THE INSTITUTE OF SPACE AND ASTRONAUTICAL SCIENCE
YOSHINODAI, SAGAMIHARA, KANAGAWA 229

ISAS RESEARCH NOTE

ISAS RN 638

**ASCA Observations of Galactic Black Hole
Candidates and Active Galactic Nuclei**

H. Inoue

February 1998

Invited Talk at
Symposium The Active X-Ray Sky
Roma, October 21-24, 1997

ASCA Observations of Galactic Black Hole Candidates and Active Galactic Nuclei

H. Inoue^a

^aInstitute of Space and Astronautical Science,
Sagamihara, Kanagawa 229, Japan

Several topics on ASCA observations of Galactic black hole candidates (BHC) and active galactic nuclei (AGN) are presented with special interests on,

- comparison of the spectral properties between in the soft state and in the hard state of BHC,
- similarities between BHC and AGN,
- implications on the disk structures in various states of black hole sources.
- spectral characteristics of Galactic relativistic jet sources.

1. Introduction

From optical observations of binary motions, the mass of several compact stars in X-ray binaries were estimated to exceed $3 M_{\odot}$, the theoretical upper limit of neutron star mass. They are generally called black hole candidates (for the list of BHC, see e.g., Tanaka and Lewin 1995). Those BHC usually exhibit either the soft state or the hard state. Since the soft (hard) state often appears when the flux is relatively high (low), the soft and hard state used to be called as the high and low state, respectively. However, accumulation of observations has revealed that the correlation of the spectral hardness with the flux is not so simple. Hence, the designation of the soft and hard state is more commonly used recently.

In the soft state, the X-ray spectrum is generally reproduced by an ultrasoft component plus a hard, power law component. The ultrasoft component is well approximated by a multicolor blackbody emission from an optically thick accretion disk (so called "disk blackbody" spectrum). The disk blackbody spectrum was first introduced to reproduce X-ray spectra of bright low mass X-ray binaries (LMXB: neutron star sources) in the normal branch by Mitsuda et al. (1984).

In the hard state, the X-ray spectrum is dominated by a power law component, although a

slight soft excess is necessary to reproduce the spectrum in the low energy range below a few keV. This state is characterized by a large flickering of the X-ray flux.

Bright LMXBs also show the soft and hard state similar to those in BHCs (Inoue 1993). Hence, it is strongly suggested that a transition between the soft and hard state is due to some changes in an accretion disk around a central compact object, irrespective of whether it is a neutron star or a black hole. Furthermore, according to recent improvements in the sensitivity of X-ray and γ -ray observations, it has become possible to extend the study of accretion disks to extragalactic black hole candidates, active galactic nuclei (AGN). Now, it is getting apparent that the similar soft and hard state appear also in AGN, and that the same physical processes causing the transition between the soft and hard state happen in an accretion disk even in AGN, irrespective of the mass and size of the central black hole, as shown in this review.

In addition to the soft and hard states, jet ejections are also commonly observed from LMXB (e.g. Cir X-1), BHC (e.g., GROJ 1655-44) and AGN (e.g. blazars). In particular, recent observations of Galactic relativistic jet sources with ASCA, RXTE, and CGRO are gradually revealing the properties of the accretion disk when the

jets are ejected.

In this review, results from several ASCA observations are presented with special interest on the properties of accretion disks around central relativistic objects in the soft, hard, and jet-ejection state.

2. The soft and hard state of Cyg X-1

Cyg X-1 changed its state from the hard state to the soft state in May, 1996 (Zhang et al. 1997a). ASCA observed this source in the soft state about two weeks after the transition (Dotani et al. 1997a). The energy spectrum in the soft state obtained with the ASCA GIS is shown in Fig.1, and is well approximated with the typical model for the BHC in the soft state, a disk blackbody plus a power law. The best-fit temperature and radius of the innermost rim of the optically thick disk are 0.43 ± 0.01 keV and $71 (+13, -2)$ $(\cos i)^{-1/2}$ km for the assumed distance of 2.5 kpc, and the photon index of the power law is 2.3 ± 0.1 .

Observations of several BHCs in the soft state showed that the innermost radius of the optically thick disk was remarkably constant against the large flux change over two or three orders of magnitude (Tanaka and Lewin 1995; Inoue 1993). This is generally considered to be due to the fact that the optically thick disk extends down to the innermost stable orbit, 3 times the Schwarzschild radius (r_s). Assuming the innermost radius of the optically thick disk to be $3 r_s$ and evaluating such several parameters as the inclination angle of the disk as viewed from us, the ratio of the observed color temperature to the real effective temperature and so on, the mass of the central black hole of Cyg X-1 is estimated to be $\sim 12 M_\odot$ (Dotani et al. 1997a).

Cyg X-1 in the hard state was also observed with ASCA several times. The spectrum in the hard state is much more dominated by a power law component than that in the soft state but still shows an excess above the power law in the lower energy range than a few keV (Ebisawa et al., 1996). If the disk blackbody model is employed for the soft excess component, the best fit temperature and radius of the innermost rim of

Figure 1. X-ray spectra of Cyg X-1 in the soft state (upper) and in the hard state (lower) obtained with ASCA.

the optically thick disk are determined as shown in Fig.2 (Dotani et al. 1997b). Here, a broken power law was used to reproduce the spectrum above ~ 2 keV and effects of the interstellar absorption and dust scattering were taken into account.

It will be very interesting to see differences between the disk-parameters in the soft and hard states. Fig. 2 shows the best-fit values of the innermost temperature and radius in the soft and hard state. T_{in} and R_{in} relations for a constant accretion rate are also indicated. The best-fit disk parameters seem to be consistent with a picture that the accretion rate of matter flowing in the

optically thick disk does not change, but the innermost radius recedes when a transition to the hard state takes place. In this picture, the accretion disk could be understood to change its geometry from a geometrically thin (optically thick) disk to a geometrically thick (optically thin) disk at a certain distance to the central black hole and the hard, power law component in the spectrum could come from the inner optically thin disk. In the soft state, the optically thick disk extends close to the innermost stable orbit and the disk blackbody component is dominant in the spectrum. Whereas, the boundary between the thin and thick disk recedes far from the innermost stable orbit in the hard state and the hard, power law component becomes dominant in the spectrum.

Figure 2. Allowed regions of T_{in} and R_{in} values obtained from the soft state and the hard state spectrum of Cyg X-1. The error regions include both the statistical errors and the systematic errors due to the time variations and uncertainty in the power law component. Solid lines are T_{in} and R_{in} relations for constant accretion rates passing through the error region in the soft state.

However, the error region in the hard state is fairly wide and the lowest end of the error of the R_{in} value in the hard state is close to that in the soft state. It should be also taken into account

that the ratio of the observed color temperature to the effective temperature is closer to unity for the lower temperature in the hard state. This effect should make the R_{in} difference between in the soft and hard state smaller. Hence, we cannot exclude another possibility that an optically thick accretion disk extends down to the innermost stable orbit even in the hard state. In that case, however, the accretion flow should be divided into two stratified patterns, where an optically thick, geometrically thin disk and an optically thin, geometrically thick disk coexist with each other. In this picture, the accretion rate in the optically thick disk and the flux in the disk blackbody component decreases in the hard state. However, the accretion flow in the optically thin disk could provide another gravitational energy release and it would make the hard power-law component dominant in the spectrum of the hard state.

Irrespectively of where the optically thick disk in the hard state extend to, the physical processes to produce the hard, power law component is still in question. Then, it should be noted that the photon index of the power law component in the energy range above a few keV is generally in the BHC, 1.5 - 2.0 and 2.0 - 2.5 in the hard and soft state, respectively, and they are significantly different from each other.

3. Time variability of NGC4258

There seem to exist several similarities between the BHCs and the AGNs (see e.g., Inoue 1989; 1995). Recent hard X-ray observations showed that the spectrum of normal Seyfert galaxies in energies above a few keV is well reproduced by a power law with photon index of 1.5 - 2.0 but has an exponential cut off around 100 keV (e.g., Zdjarski et al. 1995). These properties are very similar to those of the BHCs in the hard state.

The time variation of the X-ray flux of Seyfert galaxies is also similar to that of the BHC in the hard state except the typical time scale of the flux variation. The power spectrum density is generally flat in the low frequency range, f^{-1} in the middle frequency range, and f^{-2} in the high frequency range (see e.g., Inoue 1989), although the

knee frequencies of AGNs are much lower than those of BHCs. Here, f is the frequency. An interesting hypothesis is a linear proportionality between the variability time scale and the mass of the central black hole. Barr and Mushotzky (1986), and Wandel and Mushotzky (1986) tested it by using a flux-doubling time.

Recently, Hayashida et al. (1998) introduced a new method to define the variability time scale. They calculated normalized power spectral density (NPSD), $P(f)$, by dividing the power spectrum density by the average source flux squared and plot $f \times P(f)$ as shown in Fig.3. Then, they defined the variability time scale by the frequency at which the $f \times P(f)$ curve crosses a certain level. In their determination of the time scale, the f^{-2} part of the NPSD was employed based on an earlier finding that the shape and magnitude of the NPSD of typical BHCs in the hard state are maintained in this frequency range, almost independently of sources, occasions, and X-ray energy ranges (Belloni and Hasinger 1990; Miyamoto et al. 1992).

The proportionality of the newly defined variability time scale to the mass of the central black hole has recently been confirmed by ASCA observations of NGC4258. The mass of the central black hole of this galaxy was determined to be $3.4 \times 10^7 M_{\odot}$ by H_2O maser observations in the radio band (Miyoshi et al. 1995), whereas ASCA detected X-rays from the nucleus (Makishima et al. 1994) and their time variation (Ishisaki et al. 1998). The NPSD of the flux variation was approximated and the $f \times P(f)$ curve is plotted in Fig.3. As seen in this figure, the ratio of the cross-point frequency of NGC4258 to that of Cyg X-1 agrees with the mass ratio between the two black holes within a factor of 2.

4. Broad iron emission lines from Seyfert 1 galaxies

Several similarities between BHCs in the hard state and Seyfert-type AGNs as discussed above suggest that the same configuration of an accretion disk around a black hole as in BHCs in the hard state should be realized in the nucleus of Seyfert galaxies. The discovery of a broad

Figure 3. The $f \times P(f)$ plots for one BHC (Cyg X-1), eight AGNs, and NGC4258. Observed data points are plotted for Cyg X-1, while for 8 AGNs the best fit model is illustrated with a line and marks, respectively (Hayashida et al., 1998). A thick solid line represents the best fit model for NGC4258. The variability time scale is defined from the frequency at which the $f \times P(f)$ value equals a certain level. If we adopt 10^{-3} as indicated by a thick horizontal line, the variable time scale of NGC4258 is longer by $\sim 2 \times 10^7$ than that of Cyg X-1. The ratio is roughly consistent with the mass ratio of the two black holes.

and skewed feature of an iron emission line from Seyfert galaxies (Tanaka et al. 1995; Nandra et al. 1997) has given us important informations on the disk configuration.

The broad and skewed feature is best interpreted by introducing rotation of the line emitting matter at orbits close to the central black hole (Fabian et al. 1995). In this interpretation, the line is considered to be due to fluorescence from relatively cool matter illuminated by hard X-rays. If this is true, an optically thin, geometrically thick and hot accretion disk should coexist with an optically thick, geometrically thin and cool accretion disk which extends close to the central black hole. This seems consistent with the second picture for the configuration of the accretion disk in BHCs in the hard state among the

two possibilities raised in the previous section on Cyg X-1.

The presence of an optically thick disk close to the central black hole is also supported by the existence of the so-called “blue bump” in the spectrum of Seyfert-type AGNs. If the luminosity, L , is scaled by the Eddington limit, namely the mass of the central black hole, M , the innermost blackbody temperature of the optically thick disk should be proportional to $M^{1/4}$ since the innermost radius of the disk, R , is proportional to the mass and $L \propto r^2 T^4$. Hence, if T is 0.2 keV for the mass of $\sim 10 M_\odot$, T should be ~ 4 eV for $10^8 M_\odot$ and the blackbody emission with that temperature mainly yields UV photons.

5. Narrow line Seyfert 1 galaxies

Spectral and temporal properties of normal Seyfert 1 galaxies are similar to those of BHCs in the hard state but spectral properties of narrow line Seyfert 1 galaxies (NLS1) look similar to those of BHCs in the soft state. The X-ray spectra of NLS1 in the energy band below 1 keV are generally steeper than those of the normal (broad line) Seyfert 1 galaxies (Boller, Brandt and Fink 1996), which is attributed to the presence of strong soft excess over the hard X-ray power-law. The soft excess component is well approximated with a disk blackbody (Pounds, Done and Osborne 1995; Hayashida 1996) and the photon index of the power law component dominating in the energy range above 1 keV is 2 – 2.5 (Brandt, Mathur and Elvis 1997). These are consistent with the spectral properties of BHCs in the soft state.

The X-ray fluxes of NLS1 often exhibit large time variations (Boller, Brandt and Fink 1996) but the flux variation of BHCs in the soft state is not so large. The large time variation seems similar rather to those of Galactic relativistic jet source, GRS1915+105 (Mirabel and Rodriguez 1994) mainly observed with RXTE (e.g. Greiner, Morgan and Remillard 1996). In fact, evidence for relativistic outflows in NLS1 has been reported by Leighly et al. (1997), recently.

6. Absorption lines detected from Galactic relativistic jet sources

ASCA observed the BHC (Bailyn et al., 1995) with relativistic jets (Tingay et al. 1995), GROJ1655-40 four times. These observations were done at epochs when the hard X-ray flux was very low in the long term light curve obtained with BATSE, CGRO (Tavani et al. 1996). In particular, the source was very dim (the flux $\simeq 10\mu$ Crab flux) in the fourth ASCA observation.

Figure 4. Ratios of the observed spectra of GRO J1655-40 to the best fit continuum-models; (a) in Aug., 1995, (b) in Aug. plus Sep., 1994 (except the “dip” period), and (c) in the “dip”.

The third ASCA observation was done simultaneously with WATCH and BATSE and the overall spectrum was found to be reproduced with a disk blackbody and a power law (Zahng et al. 1997b). The best-fit innermost temperature and radius are 1.4 keV and 22 km based on assumptions of a distance of 3.4 kpc and an inclination of 80° . This innermost radius is consistent with the presence of the central black hole with several solar masses. Whereas, the best-fit photon index of the power law is 2.4 and is consistent with those of BHCs in the soft state.

A remarkable finding of these ASCA observations is the presence of iron absorption lines in the spectra (Ueda et al. 1998). Figure 4 shows ratios of the spectra to their best fit model continuum-spectra for (a) relatively high flux state in the third observation, (b) relatively low state in the first plus second observations except a “dip” period (see Fig.5) and (c) the “dip” period. The spectrum (a) shows absorption line features at ~ 6.7 keV and ~ 7.8 keV together with an edge-like feature at ~ 7.1 keV, while the spectrum (b) exhibits absorption line features at ~ 7.0 keV and ~ 8.2 keV. These line energies correspond to K_α , K_β lines of helium-like iron and those of hydrogen-like iron, respectively.

Such absorption line features were also detected from another Galactic jet source, GRS1915+105 (Kotani et al. 1998). As clearly seen in Fig.6, the features are consistent with blends of two K_α (and K_β) lines of helium- and hydrogen-like iron. Since such absorption lines have never been detected from a number of usual accretion powered sources, a situation for absorption lines to be observed would probably connect with configuration of an accretion flow forming relativistic jets.

In order for the resonant-line absorption to take place, a non-spherical configuration of partially ionized plasma around an X-ray emitter is necessary. An accretion disk with a certain optical depth around a central X-ray source is a likely candidate for the line absorber. A simple analysis for the curve of growth shows the hydrogen column density, nd , of the absorber in the line of sight to be 10^{23-24} atoms cm^{-2} assuming cosmic abundance of iron, where n and d is the density and thickness of the absorber, respectively. On

Figure 5. X-ray light curve of GRO J1655-40 observed with ASCA in August, 1994. (Upper) the count rate in 0.7–10 keV. (Lower) the hardness ratio between two energy bands, 0.7–4 keV and 4–10 keV. The flux dropped by a factor ~ 5 2 hours after the beginning of the observation. The flux stayed at a low level for about 6 hours and returned to the previous flux level. This phenomena is designated “dip” here.

Figure 6. Ratios of the observed spectra of GRS1915+105 to the best fit continuum-models, (upper) in Sep., 1994; (lower) in April, 1995.

the other hand, the ionization parameter, $\xi \equiv L/nr^2$ should be $\sim 10^3 \text{ erg cm s}^{-1}$ in order for iron to be ionized to helium-like or hydrogen-like. Since the luminosity, L , is $\sim 10^{37} \text{ erg s}^{-1}$, the distance of the absorber to the X-ray source, r is estimated to be 10^{10-11} cm on an assumption of $d \sim r$.

Here, it is very interesting to note that the ionization state of iron in the disk at the distance of 10^{10-11} cm apparently changes in accordance with the change of the X-ray flux from inside. In the ASCA observations, the absorption lines appeared at energies of helium-like iron when the X-ray flux was relatively low to the case when the lines appeared at energies of hydrogen-like iron. In particular, absorption lines disappeared and the edge-like feature at $\sim 7.1 \text{ keV}$ became strong in the “dip”. These changes of the ionization state of iron in accordance with the change of illuminating X-rays strongly suggest that photoionization processes act as the main role to heat up the plasma responsible for the line absorption. At the same time, it is also suggested that the

density and/or the geometry of the line absorber does not change so much against the large flux change. This may indicate that even when the accretion flow is stable at $r \simeq 10^{10-11} \text{ cm}$, the energy conversion efficiency to the radiation of the accreted matter could change in the extreme inner region, as discussed below.

Let us consider matter in an accretion disk at the distance, r , to the center, which is illuminated by X-rays with luminosity, L , from the inner region. L can be expressed as $\eta \dot{M} c^2$, where η is an energy conversion efficiency of the accreted matter to radiation in terms of the rest mass energy and $\dot{M}$ is the accretion rate. The accretion rate in the disk at the distance, r , to the center is approximately written in terms of the solid angle of the disk as viewed from the center, Ω , the density, n , the inward velocity, v_r as $\Omega n m_p v_{\text{in}} r^2$, where m_p is the proton mass. Hence, the ionization parameter, ξ , of the disk at the distance of r is calculated as $4 \times 10^5 (\Omega/4\pi) (\eta/0.1) (v_r/v_k) (r/10^4 r_s)^{-1/2} \text{ ergs cm s}^{-1}$, where $v_k \equiv (GM/r)^{1/2}$ and $r_s \equiv 2GM/c^2$. Since $\Omega/4\pi \simeq h/r$ and $v_r/v_k \simeq \alpha (h/r)^2$ in terms of the height of the accretion disk from the equatorial plane, h , and the viscous parameter, α in the standard accretion disk model. ξ can be rewritten approximately as $4 \times 10^5 \alpha (\eta/0.1) (h/r)^3 (r/10^4 r_s)^{-1/2} \text{ ergs cm s}^{-1}$. If the equatorial plane of the disk aligns to the orbital plane of the binary system, optical observations indicate the inclination of the disk viewed from us to be $70^\circ - 80^\circ$ (Orosz and Baylyn, 1997). Hence, in order for the accretion disk to act as the line absorber in the line of sight, h/r should be larger than $\tan 10^\circ$ and we obtain a relation, $\xi > 2 \times 10^3 \alpha (\eta/0.1) (r/10^4 r_s)^{-1/2} \text{ ergs cm s}^{-1}$.

However, the absorption lines disappeared and the absorption edge of neutral iron became strong in the “dip”. This suggests that although there is no large change in the geometry of the absorption region in the accretion disk, the ionization degree of iron decreased from helium-like and ξ decreased much less than 10^3 in the dip. If so, it would be most natural to consider that the energy conversion efficiency, η , decreases to much less than 0.1. This seems to be consistent with

an interpretation that the dip is the result of a rapid evacuation of an inner part of an optically thick disk, as suggested for a large flux excursion of GRS 1915+105 (Belloni et al. 1997).

7. Summary and discussion

We have reviewed ASCA observations of Cyg X-1, NGC4258, iron lines from Seyfert galaxies, narrow line Seyfert 1 galaxies, GROJ1655-40 and GRS1915-105. From these observations, the following implications can be reached:

An optically thick disk would extend close to $3r_g$ even in the hard state but an optically thin, geometrically thick disk should coexist with the optically thick disk in the region close to $3r_g$.

An optically thick disk would stably extend close to $3r_g$ also in the soft (quiet) state but an optically thin, geometrically thick disk should not have a large effect on the spectrum.

Large flux excursions are sometimes observed from BHCs and AGNs and they could be due to advancing or receding of the inner edge of an optically thick disk.

Jet ejection might be a result of advancing or receding of an optically thick accretion disk (see Mirabel in this proceedings).

Author would like to thank T. Dotani, K. Hayashida, Y. Ueda, and P. Hilton for their help for preparation of this manuscript.

REFERENCES

1. Barr, P. and Mushotzky, R.F., 1986, *Nature*, 320, 421.
2. Baylin, C.D. et al., 1995, *Nature*, 378, 157.
3. Belloni, T. and Hasinger, G., 1990, *A&A*, 227, L33.
4. Belloni, T. et al., 1997, *ApJL*, 479, L145.
5. Boller, Th., Brandt and Fink, 1996, *A&A*, 305, 53.
6. Brandt, W.N., Mathur, S. and Elvis, M., 1997, *MNRAS*, 285, L25.
7. Dotani, T. et al., 1997a, *ApJL*, 485, L87.
8. Dotani, T. et al., 1997b, in *IAU Symp.* 188.
9. Ebisawa, K. et al., 1996, *ApJ*, 467, 419.
10. Fabian et al., 1995, *MNRAS*, 277, L11.
11. Greiner, J., Morgan, E.H. and Remillard, R.A., 1996, *ApJL*, 473, L107.
12. Hayashida, K., 1997, *ASP Conference Series*, 113, 40.
13. Hayashida, K. et al., 1998, to appear in *ApJ*.
14. Inoue, H., 1989, in *Proc. 23rd ESLAB Symp. on Two Topics in X-ray Astronomy*, Vol.2, 783.
15. Inoue, H., 1993, in *Accretion Disks in Compact Stellar Systems*, ed. J.C. Wheeler (Singapore: World Scientific), 303.
16. Inoue, H., 1995, in *Multi-Wavelength Continuum Emission of AGN*, ed. T.J.-L. Courvoisier and A. Blecha (*IAU Symp.* 159, Kluwer Academic Press), 73.
17. Ishisaki, Y. et al., 1998, in preparation.
18. Kotani, T. et al., 1998, in preparation.
19. Leighly, K.M. et al., 1997, *ApJL*, 489, L25.
20. Makishima, K. et al., 1994, *PASJ*, 46, L77.
21. Mirabel, I.F. and Rodriguez, L.F., 1994, *Nature*, 371, 46.
22. Mitsuda, K. et al., 1984, *PASJ*, 36, 741.
23. Miyamoto, S., et al., 1992, *ApJL*, 391, L21.
24. Miyoshi, M. et al., 1995, *Nature*, 373, 127.
25. Nandra et al., 1997, *ApJ*, 477, 602.
26. Orosz, J.A. and Bailyn, C.D., 1997, *ApJ*, 477, 876.
27. Pounds, K.A., Done, C. and Osborne, J., 1995, *MNRAS*, 277, L5.
28. Tanaka and Lewin, 1995, in *X-Ray Binaries*, ed. W.H.G. Lewin, J. van Paradijs and E.P.J. van den Heuvel (Cambridge Univ. Press), 126.
29. Tanaka et al., 1995, *Nature*, 375, 659.
30. Tavani et al., 1996, *ApJL*, 473, L103.
31. Tingay, S.J. et al., 1995, *Nature*, 374, 141.
32. Ueda, Y. et al., 1998, *ApJ*, 492, in press.
33. Wandel, A. and Mushotzky, R.F., 1986, *ApJ*, 329, L61.
34. Zdziarski, A.A. et al., 1995, *ApJL*, 438, L63.
35. Zhang, S.N. et al., 1997a, *ApJL*, 477, L95.
36. Zhang, S.N. et al., 1997b, *ApJ*, 479, 381.