**XMM–Newton observations of GB B1428+4217: confirmation of intrinsic soft X-ray absorption**

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**ABSTRACT**

We report the results of XMM–Newton observations of the X-ray bright, radio-loud blazar GB B1428+4217 at a redshift of \( z = 4.72 \). We confirm the presence of soft X-ray spectral flattening at energies \( \lesssim 0.7 \) keV as reported in previous ROSAT and BeppoSAX observations. At hard X-ray energies, the spectrum is consistent with a power law, although we find that the spectral slope varied between both XMM–Newton observations and it is also significantly different from that reported previously. Whilst we cannot rule out intrinsic cold absorption to explain the spectral depression, we favour a dust-free warm absorber. Cold absorption requires a column density \( \sim 1.4–1.6 \times 10^{22} \) cm\(^{-2} \), whilst a warm absorber could have up to \( \sim 10^{23} \) cm\(^{-2} \) and an ionization parameter \( \sim 10^{7} \). The spectrum of GB B1428+4217 shows remarkable parallels with that of the \( z = 4.4 \) blazar PMN J0525–3343, in which the available evidence is also most consistent with a warm absorber model.

**Key words:** galaxies: active – galaxies: individual: GB B1428+4217 – X-rays: galaxies.

**1 INTRODUCTION**

High-redshift quasars are important objects in the study of the early evolution of massive black holes and their interaction with their host galaxies. A number of radio-loud quasars have been found to show the spectral characteristics typical of blazars. GB B1428+4217, at \( z = 4.72 \) (Hook & McMahon 1998; Fabian et al. 1997, 1998, 1999) displays spectral flattening at soft X-ray energies in ROSAT (Boller et al. 2000) and BeppoSAX (Fabian et al. 2001b) data. Here, we confirm the flattening with XMM–Newton observations. Soft X-ray flattening has also been reported from RX J1028.6–0844 (Yuan et al. 2000) and PMN J0525–3343 (Fabian et al. 2001a) at redshifts of \( z = 4.28 \) and 4.4, respectively. XMM–Newton data shows only marginal evidence for flattening in the case of RX J1028.6–0844 (Grupe et al. 2004). Conversely, the effect has been confirmed in PMN J0525–3343 (Worsley et al. 2004). Spectral flattening is consistent with a trend seen in a number of studies of lower-redshift radio-loud quasars (e.g. Cappi et al. 1997; Fiore et al. 1998; Reeves & Turner 2000).

The most consistent explanation for the flattening is intrinsic absorption with column densities of the order \( 10^{22–23} \) cm\(^{-2} \). Intergalactic absorption systems remain an unlikely possibility, given their low metallicities. Furthermore, in order to account for the flattening, the line of sight to the blazar would need to intercept two or more very high column density systems, an event of which the probability is very low. Certainly this explanation cannot account for the spectral depressions seen in an increasing number of objects. An alternative explanation for flattening is a break in the underlying blazar continuum. Hard X-ray production in blazars is likely to be due to the inverse Compton scattering of seed photons by relativistic electrons in the jet. A spectral break can arise through a low-energy cut-off in the electron population or by a peaked seed photon energy distribution; however, the break appears to be much too sharp for this to be plausible.

Given an intrinsic absorber hypothesis, there remains much discussion about the nature of the absorber. X-ray data alone have been unsuccessful in breaking the degeneracy between a cold (neutral) absorber or one that is warm (ionized). Optical observations, however, can play a crucial role in this regard. A number of the blazars showing soft X-ray flattening have optical spectra (corresponding to rest-frame UV emission) which indicate very little dust along the line of sight or show any evidence of a Lyman-limit system (for the optical data for GB B1428+4217 and PMN J0525–3343, see Hook & McMahon 1998 and Péroux et al. 2001). These point to a dust-free yet metal-enriched absorber where hydrogen has been ionized, consistent with the warm absorber such as that seen in Seyfert galaxies (e.g. Reynolds 1997; Crenshaw et al. 1999). Strong intrinsic C IV absorption is common in these galaxies and it is also a feature of PMN J0525–3343.

**2 PREVIOUS OBSERVATIONS**

GB B1428+4217 was discovered by Hook & McMahon (1998) in an optical survey for high-redshift quasars. An X-ray follow-up was conducted by Fabian et al. (1997) with the ROSAT HRI and ASCA.
Spectral fits were consistent with a power-law continuum with a photon index $\Gamma = 1.29$, although the ASCA SIS data alone were suggestive of some excess absorption. Subsequent ROSAT observations showed that X-ray flux varied by a factor of 2 over a time-scale of around 2.5 d in the rest frame of the source. Radio data also shows variability, with amplitudes of $\sim 40$ (15) per cent on rest-frame time-scales of weeks (days).

More evidence of X-ray variability was seen in a ROSAT PSPC observation (Boller et al. 2000), where changes of $\sim 25$ per cent occur on rest-frame time-scales of 1.8 h. The low-energy sensitivity of the PSPC detector clearly revealed a spectral depression in the soft X-ray band, consistent with an absorbing column density of $N_{\text{H}} \sim 1.5 \times 10^{22} \text{ cm}^{-2}$ (if intrinsic to the source).

Spectral flattening was further confirmed by BeppoSAX (Fabian et al. 2001b). The fitted spectrum was that of a $\Gamma = 1.45$ power law with an intrinsic absorption column density of $N_{\text{H}} \sim 8 \times 10^{22} \text{ cm}^{-2}$.

3 XMM–Newton OBSERVATIONS

3.1 Data reduction

XMM–Newton observed GB B1428+4217 on 2002 December 9 and again on 2003 January 17 (Table 1). All observations were performed in full-frame imaging mode with the thin filter. Data reduction was performed with the Scientific Analysis Software (SAS) v5.4.1. Periods of background flaring were excluded and the data were filtered in the standard way to include only the recommended events for spectral analysis (Ehle et al. 2003), i.e. using the event pattern ranges 0–4 and 0–12 plus the ‘FLAG = 0’ and #XMMMEA_EM filters for the pn and MOS cameras, respectively.

Spectra were extracted from circular regions centred on the source of approximate radius 40 and 60 arcsec for the pn and MOS cameras, respectively. Backgrounds were extracted from nearby source-free regions following the guidelines in Ehle et al. (2003). SAS tasks ARFGEN and RMFGEN were used to generate the appropriate response files. Background-subtracted spectra were produced and grouped to a minimum of 20 counts in each bin. Spectral analysis was performed using XSPEC v11.3.0 (Arnaud 1996).

3.2 Spectral properties

Spectral fits to a simple power law inclusive of neutral galactic absorption ($N_{\text{H}} = 1.40 \times 10^{20} \text{ cm}^{-2}$; Elvis, Lockman & Fassnacht 1994) were made over the energy range 1–12 keV. The pn and MOS data were fitted simultaneously, but the revolution 549 and 569 observations were treated separately due to source variability. 1–12 keV power-law photon indices of $\Gamma = 1.88 \pm 0.05$ and $\Gamma = 1.73 \pm 0.03$ were obtained, with 2–10 keV fluxes of $1.22 \times 10^{-12}$ and $1.09 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, respectively. Reduced chi-squared values for the fits were $\chi^2_{\text{red}} = 0.819$ and $\chi^2_{\text{red}} = 0.883$ (with $\nu = 100$ and $\nu = 283$ degrees of freedom), respectively. These can be compared to only $\chi^2_{\text{red}} = 1.06$ ($\nu = 385$) with an attempt to fit the same model to the data from both observations simultaneously.

A significant depression in the soft X-ray spectrum is seen when the whole 0.3–12 keV energy range is considered. The chi-squared statistic of the power-law models rises to $\chi^2_{\text{red}} = 1.245$ and $\chi^2_{\text{red}} = 1.302$ (for $\nu = 173$ and $\nu = 430$ degrees of freedom, respectively). Fig. 1 shows the ratio of the revolution 549 and 569 data to the 1–12 keV fitted power law. Spectral flattening is clear in both observations, with a break from the power law occurring at energies $\sim 0.6$–1 keV and the data/model ratio decreasing to $\sim 0.7$ at $\lesssim 0.4$ keV.

Even though there has been a significant decrease in flux between the observations (and possibly spectral slope variations), it remains instructive to consider the combined pn spectra in the search for spectral features which may exist at the same energy independently of other variations. To this end, the good pn camera events from both observations were merged and a single spectrum was extracted. Fig. 2 shows the ratio of the data to a 1–12 keV fitted power law with

<table>
<thead>
<tr>
<th>Revolution</th>
<th>Date</th>
<th>Good exposure times (s)</th>
<th>pn</th>
<th>MOS-1</th>
<th>MOS-2</th>
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<tr>
<td>549</td>
<td>2002 December 09</td>
<td>2625</td>
<td>4055</td>
<td>4260</td>
<td></td>
</tr>
<tr>
<td>569</td>
<td>2003 January 17</td>
<td>11534</td>
<td>14241</td>
<td>14235</td>
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The ~10 per cent reduction between the observations corresponds to a variability time-scale of ~7 d in the rest frame.

In addition to the decrease in luminosity, there are differences in the spectral properties of the source between observations. The revolution 549 data are well-fitted (in the 1–12 keV range) by a simple power law with a photon index of $\Gamma \sim 1.9$, whilst this is hardened to $\Gamma \lesssim 1.8$ during the revolution 569 observation. The break energy and soft X-ray photon index (and, equivalently, the column densities in the absorption models) are in good agreement between the observations.

There would also seem to be significant variations in the spectral shape between the XMM–Newton and earlier observations. The continuum slopes (i.e. after correction for any soft X-ray flattening) reported by ROSAT and BeppoSAX (Boller et al. 2000; Fabian et al. 2001b) were 1.4 ± 0.2 and 1.45 ± 0.1, respectively – considerably harder than the ~1.7–1.9 found with XMM–Newton. The spectral break is characterized by the column density required of an intrinsic cold absorber, the ROSAT and BeppoSAX values of which are 1.5 ± 0.3 × 10$^{22}$ and 7.8$^{+6.8}_{-5.3}$ × 10$^{22}$ cm$^{-2}$, consistent with each other and the value of ~1.4–1.6 × 10$^{22}$ cm$^{-2}$ found here.

There is marginal evidence of curvature in the residuals of the XMM–Newton fits to the 1–12 keV power law, with excesses at ~1–2 and ~5–10 keV and a deficit over ~2–5 keV (Fig. 1). The $\gtrsim 5$ keV range appears to have a harder power law (Γ ~ 1.5), which is in better agreement with the ROSAT and BeppoSAX results. A steeper 1–12 keV slope and curved residuals in the XMM–Newton data could possibly then be the result of a ~1–3 keV variable excess (~5–20 keV rest frame) superimposed upon the soft X-ray break.

To investigate further, a difference spectrum was formed by subtracting the revolution 569 spectrum from the revolution 549 one. The difference is well-fitted by a power-law model (inclusive of Galactic absorption and an intrinsic cold absorption of $N_H = 1.5 \times 10^{22}$ cm$^{-2}$) with a spectral slope of $\Gamma = 2.3 \pm 0.3$. A two power-law model (again inclusive of Galactic and intrinsic absorption) is also an acceptable fit to both data sets. The soft power-law component has $\Gamma \sim 1.8–2.6$ and the hard power-law component has $\Gamma \lesssim 1.7$.

The curved residuals, 1–3 keV excess and the success of the two power-law model point to the intriguing possibility that the spectrum may contain a additional component. The steepness ($\Gamma \sim 2.3$) of the soft component is consistent with the high-energy cut-off of a second inverse-Compton contribution. Possibilities for such a component are an underlying pile-up in the external Compton (EC) seed photon distribution (see Section 4.2), an EC component with a different external photon source, synchrotron self-Compton (SSC) emission or a bulk Compton component due to inverse-Compton scattering from a cold electron population.

### 3.3 Variability

Background-corrected light curves were extracted for both observations. The good-time-interval light curve from the revolution 549 observation is fully consistent with a constant flux (the pn count rate is 0.73 count s$^{-1}$ corresponding to 1.22 × 10$^{-12}$ erg cm$^{-2}$ s$^{-1}$). Unfortunately, the remaining ~60 per cent of the observation was affected by solar flare activity and reliable background subtraction could not be performed. The revolution 549 observation suffered from no flare periods, and ~12 ks of pn data were extracted; again, this is consistent (at the 90 per cent level) with a constant flux (a pn count rate of 0.54 count s$^{-1}$ corresponding to 1.09 × 10$^{-12}$ erg cm$^{-2}$ s$^{-1}$). The ~10 per cent reduction between the observations corresponds to a variability time-scale of ~7 d in the rest frame.

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4 DISCUSSION

There are two main possibilities for the origin of the spectral flattening observed in GB 1428+4217. The first, and our favoured explanation, is that the flattening is due to excess intrinsic absorption. The second hypothesis attributes the effect to a break in the underlying blazar emission continuum. These two alternatives are now discussed separately.

4.1 Absorption

A galactic origin to the excess column density is extremely unlikely; it would require a factor of ∼3.6 increase in the galactic column density, highly localized in the direction of GB B1428+4217. Inter-galactic absorption is also highly unlikely, the only possibility being a line of sight that passes through two or more very high column density damped Lyα systems, for which the probability is very low (O’Flaherty & Jakobsen 1997; Zwaan, Verheijen & Briggs 1999). If an absorber is the origin of the X-ray flattening, it must therefore be metal-rich and intrinsic to the source. A cold absorber model requires a column density in the region of 1.4–1.6 × 10^22 cm^{-2}.

A warm (ionized) absorber is able to reproduce both low UV and high X-ray column densities. Photoionized gas could produce significant photoelectric absorption in the soft X-ray band (mainly due to oxygen and neon species) whilst remaining transparent at UV wavelengths (hydrogen/helium both ionized). Additionally, any dust grains could be destroyed by the intense photon flux, resulting in low levels of extinction in the UV band.

The photoionization code CLOUDY (Ferland et al. 1998) was used to model the warm absorber hypothesis. Fig. 4 shows the confidence contours in the warm absorber ionization parameter and column density for the two separate observations. Neither set of contours strongly constrains the ionization parameter, provided that ξ ≲ 10^2 erg cm s^{-1}. The column density is in the range 10^{22} ≲ N_H ≲ 10^{23} cm^{-2}.

It is difficult to break this degeneracy with X-ray observations. The conclusion of a warm absorber would be the detection of photoelectric absorption edges, principally those arising from O/Ne. Due to the high redshift of the source however, these features are redshifted out of the observed band to energies ≲ 0.2 keV. A strong discriminator would be evidence of Lyman-limit absorption at 5217 Å (the present optical data start at 5970 Å). This would place constraints on the neutral hydrogen column density and thus on the ionization state of the absorber. The lack of an optically thick Lyman-limit system would immediately place an upper limit to the H1 column density of ∼10^{17} cm^{-2}, requiring the warm absorption model to have an ionization parameter ξ ≳ 1 erg cm s^{-1}.

4.2 Intrinsic spectral properties

The revolution 549 and 569 spectra can be acceptably fitted with a broken power-law model with a break at an energy ∼0.6–0.7 keV down to a flat spectral index ∼0.7–1.1. In the rest frame (Fig. 2), the break energy is ∼4 keV and is very distinct, occurring over a range of ∼2 keV. The z = 4.4 blazar PMN J0525–3343 is similar with a sharp spectral break at a rest-frame energy of ∼4.5 keV over an energy range ≲ 5 keV.

The dominant emission components in blazars are beamed synchrotron radiation from the jet (peaking in the infrared to soft X-ray band) and a high-energy component (dominating the hard X-ray to γ-ray regimes). The high-energy emission arises through the inverse Comptonization of soft photons by highly relativistic electrons in the jet plasma. Sources of the soft photons are the nuclear optical/UV emission or the local synchrotron radiation within the jet. For the brightest blazars (such as GB B1428+4217 and PMN J0525–3343), the first, known as the EC mechanism, is dominant (Sikora, Begelman & Rees 1994).

A flattening in the spectrum could be expected if there was a low-energy cut-off in the energy distribution of the electron population in the jet. In the case of the EC process, it is also possible to produce a spectral break by requiring the seed photon distribution to be sharply peaked at and/or rapidly decline below a certain frequency. There are several problems with these explanations. First, there is no evidence of any spectral breaks in the spectra of nearby radio-loud quasars, and secondly, there seems to be no plausible way to account for the sharpness of the break (only a few keV in the rest frame). For a more detailed discussion of the break-producing mechanisms, see, for example, Fabian et al. (2001a).

4.3 Comparisons with other objects

Fig. 5 shows the rest-frame combined pn spectrum of GB B1428+4217 (as a ratio to the power law above the spectral break) along with the equivalent result for PMN J0525–3343 (Worsley et al. 2004). The agreement in the position and structure of the break is remarkable. The plots are of data-to-model ratio, the instrumental response (and the Galactic absorption) have been removed. In both cases, the break from the power law occurs over a range of ≲ 5 keV in the source frame and to a photon index of Γ ∼ 1. Both also show a steeper drop in the flux at 3 keV.

If the spectral flattening is indeed due to warm absorption, then the absorbers for GB B1428+4217 and PMN J0525–3343 are almost identical in column density (of ∼2–4 × 10^{22} cm^{-2}). There is also evidence for a similar column in the XMM–Newton observations of RX J1028.6–0844 (Grupe et al. 2004), where joint fits to the XMM–Newton and previous ASCA data (Yuan et al. 2000) are consistent with an excess intrinsic column density of ∼1 × 10^{22} cm^{-2}.

5 CONCLUSIONS

We have studied the X-ray spectrum of the high-redshift, radio-loud blazar GB B1428+4217, providing definitive confirmation of the
The implied iron abundance of a warm absorber, however, is at again most able to explain the lack of significance (Ferrero & Brinkmann 2003; Fiore et al. 2003). Both warm and cold absorbers are consistent, although ionized absorption is inconsistent with both warm/cold absorption, but optical observations rule out a cold absorber scenario. The lack of significance in the UV spectra of both objects is consistent with a dust-free warm absorber that is intrinsic to the source, or to an underlying break in the blazar continuum.

A continuum break is highly speculative, given the present lack of knowledge concerning emission processes in the nuclear regions. Continuum breaks are not seen in nearby radio-loud objects where they should be readily detectable and there is no satisfactory way to account for the observed sharpness of the break. An intrinsic absorber is therefore our favoured explanation. Cold absorption requires a column density $N_H \sim 1.4-1.6 \times 10^{22} \text{ cm}^{-2}$, whilst a warm absorber could have a column density of up to $\sim 10^{23} \text{ cm}^{-2}$ and an ionization parameter $\xi \sim 10^2$. X-ray data alone are unable to distinguish between a warm or cold absorber model. Good constraints are expected from future optical observations which could place strong limits on the neutral hydrogen column density.

It is interesting to note the parallels with the blazar PMN J0525–3343 (Worsley et al. 2004), namely a relatively blue UV continuum with strong Ly$\alpha$ and C iv emission lines as well as the flat hard X-ray spectral slope and the remarkably similar form of the soft X-ray depression. The PMN J0525–3343 X-ray data are consistent with both warm/cold absorption, but optical observations rule out a cold absorber scenario. The lack of significant reddening in the UV spectra of both objects is consistent with a dust-free warm absorber.

Comparisons can also be drawn to the $z = 3.27$ radio-loud quasar PKS 2126–0158, which also shows definite soft X-ray absorption (Ferrero & Brinkmann 2003; Fiore et al. 2003). Both warm and cold absorbers are consistent, although ionized absorption is again most able to explain the lack of significant UV reddening. The implied iron abundance of a warm absorber, however, is at odds with the supersolar abundances implied by broad emission lines.

The spectrum of GB B1428+4217 is suggestive of an additional component contributing to an excess of emission in the $\sim 5–10 \text{ keV}$ rest-frame energy range. There are a number of possibilities for the emission, including a pile-up in the electron energy distribution or a feature caused by bulk Comptonization; however, the detection is marginal and further work is required.

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