The origin of the soft excess in high $L/L_{Edd}$ AGN

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We discuss the origin of the soft X–ray excess seen in AGN. There are clear advantages to models where this arises from atomic processes in partially ionised material rather than where it is a true continuum component. However, current data cannot distinguish between models where this material is seen in reflection or absorption, even for the archetypal ‘reflection dominated’ AGN MCG–6–30–15. Instead, we give physical arguments on the ionisation structure of X–ray illuminated material which exclude a reflection origin if the disc is in hydrostatic equilibrium. The same physical processes strongly favour an absorption origin for the soft excess, giving a more messy picture of the accretion environment. This implies that these apparently ‘reflection dominated’ AGN are not good places to test GR, but they do give insight into the spectra expected from the first QSO’s in the early Universe.

§1. Introduction

Many high mass accretion rate AGN show X–ray spectra which rise smoothly below 1 keV above the extrapolated 2–10 keV emission,$^1$ equivalent to a fixed temperature of $\sim 0.1 - 0.2$ keV. This is far too high a temperature to be simply the high energy tail of the accretion disc emission, and its lack of relation to the underlying disc temperature argues strongly against it being Compton scattered disc emission.$^2$ The apparently fixed temperature is much easier to explain if it arises from atomic rather than continuum processes. One potential physical association is with the large increase in opacity between 0.7–3 keV due to OV II/OVIII and Fe L shell absorption. However, the soft excess is observed to be fairly featureless, so if it is atomic in origin then there must be a strong velocity shear in order to Doppler smear the characteristic atomic features into a pseudo–continuum.

Partially ionised material with a strong velocity shear can produce the soft excess in two different geometries, one where the material is optically thick and out of the line of sight, seen via reflection (e.g. from an accretion disc). Alternatively, the material can be optically thin and in the line of sight, seen in absorption (e.g. a wind above the disc). We discuss each of these possibilities in detail below, but show that the model degeneracies mean that both can fit the data even of the archetypal ‘reflection dominated’ AGN MCG–6–30–15.

Instead we use physical arguments on the 'fine tuning' of the ionisation parameter to show that the absorption model is strongly favoured, and that reflection from a hydrostatic disc cannot produce the soft X–ray excess$^3$.

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§2. Reflection

The increase in absorption opacity between 0.7–3 keV means a decrease in reflection between these energies, or equivalently, a rise in the reflected emission below 0.7 keV, producing a soft excess. This continuum reflection is enhanced by emission lines from the partially ionised material, especially OVII/VIII Ly α at 0.6–0.7 keV as well as Lyα lines from C,N and Fe L transitions. Such optically thick reflection from material in the inner disc is strongly smeared by the disc velocity field and such models can match the shape of the soft excess. Importantly the parameters required for the relativistic smearing of the soft excess can be the same as those required to produce the associated iron Kα line emission, though objects with the highest signal-to-noise require multiple reflection components to fit the spectra\(^{5−8}\).

However, the parameters derived from these models can be uncomfortably extreme, with the amount of smearing implying extreme Kerr spacetime, with perhaps also extraction of the spin energy of the black hole\(^{8,9}\). Also, the size of the soft X-ray excess can be much larger than expected for a reflection origin with isotropic illumination\(^{10}\). The objects with these large soft X-ray excesses then require anisotropic illumination models, e.g. where the X-ray source is extremely close to the black hole so that lightbending suppresses the observed direct continuum flux and enhances the disc illumination. Alternatively, the disc might fragment into inhomogeneous regions which hide a direct view of the intrinsic source flux\(^{5,6}\). These reflection geometries are sketched in the middle panel of Fig 1.

MCG–6–30–15 is the archetypal object which shows all these features. The left panel of Fig 1 shows the XMM data for this object, deconvolved with an intrinsic power law, its reflection from two different ionisation and velocity smeared reflectors both with twice solar iron abundance, an additional narrow neutral iron line, and three narrow warm absorber systems to account for the complex absorption seen at low energies\(^{11}\). This fits the data (\(\chi^2 = 2327.2/1874\)) but requires that the intrinsic power law (with \(\Gamma = 2.17\)) is not visible, and that one of the reflectors has extreme smearing (\(r_{in} = 1.28, r_{out} = 3.5\), with highly centrally concentrated emissivity\(^{9}\)).

Fig. 1. The spectra in the left and right hand panels show the deconvolved XMM-Newton data from MCG–6–30–15 using the reflection and absorption models, respectively. The middle panel shows sketch geometries for a reflection dominated system (lightbending and disc fragmentation) compared to absorption in an outflow from the disc.
Absorption

The same physical process of the opacity increase between 0.7–3 keV can also produce the soft excess via absorption, plausibly from a wind from the accretion disc,\textsuperscript{2} as sketched in Fig 1. Again, relativistic velocity shear is required to smear out the characteristic atomic features into a pseudo–continuum but the difference between here is that these motions are no longer Keplarian, so cannot be used to simply infer the inner disc radius (and hence black hole spin).

The right hand panel of Fig 1 shows this model fit to the XMM-Newton data. The model description is the same as for the reflection fits, except that one of the smeared reflectors is replaced with the smeared absorption model, and there is no need for an additional narrow iron line. This gives a similarly good fit to the data ($\chi^2 = 2215.6/1877$) but now the intrinsic power law is seen ($\Gamma = 2.31$), and the remaining reflector has $\Omega/2\pi = 0.5$ and is not extremely smeared ($R_{\text{in}} = 25$, with emissivity consistent with the expected gravitational energy release i.e. $\propto r^{-3}$).

Plainly the 0.3–10 keV spectral fits alone cannot distinguish between a reflection and absorption origin, not even when variability is included.\textsuperscript{7,12} Nor can data at higher energies as the two models also make very similar predictions for the 10–30 keV flux of $\sim 3 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ from the observed 2–10 keV flux of $4.5 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. This is not the case in other objects, such as 1H0707-496 and especially PG 1211+104, where Suzaku HXD data may break the model degeneracies.\textsuperscript{10} The difference here is the additional complexity due to the narrow warm absorber systems at low energies which gives more freedom in deconvolving the underlying spectrum.

Reflection from a disc

We can try instead to break the model degeneracies using physical plausibility arguments as opposed to observational data. Both absorption and reflection require the same basic ionization conditions i.e. partially ionised Oxygen to produce the big jump in opacity at 0.7 keV (equivalently $\xi \sim 10^3$ where $\xi = L/nr^2$ is the photoionisation parameter). This may arise rather naturally in an absorption geometry if the material is in some sort of pressure balance.\textsuperscript{13} The front of the cloud is heated by the X–ray illumination, so expands, so its density is low and ionisation is high. Further into the cloud the heating is less intense so the material is cooler, so must be denser to be in constant pressure. The lower ionisation finally allows ion species to exist, dramatically enhancing the cooling and hence increasing the density. This rapid transition means the cloud has to contract, which may mean this neutral material is strongly clumped. A line of sight though the cloud includes only the highly ionized front edge (invisible) and the partially ionized transition region, which has an average value of $\log \xi \sim 3$ across a region with column of $\sim 10^{22–23}$ cm$^{-2}$.\textsuperscript{13}

However, the same rapid change in ionisation state in an X–ray illuminated, hydrostatic disc produces a similarly stratified vertical structure but has very different observational consequences. Again the rapid transition from completely ionised to mostly neutral occurs over a column of $10^{22–23}$ cm$^{-2}$, i.e. an optical depth of $\leq 0.01$. Thus the zone with the ‘correct’ ionisation parameter to produce the soft
excess is only a very small fraction of the total disc photosphere \((\tau = 0 \rightarrow 1)\), so the soft excess is very much smaller than that produced from constant density reflection models which can arbitrarily set \(\xi = 10^3\) over the entire photosphere (see Fig 2). Since even the constant density models require a reflection dominated geometry to match the strongest soft excesses seen, this means that reflection from a hydrostatic disc simply cannot be the origin of these soft excesses.3)

§5. Conclusions

The rapid transition from complete ionisation to mostly neutral material is characteristic of any pressure balance condition. This means that the partially ionised zone required for both atomic models of the soft X-ray excess is limited to a column of \(10^{22-23}\) cm\(^{-2}\). This strongly supports the optically thin, absorption geometry as the origin for the soft X-ray excess, and this more messy picture of these high mass accretion rate AGN means they are probably not good places to test GR.

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