Suzaku Observations of Black-Hole Binaries and ULXs

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Abstract

After a brief description of black hole investigations conducted in RIKEN, two highlights from the ongoing *Suzaku* mission are described. One is detailed understandings of the Low/Hard state of black hole binaries. The other is the reinforced interpretation of ULX objects as intermediate-mass black holes. A caution is cast upon the claimed detections of broad Fe-K lines from several Galactic X-ray sources. A mention is made also on the anticipated MAXI quest for the merger signals among active galactic nuclei.

Key words: black holes —Cyg X-1 — ULXs — Suzaku — MAXI

1. Introduction

As illustrated in Fig.1 by a pentagon, observational studies of black holes (BHs) comprises five distinct aspects of scientific importance. These are; to understand the physics of mass accretion onto BHs using their radiation as a probe; to search for general relativistic effects; to clarify how the gravitational energy release of accreting materials is partially extracted and converted into non-radiative energy outputs; to study the final stage of stellar evolution including the gravitational collapse and the BH formation; and to investigate how massive BHs at the galaxy nuclei have been formed possibly involving intermediate-mass BHs (IMBHs). These aspects are further combined to form composite research subjects, as indicated by shaded boxes in Fig.1.

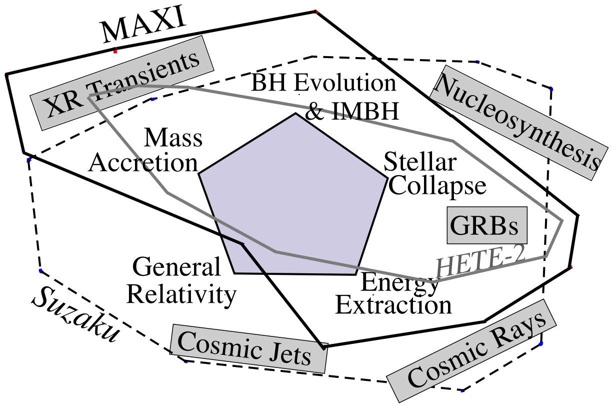

Fig. 1. A schematic overview of observational BH studies, and their coverage bythe three RIKEN-related missions; *HETE-2* (solid gray line), *Suzaku* (dashed line), and MAXI (solid black line).

2. Black Hole Researches in RIKEN

At the RIKEN Cosmic Radiation Laboratory, we have been carrying out extensive BH observations, mainly using the following three space missions. The scientifc ranges covered by them are also indicated in Fig.1.

- *HETE-2*: This is a small satellite launched in October 2000, under a collaboration among RIKEN, MIT, and a French group. It has revealed two origins of gamma-ray bursts; gravitational collapses of massive stars (for "long" events; Greiner et al. 2003), and mergers between two compact objects (for "short" ones: Villasenor et al. 2005).
- *Suzaku*: This is the 5th Japanese cosmic X-ray satellite, launched on 2005 July 10 (Mitsuda et al. 2007). We have participated in the development of the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007), in software developments, in-orbit calibrations, and verification of the timing accuracy. We also run "*Suzaku* Help Desk".
- MAXI: Since this is the central subject of the present workshop, we need only to remark that we are one of the core members of this mission, and are in particular responsible for releasing/archiving the MAXI data and leading the science using them.

Our activity as described above is collaborative with two other groups in RIKEN. One is the Nishina Center for Accelerator-Based Science, led by Dr. Y. Yano; we collaborate with them on the study of cosmic nucleosynthesis, as well as on hardware developments. The other is the Computational Astrophysics Laboratory led by Dr. T. Ebisuzaki, where they are conducting numerical studies of the formation of IMBH and super-massive BHs, and proposing for the ISS an ambitions EUSO mission to study the highest-energy cosmic rays.

3. *Suzaku* Highlights on Black Hole Binaries (BHBs)

3.1. Four spectral states of BHBs

It has been shown (e.g., Makishima 2007) that mass-accreting black-hole binaries (BHBs) take four typical spectral states, according to their accretion rates.

1. The Low/Hard State (LHS), corresponding to the normalized mass accretion rate η less than a few percent. The spectrum takes roughly a power-law shape, with a thermal cutoff at ~ 100 keV.
2. The Hight/Soft State (HSS), realized for η from a few to several tens percent. The spectrum consists of a soft component from a standard accretion disk, and an enigmatic power-law tail.
3. The Very High State (VHS), which appears at $\eta \sim 1$. Although the standard-disk is still present, its emission becomes strongly Comptonized, to form a power-law like continuum with a mild curvature.
4. The Slim Disk State (SDS) with even higher values of η (Kubota & Makishima 2004). Although the spectra resemble the HSS ones, the disk is much hotter, and its radial temperature profile is flatter than that of a standard disk.

3.2. Low/Hard state spectra

While the HSS spectra of BHBs (except for the enigmatic hard tail) have been understood well as originating from standard accretion disks, their LHS spectra have long remained ambiguous. Little is clear beyond what is rather certain, that the dominant hard X-ray continuum is a result of thermal Comptonization of some seed photons by a hot "corona" created near the BH. The seed photons could be provided either by a cool disk located somewhere in the system, or by the corona itself via thermal synchrotron process. The difficulty with the LHS lies mainly in the broad energy band in which the radiation emerges. Then, the research must be much promoted by *Suzaku*, which covers an extremely wide energy range of 0.2–600 keV with the HXD and the X-ray Imaging Spectrometer (XIS).

With the above motivation in mind, we have so far observed with *Suzaku* several BHBs, and detected two objects in a typical LHS; Cyg X-1 (Makishima et al. 2008) and GRO J1655−40 (Takahashi et al. 2008). By carefully investigating these data, we have successfully constructed a canonical model spectrum applicable to both objects over a typical energy range of 1–300 keV. As presented in Fig.2, the model consists of the following 5 components.

1. A thermal Compton continuum (`Compps_h` in Fig.2), with an electron temperature of $T_\mathrm{e} = 100 \sim 140$ keV and an optical depth of $\tau = 1.1 \sim 1.5$.
2. Another Compton continuum (`Compps_s`) with a comparable T_e, and a lower optical depth of $\tau \sim 0.3$.
3. A direct disk emission (`diskbb`) at the softest end of the spectrum, with a temperature of ~ 0.2 keV.
4. The reflection components associated with the Compton continua.
5. A fluorescent Fe-K line, only slightly broadened.

The model in Fig.2 is for Cyg X-1, while that for GRO J1655−40 differs only in the weakness of the components 3 to 5. For example, the equivalent width (EW) of component 5 is ~ 300 eV and ~ 100 eV in Cyg X-1 and GRO J1566−40, respectively. This can be explained by their difference in the disk inclination, which is estimated as $i \sim 45^\circ$ for Cyg X-1 and $i \sim 70^\circ$ for the other. If these values of i are considered, the reflector in both objects are inferred to have a solid angle of $\Omega \sim 0.4 \times 2\pi$ as seen from the corona. In this way, the differences between the two objects can be explained consistently as inclination effects; this in turn supports a natural view that the disk is flat and the corona is rather spherical.

These results imply four important consequences. First, the disk-corona view is basically correct, and the seed photons are consistent with being fed by the disk. Second, the corona is highly inhomogeneous, because the Compton continua have at least the two optical depths, and the cool disk is partially visible without Comptonized. Third, the cool disk is truncated at a radius of $\sim 8R_\mathrm{S}$, where R_S is the Shcwarzshild radius. This inference is obtained by summing the area of the directly visible disk, and that of the Compton seed-photon source. Finally, the cool disk intrudes half way into the corona, because the reflector solid angle, $\Omega \sim 0.4 \times 2\pi$, is neither too large (in which case the disk would be mostly covered by the corona), nor too small (in which case the disk must be truncated outside the corona).

We have thus for the first time succeeded in constraining a realistic geometry of the corona-disk configuration.

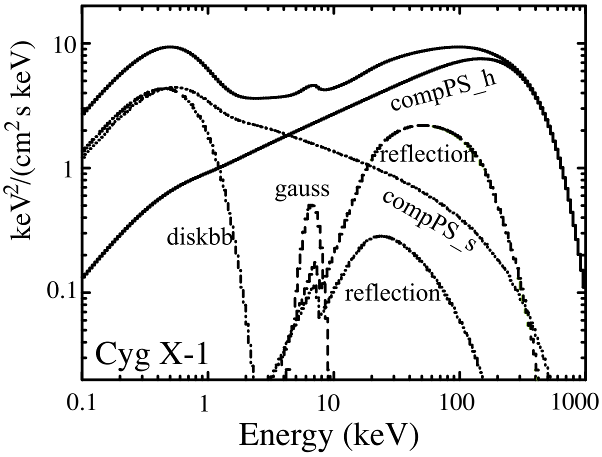

Fig. 2. A canonical $\nu F \nu$ spectrum of BHBs in the Low/Hard state, obtained by analyzing the *Suzaku* spectra of Cyg X-1 (Makishima et al. 2008) and GRO J1655-40 (Takahashi et al. 2008).

3.3. Rapid time vatiations

Another outstanding issue associated with the LHS of BHBs is their rapid flickering activity, known for more than 3 decades. Although a large number of studies have been conducted on this issue, it has remained difficult to interpret the phenomenon as a certain physical process taking place in the disk-corona system.

We analyzed the *Suzaku* data using a new method, namely judging instantaneous (on $\sim$ 1 sec time scales) source intensity using the XIS data which have higher statistics, and apply the judgement to the HXD data which have poorer statistics. We have thus obtained a pair of broad-band Cyg X-1 spectra, one covering brighter time intervals of the source, while the other fainter phases. By comparing them, we have arrived at the following inferences (Makishima et al. 2008).

1. The seed photon input to the corona increases in the brighter phase, enhancing the hard X-ray intensity.
2. Either $T_{\rm e}$ or τ (or both) of the corona decreases in the brighter phase, thus making the spectrum softer.
3. The cool disk does not vary either in its temperature or its emission area (the directly visible area plus that of the seed-photon source).
4. The relative fluxes between the two Compton continua are kept rather constant as the source varies.
5. The reflection and the Fe-K line both vary in proportion to the continuum intensity. Namely, both Ω and the Fe-K line EW remain constant.

As a possible picture that can explain all the above results, we may speculate that the corona is highly "porous" with a number of holes in it, and the source flares up in hard X-rays when the volume fraction of these holes decreases. Then, a larger number of Comptonized photons will come out even if the disk remains unchanged. The holes may correspond to regions threaded with strong magnetic fields, and the decrease of holes may be caused by their rapid reconnection.

4. The Nature of ULXs

ULXs, or Ultra-Luminous X-ray sources (Makishima et al. 2000), provide one of the most intriguing issues in the modern BH study. Since their luminosity reaches the Eddington limits of objects with 30 $\sim$ 1000 $M_\odot$, these objects could be IMBHs with such large masses (Mizuno et al. 2007; Makishima 2007). Alternatively, they could be ordinary stellar-mass BHs, radiating either at highly super-Eddington luminosities, or with a highly anisotropic angular pattern enhanced toward us.

The best way toward the elucidation of the nature of ULXs is to compare their behavior with that of BHBs, and draw appropriate analogy between the two classes. For this purpose, we studied 8 ULXs that have been observed repeatedly; M82 X-1, NGC 1313 X-1, NGC 1313 X-2, IC342 X-1, Holmberg IX X-1, Holmberg II X-1, M81 X-6, and NGC 5204 X-1. We analyzed their archival data from *Suzaku* (Mizuno et al. 2007) and *XMM-Newton*. Figure 3 show a color-color plot of these objects, using three typical energy bands; 1–2 keV, 2–4 keV, and 4–10 keV (Miyawaki 2008).

In Fig.3, the region indicated by a thick dashed circle was found to have a particular meaning; if an object falls within this circle, it exhibits the highest 1–10 keV luminosity L than in any other region of this plot. For each object, we hence employed the luminosity observed inside this circle as a fiducial luminosity $L_{\rm c}$, and normalized all its L measurements to $L_{\rm c}$. Then, all the 8 objects can be seen to behave in a very similar way in terms of $L/L_{\rm c}$. Although a few sources did not come inside the thick dashed circle, we were able to define their values of $L_{\rm c}$ in an appropriate way, so that their normalized behavior becomes parallel to that of the others.

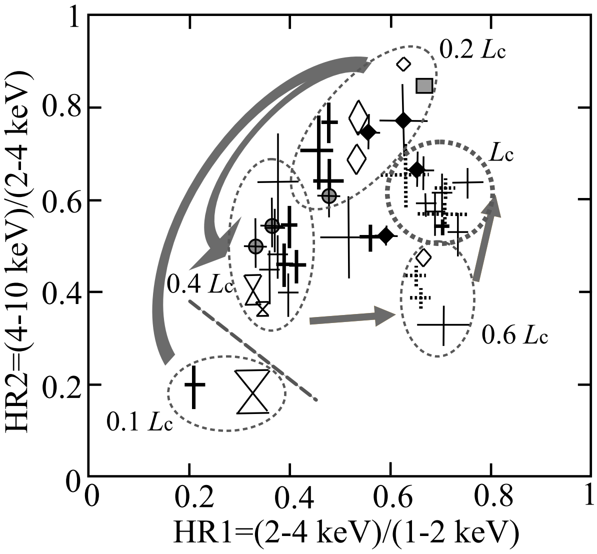

Fig. 3. A color-color plot for 8 ULXs, observed with *Suzaku* and *XMM-Newton*. Count rate ratios between the 4–10 keV to 2–4 keV bands are plotted against those between 2–4 keV to 1–2 keV (Miyawaki 2008). Thick gray arrows indicate a common luminosity evolution locus.

In Fig.3, the 8 sources form three typical branches. One of them appears at $L = (0.6 - 1.0)L_{\rm c}$, characterized by high values of HR1 and rather low HR2 values. This means that the spectrum has a strongly convex shape. Indeed, all the spectra in this branch are better fitted with a multi-color disk model than a single power-law. The second branch appears at $L = (0.2 - 0.4)L_{\rm c}$, with a relatively smaller HR1 values. Therefore, the spectra herein are suggested to be less convex. In fact, most of the spectra in this branch favor a single power-law modeling. The elongation of the branch implies that the spectral slope steepens as L increases. Finally, we find a few data points with $L \sim 0.1 L_{\rm c}$, with very soft spectra.

Invoking our discussion in § 3.1., the highest luminosity branch seen in Fig.3 may be considered analogous to the SDS of BHBs. This was argued in detail by Tsunoda et al. (2006). The second branch in Fig.3 can be considered to correspond to the VHS of BHB, both characterized by slightly curved power-law-like spectra. Finally, the least luminous branch in Fig.3 may be regarded as the HSS. These results imply that the ULXs form a rather homogenous class, and the values of $L_{\rm c}$ are close to their Eddington limits. Therefore, these ULXs may be considered as IMBHs, having significantly higher masses than the Galactic BHBs and radiating at close to their Eddington limits. Furthermore, we obtained an indication of BH spin in one ULX (Isobe et al. 2008; not shown in Fig.3).

Among the 8 ULXs in Fig.3, one of the most interesting sources is M82 X-1 (gray square point). While this object was often regarded as a special one, the *Suzaku* XIS data place it (after carefully estimating source confusion; Miyawaki 2008) in a similar position as the other objects. Furthermore, we successfully detected this object up to ~ 20 keV using the *Suzaku* HXD, and showed its spectrum to become mildly convex in energies above ~ 7 keV (Miyawaki et al. 2009). We hence interpret it in a state corresponding to the VHS.

5. Broad Fe-K lines

An extremely important issue in the BH study is to search their behavior for general relativistic effects. In this sense, the extremely broad Fe-K emission lines provide one promising evidence. After the first report by *ASCA* (Tanaka et al. 1995), this feature has been suggested in the spectra of a number of Seyfert galaxies, including MCG−6-30-15 in particular. The case of this leading candidate has been apparently reinforced by *Suzaku* observations (Miniutti et al. 2007), although controversy continues.

Miller et al. (2008) claimed a detection of similar features from the Galactic BHB GX339-4, and argued that the BH is rapidly spinning: this is because the inferred disk inner radius is smaller than the last stable orbit around a non-rotating BH, namely $3R_{\rm S}$. Furthermore, Cackett et al. (2008) argued that similar broad Fe-K lines are also present in the *Suzaku* spectra of several low-mass binaries involving neutron stars.

In spite of these reports of the broad Fe-K line detections from Galactic objects, we need a particular caution as to the reality of such features. Indeed, our results on Cyg X-1 and GRO J1655−40 clearly argue against the presence of such extremely broadened Fe-K lines. Furthermore, through our quick-look analysis of the same *Suzaku* data of GX339-4 as used by Miller et al. (2008), we found no evidence of the reported feature. According to Takahashi (2005), the broad Fe-K lines in the neutron-star binaries are also likely to be an artifact, caused by ignorance of a new spectral component which appears over a 3–7 keV; this component is likely to be an optically-thick emission from radiation-pressure-driven outflows, rather than a broad Fe-K line.

We thus caution that the claimed relativistically broadened Fe-K line features in Galactic objects are highly dependent on the continuum models used to fit the data. As a result, there is currently no convincing evidence for such features in Galactic BHs or neutron stars.

6. Future Prospects with MAXI

As seen in § 4., we interpret ULXs as IMBHs. Furthermore, as argued by Ebisuzaki et al. (2001), these objects could serve as building blocks from which the super-massive black holes at galaxy nuclei are formed through repeated and hierarchical mergers. Then, we expect some active galactic nuclei to be in their final stage of mergers, wherein two semi-massive BHs are orbiting around each other in a gradually decaying binary orbit. In such objects, we may expect the X-ray intensity to be modulated by their orbital revolution, with a period of several weeks to a few months. Evidently, the MAXI mission provides the most ideal way to search for such signals.

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