X-ray spectral analysis of the radio-loud narrow-line Seyfert 1 galaxy RX J1633+4718

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Abstract

An X-ray spectral analysis of the radio-loud narrow-line Seyfert 1 galaxy RX J1633+4718 is presented, including spectral fitting and spectral variability. Four observations by XMM-Newton and four by Suzaku from 2011 and 2012 were studied, in addition to a pointed observation by ROSAT from 1993. Main features of the 0.1–10 keV spectrum are clear signatures of intrinsic absorption around 2 keV, lack of accretion disk reflection characteristics and an unusual excess below 0.3 keV. The apparent lack of reflection could be explained by highly ionized reflection medium or intrinsically low reflection because of relativistic beaming away from the disc. The soft X-ray excess in Seyfert galaxies is typically observed above 0.3 keV and it is shown that the excess in RX J1633+4718 is adequately modeled by a blackbody. This is in contrast to other sources where the fitted blackbody temperatures typically are inconsistent with standard accretion disk theory. The temperature and luminosity of the blackbody are $31^{+2}_{-3}$ eV and $7 \times 10^{44}$ erg s$^{-1}$, respectively. This is in agreement with standard accretion disk theory when independent optical mass estimates ($\sim 4 \times 10^6$ M$_\odot$) are used. Future observations and further analysis of archival ROSAT data may reveal blackbody contributions in other sources, potentially allowing for spin measurements through disk continuum fitting or serving as an independent mass estimate.
Chapter 1

Introduction

An active galactic nucleus (AGN) is the central, dense region of a galaxy. Several characteristics set AGNs apart from regular galaxies. Most striking is the emitted radiation. AGNs emit an exceptionally large amount of radiation, an indicative value is a bolometric luminosity of $L \sim 10^{45}$ erg s$^{-1}$ ($= 2.5 \times 10^{11} \text{L}_\odot$), but AGN luminosities in general span more than nine orders of magnitude, and some AGNs are among the most luminous persistent sources of radiation. Furthermore, the spectrum of an AGN commonly extends over more than ten orders of magnitude in frequency, ranging from radio to X-ray wavelengths, and in some cases extending even further into γ-rays. Besides characteristic continua, AGNs emit very strong and broad spectral lines. Some AGNs launch powerful relativistic particle jets which may generate vast radio lobes (Carroll and Ostlie, 2013).

AGNs display variability on different timescales. Observed variability on timescales of days implies that the source must be very compact since the spatial extent of the source is constrained by the light travel distance for a given time, i.e. due to causality. The prevailing model is that AGNs are fueled by accretion of matter onto a supermassive black hole (SMBH) located in the center of the galaxy (Lynden-Bell, 1969). The energy released is part of the gravitational potential energy of the infalling matter, which is converted to radiation in the accretion process.

The importance of AGNs has become increasingly clear over the past decades and has given rise to significantly increased activity in the field. The size of a SMBH is very small in comparison to the size of its host galaxy, the ratio is roughly the same as that of a coin compared to the Earth. However, there is compelling evidence that AGNs are strongly connected to their hosts. For instance, the mass of the SMBH ($M$) and the mass of the host bulge ($M_{\text{bulge}}$) tightly follows the relation $M_{\text{bulge}} \approx 200M$ (Kormendy and Ho, 2013), which shows that there is an active interplay between the SMBH and the host.

The emission from AGNs spans almost the entire spectrum, but emission in different energy bands typically originates from distinct parts of the AGN. Radio emission is generally taken to be an indication of a jet whereas optical emission is primarily emitted by gas and dust at an intermediate distance from the SMBH. A significant fraction of the total bolometric luminosity of an AGN is emitted in X-ray, which is generated in the innermost regions. The dominant processes driving the X-ray emission are accretion, jets, and coronas, all of which display unique spectral and temporal features. Secondary
effects such as relativistic disk reflection and absorption along the line-of-sight are also commonly studied. This makes X-ray analysis a very powerful tool when exploring the inner regions, which are otherwise unresolvable or only weakly emitting at other wavelengths (Reynolds, 2015; Fabian, 2015).

1.1 Aim

The AGN of focus for this study is RX J1633+4718. It has previously been reported to exhibit unique spectral features, primarily an unusual, soft excess below 0.3 keV (Yuan et al., 2010). The favored explanation is that the accretion disk is directly seen as blackbody emission for this source. However, new data are now available using significantly more powerful instruments. It is therefore of interest to use all data to further investigate the claim. Additional goals are to study the entire X-ray spectrum in the 0.1–10 keV with the purpose of finding a consistent picture of the underlying physical processes in the innermost regions of RX J1633+4718.

1.2 Outline of the Thesis

The thesis is organized as follows. The background is provided in chapter 2 followed by a description of relevant telescopes in chapter 3. Details concerning observations and data reduction are given in chapter 4. The main results on variability are described in chapter 5 while chapter 6 presents the spectral analysis. This is followed by a discussion in chapter 7. Finally, a summary and conclusions are given in chapter 8.

An assumed standard ΛCDM cosmology with Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and cosmological constant $\Omega_\Lambda = 0.73$ will be used (Komatsu et al., 2011), i.e. the default flat cosmology of XSPEC (Arnaud, 1996). A photon index $\Gamma$ following the definition $N(E) \propto E^{-\Gamma}$ will be used, where $N$ is number flux and $E$ is photon energy. The centimeter-gram-second system of units will be used unless otherwise stated. Reported energies are in the observed frame with the exception for intrinsic luminosity and the default confidence level is 90 %, although one standard deviation is also used in some plots and will be clearly stated. Fit statistics are presented as $\chi^2$/d.o.f. = $\chi^2_{\text{red}}$ where $\chi^2$ is the standard fit statistic, d.o.f. is the number of degrees of freedom, and $\chi^2_{\text{red}}$ is the reduced fit statistic.

1.3 Author’s Contribution

All plots and figures were made by the author unless clearly cited in the caption. Everything else presented in this thesis is original work by the author. This is including, but not limited to, data reduction and analysis, development of the routines used throughout the process, and finally the writing of the thesis.
Chapter 2

Background

The purpose of this section is to outline the essential physical concepts and phenomena. The reader is introduced to AGN structure in general in section 2.1 and AGN classification in section 2.2. The concept of Eddington limit is described in section 2.3 and different accretion models are presented in section 2.4. Emission processes are studied in section 2.5 which leads on to section 2.6 on X-ray spectra, which describes observational signatures based on different physical scenarios. Finally, a summary of properties and previous studies of RX J1633+4718 is provided in section 2.7.

2.1 AGN components

AGNs consist of several different components, shown in figure 2.1. The largest scale structure in AGNs are jets, which are observed in \(~\sim\sim \sim \sim \sim 10\%\) of all AGNs. Jets are powerful, highly relativistic outflows of particles that are generated on small scales but extend to Mpc-scales in extreme cases (e.g. Willis et al., 1974). Relativistic velocities causes apparent superluminal motion to be observed in some cases (e.g. Pearson et al., 1981). It has been suggested that weaker jets are formed but unsuccessfully launched in more AGNs, naturally making them more difficult to detect (Ghisellini et al., 2004). Jets have been traced all the way down to the innermost parts of AGNs (e.g. Krichbaum et al., 1998; Junor et al., 1999) and are believed to be generated by magnetohydrodynamic processes (Blandford and Payne, 1982). However, the details regarding their formation still remain poorly understood (McKinney et al., 2012). Although some observational difficulties arise due to orientation effects, compelling evidence show that jets come in pairs, which are launched in opposite directions. An additional characteristic property of jets is strong radio emission. This makes jetted AGNs some of the strongest observed radio sources despite the extragalactic distances (Carroll and Ostlie, 2013).

The narrow-line region (NLR) is a region found at a distance of \(\sim 100–3000\) pc (Netzer, 2013). Although the NLR occupies a large volume, its opacity is relatively low due to a low density. The NLR is given its name by the small width of the spectral lines from this region. The width of the narrow lines generally vary between 200 km s\(^{-1}\) and 900 km s\(^{-1}\) (Osterbrock and Ferland, 2006). The most prominent lines from the NLR are those observed in optical and ultraviolet (UV). Forbidden lines are also observed in the NLR. The term “forbidden” is somewhat misleading. They are simply originating from quantum mechanically highly unlikely transitions. Forbidden lines are only observed when the density of the gas is low, else collisions would trigger emission through allowed
Figure 2.1: A schematic showing the principal components of an AGN. The illustration is not to scale but it can be said that it is closer to a logarithmic than a linear scale in terms of distance from the center. Several details are debatable, such as the exact geometry of the torus and accretion disk, the depicted shapes are only indicative. Figure courtesy of Middelberg and Bach (2008).

Transitions. Forbidden lines are denoted by brackets, e.g. [O\textsc{iii}], and have width that are on the order of 500 km s\(^{-1}\) (Osterbrock and Ferland, 2006). It has been shown that properties of these spectral lines can be used to infer the accretion rate and the total bolometric luminosity of AGNs (e.g. Heckman et al., 2005). However, this method suffers from large uncertainties because several assumptions have to be made to link line width to luminosity.

Even closer to the black hole is the torus. It consists of dust and is located in a region of radius \(\sim 1\)–100 pc. The term torus might be slightly misleading since the actual shape might be quite different from a torus. One of the most prominent properties of the torus is its comparatively large optical thickness. The high opacity leads to significant observational differences depending on the orientation of the torus with respect to the line-of-sight. As a consequence of the large column density, the torus acts as a mirror which is capable of reflecting the light emitted from the central parts of the AGN. The outer parts of the torus normally radiate most strongly in the infrared because almost all of the energy input is either absorbed or reflected at the inner edge (Netzer, 2013).

The next region is the broad-line region (BLR), found at radii \(\lesssim 1\) pc. This region is similar to the NLR in the sense that both share the characteristic of emitting spectral lines, mainly in optical and UV. However, as implied by the terminology, the lines emitted in the BLR are broader due to the higher gas velocity. Observed widths typically correspond to gas velocities of 1000–5000 km s\(^{-1}\) (Osterbrock and Ferland, 2006). Furthermore, the BLR also has a higher density than the outer regions. Since the BLR extends almost all the way to the black hole, it is possible to observe variability on
timescales of a few days. It is important to emphasize that the BLR is located inside the torus. Emission is therefore blocked unless viewed along the symmetry axis of the torus (Netzer, 2013).

The innermost part of a AGN is the black hole region, a term which includes the black hole as well as the accretion disk. Almost all of the gravitational potential energy that is used to fuel an AGN is converted in the accretion disk. Observations of the black hole region is usually made at X-ray energies, although observations are not possible for all AGNs because of obscuration by surrounding gas. The radius of the black hole region is \( \sim 10^{-3} \) pc, which makes emission from this region highly variable, sometimes on timescales as low as a few minutes (Itoh et al., 2013).

SMBHs in this context have masses greater than \( \sim 10^6 \) M\(_\odot\), but very few are observed to have masses greater than \( 10^{10} \) M\(_\odot\). The extreme conditions in the vicinity of SMBHs make relativistic effects very prominent. The velocities involved makes both relativistic Doppler shift and beaming important. Radiation emitted by matter moving towards an observer will be both blueshifted as well as intensified by the beaming effect. Furthermore, the gravitational effects of the SMBH give rise to redshifts and light bending, causing additional distortions. A simulation of the accretion disk displaying the aforementioned phenomena is shown in figure 2.2.

Even though SMBHs are among the most extreme objects in the Universe, they remain simple in the sense that very few parameters are required to describe them fully. There are in total three parameters, namely mass \( (M)\), the dimensionless spin parameter \( (a)\) and charge \( (q)\). However, the charge is almost always assumed to be zero in astrophysical contexts because opposite charges attract each other, canceling any macroscopic excesses. The dimensionless spin parameter, henceforth referred to as spin, is a measure of the angular momentum \( J\). The relation is

\[
a = \frac{Jc}{GM^2}
\]

where \( c \) and \( G \) are the speed of light and the gravitational constant, respectively. The spin of a black hole is thought to affect jet formation and carry information on the formation and evolution of the black hole itself. It is therefore interesting to measure the spin, a
task that only recently has become feasible (e.g. Dabrowski et al., 1997; Young et al., 1998; Brenneman and Reynolds, 2006; Risaliti et al., 2013).

Other quantities typically used in the context of black holes are the Schwarzschild radius $r_S$ and the gravitational radius $r_g$, defined as

$$r_S = 2r_g = \frac{2GM}{c^2}.$$  \hfill (2.2)

Standard accretion disk theory commonly assumes that the disk extends to the innermost stable circular orbit (ISCO), beyond which all matter plunges into the SMBH. This radius is $r_{\text{ISCO}} = 3r_S = 6GM/c^2$ for a non-spinning black hole. Accretion disks will be discussed in detail in section 2.4.

### 2.2 AGN classification

There are several terms used in AGN research to classify different types of AGNs based on a variety of observed properties. The general approach is to construct categories depending on certain parameters. AGNs are commonly categorized based on the optical and UV emission line properties, namely depending on the width of the emission lines. A distinction is also made between radio-quiet and radio-loud based on the ratio between radio and total bolometric luminosity (Krolik, 1999). Variability, polarization and luminosity are also distinguishing factors, although the reason for luminosity being a classifier is largely historical in the sense that luminosity is an apparent feature, rather than representing qualitatively different underlying physical processes.

Having defined the possible attributes for an AGN, all that remains is to assign attributes to different AGN categories. The first AGNs to be identified were Seyfert galaxies, named after Carl K. Seyfert, who described this class in 1943 (Seyfert, 1943). Seyferts are subdivided into Seyfert 1s and Seyfert 2s. Seyfert 1s show very broad allowed lines such as H$\alpha$ and H$\beta$, narrower forbidden lines, notably [O III], as well as narrow allowed lines, although the narrow lines are significantly broader than corresponding lines emitted by normal galaxies. The widths indicate that allowed lines are emitted from both the NLR and BLR whereas forbidden lines originate in the NLR. Seyfert 2s have both allowed and forbidden narrow lines but no broad lines, i.e. only emission from the NLR is observable. Aside from the spectral lines, both types of Seyferts emit a relatively smooth continuum. As for Seyfert 1s, the continuum commonly provides enough power to outshine the entire host galaxy, making the AGN appear pointlike. At least 90 % of the Seyferts appear to reside in spiral galaxies (Carroll and Ostlie, 2013).

Another class of AGNs is radio galaxies, which are characterized by strong radio emission, up to several million times the radio luminosity of a normal galaxy. Radio galaxies can be subdivided into broad-line radio galaxies (BLRGs) and narrow-line radio galaxies (NLRGs), defined analogously to Seyfert 1s and Seyfert 2s, respectively. Radio galaxies emit radiation from giant radio lobes outside of the galaxy or from a central region with a size comparable to the size of the galaxy. The radio power emitted is supplied by powerful particle jets generated in the AGN, which interact with the matter they encounter. Lastly, it should be noted that the host galaxies generally are ellipticals (Carroll and Ostlie, 2013).

Astronomers started identifying an increasing number of radio sources around the 1960s, which appeared stellar in some respects. The sources were therefore called quasi-
stellar radio sources, which subsequently were dubbed quasars. The most striking property of quasars is the high bolometric luminosity, $5 \times 10^{46}$ erg s$^{-1}$ being a typical value. Quasars are also divided into radio-loud and radio-quiet, where radio-quiet constitutes 90 % of the total quasar population. Similarly to radio galaxies, quasars are found in elliptical galaxies, but the ratio of the luminosity at higher frequencies to radio luminosity is much higher than for radio galaxies. The number of quasars per comoving volume was 1000 times higher at redshift $z = 2$ than at present times, meaning that most quasars are observed at great distances. However, quasars are still relatively easy to detect owing to their high luminosity (Carroll and Ostlie, 2013).

Yet another class of AGNs is blazars, which in turn is divided into the two subcategories BL Lac objects and flat spectrum radio quasars (FSRQs). BL Lacs are distinguished by highly linearly polarized optical light, rapid variability and continua with very weak spectral lines. FSRQs are much the same as BL Lacs but with significantly higher luminosity and, in some cases, broad emission lines. Similarly to quasars, blazars are observed at cosmological distances and 90 % of the resolved blazars are found to have elliptical hosts (Carroll and Ostlie, 2013).

The above-mentioned classification gives an idealized overview of the different AGN classes and is not comprehensive. Unfortunately, the real situation is complicated by the fact that many features are not as bimodal as the classification suggests, it is common for features to vary continuously between the extremes. Consequently, categories such as Seyfert 1.5 galaxies can be found in literature (e.g. Osterbrock, 1977; Keck et al., 2015), representing an intermediate class between type 1 and type 2 Seyferts.

2.2.1 Radio-loud narrow-line Seyfert 1 galaxies

RX J1633+4718 is a radio-loud narrow-line Seyfert 1 (RLNLS1) galaxy. A more detailed description of this subclass is therefore provided. Its parent class, narrow-line Seyfert 1 galaxies (NLS1s), is a subcategory of AGNs that was first identified by Osterbrock and Pogge (1985). NLS1s are generally thought to be young Seyfert galaxies (Mathur, 2000).

NLS1s are defined by having narrow permitted lines, i.e. lines with a full width at half maximum (FWHM) less than 2000 km s$^{-1}$ (Goodrich, 1989). Their permitted lines are only slightly broader than forbidden lines (Osterbrock and Pogge, 1985) and the $\text{[O III]}\lambda 5007$ emission line is weak, customarily defined as $\text{[O III]}/\text{H}\beta < 3$ (Shuder and Osterbrock, 1981). Finally, NLS1s also display strong Fe $\text{II}$ emission lines (Goodrich, 1989).

Typical characteristics of NLS1s are strong X-ray variability and relatively high luminosities. They also commonly display steep soft X-ray spectra with a considerable soft X-ray excess (Zhou et al., 2006). These characteristics indicate comparatively low central black hole masses in the range $\sim 10^6$–$10^8$ M$_\odot$ and high accretion rates, i.e. close to or above the Eddington limit (Grupe et al., 2010). NLS1s are generally radio-quiet with a radio-loudness defined as $R = S_{\text{radio}}/S_{\text{optical}}$ smaller than 10, where $S_{\text{radio}}$ and $S_{\text{optical}}$ usually are taken to be the spectral flux densities at 6 cm and 4400 Å, respectively, following Kellermann et al. (1989). Only $\sim 7$ % are categorized as radio-loud and $\sim 2.5$ % being very radio-loud, i.e. $R > 100$ (Komossa et al., 2006). NLS1s are also normally hosted in spiral galaxies (Foschini, 2011) and it is widely believed that they are being viewed from a pole-on orientation (Berton et al., 2016).

One of the general distinctions between Seyfert 1s and Seyfert 2s was the existence of
broad emission lines in type 1s. Thus, it might seem like NLS1s would be more appropriately classified as type 2s. However, NLS1s exhibit strong high-ionization lines such as [Fe\textsuperscript{vii}] and [Fe\textsuperscript{x}] and a strong continuum which are typical for Seyfert 1s (Osterbrock and Pogge, 1985). In addition, the criterion [O\textsuperscript{iii}]/H\beta < 3 is more typical for Seyfert 1s as the ratio is higher for Seyfert 2s in general. NLS1s also show X-ray variability characteristics similar to those of Seyfert 1s (Carroll and Ostlie, 2013). Finally, it is worth pointing out that NLS1s have remarkably soft X-ray emission (Boller et al., 1996; Leighly, 1999; Crummy et al., 2006; Meier, 2012).

Radio-loud narrow-line Seyfert 1 galaxies (RLNLS1s), which constitute \(\sim 7\%\) of the NLS1 population, have attracted a great deal of attention recently due to the discovery of high-energy \(\gamma\)-ray emission as well as apparent superluminal motion in some cases (Abdo et al., 2009; D’Ammando et al., 2012, 2015; Yao et al., 2015). Combining these observations, it is possible to conclude that RLNLS1s emit highly relativistic jets (D’Ammando et al., 2012). This makes RLNLS1s challenge the picture that a very high black hole mass is necessary to launch jets since NLS1s are thought to be of relatively low mass. In addition, jet-launching AGNs typically reside in ellipticals in contrast to RLNLS1s, which are believed to be hosted by spiral galaxies similar to NLS1s (Foschini, 2011).

### 2.2.2 Unification

Although AGN classification is seemingly complicated, several properties can be explained solely in terms of orientation. This is commonly referred to as AGN unification. Orientation essentially determines if the central region can be observed along the symmetry axis of the torus, or if it is obscured by the torus. Properties unique to the central region are, for example, variability on short timescales and broad emission lines. Effectively, this means that type 1 and 2 objects are intrinsically the same but viewed at different inclination.

Orientation of jets also further simplifies the categorization. Radio-loudness is a direct consequence of the AGN having jets. This creates a simple relation between radio galaxies, blazars and quasars. An illustration can clearly visualize the unification as variations in orientation and existence of jets, shown in figure 2.3.

The unified model is simple and effects due to orientation are expected. Further support comes from spectropolarimetry which is capable of separating out the emission that has been scattered, effectively allowing observations round the torus. This has revealed an obscured broad line region in type 2 galaxies (e.g. Antonucci and Miller, 1985). However, observations show that additional parameters such as the black hole mass, accretion rate and absorber geometry have to be taken into account to fully explain all observed features.

### 2.3 Eddington limit

In the extreme environments of an accreting SMBH it is necessary to take the pressure of the emitted radiation into account. Of central importance is the Eddington luminosity, named after Arthur Eddington, at which the outward radiative pressure on the infalling matter balances the inward gravitational force. Hence, in a simplified picture, the Eddington luminosity serves as an upper limit to the luminosity of an accreting object.
A rough derivation can be made by assuming spherical symmetry, dynamic equilibrium and by approximating the gas that absorbs the radiation with pure, ionized hydrogen. The radiative force $F_{\text{rad}}$ exerted by an object with a luminosity $L$ as a function of distance to the source $r$ is

$$F_{\text{rad}} = \frac{L}{4\pi r^2} \times \frac{E}{c} \times \sigma_T$$

where $E$ is the photon energy, $c$ is the speed of light and $\sigma_T = 6.65 \times 10^{-29}$ m$^2$ is the Thomson cross section for electron scattering. This is more transparent if the identification that the first factor $L/(4\pi r^2 E)$ is the number flux of photons, which is multiplied by the momentum per photon $E/c$, with an interaction probability given by the cross section $\sigma_T$. It is also known that the gravitational force $F_{\text{grav}}$ is given by

$$F_{\text{grav}} = \frac{GM}{r^2} (m_p + m_e)$$

where $G$ is the gravitational constant, $M$ is the mass of the central object and $m_p$ and $m_e$ are the proton and electron mass, respectively. The Eddington luminosity ($L_{\text{Edd}}$) is the luminosity such that the radiative force equals the gravitational force. From equations (2.3) and (2.4), $L_{\text{Edd}}$ is

$$L_{\text{Edd}} = \frac{4\pi m_p G M c}{\sigma_T} \approx 1.3 \times 10^{38} \frac{M}{M_\odot} \text{ erg s}^{-1}$$

where the approximation $m_p + m_e \approx m_p$ has been made (Melia, 2009).
At first it might seem like the Eddington limit simply serves as an upper limit to the luminosity and consequently the accretion rate. However, it turns out that the Eddington ratio, defined as \( L/L_{\text{Edd}} \), is one of the key parameters that characterize the underlying physical processes. Some observables influenced by the Eddington ratio are emission line properties (Boroson and Green, 1992; Shen and Ho, 2014), spectral slopes (Boroson, 2002; Shemmer et al., 2008) and evolutionary stage of an AGN (Mathur, 2000).

### 2.4 Accretion models

Accretion is the process by which matter is gravitationally attracted and falls onto a compact, central source. In the context of AGNs, the source is a SMBH residing in the center of a galaxy. Accretion plays a central role to AGNs because all energy that is emitted is converted from the infalling matter. In other words, if the accretion process does not transform kinetic energy into radiation, nothing would be emitted, regardless of the accretion rate.

It is crucial that the process that drives an AGN is highly efficient, i.e. able to convert a large portion of the supplied rest mass to radiation. If this was not the case, an unreasonable amount of fuel would be required to explain the observed luminosities of AGNs. Efficiency is usually measured in terms of an efficiency parameter \( \eta \) defined by

\[
L = \eta \dot{M} c^2,
\]

where \( L \) is the total bolometric luminosity, \( \dot{M} \) is the accretion rate and \( c \) is the speed of light. A comparison between different mechanisms can be made. The efficiency of chemical reactions such as burning of coal is \( \sim 10^{-8} \% \), that of nuclear fusion, specifically \( \text{4H} \rightarrow \text{He} \) (a typical stellar process), is \( \sim 0.7 \% \) whereas a typical value for accretion is \( \sim 10 \% \). Thus, it is manifestly clear that accretion is highly efficient.

A basic description of accretion is the Bondi accretion model, named after Hermann Bondi (Bondi, 1952). The model describes steady spherical accretion, ignoring the effects of angular momentum which clearly is a significant simplification. A more sophisticated model is thin disk accretion, which describes accretion in a geometrically thin and optically thick disk, presented in detail in the following section. It should be pointed out that other models exist, such as advection-dominated accretion flows (Ichimaru, 1977; Rees et al., 1982; Narayan and Yi, 1995) and slim disk accretion (Abramowicz et al., 1988; Beloborodov, 1998). Advection-dominated accretion flows describe low-luminosity accretion, i.e. when most energy is advected into the black hole rather than radiated. The accreting gas is normally hot, optically thin, and quasi-spherical and has a spectral signature described by a power law, which is typical for non-thermal emission. Slim disk accretion is invoked at very high accretion rates. The primary difference to standard thin disk theory is that slim disks considers matter which is advected into the black hole before managing to transform its kinetic energy to radiation because of the high accretion rate.

#### 2.4.1 Thin disk accretion

The angular momentum of accreting matter is the limiting factor for accretion under normal astrophysical conditions. Since the gravitational potential in an AGN is approximately spherically symmetric and frictional forces come into play, it is expected that the
accreting matter will form a geometrically thin, optically thick disk. This is known as the standard accretion disk model \cite{Shakura and Sunyaev, 1973}. The goal is to determine the spectrum and luminosity, which are the primary observables, and how they relate to other quantities, e.g. temperature. The following derivation is a simplification of the derivation by \cite{Melia, 2009}, but an attempt to preserve key physical concepts has been made.

In the remainder of this section the dynamics of a rotating, non-rigid disk are considered. Let $m$ be the mass of a fictitious particle, $v = v_r + v_\phi$ is the velocity which is decomposed into a radial $v_r$ and azimuthal component $v_\phi$. It is clear that the angular momentum $s$ at radius $r$ is given by

$$s = mv_\phi r. \quad (2.7)$$

Furthermore it can be assumed that the azimuthal velocity is Keplerian, i.e. given by equating the centripetal with the gravitational acceleration $v_\phi^2/r = GM/r^2$, where $G$ is the gravitational constant and $M$ is the black hole mass. The angular velocity $\Omega$ is given by $v_\phi = r\Omega$, which combined with the Keplerian velocity yields

$$\Omega = \frac{v_\phi}{r} = \sqrt{\frac{GM}{r^3}}. \quad (2.8)$$

In the non-rigid disk scenario, random motions of the particles are the main reason for the energy exchange. It is assumed that particles move between $r = A$ and $r = A + \lambda = B$ with velocity $\tilde{v}$, where $\lambda$ is a distance which can be though of as the mean free path and $\tilde{v}$ is the characteristic velocity of the random motion. The torque ($\tau$) is then given by

$$\tau = M_{\text{out}}BA\Omega(A) - M_{\text{in}}AB\Omega(B), \quad (2.9)$$

where $M_{\text{out}}$ and $M_{\text{in}}$ are the outward and inward flow of matter. The first term can be motivated by noting that $A\Omega(A)$ is the velocity of the particle starting at $A$, which in its new position has angular momentum $BA\Omega(A)$, and the same goes for the other particle. At dynamic equilibrium, $M_{\text{out}} = M_{\text{in}} = 2\pi r\Sigma\tilde{v}$ where $\Sigma$ is the surface density. Thus $\Sigma\tilde{v}$ is the flow of matter per unit length around a loop in the disk. The difference $\Omega(A) - \Omega(B)$ can be thought of a differential for small $\lambda$, implying

$$\Omega(A) - \Omega(B) = -\lambda \frac{\partial \Omega}{\partial r} \equiv -\lambda \Omega_r. \quad (2.10)$$

Equation (2.9) can now be written

$$\tau = -2\pi r \Sigma \tilde{v} AB \lambda \Omega_r. \quad (2.11)$$

An important definition will now be made, introduce $\nu$ as the viscosity, then

$$\nu = \lambda \tilde{v} = \alpha c_s H, \quad (2.12)$$

where $c_s$ is the speed of sound, $H$ is the height of the disk and $\alpha$ is a system-dependent parameter \cite{Shakura and Sunyaev, 1973}. Although $\alpha$ is unknown, it is physically reasonable to assert that $\lambda \lesssim H$ and $\tilde{v} \lesssim c_s$, thus confining $\alpha$ to $0 < \alpha \lesssim 1$. Using $\nu$ as well as $A = r \approx B$, equation (2.11) can be rewritten as

$$\tau = -2\pi \nu \Sigma R^3 \Omega_r. \quad (2.13)$$
Knowing the torque, it is possible to calculate the power emitted \( (P) \) as

\[
P = -\Omega \frac{d\tau}{dr} dr = - \left( \frac{d}{dr} (\tau \Omega) - \tau \frac{d\Omega}{dr} \right) dr
\]

(2.14)

where the reverse chain rule was used in the last equality. Omitting the mathematical details, the first term corresponds to the net outward flow of rotational energy, i.e. the energy which is not being emitted as radiation. The second term is of interest because it corresponds to the radiative energy loss. Assume that \( \nu \) is independent of \( r \) and \( \Omega_r \to 0 \) as \( r \) approaches the inner radius. It can then be shown that the second term corresponds to a dissipation rate per unit area

\[
D = \frac{3GM\dot{M}}{8\pi r^3} \left( 1 - \sqrt{\frac{r_{in}}{r}} \right)
\]

(2.15)

where \( \dot{M} \) is the accretion rate and \( r_{in} \) is the inner radius of the annular accretion disk [Melia, 2009].

A few remarks are in order. Firstly, the condition \( \Omega_r \to 0 \) when \( r \to r_{in} \) has been used. It can be loosely motivated by the idea that the innermost parts of the accretion disk would be corotating with the central body, which in this case is extended to include black holes. If the reader finds the vague physical argument unsatisfactory it can simply be argued that it is an approximation, which is sufficiently accurate for essentially all practical purposes. Secondly, it was taken that \( \Omega(r) = \sqrt{GM/r^3} \), i.e. Keplerian velocity, which is accurate enough. Lastly, it is clear from equation (2.15) that the dissipation does not explicitly depend on the viscosity. This should come as no surprise since the accretion rate appears, which naturally must depend on the viscosity, thus the dissipation still depends on the viscosity implicitly. The advantage is, however, that the accretion rate is in most cases easier to determine than the viscosity.

### 2.5 Continuum emission

Electromagnetic radiation is generally the main observational window in astrophysics. A natural consequence is that understanding of radiative processes is essential. This section will study two important processes at a rather superficial level. The purpose is to give a theoretical background to the observed spectral characteristics.

#### 2.5.1 Disk blackbody emission

Section 2.4.1 on thin disk accretion was concluded with an expression for the dissipated energy (2.15). Recall that standard thin disks are optically thick. This can be derived from the thin disk geometry, e.g. following [Melia (2009)]. Furthermore, the spectral shape of blackbodies are uniquely defined by the temperature \( T \), which is related to the dissipated energy per unit area \( (D) \) as

\[
\sigma_B T^4(r) = D(r),
\]

(2.16)

where \( \sigma_B \) is the Stefan-Boltzmann constant. And by inserting the expression for \( D \),

\[
T(r) = \left[ \frac{3GM\dot{M}}{8\pi r^3\sigma_B} \left( 1 - \sqrt{\frac{r_{in}}{r}} \right) \right]^{1/4}.
\]

(2.17)
Figure 2.4: Thin accretion disk spectrum for three different $r_{\text{out}}$. The three different intervals characterizing the outer boundary, intermediate region and inner boundary are clearly seen. Figure courtesy of Ghisellini (2013).

Note that $D$, and consequently $T$, is depending on the radius which in turn implies that the observed spectrum is a sum of blackbody contributions from multiple radii. Thin disk spectra are therefore also referred to as multicolor blackbody spectra.

The contribution from each radius is given by Planck’s law, which is then integrated over the disk to obtain the observed flux

$$F = \int_{r_{\text{in}}}^{r_{\text{out}}} \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \frac{2\pi r \cos \theta \, dr}{d^2}$$

as a function of frequency $\nu$ for an observer at a distance $d$ observing the disk at an inclination $\theta$. The multicolor disk spectrum can be divided into three regions. The low frequency limit determined by the outer radius, which is approximately described by Rayleigh-Jeans law with a scaling of $\nu^2$. The intermediate spectral range scales as $\nu^{1/3}$ covering the region between the extremes. Lastly, the high energy limit, determined by the inner radius, closely follows Wien’s approximation, resulting in an exponential cut-off. The total thin accretion disk spectrum is shown in figure 2.4.

The maximum temperature ($T_{\text{max}}$) is obtained at $r = 49/36 \, r_{\text{in}}$ under the standard assumption $r_{\text{in}} = r_{\text{ISCO}}$. The expression can then be simplified to

$$k_B T_{\text{max}} = 11.5 \left( \frac{M}{10^8 \, M_\odot} \right)^{-1/4} \dot{m}^{1/4} \, (\text{eV})$$

where $\dot{m}$ is the scaled accretion rate, i.e. $\dot{M}/\dot{M}_{\text{Edd}}$. It is clear that the temperature is relatively insensitive to both $M$ and $\dot{m}$. Take $\dot{m}$, which also depends on $M$, to be a constant for now. It is then clear that the temperature relates to mass as $k_B T \propto M^{-1/4}$. 


It is also interesting to point out that higher temperatures are expected for less massive SMBHs. In practice, \( \dot{m} \) varies with time and between individual sources. Finally, it is worth noting that \( \dot{m} \propto M^{-1} \) for constant \( \dot{M} \), i.e. that temperature is constant in this (somewhat unphysical) picture.

### 2.5.2 Compton scattering

Compton scattering, named after Arthur Compton (Compton, 1923), is the inelastic interaction between a photon and a charged particle, usually an electron in astrophysical contexts. This is due to a strong velocity dependence of Compton scattering and the fact that electrons have the lowest mass and consequently the highest velocity at a given energy, among the relevant particles. A distinction is commonly made between the case when the photon gives energy to the electron and when the photon receives energy from the electron. The term inverse Compton scattering is commonly used to refer to the latter. This is also the type which is of greater importance in this context. However, it is essentially only a matter of choice of reference frame. The following is a derivation which is correct up to a dimensionless factor, which suffices since mainly the qualitative properties of Compton spectra are of interest. A more detailed derivation can be found in the book by Rybicki and Lightman (1979).

The first step is to determine the change of energy for one photon-particle interaction. The direction of propagation of the photon is denoted by \( \Omega \), \( c \) is the speed of light and \( E \) is the energy of the photon. Let \( \gamma \) and \( m \) be the Lorentz factor and the rest mass of the particle, respectively, and define \( \beta \equiv \frac{v}{c} \), where \( v \) is the velocity of the particle. Using conventional four-vector notation and requiring four-momentum conservation, the relation

\[
P_{1\mu} + Q_{1\mu} = P_{2\mu} + Q_{2\mu},
\]

is obtained, where \( P_{\mu} = E/c(1, \Omega) \) and \( Q_{\mu} = \gamma mc(1, \beta) \) are the four-momentum of the photon and the particle, respectively. Subscript 1 and 2 denotes before and after collision. By rearranging, squaring and solving for the ratio of the photon energy before and after the interaction yields

\[
\frac{E_2}{E_1} = \frac{1 - \beta \cos \varphi_1}{1 - \beta \cos \varphi_2 + \frac{E_1}{\gamma mc^2} (1 - \cos \theta)},
\]

where \( \varphi \) is the angle between the electron and the photon and \( \theta \) is the scattering angle of the photon.

Hitherto, all equations have been in a frame in which the particle generally has a non-zero velocity, i.e. the frame of an observer. Let primed quantities denote quantities in the frame in which the particle is at rest before interaction. A simplification can be made by restricting to the case where \( E_1' \ll mc^2 \), known as the Thomson regime. Note that a consequence is \( E_1' = E_2' \) since the recoil of the electron can be neglected. An additional constraint is to assume \( \gamma \gg 1 \) or equivalently \( \beta \ll 1 \). Combining the two requirements and using an approximate formula for the Doppler shift, namely \( E' \approx \gamma E_1 \), gives the Thomson regime limit

\[
E_1 \ll \frac{mc^2}{\gamma}.
\]
The general relation (2.21) can now be reduced according to

\[
\frac{E_2}{E_1} \approx \frac{1 - \beta \cos \varphi_1}{1 - \beta} = \frac{1 + \beta}{1 - \beta^2} (1 - \beta \cos \varphi_1) \approx 2\gamma^2(1 - \cos \varphi_1) \sim \gamma^2,
\]  

(2.23)

where relativistic beaming has been taken into account, i.e. \(\cos \varphi_2 \approx 1\). Knowing the energy increase in each interaction, it is straightforward to calculate the total power. Photons sweep a volume of \(\sigma_T\) per unit time, where \(\sigma_T\) is the Thomson cross section. Furthermore, since the energy is amplified by a factor of \(\gamma^2\) per interaction, the total power \(P\) gained by the photons per unit volume is approximately

\[
P = c\sigma_T\gamma^2 U, 
\]

(2.24)

where \(U\) is the energy density of photons. Note that using \(\sigma_T\) as the cross section is only valid in the Thomson regime. Additional quantum effects have to be taken into consideration for large photon energies, effectively reducing the cross section ([Rybicki and Lightman, 1979]).

The goal is to obtain the observed spectrum, however, this would require knowledge of the distribution of \(\gamma\) for the electron distribution. It was assumed that \(\gamma \gg 1\). A thermal distribution is therefore unlikely since very high temperatures would be necessary. For example, a temperature of \(10^9\) K typically corresponds to \(\gamma \approx 1.4\) for electrons. Although, one should keep in mind that the extreme condition in AGNs makes the assumption of \(T \lesssim 10^9\) K somewhat situational. A more reasonable scenario in many contexts is to assume a non-thermal distribution, specifically a power-law distribution \(N(\gamma) d\gamma \propto \gamma^{-p} d\gamma\), where \(N\) is the number density of electrons and \(p\) is a constant which characterizes the distribution. Power-law distributions arise naturally through some processes, e.g. Fermi acceleration ([Fermi, 1949]). Using the surmised distribution of particles and the emitted power (2.24), it is straightforward to calculate the spectral profile

\[
dP \propto \gamma^2 \gamma^{-p} d\gamma \propto E^{-\frac{p+1}{2}} dE,
\]

(2.25)

where \(E \propto \gamma^2\) has been used in the last step. It is apparent that Compton spectra are given by power laws with spectral index \(\alpha = -(p - 1)/2\) if the underlying particle distribution is given by a power law. Thus, it is possible to gain information about the particle distribution through the observed spectrum. Lastly, note that the derivation assumed particles with arbitrarily large and small values of \(\gamma\). In practice, there will be cut-offs in the spectrum because of limiting values of \(\gamma\) in the underlying particle distribution.

### 2.6 X-ray spectra

The X-ray spectra of AGNs consists of several components, shown in figure 2.5. Standard accretion disks are expected to emit disk blackbody emission, as shown in section 2.5.1. Typical temperatures for AGNs with masses of \(10^6\)–\(10^{10}\) M\(_\odot\) are 50–5 eV. A blackbody temperature of 50 eV will have its spectral peak at \(\sim 0.2\) keV and is followed by a very steep cut-off, as seen in figure 2.4. These energies are at the very edge of the X-ray spectrum. Disk blackbody emission is therefore generally not observed in AGN spectra. However, objects with lower mass have higher temperature and consequently
Figure 2.5: A schematic, intrinsic X-ray spectrum consisting of three theoretically predicted components. A blackbody component with a temperature of 30 eV is seen at low energies (solid red). Higher energies are dominated by an upscattered power law (dotted green) and disk reflection (dashed blue). The apparent characteristics of the reflected continuum are strongly dependent on system parameters. For example, the extent of the red wing depends on black hole spin and the reflected continuum gets increasingly similar to a power law for larger ionization levels. The relative strength of the components are chosen for visual clarity.

emit radiation at higher energies, as seen in equation (2.17). Disk blackbody emission is therefore observed in X-ray binaries, which have stellar black hole masses.

Another component in AGN X-ray spectra is generated by inverse Compton scattering in a jet or corona. This component is usually well described by a power law over a relatively large energy interval. The low-energy limit is generally not observed, either due to limits in instrumentation or extinction and reprocessing caused by absorption before reaching the observer. When the source photons in the upscattering process come from the accretion disk, the inverse-Compton component is not expected to extend below the typical energy of the disk blackbody emission. The high-energy roll-over depends on the energy of the electron population and is not seen below 10 keV, which is close to the upper energy limit for many X-ray telescopes, for example XMM-Newton and Suzaku. The actual limit varies, roll-overs as low as 30 keV has been observed in a few sources (e.g. Fabian et al., 2015) whereas other AGNs extend into γ-rays (e.g. Ackermann et al., 2011). The observed γ-ray-emitting source are almost exclusively AGNs with a jet along the line-of-sight.

A significant contribution to observed spectra is expected to come from disk reflection. This emission originates from photons from the jet or corona that scatter against the accretion disk. Reflected spectra can be fruitfully thought of as a combination of a reflected continuum and line emission, the most prominent being the iron Kα line around 6.4 keV. Disk reflection occurs at the innermost regions of an AGN and the reflected spectra therefore show strong relativistic effects. Hence, observed iron lines are Doppler shifted, beamed, and gravitationally redshifted (Fabian, 2006). The strength of gravitational redshift is strongly dependent on distance from the SMBH. Thus, the shape of the observed iron line can be used to estimate the spin of the SMBH since the ISCO depends
on spin (e.g. Brenneman and Reynolds, 2006).

The reflected continuum is similar to the incident power-law in the sense that they span approximately the same energy range. However, reflected spectra exhibit more complex spectral features than plain power laws. It has been shown that the soft excess can be modelled by disk reflection in some sources (e.g. Crummy et al., 2006). However, reflection alone has not been able to fully describe the soft excess in all AGNs (e.g. Chevallier et al., 2006; Turner and Miller, 2009). It should be noted that the reflected soft excess is a relativistic blur of spectral lines. Reflection is also characterized by a strong contribution at high energies, known as Compton reflection hump. The hump can serve as an indication of the amount of reflection in the source, lifting degeneracies between models at lower energies (e.g. Risaliti et al., 2013). Furthermore, the reflection hump is sensitive to properties of the accretion disk and its atmosphere. Therefore, it is possible to probe the physics of the disk and corona by studying the reflected spectrum (Reynolds, 2015).

Absorption can significantly affect observed spectra. Several different types of absorption are relevant to AGNs. The obscuration that separates type 1s from type 2s is caused by a dusty torus. Absorption has also been suggested as a possible explanation for the soft excess (e.g. Chevallier et al., 2006; Turner and Miller, 2009). However, this requires the absorbing matter to be moving with relativistic velocities (Schurch and Done, 2008). The BLR can also cause absorption (e.g. Elvis et al., 2004; Puccetti et al., 2007). Typical characteristics are extinction at soft X-ray energies with relatively unaffected hard X-ray spectra. This is because the penetrating power of X-rays is increasing with energy. A column density on the order of $10^{22} \text{ cm}^{-2}$ would cause a strong decrease of flux below $\sim 2$ keV while the harder X-rays are largely unaffected. The gas in the BLR can be thought of as clouds. Therefore, it is possible that a fraction of the source is observed directly while the rest is obscured, a phenomenon referred to as partially covering absorption.

Spectral variability is commonly observed in AGNs. Several different effects can cause spectral variability. One possibility is variable absorption due to changes to the obscuring material in the BLR (e.g. Elvis et al., 2004; Puccetti et al., 2007). This primarily changes the flux at lower energies since hard X-rays are more penetrating. Consequently, the brighter states will be due to stronger contribution from low energies, effectively leading to a softer-when-brighter trend. Spectral variability can also arise because of intrinsic changes in the AGN. The most frequent trend is also softer-when-brighter, however, intrinsic changes can also display a harder-when-brighter behavior. Harder-when-brighter trends are commonly taken to be an indication of jet emission from the AGN (Kataoka et al., 2008; Abdo et al., 2010; D’Ammando et al., 2011).

### 2.7 RX J1633+4718

RX J1633+4718 (SDSS J163323.58+471859.0) is a radio-loud narrow-line Seyfert 1 galaxy at redshift $z = 0.116$ (Yuan et al., 2008; Xu et al., 2012; Foschini et al., 2015). It was first detected in the ROSAT All-Sky Survey (RASS) (Voges et al., 1999) and was first identified in optical by Moran et al. (1996). A later study showed that the galaxy hosting the AGN constitutes one galaxy of a galaxy pair, the other being a starburst galaxy separated by 4 arcsec (Wisotzki and Bade, 1997). The contribution from the partner galaxy is expected to be negligible at X-ray energies (Yuan et al., 2010). RX J1633+4718
has an Hβ width of 909 km s$^{-1}$ (FWHM), an Hβ line flux of $900 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ and an [O iii] line flux of $920 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (Yuan et al., 2008). RX J1633+4718 is very radio-loud with a radio-loudness of 167 and a radio spectral slope of $-0.30$ defined as the slope between 6 cm and 20 cm (Yuan et al., 2008). The Galactic column density along the line-of-sight has been measured to be $1.79 \times 10^{20}$ cm$^{-2}$ by the LAB Survey (Kalberla et al., 2005). The mass of RX J1633+4718 is taken to be $4 \times 10^6$ M$_\odot$, which is the arithmetic mean of the four mass estimates that was found in the literature (Yuan et al., 2008; Xu et al., 2012; Foschini et al., 2015; Järvelä et al., 2015). An estimate of the bolometric luminosity of RX J1633+4718 is $3 \times 10^{44}$ erg s$^{-1}$ (Yuan et al., 2010), corresponding to an accretion rate of 0.5 times the Eddington rate.

The most unique feature of RX J1633+4718 is that it shows an unusual, soft X-ray excess in data obtained by ROSAT, which potentially can be interpreted as radiation from a standard (geometrically thin, optically thick) accretion disk (Yuan et al., 2010). A study of RX J1633+4718 by Mallick et al. (2016) was published during this thesis project. They detect clear signs of partial absorption using the newer data from XMM-Newton and Suzaku. Their variability spectrum clearly disfavors an explanation based on absorption as the source of variability. Furthermore, they use XMM-Newton data to verify the previous claims concerning the blackbody by Yuan et al. (2010). However, the blackbody parameters found by Mallick et al. (2016) are different from those of this work, probably because they did not use the ROSAT data.
Chapter 3

Telescopes and instruments

Data from three X-ray observatories have been used, namely XMM-Newton, Suzaku and ROSAT. Each instrument offers different capabilities and complement each other in some aspects. A brief technical summary of the relevant devices is provided in Table 3.1.

One of the great challenges in X-ray astronomy is focusing of X-rays since X-rays tend to either be transmitted or absorbed, but generally not reflected. The currently most successful solution is to reflect the incoming photons against X-ray mirrors at very small angles (“gracing incidence”), relative to the surface, towards a focus. This setup requires the mirrors to be nearly aligned with the incoming X-rays making the effective area small. However, it can be increased by nesting several mirrors. An illustration of the setup of one of the X-ray mirrors on board XMM-Newton is shown in Figure 3.1.

Calibration of detectors is a difficult task and small systematic errors are expected due to instrumental artifacts. This is particularly relevant since data from several instruments are cross-fitted. It has been shown that Suzaku data yields systematically higher fluxes and softer photon indices than XMM-Newton data (Tsujimoto et al., 2011; Ishida et al., 2011; Kettula et al., 2013). The average error over the energy range 0.3–10 keV is expected to be on the order of a few percent, but might be energy dependent.

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Detector</th>
<th>Energy range [keV]</th>
<th>Spectral resolution (FWHM) [eV]</th>
<th>Effective area [cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSAT</td>
<td>PSPC-B</td>
<td>0.1–2.0</td>
<td>150–500</td>
<td>100–250</td>
</tr>
<tr>
<td>Suzaku</td>
<td>XIS0</td>
<td>0.4–10.0</td>
<td>100–150</td>
<td>160–330</td>
</tr>
<tr>
<td></td>
<td>XIS1</td>
<td>0.3–7.0</td>
<td>100–150</td>
<td>110–370</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>EPIC pn</td>
<td>0.3–10.0</td>
<td>80–150</td>
<td>300–1200</td>
</tr>
<tr>
<td></td>
<td>EPIC MOS1</td>
<td>0.3–10.0</td>
<td>70–150</td>
<td>100–400</td>
</tr>
</tbody>
</table>

Table 3.1: Technical specifications of detectors. It should be emphasized that several values are approximate, a comprehensive description can be found in the respective manuals. This is particularly relevant for the spectral resolution and effective area due to their energy dependencies. Values for XIS3 and MOS2 are assumed to be equivalent to those of XIS0 and MOS1, respectively.
Figure 3.1: A schematic of one of XMM-Newton’s telescopes equipped with a reflection grating. The incident photons seen on the left-hand side are focused in two steps by the nested mirrors. The reflection grating (inset) then directs 40% of the light towards the spectroscopic detector located at the first diffraction maximum whereas 44% reaches the MOS CCD at the primary focus. The telescope equipped with the pn-CCD is identical with the exception that no grating and secondary detector are installed [ESA: XMM-Newton SOC, 2015].

3.1 XMM-Newton

XMM-Newton is a 4000 kg, 10 m long X-ray observatory launched on December 10, 1999 by the European Space Agency (ESA) [Jansen et al., 2001]. It is one of the cornerstones in the ESA Horizon 2000 programme and is still in service. The orbit was chosen to be highly eccentric allowing non-interrupted observations for up to 40 hours. In practice, however, observations are commonly affected by high background fluxes during distinct intervals due to solar flares. The standard procedure to account for this in the analysis is to measure the background level and omit any time periods during which the background exceeds a certain threshold.

There are six science instruments on board XMM-Newton, which can be used simultaneously. The European Photon Imaging Cameras (EPIC) are the main X-ray imaging detectors. It consists of three separate cameras, two metal oxide semi-conductor (MOS) charge-coupled device (CCD) cameras [Turner et al., 2001] and the pn-CCD camera [Strüder et al., 2001]. There are two identical Reflection Grating Spectrometers (RGSs) [den Herder et al., 2001] providing high-resolution spectroscopy in the soft X-ray range, covering many lines of interest. The sixth instrument is the Optical/UV Monitor Telescope (OM) [Mason et al., 2001] with a 30 cm mirror which extends the range of XMM-Newton to UV and optical allowing simultaneous multi-wavelength measurements.

The OM has a regular mirror which is suitable for optical and UV observations. The setup for the five X-ray detectors is more complicated. XMM-Newton has three identical X-ray telescopes, one of which is equipped with the pn-CCD located at the focus. One of each RGS and MOS CCD is installed in each of the other two telescopes’ focal planes.
This is made possible by splitting the incoming light using a reflection grating and having the MOS CCD located at the primary focus and the spectroscopic detector at the first diffraction maximum, as shown in figure 3.1.

The chief strength of XMM-Newton lies in its ability to detect faint objects using its comparatively large effective area. Combining the area of all three X-ray telescopes gives an effective area of 4650 cm$^2$ at 1.5 keV. The angular resolution is fair and the point-spread function (PSF), i.e. the image of a point source, has a relatively constant FWHM of $\sim$6 arcsec in the range 1.5 keV to 8 keV (Jansen et al., 2001). Spectral resolution can be measured in terms of resolving power defined as $E/\Delta E$, where $\Delta E$ is the smallest measurable energy difference at energy $E$. EPIC has a moderate spectral resolution of 20–50 whereas the resolution of the RGSs is 200–800. The primary drawback of the RGSs is that their effective area is an order of magnitude smaller than that of EPIC.

3.2 Suzaku

The X-ray Observatory Suzaku was launched on July 10, 2005 and decommissioned on August 26, 2015. It was a collaboration between the Institute of Space and Astronautical Science of Japan Aerospace Exploration Agency (ISAS/JAXA), the National Aeronautics and Space Administration’s Goddard Space Flight Center (NASA/GSFC) and many other institutions (Mitsuda et al., 2007). It was orbiting the Earth at a near-circular orbit at an altitude of $\sim$570 km and with an orbital period of roughly 96 min. Consequently, observed objects were regularly occulted by the Earth. The main strengths of Suzaku were the relatively high throughput and broad energy range, from 0.3 keV to 600 keV.

Suzaku was equipped with five X-ray telescopes (XRTs), which focus incoming X-rays onto the base plane where detectors are located, as shown in Figure 3.2. There were initially six scientific instruments on board Suzaku; the four X–ray Imaging Spectrometers (XISs) (Koyama et al., 2007), the X-Ray Spectrometer (XRS) (Kelley et al., 2007) and the non-focused Hard X-Ray Detector (HXD) (Takahashi et al., 2007). Due to technical difficulties in the early stages of the mission, no scientific data were obtained using the XRS and it will therefore not be discussed further. The HXD covered the energy range 10 keV to 600 keV and was a pointing instrument, meaning that it was equipped with a collimator that limits the field of view but lacked imaging capabilities.

The four XISs employed CCDs, not too different from the ones in XMM-Newton, and were located in the focal plane of four of the XRTs. Each XIS consisted of one CCD and had an effective angular resolution of $\sim$20 arcsec (FWHM). The energy resolution was on the order of 100 eV, which varies depending on energy and time after launch. It is clear that the angular resolution is significantly worse than the $\sim$6 arcsec (FWHM) of EPIC, but the energy resolutions of Suzaku and XMM-Newton are comparable.

Three of the cameras, namely XIS0, XIS2 and XIS3, were front-illuminated (FI), whereas XIS1 was back-illuminated (BI). The difference between the FI cameras and the BI camera is that the FI have a lower background, higher sensitivity at higher energies as compared to the BI, which had a higher background but had its sensitivity shifted towards lower energies. Typical energy ranges are 0.4–10 keV for the FI CCDs and 0.3-7 keV for the BI CCD. Lastly, it is worth pointing out that XIS2 suffered a micro-meteorite impact on November 9, 2006, leaving the camera inoperable.

The CCDs were sensitive to optical and UV light and optical blocking filters (OBFs) have therefore been installed. It was discovered after launch that the OBFs accumulate
Figure 3.2: A schematic of *Suzaku*, showing the setup of the detectors and telescopes. Note that the HXD is a non-focusing device and thus has no X-ray focusing telescope. In addition, the XRS malfunctioned shortly after launch and was never used for scientific purposes. Adapted from Mitsuda et al. (2007).
contaminating material which primarily reduces the quantum efficiency below 2 keV. The thickness and composition of this material has steadily been monitored in order to allow accurate calibration. Furthermore, several residuals in the spectral response of the CCDs are poorly understood in the 1.6 to 2.3 keV band. This is due to imperfect modeling of the Si K edge at $\sim$1.8 keV, the Au M edge at $\sim$2.2 keV, the Al K edge at $\sim$1.6 keV, and possibly the Si K-\textalpha~fluorescence line at $\sim$1.7 keV. Although the calibration has been improved over the past years, the current state remains uncertain and the residuals are therefore in practice dealt with on a case-to-case basis. Lastly, it is known that the pointing of Suzaku wobbles due to thermal expansion. This can be adequately dealt with but requires special attention by the observer.

3.3 ROSAT

ROSAT ([Trümper, 1982; Briel et al., 1994] and references therein), short for the German word Röntgensatellit, was launched on June 1, 1990 and decommissioned on February 12, 1999. It was an X-ray telescope mission led by German Aerospace Center (DLR) with instruments built by Germany, the United States and the United Kingdom. ROSAT was launched into orbit at an altitude of $\sim$580 km, inclination 53$^\circ$ and a period of 96 min. The first phase of the mission was to perform the ROSAT All-Sky Survey, which lasted for six months. The remaining time was devoted to pointed observations of selected sources.

The scientific instruments on board ROSAT were the X-ray Telescope (XRT) and the Wide Field Camera (WFC). The WFC was an extreme UV telescope coaligned with the XRT and designed to cover the 0.04–0.20 keV range. The focusing component of the XRT is the X-ray mirror assembly (XMA) consisting of four nested grazing incidence mirrors with a focal length of 2.4 m.

There are three detectors in the focus of the XRT, two Position Sensitive Proportional Counters (PSPC-B and PSPC-C) and a High Resolution Imager (HRI) mounted on a carousel. The HRI is an imaging device at soft X-ray energies ranging from 0.1 to 2.0 keV with an optimal angular resolution along the optical axis with a FWHM of roughly 2 arcsec. The two PSPCs are redundant, however, due to a technical malfunction in the early stages of the mission the PSPC-C was lost. All pointed observations after RASS were therefore performed using PSPC-B. It offers spectral coverage in the range 0.1 to 2.0 keV with an effective area of $\sim$200 cm$^2$ over a majority of the energy range. The spectral resolution is 150–500 eV and the angular resolution is 10–40 arcsec (FWHM). It is not surprising that ROSAT performance is slightly worse than that of the more modern Suzaku and XMM-Newton. However, a strength of ROSAT is the lower limit of the energy range, which is 0.1 keV compared to 0.3 keV of Suzaku and XMM-Newton.
Chapter 4
Observations and data reduction

RX J1633+4718 was detected by RASS and was later the target of a pointed observation (denoted R1) by *ROSAT*. Four observations (denoted S1... ) were performed by *Suzaku* over the course of a year. The XIS devices were operating during all observations, except for XIS2 which was damaged prior to the first observation. Four observations (denoted X1... ) were also performed by *XMM-Newton* over roughly the same time span. Data from all *XMM-Newton* and *Suzaku* observations were used in the data analysis. However, due to the low flux, only data from the EPIC and XIS devices were analyzed. As for *ROSAT*, only data from the PSPC-B pointed observation was kept for further analysis. A summary of all observations is provided in Table. 4.1

4.1 *XMM-Newton*

The reduction of the data from *XMM-Newton* was made using the *Science Analysis Software* v.15.0.0 and the calibration database was updated on February 5, 2016. Only data from the three EPIC cameras were used. The raw event lists were filtered using good time intervals (GTIs) based on the level of background flares which were defined following the standard criteria of *Smith (2015)*. The GTIs for the three EPIC cameras were combined using AND to form a merged GTI which ensures that data from the three cameras can be combined when making the spectral analysis.

Events were filtered based on the merged GTI described above and *PATTERN* criteria following [ESA: XMM-Newton SOC (2014)] with the exception of *FLAG == 0*. The *FLAG* property is used to indicate the reliability of an event. An example of unwanted events are potential particle triggers. The option *FLAG == 0* is more conservative than the standard option as *FLAG == 0* also rejects events next to CCD edges and known bad pixels. *PATTERN* serves a similar purpose but is purely based on the pixel which is triggered and which of its near-neighbors that also registers a trigger (a geometrical “pattern” is thus defined for each event). Events which show a significant signal in a large cluster of pixels are likely particle events. A complete description can be found in [ESA: XMM-Newton SOC (2014, particularly figure 12 and 13)]

Only events in the energy range 0.3–10 keV were kept for further analysis. The soft and hard bands are henceforth defined as 0.3–2 keV and 2–10 keV, respectively. Images were created using the filtered sets, and a circle of radius 34 arcsec centered on the SDSS coordinates was chosen as the source region for all exposures. Different background regions were selected for the different cameras and observations due to CCD...
Table 4.1: A chronological summary of all observations of RX J1633+4718. The exposure times are the sums of all times during which the devices were operating within the good time intervals (GTIs), but before correcting for the live time of the detectors, since live time is detector-dependent. Details regarding the GTIs vary between instruments and can be found in the respective sections. It is worth noting that there is a gap of almost 20 years after the ROSAT observations, during which no X-ray observations of RX J1633+4718 were made. Also note that the third Suzaku observation almost overlaps with the third XMM-Newton observation.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Obs. ID</th>
<th>Notation</th>
<th>Start time</th>
<th>Exposure [ks]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSAT</td>
<td>701549</td>
<td>R1</td>
<td>1993-07-24T10:32:05</td>
<td>3.9</td>
</tr>
<tr>
<td>Suzaku</td>
<td>706027010</td>
<td>S1</td>
<td>2011-07-01T19:41:23</td>
<td>40.0</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>0673270101</td>
<td>X1</td>
<td>2011-07-09T05:50:23</td>
<td>21.7</td>
</tr>
<tr>
<td>Suzaku</td>
<td>706027020</td>
<td>S2</td>
<td>2011-07-18T12:06:54</td>
<td>37.5</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>0673270201</td>
<td>X2</td>
<td>2011-09-12T22:24:18</td>
<td>22.4</td>
</tr>
<tr>
<td>Suzaku</td>
<td>706027030</td>
<td>S3</td>
<td>2012-01-13T20:59:37</td>
<td>44.1</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>0673270301</td>
<td>X3</td>
<td>2012-01-14T15:56:47</td>
<td>14.8</td>
</tr>
<tr>
<td>Suzaku</td>
<td>706027040</td>
<td>S4</td>
<td>2012-02-05T16:16:04</td>
<td>45.5</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>0673270401</td>
<td>X4</td>
<td>2012-03-14T10:20:01</td>
<td>10.5</td>
</tr>
</tbody>
</table>

When the flux is relatively high, it is possible for several photons to deposit their energy in a single pixel between two read outs. This will result in a single event with higher energy, an effect known as pile-up. A typical manifestation is a decreased count rate towards the center of the PSF or a distribution of PATTERNs that is inconsistent with that of random single photon events. Potential pile-up was checked using `epatplot` and no significant pile-up was detected. The spectra were grouped to have at least 25 counts per bin to allow for usage of $\chi^2$-statistics in the spectral analysis. The parameter `oversample` was set to 3, preventing any energy bins to be smaller than one third of the energy resolution FWHM at a given energy. Correction for vignetting, detector live time, scaling to compensate for the PSF outside the source region and other effects were mainly performed by the tasks `epiclccorr` and `arfgen` for the light curves and spectra, respectively (ESA: XMM-Newton SOC, 2014). The light curves were background subtracted and corrected for several instrument errors using the default options of `epiclccorr`. 

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The sky image of EPIC pn from the second XMM-Newton observation of RX J1633+4718. The grid which splits the frame into twelve parts is the CCD gaps. The green and cyan circles are the source and background regions, respectively. Note that these are chosen to be on the same CCD chip and (approximately) same RAWY coordinate.

4.2 **Suzaku**

The data from Suzaku were reduced using HEAsoft version 6.18 which includes Suzaku FTOOLS Version 22 (Blackburn, 1995). Only data from the two front-illuminated XIS0 and XIS3 and the back-illuminated XIS1 were used. The calibration database (CALDB) was updated on Mars 8, 2016 and the unfiltered data were reprocessed using aepipeline with default parameters to ensure that the same pipeline version was applied to all observations. The temporal filtering based on GTIs was also performed at this stage as a part of the pipeline. Thermal wobbling was corrected for using aeattcor2 and xiscoord and no pile-up was detected by pileest.

Spectra, light curves, and images were generated using extractor. Only events in the energy ranges 0.4–10 (FI) and 0.3–7 keV (BI) were kept for further analysis. Furthermore, the events in the interval 1.5–2.3 keV were excluded due to uncertain calibration. No strong spectral features are seen in the interval in the XMM-Newton spectra and the results remain essentially unchanged if the poorly calibrated range is included. The decision to exclude the interval was based on the description of the current state found in [ISAS/JAXA/NASA (2013)](https://example.com) and [ISAS/JAXA/NASA (2015)](https://example.com). The source region was defined to be a circle of radius 260 arcsec centered on the SDSS coordinates. Additionally, the background region was chosen to be an annulus of inner radius 260 arcsec and outer radius 360 arcsec for all exposures. The backgrounds were centered on the source and extracted from each CCD. The RMF and ARF were generated using xisrmfgen and xissimarfgen, respectively.

The spectra were then grouped analogously to the XMM-Newton data. However, no
task in Suzaku FTOOLS considers the oversampling of the energy resolution. Instead, the energy resolution was calculated using the information contained in the response file, i.e. the product of the RMF and ARF. The response effectively describes the probability of an incident X-ray photon with a certain energy being detected in a particular spectral channel, as well as accounting for the physical properties of the detector and telescope. Utilizing this information, it is straightforward to compute the energy resolution FWHM as a function of energy and group the spectra accordingly. The trailing channels were grouped together despite the count being lower than 25, however, it was verified that the last channel always fell outside of the accepted energy interval. It should be pointed out that the minimum 25-count requirement was enforced alongside the oversampling criteria.

The Suzaku light curves were obtained using extractor and background subtracted using lcmath. No other corrections were applied meaning that the count rate unit is instrument dependent because of vignetting, bad pixels, dead time (due to readout), CCD gaps, quantum efficiency of the detector, effective area of the telescope, and PSF outside of the source region. For XMM-Newton data, the effects were all corrected for by epiclccorr, however, the count rate is still expressed in terms of counts per second and not a physical unit such as counts per second per unit area. This is due to subtleties in the error correction. For instance, the detector response used by epiclccorr is less accurate than the one used for spectral analysis since epiclccorr uses a default response for computational efficiency.

4.3 ROSAT

The ROSAT data were reduced using HEAsoft version 6.18. The source extraction region was a circle centered on the SDSS coordinates with a radius of 120 arcsec and the background was an annulus with inner and outer radii 240 and 360 arcsec, respectively. RX J1633+4718 was observed on-axis allowing use of the response matrix pspcb_gain2_256.rsp (formerly known as pspcb_93jan12.rmf), which was taken from NASA’s anonymous ftp [1]. Finally, the same spectral binning procedure as for Suzaku data was applied to the ROSAT data, making all the spectra comparable. Only data in the energy range 0.1 to 2.0 keV was used for spectral analysis. Although the absolute energy interval is relatively small, it is worth emphasizing that the energy range of ROSAT extends to lower energies than either Suzaku or XMM-Newton.

4.4 Spectral fitting

All fits were performed using XSPEC 12.9.0i [Arnaud, 1996] with default options. As described above, the binning was made such that every spectral bin contained at least 25 counts for all data sets, allowing for the use of $\chi^2$ statistics. The reduced $\chi^2$ from different instruments are comparable since the binning also took oversampling into account.

Galactic absorption was included in all models using the XSPEC model phabs with a frozen column density of $1.79 \times 10^{20}$ cm$^{-2}$ [Kalberla et al., 2005]. It was verified that exchange of phabs for wabs or tbabs made no significant difference. The redshift was
frozen to $z = 0.116$ for all redshifted model components, i.e. all components with a $z$ prefix. Other parameters are assumed to vary freely (within default limits) decoupled from each other unless stated otherwise.

The XMM-Newton data were fitted over the 0.3–10 keV interval. All EPIC detectors were coupled by tying the parameters without introducing additional cross-normalizations between the cameras. Fitting is less straightforward for Suzaku because the different cameras have different energy ranges. XIS0 and XIS3 were fitted over 0.4–10 keV whereas XIS1 was fitted over 0.3–7 keV. Furthermore, the interval 1.5–2.3 keV was excluded for all XIS cameras because of uncertain calibration. Consistency between the XIS cameras was verified for all observations, allowing for simultaneous fitting using all XIS data. Lastly, data from ROSAT’s PSPC-B was fitted from 0.1 to 2 keV. This setup of cameras and energy ranges will henceforth be the standard setup.

It has been shown by Tsujimoto et al. (2011) that the calibration of the three EPIC detectors are inconsistent. The error introduced by tying parameters between the EPIC detectors and XIS cameras, respectively, was studied by fitting an absorbed power law (\texttt{phabs(powerlaw)}) and comparing the best fit normalizations and photon indices. Variations between the cameras were observed but the error introduced by tying the parameters was deemed to be small in comparison to other errors. It is also possible that the calibration files have undergone a significant improvement in recent years.
Chapter 5

Light curves

The light curves for the four XMM-Newton and four Suzaku observations (henceforth referred to as the recent observations) and the observed fluxes and intrinsic luminosities for all observations are presented in this chapter. In addition, the hardness ratio for the recent observations are plotted, providing superficial insight into spectral variability. The notes on spectral fitting detailed in section 4.4 apply.

As mentioned in chapter 3, systematic errors are expected due to calibration uncertainties (Tsujimoto et al., 2011; Ishida et al., 2011; Kettula et al., 2013). It has been shown that Suzaku observes higher fluxes than XMM-Newton, a trend which is seen in this chapter, in particular in the 0.3–2 keV energy range. However, no observations are simultaneous (although S3 and X3 almost overlap) and the differences in flux can be considered small compared to the variability on the given timescales. The differences could therefore also be caused by intrinsic variations in the source.

5.1 Short timescales

The light curves for the recent observations are shown in figure 5.1. The ROSAT observation is excluded because it is too short to construct a light curve from.

Variability is observed on both short and long timescales. Short in this context will henceforth mean ∼1 ks, i.e. a small fraction of an observation, whereas long corresponds to timescales comparable to the time elapsed between observations or longer. No systematic trends with time are seen. The largest variation in the XMM-Newton observations on short timescales is a factor of ∼1.6 in X1, i.e. the ratio of the maximum 1 ks bin to the minimum 1 ks bin within one observation. The corresponding value for Suzaku is ∼3.0 in S4. However, it must be emphasized that the statistical uncertainty of S4 is much larger than that of X1, as can be seen in figure 5.1. RX J1633+4718 shows periods of slightly increased activity, such as the latter parts of X3 and S3.

Two transitions between low flux and high flux states were chosen for flux-resolved spectral analysis, presented in section 6.3. The low/high state from the first/third XMM-Newton observation will henceforth be denoted X1L, X1H, X3L, and X3H. These intervals are all 3 ks and were chosen based on duration and difference in flux. The purpose was solely to analyze variability on short timescales qualitatively since the data quality of 3 ks exposures is expected to be too low to allow for detailed fitting. There was therefore no rigorous selection criteria. Instead, the intervals were essentially chosen based on inspection of the light curve in figure 5.1. It is worth mentioning that X3L and X3H are
Figure 5.1: The light curves for the four observations by XMM-Newton (upper, EPIC-pn 0.3–10 keV) and for Suzaku (lower, XIS0 0.2–12 keV) with a binning of 1 ks for both instruments. The red bins in the pn light curves indicate that less than half of the time spanned by the bin belongs to the GTI due to background flares. The corresponding bins for XIS0 are omitted for clarity. A large number of bins would otherwise have been red because of regular Earth occultation. The shaded time intervals are periods which were chosen for flux-resolved spectral analysis. Each of the four shaded segments is 3 ks and green and blue indicate low and high flux, respectively. It should be noted that the count rate on the $y$-axis is expressed in terms of the instrument dependent unit (photons) s$^{-1}$. The two plots are therefore not comparable, which is why they have been plotted separately. The small ticks on the $x$-axis are hours and the error bars are one standard deviation.
Table 5.1: Observed flux \( (F_o) \) and intrinsic luminosity \( (L_i) \) in the soft and total energy band. The energies for \( F_o \) are given in terms of observed energies, whereas energies for \( L_i \) are given in the source rest frame. No confidence intervals are presented for the intrinsic \( L_i \) because the XSPEC task used (lumin) does not support error estimation.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>( F_o ) 0.3–2 keV [10(^{-12}) erg cm(^{-2}) s(^{-1})]</th>
<th>( F_o ) 0.3–10 keV [10(^{-12}) erg cm(^{-2}) s(^{-1})]</th>
<th>( L_i ) 0.3–2 keV [10(^{43}) erg s(^{-1})]</th>
<th>( L_i ) 0.3–10 keV [10(^{43}) erg s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0.88(^{+0.09}_{-0.08})</td>
<td>7.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>1.09(^{+0.06}_{-0.07})</td>
<td>2.34(^{+0.08}_{-0.09})</td>
<td>8.0</td>
<td>12.5</td>
</tr>
<tr>
<td>X1</td>
<td>0.87 ± 0.01</td>
<td>1.99 ± 0.04</td>
<td>7.1</td>
<td>11.1</td>
</tr>
<tr>
<td>S2</td>
<td>1.05 ± 0.04</td>
<td>2.21 ± 0.06</td>
<td>8.9</td>
<td>13.2</td>
</tr>
<tr>
<td>X2</td>
<td>0.87 ± 0.01</td>
<td>2.06 ± 0.04</td>
<td>7.1</td>
<td>11.3</td>
</tr>
<tr>
<td>S3</td>
<td>1.13 ± 0.04</td>
<td>2.71(^{+0.06}_{-0.07})</td>
<td>9.1</td>
<td>15.0</td>
</tr>
<tr>
<td>X3</td>
<td>0.97 ± 0.01</td>
<td>2.54 ± 0.05</td>
<td>7.4</td>
<td>13.1</td>
</tr>
<tr>
<td>S4</td>
<td>0.94 ± 0.06</td>
<td>1.96(^{+0.07}_{-0.08})</td>
<td>7.6</td>
<td>11.3</td>
</tr>
<tr>
<td>X4</td>
<td>0.71(^{+0.01}_{-0.02})</td>
<td>1.92 ± 0.06</td>
<td>6.2</td>
<td>10.3</td>
</tr>
<tr>
<td>X1L</td>
<td>0.76(^{+0.03}_{-0.04})</td>
<td>1.72(^{+0.11}_{-0.10})</td>
<td>6.4</td>
<td>9.7</td>
</tr>
<tr>
<td>X1H</td>
<td>0.85 ± 0.03</td>
<td>2.36 ± 0.12</td>
<td>7.0</td>
<td>12.0</td>
</tr>
<tr>
<td>X3L</td>
<td>0.93 ± 0.04</td>
<td>2.15 ± 0.12</td>
<td>7.0</td>
<td>11.9</td>
</tr>
<tr>
<td>X3H</td>
<td>1.04(^{+0.03}_{-0.04})</td>
<td>3.23 ± 0.15</td>
<td>7.7</td>
<td>15.2</td>
</tr>
</tbody>
</table>

5.2 Long timescales

5.2.1 Observed flux

The observed fluxes \( (F_o) \) for all nine observations in the soft (0.3–2 keV) and the eight recent observations in the entire (0.3–10 keV) energy intervals are provided in table 5.1 and plotted in figure 5.2. All values were obtained using the XSPEC model cflux applied to an underlying model consisting of Galactic absorption, a broken power law and a redshifted blackbody, i.e. cflux(phabs(bknpower+zbbody)). An exception was made for R1, which was adequately described by a power law in place of the broken power law. The primary purpose of these fits was to determine the observed flux, hence the physical interpretation is irrelevant at this stage. Priority was given to statistically good fits that describe the observed data well. Each observation was therefore fitted individually.

No systematic trends with time are seen. The maximum variation is a factor of \( \sim 1.4 \), i.e. the ratio of S3 to X4. It is clear that RX J1633+4718 displays variability on long timescales. Both S3 and X3 are in a higher state compared to the other six observations which are all on a fairly similar luminosity level.
Figure 5.2: The observed flux for all nine observations in the soft 0.3–2 keV band (upper) and total 0.3–10 keV flux (lower) for the eight recent observations. Note the time intervals on the horizontal axis, especially the large time difference between R1 and the recent observations. Additionally, it is worth pointing out that S3 and X3 almost overlap. Lastly, note that the ROSAT flux happens to be close to the average of the eight recent observations in the soft band. The small ticks on the x-axis are days and error bars are one standard deviation.
The ROSAT flux is naturally only calculated at soft energies due to the limited energy range of the PSPC-B detector. Interestingly, the flux measured by ROSAT happens to be very close to the average of the recent observations. Note that the R1 flux is particularly close to the X2 flux, which happens to be the observation with the highest total net count.

5.2.2 Intrinsic luminosity

The calculated intrinsic luminosities ($L_i$) are presented in table 5.1. These have been calculated using the XSPEC task `lumin`. The intrinsic luminosity was calculated by fitting the favored partially absorbed model and then removing both absorption components. The model consists of Galactic absorption, intrinsic partial covering, redshifted power law, and redshifted blackbody, i.e. `phabs(zpcfabs(zpowerlw+zbbbody))`. A detailed motivation for this model is presented in section 6.1.

The variability in observed flux and intrinsic luminosity are closely related because the absorption varies weakly across observations. It is worth mentioning that the defined energy ranges for $L_i$ is given in rest frame energies of the source, in contrast to energy ranges for $F_o$, which are expressed in terms of observed energies. This difference is relatively small for the source redshift of $z = 0.116$.

5.3 Hardness

A common way to search for spectral variability is to study the hardness as a function of total count rate. The hardness is defined as the ratio of the hard (2–10 keV) to the soft (0.3–2 keV) count rate. Spectral variations are necessary but not sufficient for a non-constant hardness. From this perspective, one can think of the hardness as a two-bin spectrum.

The hardness plots are shown in figure 5.3. Clear systematic variations are seen in terms of a harder-when-brighter trend, albeit X4 indicates more complex behavior than a linear relation. It is worth pointing out that the trend seems to hold on both short and long timescales. A consequence is that the time average performed over each observation duration introduces an error, i.e. an average is performed over different spectral states. It should be safe to assume that this error is small and a detailed study is deferred to section 6.3.
Figure 5.3: The hardness is defined as the ratio of the hard (2–10 keV) to soft (0.3–10 keV) count rate, plotted versus the total count rate. Observations by EPIC-pn (left) and XIS0 (right) are shown separately since count rate is instrument dependent. A tentative harder-when-brighter trend is seen, although X4 seems to deviate slightly from this pattern. The bin sizes are 3 ks and 10 ks for EPIC-pn and XIS0, respectively. However, the effective time per bin for XIS0 is approximately 5 ks due to the regular occultation of Suzaku. Error bars are one standard deviation.
Chapter 6
Spectral analysis

All spectral fitting will follow the details presented in section 4.4. In addition, it will be assumed that all data from the recent observations are used, omitting R1, unless otherwise stated. This is done because a majority of the models are unconstrainable using R1 data or outside of the energy range of ROSAT.

The outline of this chapter is as follows. Firstly, the spectra are studied and an analysis is presented in section 6.1. Although not strictly required by the observations at hand, it is relevant to study potential reflection. This is presented in section 6.2. Finally, section 6.3 is devoted to flux-selected spectral analysis.

6.1 Models

6.1.1 Power law

The main spectral component in the relevant energy range is expected to be well described by a power law. It is therefore natural to start by fitting a power law to each observation and study the spectra in terms of deviations from the power law. Additionally, it is known that Galactic absorption is significant. The current model is thus \texttt{phabs(zpowerlw)} using XSPEC terminology. The redshifted power law component \texttt{zpowerlw} has two free parameters, namely the photon index ($\Gamma$) and a normalization constant ($C_p$). The normalization is defined to be the number of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV\(^\dagger\).

The residuals of the fit is shown in figure 6.1 and the fit statistic is 3355/2356 = 1.42. Note that the differences in residuals between the different cameras are expected since the residuals are given in units of standard deviations ($\sigma$), which is instrument dependent. The advantage of a dynamic unit is that large fluctuations due to uncertainty are suppressed, for instance low signal-to-noise for the XIS cameras at high energies.

Fitted parameter values are provided in table 6.1 along with the best fit values of other models for comparison. The photon indices for the current, absorbed power law model are within the interval 1.57–1.82. It is manifestly clear that a simple power law model poorly describes the observed spectra.

The residuals in figure 6.1 are clearly systematic. In particular, the residuals above 2 keV appear to be solely caused by an underestimation of $\Gamma$. Thus, it is motivated to only fit the power law, still with the free parameters untied across observations, to data.

\footnote{https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSmodelPowerlaw.html}
Figure 6.1: Residuals of a power law component with Galactic absorption fit to the data from 0.3 to 10 keV. XMM-Newton data are blue and Suzaku data are green. This is clearly a poor fit with strong systematic residuals. Rebinning with a factor of 10 has been made for clarity. Error bars are one standard deviation and energies are given in the observed frame.

Figure 6.2: Residuals of a power law component with Galactic absorption fit to the hard (2–10 keV) interval and extrapolated to 0.3 keV. XMM-Newton data are blue and Suzaku data are green. A clear deficit is seen below 2 keV. Rebinning with a factor of 10 has been made for clarity. Error bars are one standard deviation and energies are given in the observed frame.
<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{\text{pc}} \quad [10^{20} \text{ cm}^{-2}]$</th>
<th>$f_{\text{pc}} \quad [10^{20} \text{ cm}^{-2}]$</th>
<th>$N_i$</th>
<th>$\Gamma$</th>
<th>$k_B T \quad [\text{eV}]$</th>
<th>$C_{\text{bb}} \quad [10^{-4} \text{ erg}<em>{39} \text{ kpc}</em>{10}^2]$</th>
<th>$\chi^2_{\text{red}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pha(zpow)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pha(zpow)$^\dagger$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pha(zphabs(zpow))</td>
<td>0–77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pha(zpcf(zpow))</td>
<td>70–110</td>
<td>0.46–0.71</td>
<td></td>
<td></td>
<td>1.91–2.32</td>
<td></td>
<td>2471/2340 = 1.06</td>
</tr>
<tr>
<td>pha(zpcf(zpow+zbbody))</td>
<td>30–90</td>
<td>0.44–0.73</td>
<td></td>
<td>1.78–2.23</td>
<td>17–97</td>
<td>0–300</td>
<td>2420/2324 = 1.04</td>
</tr>
<tr>
<td>pha(zpcf(zpow+zbbody))$^\dagger$</td>
<td>40–100</td>
<td>0.50–0.71</td>
<td></td>
<td>1.78–2.27</td>
<td>80</td>
<td>0.078</td>
<td>2434/2338 = 1.04</td>
</tr>
<tr>
<td>pha(zpcf(zpow+zbbody))$^\ddagger$</td>
<td>60–110</td>
<td>0.40–0.71</td>
<td></td>
<td>1.84–2.31</td>
<td>31</td>
<td>3.5</td>
<td>2455/2348 = 1.05</td>
</tr>
<tr>
<td>pha(zpcf(zpow+zbbody))$^\ddagger$</td>
<td>60–100</td>
<td>60</td>
<td></td>
<td>1.98–2.26</td>
<td>31</td>
<td>3.0</td>
<td>2486/2356 = 1.06</td>
</tr>
</tbody>
</table>

**Table 6.1:** Fitted parameter values for all absorbed power law and blackbody models. Intervals indicate the range spanned by the best fit values of parameters that were left untied between observations, i.e. not confidence intervals. Conversely, scalar values imply that the parameter was tied across observations. The last, partially absorbed blackbody model, with tied $f_{\text{pc}}$, $k_B T$, and $C_{\text{bb}}$, is the favored model based on the analysis presented in section 6.1. The fitted values of each individual observation for pha(zpcf(zpow)) and the last two models are provided in tables 6.2, 6.4, and 6.3 respectively.

Columns: (1) Model expressed using XSPEC terminology, (2) column density of the partial covering absorber, (3) covering fraction of the partial covering material, (4) column density of completely covering intrinsic absorption, (5) photon index, (6) temperature of the blackbody component, (7) normalization of the blackbody component, (8) fit statistic.

$^\dagger$ Only fit to the hard interval (2–10 keV).

$^\ddagger$ Including R1.
above 2 keV and extrapolating it to 0.3 keV. Residuals of this fit is shown in figure 6.2 and the fitted parameter values are provided in table 6.1. The power law fits the hard energy range well and the photon indices are in the range 1.73–2.14. No systematic residuals can be seen and the \( \chi^2_{\text{red}} \) value is 1450/1423 = 1.03 (excluding the 0.3–2 keV range). It is worth emphasizing that no sign of an iron line is observed around 6.4 keV. Further analysis of reflection will be presented in section 6.2. Finally, note that a very prominent soft deficit is evident at low energies.

6.1.2 Absorption

The strong residuals at low energies in figure 6.2 indicate that intrinsic absorption by the host galaxy may be important. The most straightforward approach is to add an additional intrinsic absorption component, making the current model phabs(zphabs(zpowerlw)). The intrinsic absorption component zphabs has one free parameter, specifically the column density \( N_i \), defined analogously to the Galactic column density \( N_G \). The column density was allowed to vary between observations. The fit is poor and the residuals are shown in figure 6.3 and the fitted parameter values are given in table 6.1. The overall tendency is that although the flux drops below the power law extrapolation, it is far from totally extinct at very low energies. The residuals of the absorbed and unabsorbed fits are very similar as can be seen by comparing figures 6.1 and 6.3.

Since the overall trend was that absorption results in over-extinction at very low energies for any substantial, additional column density, it seems natural to try partial absorption. The model is thus refined by replacing the intrinsic absorption with partial absorption, resulting in the model phabs(zpcfabs(zpowerlw)). Partial covering absorption has a free column density parameter \( N_{pc} \), defined analogously to the aforementioned column densities. Furthermore, partial covering introduces an additional free parameter, namely the partial covering fraction \( f_{pc} \). This is simply the fraction of the source obscured by the partial covering material. The additional parameters are also allowed to vary freely across observations. The residuals of the partially absorbed model are shown in figure 6.4. The fit statistic is 2471/2340 = 1.06 and no systematic deviations are seen. The best fit photon indices are in the range 1.91–2.32. All fitted values of this model for individual observations are provided in table 6.2. A summary of all fits and ranges of relevant best fit values are summarized in table 6.1.

6.1.3 Blackbody emission

A remark is in order before going into the details of a possible blackbody. From figure 6.4 it might seem that the data from R1 are inconsistent with the more recent observations below 0.4 keV. However, recall that the energy resolutions of XMM-Newton and Suzaku is significantly better than that of ROSAT, which is \( \sim 250 \) compared to \( \sim 100 \) eV (FWHM) at the relevant energies. Thus, it is possible for a very luminous component below 0.3 keV to prominently increase the observed flux at energies slightly above 0.3 keV in ROSAT spectra.

The R1 data in figure 6.4 clearly shows an excess at very low energies. To take the excess into account, it was tested if an additional blackbody component improves the fit, as was found by Yuan et al. (2010). This can be done by simply adding a red-shifted blackbody component to the partially absorbed model, resulting in the model
Figure 6.3: Residuals of a model with intrinsic absorption. *XMM-Newton* data are blue and *Suzaku* data are green. This model is clearly not able to describe the observed data and the fit statistic is $3150/2348 = 1.34$. The residuals display similar behavior to those seen in figure 6.1. The data have been rebinned with a factor of 10 for clarity. Error bars are one standard deviation and energies are given in the observed frame.

Figure 6.4: Residuals of a model with partial intrinsic absorption. *XMM-Newton* data are blue and *Suzaku* data are green. R1 data (red, encircled crosses) are overlaid with residuals calculated using the fit to X2. It is clearly a good fit to all recent observations with a $\chi^2_{\text{red}}$ value of $2471/2340 = 1.06$. A strong excess is evident at very low energies, discussed in section 6.1.3. The fitted parameter values are given in table 6.2. Recent data have been rebinned with a factor of 10 for clarity. Error bars are one standard deviation and energies are given in the observed frame.
Table 6.2: Fitted parameter values for the partially covered power law model in chronological order. The $\chi^2_{\text{red}}$ value for the fit is 2471/2340 = 1.06. Error intervals are 90\%.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>$N_{pc}$ $[10^{20}\text{cm}^{-2}]$</th>
<th>$f_{pc}$</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>$71^{+22}_{-21}$</td>
<td>0.58$^{+0.08}_{-0.10}$</td>
<td>2.15$\pm$0.12</td>
</tr>
<tr>
<td>X1</td>
<td>67$\pm$7</td>
<td>0.60$\pm$0.04</td>
<td>2.16$\pm$0.06</td>
</tr>
<tr>
<td>S2</td>
<td>$95^{+20}_{-21}$</td>
<td>0.64$^{+0.07}_{-0.10}$</td>
<td>2.32$\pm$0.13</td>
</tr>
<tr>
<td>X2</td>
<td>$67^{+8}_{-7}$</td>
<td>0.58$\pm$0.04</td>
<td>2.12$\pm$0.06</td>
</tr>
<tr>
<td>S3</td>
<td>109$\pm$16</td>
<td>0.71$^{+0.05}_{-0.06}$</td>
<td>2.27$\pm$0.10</td>
</tr>
<tr>
<td>X3</td>
<td>73$\pm$8</td>
<td>0.66$^{+0.03}_{-0.04}$</td>
<td>2.08$\pm$0.06</td>
</tr>
<tr>
<td>S4</td>
<td>85$\pm$31</td>
<td>0.51$^{+0.11}_{-0.15}$</td>
<td>2.13$^{+0.15}_{-0.14}$</td>
</tr>
<tr>
<td>X4</td>
<td>$94^{+22}_{-20}$</td>
<td>0.46$^{+0.09}_{-0.11}$</td>
<td>1.91$\pm$0.10</td>
</tr>
</tbody>
</table>

The blackbody component has the free parameters temperature ($k_B T$) and normalization ($C_{bb}$). The unit of $C_{bb}$ is erg$_{39}$ kpc$_{10}^2$, where erg$_{39}$ and kpc$_{10}$ denotes 10$^{39}$ erg s$^{-1}$ and 10 kpc, respectively. No free parameters were tied between observations at this stage.

Data from R1 is still excluded in this first step because of the large difference in time. The addition of the blackbody component improves the fit to 2420/2324 = 1.04, i.e. $\Delta \chi^2 = -52$ for 16 fewer degrees of freedom, for the recent data. However, the best fit normalization is varying by more than an order of magnitude and the temperatures almost span a factor of five between individual observations, as can be seen from table 6.1. It is therefore clear that each observation is incapable of constraining a potential blackbody since blackbody emission is expected to be relatively constant given the small variations in observed flux.

As a possible blackbody component is impossible to constrain using individual observations, a natural option is to tie blackbody parameters between observations. This introduces an error since the eight observations are non-simultaneous, but this should be small in comparison to the statistical uncertainties. Both the blackbody normalization and temperature were tied. Unreasonably large variations were obtained if only one of the two was coupled, similar to when both parameters were untied. Furthermore, if the emission is emitted by an accretion disk that is truly varying, then changes in normalization and temperature are expected to be related. So if one is tied, the other ought to remain largely constant.

The same blackbody model is therefore fit with the modification that all observations have both $C_{bb}$ and $k_B T$ tied. The improvement when including a blackbody using this setup is $\Delta \chi^2 = -37$ for two additional parameters, resulting in 2434/2338 = 1.04. The best fit of the blackbody temperature is $k_B T = 80^{+12}_{-15}$ eV with a normalization of 0.078$^{+3.9}_{-2.7} \times 10^{-4}$ erg$_{39}$ kpc$_{10}^2$. These values are also shown in table 6.1. It is also interesting to note that the total blackbody luminosity is $\sim 2 \times 10^{43}$ erg s$^{-1}$. Firstly, this is not consistent with the fit when R1 data is considered, as will be shown below.

\footnote{https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSmodelBbody.html}
Secondly, both the temperature and luminosity are inconsistent with theory, as will be seen in section 7.1. Lastly, the fit is unreliable in the sense that it is more sensitive to errors in the spectra because only a small fraction of the blackbody extends into the energy range of XMM-Newton and Suzaku for the given temperature. The fit is therefore rejected despite being statistically acceptable.

It is possible to put more reliable constraints on a potential blackbody when ROSAT data is included. Given that R1 seems to be consistent with the recent observations above 0.3 keV, it is assumed that including R1 and tying its blackbody parameters with those of the recent observations is reasonable. This is simply to explore the scenario that the blackbody component is constant. In addition, the partial covering fraction is tied across observations, a restriction motivated in section 6.1.4.

R1 data are unable to constrain \( N_{\text{pc}}, C_p, \) and \( \Gamma, \) which are the remaining untied parameters for each observation. The photon index was therefore frozen to 2.1, which was chosen to be close to the average of the recent observations. Furthermore, the blackbody is relatively insensitive to the other components because it dominates at low energies, as seen in figure 6.6. In other words, even if the continuum besides the blackbody is unreliable or weakly constrained at low energies, the error in the magnitude of the blackbody would only be on the order of a few percent.

Residuals of the fit and the unabsorbed model are shown in figures 6.5 and 6.6, respectively. Model parameters for each observation are presented in table 6.3. The best fit blackbody temperature for this model is \( k_B T = 31 +2 -3 \text{ keV} \) with a normalization of \( 3.0 +1.8 -0.7 \times 10^{-4} \text{ erg cm}^{-2} \text{ keV}^{-1} \text{kpc}^2 10^{-4}. \) The corresponding blackbody luminosity is \( \sim 7 \times 10^{44} \text{ erg s}^{-1}, \) which is in the correct ballpark for an expected accretion disk, in particular when the large uncertainties are taken into account. This will be discussed further in section 7.1. Lastly, these blackbody parameters still give an improvement of \( \Delta \chi^2 = -5 \) for two fewer degrees of freedom when fit to only the recent data compared to the corresponding model without a blackbody. This implies that the error introduced by tying R1 with recent data most likely is relatively small.

Finally, it is relevant to determine the statistical significance of the additional blackbody component. One option is to compute the posterior predictive p-value following Protassov et al. (2002). It should be mentioned that the first step was skipped, i.e. the simulated spectra were all samples of the best fit power law, without sampling of the best fit parameters. This is not expected to qualitatively alter the result.

Each \( \Delta \chi^2 \) was obtained by first simulating nine spectra from the best fit partially absorbed model without blackbody component, i.e. \texttt{phabs(zpcfabs(zpowerlw))}. These spectra represent the nine observations and were made using the XSPEC command \texttt{fakeit}. The task takes background, detector response, and exposure time of the individual observations into account when generating the fake spectra. The aforementioned partially absorbed model and the same model with a blackbody component were then fitted. The \( \Delta \chi^2 \) value was obtained by subtracting the fit statistic of the model without blackbody component from that of the model with a blackbody component. By comparing the distribution of simulated \( \Delta \chi^2 \) values with the one calculated from the observed spectra, it is possible to determine the probability that the observed outcome occurs by chance.

The simulated probability distribution is shown in figure 6.7. The observed \( \Delta \chi^2 \) value was 259 which is significantly higher than any of the 3000 simulated spectra. It is therefore clear that the blackbody component is strongly favored in the scenario that it
Figure 6.5: Residuals of partially absorbed model with blackbody fit including R1 (red, encircled crosses) with tied partial covering fraction. XMM-Newton data are blue and Suzaku data are green. It is clearly a good fit with a $\chi^2_{\text{red}}$ value of 1.06. It is interesting to make a comparison with figure 6.4 note the change between R1 and the recent observations around 0.4 keV. The fitted parameter values are given in table 6.3. Recent data have been rebinned with a factor of 10 for clarity. Error bars are one standard deviation and energies are given in the observed frame.

Figure 6.6: The unabsorbed model consisting of a blackbody (dotted red) and power law (dashed blue) and the sum (solid black). The power law normalization and photon index for this particular model are from the fit to X2 and the other parameters are coupled. The blackbody mainly contributes below 0.3 keV explaining why it only was detected by ROSAT. Energies are given in the rest frame of RX J1633+4718.
Table 6.3: Fitted parameter values for the favored, partially covered blackbody model in chronological order. The values for the tied parameters are partial covering fraction $f_{pc} = 0.60^{+0.02}_{-0.02}$, blackbody temperature $k_B T = 31^{+3}_{-3}$ eV, and blackbody normalization $C_{bb} = 3.0^{+1.8}_{-0.7} \times 10^{-4}$ erg cm$^{-2}$ kpc$^{-2}$. The $\chi^2_{\text{red}}$ value for the fit is $2486/2356 = 1.06$. Superscript f denotes that the parameter was frozen. Error intervals are 90%. Columns: (1) Observation, (2) column density of the partial covering absorber, (3) photon index, (4) power law normalization.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>$N_{pc}$ [10$^{20}$ cm$^{-2}$]</th>
<th>$\Gamma$</th>
<th>$C_p$ [$10^{-4}$ keV$^{-1}$ cm$^{-2}$ s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>$80^{+72}_{-60}$</td>
<td>2.10$^f$</td>
<td>$8.0^{+1.2}_{-2.8}$</td>
</tr>
<tr>
<td>S1</td>
<td>$71^{+20}_{-20}$</td>
<td>2.17$^{+0.06}_{-0.07}$</td>
<td>$7.9^{+0.8}_{-0.9}$</td>
</tr>
<tr>
<td>X1</td>
<td>$62^{+08}_{-08}$</td>
<td>2.15 $^{+0.03}_{-0.03}$</td>
<td>$6.9 \pm 0.3$</td>
</tr>
<tr>
<td>S2</td>
<td>$89^{+20}_{-18}$</td>
<td>2.26$^{+0.05}_{-0.06}$</td>
<td>$8.7 \pm 0.8$</td>
</tr>
<tr>
<td>X2</td>
<td>$63^{+07}_{-07}$</td>
<td>2.12 $^{+0.03}_{-0.03}$</td>
<td>$7.0 \pm 0.3$</td>
</tr>
<tr>
<td>S3</td>
<td>$94^{+17}_{-14}$</td>
<td>2.10 $^{+0.04}_{-0.04}$</td>
<td>$9.4^{+0.7}_{-0.6}$</td>
</tr>
<tr>
<td>X3</td>
<td>$63^{+07}_{-08}$</td>
<td>1.98 $^{+0.04}_{-0.04}$</td>
<td>$7.7 \pm 0.4$</td>
</tr>
<tr>
<td>S4</td>
<td>$93^{+26}_{-26}$</td>
<td>2.24$^{+0.06}_{-0.07}$</td>
<td>$7.3^{+0.7}_{-0.8}$</td>
</tr>
<tr>
<td>X4</td>
<td>$95^{+18}_{-16}$</td>
<td>2.05 $^{+0.04}_{-0.04}$</td>
<td>$6.1 \pm 0.3$</td>
</tr>
</tbody>
</table>

is constant between R1 and the recent data.

### 6.1.4 Variability of model parameters

The light curves (figure 5.1) for the observations clearly show some level of variability, and the hardness plots (figure 5.3) indicate that the change is caused by more than just a constant factor, i.e. the spectrum is changing its shape. It is thus interesting to study the evolution of the physical parameters for the partially covered blackbody model ($\text{phabs(zpcfabs(zpowerlw+zbbody))}$) from section 6.1.3 if the covering fraction was left untied. Data from R1 are used as it was shown that they are necessary to constrain the blackbody component.

The four parameters that were allowed to vary between observations are the partial covering column density ($N_{pc}$), partial covering fraction ($f_{pc}$), photon index ($\Gamma$), and power law normalization ($C_p$). In these fits, as explained in section 6.1.3, the parameters for the blackbody are coupled across observations. The residuals of this fit are shown in figure 6.8. It is clearly a good fit with a fit statistic of $2455/2348 = 1.05$. Though significant fluctuations were observed, no variable parameters showed any obvious systematic dependence on time, as seen in table 6.4.

An important parameter in this context is flux. No systematic flux dependence was found for $N_{pc}$. A correlation was, however, found for $f_{pc}$, plotted in figure 6.9. A plot of $\Gamma$ against $F_o$ is also shown in figure 6.9. For later comparison, note that the ratio between the largest and smallest $C_p$ is $\sim 2.7$, although the corresponding value for $F_o$ is $\sim 1.4$.

A clear trend is seen for $f_{pc}$, whereas $\Gamma$ shows no obvious systematic variation with flux. It seems unnatural that $f_{pc}$ is correlated with $F_o$. In fact, $f_{pc}$ is expected to be anticonsistent with $F_o$ because an increased $f_{pc}$ implies increased absorption, which in
Figure 6.7: Probability distribution function for $\Delta \chi^2$ when an additional blackbody component is added. 3000 spectra were simulated and none are close to the observed $\Delta \chi^2$ value of 259 (not shown for clarity). This clearly favors the additional blackbody component. Some negative values are a consequence of the numerical algorithm used by XSPEC (Levenberg-Marquardt algorithm) stopping before finding the global minimum. A few values are relatively large (both positive and negative). The x-axis is therefore set to include all bins although they are not clearly visible.

Figure 6.8: Residuals of partially absorbed model with blackbody fit including R1 (red, encircled crosses) with untied partial covering fraction. *XMM-Newton* data are blue and *Suzaku* data are green. It is clearly a good fit with a $\chi^2_{\text{red}}$ value of 1.05. The fitted parameter values are given in table 6.4. Recent data have been rebinned with a factor of 10 for clarity. Error bars are one standard deviation and energies are given in the observed frame.
to study the correlation between $\Gamma$ and $f$ increased obscuration is fit to match the increase in hardness. It is therefore compelling instead of fitting harder spectra to higher flux states, a power law of similar slope with $f$ seen between $f$ degeneracies of the fit rather than being physical.

Consequently, it is reasonable to expect an anticorrelation between $\Gamma$ and $F$. This suggests that the observed changes may be driven by the degeneracies of the fit rather than being physical.

Both of these issues are resolved if intrinsic variations in $\Gamma$ are attributed to changes in $f_{pc}$ when fitting, i.e. that the two parameters are degenerate. In practice, this means that instead of fitting harder spectra to higher flux states, a power law of similar slope with increased obscuration is fit to match the increase in hardness. It is therefore compelling to study the correlation between $\Gamma$ and $f_{pc}$, shown in figure 6.10. A clear correlation is seen between $f_{pc}$ and $\Gamma$. This suggests that the observed changes may be driven by the degeneracies of the fit rather than being physical.

The difference made by tying $f_{pc}$ between observations is an increase of $\Delta \chi^2 = 31$ for eight additional degrees of freedom, resulting in a new $\chi^2_{\text{red}}$ of 2486/2356 = 1.06. The residuals of this fit are shown in figure 6.5 with the best fit values given in table 6.3. The fit is still good, especially given that some variations in $f_{pc}$ are expected, i.e. an additional small error is introduced. The aforementioned figure and table can be compared with figure 6.8 and table 6.4, which are the corresponding figure and table for the model with untied $f_{pc}$. It is evident that the model is capable of describing the spectra regardless of $f_{pc}$ being tied or not. It is therefore motivated to explore the case of $f_{pc}$ being tied between the observations.

Plots of the partial covering density $N_{pc}$ and $\Gamma$ against $F_\odot$, respectively, are shown

<table>
<thead>
<tr>
<th>Obs.</th>
<th>$N_{pc}$ [10^{20} \text{ cm}^{-2}]$</th>
<th>$f_{pc}$</th>
<th>$\Gamma$</th>
<th>$C_p$ [10^{-4} \text{ keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>$62^{+133}_{-42}$</td>
<td>0.63$^{+0.14}_{-0.20}$</td>
<td>2.10$^4$</td>
<td>7.4$^{+8.8}_{-2.3}$</td>
</tr>
<tr>
<td>S1</td>
<td>$68^{+22}_{-21}$</td>
<td>0.57$^{+0.08}_{-0.10}$</td>
<td>2.13$^{+0.12}_{-0.13}$</td>
<td>7.6$^{+1.5}_{-1.2}$</td>
</tr>
<tr>
<td>X1</td>
<td>61 $\pm$ 8</td>
<td>0.59$^{+0.04}_{-0.05}$</td>
<td>2.14$^{+0.03}_{-0.06}$</td>
<td>6.8 $\pm$ 0.5</td>
</tr>
<tr>
<td>S2</td>
<td>93 $\pm$ 21</td>
<td>0.63$^{+0.07}_{-0.10}$</td>
<td>2.31 $\pm$ 0.13</td>
<td>9.3$^{+2.0}_{-1.7}$</td>
</tr>
<tr>
<td>X2</td>
<td>61 $\pm$ 8</td>
<td>0.58 $\pm$ 0.04</td>
<td>2.10 $\pm$ 0.06</td>
<td>6.8 $\pm$ 0.5</td>
</tr>
<tr>
<td>S3</td>
<td>108 $\pm$ 16</td>
<td>0.71$^{+0.05}_{-0.06}$</td>
<td>2.26 $\pm$ 0.19</td>
<td>12.0$^{+2.9}_{-1.9}$</td>
</tr>
<tr>
<td>X3</td>
<td>69 $\pm$ 8</td>
<td>0.65 $\pm$ 0.04</td>
<td>2.06 $\pm$ 0.06</td>
<td>8.5 $\pm$ 0.7</td>
</tr>
<tr>
<td>S4</td>
<td>90 $\pm$ 32</td>
<td>0.48$^{+0.12}_{-0.15}$</td>
<td>2.10$^{+0.15}_{-0.14}$</td>
<td>5.9$^{+1.5}_{-1.1}$</td>
</tr>
<tr>
<td>X4</td>
<td>76$^{+24}_{-23}$</td>
<td>0.40$^{+0.10}_{-0.12}$</td>
<td>1.84 $\pm$ 0.10</td>
<td>4.5$^{+0.7}_{-0.6}$</td>
</tr>
</tbody>
</table>

Table 6.4: Fitted parameter values for the partially covered blackbody model with untied covering fraction in chronological order. The values for the tied parameters are blackbody temperature $k_B T = 31^{+4}_{-1}$ eV, and blackbody normalization $C_{bb} = 3.5^{+4.9}_{-2.0} \times 10^{-4}$ erg$_{\odot}$/kpc$^2$. The $\chi^2_{\text{red}}$ value for the fit is 2455/2348 = 1.05. Superscript f denotes that the parameter was frozen. Error intervals are 90 %.

Columns: (1) Observation, (2) column density of the partial covering absorber, (3) covering fraction of the partial covering material, (4) photon index, (5) power law normalization.
Figure 6.9: Plots of $f_{pc}$ (left) and $\Gamma$ (right) against $F_o$. A clear correlation is seen between $f_{pc}$ and $F_o$ whereas $\Gamma$ displays no systematic trends with $F_o$. Error bars are 90%.

in figure 6.11. No solid conclusion can be drawn for $N_{pc}$, except that X4 is statistically different from the other *XMM-Newton* observations. The harder-when-brighter trend is seen for $\Gamma$, particularly when considering data from *XMM-Newton* and *Suzaku* separately and considering X4 an outlier.

In addition, the ratio between the largest and smallest $C_p$, which previously was $\sim 2.7$, is now $\sim 1.5$, which is in agreement with the corresponding value for $F_o$ of $\sim 1.4$. This is because the spectral variations previously were explained by variable obscuration. To keep the observed flux at the actually observed level, the normalization had to counteract the decrease in flux due to increased absorption. In other words, this further supports tying $f_{pc}$ across observations.

In light of the analysis, the favored model is a partially absorbed model consisting of a power law and blackbody with covering fraction and blackbody parameters tied across the observations. This is not the statistically best model but several arguments have been put forward to support the conclusion. A summary of all models is provided in table 6.1 and the best fit parameters for the favored model are presented in table 6.3.

6.2 Reflection

Reflection has so far been neglected because no iron line was seen (e.g. figure 6.5) and since other models fit the observed spectra well. However, reflection is a common component of NLS1 spectra ([Crummy et al., 2006]; [Reynolds, 2015]; [Fabian, 2015]). It is therefore interesting to obtain limits to reflection.

One method of quantifying the lack of an iron line is to compute the 90% upper limit on the equivalent width $W$ using the XSPEC task *eqwidth* and its option *err*. This was done by fitting a power law with an additional redshifted Gaussian (*zgauss*) to the hard spectra (2–10 keV). It has been shown in figure 6.2 that the power law is a good fit to the continuum in the relevant interval. The *zgauss* component has three free
Figure 6.10: A contour plot of $\Delta \chi^2$ for $f_{pc}$ and $\Gamma$ for X2 on a $64 \times 64$ grid, clearly showing a degeneracy between the two parameters. The color scale shows $\Delta \chi^2$ according to the logarithmic colorbar. The two other parameters that were allowed to vary were the covering density ($N_{pc}$) and power law normalization ($C_p$). The best fit value (orange dot) had a $\chi^2_{red}$ of $2455/2348 = 1.05$. The confidence contours are 68 % (red), 90 % (green), and blue 99 %.

Figure 6.11: The difference from figures 6.9 is that $f_{pc}$ is coupled across the observations. Note that X4 (leftmost data point) is an outlier in both plots. There are also tendencies indicating a possible systematic error between XMM-Newton and Suzaku, as mentioned in chapter 3. Error bars are 90 %.
parameters, specifically line energy, line width (represented by $\sigma$ of the Gaussian) and a normalization corresponding to the total number of photons cm$^{-2}$ s$^{-1}$ in the line.

Fits were attempted for free line energies in the range 5–8 keV as well as free widths in the interval 0–2 keV. However, any free parameters were pegged at limits for most of the observations. Line energies and widths were therefore frozen to 6.4 and 0.1 keV, respectively, in order to obtain limits on a narrow line from neutral material. The average upper limit to the equivalent width for all observations was 0.10 keV, with values within the range 0.06–0.13 keV. Interestingly, no lower limit was found for any observation, i.e. $W = 0$ keV was within the calculated 90% confidence intervals.

The full reflection spectrum was studied using the model relxill\textsuperscript{4} version 0.4a (García et al., 2014). The relxill model is based on the models xillver (García et al., 2013) and relline (Dauser et al., 2013). The xillver component accounts for the detailed physics of reflection and composition of the accretion disk. Two properties of the accretion disk are considered, specifically the ionization ($\xi$), and iron abundance relative to its solar value ($A_{\text{Fe}}$). It assumes that an accretion disk is being illuminated by a power law with photon index $\Gamma$ and calculates the reflected spectrum. The model does not distinguish between power-law emission from jets and coronas. The most notable features are that a rich set of emission lines and absorption at soft energies are obtained for low levels of ionization ($\xi < \sim 200$). Reflected spectra get increasingly similar to the incident power laws for higher ionization levels.

The relline component computes the relativistic effects on a reflected emission line. This is strongly dependent on the black hole spin ($a$) since the ISCO gets smaller for increasing $a$. Furthermore, the emissivity of the disk is assumed to depend on distance from the black hole. This is modelled as $r^{-\epsilon}$, where $r$ is radial distance and $\epsilon$ is the emissivity index. The result of relativistic reflection is that lines get broadened and obtain a red wing due to gravitational redshift.

The relxill model combines xillver and relline. It computes the relativistically blurred reflection at each observed point of the accretion disk. This has to be done because the convolution of the reflected spectra is dependent on radius. Furthermore, it calculates observed spectra as a function of inclination ($\theta$), in contrast to previous models, which were angle-averaged. The geometry is described by the reflection fraction ($f_r$). It is defined as the ratio of power law emission to reflected emission at the origin of the radiation. Finally, the spatial extent of the accretion disk is given by the inner radius ($r_{\text{in}}$) and outer radius ($r_{\text{out}}$) and the high-energy roll-over of the power law is given by $E_{\text{cut}}$ (the low-energy limit is effectively set by 0.1 keV, below which the model is undefined).

The underlying power law in the favored model from section 6.1.4 was replaced by relxill, which results in the new model phabs(zpcfabs(relxill+zbody)). R1 data were used in the fit to constrain the blackbody, however, this does not affect the reflection parameters significantly. The partial covering absorption was required for fits to be acceptable. A power law is a special case of relxill, namely when the reflection fraction $f_r$ is zero. Any fits with relxill will thus be strictly better, in $\chi^2$ sense. Both partial absorption parameters $N_{pc}$ and $f_{pc}$ have to be coupled across observations due to poor constraints when fitting. Many of the reflection parameters also had to be frozen for the same reason, specifically: $\epsilon = 3$, $a = 0.998$, $\theta = 10^\circ$, $r_{\text{in}} = r_{\text{ISCO}}$, $r_{\text{out}} = 400$ gravitational...\textsuperscript{5}
radii, $A_{\text{Fe}} = 1$, and $E_{\text{cut}} = 300$ keV. All values are their respective defaults except for the inclination which was set to $10^\circ$ (instead of its default value of $30^\circ$) because NLS1s are assumed to be viewed face-on (Berton et al., 2016).

This leaves the photon index, ionization, reflection fraction, and normalization ($C_r$) free and decoupled. These four parameters are still only loosely constrained as can be seen in the $\Delta \chi^2$ contour plots of $f_r$ and $\xi$ in figure 6.12. The corresponding plots for the six remaining observations are included in appendix A. The fit statistic was $2456/2349 = 1.05$ and the photon indices from all observations were within the range 1.94–2.30. Contours for different observations vary unsystematically, which indicates that the fitted values might be unstable, i.e. sensitive to small fluctuations. It is therefore difficult to draw any quantitative conclusions. However, it is evident from the plots that the combination high reflection fraction and low ionization is unacceptable for all observations. This indicates that it is a relatively robust feature for all spectra, despite the large fluctuations. In other words, any reflection must come from highly ionized material.

It is interesting to study variability from a disk reflection perspective. The additional level of detail of the model could potentially shed light on which underlying components that are varying. In addition, it has been suggested that X-ray variability in NLS1s can be explained by a constant reflection component in conjunction with a power law of constant slope and varying normalization (e.g. Fabian and Vaughan, 2003; Ponti et al., 2006; Zoghbi et al., 2010).

Leaving parameters free was not an option due to the data being unable to constrain the parameters. It was, however, possible to test if a fit with constant $\Gamma$ was reasonable, i.e. if it is possible to fit a model with tied photon indices. This is to test if a scenario where a combination of only the normalization, ionization, and reflection fraction are capable of matching the observed variability. The change in fit statistic was $\Delta \chi^2 = 36$ for eight additional degrees of freedom, resulting in $2492/2353 = 1.06$. This is interpreted as a decent fit, given that tying the photon indices is a rather strong restriction. The conclusion is thus that it is not possible to rule out the scenario where the observed spectra are described by a power law of (nearly) constant slope. The spectral variability in this picture is attributed solely to changes in level of ionization and reflection fraction.

### 6.3 Flux-selected spectra

Variations have so far only been studied on long timescales, i.e. across observations. However, the hardness plots clearly indicate spectral variations on long as well as short timescales. Additionally, both variations appear to depend on flux. Four time intervals (two flux transitions) were therefore chosen for flux-selected spectral analysis, described in section 5.1 and shown in figure 5.1.

The spectrum from each time interval is shown in figure 6.13. Since the blackbody is unconstrainable using only XMM-Newton data and the partially absorbed power law model is a good fit without R1, the blackbody component was omitted. Best fit values are presented in table 6.5. The partial covering parameters were coupled over the transitions. It was verified that no statistically significant improvement was obtained by decoupling them and the parameters are also not expected to vary significantly on short timescales.

A weak harder-when-brighter trend can be seen in $\Gamma$, although it should be emphasized that the confidence intervals are slightly overlapping for both transitions. This means that the short term variations can be described by a pivoting power law component.
Figure 6.12: Contour plots of $\Delta \chi^2$ for $f_r$ and $\xi$ for X2 (upper) and S4 (lower) on $128 \times 128$ grids. Color scale shows $\Delta \chi^2$ according to the logarithmic colorbar. The periodic features are most likely due to `relxill` being a table model. The two other parameters which were allowed to vary were the photon index $\Gamma$ and reflection normalization $C_f$. The best fit values (orange dots) had a $\chi^2_{\text{red}}$ value of $2456/2345 = 1.05$ (all observations were fit together). The confidence contours are 68 % (red), 90 % (green), and blue 99 %. Corresponding plots for all recent observations are included in appendix A.
Figure 6.13: The low (green) and high (blue) flux spectra from X1 (upper) and X3 (lower). The three spectra from each observation are from pn, MOS1 and MOS2. Note that the difference between low and high states increases with energy, with almost no variations at the low limit. Error bars are one standard deviation and energies are given in the observed frame.

However, note that the only untied parameter that changes the shape of the spectrum is $\Gamma$. It is therefore not possible to rule out other causes for the variation using this simple model.

It is also clear from figure 6.13 that the variations are primarily driven by an increase of the contribution at high energies with a relatively stable soft component. This can be compared to the variations of observed flux on long timescales, which generally also show a harder-when-brighter trend as seen in the hardness plots (figure 5.3). However, it is clear that both the soft and the hard contribution varies on long timescales, as can be seen in table 5.1. So, the variability on long timescales is in line with that on short timescales with additional complexity. This is especially evident when comparing X4 to the other observations.
Table 6.5: Fitted parameter values for the flux selected spectra. The partial covering parameters were coupled over respective transition since no significant difference was detected. Error intervals are 90 %.

Columns: (1) Observation, (2) column density of the partial covering absorber, (3) covering fraction of the partial covering material, (4) photon index, (5) power law normalization.
Chapter 7
Discussion

The results in chapter 5 show that RX J1633+4718 varies only moderately during the observations. Short timescale variations are generally smaller than a factor of two, and the variations on long timescales are of even smaller magnitude. It is also clear that the observed spectra get harder during high flux intervals. This trend is seen on both short and long timescales. However, long timescales also display more complex behavior.

It was furthermore shown in chapter 6 that the observed spectra of RX J1633+4718 favors a model consisting of a power law and an additional blackbody component that are both partially absorbed. An iron Kα line is not observed in any spectra, indicating that reflection characteristics are weak. The variability on short timescales is primarily driven by an increased contribution at high energies with a relatively constant soft component. A hardening of the power law component is a possible explanation. Although, other options cannot be ruled out.

A discussion on the blackbody emission and the soft excess is provided in section 7.1. Emphasis is put on how the observed excess relates to that observed in other sources and comparing the fitted blackbody with standard disk theory. This is followed by a discussion on reflection in section 7.2 and variability in section 7.3. It is then possible to draw some conclusion that constrain the geometry of RX J1633+4718, which is done in section 7.4. RX J1633+4718 is compared with other AGNs in section 7.5. Finally, a discussion on future work is given in section 7.6.

7.1 Blackbody and soft X-rays

Firstly, a clarification is in order. The term “soft excess” is frequently used to describe the surplus above a power law in the range 0.3–2 keV when extrapolating the fit from the 2-10 keV energy range. It is important to distinguish this 0.3–2 keV component from the spectrum below 0.3 keV since very different behavior can be observed in these energy intervals. The term soft will continue to be used to refer to 0.3–2 keV whereas the low ROSAT energies 0.1–0.3 keV will be stated clearly.

At first glance it might seem like the 0.1–0.3 keV interval is relatively small. However, it still spans a factor of three in energy, or alternatively, blackbody temperature $k_B T$. When translated to black hole mass $M$, this corresponds to almost two orders of magnitude for a fixed accretion rate because of the $k_B T \propto M^{-1/4}\dot{M}^{1/4}$ dependence from equation (2.19). For a black hole accreting at the Eddington limit, a temperature of 0.03 keV (which is most prominent in the 0.1–0.3 keV range as seen in figure 6.6) gives
a mass of $2 \times 10^6 \, M_\odot$. Hence, it is clear that a large portion of the (low mass) AGN population could have blackbodies visible in the 0.1–0.3 keV range.

The blackbody temperatures found in literature are commonly within a narrow range 0.1–0.2 keV, independent of mass (Vaughan et al., 1999; Gierliński and Done, 2004; Crummy et al., 2006), which is inconsistent with the standard disk theory (Shakura and Sunyaev, 1973). This has led to the development of other models for the soft excess based on absorption (Chevallier et al., 2006; Turner and Miller, 2009; Tombesi et al., 2010), upscattering of low-energy blackbody photons (Done et al., 2012), and reflection (Ross and Fabian, 2005; García et al., 2014), which have shown varying levels of success in describing observed spectra. Blackbody contribution is therefore generally considered to be of little importance in explaining the observed spectra. However, it is important to note that these results rely on data above 0.3 keV because no modern instruments, such as XMM-Newton and Suzaku, have an energy range that extends to lower energies.

It might thus seem peculiar that RX J1633+4718 would require a blackbody component at a high significance level, which also results in best fit parameters far outside of the ordinarily observed ranges. Note that emphasis was put on the distinction between soft energies and the 0.1–0.3 keV range. Almost all models studied in recent literature have exclusively been fitted to data above 0.3 keV since no current instrument offers high quality spectroscopic capabilities at lower X-ray energies. So, the extreme values obtained for RX J1633+4718 are possibly just a natural consequence of using ROSAT data, which was necessary to constrain the blackbody component. In fact, RX J1633+4718 is not unique when put in context with other ROSAT studies, many of which find blackbody temperatures below 100 eV (e.g. Pounds et al., 1994; Gondhalekar et al., 1994; Puchnarewicz et al., 1995; Pounds et al., 1995; Fink et al., 1997). However, these relatively old studies suffer from lack of knowledge that is now available, for instance based on high quality data at harder energies, which allows for more solid conclusions to be drawn. It has also been shown that extremely steep spectra below 0.3 keV is a very robust feature among NLS1s (Boller et al., 1996), whereas quasars have harder corresponding spectra (Laor et al., 1997). A tentative conclusion is thus that NLS1s which are less massive have an underlying blackbody contribution that might be more or less dominant around 0.2 keV, while quasar blackbodies fall outside of ROSAT’s energy range since they are more massive. Lastly, it is worth mentioning that certain objects with extremely low mass have been adequately modeled by blackbodies above 0.3 keV (e.g. Boller et al., 2001; Zoghbi et al., 2010).

An explanation is still in order for the apparent deficit at soft energies, in contrast to the frequently mentioned excess (e.g. Crummy et al., 2006). Even though excess is more common, absorption is still seen in other sources. The survey of NLS1s by Leighly (1999, her figure 1) present numerous soft X-ray spectra, several of which show different levels of lack of soft excess. RX J1633+4718 can also be compared to other RLNLS1s in the surveys by Foschini et al. (2015, their table 5) where its photon indices appear relatively unique. It seems reasonable that the main reason why RX J1633+4718 shows a soft deficit is because of partial absorption. However, this does not explain why the blackbody remains very prominent, i.e. the ratio of 0.1–0.3 to 0.3–2 keV flux seems larger than for other sources. So, a possibility is that the intrinsic soft excess is weak in addition to being absorbed. This is also in line with the reflection origin of soft excess, which was shown to only contribute weakly to the spectrum of RX J1633+4718.

As mentioned in the introduction, the X-ray spectrum in RX J1633+4718 has pre-
viously been studied by Yuan et al. (2010), who reported a blackbody temperature of $32.5^{+8.0}_{-6.0}$ eV using only ROSAT data. Furthermore, Mallick et al. (2016) used the four XMM-Newton observations and obtained a temperature of $39.6^{+5.2}_{-5.4}$ eV. These values can be compared with the $31^{+2}_{-3}$ eV presented here, which was obtained when fitting to all available data from XMM-Newton, Suzaku and ROSAT. It was shown in section 6.1.3 that the ROSAT data were consistent with the recent observations, meaning that the same model can be used to describe all observed spectra.

The apparent discrepancy between the estimated temperatures is not surprising when differences in methods and models are taken into account. Mass estimates based on optical data have been reported in the literature and all estimates are in the range $2.8 \times 10^6 M_\odot$ (Yuan et al., 2008; Xu et al., 2012; Foschini et al., 2015; Jarvelä et al., 2015) with an arithmetic mean close to $4 \times 10^6 M_\odot$, which will henceforth be taken as the mass ($M$) of the SMBH in RX J1633+4718. This corresponds to an Eddington limit of $5 \times 10^{44}$ erg s$^{-1}$. The total thermal luminosity (excluding any jet contribution) of RX J1633+4718 can be estimated to be $\sim 3 \times 10^{44}$ erg s$^{-1}$ using optical data and relations for radio-quiet AGNs (Greene and Ho, 2005; Richards et al., 2006; Yuan et al., 2010). An independent method of obtaining an accretion disk temperature can now be made using solely optical data and equation (2.19), which gives $k_B T = 21$ eV for the values above. This is not within the range of the value $31^{+2}_{-3}$ eV, however, uncertainties in the optical estimates are practically unknown and error bars of the best fit value do not consider any errors besides statistical uncertainty. A detailed discussion of possible errors is deferred to the end of this section.

A problem with the estimate presented above is that the optical luminosity was significantly lower than the luminosity of solely the best fit blackbody, which had a luminosity of $7 \times 10^{44}$ erg s$^{-1}$. Another luminosity estimate is to simply use the sum of the best fit blackbody and the contribution of the power law within the energy range 0.3–10 keV. This is a conservative lower limit on the bolometric luminosity given the picture presented in section 6.1. Note that the mass is still taken to be the optical estimate and the temperature and normalization parameters in the zbody model are not directly connected, i.e. this is not circular reasoning. The average luminosity using the outlined method is $L = 8 \times 10^{44}$ erg s$^{-1}$, corresponding to an accretion rate of 1.7 times the Eddington limit. These are henceforth taken to be the best estimates. A blackbody temperature can now be calculated using equation 2.19, giving $k_B T = 29$ eV, in excellent agreement with the best fit values. It is worth mentioning that Yuan et al. (2010) and Mallick et al. (2016) found blackbody luminosities of $3.5 \times 10^{44}$ erg s$^{-1}$ and $1.51 \times 10^{44}$ erg s$^{-1}$, respectively. However, the former did not take absorption into account and the latter only used XMM-Newton and thus obtained a lower luminosity, a trend also seen in section 6.1.

Note that the super-Eddington accretion rate is relatively high, but sensitive to errors in mass estimates. For example, if the mass of Foschini et al. (2015) is used (i.e. $7.9 \times 10^6 M_\odot$), an accretion rate of 0.8 is obtained. Furthermore, a recent study has shown that the masses of NLS1s might be systematically underestimated (Baldi et al., 2016). An argument can be made that the observed blackbody temperature shows that the mass estimate of RX J1633+4718 is (approximately) correct. However, it is possible that a more massive black hole would appear to have a higher temperature, for example because of a high black hole spin (Middleton, 2015) or spectral hardening (Done et al., 2012). Finally, it is worth noting that NLS1s are expected to have high accretion rates (Collin and...
Kawaguchi, 2004; Foschini et al., 2015), so the estimated accretion rate of 1.7 times the Eddington rate should not be considered extreme.

Another question worth investigating is if the area of the blackbody is consistent with the size of an accretion disk. Assume the accretion disk to be a two-sided annulus with inner radius equivalent to the innermost stable circular orbit (ISCO). The measured and estimated quantities then gives an outer radius of 3.2 ISCO. The corresponding value for a standard Shakura-Sunyaev thin disk is 3.6. These two values are considered to be in good agreement considering the underlying simplifications.

It is clear that a blackbody is required in addition to an underlying, absorbed power law and the best fit values are consistent with standard disk theory. However, several crucial assumptions have been made. Firstly, the need of a blackbody was based on the statistical rejection of a pure power law continuum, implying that these were the only options available. It is therefore of interest to study other components, in place of the blackbody component, that are able to fit the data. Only two reasonable components were statistically acceptable due to the extreme steepness observed by ROSAT, namely Raymond-Smith thin plasma (Raymond and Smith, 1977) and thermal bremsstrahlung (Karzas and Latter, 1961; Kellogg et al., 1975), both originally discussed by Yuan et al. (2010). However, both models describe scenarios where the source gas would have to be optically thick, given basic assumptions about properties of RX J1633+4718. This, in conjunction with the fact that an accretion disk is predicted by theory, give solid reason to adopt the blackbody model. Secondly, it has been assumed that the black hole is non-rotating (except when studying reflection), primarily affecting the relations between temperature, mass, and accretion rate. It was unsuccessfully attempted to fit more sophisticated blackbody models, particularly Kerr black body (Li et al., 2005) which takes numerous other effects into account as well, such as inclination and emission due to torque at the inner boundary of the accretion disk. Lastly, another effect which significantly affects the predicted parameters of interest is potential spectral hardening\(^1\). The importance of spectral hardening for AGNs is not entirely settled (Davis et al., 2006; Done et al., 2012; Jin et al., 2012; Pal et al., 2016). Spectral hardening is effectively upscattering of softer photons, which distorts the spectral shape and significantly affects the fitted parameter values.

7.2 Reflection

The first sign that any disk reflection in this source might be weak is the lack of an iron line around 6.4 keV. It is established that the effective width of the iron line decreases with increasing hard X-ray luminosity, an effect known as the Iwasawa-Taniguchi effect (Iwasawa and Taniguchi, 1993), sometimes called X-ray Baldwin effect after the analogous effect in optical (Baldwin, 1977). The equivalent width upper limit of 100 eV and average hard X-ray luminosity of \(\sim 5 \times 10^{43} \text{ erg s}^{-1}\) puts RX J1633+4718 among the reflection-weak sources (e.g. Iwasawa and Taniguchi, 1993; Jiang et al., 2006; Bianchi et al., 2007), in particular when considering that the best fit values are significantly lower than 100 eV.

There are primarily two explanations for the lack of disk reflection, essentially shown in the contour plots of \(f_r\) and \(\xi\). Firstly, the geometry could be such that no reflection

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\(^1\) Also referred to as Comptonization, upscattering, effective temperature, or color correction.
occurs or reaches the observer, i.e. small reflection fraction $f_r$. Alternatively, the reflecting gas could be highly ionized, resulting in the reflected spectrum being very similar to a power law. Note that this still implies a large amount of reflection, but without many of the characteristic reflection features.

One pitfall concerning disk reflection is the measure of the amount of reflected radiation. Both reflection fraction and reflection strength are used in literature and a clarification on this topic has been made by Dauser et al. (2016). Further complications arise because of a bug in versions of relxill earlier than 0.4a (released on January 18, 2016) rendering some earlier values of $f_r$ unreliable. The reflection fraction used by relxill is the ratio of reflected flux over primary flux. Thus, the parameter ranges $0–1$ and $1–\infty$ (model only defined to 10) of $f_r$ are comparable. The only conclusion that can be drawn from the contour plots of $f_r$ and $\xi$ (figure A.1) is therefore that solely the primary continuum is visible unless the reflecting material is highly ionized, in which case the reflection geometry is fully unconstrained.

7.3 Origin of variability

Before looking into the details of variability in RX J1633+4718, a remark is in order regarding the blackbody component. Some changes in blackbody temperature due to variability of accretion rate are expected because of the temperature-accretion rate relation, i.e. equation (2.19). However, the blackbody component had to be coupled between the observations, and ROSAT data is furthermore of too low quality to pin down the small variations. This effect has only been observed using XMM-Newton (e.g. in Mrk 766, Boller et al., 2001). Variability will therefore only be discussed in the 0.3–10 keV range. It must be emphasized that this assumption has very important consequences. In fact, all reported variability may be attributed to redistribution of emission between the blackbody and the harder components, i.e. implying constant intrinsic luminosity or equivalently, accretion rate. The 0.1–0.3 keV luminosity is almost a factor of ten larger than that in the 0.3–10 keV interval, so if only a few percent of the blackbody emission is reprocessed, a very significant change will be observed.

Both short and long timescale variability are seen in the hardness plots (figure 5.3). The plots also clearly indicate that flux generally is the main driver behind spectral variability. Flux dependence is not surprising since it is closely related to Eddington ratio and it has been clearly shown that Eddington ratio is of utter importance to AGNs (Boroson and Green, 1992; Boroson, 2002; Shen and Ho, 2014). The observed harder-when-brighter trend (on short timescales) typically implies dominant jet contribution, which is commonly seen in blazars (Kataoka et al., 2008; Abdo et al., 2010; D’Ammando et al., 2011). Theoretical studies of Compton-cooled disk coronas predict flux-driven variations of hardness, but the exact relation is complex and depends on several parameters (Haardt et al., 1997).

7.3.1 Short timescales

The origins of short and long timescale variability will be treated separately since the underlying processes might differ. Flux-selected spectral analysis was attempted to inves-
tigate short-term variability. The selected spectra are shown in figure 6.13. It is clearly seen from the figure that the difference is mainly driven by an increase of the hard contribution whereas the soft flux is relatively constant. This is further supported by the root mean square (RMS) spectrum for RX J1633+4718 in Mallick et al. (2016, their figure 7), which shows a correlation between variability and energy. The constant soft component and variable hard component rules out changes in absorption as the source of short timescale variability. If absorption was the main driver, the expected outcome would be variations at soft energies with a relatively constant hard component.

At first glance, it seems like the most natural explanation would be a variable power-law component that is pivoting around soft energies. This would correspond to changes in the underlying source of the power law, i.e. a corona or, more likely, a (base of a) jet. Indeed, it was shown that the observed variability on short timescales can be ascribed to variations in $\Gamma$.

The two latter models cannot be distinguished on short timescales using available data. A trade-off has to be made between either an explanation that requires pivoting around soft energies, with lack of an expected reflection component, or a reflection component that is relatively constant. It is worth mentioning that light bending has been invoked to motivate constant reflection with variable direct continuum (Martocchia et al., 2000; Miniutti and Fabian, 2004).

7.3.2 Long timescales

Characteristics on short timescales were also observed on long timescales, meaning that all arguments apply equally well. However, deviations from the aforementioned trends were found for one observations, namely X4. This indicates that the complete picture has to be more complicated when long timescales are considered.

No clear signs of increased absorption were detected during X4. It was shown in figure 6.9 that X4 was fitted with the lowest covering fraction with a statistically insignificant increase in column density when both partial covering parameters were untied. Therefore, it seems like the observed changes in RX J1633+4718 are intrinsic and more complicated than simply originating from changes in one parameter which is proportional to luminosity.

A possible explanation for the variability is that the unobscured continuum would exhibit an excess caused by constant disk reflection that dominates at soft energies. Variability would then primarily be caused by changes in the normalization of a power law component of constant slope, which would cause an apparent change in hardness. Arguments very similar to the one above have been successfully applied to some sources (e.g. Fabian and Vaughan, 2003; Ponti et al., 2006; Zoghbi et al., 2010), and found to be inadequate in other cases (e.g. Taylor et al., 2003).

This was tested on long timescales in section 6.2 and it was shown that the observed variability on long timescales can be described by changes in the normalization, ionization, and reflection fraction exclusively. It was not possible to study the variability of the parameter values because both the reflection fraction and ionization were varying unsystematically. The only trend was that a combination of a high reflection fraction and low level of ionization was disfavored. However, this was also the case when $\Gamma$ was untied, as shown in the plots of $f_r$ and $\xi$ in figure A.1. Therefore, it is only possible to draw the conclusion that this scenario is possible, without excluding other options. It
Figure 7.1: The geometry of the black hole region in RX J1633+4718. A standard accretion disk that extends to the ISCO is observed (red to yellow). The results also support that RX J1633+4718 hosts a relativistic jet with a jet base or corona (gray). Partial obscuration is also observed (red).

should be noted that the argument applies to short timescales as well. Although, since the fit was difficult to constrain using all data, it was not attempted to use only the short, flux-selected spectra.

7.4 Geometry

The suggested geometry is illustrated in figure 7.1. Firstly, an accretion disk must be present in RX J1633+4718. It is clearly visible below 0.3 keV and both the temperature and magnitude are remarkably consistent with standard disk theory (Shakura and Sunyaev, 1973). When combining the observed temperature, mass and luminosity estimates it is possible to draw the conclusion that the accretion disk must extend to the ISCO of the black hole if it is non-rotating. This is in contrast with theories that suggest that the standard disk is truncated by an advection-dominated accretion flow close to the black hole in jet-launching AGNs, based on analogies with X-ray binaries.

Secondly, every spectrum also required a partial covering component. It is clearly seen in the X-ray spectra and is rather constant during all observations. Partial absorption have been observed in other sources and previous analysis shows that the absorbing medium likely is line-driven winds or more stationary clouds (e.g. Elvis et al., 2004; Puccetti et al., 2007) in the broad line region.

RX J1633+4718 is very radio loud and has been studied in radio (Doi et al., 2007; Gu and Chen, 2010; Doi et al., 2011). Doi et al. (2011) concludes that RX J1633+4718 emits a jet which is not relativistically beamed along the line-of-sight based on RX J1633+4718 having a steep radio spectrum. However, it has also been reported that the radio spectrum of RX J1633+4718 is flat (Yuan et al., 2008; Foschini et al., 2015). The inclination can probably be assumed to be small even though the radio data is inconclusive. This is
further supported by the properties of NLS1s being consistent with a face-on view of the accretion disk (Berton et al., 2016). Note that the X-ray spectra of RX J1633+4718 were harder when brighter, which is in line with the view that jet launching AGNs are harder when brighter, and conversely for AGNs without jets (Kataoka et al., 2008; Abdo et al., 2010; D’Ammando et al., 2011).

Disk reflection either require a low reflection fraction or highly ionized reflection medium. A low reflection fraction could possibly be explained by the jet emission being relativistically beamed away from the disk. Beaming is supported by jet-dominated AGNs often showing weaker soft excesses, but there are exceptions to this trend (e.g. D’Ammando et al., 2014). Lastly, it should be noted that high ionization levels ($\xi\sim1000$) have previously been reported for other RLNLS1s (e.g. Ghosh et al., 2016).

Little can be deduced about a potential corona in RX J1633+4718. There is no need for an additional non-thermal source besides the jet to describe the spectra, i.e. two distinct power law components are not seen in the spectra. Furthermore, if there is a corona, then reflection certainly would be expected and the reflecting medium would then have to be ionized. The distinction between base of jets and coronas is also not clear, i.e. there might be a corona which essentially is just the base of the jet.

### 7.5 RX J1633+4718 compared to other AGNs

The photon indices of the favored model are within the range 1.98–2.26, as seen in table 6.1. These values can be compared to those of other RLNLS1s in the survey by Foschini et al. (2015, their figure 2). It is clear that RX J1633+4718 is close to the average among RLNLS1s. This happens to be harder than most of the radio-quiet NLS1s (Grupe et al., 2010; Foschini et al., 2015) and a bit softer than many FSRQs (Donato et al., 2001; Foschini et al., 2015). Hard photon indices are normally interpreted as an additional indication of jet emission.

Furthermore, the harder-when-brighter trend is typically observed in jet-emitting AGNs (Kataoka et al., 2008; Abdo et al., 2010; D’Ammando et al., 2011) whereas AGNs that are not launching jets display the opposite trend (e.g. Lamer et al., 2003). Additionally, the harder-when-brighter trend is also observed in X-ray binaries when in their high state (e.g. Wu and Gu, 2008).

Weak reflection signatures are also common for jet-dominated AGNs (Kataoka et al., 2008; D’Ammando et al., 2014). This is could be because of relativistic beaming by the jet resulting in a majority of the radiation being directed away from the disk. Although, another explanation is that the reflecting material is highly ionized, which has been seen in other sources (e.g. D’Ammando et al., 2014; Ghosh et al., 2016). Reflection fractions cannot be compared since it was incorrectly computed prior to January 18, 2016 due to a bug in relxill.

The lack of soft excess is frequently observed in jet-launching AGNs, although, there are some exceptions where a soft excess is observed (Kataoka et al., 2008; D’Ammando et al., 2014; Ghosh et al., 2016). However, partial absorption was clearly necessary to describe the observed spectra of RX J1633+4718. This is in contrast with the RLNLS1s that are $\gamma$-ray-emitting (Kataoka et al., 2008; D’Ammando et al., 2012, 2014, 2015).

[http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/index.html](http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/index.html)
Hence, it is possible that the lack of soft excess in RX J1633+4718 might be due to absorption whereas other sources lack an excess intrinsically.

Whether or not the blackbody emission is unique to RX J1633+4718 is a difficult question to answer using only available literature. The most probably explanation is that the apparent uniqueness is because *ROSAT* data are used. A study of archival *ROSAT* data with modern observations will likely be able to settle this issue. Regardless of its origin, the excess in RX J1633+4718 detected by *ROSAT* fails to be adequately described by models without a blackbody component. In other words, some rare explanation must be invoked.

### 7.6 Future work

More detailed spectral fitting and spectral variability analysis of RX J1633+4718 can be performed if data quality allows. The flux-resolved spectral analysis is just the first step of time resolved spectral analysis. Further studies could investigate if the short term variability changes on long timescale, perhaps shedding some light on why X4 appears different. Absorption was just modeled using the most simple model, other possibilities include ionized absorption and absorption lines and edges \( \text{(Turner and Miller, 2009)} \). This could potentially reveal details about the absorbing material and the broad line region. Careful timing studies has proven to be a powerful method, which is capable of revealing disk reflection characteristics through lag signatures \( \text{(e.g. Zoghbi et al., 2010)} \). A suitable aim for future X-ray studies of RX J1633+4718 are closer scrutiny of the (lack of) soft excess and absorption, i.e. trying to determine the intrinsic strength of the soft excess. This is connected to the amount of reflection in the source, which in turn is related to the geometry and the underlying physical processes. Data above 10 keV could also help constrain reflection properties. Lastly, it is worth mentioning that the very prominent blackbody emission could allow for spin estimation if higher quality data is obtained below 0.3 keV.

Further study of accretion disks are necessary to fully understand the emission below 0.3 keV and solidify the current blackbody model. One of the main questions is why few blackbodies consistent with theory have been observed. The answer is probably a combination of blackbody masses and energy ranges of available instruments. A careful study of supermassive black holes with extremely low mass could offer new insights because the disk contribution would then become visible above 0.3 keV, where the current instruments have significantly higher spectroscopic capabilities. An alternative would be to systematically analyze archival data available below 0.3 keV, e.g. *ROSAT* observations. Although each individual spectrum might be insufficient for convincing conclusions, it might still be possible to survey a large sample. Modern observations could be fit simultaneously to help constrain models, analogous to this work. Though, variability might be an issue. It is worth emphasizing that once accurate measurements of disk emission can be performed reliably, it offers an independent method of mass or spin estimation.
Chapter 8

Summary and conclusions

An active galactic nucleus (AGN) is powered by accretion onto a supermassive black hole. They have been actively researched for a long time but several questions still remain unanswered. The accretion disk of infalling matter is expected to show a blackbody signature in soft X-rays and extreme ultraviolet, but observational evidence is relatively weak. This is further complicated by a so-called soft X-ray excess, which is evident in most sources. The origin is still under debate but significant progress has been made in recent years. Some AGNs emit powerful, relativistic particle jets which are launched from the innermost regions in the immediate vicinity of the black hole. The mechanics driving jets are not understood, so insights into the geometry and processes in the black hole region are of great importance.

RX J1633+4718 is a radio-loud narrow-line Seyfert 1 galaxy which has been analyzed using X-ray spectroscopy. Data from a total of nine observations were used, four by XMM-Newton and four by Suzaku in 2011 and 2012, and one by ROSAT in 1993. Convincing results show that the strong emission below 0.3 keV is consistent with theoretical predictions for a standard Shakura-Sunyaev thin disk. The X-ray spectra also clearly lacks a soft excess, primarily attributed to intrinsic partial covering absorption. Reflection features from the disk are not seen in the observed spectra. This can be caused by either intrinsically low amounts of reflection or a highly ionized reflecting medium. Short timescale variability can be explained by a single flux-proportional parameter. Whether the variations are caused by a pivoting power law, a combination of constant reflection and a variable power law normalization or more complex models cannot be distinguished. Variations on longer timescales are qualitatively analogous to those on short timescale with some exceptions, revealing additional complexity. Most of the results indicate that the observed X-ray emission from RX J1633+4718 is dominated by a jet that is beamed along the line-of-sight.

The results motivate further studies of accretion disk spectra in other sources. Once accurate measurements of disk emission can be made, it will be possible to perform independent mass or spin estimates. Details concerning the geometry are relatively difficult to constrain. Future observations will hopefully be able to disentangle highly ionized reflection from direct continuum emission, in which case conclusions can be drawn about whether or not effects such as beaming suppresses reflection.
Chapter 9

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Appendix A

Contour plots of reflection parameters

The contour plots of $\Delta \chi^2$ for $f_r$ and $\xi$ for all observations are shown in figure A.1.
Figure A.1: Contour plots of $\Delta \chi^2$ for $f_r$ and $\xi$ for S1 (upper) and X1 (lower) on $128 \times 128$ grids. Color scale shows $\Delta \chi^2$ according to the logarithmic colorbar. The periodic features are most likely due to \texttt{relxill} being a table model. The two other parameters which were allowed to vary were the photon index $\Gamma$ and reflection normalization $C_f$. The best fit values (orange dots) had a $\chi^2_{\text{red}}$ value of $2456/2345 = 1.05$ (all observations were fit together). The confidence contours are 68 % (red), 90 % (green), and blue 99 %. 

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Figure A.1: Continued, S2 (upper) and X2 (lower).
Figure A.1: Continued, S3 (upper) and X3 (lower).
Figure A.1: Continued, S4 (upper) and X4 (lower).
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