The first XMM-Newton spectrum of a high redshift quasar - PKS 0537–286.

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Abstract. We present XMM-Newton observations of the high redshift ($z = 3.104$), radio-loud quasar PKS 0537–286. The EPIC CCD cameras provide the highest signal-to-noise spectrum of a high-$z$ quasar to date. The EPIC observations show that PKS 0537–286 is extremely X-ray luminous ($L_X = 2 \times 10^{47}$ erg s$^{-1}$), with an unusually hard X-ray spectrum ($\Gamma = 1.27 \pm 0.02$). The flat power-law emission extends over the whole observed energy range (0.4 to 40 keV in the quasar rest frame); there is no evidence of intrinsic absorption, which has been claimed in PKS 0537–286 and other high $z$ quasars.

However, there is evidence for weak Compton reflection. A redshifted iron K line, observed at 1.5 keV - corresponding to $\sim$6.15 keV in the quasar rest frame - is detected at 95% confidence. If confirmed, this is the most distant iron K line known. The line equivalent width is small (33 eV), consistent with the 'X-ray Baldwin effect' observed in other luminous quasars. The reflected continuum is also weak (R $\lesssim$ 0.25). We find the overall spectral energy distribution of PKS 0537–286 is dominated by the X-ray emission, which, together with the flat power-law and weak reflection features, suggests that the X-radiation from PKS 0537–286 is dominated by inverse Compton emission associated with a face-on relativistic jet.

Key words: galaxies: active – quasars: individual: PKS 0537–286 – X-rays: galaxies

1. Introduction

At the present time there is little known about the X-ray spectra of high redshift quasars, and thus a lack of understanding of the nature of the quasar central engine at the highest redshifts. However the situation is improving; the ROSAT mission substantially increased the number of high $z$ quasars with detected X-ray emission (Brinkmann et al. 1997), whilst ASCA obtained the first broad-band spectra (e.g. Cappi et al. 1997, Reeves et al. 1997, Vignali et al. 1999), albeit with rather limited photon statistics and sensitivity. The high throughput and bandpass of XMM-Newton is about to revolutionize studies of high redshift quasars. Many high redshift quasars should be found routinely through follow-up surveys of XMM fields (Watson et al. 2001), detailed spectral studies can be performed on the brightest objects and the high sensitivity limit of XMM-Newton should enable the detection of the most distant known quasars at $z > 5$ (Brandt et al. 2000).

At $z = 3.104$, PKS 0537–286 is one of the brightest known high $z$ quasars, first recognised as a 1 Jy Parkes southern radio source (e.g. Bolton et al. 1975) and later identified as a QSO (Wright et al. 1978). The optical (rest frame UV) spectrum shows two strong absorption systems associated with the quasar, one of which produces a cut-off in the quasar continuum at the Lyman-limit. The redshift of PKS 0537–286 has been confirmed at $z = 3.104 \pm 0.001$ (Osmer et al. 1994). PKS 0537–286 was first detected as an X-ray source by the Einstein observatory (Zamorani et al. 1981), with a position within 1' of the radio and optical source. The identification was later confirmed by ROSAT (Bühler et al. 1995), and with ASCA there were enough counts to obtain a crude X-ray spectrum (Siebert et al. 1996, Cappi et al. 1997, Reeves et al. 1997). These observations revealed a luminous X-ray source, with a flat X-ray spectrum perhaps indicative of a soft X-ray cut-off due to absorption. We now present the XMM-Newton observations of PKS 0537–286. Values of $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ have been assumed and all fit parameters are given in the quasar rest-frame.

2. XMM-Newton observations

PKS 0537–286 was observed during orbit 51 of the Cal-PV phase of XMM-Newton. Processing was performed us-
ing the XMM SAS (Science Analysis Software). The initial data files were processed with the EMCHAIN and EPCHAIN scripts, using the latest known calibration. X-ray events corresponding to patterns 0-12 for the 2 MOS cameras (similar to grades 0-4 in ASCA) were used; for the PN, only pattern 0 events (single pixel events) were selected. For the MOS detectors, electronic noise was screened out by rejecting events with negative E3 values. Known hot or bad pixels were also removed during screening. We refer the reader to Turner et al. (2001) for an in-depth description of the EPIC-MOS instruments, whilst a detailed account of the EPIC-PN detector can be found in Strüder et al. (2001). The non X-ray background remained relatively low throughout the observations, so it was not necessary to filter events on time. We also found no variability in the source count rate during the observation.

The screening process yielded 19.2 ksec of data for MOS-1, 28.0 ksec for MOS-2 and 38 ksec for the PN detector. Source spectra were extracted from circular regions of 30″ radius for the PN (to avoid the edge of the chip) and 1′ radius for the MOS. Background spectra were taken from an identical circular region, offset from the source position. The majority of source counts fall onto these source regions (at least 80% for the PN and >90% for the MOS), whilst the background count rates are very low; 1.07 ± 0.17 × 10^−2 cts s^−1, 4.8 ± 1.5 × 10^−3 cts s^−1 and 8.8 ± 1.1 × 10^−3 cts s^−1 for the PN, MOS-1 and MOS-2 respectively. The net source count rates obtained are 0.257±0.004 cts/s, 0.268±0.003 cts/s and 0.513±0.004 cts/s, for MOS-1, MOS-2 and the PN respectively. At this level, even in full-frame mode, photon pile-up is negligible. We do not consider the RGS data in this paper, as the count rate is too low (< 0.1 cts/s) for a reliable analysis of the dispersed spectrum. The background subtracted EPIC spectra were fitted, using XSPEC v11.0, with the latest response matrices produced by the EPIC team; the systematic level of uncertainty is < 5%. Spectra were binned to a minimum of 20 counts per bin, to apply the χ^2 minimisation technique. All subsequent errors are quoted at 90% confidence (Δχ^2 = 4.6 for 2 interesting parameters).

3. EPIC Spectral Analysis

We initially fitted the individual X-ray spectra from the 3 EPIC detectors, to check for consistency between the datasets. From a simple power-law fit it was found that the photon index agreed for all 3 detectors (Γ=1.25-1.30) and that the relative normalisations were consistent to within 5%. Therefore we proceeded to fit all three datasets simultaneously, assuming a Galactic column of N_H = 1.95 × 10^{20} cm^−2 (Elvis et al. 1989). The EPIC spectrum is plotted in Figure 1 and the results from a power-law fit to the broad-band data are shown as fit 1 (in table 1). Clearly a power-law is a good fit (χ^2 ∼ 1), with no obvious continuum curvature present. We note that the power-law photon index of Γ = 1.27 ± 0.02 is considerably flatter than the mean quasar index (e.g. Reeves & Turner 2000), even for radio-loud quasars which have a typical mean of Γ = 1.6. The observed broad-band (0.2-10 keV) flux is 3.1 × 10^{−12} erg cm^−2 s^−1, which, under the assumption of isotropic X-ray emission, corresponds to a luminosity at z = 3.104 of 2.2×10^{47} erg s^−1 (0.8-40 keV in the QSO frame). This makes PKS 0537–286 one of the most luminous known quasars in the Universe.

We also searched the spectrum for signs of photoelectric absorption. There are several reported cases in the lit-
The relative brightness of PKS 0537−286 allows us, for the first time, to search for signs of the iron Kα emission line in a high redshift quasar. We restricted our search to the 1–2 keV band, where the iron K line should appear at this redshift; conveniently the throughput of the XMM-Newton EPIC instrument reaches a maximum in this band. We initially fixed the line width at $\sigma = 10$ eV and the result is shown as fit 2. A narrow Fe K line is detected (equivalent width EW=33eV, QSO frame), at 95% confidence for 2 parameters, whilst the line peaks at 6.15±0.15 keV (or 1.5 keV observed-frame). A close-up of the EPIC PN and MOS data, illustrating the line detection at $z=3.104$, is shown in Figure 3. The confidence contours to the line, from a fit to the MOS and PN data, are also shown in Figure 4. Although the line energy is consistent with neutral material, the apparent redshift of the line may indicate an origin from the inner quasar accretion disk (Fabian et al. 1989) or from reprocessing in infalling matter. The velocity width of the line is not well constrained, with an upper limit of $\sigma < 500$ eV.

3.2. The effect of Aluminium Kα on the Iron Line

Since the proposed iron K line (observed at 1.5 keV) lies near the Al-Kα line, at 1.487 keV, in the detector background, we have checked to see whether this can contribute towards the observed Fe line flux at 1.5 keV. To do this we extracted a large source-free background region, of 4’ radius, from the PKS 0537−286 PN field, and then measured the strength of the Al Kα line directly. We re-normalised the background fluxes (from an area 63 times larger), to the size of our source extraction region. It was found that the total integrated count rate from the Al Kα line was $7.5 \pm 2.6 \times 10^{-5}$ ct s$^{-1}$, compared to the quasar line count rate of $1.85 \pm 0.6 \times 10^{-3}$ ct s$^{-1}$. Thus we can conclude that the Al Kα line contributes only ~4% of the quasar line flux, before background subtraction. Note that at 1.5 keV, the total background count rate is <1% of the total quasar count rate. There are also no strong variations in background, across the central chips, for either the MOS or PN.

As a final check, we also used a long closed-filter PN observation (in orbit 59) to estimate the background count rate from the Al Kα line. We found that the total flux in the Al line (for an area the size of the PN source extraction...
The majority of the observed quasar power is radiated in the X-ray band (typically in AGN the X-ray emission is only 5% of the bolometric luminosity; e.g. Elvis et al. 1994). The optical-UV emission is also relatively weak in comparison to the X-rays ($\alpha_{ox} = -0.94$). However this is consistent with the observations of other high redshift blazar-like AGN (see Fabian et al. 1999), where a strong, but flat, X-ray emission component is also seen.

**4. Discussion**

The **XMM-Newton** observations have showed that PKS 0537–286 is an extremely luminous quasar, with a particularly flat X-ray spectrum and weak iron K emission and reflection features. Indeed the total power output of PKS 0537–286 is dominated by the X-ray emission. A likely interpretation is that the X-rays mainly arise through the inverse Compton emission associated with a relativistic jet. In this scenario relativistic electrons (or positrons) in the jet Compton upscatter either the low energy synchrotron photons produced in the jet (Synchrotron Self Compton - Jones, O’Dell & Stein 1974, Ghisellini, Maraschi & Treves 1985) or alternatively the thermal optical/UV photons from the accretion disk (External Inverse Compton - Ghisellini & Madau 1996). This can naturally account for the hard spectrum of PKS 0537–286, as in the X-ray band we are observing the onset of this Inverse Compton component, presumably extending out to $\gamma$-ray energies.

As it appears that we can rule out a scenario whereby all of the primary X-ray emission originates above the accretion disk, we instead tried to fit the data with two continuum emission components: a ‘Seyfert-like’ steep power-law (with $\Gamma$ fixed at 1.9) originating from near the accretion disk, and a hard, bright jet component with a flat X-ray slope (i.e. $\Gamma = 1.2 \pm 1.3$ as before). We modified the Seyfert-like power-law with a continuum reflection component (assuming R=1) and also added a narrow iron K line of equivalent width 150 eV. Although poorly constrained, we obtained a good fit to the data when the Seyfert-like component was typically 4-5 times weaker than the flat jet component. Thus in PKS 0537–286 we may be observing two X-ray components; the steep Seyfert-like emission from near the disk, responsible for the iron K line, and the

**Table 1.** X-ray spectral fits to PKS 0537–286.

| Fit | Model                  | $T$   | Iron line | Iron edge | Reflection | $\chi^2$/dof |
|-----|------------------------|-------|-----------|-----------|------------|--------------|
| 1.  | PL only                | 1.27±0.02 | 6.15±0.15 | 7.1       | 0.05±0.05  | 1049.2/1000  |
| 2.  | PL + GA + EDGE         | 1.27±0.02 | 6.15±0.15 | 7.1       | 0.05±0.05  | 1038.5/997   |
| 3.  | PL + GA + PEXRAV       | 1.28±0.04 | 6.15     | 33        | 0.25±0.11  | 1044.5/998   |
| 4.  | PL + GA + PEXRAV       | 1.29±0.04 | 6.15±0.15 | 33        | 0.11±0.09  | 1038.6/998   |
| 5.  | PL + GA + PEXRAV       | 1.30±0.04 | 6.15±0.15 | 33        | 0.03±0.03  | 1036.9/998   |

The small amount of reflection (with $R < 0.25$) is consistent with the low equivalent width of the iron K line.

We note however, that our assumption for the high energy cut-off of the hard X-ray power-law may affect the fits. To test this we tried two additional fits, one with a cut-off at 250 keV and one fit with no high energy cut-off (fits 4-5). For the former we find that the reflection component is even weaker ($R < 0.25$), whilst with no cut-off the value of $R$ is consistent with zero ($R < 0.10$). Comparing the statistics of fits 3-5, there is a preference for very weak reflection and no high energy cut-off, although the differences are not significant. Finally we tried fixing $R$ at 1 in our fits. In this case, whatever cut-off energy was assumed, the fit obtained was always considerably worse (by $\Delta \chi^2 > 100$, or at > 99.99% confidence).

**3.4. The Spectral Energy Distribution of PKS 0537–286**

In Figure 5, we compile all the published multi-wavelength data on PKS 0537–286, together with the **XMM-Newton** spectrum. The SED (spectral energy distribution) of PKS 0537–286 is extreme when compared to a typical radio-loud quasar (Elvis et al. 1994). In PKS 0537–286 the region) was $9.0 \times 10^{-5}$ ct s$^{-1}$, consistent with the value given above, corresponding to only 5% of the quasar line counts. Therefore it is highly unlikely that the background subtraction at 1.5 keV contributes towards the detection of the quasar iron K line.

**3.3. Constraints on the Compton Reflection Continuum**

Having detected these weak iron K features, we next tried to constrain the properties of the Compton reflection ‘hump’, particularly as the observed emission extends up to 40 keV in the quasar rest frame. We used the PEXRAV model in XSPEC (Magdziarz & Zdziarski 1995), assuming a disk inclination of 30° and a high energy cut-off equal to 100 keV. We left $R$, the fraction of material (of $2\pi$ steraian solid angle) that is irradiated by the X-ray source (where $R = \Omega / 2\pi$), as a free parameter in the fits. The results are given as fit 3. We find a best-fit value for the reflection continuum of $R = 0.25^{+0.11}_{-0.09}$ indicating that the reflecting material subtends a solid-angle lower than the $2\pi$ steraian expected from an accretion disk geometry. The small amount of reflection (with $R < 0.25$), is consistent with the low equivalent width of the iron K line.

We note however, that our assumption for the high energy cut-off of the hard X-ray power-law may effect the fits. To test this we tried two additional fits, one with a cut-off at 250 keV and one fit with no high energy cut-off (fits 4-5). For the former we find that the reflection component is even weaker ($R = 0.11^{+0.09}_{-0.08}$), whilst with no cut-off the value of $R$ is consistent with zero ($R < 0.10$). Comparing the statistics of fits 3-5, there is a preference for very weak reflection and no high energy cut-off, although the differences are not significant. Finally we tried fixing $R$ at 1 in our fits. In this case, whatever cut-off energy was assumed, the fit obtained was always considerably worse (by $\Delta \chi^2 > 100$, or at > 99.99% confidence).
hard component from the jet, which considerably dilutes
the disk reflection and line features.

This provides a possible explanation for the apparent
weakness of the iron K line and Compton reflection hump,
when compared to other observations of Seyfert galaxies
and quasars. If the relativistic jet is orientated close to
the line-of-sight, as expected in unification schemes for
quasars (Antonucci 1993), then any disk reflection fea-
tures can be diluted due to Doppler boosting of the fea-
tureless X-ray continuum, through the bulk motion of
the jet. This is consistent with other observations of X-
ray luminous, predominantly radio-loud quasars, where
the strength of the iron line is diminished (the so-called
‘X-ray Baldwin effect’ - Iwasawa & Taniguchi 1993). For
PKS 0537−286, at a redshift of z = 3.104, any iron K
emission features are redshifted into a more favourable
part of the EPIC bandpass, where the effective area is
near its maximum. This has enabled us to detect a weak
iron K line in PKS 0537−286; indeed at z = 3.104 this is
the most distant iron K emission line detected to date. The
limited statistics do not allow the line width or shape to
be constrained. However, the median energy of 6.15 keV
implies reprocessing in ‘cold’ matter close to the central
black hole or from infalling material at v ∼ 13000 km s−1.
Clearly, more detailed studies with XMM-Newton of other
high redshift quasars, both radio-loud and radio-quiet, are
required to explore this.

Past studies with ROSAT and ASCA have showed that
several high redshift radio-loud quasars appear to show in-
trinsic X-ray absorption, above that from our own Galaxy
(see Bechtold et al. 1994, Elvis et al. 1994b, Reeves et al.
1997, Cappi et al. 1997, Fiore et al. 1998). Correlations
involving samples of quasars (Reeves et al. 1997, Reeves
& Turner 2000) have showed that this apparent excess
absorption is correlated with object redshift, with many
high z quasars requiring substantial absorption columns
(up to 10^{22} cm^{-2}), whilst low z quasars remain unab-
sorbed. Recently even, evidence has been presented for
substantial soft X-ray absorption towards one blazar-like
object (GB 1428+4217) at z = 4.71 (Boller et al. 2000).
At present the nature of this absorption is unclear, but it
could be related to the dense Galactic-scale environments
proposed in the early evolutionary stages of quasars (see
Fabian 1999). Alternatively in some objects the X-ray ab-
sorption may originate from intervening damped Lyman-α
systems, which are thought to be associated with the disks
of young protogalaxies (e.g. Wolfe et al. 1994).

From the published optical (rest frame UV) spectrum,
it is known that PKS 0537−286 has substantial UV ab-
sorption, with at least two different Lyman-limit sys-
tems observed close to the known redshift of the quasar
(Wright et al. 1978, Osmer et al. 1994). The velocities
of these systems are Δv = 4200 and 40000 km s−1,
blueshifted with respect to the quasar. The latter system
has a very deep Lyman-continuum cut-off at 912 Å (rest
frame), where the quasar continuum flux drops close to
zero. So it perhaps seems surprising at first that in this
XMM-Newton observation we detect no intrinsic X-ray
absorption towards PKS 0537−286. However in order to
measure appreciable line-of-sight X-ray absorption (of the
order NH ∼ 10^{22} cm^{-2}), one would have to encounter a
damped Lyman-α system. We can now rule this scenario
out in PKS 0537−286, and note the chance coincidence of
such a system out to z = 3 is ∼20-30% (e.g. Steidel 1992).

The XMM-Newton observation is in contrast to some
earlier ASCA and ROSAT observations of PKS 0537−286,
where a low energy X-ray cut-off had been claimed (Reeves
& Turner 1997, Cappi et al. 1997). One possibility is that
the absorption is variable; we note the ‘warm’ absorbers
observed in low z AGN are known to vary (e.g. MCG-6-
30-15, Otani et al. 1996; NGC 3227, George et al. 1998).
It is also possible that if the absorption is associated with
a high velocity system, the absorbing material may move
out of the line-of-sight. Finally, the photon statistics on
the earlier ASCA and ROSAT observations were quite
poor, so it is possible that the earlier detection was spuri-
ous. We conclude that it will be particularly important to
utilise future XMM-Newton observations to estimate the
frequency of these ‘absorbed quasars’, as a probe of some
of the most distant matter in the Universe, and to deter-
mine the environments of some of the earliest quasars.

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