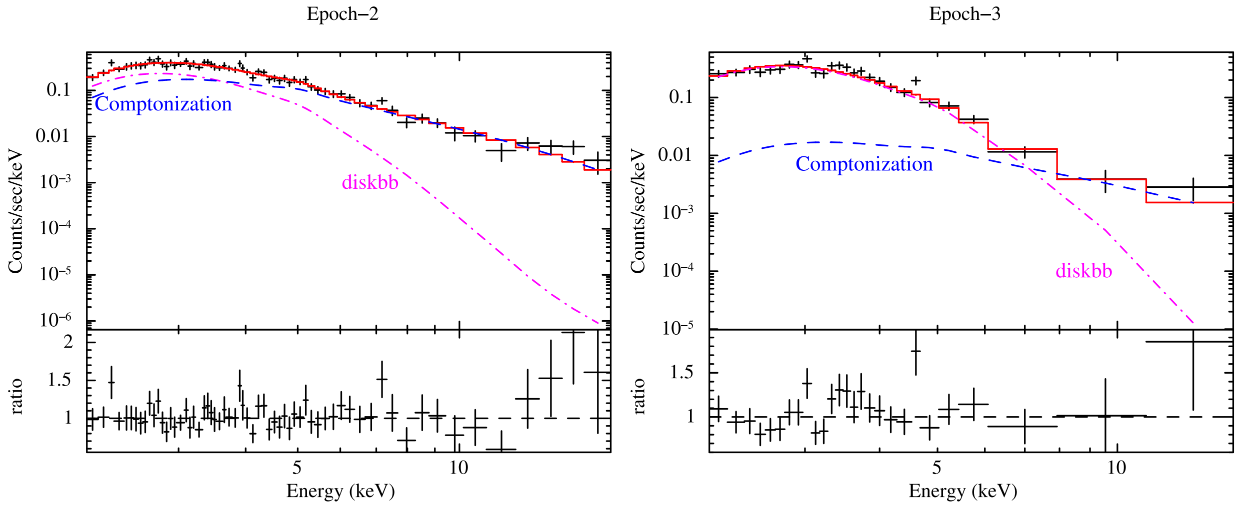

Fig. 8. *MAXI*/GSC spectra of GX 339–4 in Epoch-2 (left) and -3 (right), folded with the energy response (upper panels). The best-fit model is overplotted with the separate contributions from the MCD and its Comptonization components. The ratios between the data and best-fit model are shown in the lower panel.

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