ASCA Investigation of Ultra Luminous Compact X-ray Sources in Nearby Spiral Galaxies

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Abstract

To investigate the properties of Ultra Luminous compact X-ray sources (ULXs), nine spiral galaxies, containing twelve ULXs, were observed with ASCA. For comparison, three luminous extragalactic supernova remnants (SNRs) were also studied. Most of the objects are consistent with point-sources within the spatial resolution of ROSAT HRI. ASCA spectra of SNRs and ULXs show a clear difference; the former show the features of an optically-thin hot plasma, whereas the latter lack such spectral properties, implying that a ULX is not an unidentified SNR. Among twelve ULXs, nine exhibit spectra which can be represented with a so-called multi-color disk blackbody (MCD) emission describing optically-thick multi-temperature emission from a standard accretion disk; one shows spectrum which can be expressed with the MCD plus a power-law model; and two have power-law spectra of photon index $\sim 1.5$. These spectral properties suggest that ULXs are luminous extragalactic mass-accreting black-hole binaries. The bolometric luminosities of the MCD emission are $10^{39-40}$ erg s$^{-1}$, requiring high black-hole mass up to $\sim 100 M_\odot$ to sustain sub-Eddington radiation. However, the observed inner-most disk temperatures, ranging 1.0–1.8 keV, are too high to account for the inferred high black-hole mass if we assume a standard accretion disk around a Schwarzschild black hole. Changes of the inner-disk radius have also been detected from three ULXs, which contradict the properties of Galactic and Magellanic black-hole binaries. Several attempts were made to solve these problems. Finally the interpretation of ULXs as emission from an optically-thick accretion disk around a rapidly rotating black hole is proposed.
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Acknowledgement
In spiral galaxies, including our own Galaxy, discrete X-ray sources are the major component of X-ray emission. The brightest of them are X-ray binaries (XRBs), i.e., close binary systems consisting of mass-donating ordinary stars and mass-accreting collapsed objects (white dwarfs, neutron stars, or black holes). In such a system, matter from the ordinary star is gravitationally captured by the collapsed star, form a disk-like structure (accretion disk), and emits intense X-rays via the release of gravitational energy. Therefore, X-ray information provides a powerful tool to investigate the involved compacts objects, and extensive X-ray studies of Galactic XRBs have been conducted over the last three decades. These observations have successfully yielded fundamental parameters of neutron stars, including the mass, radius, and the surface magnetic field strength. Furthermore, the X-ray information has provided a unique capability of identifying more than a dozen mass-accreting black holes (BHs), and measuring their masses.

In our Galaxy and M31 (the Andromeda Nebula), the luminosity of each XRB is at most a few times $10^{38}$ erg s$^{-1}$, being consistent with the theoretical upper-limit luminosity, called Eddington limit, for a neutron star or a BH of $\sim 10 \, M_\odot$. However, in spiral arms of some external spiral galaxies, we often find one class of enigmatic X-ray objects which we call “Ultra Luminous compact X-ray sources” (ULXs). A ULX has a point-like appearance, and most importantly, exhibits a quite high luminosity up to $\sim 10^{40}$ erg s$^{-1}$, which exceeds the Eddington limit for a neutron star by two orders of magnitude. If a ULX is a mass accreting BH, its mass must be unusually high up to $\sim 100 \, M_\odot$, in order for the emission not to violate the Eddington limit.

Although the ULXs have been known for two decades, their nature has long remained a big mystery. This is partly due to the absence of ULXs in our Galaxy and M31, which prevents us from studying them in detail, and partly due to rather poor spectroscopic capabilities of previous imaging X-ray instruments, which hampered the identification of the ULX emission mechanism. Without clarifying the nature of ULXs, we would not be qualified to say that we have acquired sufficient knowledge about the collapsed stars.

The study of ULXs has made a remarkable progress after the launch of ASCA (in February 1993; Tanaka et al. 1994), the first X-ray satellite with imaging optics having a sensitivity up to $\sim 10$ keV and a much improved spectral resolution (Chapter 3). Using ASCA, several authors found that the spectra of some ULXs can be considered as emission from optically-thick accretion disks around compact objects (e.g. Takano et al. 1994; Uno 1996; Okada et al. 1998; § 2.6). Therefore, the black-hole binary (BHB) interpretation of ULXs has become promising. However, this scenario has been shaded by one serious
self-inconsistency, that the measured disk temperature of ULXs are too high (Okada et al. 1998; Mizuno et al. 1999). Thus, further investigation has been needed.

Following these pioneering works, in the present thesis we perform extensive studies of ULXs, mainly using the ASCA data. We establish that the ULX spectra can be understood in a unified way as emission from optically-thick accretion disks, which strongly reinforces the BHB interpretation. We also find apparent changes of the disk radius, which provides a key to the nature of ULXs. After a series of careful inspections, we finally reach a scenario of rapidly spinning massive BHs fed with a very high mass accretion rate (Chapter 7). This for the first time provides a realistic explanation to the ULX phenomenon.

The present thesis is constructed in the following way. In Chapter 2, we review the X-ray emission from spiral galaxies, focusing on the discrete sources seen there. We describe the instrumentation of ASCA in Chapter 3, and select the ULX targets in Chapter 4. In Chapter 5, we investigate X-ray images and light curves of the target ULXs, to constrain their physical size. The spectral analysis, the main part of this thesis, is described in Chapter 6, where we establish common spectral properties of the observed ULXs. We discuss implications of the obtained results in Chapter 7, followed by a brief summary in Chapter 8.
Chapter 2

REVIEW

2.1 Overview of X-Ray Emission from Galaxies

Since the first discovery of the cosmic X-ray source, namely Sco X-1 (Giacconi et al. 1962), Galactic X-ray sources have been the major targets of X-ray astronomy. These objects can be grossly divided into supernova remnants (SNRs) and X-ray binaries (XRBs). An XRB is a close binary system consisting of a mass-donating ordinary star and a mass-accreting collapsed object, and classified according to the type of the compact star; white dwarf binaries (WDBs), neutron star binaries (NSBs), and black hole binaries (BHBs). NSBs are further divided into two subgroups; binaries with population I stars or “High-Mass X-ray Binaries” (HMXBs), and those with population II stars or “Low-Mass X-ray Binaries” (LMXBs). In addition, there exist other types of Galactic X-ray sources: On one hand, there are low-luminosity discrete objects such as rotation-powered neutron stars and stellar coronae, while on the other hand, we observe diffuse X-rays from large-scale interstellar plasmas of various densities and temperatures. The classification of these X-ray sources is summarized in Figure 2.1.

The X-ray observations of these sources provide us with rich astrophysical information. By observing XRBs, we can obtain fundamental natures of the involved compact objects (WDs, NSs, BHs); e.g., the radius of NSs, the mass of BHs, and so on. Studies on the metal abundances in SNRs provide a key information on the nucleosynthesis in stellar evolutions and supernova explosions. The hot gaseous components with various temperatures and scales are thought to reflect the current and past supernova rates, which in turn provide a good measure of the star formation activity.

However, the knowledge on our Galaxy is not necessarily adequate to fully appreciate the implication of the X-ray information. Galactic sources suffer from heavy interstellar absorption. Their distances, hence luminosities, often remain uncertain. Furthermore, the X-ray source population may differ significantly from galaxy to galaxy. Therefore, we need to explore external galaxies in X-rays. As the most fascinating possibility, in some external galaxies we may find a new class of X-ray objects that are absent in our Galaxy.

Some external galaxies had already been detected in X-rays from early stages of the cosmic X-ray study, with the Uhuru satellite (launched in 1970) and others. However, these objects are so called “active galaxies”, of which the X-ray emission is dominated by their active galactic nuclei (AGNs), i.e. mass accreting giant ($10^{6-9} M_\odot$ where $M_\odot$ is the solar mass) black holes sitting at their very centers. Although the AGN phenomenon itself is extremely interesting and deserves detailed X-ray studies, the emission is so bright that
it overwhelms other weaker X-ray sources in the host galaxy. Therefore, for the purpose of studying the source population and related astrophysics, we need to study “normal” galaxies that do not host luminous AGN. Then, we need, in turn, an instrument with a high sensitivity because the individual objects in external normal galaxies are of no doubt quite faint. Furthermore, we need X-ray imaging capability to resolve, at least partially, each galaxy into individual sources — a low-luminosity AGN (LLAGN; if any), SNRs, XRBs, large-scale diffuse emission, and so on.

We have become able to study external normal galaxies in X-rays for the first time with the *Einstein Observatory* launched in 1979 (Giacconi et al. 1979). This is the first satellite that employed X-ray imaging optics. With its high sensitivity down to $\sim 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$, over 200 galaxies were detected in the soft X-ray band of 0.2–4.0 keV (Fabbiano et al. 1992). It was shown that elliptical galaxies are usually more X-ray luminous than spirals, and their X-rays are dominated by a large-scale hot gaseous component of temperature $\sim 1$ keV; the hot gas is thought to originate from random motion of the stars, be augmented by the supernova activity, and be hydrostatically confined in the gravitational potential of the galaxy. Among spirals, starburst galaxies are rather X-ray luminous, and they also possess a hot gaseous component which originates from the star formation activity of the host galaxy. The gas in starburst galaxies is often hotter than those in elliptical galaxies, and may be outflowing. Other normal spirals consist in most cases of individual bright X-ray sources, mainly XRBs. In particular, the X-ray emission from M31 (the Andromeda Nebula) has been shown to be a collection of $\sim 100$ LMXBs (Fabbiano et al. 1987, Makishima et al. 1989), as described in § 2.4.

In addition, a new class of X-ray sources have also been found from some spiral galaxies. They locate at off-nucleus regions of the host galaxy, show point-like appearances, and have X-ray luminosities ($L_X$) up to $\sim 10^{40}$ erg s$^{-1}$, which are almost two orders of magnitude higher than those of the most luminous Galactic individual X-ray sources. The number of these luminous X-ray sources is over 20, as mentioned in § 2.5.1. While only a few of them are identified with young SNRs, such as SN 1978K in NGC 1313 (Fabbiano and Trinchieri 1987), SN 1986J in NGC 891 (Houck et al. 1998), and the most bright X-ray source in NGC 6946 (Schlegel 1994), others have not been identified securely in other wavelength. We call these non-AGN and non-SNR luminous X-ray sources “Ultra Luminous compact X-ray Sources” (hereafter ULXs). Clarifying the nature of ULXs is of great importance, because they strongly influence our understanding of the X-ray emission from normal spiral galaxies. Their high luminosities would overwhelm the X-ray emission of the host galaxy. In addition, a ULXs located close to the galaxy center, such as M33 X-8 (Markert and Rallis 1983, Trinchieri et al. 1988) show in Figure 2.2, would be mistaken for an LLAGN. As described in § 2.5, early studies on ULXs showed that most of them are not collections of less luminous sources or background contaminants, but really point-like single objects, hence may be XRBs (Long and Van Speybroeck 1983, Fabbiano 1989). However, the absence of ULXs in the Milky Way and M31 has hampered any clear identification of their nature. The breakthrough has been brought by *ASCA* (Tanaka et al. 1994), the first X-ray satellite with imaging optics which have sensitivity in the hard X-ray band (up to $\sim 10$ keV). The main theme of this thesis is the *ASCA* investigation of ULXs.
Figure 2.1: A classification of typical X-ray sources in galaxies.

Figure 2.2: An X-ray image of M33 (NGC 598) obtained with Einstein, superposed on the optical image (Trinchieri et al. 1988). The main component of X-ray emission is individual bright sources of $L_X = 10^{37} - 38$. The most luminous one, M33 X-8, is located at the nucleus of the host galaxy. Its luminosity is $\sim 10^{39}$ erg s$^{-1}$, about 10 times higher than those of the most luminous Galactic X-ray sources. In spite of the positional coincidence with the nucleus, observations in X-ray and other wavebands indicate that this source is not an LLAGN, but a ULXs. (see § 2.4 and § 2.6).
2.2 Eddington Limit on the Source Luminosity

As described in the previous section, many of the luminous X-ray sources in the Milky Way and the Local Group galaxies are the XRBs, each consisting of a collapsed object and an ordinary star. X-rays are emitted from the vicinity of the collapsed star, as it accretes gas from the normal stellar companion, via release of the gravitational energy of accreting matter. Although the mass accretion rate in such a close binary system can vary largely from object to object, there is a natural upper limit on the luminosity available through mass accretion, called Eddington limit. This limit is determined by the balance between the outward radiation pressure and the inward gravitational force from the accreting star. The balance between these two oppositely-directed forces is written as

\[
\frac{L n \sigma_T}{4 \pi R^2 c} \leq \frac{G M \rho}{R^2},
\]

where \( L \) is the bolometric luminosity of the source, \( n \) is the number density of the electrons, \( \sigma_T \) is the Tomson scattering cross section, \( R \) is the distance from the center of the accreting star, \( c \) is the light speed, \( G \) is the gravitational constant, \( M \) is the mass of the accreting star, and \( \rho \) is the mass density of the gas. If we assumed a fully ionized gas consisting of hydrogen and helium with the cosmological ratio of 0.76:0.23 in weight, the maximum luminosity in the above equation, namely Eddington limit \( (L_E) \), can be expressed as

\[
L_E = 1.5 \times 10^{38} M/M_\odot \text{ erg s}^{-1},
\]

(2.1)

where \( M_\odot = 2.0 \times 10^{33} \) g represents the solar mass. When the source luminosity exceeds this Eddington limit, the radiation pressure overcomes the gravitational force. Hence, the accreting matter is blown away, and the luminosity remains below the Eddington limit.

Most of the bright Galactic X-ray sources are NSBs and have luminosities below the Eddington limit for a 1.4 \( M_\odot \) neutron star, which is expressed as

\[
L_{E}^{\text{NS}} = 2 \times 10^{38} \text{ erg s}^{-1}.
\]

(2.2)

Moreover, the observations of X-ray bursts strongly support the hypothesis of the Eddington limit. X-ray bursts are a phenomenon of abrupt increase of X-ray luminosities from some, if not all, NSBs. The burst occurs through unstable nuclear fusion of the accreted matter (hydrogen plus helium) on the surface of a neutron star. As shown in Figure 2.3, the bolometric burst flux reaches a ceiling, which is well reproducible among bursts from the same source. In addition, after estimating the source distances in some ways, the flux ceiling levels for different burst sources translate to a common luminosity ceiling (Inoue et al. 1981, Ebisuzaki et al. 1984). This value is consistent with \( L_{E}^{\text{NS}} \).

Another observational confirmation of the hypothesis of the Eddington limit comes from BHB transients. Most of Galactic BHBs are transient sources (see § 2.3.4 for details), and show sudden increases of luminosity by a factor of \( 10^3 \)–\( 10^4 \), as exemplified in Figure 2.4. Thus, the luminosities at the outburst peak are typically several times \( 10^{38} \) erg s\(^{-1} \), which remain below the Eddington limit of the central BHs. These examples indicate that equation 2.1, the Eddington limit calculated assuming a spherical radiation, also applies in good approximation to the non-isotropic radiation from BHBs, where X-rays are emitted from accretion disks around central BHs as described in § 2.3.4.

The application of Eddington limit on ULXs provides us with important information. The most luminous ULXs have luminosities up to \( \sim 10^{40} \) erg s\(^{-1} \). If ULXs are really
point-like sources and indeed mass-accreting XRBs as described in § 2.1, and satisfy the Eddington limit, we can infer from equation 2.1 that the central object is a stellar BH of mass \( \sim 100 M_\odot \) or higher. However, how to make such a massive BH remains an open question, because a normal star heavier than \( \sim 70 M_\odot \) is thought to be radiatively unstable, and cannot evolve to become a BH. We discuss this issue in Chapter 7.

Another candidates for ULXs are bright SNRs, since SNRs are not mass-accreting emitter and their luminosities need not be restricted by the Eddington limit. In fact, some external SNRs have luminosities above \( 10^{38} \text{ erg s}^{-1} \) as described in the previous section, although the Galactic SNRs are not so luminous (\( \sim 10^{36} \text{ erg s}^{-1} \)). Therefore, there is a possibility that some ULXs are bright extragalactic SNR, although not identified in other wavebands. Thus, we treat in this thesis such luminous extragalactic SNRs, and compare their features, especially spectra, with those of ULXs.

![Figure 2.3: Examples of time profiles of typical X-ray bursts.](image)

In the X-ray band, SNRs emit in three distinct emission mechanisms, with their relative weights varying from object to object. The X-ray emission from shell-like SNRs is pro-

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2.3 Discrete Sources in Normal Galaxies

In order to study the nature of ULXs, we must compare them with well-known X-ray sources. Therefore we briefly describe typical bright X-ray sources seen in normal galaxies in this section, and source population in the Local Group galaxies in the next section.

2.3.1 SNRs

In the X-ray band, SNRs emit in three distinct emission mechanisms, with their relative weights varying from object to object. The X-ray emission from shell-like SNRs is pro-
duced mainly in the shock-heated interstellar medium and metal-rich ejecta, so that the spectrum is dominated by thermal Bremsstrahlung (TBS) continuum and many atomic emission lines, as shown in Figure 2.5a. The characteristic temperature of the X-ray emitting plasma is 0.3–2 keV, and the emission lines from various heavy elements has not yet reach collisional ionization equilibrium in young SNRs. The other type of SNRs are Crab-like ones, which usually show featureless power-law spectra of photon index $\sim 2.0$. The emission mechanism is synchrotron radiation powered by a rotating neutron star at its center. A hard power-law spectral component is also seen from some shell-like SNRs, as in SN 1006 (Koyama et al. 1995), and is explained as a synchrotron emission arising from electrons accelerated up to $\sim 10^{14}$ eV by Fermi processes within the shocks. This component forms a spectral “hard tail”, superposed on the soft thermal plasma emission.

### 2.3.2 LMXBs

A LMXB is a close binary system consisting of a weakly-magnetized neutron star and a low-mass star, found preferentially in the bulge region of normal galaxies including our own Galaxy. Some of them are the source of the X-ray bursts as mentioned in § 2.2. Bright LMXBs show spectra similar in shape to a TBS emission with temperature $\sim 10$ keV, although thin plasmas are not appropriate for the emission mechanism of such a compact source.

Mitsuda et al. (1984) analyzed the 2–30 keV spectra of bright LMXBs obtained by *Tenma*, and successfully decomposed their spectra into two components, as shown in Figure 2.5b; a soft component and a hard component with similar luminosities. The soft component shows weaker variability and its shape is expressed by a so-called multi-color disk-blackbody (MCD) model, a superposition of multi-color (multi-temperature) blackbody elements from individual parts of an optically-thick accretion disk around the neutron star. The color temperature of the innermost portion of the disk, $T_{in}$, is $\sim 1.5$ keV. The MCD formalism is reviewed in further detail in § 2.7. On the other hand, the hard
component shows large variability and its spectral shape is expressed by a black body model of temperature $\sim 2$ keV. This component can be attributed to emission from the neutron-star surface.

### 2.3.3 HMXBs

Contrary to the case of LMXBs, neutron stars in HMXBs often undergo binary eclipses, and have strong magnetic fields of $\sim 10^{12}$ G. Because matter from the companion star accretes along this magnetic field, an HMXB usually becomes an accretion-powered X-ray pulsar, of which the X-ray intensity is periodically modulated as the central neutron star rotates. The continuum spectrum, which is thought to be formed via Comptonization in the hot accretion column (e.g., Alexander and Mészáros 1991), can be well represented by a power-law with high-energy exponential cutoff beyond a certain energy, as shown in Figure 2.5c. The typical cutoff energy is 10–20 keV or higher, and the spectral photon index is $\Gamma = 0.8–1.5$ below this energy (Nagase 1989). Thus, in the relatively low energy band of $\leq 10$ keV, the spectra of HMXBs can be expressed by a single power-law model of $\Gamma \sim 1$.

In the 10–50 keV energy range, many HMXBs (i.e., binary X-ray pulsars) exhibit spectral absorption features due to electron cyclotron resonance, which allow accurate determinations of the surface magnetic fields. This has so far been achieved for about a dozen X-ray pulsars, and the measured surface magnetic field exhibits a tight concentration in the $(1–4) \times 10^{12}$ G range (Makishima et al. 1999).

### 2.3.4 BHBs

Most of the BHBs are transients, and only three BHBs are known as persistent sources (Cyg X-1, LMC X-1, and LMC X-3). However, both two types of BHBs show common spectral properties in the X-ray band. They may be found in either of two typical states; the soft (high) state and the hard (low) state. The BHBs show strong variability in the hard state. The spectrum in this state is expressed by a single power-law, whereas that in the soft state is characterized by an ultrasoft component with a power-law hard tail, as shown in Figure 2.5d. The characteristic photon index of the power-law is $\sim 1.5$ in the hard state, and 2.0–2.5 in the soft state. Their origin is not clear, although a possible mechanism is Comptonization in an optically-thin accretion disk, where the electron temperature reaches $\sim 100$ keV while the ion temperature can be much higher. The ultrasoft component seen in the soft state is expressed by the MCD model, and considered to be optically-thick emission from the accretion disk around the BH. The characteristic innermost disk temperature is $T_{\text{in}} = 0.5–1.2$ keV, lower than those of LMXBs. For a review, see Tanaka & Lewin (1995).

### 2.4 X-Ray Source Population in the Local Group Galaxies

The Galaxy As described in § 2.1, the major component of Galactic X-ray sources are XRBs (WDBs, NSBs, and BHBs). One of the most luminous XRBs are NSBs, and their luminosities remain below $L^{\text{NS}}_E = \ldots$. There are a few hundreds NSBs so far
Figure 2.5: Typical spectra of Galactic X-ray sources. (top left) Spectrum of the shell-type SNR, Cas A, obtained by *ASCA* (Holt et al. 1994). We can see many emission lines on the continuum. (top right) Spectrum of the brightest LMXB, Sco X-1, obtained by *Tenma* (Mitsuda et al. 1984). The spectrum is decomposed into an MCD component and a black-body component. (bottom left) Spectrum of Vela X-1, an X-ray pulsar, obtained by *Ginga* (Nagase 1989), whose continuum can be represented by a power-law model with exponential cutoff. Note that the spectrum was deconvolved against the detector response. (bottom right) Spectrum of the BHB transient GX 339-4 obtained in the soft state by *Tenma* (Makishima et al. 1986). An MCD model plus a power-law hard tail can express the continuum well.
catalogued. About \( \sim 70 \) of them are HMXBs, while the remaining majority are LMXBs. BHBs are also luminous X-ray sources. However, their number is relatively small (\( \sim 20 \)) even if we include transients. The most famous, persistent BHB in our galaxy is Cyg X-1, whose luminosity can reach \( \sim 3 \times 10^{37} \text{ erg s}^{-1} \). Of course, BHBs can become more luminous if mass accretion rate is sufficiently high. In fact, some BH transients have luminosity up to \( \sim 10^{39} \text{ erg s}^{-1} \) (§ 2.2). Galactic SNRs are less luminous than bright XRBs; they have luminosities of \( \sim 10^{36} \text{ erg s}^{-1} \).

**Large and Small Magellanic Clouds** With their proximity of about 50 kpc, Large and Small Magellanic Clouds (LMC and SMC respectively) are the only galaxies besides our Galaxy where early non-imaging X-ray observations could study individual sources. XRBs in Magellanic clouds are known to have higher luminosities than the XRBs in our Galaxy. Two BHBs in LMC, LMC X-1 and LMC X-3, have luminosities of \( 1-5 \times 10^{38} \text{ erg s}^{-1} \) (Tanaka & Lewin 1995). In addition, some NSBs in Magellanic clouds also show luminosity of \( 5 \times 10^{38} \text{ erg s}^{-1} \) (van Paradijs et al. 1995), a few times higher than \( L_{\text{NS}}^E \). For example, LMC X-2 is known as the most luminous LMXB, and SMC X-1 is known as the most luminous HMXB in the Local Group galaxies. The high luminosities of these bright NSBs have been ascribed to the low metallicity of the host galaxies (Clark et al. 1978).

**M31** At a distance of \( \sim 720 \) kpc, M31 (the Andromeda Nebula) is the nearest large spiral galaxy. X-ray emission from M31 has been resolved into more than 100 sources by observation with *Einstein* (Fabbiano 1989). As described in § 2.1, a large fraction of these sources are thought to be LMXBs, because they are concentrated in the bulge of M31 just like the Galactic LMXBs are found in the Galactic bulge region. Makishima et al. (1989) obtained the spatially averaged 2–20 keV spectrum of M31 with the *Ginga* satellite, as shown in Figure 2.6, and confirmed this interpretation by analyzing the spectrum. The spatially integrated 2–20 keV luminosity is \( 5 \times 10^{39} \text{ erg s}^{-1} \), indicating that the \( \sim 100 \) bright sources have an average luminosity of \( 5 \times 10^{37} \text{ erg s}^{-1} \). The number of detected individual sources has been increased up to \( \sim 400 \) by the *ROSAT* observation (Supper et al. 1997). The most luminous ones have X-ray luminosities close to \( L_{\text{NS}}^E \).

**M33 (NGC 598)** This is a relatively small Sc galaxy, yet the third largest member of the Local Group. Ten or more point-like sources with X-ray luminosity over \( 10^{37} \text{ erg s}^{-1} \) were detected by the *Einstein Observatory* (Long et al. 1981). As is the case in our Galaxy and M31, most of them have luminosities below \( L_{\text{NS}}^E \). The only exception is M33 X-8, which is located at the optical nucleus of the host galaxy (Figure 2.2). It has a luminosity as high as \( \sim 10^{39} \text{ erg s}^{-1} \), and is the most luminous X-ray source in the Local Group galaxies. The positional coincidence of M33 X-8 with the nucleus lead some authors to suspect it as an optically quiet, low-X-ray-luminosity active nucleus. However, this source is now considered to be a close binary system containing a black hole, based on the observation by *ASCA* (Takano et al. 1994) and *ROSAT* (Dubus et al. 1997). Further details of this source are given in § 2.6.

Thus, most of the X-ray sources in the Local Group galaxies, except for BH transients, exhibit X-ray luminosities below \( L_{\text{NS}}^E \). The rare exceptions are X-ray sources in LMC and
SMC, in which the low metallicity of the host galaxies would explain the high luminosities of sources, and M33 X-8, which has a luminosity of about $10^{39}$ erg s$^{-1}$ and is thought to be a binary system containing a BH with mass of $\sim 10 M_\odot$. Later, we regard M33 X-8 as a prototype of ULXs.

![Figure 2.6](image)

Figure 2.6: The spatially-averaged X-ray spectrum of M31 observed with *Ginga* (Makishima et al. 1989), compared with that of a typical Galactic LMXB, 4U 1820-30. The two spectra are almost identical in shape. This fact indicate that the main component of the X-ray emission from M31 is a collection of LMXBs.

### 2.5 ULXs in External Spiral Galaxies

#### 2.5.1 The ULXs catalogue

The most comprehensive catalogue of normal galaxies in the X-ray band is based on the *Einstein* data (Fabbiano et al. 1992), where a list of luminous point-like sources, or ULX candidates, found in the observed galaxies, is given. We have therefore extracted “a list of historical ULXs” from this list, and its updated version in Fabbiano (1995), under a criterion that the object should be more luminous than $5 \times 10^{38}$ erg s$^{-1}$ in order to securely rule out NSBs. We also excluded those objects which are likely to be LLAGNs of the host galaxy. In the original papers by Fabbiano et al. (1992) and Fabbiano (1995), the distance was calculated assuming the Hubble constant of $H_0=50$ km s$^{-1}$ Mpc$^{-1}$. We therefore re-calculated the source luminosities based on the distances taken from Tully (1988), in which $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ is assumed in agreement with the contemporary consensus on $H_0$. If available, we used more reliable distance estimates, such as Cepheid based distances obtained by the Hubble Space Telescope.

The obtained list of historical ULXs is given in Table 2.1. Thus, at least a dozen spiral galaxies within a distance of $\sim 10$ Mpc are known to host at least one, or sometimes a
few, ULX(s). However, Table 2.1 is not meant to be a complete sample in any sense. The list includes SN 1980K in NGC 6946, a luminous extragalactic SNR, for comparison with ULXs (This SNR has faded away today, however). On the other hand, SN 1978K, the bright SNR in NGC 1313, is not tabulated there, since the source used to be quite faint in X-rays in the Einstein era.

Table 2.1: Historical ULXs observed by Einstein. This table was made based on Fabbiano et al. (1992), Fabbiano (1995), and references therein. Some of ULXs are named after those references. A bright SNR in NGC 1313, namely SN 1978K, is not included, since it was below the Einstein detection limit at that time.

<table>
<thead>
<tr>
<th>Host galaxy</th>
<th>galactic latitude (°)</th>
<th>Typea)</th>
<th>Distanceb) (Mpc)</th>
<th>Source name or No. of sources</th>
<th>$L_X^{c)}$</th>
<th>$L_X^{d)}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 598 (M31)</td>
<td>-31.3</td>
<td>Scd</td>
<td>0.72</td>
<td>X-8</td>
<td>15</td>
<td>9.3</td>
<td>Trinchieri et al. 1988</td>
</tr>
<tr>
<td>NGC 1313</td>
<td>-44.6</td>
<td>Sd</td>
<td>4.5</td>
<td>source A</td>
<td>1.9</td>
<td>46</td>
<td>Fabbiano et al. 1992</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>-21.2</td>
<td>Sd</td>
<td>4.2</td>
<td>source 3</td>
<td>0.83</td>
<td>10</td>
<td>Fabbiano et al. 1992</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>-30.9</td>
<td>Scd</td>
<td>0.8</td>
<td>X-8</td>
<td>1.0</td>
<td>15</td>
<td>Fabbiano 1988</td>
</tr>
<tr>
<td>NGC 3034 (M82)</td>
<td>40.6</td>
<td>Peculiar</td>
<td>3.3</td>
<td>8 sources</td>
<td>0.3–0.7</td>
<td>5–9</td>
<td>Watson et al. 1984</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>64.8</td>
<td>Sb</td>
<td>7.7</td>
<td></td>
<td>0.42</td>
<td>30</td>
<td>Fabbiano et al. 1992</td>
</tr>
<tr>
<td>NGC 4258</td>
<td>68.8</td>
<td>Sbc</td>
<td>6.8</td>
<td></td>
<td>0.84</td>
<td>46</td>
<td>Fabbiano et al. 1992</td>
</tr>
<tr>
<td>NGC 4631</td>
<td>84.2</td>
<td>Sc</td>
<td>6.9</td>
<td></td>
<td>0.25</td>
<td>14</td>
<td>Fabbiano &amp; Trinchieri 1987</td>
</tr>
<tr>
<td>NGC 5194 (M51)</td>
<td>68.6</td>
<td>Scb</td>
<td>7.7</td>
<td>source 3</td>
<td>0.09–0.13</td>
<td>6.4–9.2</td>
<td>Palumbo et al. 1985</td>
</tr>
<tr>
<td>NGC 5236 (M83)</td>
<td>32.0</td>
<td>Sc</td>
<td>3.75</td>
<td></td>
<td>0.22</td>
<td>6.9</td>
<td>Trinchieri et al. 1983</td>
</tr>
<tr>
<td>NGC 5549 (M101)</td>
<td>99.8</td>
<td>Sb</td>
<td>7.2</td>
<td>4 sources</td>
<td>0.15–0.45</td>
<td>0.4–2</td>
<td>Trinchieri et al. 1990</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>11.7</td>
<td>Scd</td>
<td>5.8</td>
<td>SN 1980K</td>
<td>0.91</td>
<td>34</td>
<td>Fabbiano &amp; Trinchieri 1987</td>
</tr>
<tr>
<td>IC 342</td>
<td>10.6</td>
<td>Scd</td>
<td>3.3</td>
<td>source 1</td>
<td>1.2</td>
<td>31</td>
<td>Fabbiano &amp; Trinchieri 1987</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>source 2</td>
<td>0.78</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>source 3</td>
<td>1.1</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

a) Taken from Tully (1988).

b) The distance was taken from de Vaucouleurs (1963) for NGC 1313, Freedman & Madore (1988) for NGC 2403, Freedman et al. (1994) for NGC 3034, de Vaucouleurs (1979) for NGC 5236, and Tully (1988) for all other galaxies.

c) X-ray flux in units of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$. The flux in this column is taken from original references, and were calculated for most of ULXs, though not all, in the energy range of 0.2–4 keV.

d) X-ray luminosity in units of $10^{38}$ erg s$^{-1}$.

2.5.2 Properties of ULXs

The most outstanding properties of ULXs, by definition, are their point-like X-ray appearances, and their high X-ray luminosities much exceeding $L_E^{NS}$. As seen from Table 2.1, they can be nearly two orders of magnitude more luminous than NSBs. None of ULXs have been identified securely in other frequencies.

Table 2.1 reveals another interesting feature of the ULXs. That is, their host galaxies are mostly classified as type Sc or Sd, namely late-type spirals that have prominent spiral arms and exhibit high star-formation activities. This fact suggests that ULXs are young population objects. X-ray images of individual galaxies reinforce this interpretation: as show in Figure 2.7, a fair number of ULXs are found in spiral arms, hence may be associated with population I stars. This also agrees with the fact that no ULX is known in elliptical or S0 galaxies. However, this could be a result of selection effects, because there are few galaxies of these types within $\sim 10$ Mpc, and because the very bright extended thermal emission from these galaxies would mask any discrete source.

Some ULXs exhibit clear time variability. Early observations with Einstein already revealed that some ULXs, such as one in M101, changed in intensity between separate observations (Long and Van Speybroeck 1983). In some extreme cases, a ULX can vary on a few hours (see § 2.6 and § 5.2). Accordingly, such a source cannot be a collection of
many fainter sources, but likely to be a single compact objects with a very high luminosity reaching \( L_X = 10^{39-40} \) erg s\(^{-1}\).

For other sources which do not show significant time variability, the size of the emission region can be loosely constrained by their point-like appearance, when observed with the high-resolution imager (HRI) onboard \textit{Einstein} or \textit{ROSAT}, which has a typical angular resolution of \( \lesssim 10'' \). For example, in a galaxy located at a 10 Mpc distance, this angular size restricts the physical size to within \( \sim 0.5 \) kpc. As explained in the next subsection, X-ray emission from such limited regions is difficult to be understood as a collection of a large number of fainter sources.

The spectral information is expected to provide a clue to the nature of ULXs. However before \textit{ASCA}, the information remained quite poor, because the previous missions such as \textit{Einstein} and \textit{ROSAT} had a quite limited bandpass up to \( \sim 3 \) keV and a relatively poor energy resolution (\( \Delta E/E \sim 0.5 \)). Only in some limited cases, ULXs were known to exhibit relatively hard spectra comparable to those of Galactic XRBs (e.g. Fabbiano and Trinchieri 1987).

(a) NGC 5194 (M51)  
(b) NGC 5457 (M101)

Figure 2.7: X-ray intensity contour maps of two galaxies which host ULXs, superposed on the optical image. Panel (a) represents NGC 5194 (M51) taken from Martson et al. (1995), and panel (b) corresponds to NGC 5457 (M101) obtained from Trinchieri et al. (1990). The bright X-ray sources (ULXs) are associated with the spiral arms of the host galaxy.

### 2.5.3 Possible explanations of ULXs

Before the present thesis, several attempts have been made to explain the ULXs. Here we review representative scenarios so far considered.

**Foreground or background contaminants** The simplest account of the ULXs is to regard them as foreground (presumably Galactic) or background (most likely AGNs) contaminants. However, the foreground contamination is unlikely, because the ULXs
in Table 2.1 are found in galaxies with high Galactic latitudes, as well as in those with low latitudes. Even in low-latitude galaxies, none of ULXs in Table 2.1 are identified optically with foreground objects.

Then, how about background objects? According to the log $N$–log $S$ relation of Gioia et al. (1984) for extragalactic X-ray sources, the chance probability to find an X-ray source of 0.3–3.5 keV flux exceeding $\sim 5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in a sky region of $10' \times 10'$ in size (a typical optical size of the galaxies in Table 2.1) is only $\sim 0.8\%$. Since Table 2.1 is based on the *Einstein* detections of $\sim 100$ spiral galaxies, the expected number of sources which might be a background object is $\sim 1$. We can therefore securely conclude that most of the historical ULXs in Table 2.1 are not background contaminants, as already argued by Fabbiano (1988). We hence consider that most of the ULXs are actually associated with the host galaxies.

**A collection of fainter sources** Yet another simple explanation of ULXs is to regard each of them as a “composite” of a large number of low-luminosity objects. For example, a group of about 100 luminous LMXBs, each radiating at $\sim L_{E}^{\text{NS}}$, would make a most luminous ULX. However, this cannot apply to the ULXs that show strong time variation. Even for a non-variable ULX, the physical upper-limit size ($\sim 1$ kpc or less; see previous subsection) set by the angular size make this interpretation difficult, because such a dense concentration of many X-ray sources in such a small region is not observed in our Galaxy or M31, except in a bulge region or in globular clusters. The preferred location (i.e. spiral arms) of ULXs is clearly different from these environments. Thus, the composite scenario is also unsuccessful.

**Young SNRs** As already mentioned in § 2.2. SNRs could explain the high luminosity of ULXs, since they are free from the Eddington limit. In fact, some external SNRs have luminosities above $10^{38}$ erg s$^{-1}$ as already mentioned. Therefore, this remains an open possibility; all the ULXs could be young SNRs, even though they are not identified in that way. In order to examine this possibility, we compare the spectra between the securely identified extragalactic SNRs and other ULXs in Chapter 6.

**Beamed radiation from LMXBs or BHBs** One attempt to explain the ULXs, frequently proposed by several authors, is to assume that the X-ray emission is strongly collimated toward us. However, this assumption is difficult to accept. Luminosities of the most luminous Galactic LMXBs fall $\sim 100$ times short of those of the most luminous ULXs. Even if we assume BHBs with ordinary masses ($10–20 M_{\odot}$), the luminosity is $\sim 10$ times in short to explain the ULXs. Therefore, uncomfortably high collimation ($10–100$) is needed to explain ULXs as beamed radiation from LMXBs, or BHBs of ordinary masses. There is no known mechanism to produce such a strong X-ray beaming.

**Massive ($\sim 100$) BHBs** Because the Eddington limit is proportional to the object mass as described in § 2.2, a massive ($\sim 100 M_{\odot}$) BH can potentially explain a ULX without invoking any super-Eddington radiation or radiation beaming. This hypothesis however involves two problems. One is that the required black-hole mass, $100 M_{\odot}$ or higher, is uncomfortably high. Such massive BHs have never been observed, and invoking such objects may contradict our current understanding of stellar evolution.
The other, more delicate problem is that if we assume ULXs as the BHBs in the soft (high) state, the measured values of $T_{\text{in}}$ are rather high compared to those of Galactic and Magellanic black-hole binaries (typically 0.5–1.2 keV). As first pointed out by Okada et al. (1998) with respect to a ULXs in IC 342, this raises a serious self-inconsistency in the black-hole interpretation of ULXs. We describe this issue in the next subsection.

2.6 \textit{ASCA} Observation of ULXs

Accurate spectral studies of ULXs have been enabled for the first time with \textit{ASCA}, thanks to its good energy resolution and a high sensitivity up to 10 keV. Prior to the present thesis, several authors already studied the \textit{ASCA} spectra of a few ULXs, including; M33 X-8 (Takano et al. 1994), IC 342 source 1 and 2 (Okada et al 1998), M81 X-6 (Uno 1996), Dwingeloo 1 X-1 (Reynolds et al. 1997), NGC 1313 source A and B (Petre et al 1994), off-center source in NGC 3628 (Yaqoob et al. 1995), a newly detected ULX in NGC 1365 (Iyomoto et al. 1997), and two ULXs in NGC 4565 (Mizuno et al. 1999). We summarize these previous \textit{ASCA} results in Table 2.2.

Among them, M33 X-8 and IC 342 source 1 have highest X-ray fluxes which allowed detailed spectral studies. Below, we briefly quote the results on these two sources. An important finding from these observations is that the spectra of both sources can be expressed by an MCD model (or a composite model involving an MCD component). The MCD formalism is reviewed in the next section.

![Table 2.2: \textit{ASCA} spectral results of ULXs](image)

<table>
<thead>
<tr>
<th>Host galaxy</th>
<th>Distance(^a) (Mpc)</th>
<th>Source name</th>
<th>Assumed model</th>
<th>Parameter</th>
<th>$f_X^{b)}$</th>
<th>$L_X^{c)}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 598 (M33)</td>
<td>0.72</td>
<td>X-8</td>
<td>MCD+PL</td>
<td>$T_{\text{in}}=1$ keV</td>
<td>16</td>
<td>10</td>
<td>Takano et al. (1994)</td>
</tr>
<tr>
<td>NGC 1313</td>
<td>4.5</td>
<td>Source A</td>
<td>PL</td>
<td>$\Gamma=1.8$</td>
<td>1.6</td>
<td>39</td>
<td>Petre et al. (1994)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Source B</td>
<td>TBS</td>
<td>$kT=4$ keV</td>
<td>1.4</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SN 1978K</td>
<td>PL</td>
<td>$\Gamma=2.2$</td>
<td>0.62</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>NGC 1365</td>
<td>18.3</td>
<td>SW-source</td>
<td>PL</td>
<td>$\Gamma=1.7$</td>
<td>1.3</td>
<td>530</td>
<td>Iyomoto et al. (1997)</td>
</tr>
<tr>
<td>NGC 3031 (M81)</td>
<td>3.6</td>
<td>X-6</td>
<td>MCD</td>
<td>$T_{\text{in}}=1.5$ keV</td>
<td>3.4</td>
<td>53</td>
<td>Uno (1996)</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>7.7</td>
<td>off-center</td>
<td>PL</td>
<td>$\Gamma=2.4$</td>
<td>0.34</td>
<td>24</td>
<td>Yaqoob et al. (1995)</td>
</tr>
<tr>
<td>NGC 4565</td>
<td>10.4</td>
<td>off-center</td>
<td>MCD</td>
<td>$T_{\text{in}}=1.4$ keV</td>
<td>1.7</td>
<td>220</td>
<td>Mizuno et al. (1990)</td>
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<tr>
<td>Dwingeloo 1</td>
<td>3</td>
<td>X-1</td>
<td>PL</td>
<td>$\Gamma=2.0$</td>
<td>0.75</td>
<td>8</td>
<td>Reynolds et al. (1997)</td>
</tr>
<tr>
<td>IC 342</td>
<td>3.9</td>
<td>Source 1</td>
<td>MCD</td>
<td>$T_{\text{in}}=1.8$ keV</td>
<td>8.3</td>
<td>150</td>
<td>Okada et al. (1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Source 2</td>
<td>PL</td>
<td>$\Gamma=1.3$</td>
<td>3.4</td>
<td>62</td>
<td></td>
</tr>
</tbody>
</table>

\(a\) The distance is taken from de Vaucouleurs (1963) for NGC 1313, Silbermann et al. (1999) for NGC 1365, Freedman et al. (1994) for NGC 3031, Kraan-Korteweg et al. (1994) for Dwingeloo 1, and Tully (1988) for all other galaxies except for NGC 4565, for which we adopted the weighted mean of three independent distance indicators after Mizuno et al. (1999). (see § 7.3.1)

\(b\) X-ray flux in units of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$. The flux in the column is taken from original references, and are calculated for most of ULXs, though not all, in the energy range of 0.5–10 keV.

\(c\) X-ray luminosity in units of $10^{38}$ erg s$^{-1}$, calculated assuming the isotropic radiation.
2.6.1 M33 X-8

The central source of M33 (M33 X-8) is known to have a luminosity of $10^{39}$ erg s$^{-1}$. It is the most luminous point-like X-ray source in the Local Group galaxies. Although it is nearly coincident in position with the optical nucleus, there is no evidence for the nuclear activity in M33 in other wavebands. Therefore, the nature of M33 X-8 has long been a mystery.

Takano et al. (1994) observed M33 with ASCA and analyzed the spectra of X-8. They discovered that the spectra are well represented by the power-law plus MCD model. The inner-disk temperature, $T_{\text{in}}$, is $\sim 1$ keV, and the bolometric flux of the MCD component is $\sim 1.25 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. Thus, the inner-most disk radius, $R_{\text{in}}$, is calculated from equation 2.10 as $\sim \frac{60}{\cos i}$ km, where $i$ is the inclination angle. Although the MCD emission is associated with either LMXBs or BHBs, the obtained value of $R_{\text{in}}$ is significantly larger than those typically found from LMXBs ($\sim 10$ km), while comparable to those of typical BHBs. In addition, the existence of the power-law hard tail is characteristic of the spectra of Galactic and Magellanic BHBs. Therefore, they suggested that M33 X-8 is a close binary system containing a black hole of about $10 M_\odot$; its high-luminosity can be explained within the sub-Eddington regime. Their results have been reconfirmed by Colbert & Mushotzky (1999). The discovery of a 106 day periodicity by Dubus et al. (1997) from X-8 has strongly reinforced the interpretation of X-8 as a close binary system.

2.6.2 IC 342 source 1

IC 342 is a nearby Sc galaxy, and is known to host a few ULXs in its spiral arms (Fabbiano et al. 1987). Okada et al. (1998) analyzed ASCA spectra of ULXs in IC 342, and found impressive properties of so-called “source 1”, named after Fabbiano et al. (1987). This source has a high luminosity of $\sim 10^{40}$ erg s$^{-1}$ in the ASCA band, and exhibited clear time variability on time scales of a few hours, as shown in Figure 2.8. Therefore, the source cannot be a collection of fainter sources, but must be a single compact one. They also pointed out that the spectrum can be expressed well by an MCD model of $T_{\text{in}} \sim 1.8$ keV, whereas the power-law and TBS models failed to represent the data. Considering this spectral result and the obtained high luminosity, IC 342 source 1 is suspected to be a BHBs, as is the case of X-8 in M33. However, the obtained value of $T_{\text{in}}$ is uncomfortably high compared to those of Galactic and Magellanic BHBs (0.5–1.2 keV). As discussed by Okada et al. (1998), this leads to a serious self-inconsistency; by substituting the value of $T_{\text{in}}$ and the bolometric flux of $\sim 1.1 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ into equation 2.12, we obtain $R_{\text{in}} \sim \frac{100}{\cos i}$ km (assuming the distance $D=3.9$ Mpc). Thus, the black-hole mass can become at most $\sim \frac{10}{\cos i} M_\odot$ if we assume a Schwarzschild BH. On the other hand, the observed luminosity requires $\sim \frac{70}{\cos i} M_\odot$ to sustain sub-Eddington radiation, in contradiction to the above mass estimation. Thus, Okada et al. (1998) cast a doubt on the BH interpretation. Further details of this issue are described in Chapter 7.
2.7 Optically-Thick Emission from Accretion Disks

2.7.1 Standard model and MCD approximation

X-ray binaries emit X-rays via the release of gravitational energy of accreting matter on the compact object. Since they are close binary system, accreting matter has angular momentum with respect to the compact star. Hence, matter from the companion star does not accrete spherically, but rotates around the compact object and will form a disk-like structure, called accretion disk. An analytic solution to the accretion disk structure was obtained by Shakura & Sunyaev (1973), assuming an optically thick, geometrically thin disk. In this subsection, we briefly explain their solution, called standard accretion disk model, and its approximation, an MCD model.

The standard disk model assumes that the motion of the accreting matter is dominated by Kepler motion, i.e., \( v_R \ll v_\phi = \sqrt{GM/R} \), where \( v_R \) and \( v_\phi \) is the radial and rotational velocity of the disk respectively, \( G \) is the gravitational constant, \( M \) is the mass of the compact object, and \( R \) is the distance from its center. The disk rotates differentially according to the Kepler’s law, and the accreting matter loses its angular momentum via the viscous stress and fall onto the compact star. While the radial infall of accreting matter is regulated by the angular momentum transfer in outer disk regions, the energy release mechanism becomes the regulating factor in inner disk regions. The standard disk solution assumes that the accreting matter can release its gravitational energy, hence radially fall in, only by radiating away half the liberated energy (the remaining half goes into the Keplerian kinetic energy). The energy flux is expressed as

\[
f = \frac{3GM\dot{M}}{8\pi R^3} \left( 1 - \sqrt{\frac{R_{\text{in}}}{R}} \right),
\]

(2.3)

where \( \dot{M} \) is the mass accretion rate and \( R_{\text{in}} \) is the inner-most disk radius. The energy flux \( f \) becomes maximum at \( R = \left( \frac{7}{6} \right)^2 R_{\text{in}} \). If we assume a black body radiation, \( f = \sigma T_{\text{eff}}^4 \),
where $T_{\text{eff}}$ denotes the effective temperature. Therefore, we obtain

$$T_{\text{eff}} = \left[ \frac{3GM \dot{M}}{8\pi\sigma R^3} \left( 1 - \sqrt{\frac{R_{\text{in}}}{R}} \right) \right]^{1/4}. \quad (2.4)$$

Through observation, we can only measure the color temperature $T$, but not the effective temperature. By expressing the ratio of the color temperature to the effective temperature as $\kappa$ (i.e., $\kappa \equiv T/T_{\text{eff}}$), the color temperature profile is obtained as,

$$T \equiv \kappa T_{\text{eff}} = \kappa \left[ \frac{3GM \dot{M}}{8\pi\sigma R^3} \left( 1 - \sqrt{\frac{R_{\text{in}}}{R}} \right) \right]^{1/4}. \quad (2.5)$$

This profile is approximated by the MCD model, defined as,

$$T(R) = T_{\text{in}} \left( \frac{R_{\text{MCD}}}{R} \right)^{3/4}, \quad (2.6)$$

where $R_{\text{MCD}}$ is the inner-most disk radius used in the MCD model, and $T_{\text{in}}$ is the color temperature at $R = R_{\text{in}}$. To represent the observed spectrum from an optically-thick accretion disk, the MCD approximation is more preferred than the original Shakura & Sunyaev formula in several respects. The expression of the temperature profile (equation 2.6) is, of course, simpler. It is characterized by $T_{\text{in}}$, the physical quantity that describes the actual property of the disk, whereas the original Shakura & Sunyaev function (equation 2.5) is represented by $M$ and $\dot{M}$. In addition, this approximation has been used to describe the spectra of Galactic and Magellanic XRBs (e.g., Mitsuda et al. 1984, Makishima et al. 1986, Ebisawa 1991, Dotani et al. 1997, Kubota et al. 1998), hence the direct comparison with the previous observational results can be performed. In order to examine the goodness of the MCD approximation, we calculated the spectrum from the Shakura & Sunyaev disk of equation 2.5 with the maximum temperature of 1.50 keV, and adjusted $T_{\text{in}}$ of the MCD model to best approximate the Shakura–Sunyaev spectrum over the 0.5–10 keV range where ASCA has a sufficient sensitivity (Chapter 3). As shown in Figure 2.9, a good agreement was achieved for an MCD temperature of $T_{\text{in}}=1.54$ keV, and the two spectra are similar in shapes within $\sim 5\%$. Hence, the deviation of the MCD model from the standard Shakura & Sunyaev one is small and is considered not to affect our spectral analysis performed in Chapter 6. Therefore, we utilize the MCD approximation throughout this thesis. More details of this issue will be described in § 6.2.1 and § 6.3.2.

In the MCD approximation, the bolometric luminosity of the disk is calculated as

$$L_{\text{bol}} = \int_{R_{\text{in}}}^{R_{\text{out}}} 4\pi R \sigma T_{\text{eff}}^4 dR = \int_{R_{\text{in}}}^{R_{\text{out}}} 4\pi R \sigma \left( \frac{T}{\kappa} \right)^4 dR \sim 4\pi \left( \frac{R_{\text{MCD}}}{R_{\text{in}}} \right)^2 \sigma \left( \frac{T_{\text{in}}}{\kappa} \right)^4, \quad (2.7)$$

where $R_{\text{out}}$ is the outer disk radius, and the relation of $R_{\text{in}} \ll R_{\text{out}}$ is assumed. Since the MCD approximation neglects the term $\left( 1 - \sqrt{\frac{R_{\text{in}}}{R}} \right)$ in equation 2.5, $R_{\text{MCD}}$ differs from $R_{\text{in}}$. By equating $\xi = R_{\text{in}}/R_{\text{MCD}}$, we obtain,

$$L_{\text{bol}} = 4\pi \left( \frac{R_{\text{in}}}{\xi} \right)^2 \sigma \left( \frac{T_{\text{in}}}{\kappa} \right)^4. \quad (2.8)$$
We assume $\xi=0.41$ after Kubota et al. (1998), and $\kappa=1.7$ after the numerical calculation by Shimura & Takahara (1995). From this equation, we can express the observed flux as

$$f_{\text{bol}} = 4\pi \left( \frac{R_{\infty}}{\xi} \right)^2 \sigma \left( \frac{T_{\text{in}}}{\kappa} \right)^4 \cos i \frac{\sqrt{4\pi D^2 f_{\text{bol}}}}{2\pi D^2},$$

where $D$ is the distance to the source and $i$ is the inclination of the disk. The value of $T_{\text{in}}$, which determines the spectral shape, is directly obtained through the spectral fitting. Then we can calculate the value of $R_{\infty}$, which describes the disk structure, from the observed flux as a function of $D$ and $i$.

### 2.7.2 Application to BHBs

The application of the MCD formalism to BHBs is quite important, because the innermost disk radius, $R_{\infty}$, may be regarded to the last stable Keplerian orbit. Thus, for a non-spinning BHBs, we have $R_{\infty} = 3R_S$ where $R_S = \frac{2GM}{c^2} = 2.95(\frac{M}{M_\odot})$ km. More generally, we may write as

$$R_{\infty} = 3\alpha R_S = 8.85\alpha \left( \frac{M}{M_\odot} \right) \text{ km},$$

using a positive parameter $\alpha$, which is 1 for a Schwarzschild BH and $\frac{1}{6}$ for a maximally rotating one (see § 7.4.2). From equation 2.9, we can estimate $R_{\infty}$ as

$$R_{\infty} = \xi\kappa^2 \frac{1}{\cos i} \sqrt{\frac{4\pi D^2 f_{\text{bol}}}{8\pi \sigma T_{\text{in}}^4}}.$$

Thus, combined with the equation 2.10, the mass of central BH is calculated as

$$M = \frac{c^2}{6\alpha G^2} \xi\kappa^2 \frac{1}{\cos i} \sqrt{\frac{4\pi D^2 f_{\text{bol}}}{8\pi \sigma T_{\text{in}}^4}}.$$  

This mass-estimation has been performed on many X-ray emitting BHBs, e.g., Makishima et al. (1986), Ebisawa (1991) Dotani et al. (1997), and Kubota et al. (1998). As shown by Ebisawa (1991), some BHBs provide constant value of $R_{\infty}$ within $\sim \pm 20\%$ while their flux change significantly (by a factor of 10–100). Moreover, this mass estimation succeeded to obtain a mass comparable with that determined optically if available. Therefore, the interpretation of $R_{\infty}$ as the last stable orbit was strongly confirmed. Details of these issues will be mentioned in § 7.3.4 and § 7.3.5.

We end this section by introducing some useful equations. By substituting equation 2.10 into equation 2.8, we can obtain

$$L_{\text{bol}} = 7.1 \times 10^{38} \left( \frac{\xi}{0.412} \right)^{-2} \left( \frac{\kappa}{1.7} \right)^{-4} \alpha^2 \left( \frac{M}{10M_\odot} \right)^2 \left( \frac{T_{\text{in}}}{\text{keV}} \right)^4 \text{ erg s}^{-1},$$

implying that a luminosity of a given BHB changes as $\propto T_{\text{in}}^4$. It is convenient to write $L_{\text{bol}}$ as

$$L_{\text{bol}} = \eta L_E \propto \eta M,$$
where a non-dimensional parameter $\eta$ means the disk bolometric luminosity normalized to the Eddington luminosity of equation 2.1. By substituting these two equations into equation 2.13, we can obtain another temperature-luminosity relation as

$$L_{\text{bol}} = 3.1 \times 10^{39} \left( \frac{\xi}{0.412} \right)^2 \left( \frac{\kappa}{1.7} \right)^4 \alpha^{-2} \eta^2 \left( \frac{T_{\text{in}}}{\text{keV}} \right)^{-4} \text{erg s}^{-1}.$$  \hspace{1cm} (2.15)

Thus, when normalized by $\eta$, luminosity of the disk becomes higher as the temperature decreases. We finally equate two equation, 2.13 and 2.15, to obtain a relation of

$$T_{\text{in}} = 1.2 \left( \frac{\xi}{0.412} \right)^{1/2} \left( \frac{\kappa}{1.7} \right)^{-1/2} \alpha^{-1/4} \eta^{1/4} \left( \frac{M}{10M_\odot} \right)^{-1/4} \text{keV}.$$  \hspace{1cm} (2.16)

Therefore, a heavier BH tends to show a lower disk temperature.

Figure 2.9: Comparison between the Shakura & Sunyaev model spectrum and its MCD approximation. The maximum temperature of the Shakura & Sunyaev disk is 1.50 keV, whereas the inner-disk temperature $T_{\text{in}}$ of the MCD model is 1.54 keV.
Chapter 3

INSTRUMENTATION

3.1 The ASCA Satellite

3.1.1 Overview

The scientific satellite ASCA (Advanced Satellite for Cosmology and Astrophysics) is the Japan’s fourth cosmic X-ray mission following Hakuchō (1979), Tenma (1983), and Ginga (1987). ASCA is a project of the Institute of Space and Astronautical Science (ISAS), developed under a Japan-US collaborations. The satellite was successfully launched on 1993 February 20 with the M-3S-II rocket from Kagoshima Space Center (KSC) of ISAS at Uchinoura, Kagoshima. It was put into an approximately circular orbit with a perigee and an apogee of 520 and 620 km, respectively. The orbital period is approximately 96 minutes and an inclination is about 31° (Tanaka et al. 1994).

Figure 3.1 shows the in-orbit configuration of ASCA. It weights about 420 kg, and has an octagonal-shaped body of 1.2 m where six solar panels are attached. The spacecraft has a nested double-cylinder structure, with the outer cylinder serving as the spacecraft body while the inner cylinder serving as an extendible optical bench (EOB). At the top of the EOB, four sets of identical X-ray telescopes (XRT) are placed. They are aligned along the satellite Z axis with a common focal length of 3.5 m. As illustrated in Figure 3.2, the focal plane of the XRTs are equipped with four position-sensitive X-ray detectors; two SIS (Solid-state Imaging Spectrometer) detectors called SIS 0 and SIS 1, and two GIS (Gas Imaging Spectrometer) detectors called GIS 2 and GIS 3. Owing to the large effective area of the XRT up to 10 keV and the good spatial and energy resolution of the SIS/GIS, ASCA is capable of performing imaging and spectroscopic observations simultaneously for the first time over a wide energy range of 0.5–10 keV.

The first eight months of the ASCA mission were devoted to performance verification (PV) phase. Having established the quality of performance of all ASCA’s instruments, the project changed to a guest observation phase for the remainder of the mission. In this phase the observing program is open to astrophysicists based at Japanese and US institutions, as well as those who are located in member states of the European Space Agency.
3.1.2 Data acquisition

The observed data are processed by the on-board data processing unit, and stored in the on-board data recorder (Bubble Data Recorder; BDR). The BDR has a capacity of 134 Mbits and three different acquisition rate are available; high bit rate (32 kbit s$^{-1}$), medium bit rate (8 kbit s$^{-1}$), and low bit rate (1 kbit s$^{-1}$). Therefore the BDR can cover only 68 and 273 minutes for high and medium bit rate mode, respectively. In order to accumulate as much data as possible, the stored data are downlinked at ground stations including KSC and the NASA Deep Space Network (DSN) stations. At KSC, there are usually five contacts per day between the satellite and the station, and at the DSN there are also several contacts per day. The data acquired at KSC are transmitted to ISAS in real time, while the data acquired at DNS station usually are transmitted within 24 hours.

![Image](image.png)

Figure 3.1: In orbit configuration of the ASCA satellite.

3.2 X-Ray Telescope (XRT)

3.2.1 Overview of the XRT

The four XRTs on-board ASCA were built by NASA’s Goddard Space Flight Center and Nagoya University, and provide large effective area up to $\sim 10$ keV.

Soft X-rays are totally reflected off a smooth surface, when the incident angle is shallower than a certain critical value. The critical angle, typically of order 1 degree or so, is inversely proportional to the X-ray energy and increases with increasing free electron density of the reflecting material. X-ray telescopes use this mechanism usually in so called Wolter type I configuration (Figure 3.3), which employs paraboloid and hyperboloid surface as the primary and the secondary mirrors so as to remove the first-order abberation. The two mirrors have a common focus and reflect X-rays in series (double reflection).
This Wolter type I optics have been used for previous X-ray astronomy satellites, such as *Einstein*, *EXOSAT*, and *ROSAT*.

However, these previous observations were limited by the mirror to a relatively narrow, low-energy band (up to \(\sim 3\) keV; see Figure 3.4). In order to ensure both high reflectivity and a large effective area for harder X-rays, which have smaller critical angle, we must nest many mirror shells with a tight spacing. This can be realized by a design called multiple thin-foil optics, a special version of the Wolter I optics (Serlemitsos 1981). This design makes each shell extremely thin by using metal foils and drastically increase the number of nesting. However, it is very difficult to shape a thin foil into a paraboloid or a hyperboloid. Therefore a conical surface is instead used as its approximation, which reduces the imaging quality.

A prototype multiple thin-foil mirrors were used in the BBXRT (Broad-Band X-Ray Telescope) experiment flown on-board the Space Shuttle mission in 1990 (Serlemitsos 1988). Then this technique has been applied to the *ASCA* XRT (Serlemitsos et al. 1995). The reflector shells of the *ASCA* XRT are made of thin (127 \(\mu\)m) aluminium foil, coated by a 10 \(\mu\)m acrylic layer to improve the surface smoothness. Because of the strong dependence of the reflection efficiency on the atomic number \(Z\) of the surface material, 50 nm of gold was evaporated over the acrylic layer. The XRT aperture is an annulus with inner and outer diameters of 120 and 345 mm respectively. Filling this aperture are 120 reflectors stacked as tightly as possible, without causing interference among neighbors for axial ray. Mirror assembly is in quadrants and the reflectors are supported by 13 slotted radial supports in each quadorant (Figure 3.5). Four quadrants make up the “paraboloid” section of 100 mm long, and another set of four quadrants makes up the “hyperboloid” section. On the focal plane, 1.0 arcmin is equivalently 1.0 mm. Design parameters and basic performance of the *ASCA* XRT are summarized in Table 3.1.

![Figure 3.2: On-board instruments of the *ASCA* satellite.](image)
Table 3.1: Design parameters and characteristics of the ASCA XRT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror substrate</td>
<td>17 μm aluminium foil</td>
</tr>
<tr>
<td>Mirror surface</td>
<td>Acrylic lacquer 10 μm + Au (500 Å)</td>
</tr>
<tr>
<td>Mirror length</td>
<td>100 mm</td>
</tr>
<tr>
<td>Mirror number</td>
<td>120 foils</td>
</tr>
<tr>
<td>Outer (inner) diameter</td>
<td>345 (120) mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>3500 mm</td>
</tr>
<tr>
<td>Incident angle</td>
<td>0°24–0°70</td>
</tr>
<tr>
<td>Number of telescopes</td>
<td>4</td>
</tr>
<tr>
<td>Mirror weight</td>
<td>9882 g(M0), 9885 g(M1), 9795 g(M2), 9808 g(M3)</td>
</tr>
<tr>
<td>Total mirror weight</td>
<td>39340 g</td>
</tr>
<tr>
<td>Geometrical area</td>
<td>588 cm²/telescope</td>
</tr>
<tr>
<td>Field of view</td>
<td>24′ (FWHM@1 keV), 16′ (FWHM@7 keV)</td>
</tr>
<tr>
<td>Energy range</td>
<td>≤ 10 keV</td>
</tr>
<tr>
<td>Effective area</td>
<td>~ 1300 cm² (@1 keV), ~ 600 cm² (@7 keV)</td>
</tr>
<tr>
<td>Half power diameter</td>
<td>~ 3 arcmin</td>
</tr>
</tbody>
</table>

Figure 3.3: Wolter type I optics.
Figure 3.4: Comparison of the ASCA XRT effective area (4 XRTs summed up, on-axis) with that of mirrors on previous missions.

Figure 3.5: XRT quadrant housing. 120 foil reflectors are installed in each of the two layers. Also shown are the 13 slotted radial bars which support the reflectors in the housing.
3.2.2 Performance of the XRT

The effective area of the XRTs is energy-dependent, because of the energy dependence of the critical angle and the absorption edge of the surface material. Off-axis rays suffer additional obscuration, caused by shadowing. In addition, since the photons with higher energies are reflected at smaller critical angles, higher energy photons are not reflected by outer foils, where the cone angles are larger. As a result, normalization and energy-dependence of the effective area change with the incident angle, as shown in Figure 3.6.

A point spread function (PSF) also depends on both energy and incident angle, as shown in Figure 3.7. The PSF has a sharply peaked core, although it is somewhat broadened in the image by the finite position resolution of the GIS. For a point source observed on axis with the GIS, half the detected counts are contained within a diameter of 3.2′ on the focal plane. This diameter, called half-power diameter (HPD), gives a rough measure of the combined XRT+GIS angular resolution.

Unfortunately, the PSF does not have a cylindrical symmetry. Instead, it has a 4-times rotational symmetry when measured on-axis as shown in Figure 3.7, where the four butterfly-like wings are apparent as a result of the quadrant structure of the XRT. We also notice extended wings in the image. Thus the PSF has wide outskirts with significant flux extending almost over the whole GIS field of view. Moreover, it is clear that at higher energies the PSF has wider outskirts. This is mainly due to micro roughness of the reflecting surface of the XRT, which causes non-specular reflection, i.e. scattering of incident X-rays. The scattering generally increases with the increasing X-ray energy.

The PSF also depends strongly on the position in the focal plane, in such a way that even the 4-times rotational symmetry is rapidly violated as the off-axis angle increase, as indicated by Figure 3.7b and Figure 3.7c. When analyzing the ASCA data, all these properties should be taken into account.

![Graphs](image)

Figure 3.6: Properties of the ASCA XRT effective area. Panel (a) represents the energy dependence at $\theta=0^\prime$, $10^\prime$, and $20^\prime$, all for $\phi=0^\circ$. Panel (b) shows $\theta$ dependence at $E=1$, 2, 4, and 8 keV, for $\phi=0^\circ$ and $45^\circ$. 
Figure 3.7: Examples of the XRT PSF taken by GIS 2. (a) 1.8′, (b) 8′, (c) 17′ offset Cyg X-1 images (left panels) and the radial profiles (right panels). For left panel images, the origin of the coordinates are the optical axis of GIS 2. All radial profiles in the right panels are scaled so that the volume in $r \leq 6$ mm is equal to 1.0.
### 3.3 Solid State Imaging Spectrometer (SIS)

#### 3.3.1 Overviews of the SIS

The SIS utilizes X-ray sensitive CCD cameras, and has superior energy resolution and fine position resolution. The construction of the SIS was a joint effort of Massachusetts Institute of Technology (MIT), Osaka University, and ISAS. The cross sectional view of the SIS is shown in Figure 3.8.

The SIS on ASCA consists of two camera assemblies. In one SIS, four CCD chips align in a square with narrow gaps between them. Each CCD chip has $420 \times 422$ pixels, and the size of one pixel is $27 \ \mu m \times 27 \ \mu m$. The CCDs are front-side illuminated. The imagers are made of $6.5 \ \Omega \cdot cm$ $p$-type float-zone silicon for depletion depth of about $30 \ \mu m$, which limits the high-energy efficiency. On the other hand, the low-energy cutoff is determined by the thickness and the structure of the electrodes. The detection efficiency is shown in Figure 3.9 as a function of incident energy. The dimensions of one CCD chip are $11 \ mm \times 11 \ mm$, thus the field of view of the SIS at the focal plane is $22' \times 22'$. In flight, the CCDs are cooled to a stabilized operating temperature of about $-60^\circ C$. Design parameters and basic performance of the SIS are summarized in Table 3.2.

X-rays reflected by the XRT are absorbed in a depletion layer through photo-electric absorption. The photo-electron generates electron-hole pairs through ionization and excitation processes. Since the number of pairs is proportional to the energy of incident X-rays, we can measure the X-ray energy by measuring the number of electron-hole pairs. The energy resolution is determined by a fluctuation of the number of electron-hole pair, and read-out noise. Therefore, the energy resolution can be expressed as

\[
\frac{\Delta E}{W} \text{ (FWHM)} \sim 2.35 \sqrt{N^2 + \frac{FE}{W}},
\]

where $E$ is the energy of incident X-ray, $N$ is the equivalent read-out noise in unit of the number of electrons, $F$ is the Fano factor, and $W$ is the mean energy to produce one electron-hole pair. For the SIS, $N \sim 5$, $F \sim 0.12$, and $W \sim 3.65 \ eV$. Thus, SIS achieved superior good energy resolution of $\sim 2\%$ at $5.9 \ keV$, as given in Figure 3.9 as a function of incident photon energy.

#### 3.3.2 On-board data processing of the SIS

Various modes are available for observing a source with the SIS, the choice depending on source brightness, the extent of the source and the time resolution desired. The SIS mode has two aspects; the clocking mode (or CCD mode), which determines how the CCDs are read out, and the data mode, which determines how the charge cloud created by a photon is described.

The SIS CCDs are operated in what is known as “frame-transfer” configuration. Each CCD is divided into two areas, the imaging area, which is exposed to the X-ray optics, and the readout area, which is shielded. Each imaging-area pixel has a corresponding pixel in the readout area to which the charge is transferred (in 16 ms). Once transferred, the charge resides in the readout pixel until the pixel takes its turn to be read out. Readout is effected by applying pulses of voltage (“clock” pulses) across the CCD which move the charge packets - row by row, pixel by pixel - to the amplifier. Reading out an entire
Table 3.2: Design parameters and characteristics of the ASCA SIS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination method</td>
<td>Front-side illumination</td>
</tr>
<tr>
<td>Transfer method</td>
<td>Frame store method</td>
</tr>
<tr>
<td>Gate and clock</td>
<td>3-phase drive</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>horizontal $420 \times 422$ (Imaging region)</td>
</tr>
<tr>
<td>Pixel size</td>
<td>$27 \mu m \times 27 \mu m$: Imaging region; equal to positional resolution</td>
</tr>
<tr>
<td></td>
<td>$18 \mu m \times 24 \mu m$: Frame store region</td>
</tr>
<tr>
<td>Area of chip</td>
<td>$11 \text{mm} \times 11 \text{mm}$ : 1chip</td>
</tr>
<tr>
<td>Field of view</td>
<td>$22' \times 22'$ : 4chip</td>
</tr>
<tr>
<td>Time resolution</td>
<td>4–16 sec : faint and bright mode</td>
</tr>
<tr>
<td></td>
<td>16 msec : fast mode</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>$2%(@6 \text{keV})$</td>
</tr>
<tr>
<td>Purity of substrate</td>
<td>$6.5 \text{k}\Omega \text{cm}$ : depletion layer $\sim 25–30 \mu m$</td>
</tr>
<tr>
<td>Energy band</td>
<td>$0.4–10 \text{keV}$</td>
</tr>
<tr>
<td>Operation temperature</td>
<td>$-61^\circ \text{C}$</td>
</tr>
</tbody>
</table>

Figure 3.8: (left) Cross section view of the SIS. (right) Alignment of the CCD chips in the SIS
Figure 3.9: Performance of the SIS. Left panel represents the detection efficiency and right panel represents the energy resolution plotted for different read-out noise N, noted by the equivalent number of electrons.

CCD in this way takes 4 seconds (the slower the readout, the lower the readout noise). Each SIS camera has four CCDs, and the time resolution is determined by the ordering of the imaging/readout cycles of the four CCDs. The clocking mode corresponds to this ordering, and broadly divided into three patterns; 1 CCD, 2 CCD, and 4 CCD modes, where 1, 2, and 4 represents the number of chips to be read out. In addition, a special clocking mode known as the “parallel sum mode” is used in conjunction with FAST mode.

Typically, the charge cloud produced by an X-ray photon is not localized to one pixel but spread out over several pixels. There are three basic data modes, FAINT, BRIGHT and FAST mode. These modes correspond to three different schemes of analyzing and telemetering this spread to the ground, as summarized in Table 3.3 and mentioned below.

**FAINT mode** In this mode, the pixel position of the center of the event is given, along with the pulse height recorded in the nine pixels around it (central pixel plus eight surrounding pixels in a $3 \times 3$ sq-pixel grid). The pulse height is converted into integer values of 12 bits length (hereafter PH data), thus the SIS spectra in this mode have 4096 channels.

**BRIGHT mode** SIS spectra in this mode have 2048 channels. The compression of channels, compared with FAINT mode, is achieved by binning up channels 1024–2047 by a factor of two and channels 2048–4095 by a factor of four. The pixel position of the center of the event is given, together with the grade, which describes the nature of the spread as defined in Figure 3.10. The total pulse height above an adjustable threshold is also recorded.

**FAST mode** This mode implies the use of “parallel sum” clocking mode. One CCD is exposed and charges are continually transferred (every 15.625 ms). This mode sacrifices position information for temporal resolution. Events are time-tagged with a precision of 15.625 ms, with only 1 bit for spatial information (whether an event was “inside” or “outside” the selected region). There are 2048 channels in FAST mode spectra (same binning as BRIGHT mode), with a 1-dimensional version of grade.
To eliminate events due to charged particles and to attain the expected energy reso-
lution, X-ray events in the depletion layer from each readout are identified and classified.
The first step in finding an X-ray event is to apply the criterion that the central pixel of
a $3 \times 3$ sq-pixel block must have the highest pulse height. In FAINT Mode, if the pulse
height of a pixel which satisfies this criterion is higher than the event threshold, the pulse
heights of the $3 \times 3$ sq-pixel block will be sent to the ground. In BRIGHT Mode, the
eight pixels around the central pixel will be compared with the split event threshold which
is lower than the event threshold. Based on the distribution of the pixels which have a
pulse height higher than the split event threshold, the event is classified, i.e., assigned a
grade. There are eight pattern of grades, which are extensions of four basic groups: S
(single), P (single-sided split; subdivided into Vertical, Left and Right), L (L-shaped) and
Q (square-shaped). The extensions arise because of the existence, in some events, of cor-
ner pixels which do not belong to the block since they touch the distributions only at the
corners (so-called “detached” corners). The definition of grades are shown in Figure 3.10.
Usually, on-board BRIGHT mode telemetry includes events with grades 0–6, and at the
stage of the ground data processing, grade 1, 5, and 6 are thrown out as non X-ray events.

In FAST mode, a simpler version of grade is used: FAST mode grade 0 corresponds
to BRIGHT mode grades 0 and 2, i.e., to good data. FAST mode grade 1 corresponds
to all other BRIGHT mode grades, i.e., to the remaining good plus the bad grades.

<table>
<thead>
<tr>
<th>Table 3.3: Summary of the SIS modes.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observation mode</strong></td>
</tr>
<tr>
<td>Time resolution</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Event transfer rate</td>
</tr>
<tr>
<td>(events/sec/(S0+S1))</td>
</tr>
<tr>
<td>Number of bits for PH channels</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of bits for event position</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of Grade patterns</td>
</tr>
</tbody>
</table>

### 3.3.3 Summary of issues related to the SIS date reduction

**Hot and flickering pixels**

Each CCD chip in the two SIS cameras has a small number of catalogable pixels which
have a higher than normal dark current, namely “hot pixels”. Even though the number
of these pixels is small as a percentage of the array total, each such pixel produces a
false event which is not rejected by the on-board digital processor and is telemetered. In
addition, there is also a class of “flickering pixels”. As implied by the name, they are
not persistent like the hot pixels, but repeat with a variety of duty cycles on time scales
typically ranging from minutes to days. The flickering pixels are thought to be a symptom
Figure 3.10: Definition of grades of events. Grade 7 corresponds to all other patterns.
of radiation damage. As a result, the rates of flickering pixels show a secure increase, and are causing severe problems of telemetry saturation in many modes. Since the flickering pixels are caused by an accumulation of dark currents, the longer the integrate time, the higher the probabilities are that a charge in a given pixel will exceed the event threshold. Thus the flickering pixel problem is most severe in the 4-CCD mode, whereas in the 1-CCD mode, their rate remains relatively unchanged since launch. Therefore, most of recent observations are operated in the 1-CCD mode.

True X-ray photons are spread over many pixels of the CCDs, because of the vast oversampling of the XRT PSF. Therefore, for a typical observation, the total number of X-ray photons detected in each pixel remains small. In contrast, hot pixels and the more active flickering pixels are “detected” far more often than the surrounding pixels that received a similar X-ray flux. Therefore, the hot and flickering pixels can be rejected by comparing the number of events with that of surrounding pixels.

On the other hand, it is impossible to exclude very low duty cycle flickering pixels. Combined with the fact that the flickering pixel rate is increasing, this may lead to an imperfect subtraction of background. For example, if the PV phase blank sky field is used as background for a more recent observation (particularly of low surface brightness extended objects), it may result in a spurious low-energy excess. Despite this, for most observations, the practical effects of hot and flickering pixels is limited to the danger of telemetry saturation.

**Echo effect**

Echo effect is a phenomenon that a small fraction of a charge in a pixel is added to a pixel which is read out next, i.e., a right-hand pixel. The fraction is called “echo fraction” and shows a secure increase of unknown origin. Echo effect arises in the analog electronics on-board and would lead a wrong measurement of energy or misassignment of grade. Thus, one should correct this effect or use a response matrix taking into account the echo phenomenon. For FAINT mode data, the grade and PH (related to energy) of each event can be easily corrected because in this mode the pulse height of a $3 \times 3$ sq-pixel grid is recorded. For BRIGHT mode data, it is impossible to correct the echo effect event-by-event. Instead, the echo effect is accounted for by using detector response functions, when analyzing the spectrum, which have the aggregate effect built in.

**Dark frame error (DFE) and residual of dark distribution (RDD)**

Even when no events – photons or particles – are detected, a small amount of charge flows through the CCDs. This residual level is called dark frame level and must be subtracted from PH values to derive their true values. The dark frame level varies across each chip and depends on the radiation environment of the instrument. Because of these dependencies, the on-board computer calculates a coarse map of the dark frame for each chip. However during the course of the PV phase, it was discovered that the on-board calculation of this level is not always accurate. The uncertainty, known as the dark frame error (DFE), arises from incomplete estimation of dark level on board.

The dark frame is calculated on board by averaging pixels with PH values between -40 and +40 ADU (1 Analog-Digital Unit is about 3.5 eV). If the distribution of dark current around the dark level, namely Residuals of Dark Distribution (RDD), is symmetrical
around 0, the value calculated by the method above would give an accurate indication of the true dark level. However, radiation damage has produced a population of pixels with higher dark currents (the extreme of which are detected as flickering pixels), thus skewing the RDD, as shown in Figure 3.11, and lead wrong estimation of dark frame. In addition, when fluctuations in the dark frame occur on time scales less than the averaging period, further miscalculation of the dark level occurs. For example, DFE jumps sharply at the transition between satellite day and night, and returns exponentially to the pre-jump level as the on-board software updates the dark frame.

Since DFE causes wrong measurement of pulse height or misassignment of grade, it should be corrected or taken into account. For FAINT mode date, DFE is corrected by examining the PH distribution of the corner pixels of each 3 x 3 sq-pixel event. Only grades 0, 2, 3 and 4 are used because the corner pixels of these grades are not thought to contain charge due to X-rays or particles, i.e., they represent the true dark level. For BRIGHT mode data, the effect of DFE is built in the response matrices. Although DFE is small, its maximum value of about 0.07 keV means that it should not be neglected in studies of spectral line features. For such observation, the operation with FAINT mode is recommended.

![Figure 3.11: Distribution of pixel levels of corner pixels, which represents a distribution of pixel levels of pixels with no incident particle. One can clearly see the asymmetric distribution.](image)

Effects of RDD and correction

As described above, the RDD is asymmetry around 0. This is mostly because of the spatially distribution of dark currents over a chip. While the dark current of each pixel is distributed rather symmetry around its dark level, the dark level differs from chip to chip, hence produces the asymmetric RDD.

RDD can lead to mis-classification of event. For example, a grade 0 event may be recognized as a higher grade event when a neighboring pixel is very active. For higher grades, this effect is worse and can even result in a true photon event being classified as grade 7, i.e., as a rejected particle event. Thus RDD causes the effective quantum
efficiency of the SIS to become lower. In addition, RDD degrades the spectral resolution, since the PH value may be incorrect depending on the level of dark current, even if the grade is correctly determined. When mis-classification of event is involved, the error in the resultant PH value can be even larger. The amount of dark current depends on the readouts time, hence the effect of the RDD is more significant in the 4 CCD mode than in the 2 CCD and 1 CCD modes.

It appears that each pixel of each chip of SIS has a characteristic dark current level, which is stable over several months, resulting in a similar dark charge level for a given clocking mode. Therefore we can estimate the spatial distribution of dark currents called "RDD map", and can correct RDD to FAINT mode data.

3.4 Gas Imaging Spectrometer (GIS)

3.4.1 Overview of the GIS

The Gas Imaging Spectrometer (GIS; Ohashi et al. 1996, Makishima et al. 1996) has been developed by the University of Tokyo (Department of Physics), ISAS, Tokyo Metropolitan University (Department of Physics), Meisei Electronic Co. Ltd., and Japan Radio Company, with collaborators at Institute of Physical and Chemical Researches (RIKEN), Kyoto University (Department of Physics), and NASA/Goddard Space Flight Center (GSFC). The design of the GIS is mainly based on the GSPC experiment on-board Tenma (Koyama et al. 1984).

The GIS consists of two detector assemblies (GIS-S), namely GIS 2 and GIS 3, and the main electronics called GIS-E. GIS 2 carries small radiation-belt monitor (RMB) made of PIN diode detector. Apart from RBM, GIS 2 and GIS 3 are almost identical. The cross section view of GIS 2 is schematically shown in Figure 3.12. The weight is 4.30 and 4.16 kg for GIS 2 and GIS 3, respectively. Each of them consists of a detector assembly and high-voltage supply units. The detector assembly is made up from a gas cell, an imaging photomultiplier tube (IPMT), and front-end electronics. The top section is a hood, which limits the field of view of GIS into the mirror direction. In order to prevent plasmas from entering into the gas cell section, an aluminized mylar film of 0.5 µm thick with 300 Å of aluminium is placed inside the hood. The middle section accommodates the gas cell and the photomultiplier tube, and the bottom section holds the front-end electronics. The X-ray performance of the GIS is summarized in Table 3.4.

Table 3.4: Characteristic of ASCA GIS experiment.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy-range (10% efficiency)</td>
<td>0.7–20 keV(^a))</td>
</tr>
<tr>
<td>Effective area</td>
<td>50 mm diameter</td>
</tr>
<tr>
<td>Energy resolution (5.9 keV)</td>
<td>8% FWHM ((\propto E^{-0.5}))</td>
</tr>
<tr>
<td>Position resolution (5.9 keV)</td>
<td>0.5 mm FWHM ((\propto E^{-0.5}))</td>
</tr>
<tr>
<td>Non X-ray background (2–10 keV)</td>
<td>(\sim 6 \times 10^{-4}) c s(^{-1}) cm(^{-2}) keV(^{-1})</td>
</tr>
<tr>
<td>Time resolution</td>
<td>61 µs (maximum)</td>
</tr>
<tr>
<td>Source intensity</td>
<td>(\leq 20) Crab flux</td>
</tr>
</tbody>
</table>

\(^a\) The upper bound becomes 10 keV when combined with the XRT.
3.4.2 The sensor system and the process of X-ray detection

Each sensor system of the GIS is broadly divided into two parts; gas cell and imaging photomultiplier tube (IPMT). The structure of them is shown in Figure 3.13.

Gas cell

The gas cell is made of a ceramic cylinder of 92 mm inner diameter with a beryllium entrance window and a quartz exit window, filled with a mixture of xenon (96% volume) and helium (4%) at 1.20 atm at 0°C. Inclusion of helium slightly raises the drift velocity of electrons and helps to find a very small leak with leak detector.

The gas volume is divided by a mesh electrode into two parts, the drift region in the top 10 mm and the scintillation region in the bottom 15 mm. X-ray reflected by the XRT enter through the window, whose potential is held at −6 kV, and are absorbed in the drift region. The electron cloud, created through the photon-ionization and the subsequent ionization process with a mean potential of 21.5 eV per electron, slowly drifts to the first mesh (−5.3 kV). The cloud is then accelerated due to the strong field toward the ground mesh which is placed just above the quartz window. The electrons excite xenon atoms and produce a large number of UV photons whose wavelength is about 170 nm. Through the quartz window, these UV photons are collected by the IPMT which measures light distribution and the overall intensity of the UV flux, which is proportional to the X-ray energy. The multiplication process does not involve the electron avalanche like ordinary proportional counters, thus results in a good energy resolution.

The sensitivity for soft X-rays has been dramatically improved compared with previous gas counters, by using X-ray entrance window made of 10 μm thick beryllium foil. The window has a 35% transmission at 1.0 keV, and the opening area is 52 mm in diameter. The window support is made of a thin molybdenum grid plated with copper, and a
stainless steal mesh coated with tin is placed between the grid and the beryllium foil to provide a fine support.

A weak radioactive isotope, $^{55}\text{Fe}$, with a pre-launch counting rate of about $0.3 \text{ c s}^{-1}$ is mounted at the edge of the X-ray entrance window for each detector. This source continuously radiates the detector $5.9 \text{ keV}$ X-rays and helps to monitor the detector gain and the rise-time properties.

When X-rays are properly absorbed in the drift region, all the signal should exhibit a rise time (RT) of about $2.8 \mu\text{s}$ which corresponds to the drift time of electrons in the scintillation region. Particle events creating a long ionization track in the drift region exhibit longer RTs. Events penetrating the drift region and stopped in the scintillation region produce short rise-time signal. Compton scattered electrons by gamma-rays in the ceramic wall produce signals with rather long RT since the electric field near the wall is weak. In this way, RT discrimination can efficiently remove the non X-ray background.

**Imaging photomultiplier tube**

The X-ray photons absorbed in the gass cell causes UV light emission from the scintillation region. The shape of the light source is a straight line over the length of the scintillation region, and the emission continues $2-3 \mu\text{s}$. Hamamatsu Photonics type R4268 is employed as the position-sensitive phototubes (IPMT). The phototube is equipped with a 3-inch quartz window of 3 mm thickness and 10-stage dynodes. Since each dynode has a grid shape with about 50% transmission, the size of the electron cloud during the multiplication process is fairly confined. This feature enables the position determination using the cross-wire anodes.

The anode has a cross-wire configuration with 16 wires running in each X and Y direction at an interval of 3.75 mm. The position information is obtained from the charge distribution among different anodes, and the pulse height (PH) and the RT information are taken from the last dynode which gives a signal of opposite polarity. The intrinsic position resolution of the phototube is measured to be about 0.1 mm FWHM.

**3.4.3 On-board data processing of the GIS**

The outline of the signal processing in the GIS system is schematically shown in Figure 3.14. The front-end processing is carried out within the GIS sensor part (either GIS 2 or GIS 3), which is followed by a detailed evaluation in the main electronics section (GIS-E).

The pulse-height signal taken from the IPMT last dynode is integrated with a front-end charge-sensitive amplifier and transmitted to GIS-E. In GIS-E, the signal goes to pulse-height and RT ADCs. The RT data is used for background rejection. The position information is obtained from the 32 (16 each X and Y) anode signals. The resultant digital signals are transferred to the CPU for the calculation of the X-ray position.

In the analog processing part in GIS-E, each detected event within the proper PH vs. RT region yields 32 position data (16 each in x and y direction) with 8 bits each, 12-bit PH data, and 12-bit RT data. These position information together with the PH and RT information are analyzed with the on-board CPU. Two major tasks of the CPU are the calculation of the event position and the background rejection. First, two-dimensional position for X-ray events are calculated from the light distribution given by the 32 anode
signals. Second, the width of the light distribution obtained in the course of the position calculation can be used to further discriminate non-X-ray events. Particles penetrating in the gas cell will produce electron clouds with a large lateral extent. The CPU can effectively discriminate those events when the light spread is larger than the X-ray events. The other typical type of background is the wall events, which show light distribution peaked as the edge of the detector. These are considered mostly Compton knock-on electrons from the detector wall produced by charged particles. The shape of the light distribution, i.e. a monotonous rise of the X-ray sensitive region, tells these background events.

The GIS system has three telemetry modes. The standard telemetry mode, in which most of the observations have been carried out, is the PH (pulse-height) mode. In this mode, each X-ray event is transmitted as a 32-bit word train. The items contained in a word train are detector ID (1), PH (10), X and Y positions (8 each), RT (5), photon spread (0), and timing information (0). The numbers in parentheses show the number of bits in the standard setting, and the bit assignments can be varied. The highest time resolution available (for 10 bits of timing information) is 61 µs in the high bit rate. The maximum count rates observable in the PH mode and the time resolution are summarized in Table 3.5.

Other two modes are PCAL mode and MPC mode. The PCAL mode is used for a diagnostic purpose. In this mode, all of the 32 PHs of the anodes are transmitted. The read out speed is factor of 8 slower than the PH mode. This mode enables position determination in the ground and can be used in the case of a CPU failure. In the MPC mode, pulse-height spectra are accumulated on board with no positional information. The maximum observable intensity in this mode is a factor of several hundred higher than that in the PH mode, and can be used when one observes unusually bright (more than 10 times the Crab Nebular) X-ray source.
Table 3.5: Characteristic of GIS data in the PH mode.

<table>
<thead>
<tr>
<th>Bit rate</th>
<th>Maximum flux(^a)</th>
<th>Time resolution for # of timing bit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( c \text{s}^{-1} )</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>128</td>
<td>62.5 ms</td>
</tr>
<tr>
<td>M</td>
<td>16</td>
<td>500 ms</td>
</tr>
<tr>
<td>L</td>
<td>4</td>
<td>2s</td>
</tr>
</tbody>
</table>

\(^a\) Count rate for the two GIS detectors.

Figure 3.14: The block diagram of the electronics system.
3.5 Background

The background of both the SIS/GIS consists of Cosmic X-ray background (CXB) and non-X-ray background (NXB). The CXB is isotropically arriving cosmic-origin X-ray events, and considered to be a superposition of faint extragalactic sources (Ueda 1996, Ishisaki 1996), whereas the NXB is detector-origin events mainly caused by charged particles and $\gamma$-rays. Thus, we can reduce the NXB, for both the SIS and the GIS, by restricting the geomagnetic cut-off rigidity (COR) which the spacecraft experiences.

For the SIS, the NXB can be reduced effectively by applying the grade selection, as mentioned in § 3.3.2. The SIS NXB is grossly divided into two components, that accumulated on the imaging region and on the frame store region. The first component is proportional to the sky exposure time, while the second proportional to the number of readouts, thus depends on the SIS clocking mode. Because of this second component, the NXB count rate in the 4-CCD mode exceeds that in the 1-CCD mode by a factor of $\sim 1.2$. Moreover, due to the radiation damage, the NXB level has been increased especially in the soft energy band, as mentioned in § 3.3.3. Thus, the SIS background level depends both on the clocking mode and the date of the observation.

We can remove the GIS NXB effectively by applying the RT screening, as described in § 3.4.3. Since the RT distribution broadens significantly for lower values of PH, as indicated in Figure 3.15, only the coarse RT windows is set in-orbit. Further reduction of the NXB is achieved by applying a tighter RT cut on ground. For a limited number of observations, the RT information is sacrificed, for example, to improve the time resolution. For such a case, we cannot apply off-line RT cut. Although the GIS background level has been increased gradually (e.g., $\sim 10\%$ in the first two years after Ishikaki 1996), the effect is negligible for ordinary observations, and we show an example of the GIS background spectra in Figure 3.16.
Figure 3.15: (Left panel) An example image of a celestial X-ray point source, obtained with GIS-S2 in an early observation. No background rejection was applied, except for the pulse-height upper-discriminator. An event concentration near to the detector rim is partly due to a background enhancement, and partly due to a position non-linearity. (Right panel) X-ray event contained in the image of the left panel, displayed on the plane of PH vs. RT. The two horizontal lines represent the standard on-board RT discriminator window. Both figures are taken from Makishima et al. (1996).

Figure 3.16: Typical GIS spectra averaged of the two detectors, taken from Makishima et al. (1996). One spectrum, denoted Night Earth, was obtained in night-earth pointing and represents NXB. Another, denoted Blank Sky, was obtained in blank-sky observation, and consists of NXB plus CXB. The other (Day earth) is from day-earth pointings, containing NXB plus solar X-rays scattered off the atmosphere.
Chapter 4

OBSERVATION

Hereafter, we analyze the ASCA data of ULXs, in order to reveal their nature. In this chapter, we select targets, describe their ASCA observations, and summarize their properties so far reported.

4.1 Sample Selection

The first step of studying ULXs is to select targets. As mentioned in § 2.6, the spectral analysis have already been performed by several authors on some ULXs observed with ASCA. However, the attempted spectral models, as well as the utilized detector response functions, vary from authors to authors. Moreover, although some ULXs have been observed twice or more, only the result of the first observation has been published for most of them. We hence analyze not only the unreported sources, but also those for which the results of the spectral analysis have already been published, in order to obtain a unified understanding of ULXs.

By 1999 April, about 100 galaxies (not including AGNs) had been observed by ASCA. We first selected galaxies based on Table 2.1, a list of ULXs observed by Einstein, taking advantage of its high spatial resolution. Fortunately, all of the galaxies tabulated in Table 2.1 had been observed by ASCA and their data were available; they are either in archive, or accessible by the present author because he is included as a co-investigator. Among them, we chose galaxies where ULXs are clearly separated from neighboring sources in the ASCA image, in order to obtain the spectra free from contamination. We hence excluded galaxies having complex X-ray morphology, i.e., NGC 3034 (M82), NGC 4258, NGC 5194 (M51), NGC 5236 (M83), and NGC 5457 (M101). Next we searched galaxies, from the remaining ones, which host off-nucleus luminous sources in the ASCA image. After excluding elliptical and S0 galaxies as well as spirals which host an LLAGN, ∼20 spirals remained to be promising. We performed visual inspection on these galaxies, and picked up Dwingeloo 1 and NGC 4565; both had already been reported to host ULXs by Reynolds et al. (1997) and Mizuno et al. (1999). We also included NGC 1365 to our sample galaxies. Although this galaxy hosts an LLAGN, a newly appeared luminous source can be separated from the nucleus in the ASCA image, as reported by Iyomoto et al. (1997).

As mentioned in § 2.5.3, one of the possible explanations of ULXs is X-ray bright SNRs. Thus, we also analyze X-ray luminous SNRs for comparison. Among our sample galaxies, NGC 1313 hosts an X-ray luminous SNR, SN 1978K, and NGC 6946 has the
brightest source at its north-arm region, which were identified as an SNR based on the positional coincidence by Schlegel et al. (1994). We also added NGC 891 to our sample galaxies, since this object is known to have X-ray luminous SNR, SN 1986J (Houck et al. 1998). Hereafter we analyze these SNRs as well as ULXs. In § 6.9, we compare spectral properties of ULXs with those of the securely identified extragalactic SNRs, to investigate whether they have common properties or not. All of our sample galaxies are summarized in Table 4.1, and the properties of host galaxies as well as those of involved ULXs (and SNRs) are mentioned in the next subsection.

We end this section by describing the sample completeness. As already mentioned above, the number of galaxies (without AGN) ASCA has already observed is up to only \(\sim 100\), apparently much smaller than that of galaxies themselves; e.g., in a catalogue of Tully (1988), \(\sim 800\) galaxies located within 20 Mpc are listed. In addition, ASCA observation is usually based on the X-ray detection of the targets by the previous missions such as Einstein and ROSAT. Hence, ASCA observations of galaxy cannot be either complete or unbiased. However, our selection of ULXs is mostly based on the observation by Einstein Observatory. This was the first X-ray satellite with imaging instruments, so that its sample selection was relatively unbiased. We therefore regard our sample objects as a relatively good representation of whole ULXs, although we do not claim the completeness of our sample.

Table 4.1: ASCA observational log of the host galaxies

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Type(^a)</th>
<th>Distance(^b) (Mpc)</th>
<th>Galactic (N_H) ((10^{22}\text{cm}^{-2}))</th>
<th>Date(^c) yymmd</th>
<th>Exposure (ks)(^d)</th>
<th>SIS Mode(^e)</th>
<th>Clock(^f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 598 (M33)</td>
<td>Scd</td>
<td>0.72</td>
<td>0.06</td>
<td>93 07 22</td>
<td>15.4</td>
<td>17.4</td>
<td>F/B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>93 07 23</td>
<td>14.6</td>
<td>17.7</td>
<td>F/B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94 01 21</td>
<td>44.7</td>
<td>49.0</td>
<td>F/B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>96 01 29</td>
<td>51.7</td>
<td>56.2</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95 11 29</td>
<td>33.2</td>
<td>32.9</td>
<td>F/F</td>
</tr>
<tr>
<td>NGC 891</td>
<td>Sb</td>
<td>9.6</td>
<td>0.07</td>
<td>94 08 12</td>
<td>8.1</td>
<td>9.1</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95 01 25</td>
<td>34.0</td>
<td>36.9</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>97 10 29</td>
<td>26.5</td>
<td>29.1</td>
<td>F/B</td>
</tr>
<tr>
<td>NGC 1313</td>
<td>Sd</td>
<td>4.5</td>
<td>0.035</td>
<td>93 07 12</td>
<td>21.2</td>
<td>27.7</td>
<td>F/B</td>
</tr>
<tr>
<td>NGC 1365(^f)</td>
<td>Sb</td>
<td>18.3</td>
<td>0.014</td>
<td>94 08 12</td>
<td>8.1</td>
<td>9.1</td>
<td>F/F</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>Scd</td>
<td>3.2</td>
<td>0.04</td>
<td>94 04 01</td>
<td>31.6</td>
<td>37.6</td>
<td>F/F</td>
</tr>
<tr>
<td>NGC 3031 (M81)</td>
<td>Sab</td>
<td>3.6</td>
<td>0.04</td>
<td>94 10 21</td>
<td>37.4</td>
<td>46.0</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95 04 01</td>
<td>17.6</td>
<td>19.7</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95 10 24</td>
<td>34.5</td>
<td>37.3</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>96 04 16</td>
<td>43.2</td>
<td>47.7</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>96 10 27</td>
<td>27.8</td>
<td>31.0</td>
<td>F/F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>97 05 08</td>
<td>41.0</td>
<td>48.9</td>
<td>F/F</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>Sb</td>
<td>7.7</td>
<td>0.02</td>
<td>93 12 12</td>
<td>21.0</td>
<td>23.1</td>
<td>B/B</td>
</tr>
<tr>
<td>NGC 4565</td>
<td>Sb</td>
<td>10.4</td>
<td>0.013</td>
<td>94 05 28</td>
<td>30.8</td>
<td>34.5</td>
<td>F/F</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>Scd</td>
<td>5.5</td>
<td>0.2</td>
<td>93 05 31</td>
<td>20.6</td>
<td>26.4</td>
<td>F/B</td>
</tr>
<tr>
<td>IC 342</td>
<td>Scd</td>
<td>3.9</td>
<td>0.3</td>
<td>93 09 19</td>
<td>35.8</td>
<td>38.4</td>
<td>F/B</td>
</tr>
<tr>
<td>Dwingeloo 1</td>
<td>Sbc</td>
<td>3.0</td>
<td>0.7</td>
<td>95 09 14</td>
<td>36.1</td>
<td>38.9</td>
<td>F/F</td>
</tr>
</tbody>
</table>

\(^a\) Taken from Tully (1988) except for Dwingeloo 1, which is classified as Scb or Sc by Kraan-Korteweg et al. (1994).
\(^b\) The distance is taken from de Vaucouleurs (1963) for NGC 1313, Silbermann et al. (1999) for NGC 1365, Freedman & Madore (1988) for NGC 2403, Freedman et al. (1994) for M81, and Tully (1988) for all other galaxies except for NGC 4565, for which we adopted the weighted mean of three independent distance indicators after Mizuno et al. (1999). (see § 7.3.1)
\(^c\) Observation start date. Although M81 have been observed 18 times till today, we utilized the last seven observations whose data is archived in 1999 April (see also § 6.4). Thus we tabulate here only these seven observations.
\(^d\) An average of two SIS sensors or two GIS sensors, after the data screenings (§ 5) are applied.
\(^e\) Clocking mode of S0 for Bit-H/Bit-M.
\(^f\) GIS bit assignment for Bit-H/Bit-M (PH-X-Y-RT-SP-Time) is 8-8-8-0-0-7/8-8-8-0-0-7 for NGC 1313 in the 1995 observation, and 8-8-8-0-0-7/8-6-6-0-0-10 for M81 in the last three observations.
4.2 Properties of Our Sample Objects

NGC 598  As already mentioned in §2, this galaxy has the brightest source in the Local Group galaxies at its nucleus, namely M33 X-8, and Takano et al. (1994) analyzed the spectra of this ULXs obtained with ASCA. They discovered that its spectra are well represented by the power-law plus MCD model of $T_{\text{in}} \sim 1$ keV, and suggested that the source is a close binary system containing a black hole of $\sim 10 M_\odot$ (§ 2.6.1). We re-analyze its spectra in § 6.3.

NGC 891  This galaxy is an almost perfectly edge-on spiral like NGC 4565. SN 1986J was first discovered in the radio band (Rupen et al. 1987), and its first X-ray observation was performed in 1991 by ROSAT. Houck et al. (1998) reported, based on its X-ray data obtained by ROSAT and ASCA, that the supernova flux decreased in proportion to $t^{-2}$. They also detected Fe-K line at $\sim 6.7$ keV in the spectrum obtained with ASCA. We re-analyze the ASCA spectra of SN 1986J in § 6.9 together with other luminous SNRs.

NGC 1313  This is a nearby face-on, late-type Sb galaxy at a distance of 4.5 Mpc (de Vaucouleurs 1963). X-ray observations using Einstein Observatory, ROSAT, and ASCA (Fabbiano & Trinchieri 1987; Colbert et al. 1995; Miller et al. 1998; Petre et al. 1994) showed that its X-ray emission is dominated by three extremely luminous point-like sources of $L_X \sim 10^{39}$ erg s$^{-1}$ each. One of them is an X-ray luminous supernova, namely SN 1978K. We call the other two ULXs as source A and source B after Petre et al. (1994), the former located close ($\sim 45''$) to the galaxy nucleus. We describe source A and source B in § 6.6 and § 6.5, respectively, and SN 1978K in § 6.9.

NGC 1365  This is a bright barred spiral galaxy in the Fornax cluster. Silbermann et al. (1999) estimated the distance to be 18.3 Mpc by observing its Cepheids with the Hubble Space Telescope (HST). Iyomoto et al. (1997) observed this galaxy twice with ASCA. They detected Fe-line emission from the nucleus, and confirmed that this galaxy hosts an obscured AGN. They also reported that a very luminous source of $L_X \sim 10^{40}$ erg s$^{-1}$ newly appeared in the second observation, located at the south-west of the nucleus with a separation of $\sim 1'2$. Komossa and Schulz (1998) studied long-term variability of this source with ROSAT. We focus on the newly discovered SW source, and re-analyze its spectrum in § 6.8.

NGC 2403  The nearby Sc galaxy NGC 2403 is a member of the M81 group (Tamman & Sandage 1968). The distance to this galaxy was estimated to be $\sim 3.2$ Mpc by observing its Cepheids (Freedman and Madore 1988). With the Einstein Observatory Fabbiano & Trinchieri (1987) detected three point-like sources of $L_X = 10^{38-39}$ erg s$^{-1}$, called source 1, source 2, and source 3. We analyze the ASCA spectrum of the brightest one, source 3, in § 6.8.

NGC 3031 (M81)  This object is a nearby early-type spiral galaxy with a prominent bulge and well-defined spiral arms, and has a Cepheid-based accurate distance of 3.6 Mpc from the HST observations (Freedman et al. 1994). Fabbiano (1988) observed this galaxy with Einstein and detected several sources, including the brightest one, called X-5, at the nucleus. Using ASCA, Ishisaki et al. (1996) confirmed that X-5
is a typical LLAGN of $L_X \sim 10^{40}$ erg s$^{-1}$, exhibiting a hard power-law continuum and a weak Fe-K line. The most luminous off-nucleus source is called X-6, and has a luminosity of $L_X \sim 1 \times 10^{39}$ erg s$^{-1}$. Uno (1996) reported that its spectrum in the 1994 observation can be represented by an MCD model of $T_{\text{in}} \sim 1.5$ keV. Due to the explosion of SN 1993J in M81, ASCA has frequently observed the M81 region (Kohmura et al. 1994; Kohmura 1994; Uno 1997). We analyze the spectra of M81 X-6 in § 6.4, particularly focusing on its long-term variability.

NGC 3628 This galaxy, a member of the Leo Triplet of galaxies, is viewed nearly edge-on ($\sim 80^\circ$) and classified as a starburst galaxy on the basis of its strong, warm far-infrared emission (Rice et al. 1988). Fabbiano et al. (1990) observed this galaxy with Einstein and detected an off-nucleus source with $L_X \geq 10^{39}$ erg s$^{-1}$. Yaqoob et al. (1995) obtained the spectrum of this source with ASCA, and reported that it can be represented by a power-law model of $\Gamma \geq 2$. We re-analyze this ULX in § 6.8.

NGC 4565 This object, a member of the Coma I group, is an almost perfectly edge-on Sb galaxy similar in size to M31 and the Milky Way. Observation with ROSAT revealed two strong point-like sources of $L_X \geq 10^{39}$ erg s$^{-1}$, one at the nucleus while the other $\sim 1'$ above the disk (Volger et al. 1996). Mizuno et al. (1999) showed that their spectra can be represented by an MCD model of $T_{\text{in}} \sim 1.5$ keV. They argued that both objects are ULXs, even though one of them apparently coincides in position with the nucleus (§ 6.7).

NGC 6946 This is a face-on Scd galaxy and hosts a bright starburst nucleus (e.g., Telescope and Harper 1980). In X-rays this galaxy has a strong ($\geq 10^{39}$ erg s$^{-1}$) point-like source on its north arm (Fabbiano & Trinchieri 1987). Schlegel et al. (1994) observed the galaxy with ROSAT and identified this source as an X-ray luminous SNR based on the positional coincidence. We analyze its spectrum in § 6.9, together with SN 1986J in NGC 891 and SN 1978K in NGC 1313.

IC 342 This is a nearby starburst Scd galaxy, located close to the Galactic plane ($b \sim 10^\circ$). Fabbiano and Trinchieri (1987) observed it with Einstein and showed that its X-ray emission is dominated by three luminous point-like sources with $L_X \geq 10^{39}$ erg s$^{-1}$, called source 1, source 2, and source 3. Okada et al. (1998) obtained the 0.5–10 keV spectra of these sources and detected short-term variability from source 1, as mentioned in § 2.6.2. The central source, namely source 3, has been resolved into three separate sources in the ROSAT HRI image (Bregman et al. 1993, see also the image in Appendix C). Accordingly, we re-analyze the other two sources in this thesis; source 1 in § 6.2 and source 2 in § 6.8.

Dwingeloo 1 Kraan–Korteweg et al. (1994) newly discovered a spiral galaxy behind the Milky Way, namely Dwingeloo 1. Reynolds et al. (1997) observed this galaxy in 1995 for the first time in X-rays with ASCA, and found an off-center source (Dwingeloo 1 X-1) with $L_X \sim 10^{39}$ erg s$^{-1}$. We treat this ULXs in § 6.8.
Chapter 5

X-RAY IMAGES AND LIGHT CURVES OF ULXS

5.1 X-Ray Images of ULXs

In this section, we describe the reduction processes applied for the ASCA data, and investigate the obtained images to identify the involved ULXs. In order to study the source extent, we also use the ROSAT HRI data taking advantage of its high ($\leq 10''$) spatial resolution.

5.1.1 Reduction of the ASCA images

The original ASCA data collected on-board includes several types of false events that should be rejected in the course of data analysis to achieve a good signal-to-noise ratio. In most cases in this thesis, the screening process applied for the data is the same. Therefore we explain the process, applied for the data of NGC 1313 in the 1993 observation, as an example.

As mentioned in Chapter 3, the SIS data are contaminated by hot and flickering pixels. Figure 5.1a is the original SIS 0 image of NGC 1313 in the 0.5–10 keV energy band obtained in 1993 July. We can see hot and flickering pixels as black spots in the image, which obscure the real X-ray sources in the galaxy. These hot and flickering pixels can be removed by comparing the number of events with those of surrounding pixels (§ 3.3.3). Figure 5.1b is the image after removing the hot and flickering pixels.

Next, in order to achieve a good signal-to-noise ratio, the data should be screened to avoid the periods when the background level is uncomfortably high. This process is done by utilizing the orbital information of the satellite. In fact, we applied the following data-screening criteria:

1. The time after passage through the South Atlantic Anomaly (SAA) should be larger than 1 minute.

2. The object should be at least 10° above the night Earth’s limb. This is because the Earth’s outer atmosphere absorbs and/or scatters X-rays, hence distorts the spectrum.

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3. The object should be at least 20° above the bright Earth’s limb, since the SIS has sensitivity not only to X-rays but also to optical and UV radiation, due to a particle damage to the optical blocking filter.

4. The cutoff rigidity (COR) of cosmic rays should be larger than 6 GeV/c.

5. The time after day/night transition should be greater than 100 s. This is because the dark-frame level changes so rapidly when the satellite crosses the day/night boundary that the calculation of the dark level becomes wrong (see § 3.3.3).

Finally, the grade selection (§ 3.3.2) was applied to remove the remaining particle events. Figure 5.1c is the obtained SIS 0 image, where three sources are visible. We can see a significant improvement in signal-to-noise ratio.

Figure 5.1: SIS 0 image of NGC 1313 in the 0.5–10 keV band, observed in 1993 July. (a) The original image. (b) The image obtained after removing the hot and flickering pixels. (c) The finally obtained image after applying the data selection utilizing the orbital information and grade selection.

For the GIS, we first show in Figure 5.2a the image only after masking the calibration source and the detector rim, where the background level is high. The screening criteria are slightly looser than those of the SIS. Specifically, we applied the following criteria.

1. The time after the SAA passage should be larger than 1 minute.

2. The object should be at least 10° above the Earth’s limb.

3. The COR should be greater than 6 GeV/c.

As described in § 3.5, the on-board rise-time screening is relatively coarse. Thus, to remove the remaining particle events, we applied the tighter rise-time rejection, as well as the spread discrimination. The finally obtained image is shown in Figure 5.2b, which reveals the same three sources as detected with the SIS.

We summed thus obtained two SIS (SIS 0 and SIS 1) images into a single SIS image, and two GIS (GIS 2 and GIS 3) images into a single GIS image, and show them in
Figure 5.3b and 5.3c, each superposed on the optical image. There, three strong X-ray sources, corresponding to source A, source B, and SN 1978K, are seen. For other galaxies, we summarize the ASCA images in Appendix C. All ULXs of our interest are clearly seen in the ASCA SIS and/or GIS images.

(a) ![GIS 2 image of NGC 1313 in the 0.5–10 keV band, observed in 1993 July.](image)
(b) ![GIS 2 image of NGC 1313 in the 0.5–10 keV band, observed in 1993 July.](image)

Figure 5.2: GIS 2 image of NGC 1313 in the 0.5–10 keV band, observed in 1993 July. (a) The original image only after masking the calibration source and the detector rim. (b) The finally obtained image after applying the data selection utilizing the orbital information, rise-time rejection, and spread discrimination.

5.1.2 ROSAT HRI observations

Although the ULXs are clearly detected in the ASCA images (Appendix C), the angular resolution of ASCA is far too insufficient to perform meaningful examinations whether they are really pointlike or not. The ROSAT HRI, having an order of magnitude higher angular resolution, is much more suited for constraining the angular size of the ULXs. We therefore investigate the archival ROSAT HRI data, on which the standard data reduction (e.g., exclusion of the periods of high background counts, earth occultations, and so on) has already been performed. Except for Dwingeloo 1, all of our sample galaxies were observed with the HRI. Some galaxies were observed more than once. However, for each ULX we here utilize the data from one observation only, because superposition of images taken on different occasions might degrade the angular resolution due to possible errors in the aspect solution.

The log of the HRI observations, which we utilized here, is summarized in Table 5.1. We show the HRI image of NGC 1313 in Figure 5.3a, and those of other galaxies in Appendix C. Thus, each of the ULXs (or SNRs) seen in the ASCA images corresponds to a single, point-like source in the HRI image. Further investigation of the source extent is performed in the next subsection.
5.1.3 Studying the source extent

To quantitatively examine the angular extent of the ULXs in the HRI images, we made radial intensity profiles of the individual sources within the radius of 20", and compared each of them with the HRI point spread function (PSF). The analytic formula of the in-flight, on-axis, nominal PSF of the ROSAT HRI is given as

\[ A_1 \exp \left[ -0.5 \left( \frac{r}{\sigma_1} \right)^2 \right] + A_2 \exp \left[ -0.5 \left( \frac{r}{\sigma_2} \right)^2 \right] + A_3 \exp \left[ -\frac{r}{\sigma_3} \right] \text{(counts/pixel)} \], \quad (5.1)

(David et al. 1999), where \( r \) denotes the radius from the source center, \( A_1 = 0.96 \), \( \sigma_1 = 2.5'' \), \( A_2 = 0.18 \), \( \sigma_2 = 4.70 \), \( A_3 = 0.0009 \), and \( \sigma_3 = 31.7'' \). The position dependence of the PSF can be neglected if the source is located within \( \sim 5'' \) from the optical axis (e.g. Boese 1998). Therefore, equation 5.1 is valid for all of our objects.

The PSF formula given by equation 5.1 corresponds to an ideal observation of a point source (David et al. 1999). Due to random errors of the aspect solution, however, the PSF usually becomes wider in actual observations. These effects can be expressed by introducing an additional broadening factor \( \sigma_{\text{add}} \), and replacing \( \sigma_1 \) in equation 5.1 with \( \sqrt{\sigma_1^2 + \sigma_{\text{add}}^2} \) and \( \sigma_2 \) with \( \sqrt{\sigma_2^2 + \sigma_{\text{add}}^2} \). This \( \sigma_{\text{add}} \) usually takes values of 2'' - 3'' even for a point source (e.g., Morse 1994; Boese 1998; David et al. 1999). If the source is extended, \( \sigma_{\text{add}} \) increases beyond these values.

In order to estimate \( \sigma_{\text{add}} \) for our objects, we fitted the radial profiles with the modified PSF plus a constant background, with \( \sigma_{\text{add}} \), the PSF normalization, and the background left free. The fitting results are shown in Table 5.2 and Figure 5.4. For most cases, the fit has been acceptable and \( \sigma_{\text{add}} \) turned out to be \( \sim 1.5'' - 3.5'' \), implying that the objects can be regarded as point sources. Only for M33 X-8 the fit failed \( (\chi^2/\nu=85.3/17) \), because of significant residuals around the source center. This may be due to contamination of diffuse emission around the nucleus (Schulman and Bregman 1995). We therefore replaced the constant background with a Gaussian distribution, to represent this diffuse emission, and re-fitted the profile. Now, the fit became acceptable \( (\chi^2/\nu=22.6/16) \), and the modification of the PSF turned out to be \( \sigma_{\text{add}} = 2.2'' \pm 0.1'' \), which is again comparable to that of a point source. The diffuse emission is expressed with a Gaussian of \( \sigma = 8.6'' \pm 0.5'' \), and its contribution to the total events within 20'' is estimated to be only \( \sim 13\% \).

Since the source counts of two ULXs in NGC 4565 and NGC 1365 SW-source are insufficient for a reliable fitting, we made image projections instead of radial profiles. For NGC 4565, we projected the events within a 25'' \( \times \) 100'' rectangle region on the line connecting the two sources, and for NGC 1365 SW-source, we projected the events within 25'' \( \times \) 25'' square region. They are also shown in Figure 5.4, where the two sources in NGC 4565 are clearly separated and the widths of the projected profile are \( \sim 10'' \) in FWHM. Therefore, the X-ray extent is similar to those of other sources. NGC 1365 SW-source was also point-like to the HRI, although its signal counts are quite low \( (\sim 20) \). Therefore, we regard all these sources studied here to be consistent with point sources within the spatial resolution of the ROSAT HRI. Although Dwingeloo 1 X-1 has not been observed by HRI, Reynolds et al. (1997) already confirmed it to be point-like within the spatial resolution of ASCA.
Table 5.1: *ROSAT* HRI observational log of the galaxies. Only the observations utilized here are tabulated.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Date (ymmd)</th>
<th>Exposure (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 598 (M33)</td>
<td>96 01 18</td>
<td>46</td>
</tr>
<tr>
<td>NGC 891</td>
<td>95 01 26</td>
<td>98</td>
</tr>
<tr>
<td>NGC 1313</td>
<td>94 06 23</td>
<td>22</td>
</tr>
<tr>
<td>NGC 1365</td>
<td>94 07 20</td>
<td>10</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>95 09 18</td>
<td>26</td>
</tr>
<tr>
<td>NGC 3031 (M81)</td>
<td>97 09 30</td>
<td>20</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>91 12 07</td>
<td>14</td>
</tr>
<tr>
<td>NGC 4565</td>
<td>95 07 05</td>
<td>5.3</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>94 05 14</td>
<td>60</td>
</tr>
<tr>
<td>IC 342</td>
<td>91 02 13</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 5.2: Estimates of the X-ray extent of our sample objects, using *ROSAT* HIR data. Sources are fitted with a modified PSF plus a constant background (see text). Only for M33 X-8, the constant background is replaced with a gaussian distribution, to represent the diffuse emission. Due to the aspect errors, $\sigma_{\text{add}}=2^"-3"$ is usually required even for a point source (Morse 1994, Boese 1998, David et al. 1999).

<table>
<thead>
<tr>
<th>Host galaxy</th>
<th>Source name</th>
<th>$\sigma_{\text{add}}$ (&quot;)</th>
<th>$\chi^2/\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 598 (M33)</td>
<td>X-8</td>
<td>2.2±0.1</td>
<td>22.6/16</td>
</tr>
<tr>
<td>NGC 891</td>
<td>SN 1986J</td>
<td>1.7±0.2</td>
<td>14.7/17</td>
</tr>
<tr>
<td>NGC 1313</td>
<td>Source A</td>
<td>1.3±0.2</td>
<td>13.9/14</td>
</tr>
<tr>
<td></td>
<td>Source B</td>
<td>1.5±0.4</td>
<td>10.2/11</td>
</tr>
<tr>
<td></td>
<td>SN 1978K</td>
<td>1.5±0.3</td>
<td>10.2/5</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>Source 3</td>
<td>3.5±0.3</td>
<td>16.4/7</td>
</tr>
<tr>
<td>NGC 3031 (M81)</td>
<td>X-6</td>
<td>1.8±0.3</td>
<td>14.6/12</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>off-center</td>
<td>1.8±0.5</td>
<td>9.9/4</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>north-arm SNR</td>
<td>1.7±0.2</td>
<td>13.6/13</td>
</tr>
<tr>
<td>IC 342</td>
<td>Source 1</td>
<td>2.6±0.3</td>
<td>1.2/5</td>
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<tr>
<td></td>
<td>Source 2</td>
<td>2.3±0.5</td>
<td>3.8/5</td>
</tr>
</tbody>
</table>
Figure 5.3: X-ray contours of NGC 1313, superposed on the optical (Digital Sky Survey) image. (a) The ROSAT HRI image. (b) The ASCA SIS image in the 0.5–10 keV band. (c) The ASCA GIS image in the same energy band as the SIS image. The HRI image, the SIS image, and the GIS image are smoothed with a gaussian distribution of $\sigma = \text{0.'05, 0.'1, and 0.'5, respectively}$. All the images are displayed in sky coordinates using J2000 equinox, hence being rotated counterclockwise by $\sim45^\circ$ compared with Figure 5.1 and 5.2. Note that panel (c) has a different scale.

5.2 Light Curves of ULXs

As mentioned in the previous section, most of our sample objects can be regarded as point sources within the angular resolution of the ROSAT HRI ($\leq 10''$), and are likely to be single objects. The source size can be limited more tightly when short-term variability is observed, since the size of the emission region should be less than the light speed multiplied by the time scale of variability. Moreover, any spectral variation associated with time variability may provide us with a key information to identify the emission mechanism of ULXs. Therefore, we produced ASCA light curves of our ULXs (and also SNRs) to investigate their variability. The event extraction was performed over a circular region with a typical radius of 3'. We use them also to accumulate the source spectra in Chapter 6, where details of the event accumulation region are described.

We added events from SIS 0 and SIS 1, or those of GIS 2 and GIS 3, and obtained SIS/GIS light curves in the 0.5–10 keV range, including background. We used only the SIS data for NGC 1365 SW-source and SNR in NGC 6946, to minimize the contamination from the neighboring sources, and only the GIS data for NGC 3628 off-center source, since the source drops in the SIS inter-chip gap. We did not utilize the data of M81 X-6 here, since the M81 nucleus located in the neighborhood is known to be variable (Ishisaki et al. 1996, Iyomoto 1999), which would affect the light curves of X-6.

We fitted the obtained light curves with a constant count rate model. The light curves are summarized in Appendix D, and the $\chi^2$ values against the constant-intensity hypothesis are tabulated in Table 5.3. Thus, among the 33 light curves, three (IC 342 source 1 for SIS/GIS and NGC 1313 source A in the 1995 observation of SIS) show statistically significant ($\geq99\%$) short-term variability, marginal (90–99%) variability is detected for another three (NGC 1313 source B in the 1993 observation of SIS/GIS and IC 342 source 2 for
Figure 5.4: *ROSAT* HRI radial profiles of our sample objects, fitted with a modified PSF and a constant background (see text). The crosses represent the data, whereas the histograms indicate the model. For M33 X-8, a gaussian distribution is used instead of the constant background, and the contribution of each component is shown as dotted (modified PSF) and dot-dashed (gaussian distribution) lines. For NGC 1365 SW-source and two sources in NGC 4565, only the projected profiles are displayed.
Figure 5.4: Continued.
GIS), and the others are consistent with the constant count rate hypothesis. Here we show two fascinating cases in Figure 5.5, IC 342 source 1 and NGC 1313 source A in the 1995 observation, the former exhibited strong time variability as already reported by Okada et al. (1988), and the latter show intensity decreases. These two sources are highly unlikely to be composite objects. They are also difficult to be understood as a diffuse emission like SNRs, since the variability of 1–10 ks time scale limit their physical size within $10^{14} - 10^{15}$ cm. For these two observations, we analyze the change of the spectral shape associated with the time variability in the next chapter. We also show the light curves of M33 in Figure 5.5, as an example of those which are consistent being constant.
Table 5.3: $\chi^2$ values for ULX (and SNR) light curves against the constant-intensity hypothesis.

<table>
<thead>
<tr>
<th>Host galaxy</th>
<th>Date</th>
<th>Source</th>
<th>Instrument</th>
<th>$\chi^2/\nu$</th>
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<tr>
<td>M33</td>
<td>99 07 22</td>
<td>X-8</td>
<td>SIS</td>
<td>45.0/50</td>
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<td></td>
<td>(position 1)</td>
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<td>GIS</td>
<td>62.1/60</td>
</tr>
<tr>
<td></td>
<td>99 07 23</td>
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<td>SIS</td>
<td>36.3/37</td>
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<td>(position 2)</td>
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<td>GIS</td>
<td>51.2/49</td>
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<td>SN 1986J</td>
<td>SIS</td>
<td>40.2/34</td>
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<td>GIS</td>
<td>38.6/36</td>
</tr>
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<td>SIS</td>
<td>40.3/45</td>
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<td>Source A</td>
<td>SIS</td>
<td>46.6/45</td>
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<td>71.7/59</td>
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<td></td>
<td></td>
<td>Source B</td>
<td>SIS</td>
<td>56.1/37</td>
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<td>GIS</td>
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<td>119.3/53</td>
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<td>GIS</td>
<td>66.1/53</td>
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<tr>
<td></td>
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<td>GIS</td>
<td>56.8/53</td>
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<td></td>
<td>SN 1978K</td>
<td>SIS</td>
<td>28.4/28</td>
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<td>51.3/46</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>93 12 12</td>
<td>off-center</td>
<td>GIS</td>
<td>18.8/22</td>
</tr>
<tr>
<td>NGC 4565</td>
<td>94 05 28</td>
<td>two ULXs are summed up</td>
<td>SIS</td>
<td>45.3/43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GIS</td>
<td>55.9/50</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>94 12 28</td>
<td>North-arm SNR</td>
<td>SIS</td>
<td>38.5/45</td>
</tr>
<tr>
<td>IC 342</td>
<td>93 09 19</td>
<td>Source 1</td>
<td>SIS</td>
<td>321.6/60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GIS</td>
<td>326.6/66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Source 2</td>
<td>SIS</td>
<td>51.2/50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GIS</td>
<td>79.3/62</td>
</tr>
<tr>
<td>Dwingeloo 1</td>
<td>95 09 14</td>
<td>X-1</td>
<td>SIS</td>
<td>60.9/63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GIS</td>
<td>54.8/66</td>
</tr>
</tbody>
</table>
Figure 5.5: Examples of ULX light curves obtained by ASCA in the 0.5–10 keV energy range, including background. The typical background count rate is 0.02 and 0.01 c s\(^{-1}\) for the SIS and the GIS, respectively. Each light curve is tested against a constant-intensity hypothesis, and the assumed count rate is represented in the figure as a horizontal straight line. IC 342 source 1 and NGC 1313 source A (obtained in 1995 November) showed time variability, whereas the light curves of M33 are consistent with being constant. The light curves of the other sources are summarized in Appendix D.
Chapter 6

SPECTRAL PROPERTIES OF ULXs

6.1 Spectral Analysis

Spectra of ULXs will provide us with a key information on the source nature. Since ASCA has a wide effective area over a wide energy band (0.5–10 keV) together with the improved energy resolution, we can obtain high-quality spectra of ULXs which have not been provided by any previous missions. Before describing the individual spectra of ULXs, we briefly explain the procedure of spectral analysis in this section.

6.1.1 Accumulation of source and background spectra

As mentioned in § 3.2, the ASCA XRT has rather poor spatial resolution; half power diameter is $\sim 3'$ (Table 3.1), and its point-spread function exhibits broad wings that extend beyond $\sim 10'$. Therefore, we have to use relatively wide integration regions, typically $\sim 3'$ in radius, to accumulate the source spectrum, even for point sources. The on-source spectrum accumulated in this way includes not only signal photons from the target source, but also background events (§ 3.5) that must be estimated separately and then subtracted away. For the GIS, the background spectrum is obtained from blank-sky data, by accumulating events within the same region as is used for extracting the source spectrum. For the SIS, on the other hand, the background spectrum is obtained in most cases from source-free regions of the same observation. This is because the non X-ray background of the SIS detector depends on the SIS clocking mode, and has gradually changed since the launch of ASCA due to radiation damage (§ 3.3.3 and § 3.5). However, for a limited number of observations performed in a 4-CCD mode in early phases of the mission (roughly speaking, within one year since the launch), we can derive the SIS background spectrum from blank-sky data, that were also taken in the 4-CCD mode. This improves the photon statistics, since we can sum up many blank-sky data to achieve a long exposure, e.g. $\geq 100$ ks in total. When the source is located on the Galactic plane, such as Dwingeloo 1 X-1 (§ 4.2), we use source free regions of the on-source data to obtain the background spectrum for both the SIS and the GIS, in order to eliminate diffuse emission from the Galactic plane, called Galactic Ridge X-ray Emission (Worrall et al. 1982, Koyama et al. 1986, Kaneda 1998). We quantify the background-subtracted spectrum in terms of various spectral models, either theoretical or empirical, as described in the next
subsection.

6.1.2 Detector response and spectral fitting

We usually quantify the background-subtracted spectrum in the following way; first modeling the spectrum, then multiplying it with the instrumental response, and finally comparing the model-predicted pulse-height distribution with the actually observed spectrum. More specifically, expected pulse-height distribution $S(PHA)$ is calculated from the model function $M(E)$ as

$$S(PHA) = \sum_E R(PHA, E)A(E)M(E),$$

where $E$ is the X-ray energy, $PHA$ is the observed pulse height, $A(E)$ is called ancillary response file (ARF), and $R(PHA, E)$ is called response matrix file (RMF). Simply saying, the ARF is an instrumental efficiency as a function of incident X-ray energy and expressed in the form of a vector, whereas the RMF describes the expected pulse-height distribution for incident monochromatic X-rays of energy $E$ and expressed in the form of a matrix. The ARF is contributed by both the XRT and the detector (the SIS or the GIS), while the RMF is determined by the detector alone.

In order to extract the spectrum, we must specify the position, shape (mostly circular centered on the source) and size of the extracting region. The ARF depends on the size and position of the extracting region, so that we should calculate ARF for each observation. On the other hand, the RMF is thought to be the same over the whole detector area of the GIS, and we can use the standard single RMF. Since the detector response of the SIS shows time variability due to radiation damage (§ 3.3.3), we calculate the SIS RMF for each observation.

Although the response ($ARF \times RMF$) is not the same among the four sensors (SIS 0, SIS 1, GIS 2, and GIS 3), the difference between the two SISs or the two GISs is relatively small. Therefore, we sum the two SIS (SIS 0 and SIS 1) spectra into a single SIS spectrum, and the two GIS (GIS 2 and GIS 3) spectra into a single GIS spectrum, in order to improve photon statistics when analyzing the spectra of ULXs. We also sum the detector response ($ARF \times RMF$) in the same way. Thus, we obtain the spectrum and detector response for the SIS and the GIS, and fit them jointly. We use the $\chi^2$ minimization method to find the best fit parameters. That is, we adopt a single spectral model, calculate model predictions for the SIS and the GIS using respective responses, compare the predictions to the corresponding spectra, and sum up the $\chi^2$ values from the two instruments. Unless otherwise stated, we estimate errors of one interesting parameter as 90% confidence range, i.e., the value of $\chi^2$ is decreased by 2.71 from the minimum value.

Before performing actual spectral fittings of ULXs, we must examine how the response and model uncertainties affect the obtained results. As mentioned in Appendix B, the GIS (plus XRT) spectral response at the nominal focal-plane position has been calibrated (except the flux normalization) down to an uncertainty of $\sim$1.5%, which is small enough compared with the photon statistics of our sources. Therefore for the GIS data, we consider only the statistical errors in calculating the $\chi^2$ values. For the SIS, the spectral response is cross-calibrated with the GIS by observing moderately strong sources, e.g., 3C273, which is more than 10 times brighter than any of our sample objects. Hence, we assume the calibration uncertainty of the SIS to be at a comparable level to that of the GIS, and calculate the values of $\chi^2$ based on the statistical errors alone, too. The effect
of these response uncertainties on the spectral results is described in § 6.2.1 and § 6.3.2, for ULXs having relatively good photon statistics.

We should also consider how the spectral results depend on the source position on the focal plane. As for the spectral shape, Fukazawa et al. (1997) confirmed that the dependence on the source location is relatively small based on the multi-pointing observations of the Crab Nebula; the derived photon index $\Gamma$ scatters $\sim \pm 0.05$ over a major part of the GIS field of view (see Appendix B). This implies $\sim \pm 12\%$ difference in the flux ratio at 1 keV to 10 keV. If we assume an MCD spectrum (see § 2.7) of $T_{\text{in}} = 1.5$ keV, this difference corresponds to only $\pm 2\%$ uncertainty in the value of $T_{\text{in}}$. As shown in later part of this chapter, this uncertainty is much smaller than the statistical errors for all of our sample ULXs, hence negligible. On the other hand, Fukazawa et al. (1997) reported that the measured flux depends by $\sim \pm 10\%$ on the observed position, as also described in Appendix B. Actually, we often find that the SIS and the GIS spectra require somewhat discrepant model normalizations by up to $\sim 15\%$, particularly depending on the source location on the focal plane. Accordingly, in the joint spectral fitting, we require the model to have identical shapes between the SIS and the GIS, but allow the relative normalization to be free between them. As a result, the two instruments sometimes give slightly different source fluxes. In such a case we generally refer to the GIS flux, because the SIS results sometimes suffer from the inter-chip gaps. The flux uncertainty by 10–20% does not affect our discussions in Chapter 7. We emphasize that the SIS/GIS discrepancy occurs only in their relative photometric normalization, not in the spectral shape.

We finally examin the influence of utilizing an MCD approximation instead of a standard Shakura & Sunyaev model (see § 2.7 for model descriptions). For this purpose, we numerically calculated spectra expected from a standard disk model, with the peak temperature of 1.0, 1.5, and 2.0 keV. They are modified with photoelectric absorption (see Appendix A) of $N_{\text{H}} = 0.1 \times 10^{22} \text{ cm}^{-2}$, and convolved with the ASCA spectral response function to produce simulated spectral datasets. Then, we fitted the obtained spectra with an absorbed MCD model. Regardless of the assumed peak temperature, the fit residuals are at most $\sim 7\%$, and only $\leq 2\%$ in the energy range of 0.7–7 keV, implying that the difference between these two models is almost indistinguishable, as shown in Figure 6.1. Although the obtained values of $N_{\text{H}}$ (0.07–0.09 $\times 10^{22} \text{ cm}^{-2}$) are somewhat smaller than what was assumed initially, the difference is again smaller than the statistical errors of our sample objects. Therefore, the MCD approximation does not affect our spectral analysis, either.

### 6.2 IC 342 Source 1

Among our sample, IC 342 source 1 has the highest flux next to M33 X-8, and one of the highest luminosities up to $L_X \sim 10^{40} \text{ erg s}^{-1}$, as shown in Table 2.2. Therefore this source can be regarded as a typical ULX, and is suitable for the start point of our spectral studies. As shown in Figure 5.5, this source showed strong time variability during the ASCA observation, while the spectral shape also changed as reported by Okada et al. (1998). We first study the time-averaged spectra in § 6.2.1–§ 6.2.3, and then sort the data in § 6.2.4 according to the source intensity and study the spectra individually.
6.2.1 Time averaged spectrum

We extracted the SIS and GIS spectra from a circular region of 3′ radius centered on the source. The size of the region is determined to avoid the overlap with the region used to extract the spectrum of source 2 (§ 6.8), and is the same as that utilized previously by Okada et al (1998). The background spectra were obtained from blank-sky data, and were subtracted from the source spectra. Before performing spectral fitting, we plotted the “unfolded” (detector efficiency removed) spectra in Figure 6.2. Although unsuitable for quantitative analysis, the unfolded spectra are useful to visualize rough spectral properties. In fact, the counts in the low-energy range (≤1.5 keV) drop off, implying that the actual spectra suffer absorption. In addition, the continua exhibits a rather convex curvature. These features are confirmed by the spectral fitting as performed below.

We fitted the background-subtracted spectra with typical single component models; a power-law model, a thermal Bremsstrahlung (TBS) model, a Raymond-Smith (R-S) plasma emission model, or a multi-color disk blackbody (MCD) model, each multiplied by the factor representing photoelectric absorption due to an interviewing gas with an equivalent hydrogen column density of $N_H$. A power-law model is one of the simplest, widely used model, and also represents non-thermal emission as is seen from AGNs, X-ray pulsars, and so on. This model is characterized by a photon index $\Gamma$. A TBS model is a thermal emission from optically-thin plasmas and characterized by its temperature. This model also approximates the spectrum from bright LMXBs (§ 2.3.2). A R-S model describes thin-thermal emission with lines emitted by hot plasmas, of which the metal abundance and the plasma temperature are the characteristic model parameters. An MCD model (see § 2.7) represents emission from optically-thick accretion disks around NSs or BHs. The inner-most disk temperature, $T_{in}$, determines the spectral shape, whereas the inner-most disk radius, $R_{in}$, determines the normalization. Further details of these models are described in Appendix A.

The results of the spectral fitting with these models are summarized in Table 6.1 and
Figure 6.3. Thus, the single power-law model is completely unacceptable. The R-S model requires quite low metallicity, so that it is almost identical to the TBS model: this is the reason why we do not show the Raymond-Smith fit in Figure 6.3. In any case, the R-S and TBS fits are also rejected with a high significance (at 99% confidence). The fit residuals of these models in Figure 6.3 imply that the actual spectrum has rather convex shape in logarithmic plot, in agreement with the impression of Figure 6.2. In fact, the MCD model, which has the most convex shape among our four models tested here, can successfully represent the data. The value of $N_H$ obtained with the MCD model is not much different from the Galactic line-of-sight column density ($3 \times 10^{21}$ cm$^{-2}$). In contrast, the other unsuccessful models require larger values of $N_H$, in order to make the model shape artificially more convex than it is.

As already described in § 2.7.1 and § 6.1.2, the MCD model is almost indistinguishable from the standard Shalura & Sunyaev one. Actually, the fit is not improved significantly by replacing the MCD model with the standard model; the value of $\chi^2$ has decreased only by 0.5, implying that the MCD approximation does not affect the confidence level. We also considered the influence of the detector response uncertainty on the value of $\chi^2$. As we have seen in the previous section, the calibration uncertainty of the response functions is estimated to be $\sim 1.5\%$. Thus, we introduced 1.5% systematic errors on the spectral fitting of this ULX (fitted with the single MCD model). Then, the decrease of the $\chi^2$ value is only 4.4, which do not affect our statement of the model acceptability either.

### 6.2.2 Limits on the hard component

Thus, the spectra of IC 342 source 1 can be reproduced successfully with the MCD model, which describes optically thick emission from a standard accretion disk around a compact object (§ 2.7 and Appendix A). So far, the MCD spectra have been observed from two types of Galactic XRBs; one is LMXBs, and the other is BHBs in the soft state (§ 2.3.2 and § 2.3.4). In addition to the MCD component, Galactic LMXBs generally exhibit a black-body component of $kT$ $\sim$ 2 keV, and Galactic BHBs in the soft state often show a hard component that can be expressed with a power-law of photon index $\Gamma$=2.0–2.5. Therefore, we investigate the presence of these hard components in the spectra of IC 342 source 1.

We refitted the spectra by adding a black-body component or a power-law component to the MCD model. We fixed the temperature of the black-body component at 2 keV, a typical value observed from LMXBs, in order to obtain a stable fitting. We also fixed the photon index of the power-law component at 2.2, to simulate typical spectra of BHBs in the soft state. However, the data did not require either hard component. The reduction of $\chi^2$ is only 0.7 by including the power-law component, and 2.2 by including the black-body component. Therefore, the presence of these hard components is insignificant at 90% confidence from an $F$-test. The contribution to the 0.5–10 keV flux of the power-law component is only $\sim$20% at most (at 90% confidence), and the best-fit MCD temperature, $T_{in}$, increased slightly to 1.81 keV. This value is the same, within the statistical errors, as obtained when we fit the spectra with the MCD model alone. The contribution of the black-body component to the flux in the same energy range is also low, $\sim$30% at most, although the best-fit value of $T_{in}$ decreased noticeably to 1.33 keV.
6.2.3 Other acceptable models

Although the single MCD model successfully represents the spectrum of IC 342 source 1, there remains a possibility that other single component models can also express the spectrum adequately. The source is suitable for such a study, because of its high photon statistics.

Any model to be tested here must have a mildly convex shape, like the MCD model. One possibility is so-called unsaturated Comptonization (UC) model, expected when hot thermal electrons Compton up-scatter some soft seed photons into X-rays. This model is characterized by an electron temperature, $T_e$, and an optical depth for electron scattering, $\tau_{es}$. Another popular empirical model having an MCD-like shape is a broken power-law model, which is frequently used to represent synchrotron emission, e.g., from blazars. This model is characterized by three parameters; photon indices in the lower and higher energies, $\Gamma_1$ and $\Gamma_2$ respectively, and the break-point energy, $E_{bk}$. Further details of these two models are described in Appendix A.

We jointly fitted the GIS and SIS spectra with these two models, and summarize the results also in Table 6.1 and Figure 6.3. Thus, the broken power-law fit is somewhat poor: it is rejected at 90% confidence. Although the UC model is statistically acceptable, it shows a relatively worse $\chi^2$ compared with the MCD model, or, in other words, the confidence level is lower than that of the MCD one (25% for the UC model whereas 43% for the MCD one). We further examined whether the response uncertainty of 1.5% affects this choice of the best-preferred model. For this purpose, we introduced the uncertainty in a conservative manner, i.e., we artificially increased the observed source counts by 1.5% at 10 keV, reduced by 1.5% at 0.5 keV, and modified for the intermediate energy based on the linear interpolation (or, vise versa). Then we re-fitted the obtained spectra with the MCD, the UC, and the broken power-law model, and found that the change of the $\chi^2$ value is below 0.5. Thus the MCD model is certainly preferred than the other two models with respect to the fit confidence. In addition, both the UC and broken power-law models require excess absorption compared with the MCD one. We discuss physical meanings of them in Chapter 7. In summary, the single MCD model gives the best description of the observed spectra of IC 342 source 1. We therefore use this model as a standard tool to analyze the spectra of other objects among our sample.

6.2.4 Time variability

Now that we have quantified the average spectrum of IC 342 source 1, we examine its time variability. We hence divided the data into five time regions, as defined in Figure 5.5. In order to grasp the rough spectral information, we first summed phase 2 spectra and phase 4 spectra into “low-flux phase” spectra, and summed phase 1, 3, and 5 spectra into “high-flux phase” spectra, and fitted them with an MCD model, which successfully reproduce the time-averaged spectrum. Then, as summarized in Table 6.2 and Figure 6.4, the MCD model again turned out to be successful, and provide the value of absorption consistent with the time-averaged one. Therefore we fitted five time-sorted spectra by the MCD model, with the absorption fixed at the best-fit value of time-averaged spectra, i.e., $N_H=4.7\times10^{21}$ cm$^{-2}$. The results are summarized in Table 6.3. Thus, all the five spectra are well fitted and an positive correlation between $T_{in}$ and $f_X$ is clearly seen.

As described in § 2.7, the MCD model provides us with two basic quantities of the
accretion disk; the inner-most disk temperature, $T_{\text{in}}$, and the inner-most disk radius, $R_{\text{in}}$. In order to examine changes in these two quantities, we plotted the confidence contours of the five spectra on the $T_{\text{in}}$-$R_{\text{in}}^2$ plane in Figure 6.5. Thus, $R_{\text{in}}$ gradually decreases as $T_{\text{in}}$ increases, and the relation is approximated as $R_{\text{in}} \propto T_{\text{in}}^{-1}$. Further examination of these results will be performed in Chapter 7.

Table 6.1: Joint fit results of the SIS/GIS spectra of IC 342 source 1 using single component models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_H$ (10$^{22}$ cm$^{-2}$)</th>
<th>Parameters$^a$</th>
<th>$f_X$ $^b$ (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-law</td>
<td>0.93±0.06</td>
<td>1.90±0.05</td>
<td>11.1</td>
<td>266.5/135 (≤1%)</td>
</tr>
<tr>
<td>TBS</td>
<td>0.75±0.04</td>
<td>6.7±0.6</td>
<td>10.7</td>
<td>183.2/135 (≤1%)</td>
</tr>
<tr>
<td>R-S$^c$</td>
<td>0.75±0.04</td>
<td>6.8±0.5</td>
<td>10.7</td>
<td>183.7/134 (≤1%)</td>
</tr>
<tr>
<td>MCD</td>
<td>0.47±0.03</td>
<td>1.77±0.05</td>
<td>10.2</td>
<td>137.4/135 (43%)</td>
</tr>
<tr>
<td>UC</td>
<td>0.64±0.07</td>
<td>1.42±0.09/23±2</td>
<td>10.2</td>
<td>144.9/134 (25%)</td>
</tr>
<tr>
<td>Broken power-law</td>
<td>0.63±0.07</td>
<td>1.39±0.13/2.38±0.40/3.6±0.4</td>
<td>10.7</td>
<td>156.3/133 (8%)</td>
</tr>
</tbody>
</table>

$^a$ Photon index for the power-law model, plasma temperature (keV) for the TBS and R-S model, $T_{\text{in}}$ for the MCD model, $T_e$ (keV)/$\tau_{\text{es}}$ for the UC model, and $\Gamma_1/\Gamma_2/E_{\text{bk}}$ (keV) for the broken power-law model. 

$^b$ In unit of 10$^{-12}$ erg s$^{-1}$ cm$^{-2}$.

$^c$ The abundance has been constrained to be ≤0.03 solar.

Table 6.2: Time variability of IC 342 source 1. The SIS/GIS spectra of the high and low flux phases are fitted with a single MCD model.

<table>
<thead>
<tr>
<th>Phase</th>
<th>$N_H$ (10$^{22}$ cm$^{-2}$)</th>
<th>$T_{\text{in}}$ (keV)</th>
<th>$f_X$ $^a$ (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-flux</td>
<td>0.47±0.04</td>
<td>1.87±0.07</td>
<td>11.6</td>
<td>129.0/106 (6%)</td>
</tr>
<tr>
<td>Low-flux</td>
<td>0.47±0.07</td>
<td>1.42±0.09</td>
<td>6.4</td>
<td>115.6/107 (27%)</td>
</tr>
</tbody>
</table>

$^a$ In unit of 10$^{-12}$ erg s$^{-1}$ cm$^{-2}$.

### 6.3 M33 X-8

The ASCA spectra of M33 X-8 have been interpreted by Takano et al. (1994) as emission from an accreting BH of $\sim 10 M_\odot$, as mentioned in § 2.6. We here attempt to reconfirm their results, using the instrumental responses which have been updated significantly since Takano et al. (1994) was published.

#### 6.3.1 Single component fits

M33 was observed with ASCA twice in July 1993, as tabulated in Table 4.1. Since the two observations were performed in series, and the source intensity did not change between the two occasions, we co-add data from the two observations. We accumulated the source spectra over circular regions centered on the source, with radii of 4′ and 6′ for the SIS
Table 6.3: Fitting results of time-sorted spectra of IC 342 source 1. The SIS/GIS spectra are fitted jointly with the MCD model, fixing absorption at $N_H=4.7\times10^{21}\text{cm}^{-2}$.

<table>
<thead>
<tr>
<th>Phase</th>
<th>$T_{in}$ (keV)</th>
<th>$f_X$ a) (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.96±0.10</td>
<td>12.2</td>
<td>59.2/81 (97%)</td>
</tr>
<tr>
<td>2</td>
<td>1.50±0.10</td>
<td>7.5</td>
<td>60.4/63 (57%)</td>
</tr>
<tr>
<td>3</td>
<td>1.70±0.15</td>
<td>9.6</td>
<td>52.2/48 (31%)</td>
</tr>
<tr>
<td>4</td>
<td>1.29±0.08</td>
<td>5.5</td>
<td>54.3/60 (68%)</td>
</tr>
<tr>
<td>5</td>
<td>1.81±0.07</td>
<td>11.3</td>
<td>136.9/117 (10%)</td>
</tr>
</tbody>
</table>

a) In unit of $10^{-12}\text{ erg s}^{-1}\text{ cm}^{-2}$.

(a) Unfolded spectrum, SIS

(b) Unfolded spectrum, GIS

Figure 6.2: The background-subtracted, unfolded SIS and GIS spectra of IC 342 source 1, where the crosses represent the observed spectra. For comparison, we also plotted the best-fit MCD model (see Table 6.1) as histograms.
Figure 6.3: The background-subtracted SIS and GIS spectra of IC 342 source 1, fitted jointly with various single-component models with photoelectric absorption. The histograms show the best fit model and the crosses represent the observed spectra. The lower panel shows the fit residuals. The SIS data shows higher counts in lower energies, whereas the GIS shows higher counts in higher energies. The employed models are a power-law, a TBS, an MCD, a UC, and a broken power-law model. We do not show the R-S model fit, since it is almost identical to the TBS model.
(a) High flux phase

(b) Low flux phase

Figure 6.4: The background-subtracted SIS and GIS spectra of IC 342 source 1. Panel (a) represents the spectra obtained at the high-flux phase, whereas panel (b) the low-flux one. Both are fitted jointly with the MCD model.

Figure 6.5: The confidence contours of the MCD fit in terms of $T_{\text{in}}$ and the normalization of the MCD model, which is proportional to $R_{\text{in}}^2$. The confidence level of 68% is shown. We fixed the absorption at $N_H = 4.7 \times 10^{21}$ cm$^{-2}$. The solid line represents the relation of $T_{\text{in}} \propto R_{\text{in}}^{-1}$. The horizontal axis is logarithmic.
and the GIS, respectively, and subtracted the background spectra derived from blank-sky observations. The obtained spectra were then fitted with the typical single component models that we used for IC 342 source 1 in the previous section; a power-law, a TBS, a R-S, or an MCD model, each multiplied by photoelectric absorption. In this particular case, however, the SIS and GIS data showed some discrepancy in the lower energy range below $\sim 1$ keV, presumably because of calibration uncertainties in the soft X-ray range. This is known to occur occasionally with the ASCA data, particularly when the source has high signal statistics like in the present case. To cope with this problem, we allowed the values of $N_H$ to be different between the SIS and the GIS.

As presented in Table 6.4 and Figure 6.6, the power-law model failed completely, and the MCD model was also unacceptable at 99% confidence level. In contrast, the TBS and R-S models are both successful. (They are essentially the same, because the R-S fit requires a quite low metallicity.) Thus, the M33 X-8 spectra on average exhibit a mildly convex shape, which can be represented by a TBS model of $kT = 3$ keV. A power-law model is too straight, while an MCD model is too convex. The discrepancy in $N_H$ between the two instruments turned out to be $(0.05 - 0.1) \times 10^{21}$ cm$^{-2}$, which is small enough for our purpose.

### 6.3.2 Double component fits

Although the single MCD model thus failed to reproduce the X-8 spectra, we need to investigate the cause of the failure more closely, because the MCD model has already given the best description to the spectra of IC 342 source 1, a typical ULX. Actually, in Figure 6.6c, the residuals are significant only in energies above $\sim 5$ keV. This suggests that the failure is caused by the presence of a separate hard component, rather than by a discrepant continuum curvature.

Accordingly, we proceed to fit the M33 X-8 spectra with double-component models consisting of an MCD emission and a hard tail, as we have performed on IC 342 source 1 in § 6.2.2. As the hard component, we again use either a power-law with photon index fixed at $\Gamma = 2.2$, or a blackbody with temperature fixed at $kT = 2.0$ keV. Then, either modeling has given a fully acceptable joint fit to the data, as summarized in Table 6.5 and Figure 6.7. The fit $\chi^2$ has decreased by 84.4 and 78.6 for the power-law and blackbody modeling, respectively. Therefore, the hard component is statistically quite significant. The achieved values of $\chi^2$ are also significantly lower than that from the single TBS fit. We thus consider that the spectrum of M33 X-8 can be better described by an MCD plus hard-tail model than by a single TBS one.

Comparing the two modelings of the hard-tail in Table 6.5, the power-law modeling gives a lower value of $\chi^2$ than the blackbody one. Furthermore, a power-law hard tail is often observed to accompany the MCD emission from BHBs (§ 6.2.2). Therefore, we regard the MCD component with a power-law hard tail as the best representation of the M33 X-8 spectrum. We thus reconfirm the conclusion reached by Takano et al. (1994). In this modeling, our best-fit MCD temperature, $T_{in} = 1.15 \pm 0.03$ keV, is somewhat higher than those obtained by Takano et al. (1994); $T_{in} = 0.98 \pm 0.06$ keV from the SIS, and $T_{in} = 1.06 \pm 0.06$ keV from the GIS. This is partly because we fixed the index of the power-law component at $\Gamma=2.2$, whereas they fixed at $\Gamma=1.8$. If we fixed the index at 1.8, we again obtain an acceptable fit ($\chi^2/\nu=169.6/199$) and $T_{in}$ decreases to $1.09\pm0.03$ keV. The residual difference between our value of $T_{in}$ and that of Takano et al. (1994) is
thought to reflect the progress in the instrumental calibration.

Like IC 342 source 1, we investigated the influence of the model and response uncertainties on the fit acceptance, and obtained the same results; the value of $\chi^2$ has not changed for the MCD plus power-law fit by replacing the MCD model with the standard Shakura & Sunyaev one, and decreased only 9.0 by inclusion of the 1.5% response uncertainties. The modification of the observed source counts by $\pm 1.5\%$ changed the $\chi^2$ values by only $\leq 0.5$ for the MCD plus power-law or the MCD plus black-body model fitting. Thus, statements of the model acceptance are not affected.

Table 6.4: Joint-fit results of the M33 X-8 spectra, using single component models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_H$ a) ((10^{22}\text{cm}^{-2}))</th>
<th>$\Gamma$ or $T_{in}$ b) ((\text{keV}))</th>
<th>$f_X$ b) ((0.5-10\text{keV}))</th>
<th>$\chi^2/\nu$ c) (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>power-law</td>
<td>0.41/0.37</td>
<td>2.34</td>
<td>20.1</td>
<td>569.6/201 ($\leq 1%$)</td>
</tr>
<tr>
<td>TBS</td>
<td>0.22±0.01/0.15±0.03</td>
<td>3.4±0.1</td>
<td>19.6</td>
<td>211.2/201 (30%)</td>
</tr>
<tr>
<td>R-S c)</td>
<td>0.22±0.01/0.15±0.03</td>
<td>3.4±0.1</td>
<td>19.7</td>
<td>213.5/201 (24%)</td>
</tr>
<tr>
<td>MCD</td>
<td>0.06±0.01/≤0.01</td>
<td>1.18±0.02</td>
<td>19.1</td>
<td>251.6/201 ($\leq 1%$)</td>
</tr>
</tbody>
</table>

a) SIS/GIS.
b) In unit of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.
c) The abundance has been constrained to be $\leq 0.01$ solar.

Table 6.5: Joint-fit results of the M33 X-8 spectra, using the MCD model with a hard component.

<table>
<thead>
<tr>
<th>Model a)</th>
<th>$N_H$ b) ((10^{22}\text{cm}^{-2}))</th>
<th>$T_{in}$ c) ((\text{keV}))</th>
<th>$f_X$ c) ((0.5-10\text{keV}))</th>
<th>$\chi^2/\nu$ c) (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCD+power-law</td>
<td>0.18±0.02/0.09±0.04</td>
<td>1.15±0.03</td>
<td>19.8</td>
<td>167.2/200 (94%)</td>
</tr>
<tr>
<td>MCD+black-body</td>
<td>0.08±0.01/≤0.01</td>
<td>1.03±0.03</td>
<td>20.0</td>
<td>173.0/200 (92%)</td>
</tr>
</tbody>
</table>

a) The power-law index is fixed at $\Gamma=2.2$, and the temperature of the black-body at $kT=2.0$ keV.
b) SIS/GIS.
c) In unit of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.

6.4 M81 X-6

As we have shown in Table 2.1 in § 2.5.1, M81 hosts a ULX, called X-6 (Fabbiano 1988). Since M81 has a Cepheid-based accurate distance of 3.6 Mpc (Freedman et al. 1994), we can calculate the luminosity of X-6 without being affected by the distance uncertainty. Moreover, ASCA has observed this galaxy more than 10 times in order to study the newly exploded supernova, SN 1993J (Kohmura 1994, Uno 1997). This fact enables us to study the long-term variability of X-6. In this thesis we use data obtained after 1994, in
Figure 6.6: The background-subtracted SIS and GIS spectra of M33 X-8, jointly fitted with single component models; a power-law, a TBS, and an MCD model. The R-S model fit is almost identical to the TBS fit.
Figure 6.7: The background-subtracted M33 X-8 spectra of the SIS and GIS, fitted with double-component models. The contributions of the two components are shown by dotted lines. Although the fit is simultaneous to the SIS and GIS, we show the two spectra separately for clarify.
which SN 1993J had faded away significantly and its contamination to the X-6 spectrum is sufficiently low, as described below. Thus we analyzed seven observations in total, as shown in Table 4.1. The same datasets were already utilized by Uno (1997) in his study of SN 1993J.

### 6.4.1 Accumulation of the source and background spectra

When studying the spectrum of X-6, we should eliminate contamination from the two nearby sources, SN 1993J and M81 X-5, the latter begin the LLAGN of M81 (Ishisaki et al. 1996, Iyomoto 1999). As shown in Figure 6.8, X-6 is separated only ∼1′ from SN 1993J, and ∼3′ from X-5.

We accumulated the source spectrum of X-6 from a circular region of 1.5′ radius, which is significantly smaller than those for other sources, since a larger area would make the X-5 contamination serious. We only used the SIS data, since the poorer spatial resolution of the GIS increases the X-5 contamination. In the obtained spectrum, however, typically ∼50% photons still originate from X-5 because of its brightness. In order to remove this residual contamination, we accumulated a background spectrum over another region having the same size as was used for the on-source spectrum. This background region is located opposite to X-6 with respect to X-5, as shown in Figure 6.8, where we expect a similar amount of contamination from X-5. We multiplied a constant factor to thus obtained background spectrum, then subtracted it from the source spectrum. This “scaling factor” is introduced to take into account the ASCA XRT’s asymmetric PSF (§ 3.2.2), and is determined based on the ray-tracing (Monte-Carlo) simulation, developed by the XRT team. By simulating the X-5 event for each observation (each position of X-5 on the focal plane), we can estimate the ratio of photons in the source region to the background region. The ratio, or the scaling factor, is typically 1.5, ranging over 1.2–1.8.

Thus, we have obtained the spectrum for X-6 plus SN 1993J. The contamination from SN 1993J is difficult to eliminate because of their short separation. Instead, we take it into account in a different way. The SN 1993J spectrum was separately estimated by Uno (1997) through one-dimensional SIS image analysis, which was originally developed by Kohmura (1994). According to Uno (1997), SN 1993J had faded away significantly after one year from the explosion, and the spectrum is expressed by a power-law of Γ = 2.5 and $f_X = 0.5 \pm 0.2 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$ in 1994 April, and of Γ = 3.0 and $f_X = 0.2 \pm 0.1 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$ in 1994 October, both in the 0.5–8 keV band. We calculate their contamination to our spectrum based on the ray-tracing simulation, and take the results into account as a fixed power-law function when fitting the X-6 spectrum. The contribution of SN 1993J to the 0.5–10 keV flux turned out to be ∼10% and ∼3% in 1994 April and October, respectively. For the other data which were obtained after 1995 April, we neglect the contribution from SN 1993J, since the supernova further faded away.

### 6.4.2 Spectra of individual observations

We fitted the obtained seven spectra separately with our typical single component models, and summarized the results in Table 6.6 and Figure 6.9. Thus, the MCD model generally provides the lowest values of $\chi^2$. Moreover, the other models are sometimes rejected at 90% confidence level, whereas the MCD fit is always acceptable. Therefore we conclude
that the spectra of M81 X-6, like those of IC 342 source 1, can be represented well by the single MCD model. As was done on IC 342 source 1, we make the $T_{\text{in}}-R_{\text{in}}^2$ diagram and show it in Figure 6.11a. It indicates that our seven datasets can be grossly grouped into two representative state; a low-temperature state observed in 1995 October and 1996 April, and a high-temperature state observed on the other occasions. The low/high-temperature states correspond to the low/high-flux states; thus M81 X-6 shows similar spectral variability to IC 342 source 1. However we do not necessarily mean that the variation of X-6 is bimodal.

### 6.4.3 Spectrum of two states

According to Figure 6.11a, we summed up the seven spectra into two spectra; the high-temperature state spectrum, and the low-temperature state one. We fitted these two spectra by the same single component models as we used on IC 342 source 1, and obtained results as summarized in Table 6.7 and Figure 6.10. The power-law model has completely failed, and the TBS and R-S models are also highly unacceptable at 95% confidence. The other three models can equally represent the data, although the broken power-law model shows slightly smaller $\chi^2/\nu$.

We also included a hard component to the MCD fit; a power-law component of $\Gamma=2.2$ or a black-body component of $kT=2.0$ keV. Again, the presence of these hard components turned out to be insignificant, and the contribution to the 0.5–10 keV flux of the hard components is small; only $\sim20\%$ at most (90% confidence) when using the black-body modeling in the low-temperature state spectrum, and $\sim30\%$ for other combinations.

We finally plotted the confidence contours of the two subgrouped spectra on the $T_{\text{in}}-R_{\text{in}}^2$ plane, by fixing the absorption at the average value of the two states, $N_H=1.8\times10^{21}$ cm$^{-2}$. As shown in Figure 6.11b, $R_{\text{in}}$ increases marginally as the flux decreases, although not so noticeable as in the case of IC 342 source 1. In fact, when we fitted the two subgrouped spectra simultaneously by constraining $N_H$ and $R_{\text{in}}$ to take the same value between them (while allowing $T_{\text{in}}$ to take separate values), we obtained an acceptable fit of $\chi^2/\nu=140.4/126$, and letting $R_{\text{in}}$ to be free does not improve the fit significantly ($\chi^2/\nu=138.0/125$). Therefore $R_{\text{in}}$ is consistent with being the same between the two spectra, although a weak anti-correlation between $T_{\text{in}}$ and $R_{\text{in}}$ may be present.

### 6.5 NGC 1313 Source B

NGC 1313 was observed twice with ASCA, in 1993 July and 1995 November (Table 4.1). Thus, like M81, this galaxy is suitable to investigate the long-term variability of the three luminous sources involved, source A, source B, and SN1978k (§ 4.2). The first observation was already reported by Petre et al. (1994), who analyzed the spectra of the three sources using power-law, TBS, and R-S models. In this thesis, we study both observations and perform more detailed spectral analysis. Among the three luminous sources, we describe source B in this section, and source A, which showed time variability in the second observation, in the next section. We study SN 1978K in § 6.9 together with other luminous extragalactic SNRs.
Table 6.6: Fitting results of the individual SIS spectra of M81 X-6 using single component models.

<table>
<thead>
<tr>
<th>date</th>
<th>Model</th>
<th>$N_H$ (10^{22} cm^{-2})</th>
<th>Parameters</th>
<th>$f_X$ (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994 Apr.</td>
<td>power-law</td>
<td>0.40±0.10</td>
<td>1.79±0.17</td>
<td>3.42</td>
<td>53.6/42 (11%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.32±0.09</td>
<td>7.1±3.2</td>
<td>3.20</td>
<td>47.8/42 (25%)</td>
</tr>
<tr>
<td></td>
<td>R-S c)</td>
<td>0.31±0.10</td>
<td>7.1±3.2</td>
<td>3.23</td>
<td>47.8/41 (22%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.19±0.06</td>
<td>1.63±0.19</td>
<td>2.94</td>
<td>43.8/42 (40%)</td>
</tr>
<tr>
<td>1994 Oct.</td>
<td>power-law</td>
<td>0.48±0.12</td>
<td>1.90±0.15</td>
<td>3.68</td>
<td>58.8/47 (12%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.38±0.08</td>
<td>5.6±1.5</td>
<td>3.45</td>
<td>45.8/47 (52%)</td>
</tr>
<tr>
<td></td>
<td>R-S c)</td>
<td>0.38±0.08</td>
<td>5.7±1.5</td>
<td>3.45</td>
<td>45.9/46 (48%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.23±0.06</td>
<td>1.51±0.14</td>
<td>3.23</td>
<td>34.9/47 (90%)</td>
</tr>
<tr>
<td>1995 Apr.</td>
<td>power-law</td>
<td>0.42±0.23</td>
<td>1.77±0.27</td>
<td>3.45</td>
<td>33.9/23 (7%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.33±0.14</td>
<td>7.5±2.6</td>
<td>3.28</td>
<td>31.6/23 (11%)</td>
</tr>
<tr>
<td></td>
<td>R-S c)</td>
<td>0.36±0.20</td>
<td>7.1±2.8</td>
<td>3.28</td>
<td>31.5/22 (9%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.14±0.15</td>
<td>1.73±0.27</td>
<td>3.09</td>
<td>29.6/23 (16%)</td>
</tr>
<tr>
<td>1995 Oct.</td>
<td>power-law</td>
<td>0.34±0.14</td>
<td>2.0±0.23</td>
<td>2.43</td>
<td>18.4/21 (62%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.23±0.10</td>
<td>4.7±2.3</td>
<td>2.28</td>
<td>16.4/21 (75%)</td>
</tr>
<tr>
<td></td>
<td>R-S c)</td>
<td>0.23±0.09</td>
<td>4.6±2.2</td>
<td>2.29</td>
<td>16.0/20 (72%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.08±0.06</td>
<td>1.34±0.23</td>
<td>2.12</td>
<td>17.7/21 (67%)</td>
</tr>
<tr>
<td>1996 Apr.</td>
<td>power-law</td>
<td>0.78±0.34</td>
<td>2.31±0.32</td>
<td>2.26</td>
<td>80.3/54 (1%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.57±0.23</td>
<td>3.4±1.2</td>
<td>2.11</td>
<td>69.8/54 (7%)</td>
</tr>
<tr>
<td></td>
<td>R-S c)</td>
<td>0.56±0.26</td>
<td>3.5±1.0</td>
<td>2.12</td>
<td>69.9/53 (6%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.33±0.14</td>
<td>1.23±0.18</td>
<td>2.02</td>
<td>61.6/54 (22%)</td>
</tr>
<tr>
<td>1996 Oct.</td>
<td>power-law</td>
<td>0.31±0.09</td>
<td>1.78±0.17</td>
<td>4.06</td>
<td>32.0/31 (42%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.22±0.09</td>
<td>7.2±3.6</td>
<td>3.85</td>
<td>29.2/31 (56%)</td>
</tr>
<tr>
<td></td>
<td>R-S c)</td>
<td>0.23±0.08</td>
<td>7.2±3.7</td>
<td>3.85</td>
<td>29.2/30 (51%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.08±0.07</td>
<td>1.63±0.23</td>
<td>3.56</td>
<td>30.2/31 (51%)</td>
</tr>
<tr>
<td>1997 May.</td>
<td>power-law</td>
<td>0.35±0.11</td>
<td>1.79±0.16</td>
<td>3.68</td>
<td>59.6/40 (2%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.26±0.08</td>
<td>6.8±2.8</td>
<td>3.47</td>
<td>52.0/40 (10%)</td>
</tr>
<tr>
<td></td>
<td>R-S c)</td>
<td>0.26±0.10</td>
<td>6.8±2.8</td>
<td>3.47</td>
<td>51.9/39 (8%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.10±0.07</td>
<td>1.61±0.19</td>
<td>3.24</td>
<td>44.5/40 (29%)</td>
</tr>
</tbody>
</table>

a) The same as Table 6.1
b) In unit of 10^{-12} erg s^{-1} cm^{-2}.
d) All the best fit parameters of the abundance are below 0.2 solar.
Table 6.7: Fitting results of the grouped SIS spectra of M81 X-6 using single component models.

<table>
<thead>
<tr>
<th>Data group</th>
<th>Model</th>
<th>$N_{\text{H}}$</th>
<th>Parameters$^a$</th>
<th>$f_X$ $^b$</th>
<th>$\chi^2/\nu$ (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-temperature</td>
<td>power-law</td>
<td>0.41±0.05</td>
<td>1.83±0.07</td>
<td>3.69</td>
<td>110.0/65 (∼1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.31±0.04</td>
<td>6.5±1.1</td>
<td>3.48</td>
<td>83.0/65 (7%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R-S$^c$</td>
<td>0.31±0.04</td>
<td>6.5±1.1</td>
<td>3.48</td>
<td>83.1/64 (5%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.16±0.03</td>
<td>1.59±0.09</td>
<td>3.24</td>
<td>68.6/65 (36%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UC</td>
<td>0.26±0.06</td>
<td>$1.28^{+0.16}<em>{-0.12}/25^{+3}</em>{-3}$</td>
<td>3.22</td>
<td>67.3/64 (37%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broken power-law</td>
<td>0.25±0.06</td>
<td>$1.36^{+0.19}<em>{-0.16}/3.24^{+0.61}</em>{-0.27}/2.5^{+0.4}_{-0.3}$</td>
<td>3.42</td>
<td>63.9/63 (45%)</td>
<td></td>
</tr>
</tbody>
</table>

| Low-temperature   | power-law           | 0.52±0.12      | 2.12±0.17      | 2.36       | 93.0/59 (∼1%)           |                                  |
|                   | TBS                 | 0.38±0.10      | 4.1±0.9        | 2.19       | 79.0/59 (4%)            |                                  |
|                   | R-S$^c$             | 0.38±0.10      | 4.0±1.1        | 2.19       | 79.1/59 (3%)            |                                  |
|                   | MCD                 | 0.20±0.08      | 1.29±0.13      | 2.07       | 68.9/59 (18%)           |                                  |
|                   | UC                  | 0.20±0.15      | $0.94^{+0.10}_{-0.12}/36^{+8}_{-12}$ | 2.02   | 66.8/58 (20%) |                                  |
|                   | Broken power-law    | 0.25±0.15      | $1.37^{+0.32}_{-0.23}/3.42^{+0.34}_{-0.27}/3.8^{+0.8}_{-0.5}$ | 2.06   | 63.6/57 (25%) |                                  |

$^a$ The same as Table 6.1.
$^b$ In unit of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.
$^c$ The abundance has been constrained to be $\leq 0.12$ solar for the high-temperature state spectrum, and $\leq 0.27$ for the low-temperature state one.

Figure 6.8: An SIS 0 image of M81 region in the 0.5–10 keV band, obtained in 1994 April. We can see X-5 and X-6 as local peaks of contours. SN 1993J had faded significantly, and we marked its position as a filled star. We also show data accumulation regions for the X-6 spectra and the background spectra.
Figure 6.9: The SIS spectra of M81 X-6 acquired on seven occasions, all fitted with an MCD model. The SN 1993J contribution is taken into account only in the first two datasets (panel (a) and panel (b)), and shown as dotted lines.
High-temperature state
(a) Power-law
(b) TBS
(c) MCD

Low-temperature state
(d) Power-law
(e) TBS
(f) MCD

Figure 6.10: The SIS spectra of M81 X-6, obtained by grouping the individual datasets according to the values of $T_{\text{in}}$. The SN 1993J contribution is taken into account as dotted lines only in the high-temperature state spectrum, which contains the 1994 observations.

(a)

Confidence Contours

(b)

Confidence Contours

Figure 6.11: The same as Figure 6.5, but for M81 X-6 instead of IC 342 source 1. (a) The contours of individual observations, where only the 68% confidence levels are shown. (b) The contours of the high/low-temperature state spectra obtained by grouping the individual datasets. The 68%, 90%, and 99% confidence levels are shown. We fixed $N_H$ at $1.8 \times 10^{21}$ cm$^{-2}$. 

80
6.5.1 1993 observation

We extracted the SIS and GIS spectra from a circular region having 3′ radius, the same as utilized previously by Petre et al. (1994), and the background spectra from blank-sky observations. We fitted the background-subtracted spectra with our typical single component models. The obtained results, which are summarized in Table 6.8 and Figure 6.12, are similar to those of IC 342 source 1 and M81 X-6; the power-law model is unacceptable, the TBS and R-S models are acceptable (within 95% confidence) but require rather large values of $N_H$ compared to the Galactic line-of-sight column density ($N_H=3.5\times10^{20}$ cm$^{-2}$), whereas the MCD model is fully satisfactory. Although the UC and broken-power-law models also provide as low $\chi^2$ as the MCD model does, $N_H$ is again rather high.

The presence of hard components is, again, insignificant. The reduction of $\chi^2$ is below 0.1 for both the $\Gamma=2.2$ power-law and the $kT=2.0$ keV black body modelings. Even when we include these hard components at the allowed upper limit (90% confidence), their contribution to the 0.5–10 keV flux is only 25% and 21% for the power-law and the black-body modelings, respectively. Therefore the single MCD model is likely to be the best representation of the data.

6.5.2 1995 observation

We extracted the source spectra in the same way as the first observation. The SIS was operated in a 1-CCD mode (Table 4.1), so that we derived the SIS background spectrum from a source-free region of the on-source data. Since the GIS data were acquired in an exceptional operation mode which sacrifices rise-time information to improve the time resolution (in search for a pulsar in SN1978k), we cannot apply the off-line rise-time cut screening to the data (§ 3.4.2). Therefore we extracted the GIS background spectrum from blank-sky observations without applying the off-line rise-time cut, too.

The obtained SIS/GIS spectra have been fitted jointly with our typical single component models, in the same way as for the 1993 data. The fitting results are summarized in Table 6.8 and Figure 6.12, together with those of the first observation. Thus, the flux decreased to $\sim40\%$ of the 1993 value in two years, regardless of the assumed models. Comparison among the five single-component models leads us to the same conclusion as was obtained for IC 342, M81 X-6, and the 1993 data of NGC 1313 source B. That is, the MCD model is best preferred based on the $\chi^2$ goodness as well as the smallness of $N_H$. Data do not require separate hard components, with the $\Gamma=2.2$ power-law and the $kT=2.0$ keV black-body contributing at most 58% and 24% to the 0.5–10 keV source flux, respectively.

Since the MCD model is likely to be the best model to represent the data, for both the 1993 observation and the 1995 observation, we plotted the confidence contours in the $T_{\text{in}}-R_{\text{in}}^2$ plane in Figure 6.13, fixing the absorption at $N_H=7\times10^{20}$ cm$^{-2}$ (the average value between the two observations). Like the two variable sources so far studied, a slight increase in $R_{\text{in}}$ can be seen as the flux decreases. The change of $R_{\text{in}}$ is significant, since we obtain the significantly improved fit ($\chi^2/\nu=214.9/207$) when fitting the two observation simultaneously allowing $R_{\text{in}}$ to take separate values, compared with that ($\chi^2/\nu=222.9/208$) obtained when constraining $R_{\text{in}}$ to be common.
Figure 6.12: The SIS and GIS spectra of NGC 1313 source B, jointly fitted with single component models.
Table 6.8: Joint fit results of the SIS/GIS spectra of NGC 1313 source B using single component models.

<table>
<thead>
<tr>
<th>Data</th>
<th>Model</th>
<th>(N_H) ((10^{22} \text{cm}^{-2}))</th>
<th>Parameter (^{a)} )</th>
<th>(f_X) (^{b)} ) ((0.5–10 \text{ keV}))</th>
<th>(\chi^2/\nu) () (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993 Jul.</td>
<td>power-law</td>
<td>0.40±0.07</td>
<td>1.99±0.09</td>
<td>3.91</td>
<td>174.2/130 (\leq 1%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.26±0.05</td>
<td>5.1^{+0.8}_{-0.8}</td>
<td>3.73</td>
<td>143.2/130 (20%)</td>
</tr>
<tr>
<td></td>
<td>R-S^c)</td>
<td>0.26±0.06</td>
<td>5.1^{+0.8}_{-0.6}</td>
<td>3.73</td>
<td>143.4/129 (18%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.08±0.04</td>
<td>1.47±0.08</td>
<td>3.59</td>
<td>124.5/130 (62%)</td>
</tr>
<tr>
<td></td>
<td>UC</td>
<td>0.16±0.08</td>
<td>1.13^{+0.15}<em>{-0.10}/27^{+5}</em>{-4}</td>
<td>3.54</td>
<td>125.6/129 (57%)</td>
</tr>
<tr>
<td></td>
<td>Broken power-law</td>
<td>0.17±0.08</td>
<td>1.40±0.18/3.35^{+0.32}<em>{-0.35}/2.81^{+0.34}</em>{-0.29}</td>
<td>3.72</td>
<td>126.2/128 (53%)</td>
</tr>
<tr>
<td>1995 Nov.</td>
<td>power-law</td>
<td>0.44±0.08</td>
<td>2.46±0.13</td>
<td>1.51</td>
<td>110.3/74 (\leq 1%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.23±0.06</td>
<td>2.9±0.4</td>
<td>1.44</td>
<td>91.8/74 (8%)</td>
</tr>
<tr>
<td></td>
<td>R-S^c)</td>
<td>0.23±0.06</td>
<td>2.9±0.4</td>
<td>1.44</td>
<td>91.9/73 (7%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.06±0.05</td>
<td>1.07±0.07</td>
<td>1.39</td>
<td>89.8/74 (10%)</td>
</tr>
<tr>
<td></td>
<td>UC</td>
<td>0.20±0.10</td>
<td>0.97±0.13/24^{+5}_{-5}</td>
<td>1.40</td>
<td>89.6/73 (9%)</td>
</tr>
<tr>
<td></td>
<td>Broken power-law</td>
<td>0.24±0.10</td>
<td>1.86±0.25/3.06^{+0.42}<em>{-0.43}/3.28^{+0.61}</em>{-0.43}</td>
<td>1.45</td>
<td>87.9/72 (10%)</td>
</tr>
</tbody>
</table>

\(^{a)}\) The same as Figure 6.1.  
\(^{b)}\) In unit of \(10^{-12} \text{erg s}^{-1} \text{cm}^{-2}\).  
\(^{c)}\) The abundance has been constrained to be \(\leq 0.06 \text{ solar}\) for the 1993 observation, and \(\leq 0.08 \text{ solar}\) for the 1995 observation.

Figure 6.13: The same as Figure 6.5, but for the NGC 1313 source B instead of IC 342 source 1. We fixed the photoelectric absorption at \(N_H=7 \times 10^{20} \text{ cm}^{-2}\).
6.6 NGC 1313 Source A

As mentioned in § 5.2, this ULX showed flux decrease during the second observation. Therefore, we first analyze the time-averaged spectrum of each observation, and then investigate the short-term spectral variability in the second observation.

6.6.1 Averaged spectra of each observation

We extracted the source and background spectra in the same way as for source B. We fitted the spectra in the same way as before, and obtained the results as presented in Table 6.9 and Figure 6.14. Our spectral parameters of the power-law, TBS, and R-S models in the 1993 observation agree with those of Petre et al. (1994) within the statistical errors.

The results on source A are noticeable, because the MCD model gives the worst fit and is statistically rejected (99% confidence) for the 1993 observation, like M33 X-8. Instead, the power-law and TBS (or most identical R-S) models are acceptable for both 1993 and 1995 data. However, representing the spectra of source A by these models is not fully satisfactory; the obtained values of $N_H$ somewhat contradict the Galactic line-of-sight column density ($N_H=3.5 \times 10^{20}$ cm$^{-2}$) for the TBS and R-S modelings of the 1993 data. Moreover, either model provides inconsistent values of the absorption between the 1993 and 1995 observation, although it does not necessarily mean a problem.

Thus, we suspect that the spectra of source A had changed, for two years, not only in its hardness but also in its composition, and this causes the apparent change of $N_H$. In order to compare the spectra of the two observations in a model-independent manner, we plotted “unfolded” (detector efficiency removed) spectra of the two observations in Figure 6.15. It implies that the flux in the soft-energy band had increased for two years, while that in the hard-energy band had decreased. Such a spectral behavior reminds us of the soft-hard transitions seen in the Galactic BHBs (§ 2.3.4).

Therefore we refitted the data with a single power-law model or a power-law plus MCD model, corresponding to the hard and soft state spectra of BHBs respectively, with the absorption fixed at the Galactic value. Using the single power-law model, we obtained an acceptable fit ($\chi^2/\nu=114.8/152$) for the 1993 spectra with $\Gamma=1.69\pm0.05$, a typical value for the BHBs in the hard state. On the other hand, the fit failed ($\chi^2/\nu=170.8/101$) for the 1995 datasets and the fit residuals, which is shown in Figure 6.16a, indicate that the actual spectra has a convex shape in the 1–5 keV band so that the power-law model is too “straight” to represent the data. This is also evident from the unfolded spectra of Figure 6.15b. We hence added a MCD component for the 1995 data, to make the spectrum more “convex” in the low-energy band, and obtained an acceptable fit of $\chi^2/\nu=91.9/99$.

We summarize the fitting results in Table 6.10 and Figure 6.16; the obtained parameters have typical values for the soft-state BHBs. We hence adopt the single power-law model and the power-law plus MCD model to describe the spectra of the 1993 observation and the 1995 one respectively, although we cannot reject statistically other modelings such as the power-law model with absorption which is allowed to change.

6.6.2 Variability in the second observation

Since the flux of the source showed a monotonic decrease, we divided the data into two parts; the former half and the latter half, as shown in Figure 5.5, and accumulated the
individual spectra. In order to obtain a crude information of the spectral variability, we first make a count-rate ratio between the two datasets. As shown in Figure 6.17, the decrease of the source intensity is noticeable in the high-energy band. This suggests that the hard band power-law component changed, while the soft MCD component stayed constant. To confirm this insight, we fitted the two sets of spectra with the power-law plus MCD model, fixing $\Gamma$ and $T_{in}$ at the best-fit value of the averaged spectra to obtain a stable fitting. The results are summarized in Table 6.10 and Figure 6.18. Thus, the flux of the power-law component significantly decreased by $\sim 30\%$ from the former period to the latter one, whereas that of the MCD component is almost constant; this agrees with the implication of Figure 6.17. This behavior, i.e. variation of the hard component with little change of the MCD component, is often seen from soft-state BHBs.

In this way, the long-term variation of source A can be interpreted as a soft-hard state transition of a BHB (except for the higher flux in the hard state), and its short-term variability in 1995 can be described as a change in the hard-tail component. These results support the BH interpretation of source A. We note that the value of $T_{in}=0.67$ keV of this object (Table 6.10) is comparable to those of Galactic and Magellanic BHBs, while significantly lower than those of other ULXs.

Table 6.9: Summary of the spectral fitting results of NGC 1313 source A. The SIS/GIS spectra are fitted jointly with our typical single component models.

<table>
<thead>
<tr>
<th>date</th>
<th>Model</th>
<th>$N_H$ ($10^{22}$cm$^{-2}$)</th>
<th>$\Gamma$ or $T_{in}$ (keV)</th>
<th>$f_X$ a) (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993 Jul.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>power-law</td>
<td>0.10$\pm$0.04</td>
<td>1.79$\pm$0.07</td>
<td>3.95</td>
<td>109.5/151 (99%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>$\leq$0.03</td>
<td>7.5$\pm$1.0</td>
<td>3.87</td>
<td>107.8/151 (99%)</td>
</tr>
<tr>
<td></td>
<td>R-S$^{b)}$</td>
<td>$\leq$0.04</td>
<td>7.3$\pm$1.0</td>
<td>3.87</td>
<td>107.2/151 (99%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>$\leq$0.01</td>
<td>1.43$\pm$0.06</td>
<td>3.27</td>
<td>216.0/151 ($\leq$1%)</td>
</tr>
<tr>
<td>1995 Nov.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>power-law</td>
<td>0.36$\pm$0.06</td>
<td>2.81$\pm$0.14</td>
<td>2.96</td>
<td>88.6/100 (79%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.11$\pm$0.05</td>
<td>2.0$^{+0.3}_{-0.2}$</td>
<td>2.89</td>
<td>91.7/100 (71%)</td>
</tr>
<tr>
<td></td>
<td>R-S$^{b)}$</td>
<td>0.11$\pm$0.05</td>
<td>2.0$^{+0.3}_{-0.2}$</td>
<td>2.91</td>
<td>91.5/99 (69%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>$\leq$0.02</td>
<td>0.82$\pm$0.04</td>
<td>2.74</td>
<td>117.8/100 (11%)</td>
</tr>
</tbody>
</table>

a) In unit of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.

b) The best fit abundance is 0.08($\leq$0.27) solar for the 1993 observation, and 0.04($\leq$0.12) solar for the 1995 observation.

6.7 NGC 4565

This edge-on galaxy has two luminous sources, as already mentioned in § 4.2; one is $\sim 0.8'$ above the galaxy disk, while the other is positionally coincident with the galactic nucleus, as shown in Figure 6.19 (see also images in Appendix C). Because of a short separation ($\sim 0.8'$) of these two sources, we first analyze the summed energy spectra in § 6.7.1, and then investigate the individual spectra in § 6.7.2. These results have already been published as Mizuno et al. (1999).
Figure 6.14: The same as Figure 6.12, but for NGC 1313 source A instead of source B.
Table 6.10: Joint fit results of the SIS/GIS spectra of NGC 1313 source A in the second observation. The spectra are fitted with the power-law plus MCD model.

<table>
<thead>
<tr>
<th>Period</th>
<th>$N_{\text{H}}$ $(10^{22}\text{cm}^{-2})$</th>
<th>$\Gamma$</th>
<th>$f_X^\text{hard}$ a) $(0.5–10\text{ keV})$</th>
<th>$T_{\text{in}}$ (keV)</th>
<th>$f_X^\text{soft}$ a) $(0.5–10\text{ keV})$</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.035(fix)</td>
<td>1.74$^{+0.14}_{-0.12}$</td>
<td>1.38</td>
<td>0.67$^{+0.08}_{-0.06}$</td>
<td>1.78</td>
<td>91.9/99 (68%)</td>
</tr>
<tr>
<td>Former</td>
<td>0.035(fix)</td>
<td>1.74(fix)</td>
<td>1.60</td>
<td>0.67(fix)</td>
<td>1.82</td>
<td>68.8/64 (32%)</td>
</tr>
<tr>
<td>Latter</td>
<td>0.035(fix)</td>
<td>1.74(fix)</td>
<td>1.12</td>
<td>0.67(fix)</td>
<td>1.75</td>
<td>56.1/55 (43%)</td>
</tr>
</tbody>
</table>

a) In unit of $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$.

Figure 6.15: Changes of the source A spectra from the 1993 observation to the 1995 one. We show the “unfolded” (detector efficiency removed) spectra for direct comparison. The histograms represent the best-fit power-law model of Table 6.9. The spectrum of the 1995 observation shows higher flux in the low-energy band.

(a) Unfolded spectra of the SIS
(b) Unfolded spectra of the GIS

Figure 6.16: The spectra of source A in the 1995 observation, fitted jointly with the single power-law model or the power-law plus MCD model. In the latter case, the contribution of each component is shown as dotted lines, and the SIS/GIS spectra are separately displayed for clarify.

(a) Single power-law  (b) PL+MCD SIS  (c) PL+MCD GIS
Figure 6.17: The count-rate ratio between the former and the latter half of the 1995 observation of NGC 1313 source A.

Figure 6.18: The SIS/GIS spectra of source A in the 1995 observation, jointly fitted with the power-law plus MCD model. Panel (a) represents the spectra obtained in the former-half period, while (b) represents the spectra of the latter-half one.
6.7.1 Summation of the two sources

Before extracting the summed energy spectra, we investigate the hardness of two sources, in order to grasp rough spectral properties of them. We projected the SIS events inside the rectangle of Figure 6.19 onto its longer side. The derived one-dimensional X-ray profiles are shown in Figure 6.20, in three representative energy bands. Each profile is fitted by the projected PSF of the XRT convolved with the two point sources of which the projected positions are fixed at those indicated by the ROSAT image. We assumed a constant background and determined the intensity of the two sources in the three energy band, as tabulated in Table 6.11. Thus, the intensity ratios of the two sources are energy independent within statistical errors, indicating that the two sources have similar spectra, as reported by Mizuno et al. (1999). We therefore accumulated events over circular regions of radius 4′ and 6′ for the SIS and the GIS, respectively, both centered on the off-center (brighter) source but including the other source as well. The obtained spectra, which co-add photons from the two sources, are fitted with single-component models, as summarized in Table 6.12 and Figure 6.21a. For the spectral fitting, we used the response function for a point source located at the off-center source.

Like most of the sources we studied so far, the power-law model is completely unacceptable, the TBS and R-S models give better fits but require large absorption compared with the Galactic $N_H (1.3 \times 10^{20} \text{cm}^{-2})$, whereas the MCD model shows the lowest $\chi^2$ and a reasonable value of $N_H$. The data also need no additional hard components, and their contribution to the 0.5–10 keV flux is at most (90% confidence) $\sim 30\%$ for both the $\Gamma = 2.2$ power-law and the $kT = 2.0$ keV black-body component. In short, when the spectra of the two objects are added together, the results can be represented well by an MCD model of $T_{in} \sim 1.4$ keV, as already pointed out by Mizuno et al. (1999).

6.7.2 Individual sources

As a further investigation, we attempted to estimate the spectra of the two sources individually, after Mizuno et al. (1999). We therefore fitted the same SIS and GIS spectra jointly with a sum of two MCD components having separate temperatures, separate normalizations, and separate column densities, which were all left free to vary. In order to ensure that the two model components are well determined, we imposed additional constraints that each MCD component should correctly reproduce the three-band coarse spectrum of the corresponding source, which was produced by converting the count rates in Table 6.11. The response function to represent the three-band spectra was made by scaling and rebinning the response function used in the previous subsection. As a result, we jointly fitted four spectra (whole spectrum of the SIS, that of the GIS, three-band SIS spectrum for the off-center sources, and that for the center source) and determined the model parameters to minimize the total chi-square. We show these four spectra in Figure 6.21b.

This composite model have given an acceptable fit with $\chi^2/\nu = 147.7/124$. The obtained results, summarized in Table 6.13, imply that the two sources exhibit the same disk temperature within errors, which in turn agree with that derived in Table 6.12. This justifies our analysis performed in the previous subsection. Neither source exhibits detectable absorption, again in agreement with Table 6.12. Even when we represent the center source spectrum by a power-law model, its absorption remains rather low, $N_H$. 

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$\leq 2 \times 10^{21} \text{ cm}^{-2}$. This fact contradicts the interpretation that the center source is an LLAGN located at the galactic nucleus, since the column density along the galactic disk to the nucleus of such an edge-on galaxy ($i=86^\circ$, Hummel et al. 1984) would amount to at least $\sim 1 \times 10^{22} \text{ cm}^{-2}$. Thus, we regard both the off-center and center sources as ULXs, as already reported by Mizuno et al. (1999). Their disk temperatures, $T_{\text{in}}$, are $\sim 1.5 \text{ keV}$, similar to those of M81 X-6 and NGC 1313 source B in the 1993 observation.

Table 6.11: Observed count rates (in $10^{-2} \text{ c s}^{-1}$) of the two sources in NGC 4565.

<table>
<thead>
<tr>
<th>Source</th>
<th>soft</th>
<th>medium</th>
<th>hard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0.5–1.5 keV)</td>
<td>(1.5–3 keV)</td>
<td>(3–10 keV)</td>
</tr>
<tr>
<td>Off-center</td>
<td>1.41±0.10</td>
<td>1.24±0.09</td>
<td>0.64±0.07</td>
</tr>
<tr>
<td>Center</td>
<td>0.54±0.09</td>
<td>0.37±0.07</td>
<td>0.27±0.06</td>
</tr>
<tr>
<td>Ratio$^{c)}$</td>
<td>2.61±0.47</td>
<td>3.35±0.68</td>
<td>2.37±0.59</td>
</tr>
</tbody>
</table>

$^a)$ Count rate of the event inside the rectangle shown in Figure 6.19, obtained through fitting to the one-dimensional profile of Figure 6.20.
$^b)$ Errors represent one-sigma statistical errors, instead of the 90% confidence limit.
$^c)$ Count rate ratio of the off-center source to the center one.

Table 6.12: Results of the joint fits to the SIS and GIS spectra of NGC 4565 with single component models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_H$ $(10^{22} \text{ cm}^{-2})$</th>
<th>$\Gamma$ or $T$ $^{b)}$ or $T_{\text{in}}$ (keV)</th>
<th>$f_X$ $(0.5–10 \text{ keV})$</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-law</td>
<td>0.25±0.05</td>
<td>1.89$^{+0.09}_{-0.08}$</td>
<td>2.64</td>
<td>174.2/121 ($\leq 1%$)</td>
</tr>
<tr>
<td>TBS</td>
<td>0.14±0.04</td>
<td>5.6$^{+0.9}_{-0.7}$</td>
<td>2.47</td>
<td>152.4/121 (3%)</td>
</tr>
<tr>
<td>R-S$^{c)}$</td>
<td>0.14±0.04</td>
<td>5.5$^{+0.9}_{-0.7}$</td>
<td>2.47</td>
<td>152.3/120 (2%)</td>
</tr>
<tr>
<td>MCD</td>
<td>$\leq 0.02$</td>
<td>1.43$^{+0.07}_{-0.06}$</td>
<td>2.32</td>
<td>145.9/121 (6%)</td>
</tr>
</tbody>
</table>

$^a)$ Spectra of the two sources are co-added together.
$^b)$ In units of $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$.
$^c)$ The abundance has been constrained to be $\leq 0.1$ solar.

6.8 Other ULXs

We study all remaining ULXs together in this section, since they have rather poorer photon statistics, or do not show significant features, such as time variability, which require detailed analysis. We only use our basic single component models; a power-law, a TBS, a R-S, or an MCD model, to fit their spectra. All the fitting results are summarized in Table 6.14 and Figure 6.22.
Table 6.13: Estimates of the spectra of the individual sources in NGC 4565.a)

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_H$ $(10^{22} \text{ cm}^{-2})$</th>
<th>$T_{in}$ (keV)</th>
<th>$f_X$ b) $(0.5–10 \text{ keV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-center</td>
<td>$\leq 0.02$</td>
<td>$1.39 \pm 0.08$</td>
<td>$1.65$</td>
</tr>
<tr>
<td>Center</td>
<td>$\leq 0.05$</td>
<td>$1.59^{+0.32}_{-0.23}$</td>
<td>$0.67$</td>
</tr>
</tbody>
</table>

a) The SIS/GIS spectra of NGC 4565 were fitted jointly with two MCD components, which are constrained to reproduce the count rates in Table 6.11.

b) In unit of $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$.

Figure 6.19: ASCA SIS image of NGC 4565, superposed on the optical image (Digital Sky Survey). A rectangle in the image is used to make one-dimensional X-ray profiles (see text). See also Appendix C, where the ROSAT HRI and GIS images are shown.

Figure 6.20: The projected one-dimensional X-ray brightness distribution of NGC 4565, in 0.5–1.5 keV (panel a), 1.5–3 keV (panel b), and 3–10 keV (panel c). The SIS events within the rectangle of Figure 6.19 are used. The dotted, dashed, and dot-dashed lines indicate the model for the center-source, that for the off-center source, and a constant background, respectively.
6.8.1 IC 342 source 2

This is the second brightest source in IC 342. We accumulated the spectra in the same way as for source 1 in the same galaxy (§ 6.2). All of our four models are statistically acceptable, and the obtained fitting parameters are consistent with those reported by Okada et al. (1998). Although the MCD model provides the lowest $\chi^2/\nu$, the obtained temperature ($T_{\text{in}} \sim 3$ keV) is uncomfortably high compared with those of other ULXs we studied so far. The TBS and R-S models also show quite high temperature of $kT \geq 30$ keV, well beyond the high-energy end of the ASCA band. These facts mean that the actual data has a straight shape in logarithmic plot, and obtained high temperatures might be artifacts. We consider that the power-law model best represent the spectrum of IC 342 source A, although the other models cannot be rejected. The obtained photon index, $\Gamma = 1.47 \pm 0.17$, is similar to those of BHBs in high-state, so that the source, like NGC 1313 source A in the 1993 observation, can be explained as a BHB in high state. Regardless of the assumed model, this source shows high absorption ($N_H \geq 10^{22}$ cm$^{-2}$), well beyond the Galactic line-of-sight column density ($N_H = 3 \times 10^{21}$ cm$^{-2}$).

6.8.2 NGC 2403 source 3

This, the brightest source in NGC 2403, has been known as ULX since the Einstein era (§ 4.2). We extracted the SIS and GIS spectra from a circular region of 2’ radius, slightly smaller than usual, to avoid contamination from nearby weak sources (see ASCA images in Appendix C). Spectral fitting results are similar to those obtained from most of our sample objects; the MCD model best represents the data judging on the $\chi^2$ goodness, and provides reasonable value of $N_H$ compared with the Galactic absorption ($N_H = 4 \times 10^{20}$ cm$^{-2}$). The obtained value of $T_{\text{in}}$, $\sim 1.2$ keV, is similar to that of M33 X-8.
6.8.3 Dwingeloo 1 X-1

As mentioned in § 4.2, this galaxy was newly discovered behind the Milky way (Kraan–Korteweg et al. 1994), and Reynolds et al. (1997) found an off-center source, namely Dwingeloo 1 X-1, with ASCA. We used a 3′ radius circle to extract the source spectra. Since the source is located on the Galactic plane as mentioned in § 4.2, we extracted the background spectrum from on-source data not only for the SIS but also for the GIS. The obtained parameters of the power-law, TBS, and R-S model fittings are consistent with those of Reynolds et al. (1997), and all these three models as well as the MCD one produce similar values of \( \chi^2 \), probably because of rather poor photon statistics. However, the MCD model is somewhat preferred; it provides the value of \( N_H \) comparable to the Galactic line-of-sight column density (\( N_H = 7 \times 10^{21} \) cm\(^{-2} \)), whereas the others require excess absorption. The obtained value of \( T_{in} \) is as high as that of IC 342 source 1.

6.8.4 NGC 1365 SW source

This source is located close (\( \sim 1.2 \)) to the galaxy nucleus, an LLAGN of the host galaxy. In order to avoid the contamination from the nucleus as much as possible, we used only the SIS data which has a higher spatial resolution than the GIS, and we reduced the radius of the source-extracting region to 1.5′. In addition, we shifted the integration center from the source center by \( \sim 1′ \) to the direction opposite to the nucleus. The background subtraction is performed in the same way as for M81 X-6, in order to remove the contaminating photons from the nucleus. Because of quite poor statistics, we cannot tell which model is preferred based on the values of \( \chi^2 \), as indicated by Table 6.14. If we adopt the MCD model to describe the spectrum, the source shows a similar value of \( T_{in} \) to other ULXs, such as M81 X-6, NGC 1313 source B in the 1993 observation, and two ULXs in NGC 4565. The source flux we obtained is \( \sim 40\% \) of that reported by Iyomoto et al. (1997), mainly because they used blank-sky data to extract the background spectrum, whereas we used the on-source data and thus subtracted the contamination from the nucleus source. The spectrum reported by Iyomoto et al. (1997) was too hard for the same reason.

6.8.5 NGC 3628 off-center source

The source unfortunately fell on the inter-chip gap of the SIS, so that we used only the GIS data. Since the source has the lowest flux among our objects, we extracted the spectrum from a circular region of rather small radius, 2′; using a larger region makes the S/N ratio worse. Like NGC 1365 SW source, all our models provide similar values of \( \chi^2 \), and spectral parameters of the power-law and TBS models are consistent with those reported by Yaqoob et al. (1995). Regardless of the assumed model, the obtained spectrum shows excess absorption above the Galactic line-of-sight column density, \( N_H = 2 \times 10^{20} \) cm\(^{-2} \). If we employ the MCD model, the best-fit value of \( T_{in} \) (\( \sim 1.1 \) keV) is similar to that of M33 X-8 and NGC 2403 source 3, although the statistical error is relatively large.

6.9 SNRs

Among our sample objects, we finally analyze the X-ray luminous extragalactic young SNRs; north-arm SNR in NGC 6946, SN 1978K in NGC 1313, and SN 1986J in NGC 891.
Table 6.14: Fitting results of remaining ULXs, using single component models.

<table>
<thead>
<tr>
<th>Source</th>
<th>Model</th>
<th>$N_H$ $(10^{22} \text{cm}^{-2})$</th>
<th>$\Gamma$ or $kT$ or $T_{in}$ (keV)</th>
<th>$f_X$ $^{a)}$ $(0.5–10 \text{ keV})$</th>
<th>$\chi^2/\nu$</th>
<th>(confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 342 source 2</td>
<td>power-law</td>
<td>1.43±0.16</td>
<td>1.39±0.10</td>
<td>4.14</td>
<td>102.8/87</td>
<td>(12%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>1.35±0.13</td>
<td>37$^{+13}_{-14}$</td>
<td>4.11</td>
<td>100.1/87</td>
<td>(14%)</td>
</tr>
<tr>
<td></td>
<td>R-S$^{b)}$</td>
<td>1.35±0.13</td>
<td>37$^{+17}_{-14}$</td>
<td>4.10</td>
<td>100.0/87</td>
<td>(14%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.99±0.09</td>
<td>3.03$^{+0.38}_{-0.24}$</td>
<td>3.95</td>
<td>96.4/87</td>
<td>(23%)</td>
</tr>
<tr>
<td>NGC 2403 source 3</td>
<td>power-law</td>
<td>0.47±0.11</td>
<td>2.23$^{+0.16}_{-0.13}$</td>
<td>1.66</td>
<td>85.7/58</td>
<td>(1%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.29±0.08</td>
<td>3.7±0.6</td>
<td>1.57</td>
<td>71.0/58</td>
<td>(12%)</td>
</tr>
<tr>
<td></td>
<td>R-S$^{b)}$</td>
<td>0.29±0.08</td>
<td>3.6±0.5</td>
<td>1.58</td>
<td>71.1/57</td>
<td>(10%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.11±0.07</td>
<td>1.23±0.10</td>
<td>1.50</td>
<td>64.9/58</td>
<td>(25%)</td>
</tr>
<tr>
<td>Dwingeloo 1 X-1</td>
<td>power-law</td>
<td>1.23$^{+0.32}_{-0.28}$</td>
<td>1.87±0.26</td>
<td>0.90</td>
<td>64.4/59</td>
<td>(29%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>1.04$^{+0.23}_{-0.20}$</td>
<td>7.3$^{+3.8}_{-2.1}$</td>
<td>0.86</td>
<td>63.9/59</td>
<td>(33%)</td>
</tr>
<tr>
<td></td>
<td>R-S$^{b)}$</td>
<td>1.03$^{+0.26}_{-0.20}$</td>
<td>7.4$^{+2.6}_{-2.1}$</td>
<td>0.86</td>
<td>63.3/58</td>
<td>(30%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.75±0.18</td>
<td>1.80$^{+0.33}_{-0.26}$</td>
<td>0.80</td>
<td>64.0/59</td>
<td>(25%)</td>
</tr>
<tr>
<td>NGC 1365 SW source</td>
<td>power-law</td>
<td>0.84$^{+0.74}_{-0.59}$</td>
<td>2.00$^{+0.57}_{-0.64}$</td>
<td>0.45</td>
<td>8.8/10</td>
<td>(55%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.62$^{+0.73}_{-0.49}$</td>
<td>5.5$^{+3.7}_{-1.4}$</td>
<td>0.43</td>
<td>8.9/10</td>
<td>(55%)</td>
</tr>
<tr>
<td></td>
<td>R-S$^{b)}$</td>
<td>0.63$^{+0.95}_{-0.44}$</td>
<td>5.4$^{+3.6}_{-3.2}$</td>
<td>0.43</td>
<td>8.9/9</td>
<td>(45%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.37$^{+0.61}_{-0.35}$</td>
<td>1.51$^{+1.04}_{-0.47}$</td>
<td>0.39</td>
<td>9.3/10</td>
<td>(51%)</td>
</tr>
<tr>
<td>NGC 3628 off-center</td>
<td>power-law</td>
<td>1.14$^{+0.91}_{-0.79}$</td>
<td>2.61$^{+0.91}_{-0.59}$</td>
<td>0.39</td>
<td>5.4/12</td>
<td>(84%)</td>
</tr>
<tr>
<td></td>
<td>TBS</td>
<td>0.71$^{+0.68}_{-0.44}$</td>
<td>2.9$^{+3.2}_{-1.3}$</td>
<td>0.36</td>
<td>5.2/12</td>
<td>(95%)</td>
</tr>
<tr>
<td></td>
<td>R-S$^{b)}$</td>
<td>0.71$^{+0.77}_{-0.48}$</td>
<td>2.9$^{+3.2}_{-1.3}$</td>
<td>0.36</td>
<td>5.2/12</td>
<td>(92%)</td>
</tr>
<tr>
<td></td>
<td>MCD</td>
<td>0.42$^{+0.42}_{-0.31}$</td>
<td>1.12$^{+0.55}_{-0.41}$</td>
<td>0.34</td>
<td>5.2/12</td>
<td>(91%)</td>
</tr>
</tbody>
</table>

$^a)$ In unit of $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$.

$^b)$ The best-fit values of the abundance are below 0.1 solar for all the sources.
Figure 6.22: The spectra of remaining ULXs, fitted with single component models. We used only the SIS data for NGC 1365 SW source, and the GIS data for NGC 3628 off-center source. The spectra of IC 342 source 2 are fitted with a power-law model, while all the other sources are fitted with an MCD model.
Our aim is to compare these SNRs with ULXs so far studied, but not to study their detailed emission mechanism. Therefore, we focus on their X-ray spectral properties, and do not mention their detailed features in other wavebands. Before performing the spectral fitting of each source, we plot their unfolded spectra in Figure 6.23. By comparing them with the unfolded spectra of IC 342 source 1 in Figure 6.2, we can see distinctive features of these extragalactic SNRs in a model independent manner as below. North-arm SNR in NGC 6946 and SN 1978K have rather straight shape in the high-energy band, implying that a non-thermal emission, such as synchrotron radiation, is the emission mechanism. Although SN 1986J has relatively convex curvature like IC 342 source 1, a prominent line-feature is clearly seen around 6–7 keV. We tentatively fit the spectra in the 5–10 keV band by a power-law model with a single gaussian component, and obtained the line-center energy as 6.73±0.12 keV, which can be attributed to the line emission from highly ionized iron in the optically-thin hot plasma. Thus the R-S model with a high-temperature is expected to represent the data. To confirm these features quantitatively, we fit their ASCA spectra, first with typical single component models, and then, if needed, test more complicated ones. These spectral fitting results are summarized in Table 6.15, Table 6.16, and Figure 6.24.

**North-arm SNR in NGC 6946** This source is identified as an SNRs based on its positional coincidence by Schlegel (1994), as already described in § 4.2. ASCA observed NGC 6946 twice, in 1993 May and 1994 December (Table 4.1). Since the source is located near (∼2.5′) the galaxy nucleus, which exhibits X-ray emission probably because of starburst activity of the host galaxy, we analyzed only the SIS data and extracted the spectrum from 1.5′ radius circular region. Unfortunately, the source fell on the inter-chips gap in the 1993 observation, so that we do not use this dataset.

As already inferred from Figure 6.23, the MCD model gives the worst $\chi^2/\nu$ and is completely rejected (see Table 6.15). None of the other models are acceptable at 90% confidence, either. These failure of the fitting is caused by the excess in the soft-energy band ($\leq$1 keV), as shown in Figure 6.24a. This indicates the presence of a soft component, probably due to thin-thermal radiation frequently observed in Galactic SNRs (§ 2.3.1).

Accordingly, we added a R-S model as the soft component to the power-law or TBS models, and summarized the fitting results in Table 6.16. Both composite models represent the observed spectrum equally well, and the presence of these soft components is quite significant, at 99% confidence level based on an $F$-test. The power-law plus R-S model is somewhat preferred since the obtained $N_H$ is consistent with the Galactic line-of-sight column density ($N_H=2\times10^{21}\text{cm}^{-2}$). Thus, the emission from NGC 6946 north-arm SNR is explained by a $\Gamma \sim 2$ power-law and a $kT \leq 1$ keV plasma emission, which can be attributed, for example, to Crab-type synchrotron radiation and shock-heated thermal emission, respectively. The 0.5–10 keV luminosity becomes $5\times10^{39}$ erg s$^{-1}$ at an assumed distance of 5.5 Mpc.

**SN 1978K** The X-ray emission from SN 1978K, located in NGC 1313, was first discovered by *ROSAT* serendipitously in a 1990 observation (Ryder et al. 1993). It was recognized as a supernova first on the basis of its X-ray and radio emission, and then optically identified as a Type II supernova which detonated in 1978 June.
We accumulated the source spectrum from 2′ radius circular region, rather smaller than usual, in order to avoid the overlap with those for source A and source B. The background subtraction is done in the same way as for these sources.

Like NGC 6946 north-arm SNR, the MCD model is rejected for both the 1993 and 1995 observation. All the other models are acceptable for the 1993 observation, as already reported by Petre et al. (1994). However, none of our single component models succeed for the 1995 data and there exists soft excess, again like the SNR in NGC 6946. Accordingly, we added a R-S model to the power-law or the TBS model, and obtained the results as given in Table 6.16. Thus, the presence of these soft components is significant at 99% confidence. We also added the same soft component to the data of 1993 observation, fixing the temperature and the abundance at the best-fit values of the 1995 observation to obtain a stable fitting. As indicated by Table 6.16, the presence of these soft components is also significant, although the confidence level is relatively low, at 90% when adding the soft component to the power-law model. The source flux seems to have changed from the 1993 observation to the 1995 one for both hard and soft components, regardless of the model combination. Anyway, SN 1978K shows spectral parameters similar to those of the north-arm SNR in NGC 6946.

**SN 1986J** As already mentioned in § 4.2, three ROSAT and two ASCA observations were already reported by Houck et al. (1998). Here we analyze only the ASCA data.

For both 1994 and 1996 observations, we extracted the source spectrum from a 3′ radius region. The R-S model provide the lowest value of $\chi^2$ for both the 1994 and 1996 observations among our single component models, and can represent the Fe-line feature seen in the spectra around 6.7 keV. This result confirms the analysis by Houck et al. (1998), although they performed more detailed spectral study.

In summary, all these three SNRs show spectral features different from ULXs we studied so far. None of our ULXs shows the $kT \sim 1$ keV soft thermal radiation observed from the north-arm SNR in NGC 6946 and SN 1978K, or the Fe-line emission as is seen in SN 1986J. Thus, we securely conclude that ULXs belong to a category which is different from luminous SNRs. In particular, none of our ULXs are likely to be unidentified SNRs. We have thus ruled out one of the scenarios (§ 2.5.3) explaining the ULXs.

### 6.10 Comparison of the Spectral Modelings

Among our single component models so far tested, the power-law model represents a straight line, the TBS model has a mildly convex continuum, and the MCD model has the most convex shape in the logarithmic plot. We end this chapter by comparing these three models based on the $\chi^2$ goodness and the values of absorption.

Figure 6.25 compares $\chi^2/\nu$ between the power-law and MCD models, or between the TBS and MCD models. For the sources which were observed twice, we plotted results from the first observation for simplicity. The data points for M81 X-6 refer to the high-temperature state. Except for NGC 1313 source A, the MCD fit thus gives systematically lower values of $\chi^2/\nu$ to the ULX spectra than the power-law fit, while the three SNRs
Table 6.15: Fitting results of luminous extragalactic SNRs, using single component models.

<table>
<thead>
<tr>
<th>Source Model</th>
<th>$N_H$ (10^{22} cm$^{-2}$)</th>
<th>Parameters$^a$</th>
<th>$f_X$ (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North-arm source in NGC 6946</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>power-law</td>
<td>0.11±0.04</td>
<td>2.28±0.12</td>
<td>1.33</td>
<td>105.4/87 (9%)</td>
</tr>
<tr>
<td>TBS</td>
<td>≤0.02</td>
<td>3.0±0.3</td>
<td>1.24</td>
<td>121.4/87 (1%)</td>
</tr>
<tr>
<td>R-S</td>
<td>≤0.02</td>
<td>3.0±0.3/0.03+0.11</td>
<td>1.25</td>
<td>121.1/86 (1%)</td>
</tr>
<tr>
<td>MCD</td>
<td>0</td>
<td>0.84</td>
<td>1.05</td>
<td>210.4/87 (1%)</td>
</tr>
<tr>
<td>power-law</td>
<td>0.12±0.06</td>
<td>2.31±0.16</td>
<td>1.28</td>
<td>33.9/44 (86%)</td>
</tr>
<tr>
<td>TBS</td>
<td>≤0.03</td>
<td>3.0±0.5</td>
<td>1.38</td>
<td>45.1/44 (42%)</td>
</tr>
<tr>
<td>R-S</td>
<td>≤0.03</td>
<td>3.0±0.5/0.17+0.27</td>
<td>1.39</td>
<td>43.7/43 (44%)</td>
</tr>
<tr>
<td>MCD</td>
<td>≤0.01</td>
<td>0.86±0.08</td>
<td>1.13</td>
<td>85.3/44 (4%)</td>
</tr>
<tr>
<td>in 1995 Nov.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>power-law</td>
<td>0.24±0.05</td>
<td>2.51±0.16</td>
<td>1.21</td>
<td>119.1/68 (≤1%)</td>
</tr>
<tr>
<td>TBS</td>
<td>0.08±0.04</td>
<td>2.6±0.4</td>
<td>1.14</td>
<td>134.6/68 (1%)</td>
</tr>
<tr>
<td>R-S</td>
<td>0.08±0.04</td>
<td>2.7±0.4/0.21+0.25</td>
<td>1.15</td>
<td>129.9/67 (15%)</td>
</tr>
<tr>
<td>MCD</td>
<td>0</td>
<td>0.91</td>
<td>1.03</td>
<td>164.9/68 (1%)</td>
</tr>
<tr>
<td>power-law</td>
<td>0.26±0.07</td>
<td>1.55±0.08</td>
<td>2.28</td>
<td>170.4/138 (3%)</td>
</tr>
<tr>
<td>TBS</td>
<td>0.19±0.05</td>
<td>15.6±4.1/4.5</td>
<td>2.20</td>
<td>170.5/138 (3%)</td>
</tr>
<tr>
<td>R-S</td>
<td>0.23±0.06</td>
<td>10.3±3.1/1.0+0.48</td>
<td>2.26</td>
<td>153.2/137 (16%)</td>
</tr>
<tr>
<td>MCD</td>
<td>≤0.05</td>
<td>2.13±0.16</td>
<td>2.11</td>
<td>191.2/138 (≤1%)</td>
</tr>
<tr>
<td>power-law</td>
<td>0.26±0.06</td>
<td>1.71±0.08</td>
<td>1.80</td>
<td>196.8/189 (33%)</td>
</tr>
<tr>
<td>TBS</td>
<td>0.17±0.04</td>
<td>8.7±2.1/2.5</td>
<td>1.73</td>
<td>196.5/189 (34%)</td>
</tr>
<tr>
<td>R-S</td>
<td>0.18±0.05</td>
<td>7.6±0.8/0.76+0.34</td>
<td>1.79</td>
<td>175.5/188 (73%)</td>
</tr>
<tr>
<td>MCD</td>
<td>0.03±0.03</td>
<td>1.71±0.12</td>
<td>1.59</td>
<td>219.9/189 (6%)</td>
</tr>
</tbody>
</table>

$^a$ Photon index for the power-law model, plasma temperature (keV) for the TBS model, $kT$ (keV)/abundance (solar) for the R-S model, and $T_{\text{in}}$ for the MCD model.

$^b$ In unit of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.

---

Table 6.16: Fitting results of luminous extragalactic SNRs, using double component models.

<table>
<thead>
<tr>
<th>Source Model</th>
<th>$N_H$ (10^{22} cm$^{-2}$)</th>
<th>$T$ or $kT$ (keV)</th>
<th>$f_X^{\text{hard}}$ $^a$ (0.5–10 keV)</th>
<th>$f_X^{\text{soft}}$ $^a$ (0.5–10 keV)</th>
<th>$kT$ (keV)/Abundance(solar)</th>
<th>$T_{\text{in}}$ (0.5–10 keV)</th>
<th>$\chi^2/\nu$ (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North-arm SNR in NGC 6946</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>power-law+R-S</td>
<td>0.14±0.06</td>
<td>2.11±0.14</td>
<td>1.20</td>
<td>0.83±0.07/0.63+0.24</td>
<td>0.13</td>
<td>73.5/84 (78%)</td>
<td></td>
</tr>
<tr>
<td>TBS+R-S</td>
<td>0.09±0.07</td>
<td>4.8±1.4</td>
<td>1.01</td>
<td>0.84±0.07/0.11+0.11</td>
<td>0.28</td>
<td>72.6/84 (81%)</td>
<td></td>
</tr>
<tr>
<td>power-law+R-S</td>
<td>0.14±0.04</td>
<td>2.24±0.16</td>
<td>1.40</td>
<td>0.80(fix)/1.20(fix)</td>
<td>0.09</td>
<td>29.6/43 (94%)</td>
<td></td>
</tr>
<tr>
<td>TBS+R-S</td>
<td>0.04±0.1</td>
<td>3.8±0.9</td>
<td>1.24</td>
<td>0.82(fix)/0.25(fix)</td>
<td>0.18</td>
<td>34.5/43 (82%)</td>
<td></td>
</tr>
<tr>
<td>1995 Nov.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>power-law+R-S</td>
<td>0.35±0.12</td>
<td>2.24±0.20</td>
<td>1.01</td>
<td>0.79±0.09/1.20+0.89</td>
<td>0.23</td>
<td>76.8/65 (15%)</td>
<td></td>
</tr>
<tr>
<td>TBS+R-S</td>
<td>0.28±0.14</td>
<td>3.9±1.0</td>
<td>0.88</td>
<td>0.81±0.09/0.25&gt;0.08</td>
<td>0.31</td>
<td>75.2/65 (18%)</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ In unit of $10^{-12}$ erg s$^{-1}$ cm$^{-2}$. 

98
exhibit the opposite tendency. The same statement applies to the comparison between
the TBS and MCD modelings, though less significant.

Figure 6.26 provides a comparison of the models in terms of the absorption they
require, where we plotted only the ULXs. We also excluded M33 X-8 and NGC 1313
source A, since the former showed different values of $N_H$ between the SIS and the GIS,
and for the latter we fixed the absorption when performed spectral fitting. The values
of $N_H$ associated with the power-law fits largely exceed the Galactic $N_H$, and take rather
constant values at $(0.4 - 1) \times 10^{22}$ cm$^{-2}$. The TBS fits show similar excess in $N_H$, although
less prominent than the power-law fits. Of course, the ULXs may exhibit self-absorption,
but in that case, the excess $N_H$ would scatter from object to object, just as is seen from
X-ray pulsars. Therefore the excess absorption can be considered as an artifact required
to make the models more convex than they are. In contrast, the values of $N_H$ associated
with the MCD fits are closer to the Galactic values. In addition, the excess $N_H$ in this
case scatters randomly up to several times $10^{21}$ cm$^{-2}$. These may be attributed to the
absorption intrinsic to the ULXs, or internal to the host galaxies.

In summary, the MCD modeling can give a unified description of the ULX spectra,
except a few cases; the M33 X-8 spectra and the 1995 spectra of NGC 1313 source A
require the additional hard power-law, while the 1993 spectra of the same source A and
IC 342 source 2 prefer a single power-law.
Figure 6.24: The background-subtracted spectra of luminous extragalactic SNRs. When using double component models, the contribution of each component is indicated by dotted lines. The spectra of SN 1978K are fitted with a power-law plus R-S model, and those of SN 1986J are fitted with a single R-S model.
Figure 6.25: A comparison of the obtained $\chi^2/\nu$ between the power-law model and the MCD one (panel a), and between the TBS model and the MCD one (panel b). For the objects observed twice, we plotted the results of the first observation, and for M81 X-6, we plotted the values obtained for the high-temperature state spectrum.

Figure 6.26: Summary of the obtained values of $N_H$ for the single component models, in comparison with the Galactic line-of-sight $N_H$. The results of the power-law (panel a), the TBS (panel b), and the MCD model (panel c) are plotted. NGC 1313 source A, M33 X-8, and three SNRs are excluded (see text).
Chapter 7

DISCUSSION

7.1 Nature of the ULXs

In the previous chapter, we confirmed that the MCD model is more appropriate than the power-law and TBS ones to represent the spectra of ULXs. We also tested the models which have MCD-like continua, the UC model and the broken power-law model, for IC 342 source 1, M81 X-6, and NGC 1313 source B, since their spectra have rather good photon statistics. For the latter two objects, these three models provide similar values of $\chi^2/\nu$, although the broken power-law model gives slightly lower $\chi^2/\nu$ for M81 X-6. On the other hand, for IC 342 source 1, which has the highest photon statistics among the sources discussed here, the MCD model shows significantly smaller values of $\chi^2$ than those of the other two models as shown in Table 6.1; the confidence level of the MCD, the UC, and the broken power-law model fitting is 43%, 25%, and 8%, respectively. Moreover, regardless of the source, the MCD model provides values of $N_H$ rather consistent with the Galactic ones, whereas the other models require excess absorption, as inferred from Figure 6.26. Thus, the MCD model is best preferred.

The UC and broken power-law models are also inappropriate in view of their physical meanings. For the UC model, the obtained values of $\tau_{es}$ is 20–30. Thus, the column density of the plasma, estimated by dividing the optical depth by Thomson-scattering cross-section, would amount to $\geq 10^{25}$ cm$^{-2}$. Since the plasma temperature is not so high, $T_e \sim 1$ keV, the spectrum should show prominent Fe-K edge absorption feature at $\sim 7$ keV, which is in fact absent in any of our ULXs spectra. Furthermore, the obtained parameters considerably contradict the necessary condition for the plasma to produce the UC emission. The UC spectrum is realized only when the emission region is “effectively thin” to free-free absorption, i.e., $\tau_{eff} \sim \sqrt{\tau_{ff}(\tau_{ff} + \tau_{es})} \ll 1$ (Rybicki and Lightman 1979), where $\tau_{eff}$ and $\tau_{ff}$ denote the effective and free-free optical depths, respectively. This relation, together with the obtained value of $\tau_{es}$, requires quite low value of $\tau_{ff}$ ($\ll 1/30$). In order for this condition to be realized down to photon energies of 0.2 keV, the plasma must have a radius of $\geq 1 \times 10^8$ cm. It seems quite artificial for such an extended plasma to be heated against the intense Compton cooling. We therefore conclude that the UC interpretation of the ULXs spectra is physically unrealistic.

Understanding the ULXs as synchrotron emission in terms of the broken power-law model is also difficult. In this regime, the break in the spectral slope is attributed to the synchrotron cooling. Our objects show relatively large breaks in photon index by 1–2, whereas a steady state synchrotron cooling predicts a break by only 0.5, which is observa-
tionally supported (e.g., Tashiro et al. 1995, Takahashi et al. 1996). Moreover, our sources take similar values of break energy, i.e., $E_{\text{bk}} \sim 2.5$–3.5 keV, which is again unrealistic. For reference, the spectral breaks of blazars, determined by a balance among the electron acceleration, synchrotron cooling, and electron escape, scatter by more than three decades in energy (Kubo et al. 1998). For these reasons, the synchrotron interpretation is unlikely, too.

Thus, the MCD model is best preferred for most of the ULXs except for NGC 1313 source A in the 1993 observation and IC 342 source 2, for which the single power-law model is adequate as already mentioned in § 6.6 and § 6.8. We summarize the fitting results of the ULXs spectra in Table 7.1. It indicates that the ULXs spectra are grossly divided into two groups; one is a majority group for which the MCD model is appropriate, and the other is a minority one which can be represented by the single power-law model. As mentioned in § 2.3, the MCD emission is expected from LMXBs or BHBs. Most of ULXs have values of $T_{\text{in}}$ similar to those of Galactic bright LMXBs (typically 1.5 keV), so that the LMXB interpretation is apparently preferred. However, as already described in § 2.5.3, it is difficult for LMXBs to account for the high luminosity of ULXs. In addition, the black-body component characterizing the LMXB spectra accounts for at most $\leq 30\%$ of the 0.5–10 keV fluxes for IC 342, M81 X-6, NGC 1313 source B in the 1993 observation, and NGC 4565 (when two ULXs are summed up). These are considerably lower than the black-body contribution seen in Galactic LMXBs, $\sim 50\%$ for the most luminous LMXBs (Mitsuda et al. 1984). Thus we propose that those ULXs, whose spectra can be represented by the MCD model, are accreting BHBs. The fact that some of ULXs (e.g. M33 X-8, NGC 1313 source A in the 1995 observation) show power-law hard component together with the MCD one also reinforces the BHB interpretation.

The interpretation of ULXs as MCD emission from BHBs is supported also by an astronomical point of view. As described in § 2.5.2, ULXs are generally seen in arms of spirals galaxies. Actually among our sample galaxies, M81 and IC 342 have relatively face-on geometries, and their ULXs are clearly associated with their spiral arms (see the images in Appendix C). This indicates that the ULXs belong to young population objects, and considering the time variability seen from some ULXs, compact objects associated with population I stars, e.g., the BHBs, are the most preferred candidate species.

Among our objects, two sources, i.e., NGC 1313 source A in the 1993 observation and IC 342 source 2, can be represented by the single power-law model of $\Gamma=1.4$–1.7. These values are characteristic of BHBs in the hard state. In addition, the long-term variability of NGC 1313 source A can be expressed as a soft-hard transition, as mentioned in § 6.6. Thus, all of our ULXs can be understood as BHBs, although three problems remain to be solved as mentioned below.

### 7.2 Problems with the BHB Interpretation

#### 7.2.1 High BH mass to keep sub-Eddington radiation

The first problem is that very massive stellar BHs are needed to account for the high-luminosities of ULXs. In Table 7.1, we tabulated the luminosities for individual spectral components of the sample ULXs. For the power-law component, we assumed isotropic emission and calculated luminosities $L_{\text{pow}}^X$ in the 0.5–10 keV band, since this model in-
Table 7.1: Summary of the spectral fitting results of ULXs in terms of the MCD model. For NGC 1313 source A in the 1993 observation and IC 342 source 2, we adopt the single power-law model (see §6.6 and §6.8).

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance (Mpc)</th>
<th>Model</th>
<th>$\Gamma$</th>
<th>$f_X^{\text{low}}$ a)</th>
<th>$L_X^{\text{low}}$ b) (0.5–10 keV)</th>
<th>$T_{\text{in}}$ (keV)</th>
<th>$f_{\text{bol}}$ a)</th>
<th>$L_{\text{bol}}$ (keV)</th>
<th>$M_{\text{E}}$ d)</th>
<th>$R_{\text{in}}$ e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M33 X-8</td>
<td>0.72</td>
<td>MCD+PL</td>
<td>2.2 (fix)</td>
<td>7.71</td>
<td>4.8</td>
<td>1.18±0.02</td>
<td>14.4</td>
<td>4.4</td>
<td>2.9</td>
<td>53±7.4</td>
</tr>
<tr>
<td>NGC 1313 source A</td>
<td>4.5</td>
<td>power-law</td>
<td>1.69±0.05</td>
<td>4.13</td>
<td>100</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>67</td>
<td>–</td>
</tr>
<tr>
<td>1993 Jul.</td>
<td></td>
<td>MCD+PL</td>
<td>1.74±0.34</td>
<td>1.38</td>
<td>33</td>
<td>0.67±0.08</td>
<td>2.33</td>
<td>28</td>
<td>390±50</td>
<td>–</td>
</tr>
<tr>
<td>NGC 1313 source B</td>
<td></td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.47±0.08</td>
<td>4.16</td>
<td>50</td>
<td>33</td>
<td>110±12</td>
</tr>
<tr>
<td>1993 Jul.</td>
<td></td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.07±0.07</td>
<td>1.66</td>
<td>20</td>
<td>129±19</td>
<td>–</td>
</tr>
<tr>
<td>1995 Nov.</td>
<td></td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.51±0.04</td>
<td>0.52</td>
<td>100</td>
<td>67</td>
<td>150±186</td>
</tr>
<tr>
<td>NGC 1365 SW source 18.3</td>
<td>18.3</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.23±0.11</td>
<td>1.82</td>
<td>11</td>
<td>7.3</td>
<td>75±13</td>
</tr>
<tr>
<td>NGC 2403 source 3</td>
<td>3.2</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.12±0.04</td>
<td>0.50</td>
<td>18</td>
<td>12</td>
<td>110±126</td>
</tr>
<tr>
<td>M81 X-6</td>
<td>3.6</td>
<td>high-temp phase</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>1.59±0.09</td>
<td>3.92</td>
<td>30</td>
<td>20</td>
<td>72±7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>low-temp phase</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>1.29±0.13</td>
<td>2.63</td>
<td>20</td>
<td>89±12</td>
<td>–</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>7.7</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.80±0.34</td>
<td>1.14</td>
<td>6.1</td>
<td>4.1</td>
<td>26±8</td>
</tr>
<tr>
<td>NGC 4565</td>
<td>10.4</td>
<td>off-center</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>1.39±0.08</td>
<td>1.82</td>
<td>117</td>
<td>78</td>
<td>185±23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>center</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>1.59±0.32</td>
<td>0.72</td>
<td>47</td>
<td>31</td>
<td>89±24</td>
</tr>
<tr>
<td>Dwingeloo 1 X-1</td>
<td>3.0</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.80±0.34</td>
<td>1.14</td>
<td>6.1</td>
<td>4.1</td>
<td>26±8</td>
</tr>
<tr>
<td>IC 342</td>
<td>3.9</td>
<td>source 1 (phase 1)</td>
<td>MCD</td>
<td>–</td>
<td>–</td>
<td>1.96±0.10</td>
<td>16.2</td>
<td>147</td>
<td>98</td>
<td>104±9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(phase 2)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.50±0.10</td>
<td>10.3</td>
<td>93</td>
<td>142±18</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(phase 3)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.70±0.15</td>
<td>13.0</td>
<td>118</td>
<td>125±21</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(phase 4)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.29±0.08</td>
<td>7.95</td>
<td>72</td>
<td>168±20</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(phase 5)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.81±0.07</td>
<td>15.1</td>
<td>137</td>
<td>116±8</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(time-average)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.77±0.05</td>
<td>13.7</td>
<td>124</td>
<td>118±7</td>
<td>–</td>
</tr>
<tr>
<td>source 2</td>
<td>power-law</td>
<td>1.43±0.17</td>
<td>4.14</td>
<td>75</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>50</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

a) In units of 10^{39} erg s^{-1} cm^{-2}.

b) In units of 10^{38} erg s^{-1}.

c) In units of 10^{48} erg s^{-1}, where $i$ is the disk inclination angle.

d) The lower-limit of the mass to satisfy sub-Eddington radiation, calculated from equation 7.2. For sources that shows MCD emission, face-on ($i=0^\circ$) geometry is assumed.
e) $\frac{1}{\sqrt{\cos i}}$ km.
evitably needs a cut-off in low and high energies. For the MCD component, we tabulated bolometric luminosities $L_{\text{bol}}$ as well as $R_{\text{in}}$; the latter are calculated from equation 2.11. When the source distance $D$ and the disk inclination $i$ are changed, these quantities scale as

$$L_{X}^{\text{pow}} \propto D^2, \quad L_{\text{bol}}^{\text{disk}} \propto D^2(\cos i)^{-1}, \quad R_{\text{in}} \propto D(\cos i)^{-1/2}. \quad (7.1)$$

Hereafter we tentatively assume $i=0$, that makes $L_{\text{bol}}^{\text{disk}}$ the lowest. This assumption is not necessarily too arbitrary, since the face-on geometry provides the highest flux for a given bolometric luminosity, hence making the system more selectively detectable. Thus, many of our ULXs have luminosity $\geq 3 \times 10^{39}$ erg s$^{-1}$. In order for the radiation to remain sub-Eddington, the BH mass (hereafter $M_E$) should be

$$M_E \geq \frac{L_{\text{bol}}}{1.5 \times 10^{38} \text{ erg s}^{-1} M_\odot}, \quad (7.2)$$

as inferred from equation 2.1. Thus, as tabulated in Table 7.1, most of ULXs show quite high BH mass, typically $M_E \geq 20 M_\odot$. Especially for some sources whose $L_{X}^{\text{pow}}$ or $L_{\text{bol}}^{\text{disk}}$ exceed $10^{40}$ erg s$^{-1}$, such as IC 342 source 1, a quite massive BH of $M_E \geq 70 M_\odot$ is needed.

How to make such a massive BH remains an open question, because a normal star heavier than $\sim 70 M_\odot$ is thought to be radiatively unstable, and cannot evolve to become a BH. This itself is another consequence of the Eddington limit. The bolometric luminosity of main-sequence stars scale with the mass $M$ as

$$L = L_\odot (M/M_\odot)^{3.5} \quad (7.3)$$

where $L_\odot=3.8 \times 10^{33}$ erg s$^{-1}$ is the bolometric solar luminosity. Thus, the bolometric luminosity of main-sequence stars, which is supplied by nuclear fusion, increases rapidly as the stellar mass increases, and at $M \sim 70 M_\odot$, $L$ reaches $L_E$; the star will be blown apart by its own radiation pressure.

Hence, a massive BH of $M_E \geq 70 M_\odot$ somewhat contradicts current understanding of the stellar evolution. However, considering the distance uncertainties and recent theoretical and observational results, this problem may not be so serious as it appears, as described in § 7.3.1.

### 7.2.2 Too high temperature (too small $R_{\text{in}}$)

The second problem arises from the fact that the obtained values of $T_{\text{in}}$ of ULXs, ranging 1.0–2.0 keV except for NGC 1313 source A, are significantly higher than those of Galactic or Magellanic BHBs (0.5–1.2 keV; e.g. Tanaka, Lewin 1995). Furthermore, as inferred from equation 2.16, a heavier BH tends to show a lower value of $T_{\text{in}}$, which apparently contradicts the high $T_{\text{in}}$ seen for ULXs. In other words, within our accretion-disk formalism, the BH cannot be very massive for the disk temperature to be as high as observed. In fact, substituting a typical value of $T_{\text{in}}$, 1.5 keV, into equation 2.16, the mass of a Schwarzschild BH becomes only $\sim 4 M_\odot$ even if we assume $\eta=1$; then, the observed MCD luminosity would greatly exceed the implied Eddington limit. This self-inconsistency was already pointed out by Okada et al. (1998) and Mizuno et al. (1999).

This “too-high $T_{\text{in}}$ problem” may be best visualized in Figure 7.1, where our sources are plotted on $T_{\text{in}}$ vs. $L_{\text{bol}}$ plane, which may be called an X-ray “H–R diagram”. There,
dotted lines represent the loci of constant $M$, expressed by equation 2.13 assuming $\alpha=1$, i.e. the Schwarzschild BH. Along these lines, a BH of given mass changes its $T_{\text{in}}$ and $L_{\text{bol}}$ obeying the relation of $L_{\text{bol}} \propto T_{\text{in}}^4$; both $T_{\text{in}}$ and $L_{\text{bol}}$ become higher as the mass accretion rate increases. On the other hand, dashed lines represent the loci of constant $\eta$, expressed by equation 2.15 ($\alpha=1$). Once the luminosity normalized to the Eddington luminosity (i.e. $\eta$) is given, a BH of higher mass tends to show lower $T_{\text{in}}$ and higher $L_{\text{bol}}$, obeying the relation of $L_{\text{bol}} \propto T_{\text{in}}^{-4}$. Thus, this Figure provides a conversion diagram from $(T_{\text{in}}, L_{\text{bol}})$ to $(M, \eta)$ for non-spinning BHs within the MCD formalism. In order to consistently understand an X-ray source as an accreting non-spinning BH, the data point should fall on the region of $\eta \leq 1$ (sub-Eddington luminosity) and $M \geq 3 M_\odot$ (heavier than a NS). However, most of our ULXs (except for M33 X-8 and NGC 1313 source A) fall either on the super-Eddington region or on the $\eta \sim 1$ boundary, due to their high $T_{\text{in}}$.

We can equivalently state the problem in terms of the values of $R_{\text{in}}$. As expected from equation 2.8, the high values of $T_{\text{in}}$ of ULXs yield relatively small values of $R_{\text{in}}$. In fact, the obtained values of $R_{\text{in}}$ are as small as $\sim 100$ km except for NGC 1313 source A. Hence, from equation 2.10, only $\sim 10 M_\odot$ is allowed if we assume a non-spinning BH. On the contrary, the high luminosities of ULXs require $M_{\text{E}}$ up to $70-100 M_\odot$. We summarize this issue in Figure 7.2. Thus, most of our ULXs show much smaller values of $R_{\text{in}}$ than are needed to account for the high luminosity. Therefore, the “too high $T_{\text{in}}$ problem” can be rephrased as “too small $R_{\text{in}}$ problem”.

### 7.2.3 The change of $R_{\text{in}}$

The third problem is related to the variation of $R_{\text{in}}$. As reviewed in § 2.7, $R_{\text{in}}$ of Galactic/Magellanic BHBs generally stays quite constant as the source varies. That is, an increase in the mass accretion rate raises the disk temperature, but does not affect the disk size. This has in turn allowed us to interpret $R_{\text{in}}$ as representing the last stable orbit around the BH. It is therefore of fundamental importance to examine whether $R_{\text{in}}$ of each ULX varies or not.

We have in fact detected short-term and long-term variations from three ULXs, i.e. IC 342 source 1, NGC 1313 source B, and M81 X-6. However, contrary to the case of the Galactic/Magellanic BHBs, the disk radius of all these sources exhibited negative dependences on $T_{\text{in}}$; the changes are statistically significant as to the former two objects, while marginal for M81 X-6 (see § 6.2, 6.4, and 6.5). This effect is also visualized in Figure 7.1, which is drawn under the assumption of $R_{\text{in}} = 3 R_\odot$. There, an object would vary along the dotted lines if $R_{\text{in}}$ were constant like in the case of established BHBs, whereas the three ULXs actually vary along lines with a flatter slope: as the temperature becomes higher, the inferred BH mass apparently decreases, because of the decrease in $R_{\text{in}}$. Clearly, this behavior is distinct from those found among the Galactic/Magellanic BHBs.

Figure 7.3 summarizes the $R_{\text{in}}$ vs. $T_{\text{in}}$ relations of all the three ULXs that varied. Thus, their variations approximately follow a single common scaling of $R_{\text{in}} \propto T_{\text{in}}^{-1}$. This effect is therefore though to reflect some fundamental difference between the ULXs and the ordinary BHBs, and the origin of this difference should be clarified. In particular, we must examine whether the variations in $R_{\text{in}}$ seen from ULXs reflect real changes in the innermost disk boundary, or they are an apparent effect caused, e.g., by changes in $\kappa$. We discuss this issue in § 7.3.5.
Figure 7.1: Temperature-luminosity relation of ULXs and BHBs. All the ULX datapoints refer to our ASCA results. For LMC X-3 and GS 2000+25, we refer to the Ginga results (Ebisawa 1991) for which the MCD model is employed; we discard one GS 2000+25 data point which showed the lowest flux among the Ginga measurement, and one LMC X-3 data point which nearly overlaps M33 X-8. The dotted lines represent the relation of $L_{\text{bol}} \propto T_{\text{in}}^4$ (constant mass), and the dashed lines the relation of $L_{\text{bol}} \propto T_{\text{in}}^{-4}$ (constant $\eta$).
Figure 7.2: (Panel a) Relation between $R_{in}$ and the BH mass, where $R_{in}$ is calculated from equation 2.12, assuming $\xi=0.41$ and $\kappa=1.7$. The BH mass refers to $M_E$ for ULXs, and to the optically determined mass for Galactic and Magellanic BHBs. For ULXs, we assume $i=0^\circ$. The solid line represents the relation of $R_{in} = 3 R_S$, which corresponds to the last stable orbit of a non-spinning BH. (Panel b) The same as panel (a), but the distances for some ULXs are reduced (see text). The dashed line effectively represents the $R_{in} = 3 R_S$ relation when $\xi\kappa^2$ is increased by 50% (see text).

Figure 7.3: Relation between $R_{in}$ and $T_{in}$ for three ULXs which varied, i.e., IC 342 source 1, M81 X-6, and NGC 1313 source B. The error bars represent the 90% confidence errors tabulated in Table 7.1, and the solid line indicates the relation of $R_{in} \propto T_{in}$. 
7.3 Possible Solutions within the Standard-Disk Framework

In order to construct a self-consistent scenario of ULXs in terms of accreting black holes, we must solve the three problems pointed out above. In this section, we attempt to do so within the framework of standard accretion disks around Schwarzschild BHs.

7.3.1 Distance and inclination uncertainties

Since the ULXs are not identified in other wavebands, we cannot estimate their disk inclinations. In addition, the distance to the host galaxy is subject to a considerable uncertainty, at least for some of them. Then, the problems (at least some of them) might be a consequence of uncertainties in $i$ and/or $D$.

So far, we have somewhat arbitrary assumed $i=0^\circ$, i.e., face-on geometry, for the ULXs. However, as already mentioned, this assumption makes the source luminosity the lowest. As a result, the first problem, i.e. the uncomfortably high BH mass, gets worse if $i$ is increased. In addition, $R_{\text{in}}$ scales as $\propto (\cos i)^{-1/2}$ whereas $M_E$ scales as $\propto (\cos i)^{-1}$, as inferred from equation 7.1. As a result, the second problem (too small $R_{\text{in}}$ to account for large $M_E$) also gets worse if we increase $i$. Therefore, our assumption of $i = 0$ has already been adjusted to make the problems least severe.

Then, how about the source distances given in Table 7.1? We have carefully adopted these values referring to publications using various astronomical distance indicators, as summarized in Table 7.2. However, the estimates inevitably involve uncertainties; if the true distances are significantly shorter, $M_E$ will obviously decrease in proportion to $D^2$. Moreover, the deviation between $R_{\text{in}}$ and $M_E$ will be relaxed, because $R_{\text{in}}$ scales as $\propto D$ while $M_E$ scales as $\propto D^2$. Therefore, the distance revision can potentially solve the first two problems. Indeed, the distances to IC 342 and Dwingeloo 1 are relatively uncertain, mainly because of their large optical extinction caused by their low Galactic latitudes. However, this does not necessarily mean that we have over-estimated their distances; in fact, the distance we have adopted for Dwingeloo 1 (3.0 Mpc) is shorter than the estimate of 5.3 Mpc based on the infrared Tully-Fisher relation (Ivanov et al. 1999). NGC 2403 has significantly more accurate distance estimates. For NGC 4565, the uncertainty is even smaller, since estimates by various authors consistently indicate $\sim 10$ Mpc (Table 7.2) as already pointed out by Mizuno et al. (1999). Finally, the distances to NGC 1365 and M81 are accurately determined based on the Cepheid observations by HST, and that to M33, of course, is well established. Therefore, the source distances cannot be changed very much.

Taking these considerations into account, let us tentatively reduce the distances of those ULXs which fall on the “super-Eddington” region in Figure 7.1. Let us halve the distances to IC 342, NGC 1313, and NGC 4565, although this is too extreme at least for the last object. As to Dwingeloo 1, let us use 2.0 Mpc instead of 3.0 Mpc. We may also reduce the distances to NGC 1365 and M81 by 10%, within the tolerance of the HST measurements. These distance revisions modify Figure 7.2a into Figure 7.2b. There, $M_E$ becomes relatively low, possibly consistent with the stellar evolutionary scenario, except for NGC 1365 SW source. Therefore, the first problem could be solved in this way. However, in spite of these extreme distance modifications, the revised values of $R_{\text{in}}$ still...
contradict $M_\text{E}$ except for Dwingeloo-1 X-1. In short, the distance uncertainty can hardly solve the second problem, although it may affect details of the issue.

In addition, the first problem may be solved even without appealing to such extremely artificial assumptions. There are in fact fair number of observations of stars in the mass range of $\geq 100 \, M_\odot$ (e.g. Krabbe et al. 1995, Walborn et al. 1995), and some authors (e.g. Fryer 1999) argue that a star heavier than $\sim 40 \, M_\odot$ can directly form a BH without supernova explosion (and hence without losing much of the progenitor mass). Therefore, the high BH mass may not be a big difficulty, and we do not perform further investigation of this problem.

7.3.2 Examination of the Eddington limit

Alternatively, the problems may result from our wrong application of the Eddington limit of equation 2.1, where the spherical radiation is assumed. Here, we justify the application of this equation to the case of accretion disks around BHBs, which are obviously non-spherical.

We first refer to the paper by Chen et al. (1997), who compiled observations of BH transients as well as NS transients. They collected the data of over 30 outbursts of $\sim 15$ BH transients, and found the peak luminosities being distributed around 0.2 in Eddington units. Except for the two sources whose distances are relatively uncertain, none of their BH transients have shown luminosities above the Eddington limit. As to the persistent BHBs, i.e., Cyg X-1, LMC X-1, and LMC X-3, the observed luminosities have been also below $L_\text{E}$, as described in § 7.3.4. Hence, any known BHB has luminosity below $L_\text{E}$. Moreover, several authors theoretically show that the critical upper-limit luminosity of an axi-symmetric BH system does not differ much from the spherical one, e.g., Beloborodov (1998), Abramowicz et al. (1988), and Watarai et al. (2000). In particular, the latter two authors have shown convincingly that the disk bolometric luminosity around a stellar mass BH ($\sim 10 \, M_\odot$) saturate at $\sim L_\text{E}$ even when the mass accretion rate greatly exceeds the critical values. Therefore, we can securely apply our Eddington limit of equation 2.1 on ULXs.

7.3.3 Justification of the correction factor $\xi$

As an alternative possibility, the problems, particularly the second one, may arise because the MCD model is not accurate enough. In particular, the second problem may be solved if the values of $\xi=0.41$ and $\kappa=1.7$ can take significantly lower values, because $R_\text{in}$ scales as $\propto \xi \kappa^2$ (equation 2.11) while the disk luminosity (or $M_\text{E}$) is independent of $\xi \kappa^2$.

Among the two parameters $\kappa$ and $\xi$, the latter corrects the MCD formalism for the inner boundary condition of the accretion disk (see the difference between equation 2.4 and 2.6), in such a way that the disk temperature of the MCD model reaches maximum at $R_\text{in}/\xi$ instead of $R_\text{in}$. We can hence examine our choice of $\xi=0.41$ (Kubota et al. 1998) in reference to the “general relativistic accretion disk (GRAD) model” (Ebisawa et al. 1991) that properly takes into account this boundary condition as well as the relativistic effect on both the disk structure and photon trajectory.

We accordingly simulated a number of spectra using the GRAD model, by changing $M$, $\dot{M}$, and $i$, but fixing $\kappa$ at 1.7. We fitted the simulated spectra with the MCD model assuming $\xi=0.41$, and derived the value of $R_\text{in}$ as well as the BH mass assuming $R_\text{in} = 3 \, R_\odot$. 

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Then, over the inclination range of 0° to 75° and over the disk temperature range of $T_{\text{in}}=0.5$–2.0 keV, the mass obtained through the MCD analysis agreed within $\sim \pm 25\%$ with the BH mass $M$ employed as initial inputs to the GRAD simulations, as shown in Figure 7.4. We hence conclude that our choice of $\xi=0.41$ properly corrects the MCD formalism for the boundary condition of the disk.

### 7.3.4 Comparison with Galactic/Magellanic BHBs

Even though our MCD modeling agrees with the GRAD formalism, neither model may be accurate enough to describe real celestial BHs. Furthermore, the value of $\kappa=1.7$ might be wrong. This urges us to calibrate the combined value of $\xi \kappa^2$ based on observations; for this purpose, we employ four well-studied BHBs, Cyg X-1, LMC X-1, and LMC X-3.

Dotani et al. (1997) observed Cyg X-1 with ASCA in 1996 May, when it was in the soft state. They analyzed the spectra assuming $D = 2.5$ kpc (Cowley 1992), and obtained parameters of $T_{\text{in}} = 0.43 \pm 0.01$ keV and $R_{\text{in}} \sqrt{\cos i / \xi \kappa^2} = 71_{-2}^{+13}$ km. Together with $i = 30°$ (Cowley 1992), $\kappa = 1.7$, and $\xi = 0.41$, $R_{\text{in}}$ becomes $90_{-27}^{+17}$ km, yielding a mass estimate of $10.2_{-0.2}^{+1.9} M_\odot$. This agrees well with the optically estimated value, $10.1_{-5.3}^{+4.6} M_\odot$ (Herreo et al. 1995). We plot the data points for Cyg X-1 on Figure 7.1 and Figure 7.2a. Thus, the choice of $\kappa = 1.7$ and $\xi = 0.41$ appears reasonable. However, a drawback in this case is that the distance to Cyg X-1 is somewhat uncertain.

LMC X-1 and LMC X-3 provide still better calibration, because their distances (50–55 kpc) are reliable; here we adopt $D = 55$ kpc. Both these Magellanic sources have been observed several times with Ginga by Ebisawa (1991) and Ebisawa et al. (1993), who obtained $R_{\text{in}} \sqrt{\cos i / \xi \kappa^2} = 45 \pm 3$ km and $24.5 \pm 0.5$ km (at 50 kpc) for LMC X-1 and LMC X-3, respectively. By substituting our assumptions of $\xi \kappa^2 = 1.18$ and $D = 55$ kpc, and assuming $i=60°$ for LMC X-1 (Cowley et al. 1995) and $i=66°$ for LMC X-3 (Kuiper et al. 1988), we obtain $R_{\text{in}} = 83_{-5}^{+6}$ km for LMC X-1 and $49 \pm 1$ km for LMC X-3. Accordingly, the X-ray determined mass of LMC X-1 becomes $9.4_{-0.3}^{+0.7} M_\odot$ and that of LMC X-3 $5.5 \pm 0.1 M_\odot$. These values are consistent with the optically estimated BH mass of $M=4$–10 $M_\odot$ for LMC X-1 (Cowley et al. 1995) and 5–7 $M_\odot$ for LMC X-3 (Kuiper et al. 1988). We plot these two objects in Figure 7.1 and Figure 7.2a.

These calibrations utilizing Cyg X-1, LMC X-1 and LMC X-3 thus give a good support to our formalism, which assumes $\xi \kappa^2 = 1.18$ and the relation of $R_{\text{in}} = 3 R_S$. In other words, the value of $\xi \kappa^2$ cannot be changed very much. Just to see how the “too high disk temperature problem” can be relaxed within the tolerance, let us tentatively allow $\xi \kappa^2$ to increase by 50%, although this is obviously an extreme assumption. Because the disk radius calculated by equation 2.11 is directly proportional to $\xi \kappa^2$, for all sources $R_{\text{in}}$ increases by 50%. For the purpose of presentation, in Figure 7.2b we may lower the theoretical line of $R_{\text{in}} = 3 R_S$ to $2/3$ of the original one, instead of increasing $R_{\text{in}}$ of each data point. Most of our ULXs, except for IC 342 source 1, now show relatively consistent values between $R_{\text{in}}$ and $M_E$ within errors. However, we must keep in mind that this agreement has been obtained after a series of compromising assumptions; ULXs are radiating at the Eddington limit, we observe them under the face-on geometry, and we invoke rather extreme reduction of the distance as well as the artificial 50% increase in $\xi \kappa^2$. Such extreme assumptions would not be warranted. Moreover, as a result of raising $\xi \kappa^2$ by up to 50%, the three prototypical BHBs, Cyg X-1, LMC X-1, and LMC X-3, now show discrepancy between $R_{\text{in}}$ and the optically determined mass. Therefore, we conclude
that the second problem still remains essentially unsolved.

7.3.5 Constancy of $R_{\text{in}}$

The comparison with the Galactic/Magellanic BHBs conducted in the previous subsection may also be utilized to investigate the third problem, i.e., the change of $R_{\text{in}}$. For example, theoretical calculation by Shimura and Takahara (1995) indicates that, as $L_{\text{bol}}$ approaches $L_{\text{Edd}}$, the electron scattering effect may get severe which increases $\kappa$, e.g., from 1.7 to 1.8–2.0; then, the calculated $R_{\text{in}}$ apparently decreases. To examine whether such luminosity-dependent effects are actually observed from established BHBs, we here refer again to LMC X-3, and to the BH transient GS 2000+25.

The *Ginga* observations by Ebisawa (1991) and Ebisawa et al. (1993) recorded a factor $\sim 3$ long-term intensity variation from LMC X-3. Meanwhile, its apparent disk radius, $R_{\text{in}}\sqrt{\cos i/\xi \kappa^2}$, remained constant to within $\sim 20\%$. In Figure 7.1, we plotted those *Ginga* data points of LMC X-3 for which Ebisawa (1991) performed the MCD analysis. Clearly, the data points distribute along a dotted line up to $\sim 2/3$ of the Eddington limit, without any indication of systematic change of $R_{\text{in}}$. This makes a contrast to the ULX variation.

The bright BH transient GS 2000+25 is more suited for such an investigation, because of its large flux variations. Its BH mass and inclination angle have been constrained optically by several authors; $M=5.9–7.5 \, M_\odot$ and $i=67.5–80^\circ$ by Filippenko et al (1995), $M=4.8–14.4 \, M_\odot$ and $i=43–69^\circ$ by Beekman et al. (1996), and $M = 8.5 \pm 1.5 \, M_\odot$ and $i=65\pm9^\circ$ by Callanan et al. (1996). Here, we assume $i=69^\circ$.

This BH transient was observed by *Ginga* eight times spanning 240 days, covering almost the outburst peak. The obtained 2–30 keV spectra were all expressed with an MCD component plus a power-law hard tail. Importantly, the value of $R_{\text{in}}\sqrt{\cos i/\xi \kappa^2}$ remained constant ($\sim 11D$ km where the source distance $D$ is measured in kpc) within $\sim \pm 20\%$ as the intensity declined by a factor of 200 (Ebisawa 1991). With the assumption of $D=3$ kpc (Callanan et al. 1996), $\xi=0.41$, and $\kappa=1.7$, we obtain $R_{\text{in}} \sim 65$ km, or $M \sim 7 \, M_\odot$ assuming a Schwarzschild BH. Therefore, the X-ray and optical estimates agree nicely. These *Ginga* results on GS 2000+25 are plotted also in Figure 7.1, discarding the last data point when the source was faintest. Over a wide range of $\dot{M}$ up to near the Eddington limit, the data points thus distribute along a dotted line, i.e. constant-mass ($R_{\text{in}}$) grid line.

These results indicate that $R_{\text{in}}$ of an ordinary BHB remains quite constant as the source varies, up to luminosities close to the Eddington limit. Therefore, the third problem, like the second one, seems specific to the ULX.

7.4 Possible Scenario to Explain ULXs

We have confirmed that the MCD formalism adequately describe the properties of Galactic/Magellanic ordinary BHBs; the standard accretion disk regime must be realized in these objects. On the other hand, due to the two distinctive features of ULXs, i.e., the higher disk temperature and the change of $R_{\text{in}}$, inconsistency arises if we attempt to explain both ULXs and ordinary BHBs simultaneously under the same formalism. Therefore, ULXs are thought to be in some extraordinary physical conditions, which no longer meet our basic formalism of “standard accretion disk around Schwarzschild BHs”. 

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Table 7.2: Summary of the adopted distances to the ULXs host galaxies and their indicators. The references are tabulated in Table 4.1

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance (Mpc)</th>
<th>indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>M33</td>
<td>0.72</td>
<td>–</td>
</tr>
<tr>
<td>NGC 1313</td>
<td>4.5</td>
<td>Brightest star, Largest $\text{H}_\text{II}$ region, and Reduced diameter</td>
</tr>
<tr>
<td>NGC 1365</td>
<td>18.3</td>
<td>Cepheid by HST</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>3.2</td>
<td>Cepheid (before HST)</td>
</tr>
<tr>
<td>NGC 3031 (M81)</td>
<td>3.6</td>
<td>Cepheid by HST</td>
</tr>
<tr>
<td>NGC 3628</td>
<td>7.7</td>
<td>Virgo inflow model</td>
</tr>
<tr>
<td>NGC 4565</td>
<td>10.4</td>
<td>Three indicators agree within 1 Mpc (^a)</td>
</tr>
<tr>
<td>Dwingeloo 1</td>
<td>3.0</td>
<td>Blue band Tully-Fisher</td>
</tr>
<tr>
<td>IC 342</td>
<td>3.9</td>
<td>Virgo inflow model</td>
</tr>
</tbody>
</table>

\(^a\) 10.0^{+1.5}_{-1.3} \text{ Mpc by the globular cluster luminosity function (Fleming et al. 1995), 10.4^{+0.4}_{-0.3} \text{ Mpc by the surface brightness fluctuation (Simard and Pritchet 1994), and 10.5^{+0.8}_{-1.0} \text{ Mpc by the planetary nebular luminosity function (Jacoby et al. 1996)}}

Figure 7.4: Comparison between the GRAD and the MCD model. Spectra were simulated using GRAD model of $M = 3 \ M_\odot$, 10 $M_\odot$, and 30 $M_\odot$, by changing $\dot{M}$ and $i$. Obtained values of $M$ by spectral fitting using the MCD model (assuming $\xi=0.41$) are plotted. Although $i$ was changed from 0° to 75° by 15°, only the data for the two extreme values of $i$ are plotted for clarify.
Clearly, to identify these conditions provides the clue to the nature of ULXs. With this in mind, below we attempt to explain the spectral features of ULXs, especially IC 342 source 1, M81 X-6, and NGC 1313 source B which exhibited the variation in $R_{in}$.

Among the three objects, the degree of discrepancy between the obtained $R_{in}$ and $M_{E}$ (the value of $M_{E}$ limits $R_{in}$ below 3 $R_S = 8.85 \left( \frac{M}{M_{\odot}} \right)$ km is factor 2.5 for M81 X-6 (high-temperature phase spectrum), 2.7 for NGC 1313 source B (spectra in the 1993 observation), and 8.3 for IC 342 source 1 (spectra of phase 1), as inferred from Table 7.1 and Figure 7.2a. For the latter two sources, however, the distances to the host galaxies are somewhat uncertain, so that we tentatively try to explain the contradiction by a factor of $\sim 3$ found for M81 X-6.

### 7.4.1 Advection dominated accretion disk

The standard accretion disk model so far we have employed, first proposed by Shakura and Sunyaev (1973), is one of the oldest and the simplest accretion disk models. Although this model successfully explains the spectra from BHBs in the soft state, a significant progress has been achieved on the theory of accretion disks by several authors, e.g., Ichimaru (1977), Narayan and Yi (1994), Abramowicz et al. (1988), and so on. After the latest unified theory by Esin et al. (1997), the standard, optically thick, geometrically thin disk is realized in a limited range of the mass accretion rate $\dot{M}$, corresponding to $L_{bol} = (0.1 - 0.5) L_E$. As $\dot{M}$ becomes lower, the disk becomes optically thin, and “advection dominated accretion flow (ADAF)” occurs, where the released gravitational energy is not fully radiated away, but transported with the matter, or “advected”, into the BH. On the contrary, when $\dot{M}$ increases and approaches $L_E$, the disk becomes “optically-thick ADAF”. This model was first constructed by Abramowicz et al. (1988) (see also Katz 1977, Begelman 1978), and has been studied by several authors, including Szuszkiewicz et al. (1996) and Watarai et al. (2000). Such a disk is also named a “slim accretion disk”, since it is moderately geometrically-thick ($H \sim R$, where $H$ denotes the height of the disk). In ULXs, because of their high luminosities (high $\dot{M}$), the accretion flow configuration is expected to change from the standard disk to the slim disk (optically-thick ADAF).

To be more quantitative, the rates of viscous heating, radiative cooling, and advective cooling in an accretion disk are expressed as

$$Q_{vis}^+ \propto \frac{\dot{M}}{R^3}, \quad Q_{rad}^- \propto \frac{\dot{M}^{1/2}}{R^3\Sigma^{1/2}}, \quad Q_{adv}^- \propto \frac{\dot{M}^2}{R^{7/2}\Sigma},$$

(Kato et al. 1998), where $\Sigma$ denotes the surface mass density. The term “advective cooling” means that entropy is carried away by the radial infall of the accreting matter. Thus, the energy released via viscosity ($Q_{vis}^+$) is balanced by radiative cooling ($Q_{rad}^-$) when $\dot{M}$ is small (standard disk regime), whereas balanced by advective cooling ($Q_{adv}^-$) when $\dot{M}$ is high (slim disk regime). This is the reason why the slim accretion disk is realized when $\dot{M}$ is high.

Although the spectrum emergent from a slim disk is a superposition of local black-body radiation like in the case of a standard accretion disk, it differs from the standard-disk spectrum in the following three points (e.g., Watarai et al. 2000);

1. When the advective cooling becomes important, some portion of the released energy
is no longer radiated away. As a result, the disk luminosity does not much exceed $L_E$, even when $\dot{M}$ becomes very high (called super-critical accretion).

2. As $\dot{M}$ increases, advective energy transport becomes the dominant cooling process, especially at inner disk regions. As a result, the effective temperature profile flattens, from $T_{\text{eff}} \propto R^{-3/4}$ (equation 2.6) to $T_{\text{eff}} \propto R^{-1/2}$ at the extreme.

3. The X-rays are radiated not only from the regions outside the last stable orbit, but also from the region inside it. Watarai et al. (2000) fitted the numerically calculated disk spectrum by the MCD model (both $R_{\text{in}}^{\text{MCD}}$ and $T_{\text{in}}$ are the model parameters), and found that as $\dot{M}$ increases, $R_{\text{in}}^{\text{MCD}}$ decreases while $T_{\text{in}}$ increases. The relation between $R_{\text{in}}^{\text{MCD}}$ and $T_{\text{in}}$ in this stage is roughly approximated as $R_{\text{in}}^{\text{MCD}} \propto T_{\text{in}}^{-1}$ (hence, $R_{\text{in}} \propto T_{\text{in}}^{-1}$). Then, the bolometric disk luminosity approximately scales as

$$L_{\text{bol}} \propto R_{\text{in}}^2 T_{\text{in}}^4 \propto T_{\text{in}}^2 R_{\text{in}}^{-2}.$$  \hspace{1cm} (7.5)

Thus, by presuming that the slim disk is realized in ULXs, the “change of $R_{\text{in}}$” problem, approximately expressed as $R_{\text{in}} \propto T_{\text{in}}^{-1}$, can be explained quantitatively by item 3. Furthermore, item 1 ensures that the emergent luminosity stays close to $L_E$ even if $\dot{M}$ changes largely, which in turn justifies our assumption that the highest luminosity observed from each source is close to $L_E$.

Because the slim disk has a smaller $R_{\text{in}}$ and a higher $T_{\text{in}}$ (item 3) than a standard disk of the same parameters, it can also qualitatively explain the “too high $T_{\text{in}}$ problem”, or the “too small $R_{\text{in}}$ problem”. Let us below examine whether this idea can quantitatively explain the factor 3 discrepancy in the $R_{\text{in}}/M_E$ ratio exhibited by our ULXs. In Figure 7.1, the slim-disk scaling ($R_{\text{in}} \propto T_{\text{in}}^{-1}$) of each variable ULX holds over a typical range from the observed highest luminosity $L_{\text{max}}$ (which we tentatively identify with $L_E$) down to $\sim L_{\text{max}}/2$. Equation 7.5 then predicts that $R_{\text{in}}$ at the brightest occasion should be at least $\sqrt{2}$ time smaller than would be expected if the source is in the standard-disk regime. In this way, the slim disk scenario can explain the $R_{\text{in}}/M_E$ discrepancy by up to a factor of $\sim 1.5$. However, in order to fully resolve the factor 3 discrepancy, the source must make a transition from the standard-disk to slim-disk regimes at still lower luminosities, e.g., $L_{\text{bol}} = \frac{1}{3} L_E \sim 0.1 L_E$. This contradicts the results presented in § 7.3.5, where the standard accretion disk picture has been confirmed to be valid up to $\sim \frac{2}{3} L_E$ in the case of GS 2000+25 and LMC X-3.

The above difficulty is enhanced by recent discoveries of several Galactic BH transients with high values of $T_{\text{in}}$, including GRO J1655-40 (Zhang et al. 1997, Ueda et al. 1998), GRS J1915+15 (Belloni et al. 1997), and 4U 1630-47 (Oosterbroek et al. 1998). In particular, the mass and inclination of the Galactic jet source GRO J1655-40 have been determined accurately as $M = 7.0 \pm 0.2 M_\odot$ and $i = 69.5 \pm 0.08$ (Orosz and Bailyn 1997). Thus, the GRO J1655-40 system is very similar to GS 2000+25 and LMC X-3 both in the BH mass and the inclination. According to the Rossi X-ray Timing Explorer (RXTE) measurements (Méndez et al. 1998) during the 1995 August outburst, the flux of GRO J1655-40 decreased by almost two orders of magnitude, whereas $R_{\text{in}} \sqrt{\cos i}/\xi \kappa^2$ remained almost constant (typically $25 \pm 1$ km). We plot all these RXTE data in Figure 7.1, assuming $D = 3.2$ kpc (Hjellming and Rupen 1995), $\xi=0.41$ and $\kappa=1.7$. Because $R_{\text{in}}$ thus remained constant and the luminosity was considerably below $L_E$, the source cannot have been in the slim-disk regime. Nevertheless, $T_{\text{in}}$ of this jet source is $\sim 1.5$ times
higher than that of GS 2000+25 when compared at the same luminosity. This makes the X-ray determined mass of GRO J1655-40, \( \sim 3 \, M_\odot \), fall much short of the optical mass (7 \( M_\odot \)). Thus, the same “too high \( T_{\text{in}} \)” problem is observed from a BH system that is in the standard-disk regime rather than in the slim-disk condition.

In summary, the \( R_{\text{in}} \propto T_{\text{in}}^{-1} \) relation seen in ULXs can be solved adequately by the slim-disk scenario. However, the same idea can give only a partial solution to the “too high \( T_{\text{in}} \)” problem. The remaining part of this issue must therefore be attributed to some physical conditions that is not related to \( \dot{M} \), but intrinsic to the BH itself. In other words, there may be two types of BHs. One type comprises ordinary Galactic/Magellanic BHBs, and obey the standard-disk scenario up to a relatively high luminosity close to \( L_E \). The other type of objects, including ULXs and the high-\( T_{\text{in}} \) BH transients, exhibit rather high disk temperature, and display the slim-disk effects when the luminosity approaches \( L_E \). Then, our remaining task is to identify the origin of the difference between these two types of BHs.

### 7.4.2 Spinning BH scenario

A BH can be characterized only by three fundamental parameters; the mass \( M \), electrical charge, and the angular momentum \( J \). When it becomes an X-ray source via mass accretion, additional two parameters come in; the mass accretion rate \( \dot{M} \) and the system inclination \( i \). Out of these five system parameters, we have fully taken \( M, \dot{M} \) and \( i \) into account already. Then, the difference between the two types of BHs (previous subsection) should be attributed either to the electric charge or the angular momentum. Considering that the universe is very close to electrical neutrality, the only possibility is the angular momentum. In fact, real BHs in the universe may well have considerable angular momenta, even though we have so far assumed non-spinning (i.e. Schwarzschild) BHs for simplicity. For example, massive stars are usually fast rotators, and their collapse will produce spinning BHs described by the Kerr solution. Below, we examine whether the remaining issues can be solved by considering Kerr BHs.

Hereafter, we express the BH angular momentum \( J \) in a dimensionless manner, i.e., by a spin parameter \( a_* \equiv \frac{c}{GM^2} J \). This parameter takes values between \(-1 \) to \( 1 \); \( a_* = 1 \) means the extreme Kerr hole for a prograde disk (i.e., rotating in the same direction as the BH), \( a_* = -1 \) also represents the extreme Kerr hole but for a retrograde disk, and \( a_* = 0 \) corresponds, of course, to the Schwarzschild BH.

The most immediate effect of the BH spin is that it affects the radius of the last stable orbit, \( R_{\text{last}} \), as (e.g. Bardeen et al. 1972)

\[
R_{\text{last}} = \frac{R_{\text{S}}}{2} \left\{ 3 + Z_2 \pm [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2} \right\} ,
\]

where \( Z_1 = 1 + (1 - a_*^2)^{1/3} \left[(1 + a_*)^{1/3} + (1 - a_*)^{1/3} \right] \), \( Z_2 = (3a_*^2 + Z_1^2)^{1/2} \), and the lower and upper signs are for a prograde disk and a retrograde disk, respectively. We here pay attention only to the prograde disk, since in this case \( R_{\text{last}} \) (hence \( R_{\text{in}} \)) decreases as \( a_* \) increases, as shown in Figure 7.5a. Thus, a prograde accretion disk around a Kerr hole has a smaller \( R_{\text{in}} \), and consequently a higher \( T_{\text{in}} \), suggesting that the BH spin can explain the problem with ULXs. This idea has first been proposed by Zhang et al. (1997) to explain the observed high temperature of GRS 1915+105 and GRO J1655-40.
Neglecting relativistic effects for the moment, we can perform simple quantitative estimates. If we start from a Schwarzschild BH and increase its spin, with \( M \) and \( \dot{M} \) kept constant, then \( R_{\text{last}} = R_{\text{in}} \) decreases from \( 3 R_S \) down to \( \frac{1}{3} R_S \) as the BH approaches the extreme Kerr hole (Figure 7.5a). This implies a factor 6 decrease in \( R_{\text{in}} \). Meanwhile, the value of \( T_{\text{in}} \), which scales as \( R_{\text{in}}^{-3/4} \) (equation 2.6), becomes higher by a factor of \( (\frac{1}{6})^{-3/4} = 3.8 \). Even taking a somewhat less extreme case of \( a_* = 0.95 \), we expect \( R_{\text{last}} = R_{\text{in}} \) to decrease by a factor of 3 compared to the Schwarzschild BH case. This is apparently sufficient to explain the discrepancy between \( R_{\text{in}} \) and \( M_E \) seen in ULXs, although relativistic effects are yet to be considered (see next subsection).

Assuming BH spin has another merit, that the radiative efficiency, defined as \( L_{\text{bol}}/\dot{M}c^2 \), gets higher as the BH angular momentum increases. The efficiency is 0.057 for a Schwarzschild case, while it increases up to 0.42 for an extremely Kerr hole (e.g. Kato et al. 1998). Therefore, for a rapidly rotating BH, the same mass accretion rate can produce 5 times higher luminosity than in a non-spinning BH, although the same Eddington limit should still apply.

A Kerr BH has yet another important property. As shown by Beloborodov (1998), an optically-thick accretion disk around a Kerr BH tends to be more advective than that around a Schwarzschild one. Accordingly, we expect an optically-thick disk around a Kerr hole to make a transition into a slim disk at a considerably lower luminosity than the Schwarzschild case. This successfully answer the question which has arisen in the previous section: “why the slim disk seems to occur preferentially among ULXs, whereas not realized in ordinary BHBs?”

From these considerations, we propose that the ordinary Galactic/Magellanic BHs (Cyg X-1, LMC X-1, LMC X-3, GS 2000+25, and so on) have insignificant angular momenta \( |a_*| << 1 \), while ULXs and high-\( T_{\text{in}} \) Galactic transients (e.g. GRO J1655-40) involve Kerr BHs with prograde accretion disks. This may solve the overall issues associated with ULXs in the following manner. Firstly, the BH spin reduces \( R_{\text{in}} \) and raises \( T_{\text{in}} \) according to Figure 7.5a. Secondly, the BH spin enhances the slim-disk condition, which in turn adds to the decrease in \( R_{\text{in}} \) and increase in \( T_{\text{in}} \) (see previous subsection). Finally, the induced slim disk condition explains the observed \( R_{\text{in}} \propto T_{\text{in}}^{-1} \) relation. In the next subsection, we confirm that this final scenario is valid even when taking relativistic effects into account.

7.4.3 Spectra from accretion disks around Kerr BHs

The X-ray spectra emergent from an accretion disk is subject to several relativistic corrections, due to gravitational redshift, transverse and longitudinal Doppler shifts, and gravitational focusing. To a distant observer, both the observed color temperature and flux will deviate from the local values, depending on the inclination angle \( i \) and the BH spin.

We first examine the effects of the gravitational and transverse Doppler redshifts of a face-on disk. The ratio of the photon energy observed at infinity (\( E_o \)) and at the disk surface (\( E \)), when viewed from \( i = 0^\circ \), is given as (e.g., Cunningham et al. 1975, Asaoka
We calculated the energy ratio at $R = (7/6)^2 R_{\text{last}}$, where the disk temperature becomes maximum (§ 2.7), and show the results in Figure 7.5b. Thus, a face-on disk suffers strong gravitational and transverse redshifts, which becomes severer as $a_*$ increases. These effects are so strong that the increase in the local disk temperature, caused by the decrease in $R_{\text{in}}$ in Kerr BHs, is almost canceled out. Therefore, a nearly face-on geometry is not favored. When $i$ increases, however, the longitudinal Doppler effects start increasing the $E_o/E$ ratio, and hence the disk color temperature becomes higher.

To examine the overall relativistic effects, more detailed numerical calculations of the emergent spectra are needed. Such calculations have already been performed by several authors, including Cunningham et al. (1975), Asaoka (1989), and Zhang et al. (1997). They in fact showed that, although the spectrum from an optically-thick accretion disk around a Kerr BH is similar in shape to that around a Schwarzschild one, the color temperature of the spectrum and the integrated flux are strongly dependent on $a_*$ and $i$. Here we show the spectra of $a_* = 0$ and $a_* = 0.998$ (Schwarzschild and nearly extreme Kerr hole respectively) calculated by Cunningham et al. (1975) in Figure 7.6. The latter value of $a_*$ is that at which a black hole will equilibrate with the disk accretion (Throne 1974). They calculated the expected spectra for each viewing angle considering the relativistic effects based on their “transfer function”, which represents the relative intensity of the ray, emitted from each portion of the disk surface to the observer, as a function of $i$ and $R$. As seen in Figure 7.6, the color temperature of the spectra strongly depends on $i$ for a rapidly rotating BH, and a spectrum harder than that in the Newtonian potential is expected when viewed relatively edge-on.

Their results have been confirmed by Zhang et al. (1997) by using the same transfer functions. These authors represent the relativistic effects by two correction factors. One is the change of the color temperature denoted $\kappa_{\text{GR}}$, due to the gravitational redshift and Doppler red/blue-shifts ($T_{\text{col}}/T_{\text{eff}} \propto \kappa_{\text{GR}}$). The other is the change of the flux denoted $g(i, a_*)$, due to the viewing geometry and the gravitational focusing ($f_X \propto \frac{1}{g}$ instead of $f_X \propto \frac{1}{\cos i}$ in the Newtonian case). Because we expect $M_E \propto L \propto \frac{1}{g}$ and $R_{\text{in}} \propto \sqrt{\frac{L}{(T_{\text{eff}})^{3/2}} \propto \frac{\kappa_{\text{GR}}^2 \sqrt{g}}{\mathcal{S}}}$, the quantity $R_{\text{in}}/M_E$ scales with $\kappa_{\text{GR}}^2 \sqrt{g}$. Figure 7.7 give this combined correction factor ($\kappa_{\text{GR}}^2 \sqrt{g}$) as a function of disk inclination angle $i$, for a Schwarzschild and a nearly-extreme Kerr holes. As for a Schwarzschild BH, this correction factor is almost independent on $i$, whereas for a Kerr BH the factor increases as $i$ increases. To get a true value of $R_{\text{in}}/M_E$, we must multiply this correction factor to the apparent value of $R_{\text{in}}/M_E$ derived through the MCD fit to the data assuming an $i = 0^\circ$ standard disk around a Schwarzschild BH. Thus, for a Kerr BH, the discrepancy between $R_{\text{in}}$ and $M_E$ is relaxed as the inclination angle $i$ increases.

We also need to take into account the decrease of $R_{\text{in}}$ for a Kerr BH case. The overall correction factor, taking into account the reduction of $R_{\text{in}}$, is given as dashed-line in Figure 7.7. Therefore, if we assume a Kerr BH of $a_* = 0.998$, and view the disk from an inclination angle of $i \geq 65^\circ$, the correction factor exceeds $\sim 2$. When this is combined with another factor of $\sim 1.5$ due to the slim-disk property (§ 7.4.1), we can explain the
discrepancy by a factor of 3 between $R_{\text{in}}$ and $M_E$. Since $i \sim 60^\circ$ is what is expected on average when the disks are randomly oriented, the chance probability of finding such objects is reasonably high. For those ULXs of which the $R_{\text{in}}$ vs. $M_E$ discrepancy is smaller, e.g. Dwingeloo-1 X-1, NGC 2403 source 3 and NGC 3628 off-center source, even a Kerr hole which is closer to the face-on geometry can give adequate explanation. Obviously, M33 X-8 and NGC 1313 source A can be explained even without invoking the slim disk or BH rotation, since they originally fall on the sub-Eddington regime in Figure 7.1.

We conclude that the mystery of ULXs can be solved in terms of the slim accretion disk and the BH rotation.

Figure 7.5: (a) Radius of the last stable orbit as a function of $a_*$ for a prograde disk. (b) The ratio of the energy observed at infinity ($E_o$) and the disk surface ($E$) as a function of $a_*$, calculated at $R = \frac{49}{36}R_{\text{last}}$, where the temperature of the standard disk becomes maximum.

7.4.4 Formation of a massive spinning BH

We end this chapter by discussing how to make a massive, rapidly rotating BH. In short, there seems to exist at least three possibility to make a Kerr BH of 50–100 $M_\odot$. One is a simple, straight-forward scenario, that a massive rotating star collapses into a massive BH. Another needs two ordinary stellar-mass BHs; if they come close and merge into a single BH, it would have a doubled mass, and inherit the angular momentum from the orbital motion. The other is expected in XRBs, where the BH is spun up by the accreting matter, and obtain both the mass and angular momentum.

As already quoted in § 7.3.1, Fryer (1999) show that a massive star of $\geq 40$ $M_\odot$ will directly form a BH, without experiencing a supernova explosion. We also refer here to Nakamura et al. (1987), who showed through numerical simulations that the gravitational collapse of a rotating massive star usually produces a rather extreme Kerr hole, without exhibiting the naked singularity. Thus, among the three scenarios presented above, the first one is particularly preferred since it can naturally explain the difference between the ordinary stellar-mass BHBs and ULXs. When a BH in the ordinary mass range ($\sim 10$ $M_\odot$) is formed through supernova explosion, a large amount of mass, hence a large amount of angular momentum of the progenitor star, will be lost into the expanding supernova
Figure 7.6: Relativistic effects on the disk spectrum, taken from Cunningham (1975). (Left) The inclination dependence of the flux. Numbers along the lines indicate the values of $a_\ast$, and $\theta_0$ is the inclination. The straight line denoted “N” corresponds to the case under the Newtonian potential. (Middle) The expected spectra of the disk around a Kerr hole of $a_\ast = 0$, with the values denoting $\cos i$. “N” is the spectrum under the Newtonian potential seen from $i = 0^\circ$. (Right) The same as the middle panel, but for a case of $a_\ast = 0.998$.

Figure 7.7: Correction factor to the ratio of $R_{in}$ and $M_E$, calculated based on the correction factor of Zhang et al (1997). Diamonds indicate the correction for a Schwarzschild BH, and the squares mean that for a nearly extreme Kerr BH ($a_\ast = 0.998$). Dashed line includes the reduction of $R_{in}$. We need to multiply this correction factor to the apparent value of $R_{in}/M_E$ (see text).
ejecta. On the other hand, a very massive star will form a BH without losing much of its mass and angular momentum. Thus, if the value of the initial angular momentum is sufficient, a rapidly rotating, massive BH would be born. If this BH tidally traps another ordinary star and forms a close binary, a ULX is realized.

In order to examine this scenario, we briefly estimate the spin of a BH formed directly from a massive star. For this purpose, let us calculate the angular momentum of the sun, regarding it as a rigid rotator, as: \( \frac{2}{5} f M_\odot R_\odot^2 \dot{\phi} = 9.5 \times 10^{41} \text{ kg m}^2 \text{ s}^{-1} \) where \( R_\odot = 7 \times 10^8 \text{ m} \) is the solar radius, \( M_\odot = 2 \times 10^{30} \text{ kg} \) is the solar mass, \( \dot{\phi} \sim \frac{2\pi}{30 \text{ day}} \) is angular velocity of the solar rotation, and \( f \) is a form factor representing the mass concentration (\( f = 1 \) means that the internal mass density is uniform). Considering \( f \sim 0.18 \), the solar angular momentum is in fact comparable to the maximum angular momentum \( J_{\text{max}} \) for a \( 1 M_\odot \) BH, \( \frac{GM^2}{c} = 8.9 \times 10^{41} \text{ kg m}^2 \text{ s}^{-1} \).

Thus, even for the sun which is a slow rotator, \( \frac{J}{J_{\text{max}}} \) reaches of order unity. Since the radius of main-sequence stars is scaled as \( R \propto M^{3/4} \), the ratio \( \frac{J}{J_{\text{max}}} \propto \frac{R^2}{M^2} \dot{\phi} \propto M^{1/2} \dot{\phi} \). Therefore a massive star, which tends to have higher angular velocity than the sun, would be expected to form into a nearly extremely Kerr BH in the case of the direct collapse.

Further discussion on the formation scenario of heavy stellar-mass Kerr holes, however, is beyond the scope of the present thesis.
Chapter 8

SUMMARY AND CONCLUSION

Using ASCA, we have observed twelve ULXs in nine spiral galaxies, and three X-ray luminous SNRs for comparison. By analyzing these ASCA data and partially utilizing those from the ROSAT HRI, we have obtained the following new results.

1. Our objects are basically point-like, and four of them showed intensity variations. These results reinforce the interpretation of ULXs as high-luminosity single objects.

2. The spectra of the three SNRs have been confirmed to be distinct from those of the ULXs. Consequently, ULXs cannot be interpreted as young SNRs, but are considered to be accreting compact objects.

3. Out of the twelve ULX spectra, nine can be described with a single MCD model, one with a power-law plus MCD model, and two with a single power-law model. Since these spectra are typical of BHBs, it is indicated that the ULXs are mass-accreting black holes, where the MCD emission arises from optically-thick accretion disks.

4. The observed bolometric luminosity of the MCD emission is distributed over $10^{39-40}$ erg s$^{-1}$. For these luminosities to remain sub-Eddington, relatively high BH masses up to $\sim 100 M_\odot$ are required. This provides an observational evidence that very massive stellar BHs exist.

5. From the three variable ULXs, we have detected characteristic changes in the accretion-disk radius, which are roughly expressed as $R_{\text{in}} \propto T_{\text{in}}^{-1}$. This can be interpreted as one of first observational evidences for the optically-thick ADAF that has been theoretically predicted.

6. The disk temperature of the ULXs is unusually high at $T_{\text{in}}=1.0-1.8$ keV. Consequently, the disk radius $R_{\text{in}}$ is $\sim 100$ km, which is too small to account for the inferred high BH mass (item 4). The ADAF scenario can explain this problem partially, but not completely. We have shown that the issue can be solved if in addition the BHs are spinning rapidly, because the last stable orbit gets closer to the BH in a Kerr BH than in a Schwarzschild BH, and the accretion disk can get hotter even considering the relativistic effects. Thus, based on firm physical grounds, we have for the first time given a unified interpretation to the long-lasting mystery of ULXs.
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Appendix A

Spectral model descriptions

Here we briefly explain the spectral models used in this thesis.

**Power-law model** This is the simplest, and widely used model, mainly representing non-thermal emission as was seen in AGNs, X-ray pulsars, and so on. The photon flux per unit energy is expressed as

\[
f(E) = K \left( \frac{E}{1 \text{ keV}} \right)^{-\Gamma},
\]

where \( K \) is the normalization factor and \( \Gamma \) is the photon index, which we assume to be positive in general. Obviously, this draws a straight line in the logalithmic plot, as shown in Figure A.1a.

**TBS model** An optically this hot plasma of temperature \( T \) radiates photons due to the process called bremsstrahlung or free-free emission; photons are radiated from accelerated electrons in the Coulomb fields of ions. The spectrum is obtained by integrating the radiation over thermally distributed electrons, so that we call the emission “thermal bremsstrahlung (TBS)”. The emissivity is written as

\[
\varepsilon_{\nu}^{ff} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{E/kT} \bar{g}_{ff} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1},
\]

where \( Z \) and \( n_i \) are the charge and number density of ions, \( n_e \) is the number density of electrons, and \( \bar{g}_{ff} \) is the Gaunt factor (Rybicki and Lightman 1979). In the X-ray band, \( \bar{g}_{ff} \sim E^{-0.4} \). Therefore in the low energy range the spectrum is similar in shape to a power-law model of photon index \( \Gamma \sim 1.4 \), whereas at \( E \gg kT \), flux drops sharply as shown in Figure A.1c.

**Raymond-Smith plasma emission model** In addition to the continuum emission as described by a TBS model, a thin hot plasma shows atomic emission lines of heavy elements through collisional excitations, as shown in Figure A.1c. The center energy and equivalent width of each line depend on the abundance of the relevant element and temperature of the plasma. Although there exists several plasma emission codes (Raymond and Smith 1977, Masai 1984, Mewe et al. 1985), we use only Raymond-Smith model in this thesis, since none of objects in our sample show strong emission lines and the obtained results are almost independent of the plasma codes.
MCD model As described in § 2.7, the MCD model is an approximation of the emission from optically-thick, geometrically-thin accretion disks (Shakura and Sunyaev 1973, Mitsuda et al. 1984, Makishima et al. 1986). The spectrum is a superposition of black-body radiations from individual portions of the disk. Integrating from the innermost disk radius $r_{\text{in}}$ to the outermost disk radius $r_{\text{out}}$, and assuming $r_{\text{in}} \ll r_{\text{out}}$, we obtain the spectrum as

$$f(E) = \cos i \int_{r_{\text{in}}}^{r_{\text{out}}} 2\pi r B(E,T) dr = \frac{8\pi r^2 \cos i}{3D^2} \int_{T_{\text{in}}}^{T_{\text{out}}} \left( \frac{T}{T_{\text{in}}} \right)^{-11/3} B(E,T) dT \ , \quad (A.3)$$

where $i$ is a inclination angle of the disk, $D$ is the distance to the source, and $T_{\text{in}} = T(r_{\text{in}})$ and $T_{\text{out}} = T(r_{\text{out}})$ are the innermost and outermost disk temperature, respectively. The spectrum is approximated by a single temperature black-body radiation at high energy and drops sharply, whereas in the low energy range it resembles in shape a power-law of $\Gamma = -2/3$, as shown in Figure A.1d.

Unsaturated Comptonization (UC) model This model is realized when hot thermal electrons of a plasma Compton up-scatter some seed photons, but do not saturate to the Wien peak spectrum for most photons. The spectrum is characterized by an electron temperature, $T_e$, and an optical depth for electron scattering, $\tau_{\text{es}}$. In the high-energy range, i.e., over the electron temperature, the spectrum drop off sharply. On the other hand, the low-energy continuum has power-law like shape whose slope is determined by the combination of $T_e$ and $\tau_{\text{es}}$. Thus, when $T_e$ is close to $T_{\text{in}}$ of the MCD model and $\tau_{\text{es}}$ is optimized, this model is almost identical to the MCD one in spectral shape, and can equally represent the soft component of LMXBs or BHBs in the soft state, as described in White et al. (1988) and Ebisawa et al. (1991).

Broken power-law model This is an empirical model to represent the spectrum of a rather convex shape, and written as

$$f(E) = \begin{cases} 
K \left( \frac{E}{1 \text{ keV}} \right)^{-\Gamma_1} & E \leq E_{\text{bk}} \\
K \left( \frac{E_{\text{bk}}}{1 \text{ keV}} \right)^{\Gamma_2-\Gamma_1} \left( \frac{E}{1 \text{ keV}} \right)^{-\Gamma_2} & E \geq E_{\text{bk}} 
\end{cases} \ , \quad (A.4)$$

where $E_{\text{bk}}$ is the break-point energy, while $\Gamma_1$ and $\Gamma_2$ represent the photon indices below and above $E_{\text{bk}}$, respectively. As shown in Figure A.1 this model and the UC model resemble the MCD model when parameters are appropriately selected.

Photo-electric absorption At low energies, X-ray emission suffers absorption by cold matter between the source and the observer. The absorber can be either local to the source, associated with the host galaxy, or attributed to the interstellar medium within our Galaxy. The effect of the absorption on the incident spectrum $f(E)$ is expressed as

$$f'(E) = f(E) \times e^{-N_H \sigma(E)} \ , \quad (A.5)$$

where $\sigma(E)$ is the cross section of photo-electric absorption assuming cosmic abundances for the absorber (Marrison and McCammon 1983) and $N_H$ is equivalent hydrogen column density. Although $N_H$ represents the number of hydrogen atoms per unit area, hydrogen does not contributes much to the absorption. Instead, in
the energy range of 0.5–2 keV that is related to us, the absorption is mainly caused by K-shells of O, Ne, Mg, Si, and S, as well as L-shell of ion. We show an absorbed power-law model in Figure A.1d.
Figure A.1: Examples of typical spectral models. (a) A power-law of photon index $\Gamma=2$. (b) An absorbed power-law of photon index $\Gamma=2$. We assume $N_H=1 \times 10^{21}$ cm$^{-2}$. (c) A Raymond-Smith model of a thin-hot plasma, with the temperature $kT=3$ keV and the abundance of one solar. We can see emission lines, superposed on the continuum which is almost identical in shape with that of TBS model of the same temperature. (d) An MCD model of $T_{in}=1$ keV. This model shows the most convex shape among our models. (e) An UC model of $T_e=1$ keV and $\tau_{es}=30$. The shape of this model is similar to that of the MCD model. (f) A broken power-law model of $\Gamma_1=1$, $\Gamma_2=5$, and $E_{bk}=4$ keV. This empirical model can also represent the MCD-like convex shape.
Appendix B

Calibration of the *ASCA* spectral response

The spectral response of *ASCA* has been calibrated based on both the pre-launch experiments and the in-orbit calibrations, and is best adjusted on the 1-CCD nominal position, where the source is located near the center of S0C1. Observations of bright, well-known Galactic X-ray sources have been utilized for the calibration of the GIS (plus the XRT) response; the instrumental parameters of the GIS and XRT (e.g., the energy dependence of the energy resolution of the GIS, optical constants associated with the XRT, and so on) have been adjusted within the ground-calibration tolerance, so that the observed spectra of the calibration targets can be well reproduced by a physically reasonable model spectrum. Among the calibration objects, the Crab Nebula is regarded as a standard one and its spectrum is known to be expressed with an absorbed power-law model with $\Gamma = 2.08 \pm 0.11$ and $N_H = (0.27 - 0.33) \times 10^{22} \text{ cm}^{-2}$ (Toor & Seward 1974). As already described by Makishima et al. (1996) and Fukazawa et al. (1997), the current response functions are so well determined that the high-quality spectrum of the Crab Nebula can be fitted by the model consistent with that of Toor & Seward (1974) for both the GIS 2 and GIS 3, and the fit residuals is only $\sim 1\%$. To confirm this, we fitted the Crab spectra obtained in September 1994, when the source was observed at the 1-CCD nominal position, by an absorbed power-law model with all the model parameters independent between the GIS 2 and GIS 3. We obtained a marginally good fit ($\chi^2/\nu=719/458$), with the parameters of $\Gamma = 2.078 \pm 0.003$ and $N_H = (0.299 \pm 0.003) \times 10^{22} \text{ cm}^{-2}$ for GIS 2, and $\Gamma = 2.078 \pm 0.003$ and $N_H = (0.280 \pm 0.003) \times 10^{22} \text{ cm}^{-2}$ for GIS 3; hence both results are consistent with those of Toor & Seward (1974). The dead-time corrected normalizations between the two sensors agree with each other within 3%. Although the spectral fit performed above is statistically unacceptable and there extists an artificial winding in the fit residuals as shown in Figure B.1a, the degree of the deviations from the best-fit model is within $\sim \pm 1.5\%$. Therefore we regard this 1.5% as a typical measure of the calibration uncertainty of the GIS (plus the XRT) spectral response concerning the spectral shape.

Since the SIS suffers telemetry saturation when it observes the Crab Nebula, the cross-calibration between the SIS and the GIS has been performed by observing moderately bright sources, and the SIS response has been adjusted to produce the results consistent with those of the GIS. We present the SIS/GIS spectra of 3C273 obtained on the 1-CCD nominal position in Figure B.1b, and fitted them with a power-law plus TBS models (the latter describes soft excess). We constrained the spectral parameters to be common
between the SIS and GIS, and obtained an acceptable fit ($\chi^2/\nu=238/209$). Although the model normalizations are left free between these two instruments, they turned out to be consistent within 3%. Studies performed by the instrumental team based on the observations of various sources (including 3C273) indicate that the relative normalization among the four detectors (SIS 0, SIS 1, GIS 2, and GIS 3) agree within $\sim5\%$, and the other spectral parameters are indistinguishable in most cases within the fitting errors. Therefore we estimate the SIS (plus the XRT) spectral response uncertainty to be as small as that of the GIS plus the XRT with respect to the spectral shape.

Although the ASCA spectral response is thus well calibrated at the nominal position, the results may depend on the source position. Such studies have been done by Fukazawa et al. (1997), based on the GIS spectra of the Crab Nebula acquired at various focal-plane positions. As shown in Figure B.2, model normalizations scatter rather largely up to $\sim10\%$, whereas the values of photon index $\Gamma$, which denote the spectral hardness of the source, change within only $\sim\pm0.05$ depending on the source position. In summary, the observing position has a noticeable influence only on the source flux.

Figure B.1: ASCA spectra of X-ray bright sources. Panel (a) is the GIS 2 spectrum of the Crab Nebula, fitted with a power-law model with absorption, and panel (b) is the SIS/GIS spectra of 3C273, jointly fitted by a power-law plus TBS models, with only the relative normalization left free between the two spectra. Both sources are observed on the 1-CCD nominal position.
Figure B.2: The best-fit parameters of the Crab spectra obtained at different focal-plane positions, taken from Fukazawa et al. (1997). Photon index $\Gamma$ (panel a) and the 2–10 keV flux after a dead-time correction (panel b) are plotted as a function of the distance from the optical axis.
Appendix C

X-Ray Images of the Sample Galaxies

We present X-ray contours of our sample galaxies superposed on the optical (Digital Sky Survey) image. The ASCA images are taken in the 0.5–10 keV band for both the SIS and the GIS. X-rays are smoothed with a gaussian distribution of $\sigma = 0.05$, 0.1, and 0.5 for the HRI image, the SIS image, and the GIS image, respectively.
Appendix D

Light Curves of ULXs

We summarize the ULX (and SNR) light curves obtained by *ASCA* in the 0.5–10 keV energy range, including background. The typical background count rate is 0.02 and 0.01 c s\(^{-1}\) for the SIS and the GIS, respectively. Each light curves is tested against a constant-intensity hypothesis, and the assumed count rate is represented in the figure as a horizontal straight line. For some sources, only the SIS (or the GIS) light curve is shown (see § 5.2).

![M33 pos1 SIS](image1)

![M33 pos1 GIS](image2)

![M33 pos2 SIS](image3)

![M33 pos2 GIS](image4)
SN 1978K 93/07 SIS

SN 1978K 93/07 GIS

N1313 SA 95/11 SIS

N1313 SA 95/11 GIS

N1313 SB 95/11 SIS

N1313 SB 95/11 GIS

SN 1978K 95/11 SIS

SN 1978K 95/11 GIS
SNR in N6946 94/12 SIS

IC 342 S1 SIS

IC 342 S1 GIS

IC 342 S2 SIS

IC 342 S2 GIS

Dwingeloo 1 X-1 SIS

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