

On the hard X-ray spectra of radio-loud active galaxies

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ABSTRACT

Over the last few years X-ray observations of broad-line radio galaxies (BLRGs) by *ASCA*, *RXTE* and *BeppoSAX* have shown that these objects seem to exhibit weaker X-ray reflection features (such as the iron $K\alpha$ line) than radio-quiet Seyferts. This has led to speculation that the optically thick accretion disc in radio-loud active galactic nuclei (AGN) may be truncated to an optically thin flow in the inner regions of the source. Here, we propose that the weak reflection features are a result of reprocessing in an ionized accretion disc. This would alleviate the need for a change in accretion geometry in these sources. Calculations of reflection spectra from an ionized disc for situations expected in radio-loud AGN (high accretion rate, moderate-to-high black hole mass) predict weak reprocessing features. This idea was tested by fitting the *ASCA* spectrum of the bright BLRG 3C 120 with the constant density ionized disc models of Ross & Fabian. A good fit was found with an ionization parameter of $\xi \sim 4000 \text{ erg cm s}^{-1}$ and the reflection fraction fixed at unity. If observations of BLRGs by *XMM-Newton* show evidence for ionized reflection then this would support the idea that a high accretion rate is likely required to launch powerful radio jets.

Key words: radiative transfer – galaxies: active – galaxies: individual: 3C 120 – X-rays: galaxies – X-rays: general.

1 INTRODUCTION

In the standard disc–corona paradigm for the X-ray emission from active galactic nuclei (AGN), the hard X-ray source is energized within a magnetically dominated corona and illuminates the optically thick accretion disc below it (see Beloborodov 1999 for a recent review). The reprocessed emission from the disc imprints spectral features on the observed spectrum, most notably the Fe $K\alpha$ line (which may be broadened by relativistic effects; Fabian et al. 1989; Tanaka et al. 1995; Fabian et al. 2000) and a Compton reflection hump at about 20–30 keV due to the down scattering of higher energy photons (e.g., Pounds et al. 1990). By measuring the strength of these reflection features and comparing to models of X-ray reflection, it is possible, in principle, to constrain the solid-angle subtended by the reflector (as seen from the hard X-ray source), and hence the geometry of the accretion flow a few Schwarzschild radii away from the black hole. Thus, measurement of the X-ray reflection signatures is not only a valuable test for the disc–corona model, but also an important method to probe the central engines of AGN.

Over the last few years observations of radio-loud AGN, particularly broad-line radio galaxies (BLRGs), by *ASCA* and *BeppoSAX* have indicated that these sources may have weaker hard

X-ray reprocessing features than radio-quiet AGN at similar luminosities (e.g., Eracleous & Halpern 1998; Grandi et al. 1999, 2001; Eracleous, Sambruna & Mushotzky 2000). This has led some authors to speculate that the thin, optically thick accretion disc in radio-loud AGN changes to a hot, optically thin flow before reaching the black hole. Similar conclusions have also been drawn about Galactic black hole candidates in their low/hard state: they also appear to exhibit weaker reflection features than expected if the standard accretion disc extends down to the last stable orbit (e.g., Życki, Done & Smith 1997, 1998, 1999; Done & Życki 1999). Moreover, strong radio emission from black hole candidates tends to be seen only when they are in their low/hard state (Fender 2001). A truncated disc in radio-loud objects has also been supported by the recent theoretical work of Meier (2001) who considered the strength of the poloidal magnetic field component expected in a standard Shakura & Sunyaev (1973) disc as compared to one in an ADAF-like flow (e.g., Narayan & Yi 1995). He concluded that only the combination of a rapidly spinning black hole and a geometrically thick accretion flow (i.e., an ADAF) could produce the required jet power for a radio-loud AGN.

However, the problem of accurately determining the amount of reflection in an X-ray spectrum depends on the sophistication of the reflection models available to fit the data. Over the past 10 years numerous calculations of X-ray reflection from Compton thick matter have been performed to compare against the data (e.g., Ross

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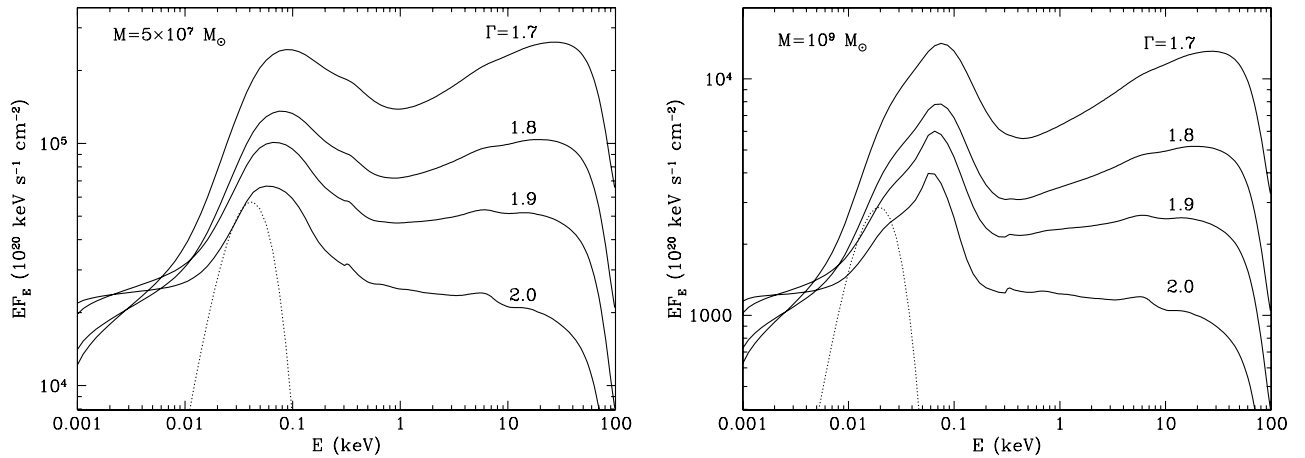


Figure 1. Computed ionized reflection spectra from an irradiated radiation-pressure dominated accretion disc accreting at 0.25 of its Eddington rate. The disc is illuminated at a distance of four Schwarzschild radii from the black hole with $F_x/F_{\text{disc}} = 10$. (Left) Results for a $5 \times 10^7 M_\odot$ black hole. (Right) Results for a $10^9 M_\odot$ black hole. In both cases the spectra exhibit very weak reflection features. The dotted lines denote the soft X-ray flux from the disc incident on the bottom of the atmosphere. The spectra have been vertically offset for clarity.

& Fabian 1993; Życki et al. 1994; Magdziarz & Zdziarski 1995; Ross, Fabian & Young 1999; Nayakshin, Kazanas & Kallman 2000; Ballantyne, Ross & Fabian 2001b). These computations have increased in sophistication over the years: first relaxing the assumption of neutral material and then enforcing the condition of hydrostatic balance on the illuminated material.

Ionization effects can have an important impact on the shape of the reflection spectrum and on the features imprinted on it (Ross et al. 1999). In fact, if the disc surface is highly ionized the reflection features become very weak, and if not taken into account, *a low reflection fraction can be measured*. Such ionized disc models have been shown to account for the measured low reflection fractions in Cyg X-1 (Young et al. 2001) and the black hole transient Nova Muscae (Done & Nayakshin 2001b). If this is the case, there is no need for a truncated optically thick accretion disc in these sources and any jet emission would then arise from a standard disc that extends down to the last stable orbit. However, the inner parts of the disc would be highly ionized, likely as a result of extreme irradiation from the corona, and possibly radiation-pressure dominated.

In this Letter, we investigate the idea that the low reflection fractions measured in the hard X-ray spectra of radio-loud AGN are simply the result of reprocessing from an ionized accretion disc. In the next section we calculate the reflection spectra from ionized discs which may be appropriate for radio-loud AGN, and show that they will exhibit weak reflection features. In Section 3 we apply ionized disc models to the *ASCA* spectrum of the BLRG 3C 120. Finally, we conclude by arguing that, in light of recent results on the radio power of active galaxies, ionized accretion discs should exist in most broad-line radio galaxies.

2 MODELS OF IONIZED REFLECTION

In this section we use the code presented by Ballantyne et al. (2001b) to compute examples of reflection spectra from an irradiated disc within a typical radio-loud AGN. Details of the numerical procedures may be found in Ballantyne et al. (2001b) and references therein. The simulations model the outer layers of an accretion disc which is illuminated by a power-law continuum of X-rays. This external radiation extends from 1 eV to a sharp cut-off at 100 keV and is parametrized by a photon-index Γ (so that

photon flux $\propto E^{-\Gamma}$). The gas structure is computed as a function of depth at a single point on the disc. Once the irradiated material has relaxed into thermal, ionization and hydrostatic balance, the reprocessed spectrum is computed.

As discussed in Section 4, recent observational evidence suggests that radio-loud AGN are likely accreting at a significant fraction of their Eddington rate. Therefore, we have modelled a radiation-pressure dominated disc accreting at 0.25 of its Eddington rate. At these high rates, standard theory (Shakura & Sunyaev 1973) predicts that the disc is puffed-up and the surface layers quite tenuous, so the calculations covered the outer 15 Thomson depths of the atmosphere in order to fully resolve the effects of the illumination. The irradiating flux was chosen to be 10 times that of the soft flux emitted by the disc (as might be expected from a magnetic flare event; Nayakshin & Kallman 2001), and strikes the surface of the atmosphere 4 Schwarzschild radii from the black hole and at an angle of $i = 54.7^\circ$ to the normal (so that $\cos i = 1/\sqrt{3}$, a crude approximation to isotropic radiation). To simulate situations appropriate for both the lower luminosity broad-line radio galaxies and radio-loud quasars, models were run with black hole masses of $5 \times 10^7 M_\odot$ and $10^9 M_\odot$.

Reflection spectra were calculated for illuminating power laws with $\Gamma = 1.7, 1.8, 1.9$ and 2.0 , and they are shown in Fig. 1. The plots show that the reflection spectra exhibit very weak reflection features as a result of the atmosphere being highly ionized by the incident radiation. In fact, in all the calculations Fe is fully stripped to at least 5 Thomson depths into the atmosphere. Therefore, Fe $K\alpha$ photons have to traverse a significant scattering layer before escaping. The Fe K edge feature also suffers from Compton scattering and so the Compton reflection hump at 20–30 keV becomes much less prominent. As was shown by Done & Nayakshin (2001a) and Ballantyne et al. (2001b), when such highly ionized spectra are modelled by neutral reflection models then low reflection fractions are easily obtained.

Although the X-ray data collected so far on broad-line radio galaxies indicates that such extreme ionization is not needed (see Section 3), it seems likely that weak reflection features are to be naturally expected from a highly accreting object.¹ It should be

¹ Results for a wider range of accretion rates are shown by Ballantyne et al. (2001b), and are consistent with the ones presented here.

pointed out, however, that this conclusion will depend on the strength of the illuminating radiation and on the disc structure. If the disc is weakly irradiated (i.e., the ratio of incident flux to disc flux $\lesssim 1$) then there will likely be strong ionized or neutral features in the reflection spectrum (Ballantyne & Ross 2002). Also, at high accretion rates the surface of the disc may become clumpy and inhomogeneous which may enhance the strength of the reflection features (Fabian et al. 2002).

3 APPLICATION OF IONIZED DISC MODELS TO 3C 120

To test whether ionized reflection models actually do fit the data of a radio-loud AGN, we downloaded the *ASCA* data of the BLRG 3C 120 from the Tartarus data base. 3C 120 ($z = 0.033$) is the brightest BLRG in the X-ray sky ($F_{2-10\text{keV}} \approx 4.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$; Sambruna, Eracleous & Mushotzky 1999), and its X-ray properties are typical for its class, i.e., controversial. The 1994 50-ks observation of 3C 120 by *ASCA* clearly showed an Fe $K\alpha$ line (see Fig. 2), but despite five different analyses of this data set there has been no consensus on the strength of the line. Workers who modelled the continuum as an absorbed power law (Reynolds 1997; Sambruna et al. 1999) consistently found the line to be very broad ($\sigma > 1.5 \text{ keV}$) and very strong (equivalent width [EW] $\sim 1000 \text{ eV}$). If, however, the continuum was modelled with reflection (Grandi et al. 1997) or with a broken power law (Woźniak et al. 1998), the line width and EW dropped by over a factor of two. Recent observations of 3C 120 by *RXTE* (Eracleous et al. 2000) and *BeppoSAX* (Zdziarski & Grandi 2001) have provided some consistency by requiring reflection to fit the continuum and obtaining an Fe $K\alpha$ EW $\sim 100 \text{ eV}$. Thus, previous work has shown that 3C 120 has a curved X-ray continuum with spectral hardening at high energies and an Fe $K\alpha$ line which may be broad.

The reflection models that have been previously fit to 3C 120 have assumed that the reprocessor is neutral and have all yielded reflection fractions smaller than unity. This result, combined with the weak Fe $K\alpha$ line, has been used as evidence for the claim that the accretion disc is disrupted in radio-loud AGN (Eracleous et al.

2000). However, as mentioned above, if the reprocessor is ionized then the reflection features are naturally weak, and there is no need for a change in accretion geometry. To test this hypothesis we fit the *ASCA* data of 3C 120 with the constant density ionized disc models of Ross & Fabian (1993) (see also Ross et al. 1999). Data between 0.8 and 10 keV from both Solid state Imaging Spectrometers (SIS-0 and SIS-1) and between 1 and 10 keV from both Gas Imaging Spectrometers (GIS-2 and GIS-3) were fitted simultaneously. The Galactic column of $1.23 \times 10^{21} \text{ cm}^{-2}$ was included in all fits. The reflection spectrum was relativistically blurred assuming that the emission arises between 10 and 1000 gravitational radii. The inclination angle was fixed at 14 degrees, as derived from observations of the radio jets (Zensus 1989, but see Wehrle et al. 1992 and Walker, Walker & Benson 1988). We obtained a good fit ($\chi^2 = 1494$ for 1437 d.o.f.) with the following parameters: $N_{\text{H}}^{\text{intrinsic}} = (5.92 \pm 0.89) \times 10^{20} \text{ cm}^{-2}$, $\log \xi = 3.621_{-0.049}^{+0.054}$, and $\Gamma = 1.875 \pm 0.015$, where ξ is the ionization parameter of the gas. The residuals to the fit and the ionized reflection model are shown in Fig. 2. The continuum parameters and EW of the Fe $K\alpha$ line ($\sim 580 \text{ eV}$) are comparable to the results of Grandi et al. (1997). Most importantly, our result is with the *reflection fraction fixed at 1*. This implies that there is no need for a truncated accretion disc in 3C 120.

The *RXTE* and *BeppoSAX* observations of 3C 120 both suggest weaker Fe $K\alpha$ lines with EWs $\sim 100 \text{ eV}$ (Eracleous et al. 2000; Zdziarski & Grandi 2001). While the *ASCA* data analysed here has higher signal-to-noise ratio and spectral resolution around 6 keV than these other data, it lacks the spectral coverage at energies greater than 10 keV which is provided by these other telescopes. A comparison between all three data sets is shown by Zdziarski & Grandi (2001, their fig. 4). There it can be seen that the shape of the *ASCA* spectrum is consistent with the *RXTE* and *BeppoSAX* data, suggesting that the ionized disc model would be applicable to these other data sets. The difference in Fe line strength may be in part owing to differences in modelling the continuum. Eracleous et al. (2000) do not take in account ionized reflection and Zdziarski & Grandi (2001) cannot deal with highly ionized discs (they assume a reflector temperature of 10^5 K , but the best-fitting slab has a surface temperature of 10^7 K). Another explanation for the

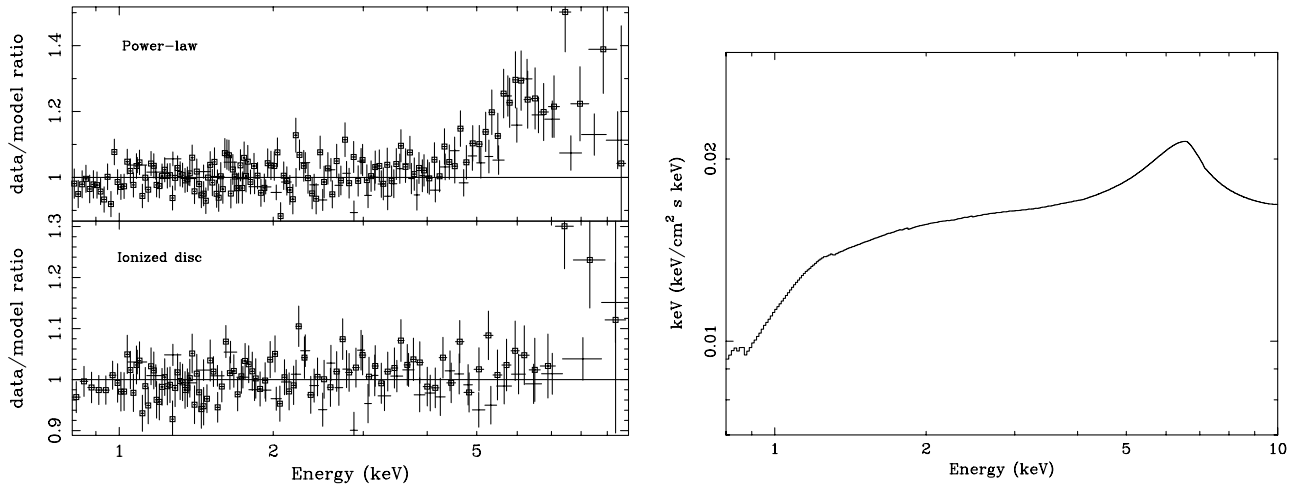


Figure 2. (Left) Data-to-model ratios for both an absorbed power-law fit (ignoring the data between 4 and 8 keV) and the best-fitting ionized reflection model to 3C 120. Open symbols denote data from the SIS-0 detector, while the points are data from the GIS-3. There does seem to be some spectral hardening at high energies that is not explained by the disc model. (Right) Ionized disc model of 3C 120 as fit to the 1994 *ASCA* data. The reflector is fairly highly ionized with $\log \xi = 3.621_{-0.049}^{+0.054}$, so the Fe $K\alpha$ line arises from He-like iron and has an EW of about 580 eV. The reflection fraction was *fixed* at unity, and solar abundances were assumed.

difference in EWs is that 3C 120 was brighter by about 50 per cent (in the 2–10 keV band) during the *RXTE* and *BeppoSAX* observations than in the *ASCA* observation (again see fig. 4 in Zdziarski & Grandi 2001). If the Fe $K\alpha$ line flux remains relatively constant, as it is observed to be in some Seyfert 1 galaxies (e.g., NGC 5548, Chiang et al. 2000; MCG–6–30–15, Lee et al. 2000), then the EW would be smaller in these later observations.

The ratio plot shown in Fig. 2 indicates that there is possible spectral hardening at high energies not accounted for by the reflection model. This may be due to dilution from the radio jets which could be particularly relevant for 3C 120 as it has a superluminal jet. Contamination from jet emission would also weaken any reflection features. However, it is unclear whether or not the jet dominates the high-energy emission of 3C 120. Although the object was detected at ~ 100 keV by OSSE (Johnson et al. 1994), it was not picked up by either Comptel or EGRET (all on the *CGRO*) at MeV energies. At much lower energies, Grandi et al. (1997) claimed to detect with *ROSAT* a variable soft-excess in 3C 120, as did Zdziarski & Grandi (2001) with *BeppoSAX*. If 3C 120 does have a soft-excess, then it is unlikely jet contamination would be important at energies < 10 keV, and an ionized disc is a valid model for the spectrum over this band. A more precise determination of the spectrum of 3C 120 requires an *XMM-Newton* observation.

4 DISCUSSION

In this Letter we have presented the idea that the weak reprocessing features seen in the *ASCA* spectra of many radio-loud AGN are the result of reflection off an ionized disc. With this explanation there does not need to be a significant difference in the accretion geometry between radio-loud and radio-quiet sources. This conclusion is supported by evidence that the traditional bimodal distribution in radio power of AGN is no longer valid. Lacy et al. (2001) used results from the FIRST Bright Quasar Survey to fill in the gap between the radio-quiet and radio-loud populations, and concluded there was a continuous distribution of radio-power that is correlated with both black hole mass and accretion rate. Similarly, Ho & Peng (2001) employed high-resolution radio and optical imaging of Seyfert galaxies to show that many of these objects that were thought to be radio-quiet are actually radio-loud (using the $R \equiv L_\nu(6\text{ cm})/L_\nu(B) > 10$ definition; Visnovsky et al. 1992). These authors also argued that there is a radio power–optical luminosity correlation in active galaxies that stretches from Seyfert galaxies up to luminous quasars.

There still remains the problem that only a small percentage of AGN exhibit powerful, kpc-scale radio jets. The results of Lacy et al. (2001) suggest that a combination of high accretion rate and large ($> 10^{8.5} M_\odot$) black hole mass is required to launch ultra-relativistic jets. The radio luminosity–optical luminosity correlations² discussed by Ho & Peng (2001) also point toward an accretion rate dependence. The actual physical mechanism responsible for the radio emission and jets presumably is a magnetohydrodynamic coupling between the accretion flow and a spinning black hole (e.g., Blandford & Znajek 1977; Macdonald & Thorne 1982; Rees et al. 1982; Begelman, Blandford & Rees 1984; Li 2000a,b), but the details are far from worked out (e.g., Ghosh & Abramowicz 1997; Livio, Ogilvie & Pringle 1999; Meier 1999, 2001). However, the key parameters must be the black hole mass

and accretion rate because it is likely that rapidly spinning black holes are found in many AGN, irrespective of their radio power (e.g., MCG–6–30–15, Iwasawa et al. 1996, 1999; Wilms et al. 2001). Indeed, studies of the hard X-ray background suggest that most supermassive black holes are rapidly spinning (Fabian & Iwasawa 1999; Elvis, Risaliti & Zamorani 2002). Perhaps only rapid accretion on to a very massive spinning black hole can provide the necessary energy to launch kpc-scale radio jets.

However, observational evidence suggests that at least one more parameter other than the black hole mass and the accretion rate is needed to explain the triggering of powerful jets. Recent *XMM-Newton* observations of some high-luminosity radio-quiet Seyferts have shown evidence for ionized Fe $K\alpha$ lines (Reeves et al. 2001; Pounds et al. 2001; Orr et al. 2001), indicating that the accretion disc is becoming more ionized as the luminosity and, likely, the accretion rate increases (Ballantyne & Ross 2002). A widening zone of extreme ionization on the accretion disc would also explain the *ASCA* observations of radio-quiet quasars which found that the EW of the Fe $K\alpha$ line becomes undetectable at a 2–10 keV luminosity of $10^{46} \text{ erg s}^{-1}$ (the so-called X-ray Baldwin effect; Iwasawa & Taniguchi 1993; Nandra et al. 1997; Reeves & Turner 2000). Although most of these quasars have an accretion rate close to Eddington and black hole masses $> 10^8 M_\odot$ (e.g., Lacy et al. 2001), they do not possess powerful radio jets. Therefore, additional quantities, such as the magnetic field strength and configuration close to the black hole, must also be important in determining the strength of the radio jets.

Nevertheless, it is possible that the weak X-ray reprocessing features from radio-loud sources provide corroborating evidence that a high accretion rate is important for the production of powerful jets. Ultrasoft Seyferts (the subset of narrow-line Seyfert 1 galaxies with unusual X-ray properties; Brandt 1999; Leighly 1999a,b; Vaughan et al. 1999b) which are likely accreting close to their Eddington limit, have shown evidence for ionized accretion discs in their X-ray spectra (Comastri et al. 1998, 2001; Turner, George & Nandra 1998; Vaughan et al. 1999a; Ballantyne, Iwasawa & Fabian 2001a; Turner et al. 2001a,b). These objects would not exhibit large-scale radio jets because they do not have massive enough black holes, or, perhaps, massive enough bulges to contain an extensive reservoir of gas. Therefore, if the weak X-ray reflection features in radio-loud AGN are due to ionization effects, then it is likely to be a result of their high accretion rate, supporting the view that a large accretion rate is required for the production of relativistic jets. High quality spectral observations of radio-loud AGN by *XMM-Newton* will be able to test this hypothesis.

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² The correlations seem to exist for both radio-loud and radio-quiet objects, but with the slope being steeper for the radio-loud ones.

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