XMM-Newton observations of an absorbed $z=0.67$ QSO: no dusty torus?

I. Georgantopoulos$^1$, A. Georgakakis$^1$, G.C. Stewart$^2$, A. Akylas$^{1,3}$, B.J. Boyle$^4$, T. Shanks$^5$, R.E. Griffiths$^6$

$^1$ Institute of Astronomy & Astrophysics, National Observatory of Athens, I. Metaxa & B. Pavlou, Penteli, 15236, Athens, Greece
$^2$ Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH
$^3$ Physics Department University of Athens, Panepistimiopolis, Zografos, 15783, Athens, Greece
$^4$ Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia
$^5$ Physics Department, University of Durham, Science Labs, South Road, Durham, DH1 3LE
$^6$ Department of Physics, Carnegie-Mellon University, 5000 Forbes Ave., Pittsburgh, PA 15213, USA

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ABSTRACT
We present XMM-Newton observations of AXJ0341.4-4453, a mildly reddened $A_V < 7$ QSO at a redshift of $z=0.672$. The XMM-Newton spectrum shows a large obscuring column $N_H \sim 10^{23}$ cm$^{-2}$ corresponding to $A_V \sim 70$, in agreement with previous results based on the lower limit of the ASCA hardness ratio. The X-ray spectrum is represented by a ‘scattering’ model with $\Gamma \approx 2.0$ with the scattered power-law normalization being a few per cent of the hard component. No FeK line is detected with a 90 per cent upper limit on its equivalent width of $\approx 360$ eV. The large discrepancy between the column density observed in X-rays and that inferred from the Balmer decrement can be explained by dust sublimation near the nucleus. Then, the X-ray and the optical obscuration come from two different regions: the X-ray close to the accretion disk while the optical at much larger > 0.25 pc scales.

Key words: galaxies:active-quasars:general-X-rays:general

1 INTRODUCTION

ASCA and BeppoSAX surveys have discovered several examples of absorbed QSOs beyond the local Universe (e.g. Boyle et al. 1998, Georgantopoulos et al. 1999, Fiore et al. 1999, Akiyama et al. 2000, Akiyama, Ueda & Ohta 2002). The X-ray spectra of these QSOs present large amounts of photoelectric absorption (typically $N_H > 10^{23}$ cm$^{-2}$). Interestingly though, their optical extinction is disproportionately small. This is in stark contrast with the optical properties of most nearby Seyfert galaxies which present large amounts of absorption in X-rays (e.g. Goodrich et al. 1994), posing questions on the physical conditions of the absorbing screen at higher redshift.

Here, we present XMM-Newton observations of a moderate redshift ($z=0.672$) QSO (AXJ0341.4-4453) detected in our deep ASCA survey (Georgantopoulos et al. 1997). The optical spectrum as well as the ASCA hardness ratio were presented by Boyle et al. (1998). The optical spectrum, obtained in the wavelength range 4000-7000 Å with the LDSS spectrograph in the Anglo-Australian Telescope, shows only narrow lines. As some of them are high excitation lines (e.g. [NeV]) it was immediately established that this is an AGN. Subsequent spectroscopic observations obtained at the CTIO by Halpern, Turner & George (1999) at longer wavelengths revealed a broad $H_\beta$ line clearly indicating that this is a broad-line (type-1) QSO. The excellent quality optical spectrum obtained by Halpern et al. (1999) allowed the determination of the reddening from the ratio of the Balmer lines: $H_\gamma/H_\beta = 0.17$ yielding $A_V = 7$. They note however, that the estimate on $A_V$ is just an upper limit, as the $H_\gamma/H_\beta$ ratio could be affected by collisional excitation, radiative transfer effects and contamination of $H_\beta$ by FeII. Indeed, the MgII/H_β ratio gives instead $A_V = 3.5$. In contrast, the ASCA hardness ratio gives a lower limit on the column density of $N_H > 4 \times 10^{22}$ cm$^{-2}$ which corresponds to $A_V \sim 30$ (Bohlin et al. 1978). The high effective area of XMM-Newton (more than an order of magnitude higher than ASCA at 1 keV) offers the opportunity to study in detail the X-ray spectrum of this object, expanding on the ASCA results and helping to explore the relation between the obscuration at different wavelengths beyond the local Universe.

Throughout this paper we adopt $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. 
2 DATA ANALYSIS

The XMM-Newton data of QSO AXJ0341.4-4453 ($\alpha = 3h41m24.4s; \delta = -44^\circ53'2.0''$, J2000) were obtained in 2002 August 26 as part of the Guaranteed Time program. The EPIC (European Photon Imaging Camera; Strüder et al. 2001 and Turner et al. 2001) cameras were operated in full frame mode with the thin filter applied.

The data have been cleaned and processed using the Science Analysis Software (sas 5.3). The event files for the PN and the two MOS detectors were produced using the standard reduction pipeline (Watson et al. 2001). The event files were screened for high particle background periods resulting in a good time interval of 26122 s. Events corresponding to patterns 0–4 and 0–12 have been included in the analysis of the PN and MOS data respectively.

AXJ0341.4-4453 is observed on-axis. Its X-ray centroid lies at about 1 arcsec away from the optical counterpart. For the X-ray spectral analysis an extraction radius of 12 arcsec is adopted. We create an auxiliary file using the SAS task ARFGEN to take into account both instrumental effects (e.g. quantum efficiency, telescope effective area, filter transmission) and the fraction of light falling outside the 12 arcsec extraction radius. The spectral response file is created using the task RMFGEN. The source spectrum is grouped, using the FTOOL GRPPHA task to give a minimum of 15 counts per bin to ensure that Gaussian statistics apply. The source spectrum is fitted using XSPEC v11.0. The Galactic column density is $1.7 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). We fit the data in the energy range 0.3-10 keV where the sensitivity of XMM-Newton is the highest. The errors quoted below correspond to the 90 per cent confidence level.

As a first approximation, a power–law model is fit to the data, yielding the intrinsic absorption column density, $N_{\text{H}}$, and the power–law photon-index $\Gamma$. The spectral fit results are summarized in Table 1 and are shown in Figure 1. An acceptable fit ($\chi^2 / \text{dof} = 24.0 / 23$) is obtained for a rest frame column density $N_{\text{H}} \sim 10^{23}$ cm$^{-2}$, consistent with the lower limit obtained by previous ASCA observations ($N_{\text{H}} > 4 \times 10^{22}$ cm$^{-2}$). Assuming the standard Galactic $A_V / N_{\text{H}}$ factor the above column density corresponds to an optical absorption $A_V \sim 70$ (Bohlin et al. 1978) much higher than the estimated amount of dust extinction $A_V < 7$ based on Balmer decrement measurements (Halpern et al. 1999).

It is clear from Figure 1, that an excess at low energies over the absorbed power–law model is present. Therefore, we investigate whether a more complex model could compensate for this spectral feature. In particular, the 'scattering' model is examined. This assumes a thick screen of absorbing material which swamps the soft X-rays, while the more energetic hards X-rays can penetrate through. In this picture the soft-band emission arise from scattering on a pure electron medium. In practice this model is realized by a two component power–law: the first power–law is absorbed by the intrinsic column density, while the second is absorbed only by the Galactic column. An additional constrain is that the scattered soft power–law should have the same slope as the hard component. This standard model appears to apply to most obscured Seyfert galaxies (e.g. Turner et al. 1997). The results of the spectral fits are also presented in Table 1. We obtain a reduction in $\chi^2$ of $\Delta \chi^2 \approx 6.1$ which is statistically significant at the $\approx 99 \text{ per cent confidence level for one}$ additional parameter according to the F-test (Bevington & Robinson 1992).

We also check whether the X-ray spectrum presents an FeK line at a rest-frame of 6.4 keV. This line is often detected in obscured Seyfert galaxies having equivalent widths $> 200 \text{ eV}$ (e.g. Turner et al. 1997). This is believed to be produced through transmission of the X-ray radiation in a dense cold medium. When we add a narrow Gaussian line (with $\sigma = 0.01 \text{ keV}$ much smaller than EPIC’s spectral resolution) we obtain $\Delta \chi^2 \approx 1.4$ which does not represent a statistically significant change. We find a 90 per cent upper limit on the equivalent width of $\sim 360 \text{ eV}$ (rest-frame). This is roughly consistent with the equivalent width of $\sim 300 \text{ eV}$ predicted for an obscuring screen of $10^{23}$ cm$^{-2}$ assuming spherical geometry (Leahy & Creighton 1993).

Moreover, we check for long-term variability between the ASCA and XMM-Newton epoch. Using the single power–law model, the source flux and luminosity in the 2–10 keV band is $8 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and $8 \times 10^{43}$ erg s$^{-1}$ respectively. Therefore AXJ0341.4-4453 presents no variability when compared to the ASCA observation: $f_{2–10\text{keV}} \approx 8.6 \pm 2.3 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$, using again the best-fit XMM-Newton spectral parameters in the single power–law case $\Gamma = 2.05$, $N_{\text{H}} = 10^{23}$ cm$^{-2}$. Finally, we check for short term variations in the XMM-Newton light curve by binning the data in 1 ks bins. A constant line is an acceptable fit to the flux of the binned data ($\chi^2 = 37.2 / 29$) and hence, the observations do not reveal short-term variability on timescales of hours.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{\text{H}}$</th>
<th>$\Gamma$</th>
<th>$f^2$</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Power–Law</td>
<td>$0.5_{-0.4}^{+0.3}$</td>
<td>$2.06_{-0.37}^{+0.56}$</td>
<td>-</td>
<td>24.0 / 23</td>
</tr>
<tr>
<td>Scattering</td>
<td>$1.6_{-0.3}^{+0.4}$</td>
<td>$2.05_{-0.26}^{+0.28}$</td>
<td>$0.035_{-0.030}^{+0.035}$</td>
<td>17.9 / 22</td>
</tr>
</tbody>
</table>

1 Neutral column density $\times 10^{23}$ cm$^{-2}$
2 Normalization of the soft relative to the hard power–law

Figure 1. The single power–law spectral fit to the PN and MOS data (upper panel) together with the residuals (bottom panel). A soft excess at low energies (< 2 keV) is clearly present.
3 DISCUSSION

The XMM-Newton observations show that AXJ0341.4-4453 presents an X-ray spectrum typical of Seyfert-2 galaxies. However, there is a large discrepancy between the obscuration estimates derived from the optical spectrum (using the Balmer decrement) and the X-ray column density. Several QSOs in the sample of Akiyama et al. (2000) as well as a couple of QSOs in the BeppoSAX HELLAS sample of Fiore et al. (1999) exhibit the same behaviour.

Granato et al. (1997) argue that dust sublimation can explain the discrepancy in the optical and X-ray $A_V$ estimates in these objects. In more detail dust is destroyed in the presence of the strong AGN radiation field in the vicinity of the sublimation radius estimated as $r = 0.5 \times 10^{12}$ pc, where $L_{46}$ is the intrinsic UV luminosity in units of $10^{46}$ erg s$^{-1}$ (Granato et al. 1997). In the case of AXJ0341.4-4453 we estimate $L_{46}$ by extrapolating the X-ray power-law to the UV. We assume an X-ray-to-optical spectral index $\alpha_{XO} = 1.6$ typical of QSOs (e.g. Schmidt & Green 1986) to convert from X-ray 2 keV flux density to 2500 Å flux density. To estimate the UV flux between 1000–3500 Å we adopt a power-law spectral energy distribution at the UV of the form $f_\nu \propto \nu^{-0.5}$. We find that dust cannot exist within a radius of $0.25$ pc.

Maiolino, Marconi & Oliva (2001) argue against the dust sublimation scenario on the basis of the observed emission-line properties. They propose an alternative model suggesting that the high densities in the nuclear regions of AGNs favor dust coagulation resulting in a dust distribution dominated by large dust grains. Detailed modeling shows that such a dust grain distribution can effectively explain the observed lower values of reddening compared to those expected from the hydrogen column density measured in X-rays assuming a standard Galactic dust-to-gas ratio (Maiolino, Marconi & Oliva 2001). Observational and theoretical evidence also support the above picture of ‘anomalous’ dust properties in the AGN nuclear regions (Maiolino et al. 2001; Clavel et al. 2000).

In a recent paper Weingartner & Murray (2002) using the sample of Maiolino et al. (2001) report the absence of any correlation between the optical reddening and X-ray column density. They interpret this as evidence that the optical obscuration and the X-ray photoelectric absorption occur in two distinct media. Consequently, they argue that the basic assumption of Maiolino et al. (2001) that the optical and photoelectric absorption are taking place on the same medium (i.e. the torus) might not hold. In their picture X-rays are absorbed by dust-free (or large dust grain) material just off the torus and/or the accretion disk, while the optical extinction occurs further out from the nucleus on a medium with nearly Galactic properties. They also claim that several narrow-line AGN in the sample of Maiolino et al. (2001) have erroneous estimates of the dust extinction due dust lanes in the host galaxy disks not associated with the torus.

Here, we re-examine the relation between the ratio of the X-ray to optical reddening in the sample of Maiolino et al. (2001), excluding the eight objects for which Weingartner & Murray (2002) raised criticism: NGC1365, MCG 5-23-16, NGC 5506, NGC 2992, IRAS 13197-1627, IRAS 0518, NGC 526a, Mrk 231. We also exclude NGC 4639 for which the error of the measurement of the column density is very large. We further add to the sample two high redshift QSOs: RXJ1333+001 (z = 2.35; Georgantopoulos et al. 1999) and AXJ0849+4454 (z = 0.9; Akiyama et al. 2002). Note that our estimate of the reddening in the case of RXJ1333+001 is only approximate. The H$_\beta$ line is not detected and hence the Balmer decrement method can only estimate a lower limit $A_V > 3$. However, as the H$_\alpha$ line is detected, the reddening cannot be much higher. We estimate that a reddening of $A_V \sim 10$ would render H$_\alpha$ undetectable to the sensitivity of the spectroscopic observations of Georgantopoulos et al. (1999). Note also that although the QSO presented in the present paper was included in the Maiolino et al. (2001) sample, only an upper limit on the ratio of the optical reddening to the X-ray column density was available at the time (a lower limit on $N_H$ was determined by ASCA ). Here, we use $A_V \approx 7$ for this object.

In Figure 2, we plot the ratio of the X-ray to optical column $R = A_O^0/A_X^0$ as a function of redshift where $A_O^0 = 2.2 \times 10^{21}$ cm$^{-2}$/$N_H$ (Gorenstein 1975). It should be noted that redshift is interchangeable with luminosity in Figure 2, i.e. the most X-ray luminous objects are also at higher $z$. The two lowest redshift objects (NGC5033, M81) apparently have an optical to X-ray obscuration higher than that predicted on the basis of the Galactic dust-to-gas ratio ($R = 1$). These two objects have the lowest luminosities: $L_X < 1.2 \times 10^{43}$ erg s$^{-1}$ (see Table 1 of Maiolino et al. 2001). The rest of the sample has $R$ values lower than unity while there is no correlation with redshift. Under the dust sublimation scenario of Granato et al. (1997) for a source with $L_X > 10^{42}$ erg s$^{-1}$ we estimate a dust sublimation radius of $r > 0.04$ pc.

Recent X-ray monitoring observations show that the size of the X-ray absorbing medium in several nearby Seyfert-2 galaxies (Risaliti et al. 2002) is roughly of the order of the Broad Line Region, < 0.03 pc. Interestingly, for the low luminosity AGNs in the Maiolino et al. sample ($L_X \sim 10^{41}$ erg s$^{-1}$) we estimate a sublimation radius of $r \sim 0.01$ pc and therefore for these systems dust does exist within the region that produces the photoelectric X-ray absorption. Hence, for these two systems it is probably not surprising that they do show large optical reddening. For more luminous QSOs, $L_X > 10^{42}$ erg s$^{-1}$, the sublimation radius is $r > 0.04$ pc and hence, the region of the X-ray absorbing medium is probably free of dust. For these systems the optical obscuration is taking place further out from the nuclear regions, presumably at pc-scale or even larger distances (e.g. parent galaxy dust lanes). The evidence above is in better agreement with the Weingartner & Murray (2002) picture where the optical and X-ray absorption are taking place on two distinct media. Additional constraints on the location of the X-ray absorbing medium come from its ionization state. If the absorbing screen is too close to the nucleus, having a low density, it will be fully ionised. From the definition of the ionization constant ($\xi = L/n_e r^2$), we find that at a distance of 0.02 pc and for the unobscured luminosity of AXJ0341.4-4453, $L_{0.1-2keV} = 5 \times 10^{44}$ erg s$^{-1}$, the ionization constant is relatively low ($\xi = 1$) only for densities as high as $n_e > 10^{13}$ cm$^{-3}$.

However, one should be cautious about this interpreta-
tion because of selection biases in the Maiolino et al. (2001) sample. In particular, these authors argue that their sample is biased against AGNs with enough optical obscuration to completely extinguish the broad lines. Therefore, the presence of AGNs with both large amounts of X-ray obscuration and large optical extinction cannot be excluded. The discovery of at least two type-2 QSOs (Stern et al. 2002, Norman et al. 2002) in Chandra surveys suggests that this class of sources does exist. Nevertheless, it is possible under our interpretation and also that of Weingartner & Murray (2002) that the extinction of the broad lines in these systems is taking place on a medium external to the nuclear regions. For example, if these nuclei reside in edge-on galaxies, this could explain the large optical reddening.

In conclusion, the large discrepancy between the X-ray absorption and the optical reddening in AXJ0341.4-4453 cannot be explained by the standard 'dusty torus' model where both the X-ray and the optical obscuration are associated with an obscuring screen outside the BLR at roughly pc-scale distances. We suggest instead, a model where the X-ray and the optical obscuration take place in two distinct media similar to that of Weingartner & Murray (2002). In particular, the X-ray absorption must take place close to the nucleus. This region is dust-free in the more luminous (and thus high redshift) AGN as dust sublimates. Then the small amount of optical reddening observed in AXJ0341.4-4453 comes from a region further away from the nucleus (> 0.25 pc) where dust remains intact.

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