How the X-ray spectrum of a Narrow-Line Seyfert 1 galaxy may be reflection dominated

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ABSTRACT
A model for the inner regions of accretion flows is presented where, due to disc instabilities, cold and dense material is clumped into deep sheets or rings. Surrounding these density enhancements is hot, tenuous gas where coronal dissipation processes occur. We expect this situation to be most relevant when the accretion rate is close to Eddington and the disc is radiation-pressure dominated, and so may apply to Narrow-Line Seyfert 1 (NLS1) galaxies. In this scenario, the hard X-ray source is obscured for most observers, and so the detected X-ray emission would be dominated by reflection off the walls of the sheets. A simple Comptonization calculation shows that the large photon-indices characteristic of NLS1s would be a natural outcome of two reprocessors closely surrounding the hard X-ray source. We test this model by fitting the XMM-Newton spectrum of the NLS1 1H 0707–495 between 0.5 and 11 keV with reflection dominated ionized disc models. A very good fit is found with three different reflectors each subject to the same \( \Gamma = 2.35 \) power-law. An iron overabundance is still required to fit the sharp drop in the spectrum at around 7 keV. We note that even a small corrugation of the accretion disc may result in \( \Gamma > 2 \) and a strong reflection component in the observed spectrum. Therefore, this model may also explain the strength and the variability characteristics of the MCG–6–30–15 Fe K\(_\alpha\) line. The idea needs to be tested with further broadband XMM-Newton observations of NLS1s.

Key words: accretion, accretion discs – line: formation – galaxies: active – X-rays: galaxies – X-rays: general – galaxies: individual: 1H 0707–495

1 INTRODUCTION

The basic model for the active nucleus of a typical Seyfert 1 galaxy consists of a black hole surrounded by an ultraviolet and soft X-ray emitting thin accretion disc above which a patchy active corona emits hard X-rays. The model is supported by strong X-ray reflection signatures due to Compton backscattering and fluorescence of the harder coronal X-rays by the dense disk (Pounds et al. 1990; Nandra & Pounds 1994; Petrucci et al. 2000). In some objects an extreme red wing is found in the iron line of the reflection spectrum (Tanaka et al. 1995; Nandra et al. 1999; Fabian et al. 2000), showing that the disk can extend very close to the black hole where large relativistic effects occur. In general the strength of the reflection spectrum indicates that the disk surface is approximately flat, although disk instabilities could well make it ribbed or clumpy, particularly if the disk is radiation-pressure dominated (e.g., Lightman & Eardley 1974; Guilbert & Rees 1988; Krolik 1999; Turner, Stone & Sano 2001). Such a situation is most likely to occur when the accretion rate is high and close to the Eddington limit, which is often thought to explain the unusual properties of Narrow-Line Seyfert 1 (NLS1) galaxies (e.g., Pounds, Done & Osborne 1995).

Recently, Boller et al. (2002) reported on a “sharp spectral feature” at about 7.1 keV in the XMM-Newton spectrum of the NLS1 1H 0707–495 (\( z = 0.0411 \)). This deep drop (over a factor of two in flux) in the spectrum occurs at almost the exact energy of the neutral iron edge, so absorption models (in particular, a partial covering model) were favoured to explain the feature. However, these models suffered from a very soft intrinsic power-law (\( \Gamma \sim 3.5 \)) and an unreasonably large value of the iron abundance (\( \sim 35 \times \) solar). Moreover, it was difficult for the partial covering model to account for the absence of a narrow Fe K\(_\alpha\) line and to explain the rapid variability of the source over the entire waveband. The sharp drop in the spectrum could also be due to the blue wing of a relativistic iron emission line, but, as the authors noted, to explain the depth of the drop at \( \sim 7 \) keV requires “invoking a very extreme Fe abundance and/or reflection fraction.” Here, we consider the possibility of a reflection dominated X-ray spectrum in detail.

The basic idea we wish to explore is that within a system which is accreting at close to the Eddington rate, disc instabilities funnel denser material into many deep rings, between which the hard X-rays are emitted by some coronal process (Figure 1).
We consider two such discs facing each other and separated by a distance $d$. The hot phase is sandwiched by the two cold discs and therefore has a cylindrical slab geometry. From a point in the mid-plane of the cylinder, at a distance $r$ from its centre, the covering fraction of the two cold sheets is

$$C(r) = \left[1 - \frac{1}{2} \left(\frac{1}{1 + \frac{4(R-r)^2}{d^2}} + \frac{1}{1 + \frac{4(R+r)^2}{d^2}}\right)\right]. \quad (1)$$

The average total covering fraction is then given by

$$C = \frac{1}{R} \int_0^R C(r) dr = 1 - \frac{d}{4R} \log \left(\frac{4R}{d} + \sqrt{1 + \frac{16R^2}{d^2}}\right). \quad (2)$$

With the hard luminosity of the hot phase being $L_H$, the reprocessed luminosity is given by

$$L_{rep} = C L_H (1 - \alpha), \quad (3)$$

where $\alpha$ is the albedo of the cold sheets. We make use of the results of Malzac, Beloborodov & Poutanen (2001) who used Monte Carlo simulations of Comptonizing coronae above dense cold material and showed that the albedo depends on the spectral index of the illuminating radiation, being smaller for steep spectra. The thermal reprocessed soft photon flux from the cold sheets is assumed to be a black-body spectrum with temperature $T_{bb,rep}$ and is calculated by the method outlined by Merloni & Fabian (2001). The hard luminosity is assumed to be due only to inverse Compton scattered photons and can be approximated as a sum of a cut-off power-law and Wien component (Wardziński & Zdziarski 2000).

The emerging spectral index of the power-law is given by

$$\Gamma - 1 = \alpha = -\frac{\ln P_{sc}}{\ln(1 + 4\Theta + 16\Theta^2)}, \quad (4)$$

where $\Theta = kT_e/m_e c^2$ is the electron temperature of the hot phase, and $P_{sc}$ is the scattering probability averaged over the source volume and depends only on the coronal optical depth $\tau$. In a slab geometry $P_{sc}$ can be approximated as (Zdziarski 1994)

$$P_{sc} = 1 + \frac{\exp(-\tau)}{2} \left(\frac{1}{\tau} - 1\right) = -\frac{1}{2\tau} + \frac{\tau}{2} E_1(\tau), \quad (5)$$

where $E_1$ is the exponential integral.

Once the geometry is fixed (by fixing the aspect ratio $R/d$), the temperature of the hot phase, and consequently the slope of the Comptonized continuum, can be calculated self-consistently by solving $L_H = L_C = \int_{2.786r_{rep}}^{\infty} L_C(x) dx$. We have calculated the spectral index $\Gamma$ for different values of the ratio $R/d$ and in Figure 2 we plot the spectral index for three different values of the optical depth of the hot phase. Clearly, as the covering fraction increases, the spectrum softens significantly. Also, the spectrum is steeper for a denser hot medium (larger $\tau$). Finally, if there is accretion energy dissipated in the cold phase, then the spectrum will be softer for a given $R/d$ (c.f., Malzac 2001).

Figure 3 shows an equivalent plot where the abscissa is now the half opening angle between the two reprocessors $\theta/2$. These plots show that spectral indices typical of NLS1s (i.e., $\Gamma > 2.1-2.2$) are a natural consequence of this scenario if the half opening angle between the two reprocessors is less than about 20 degrees. In such a case, it is likely that a observer may only detect the reflected emission arising from the walls of the reprocessors.


3 APPLICATION TO THE NLS1 1H 0707–495

In this section, we attempt to fit the broadband X-ray spectrum of the NLS1 1H 0707–495 with models of reflection dominated spectra, which might be expected if the accretion disc has broken into a number of dense segments (Fig. 1). We consider the EPIC-pn spectrum of 1H 0707–495 between 0.5 and 11 keV and fit with the constant density ionized disc models of Ross & Fabian (1993) (see also Ross, Fabian & Young 1999). The parameters of the model are the ionization parameter $\xi = 4\pi F_X/n_H$, where $F_X$ is the illuminating flux between 10 eV and 100 keV, the photon index of the power-law spectrum that strikes the slab, and a normalization constant. Relativistic blurring was applied to the model during fitting using the kernel of Laor (1991). The emissivity index was fixed at $g = 1$.

Figure 2. The spectral index $\Gamma$ as a function of the aspect ratio $R/d$, for $\tau = 0.1$ (solid line), $\tau = 1$ (dashed line) and $\tau = 10$ (dot-dashed line).

Figure 3. The spectral index $\Gamma$ as a function of the half opening angle of the couple of disc-like cold sheets for $\tau = 0.1$ (solid line), $\tau = 1$ (dashed line) and $\tau = 10$ (dot-dashed line).

The model predicts strong emission lines from Fe and O (Ross & Fabian 1993). To dilute the effect of these lines, a power-law was added to the model with the value of $\Gamma$ fixed to be the same as the reflected component. Reflection still dominated the spectrum with a reflection fraction $> 10$. The power-law improved the best fit to $\chi^2$/d.o.f. = 79/308, but required an Fe abundance greater than 5 times solar. In this fit, $\Gamma$ softened slightly to 2.52, but there was little change in the ionization parameter, the inner and outer radii, or the inclination angle ($\sim 23$ degrees). There are still residuals below 1 keV, but, interestingly, there is now a clear line-like residual just above 6 keV. Adding a Gaussian to the fit drops the $\chi^2$ by 38 with the addition of three degrees of freedom – significant at $> 99.99$ per cent, according to the F-test. Here, the best-fit model has a seven times overabundance of Fe, and $\Gamma = 2.56$. The line had an energy of 6.62 keV and a width $\sigma = 0.235$ keV, indicating that it probably also arises from somewhere in or on the disk.

To investigate this further, the power-law and Gaussian components of the model were replace by a second reflector. The second reflection component was drawn from the same group of models as the first, and was also subject to relativistic blurring. We fixed the photon-index and inclination angle to be the same for both components. The addition of this second reflector greatly improved the fit ($\chi^2$/d.o.f. = 342/305), as the combined emission removed most of the residuals from the soft X-ray band, and now only a five times overabundance of Fe was required. The ionization parameter of the second component is $\log \xi = 3.397$ resulting in a strong He-like Fe K$\alpha$ line at 6.7 keV and an inner radius of $5.4 \, r_g$. The other reflector remained relatively neutral with $\log \xi = 2.09$ and strongly blurred ($r_{in} = 1.24 \, r_g$). The photon-index flattened slightly to $\Gamma = 2.41$. While this fit is almost acceptable there is still a line-like residual above 6 keV. Adding a Gaussian component to account for this feature significantly improves the fit ($\chi^2$/d.o.f. = 292/302). This new line has an energy of 6.45 keV and a width of 0.358 keV, demonstrating that the line arises from weakly ionized Fe in the accretion disc.

The two-reflector plus Gaussian emission line model gives a very good fit to the EPIC-pn data between 0.5 and 11 keV, however it is interesting to consider replacing the line component with a third reflection spectrum. This model also results in an excellent fit to the data ($\chi^2$/d.o.f. = 287/308; Figure 4), but requires a 7 times solar abundance of Fe. The three components all have different ionization parameters: $\log \xi = 1.986$ (with $r_{in} = 2.08 \, r_g$ and $r_{out} = 7.25 \, r_g$), 3.847 (with $r_{in} = 4.18 \, r_g$), and 1.722 (with...
4 DISCUSSION

We have shown that the X-ray spectrum of 1H 0707–495 is well fitted by a reflection-dominated spectrum. The incident power-law is mildly steep with a photon index of 2.35. Furthermore, the model can completely account for the strong soft excess in this object by a combination of blurred emission lines and thermal emission from the irradiated blobs. The geometry envisaged for the source consists of a set of deep dense sheets or rings, orbiting the central black hole. The geometry may also account for larger scale variations. When observed by XMM-Newton, 1H 0707–495 was about ten times fainter than in previous observations (Boller et al. 2002). This could be due to slight changes in the geometry and not necessarily a large change in intrinsic luminosity. If the hard X-ray source was previously more directly visible (say the opening angle of the sheets or rings was larger, or the hard X-ray emitting corona extended nearer to the disk surface) then the observed flux would have been larger. Indeed, the spectrum observed by ASCA when the flux was higher (Γ ≃ 2.27, Leighly 1999), is consistent with being the unobscured continuum emission peeking through the cold sheets.

It is possible that the model we have developed here for 1H 0707–495 has a wider relevance to Seyfert 1 galaxies. The reflection fraction can exceed unity if the disk is in the form of deep rings or sheets, and leads to an intrinsic hard power-law steeper than Γ = 2. MCG–6-30-15 has sometimes been observed with a spectral index of 2.1 or steeper (Vaughan & Edelson 2001). This could be due to corrugations in its inner disk which may cause the reflection components to be stronger and more long-lasting than if the accretion disc was perfectly flat.

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