Exploring X-ray emission and absorption in AGN with XMM-Newton EPIC

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1. Introduction

The scientific case for XMM (Bleeker et al 1984) was accepted by ESA and appears not to have been formally updated since! In attempting an assessment of the impact of EPIC spectra on our current understanding of AGN it was therefore necessary to invent a circa 1999 science case. With the prominence given to the broad Fe K emission line, based largely on ASCA results (Nandra et al 1997) the potential study of strong gravity would certainly have been a high priority in a pre-launch XMM science programme. Mapping the warm absorber and outflows in general would also have been a priority target. Given the lack of understanding of the primary X-ray emission process(es) in AGN, I would have argued for a concerted effort to explore luminosity and accretion rate trends. Fourthly, while not having the high energy capabilities of RXTE or Beppo-SAX, the high sensitivity of EPIC over a broad energy band (0.2-15 keV) offered the prospect of exploring spectrally ‘hard’ sources, as in many Type 2 AGN and the dominant AGN component of the CXRB, where reflection and/or cold absorption provide an alternative to an intrinsically flat X-ray continuum.

For the present review, as XMM-Newton approaches the mid-point of (hopefully) a 10-year working life, I have re-examined EPIC spectra of 5 bright AGN to assess the impact of data of uniquely high statistical quality on the above science topics. The data are from observations for which I was a PI (1H0419-577) or Co-I (NGC5548), or have been extracted from the XMM-Newton archive (NGC4051, PG1211+143, Mkn3). Four of the sources are optical Type 1 Seyfert galaxies, covering a wide range of X-ray luminosity, while Mkn3 is a bright, nearby Seyfert 2.

2. The EPIC spectrum of NGC5548

NGC5548 is one of the best-known and most studied Seyfert 1, being a target of every X-ray mission over 30 years. As an archetypal moderate luminosity AGN, the 125 ks EPIC observation of NGC5548 on 9-12 July 2001 provided an important early opportunity for a precise measurement of the broad Fe K line indicated in the earlier ASCA observation (Nandra et al 1997). Surprisingly, only a barely resolved, narrow line is seen in the higher quality EPIC data (Fig.1), with an upper limit to the equivalent width (EW) of a broad line a factor 5 below the ASCA value. Furthermore, a simultaneous Beppo-SAX observation allowed the continuum reflection to be quantified, finding a level consistent with the narrow Fe K line EW ~60 eV.

Suggested explanations for the unexpected failure to detect reflection from matter close to the black hole in this bright Seyfert 1 were that the inner accretion disc was highly ionized by the relatively hard incident power law continuum in NGC5548, or was simply absent at the sub-Eddington accretion ratio of ~5 percent (Pounds et al 2003a).

**Fig. 1.** Power law fit to the EPIC data of the archetypal Seyfert 1 galaxy NGC5548 showing (only) a narrow Fe K line.
3. EPIC observations of NGC4051 in high and low flux states

Broad-band X-ray continua of AGN are conventionally fitted by a power law, typically of photon index $\Gamma \sim 1.7$–2.0, with a ‘soft excess’ evident below $\sim 1$–2 keV. The spectral form tends to vary systematically with the flux level of a source, suggesting that spectral variability may help resolve and identify the emission components. Two EPIC observations of the low luminosity Seyfert 1 galaxy NGC4051 appear particularly promising in this respect, a long (117 ks) observation on 16/17 May 2001, when the source was bright, being followed by a TOO observation of 52 ks on 22 November 2002, some 20 days into an ‘extended low’ flux interval. These data were recovered from the XMM-Newton archive and a comparative spectral analysis made (Pounds et al 2004a). The spectral contrast is remarkable, as evident in Fig.2 where the integrated bright and faint EPIC (pn) data are plotted against a power law of $\Gamma = 2$.

While the bright state spectrum is well fitted at 2–10 keV by the assumed $\Gamma = 2$ power law (again with only a narrow Fe K line), with a smooth soft excess at lower energies, the low flux spectrum is dramatically different. The much harder continuum $\gtrsim 3$ keV and more pronounced (but $\sim$constant flux) narrow Fe K line can be explained by retaining the strength of the reflected spectrum while the direct continuum flux is $\sim 5$ times fainter in the second observation, implying the reflecting matter is $\gtrsim 20$ light days from the continuum source (outer disc or torus?). Interestingly, a 2–10 keV power law fit excluding the 5–7 keV band (the convention used in most ASCA studies) suggests the presence of a strong and broad Fe K line in the low flux state spectrum. While this cannot be excluded with the present data, it may seem counter-intuitive for a feature requiring reflection from the innermost accretion disc to be evident only when the intrinsic continuum source is almost switched off.

An alternative suggested by enhanced structure throughout the low state EPIC spectrum is that these features are predominantly due to the imprint of absorption on the underlying continuum. Fig.3 reproduces such a model fit to the low flux EPIC spectrum of NGC4051, with the intrinsic power law partially covered by a warm absorber, modelled by XSTAR (Kallman et al 1996), of ionization parameter $\xi \sim 20$ and column densities $N_H \sim 10^{22}$ cm$^{-2}$ and $N_H \sim 10^{23}$ cm$^{-2}$. It is notable that the intrinsic power law in this low flux state fit, though much fainter, has the same spectral index $\Gamma \sim 2$ as in the high flux state.

4. The highly variable Seyfert galaxy 1H0419-577

A series of XMM-Newton observations of the luminous Seyfert 1 galaxy 1H0419-577 was carried out over the period September 2002 to September 2003, this source being chosen for detailed study as one of the most spectrally variable AGN. Five observations, each of nominally 15 ks, were made at 3-monthly intervals, during which time the source cooperated fully in exhibiting a wide range of flux states (Fig.4). As with NGC4051 the lower flux state EPIC spectra show more structure. An analysis of these data (Pounds et al 2004d) explored the spec-
Fig. 4. EPIC pn spectral data of 1H0419-577 from the observations of December 2000 (high state:black), September 2002 (low state:red), December 2002 (mid-low state:green), March 2003 (mid-high state:purple), June 2003 and September 2003 (intermediate state:light blue and magenta)

Fig. 5. (top) High state difference spectral data of 1H0419-577 plotted against a power law of $\Gamma \sim 2.4$; (middle) intermediate state difference spectral data of 1H0419-577 (red) compared with the cut-off power law model with the cold absorption removed (green); (lower) mid-low state difference spectral data of 1H0419-577 (red) compared with the cut-off power law model with the cold absorption removed (green). See text for details

A third important outcome of the above EPIC study of 1H0419-577 was that the ‘soft excess’, for so long a feature of AGN X-ray spectra, is seen to be - in substantial part - an artifact of absorption on the underlying continuum. This finding supports a recent proposal (Gierlinski and Done 2004) to address the long-standing difficulty of physically matching the soft excesses in AGN with thermal emission from the accretion disc. We now see, at least for 1H0419-577, the soft excess is a combination of a steeper (than the canonical $\Gamma \sim 1.8-2$) power law, attenuated below $\sim 1$ keV by strong and variable absorption, and a quasi-constant soft component. It seems quite likely that this true soft X-ray emission is associated with the
ionized outflow more generally observed in absorption in Type 1 AGN.

5. High velocity outflows - a major XMM-Newton discovery

The improved resolution of ASCA spectra confirmed the presence of ‘warm absorbers’ in many AGN, with spectral fits suggesting typical column densities of $N_H \sim 10^{21} - 10^{22} \text{cm}^{-2}$ and ionization parameter $\xi \sim 10 - 50$ imposing strong absorption of OVII, OVIII and Fe-L ions on the soft X-ray continuum. High resolution RGS and Chandra spectra have confirmed and quantified such ‘warm outflows’ in many AGN. The greater sensitivity of EPIC at higher energies has provided much improved spectral data in the Fe K band $\gtrsim 7$ keV, showing that significant absorption is common there too in AGN spectra. This is particularly important in providing a measure of absorption by more highly ionized gas, transparent at lower energies. The most remarkable discoveries to date have been of extremely deep Fe K absorption edges in 2 Narrow Line Seyferts 1H0707-495 (Gallo et al 2004) and IRAS13224-3809 (Boller et al 2003) and of high energy absorption lines indicating high velocity outflows.

Most of the early claims for high velocity outflows in AGN X-ray spectra have been based on XMM-Newton data, although recently there have been at least 2 similar reports from Chandra. [A current listing of 10 AGN showing X-ray evidence for high velocity outflows is included in the MPE Website covering the Ringberg meeting, where a common factor appears to be AGN with a high accretion ratio.] The luminous Seyfert 1 PG1211+143 remains one of the best examples of this phenomenon, as evidence for an ionized outflow at $v \sim 0.08 - 0.1c$ is seen in both EPIC and RGS data. Fig.6 reproduces the EPIC data where narrow absorption features are identified with Lyman $\alpha$ resonance lines of FeXXVI, SXVI and MgXII.

The wider significance of these high velocity winds, in comparison with the gentler ‘breeze’ more often seen in low energy absorption spectra, is underlined by noting that the mechanical energy involved can be comparable to the accretion energy [$Pounds et al 2003b$]. Thus, integrated over $\sim 10^8$ years, such a wind could have a major impact on the growth of the host galaxy [$King 2003$].

Fig. 6. Absorption lines in the EPIC spectrum of PG1211+143 identified (top) with highly ionized Fe ‘blue-shifted’ by $v \sim 0.1c$; (lower) with highly ionized S and Mg also ‘blue-shifted’ by $v \sim 0.1c$.

6. An EPIC observation of the nearby Seyfert 2 galaxy Mkn3

Mkn3 is a low redshift ($z=0.0135$) Seyfert 2 for which ASCA (Turner et al 1997) and Beppo-SAX (Cappi et al 1999) observations had shown a hard, reflection-dominated spectrum. A 105 ks XMM-Newton observation on 19/20 October 2000 was retrieved from the archive. The EPIC spectral data (Fig.7) extends to $\sim 15$ keV indicating a very hard spectrum; in addition a strong Fe K line and several other prominent spectral features are seen. The statistical quality and extended bandwidth of the EPIC data are well fitted with the reflection-dominated model proposed for the ASCA and Beppo-SAX spectra, though now the model parameters are better constrained. The intrinsic continuum, with a typical Seyfert power law index $\Gamma \sim 1.8$, is seen through a near-Compton-thick absorber ($N_H \sim 1.3 \times 10^{24} \text{cm}^{-2}$), with the
hard spectrum at \( \sim 3-8 \) keV being dominated by continuum reflection and fluorescent line emission.

In addition to the strong K\( \alpha \) and \( \beta \) lines of Fe, fluorescent emission from the same reprocessing matter is detected - at strengths consistent with solar abundances - for Ni, Ca, Ar, S, Si and Mg. A soft excess extending above a low energy extrapolation of the 3-15 keV model fit (Fig.8) is then impressively well resolved by the EPIC detectors (eg Fig.9). The clarity of this plot underlines the spectroscopic potential of the MOS camera, in particular, having a resolution of \( \sigma \sim 34 \) eV at 1.5 keV.

The particularly strong Fe K\( \alpha \) line is intriguing, having an energy of 6.43\( \pm 0.01 \) keV in both pn and MOS cameras. In comparison to a laboratory energy (weighted mean of the K\( \alpha \) doublet) of 6.400 keV, the data suggest a blueshift - in velocity terms - of 1400\( \pm 450 \) km s\(^{-1} \). The sharp Fe K absorption edge, presumably from the same matter, lies close to 7.1 keV excluding ionization as the origin of the line energy shift. This result fits uncomfortably with an origin of the Fe K line from the unobscured far, inner wall of a torus, unless located on much less than the conventional \( \sim \)pc scale (Pounds et al 2005b).

Resolving the soft emission from Mkn3 with EPIC (eg Fig.9) also reveals strong resonance emission lines of highly ionized N, O, Ne, Mg, Si and S. Higher resolution spectra from the RGS confirm these identifications and find the soft spectrum to be consistent with a photoionized/photo-excited outflow, as previously reported from a Chandra study (Sako et al 2000), at a projected velocity of \( \sim 800 \) km s\(^{-1} \). The integrated luminosity in this soft X-ray component is \( \sim 1 \) percent of the absorption-corrected power law continuum and represents only that part of the outflow extending above the Compton thick screen. The intriguing question as to how much greater would the soft X-ray emission be were Mkn 3 viewed at a smaller inclination (ie as a Seyfert 1) is interesting in relation to the origin of the quasi-constant soft X-ray emission in cases such as the low flux states of NGC4051 and 1H0419-577.
7. Summary and Conclusions

EPIC is proving to be a powerful instrument for the study of AGN X-ray spectra. Its sensitivity over a uniquely broad energy band has provided the best data yet for deconvolving the primary and secondary emission components, with the ability to follow flux-linked changes being particularly instructive. While not having the high spectral resolution of grating instruments, the CCD resolving power on EPIC is impressive - and probably could be more fully exploited (a potential that improved confidence in instrument calibration should help realise). Mkn3 is a good demonstration of the spectroscopic capabilities of EPIC, where the high energy response allows the obscured power law and strong reflection components to be unambiguously resolved, while providing a clear resolution of the line-dominated soft X-ray emission.

The complementarity of EPIC and the RGS on XMM-Newton is well illustrated in the study of ionized outflows in AGN. While the high spectral resolution of the RGS is essential to determine the line widths and velocities of a few 100 km s\(^{-1}\) seen in absorption in many AGN, EPIC data has demonstrated that much more highly ionized gas - transparent in the soft X-ray band - is often present. In addition, the combination of RGS and EPIC spectra is important in demonstrating the high velocity and energetically important outflows in objects such as PG1211+143 and PDS456. A further, less obvious, complementary strength of EPIC arises in quantifying absorption in cold matter, or where the absorbing gas is highly turbulent, neither case yielding the narrow features well suited to the RGS.

In conclusion, what has been learned on the priority science topics listed in our pre-launch science case update? Unfortunately, it seems the broad Fe K line remains controversial as a probe of strong gravity. As in the EPIC observation of NGC5548, only a narrow Fe K emission line, with a strength and profile consistent with an origin in cold matter distant from central Black Hole, is seen in a majority of EPIC spectra of AGN. While a recent survey of XMM observations (Reeves and Nandra, unpublished) showed a diversity of Fe K line profiles, with several having excess emission to the `red’ or `blue’ sides of the 6.4 keV line, the evidence for a relativistically broadened line containing information on the effects of strong gravity and black hole spin remains unclear. The tendency, as in NGC4051 and 1H0419-577, for a broad `line-like' feature to be most evident in low flux states supports an alternative description, where the observed feature is an imprint of enhanced absorption by cold or weakly ionised matter on the power law continuum.

The fact that this ambiguity remains despite the careful analysis of several high quality EPIC spectra, eg MCG-6-30-15, underlines the key importance of future observations being able to fully map the effects of such absorption. Meanwhile we can only speculate that the Fe K signature of re-processing in matter that must exist close to the Black Hole in any radiatively efficient AGN is often diluted by ionization or is obscured by other accreting or outflowing matter.

While the location of such absorbing matter is uncertain, perhaps residing in the outer layers of the accretion disc or base of a jet, XMM-Newton spectra have revealed strong ionized outflows in many AGN, both in absorption and emission. Perhaps the most significant new discoveries, primarily led by EPIC data, relate to the evidence for highly ionized winds moving at \(\sim 0.1-0.2c\). Simply to detect the tell-tale absorption lines of FeXXV or XXVI requires column densities of order \(N_H \sim 10^{23} \text{cm}^{-2}\), which translate into mass outflow rates comparable to, or exceeding, the accretion rates for the respective AGN unless the flow cone is narrow. A high velocity then makes these flows also important energetically, offering a natural link between black hole and host galaxy growth as implicated in observational correlation between the black hole mass and the velocity dispersion in the galactic bulge. The fact that the growing list of AGN with reported high velocity outflows may mostly (if not all) be accreting at the Eddington rate is consistent with matter being ejected - at the local escape velocity - from the inner disc region. The repeated XMM-Newton observations of another high luminosity Seyfert 1, 1H0419-577, provides a unique data base to study large-scale spectral variability. The analysis outlined here finds the dominant variable to be a relatively steep power law component, as was previously found for MCG-6-30-15, suggesting this may be a common factor, if not always so obvious. Modelling difference spectra strongly suggests - again - the presence of substantial cold absorbing matter, the column density (or cov-
ering factor) of which falls as the source flux increases.

Finally, the XMM-Newton observation of Mkn3, sitting in the data archive for over 4 years, is an impressive demonstration of the diagnostic power of EPIC. Not only do those data allow the direct observation of a ‘normal’ Seyfert 1 power law, seen through a near-Compton-thick absorber, the strong reflected continuum and associated fluorescent line spectrum are well resolved. In addition the strong Fe Kα line profile is measured with sufficient precision to provide an interesting indication that much of the re-processing matter lies at a smaller radius than the expected inner boundary of a molecular torus. Here again, improved confidence in the in-flight calibration data for EPIC would allow the strong Fe K line to be an important probe of the circumnuclear matter in Type 2 AGN.

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