ROSAT PSPC detection of soft X-ray absorption in GB 1428+4217: The most distant matter yet probed with X-ray spectroscopy

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ABSTRACT

We report on a ROSAT PSPC observation of the highly-luminous $z = 4.72$ radio-loud quasar GB 1428+4217 obtained between 1998 December 11 and 17, the final days of the ROSAT satellite. The low-energy sensitivity of the PSPC detector was employed to constrain the intrinsic X-ray absorption of the currently most distant X-ray detected object. Here we present the detection of significant soft X-ray absorption towards GB 1428+4217, making the absorbing material the most distant matter yet probed with X-ray spectroscopy. X-ray variability by $25\pm8$ per cent is detected on a timescale of 6500 s in the rest frame. The X-ray variation requires an unusually high radiative efficiency $\eta$ of at least 4.2, further supporting the blazar nature of the source.

Key words: galaxies: active – galaxies: individual: GB 1428+4217 – X-rays: galaxies

1 INTRODUCTION

Observations of high redshift quasars are of wide cosmological importance since these objects are thought to be associated with the earliest collapsed structures. Many high-redshift radio-loud quasars have recently been found to show low-energy X-ray cutoffs, and these are believed to be associated with intrinsic X-ray absorbers of column densities several times $10^{22}$ cm$^{-2}$ (e.g. Elvis et al. 1994a; Elvis et al. 1998; Fiore et al. 1998). The radio-loud quasar GB 1428+4217 is currently the most distant X-ray detected object. It has been studied with the ROSAT HRI and ASCA (Fabian et al. 1997, 1998). These observations revealed an extreme isotropic X-ray luminosity of about $1.3 \times 10^{47}$ erg s$^{-1}$ as well as variability by a factor of 2 on a timescale of about 2.4 days in the rest frame.

The ASCA observations did not allow tight constraints to be placed on X-ray absorption due to the lack of low-energy response in the 0.1–0.5 keV band and the limited low-energy calibration. The ROSAT HRI did not give the needed spectral information. Therefore, we proposed GB 1428+4217 for observation during the last ROSAT observations in December 1998, employing the excellent low-energy sensitivity of the PSPC detector to constrain the intrinsic X-ray absorption in GB 1428+4217 as well as search for flux and associated spectral variability.

A value of the Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and a cosmological deceleration parameter of $q_0 = \frac{1}{2}$ have been adopted throughout.

2 THE ROSAT PSPC OBSERVATIONS FROM DECEMBER 1998

2.1 Data quality assessment

The ROSAT PSPC observations of GB 1428+4217 were performed in the final observation period which was affected by some anomalies. Therefore careful data reduction and cleaning were required. The first anomaly was an occasional breakdown of the high voltage which was not recorded by the housekeeping system. These periods can be identified by unusually low master veto rates ($MV < 35$ counts s$^{-1}$). Moreover, the high voltage showed occasional flickering which caused periods of frequent short accepted time intervals ($< 10$s) where the nominal voltage (and thus gain value) may not be reached. Finally, a gain hole in the PSPC detector began to develop which can currently not be corrected for and came close to the on-axis position after 1998 December 13 (cf. the December month page of the ROSAT 2000 calendar). We therefore selected only time intervals before 1998 December 13 with master veto rates between 35 and 300 counts s$^{-1}$ and durations exceeding 100 s (see summary in Table 1). We have verified that within our time selection the on-axis position is not affected by the presence of
the gain hole employing the nominal gain-corrected energy image of the Al Kα line.

Additionally, we wanted to ensure that residual gain uncertainties do not affect the data quality. We have checked the onboard Al Kα measurements that were taken at spacecraft clock times (approximate seconds after launch) \( \text{SCC} = 269147793 - 269148181 \) (1998-Dec-12, 00:23 - 00:29 UT) and at \( \text{SCC} = 269196947 - 269197310 \) (1998-Dec-12, 14:02 - 14:08 UT) and could not find significant variations of the peak of the pulse height distribution. Moreover, effects due to gain uncertainties dominate at higher pulse height amplitudes and our analysis concentrates on the softer energy range. Nevertheless, we re-processed our events with varying gain values (±1.4 channels) to confirm that this effect is unimportant in our case (see the Appendix).

We note that calibration uncertainties in the very softest channels may be present, and some authors find indications that the ROSAT PSPC effective area may actually be larger than expected (e.g. Wolff et al. 1996). This would cause the column densities measured below to be systematically low, and it would only increase the intrinsic absorption in GB 1428+4217.

### 2.2 X-ray data analysis

The analysis of the cleaned ROSAT PSPC data was performed using the EXSAS software package (Zimmermann et al. 1994). The centroid position of GB 1428+4217 in the ROSAT PSPC image is R.A.(2000) = 14°30’22.0" ± 0.72", Dec.(2000) = 42°04’41" ± 11". The internal PSPC position error is about 20 arcsec. The total exposure spent on the source was 9446 seconds. The source counts were obtained using a circular source cell of radius 2.33 arcmin. The number of source plus background counts within that cell is 1669 ± 41. The background was determined from a source-free circular cell with a radius of 8.1 arcmin centered at R.A.(2000) = 14°30’28.2" ± 5.97", Dec.(2000) = 42°09’41" (a nearby X-ray source at a distance of 4.5 arcmin prevented us from using an annulus around the centroid position of GB 1428+4217).

The number of background counts expected in the source cell is 190 ± 14. The net source counts are therefore 1479 ± 43, resulting in a mean count rate of 0.156 ± 0.004 counts s⁻¹ in the 0.1–2.4 keV energy range. The timing properties of GB 1428+4217 are discussed in Section 4.

### 2.3 Constraining the intrinsic X-ray absorption

In the following we constrain the spectral properties of GB 1428+4217. The confidence intervals for the ROSAT fit parameters presented below correspond to 90 per cent intervals. First, we have performed a power-law fit (cf. Figure 1) with the neutral absorption column density constrained to be consistent with the Galactic value of \( N_{\text{H,Gal}} = (1.4 ± 0.4) \times 10^{20} \text{cm}^{-2} \). While this fit is statistically acceptable, it shows clear systematic residuals at low energies, and the derived photon index of 1.04±0.18 is substantially flatter than that measured by ASCA (1.29±0.05; Fabian et al. 1998).

The photon index was allowed to vary within the range found by ASCA. Such a model can be statistically rejected with a probability of 98.7 per cent using the \( \chi^2 \) distribution.

\[ \chi^2 = \frac{1}{2} \left( \frac{N_{\text{H,Gal}}}{(1.4±0.4) \times 10^{20} \text{cm}^{-2}} \right) \]
The absorbing column is given in units of $10^{20}$ cm$^{-2}$. Assuming intrinsic X-ray absorption the absorbing column is $N_{\text{H,fit}} = (3.14 \pm 0.35) \times 10^{20}$ cm$^{-2}$. Assuming iron K-dip at 1.2 keV is near the observed frame energy for the dip at 1.2 keV is near the observed frame energy for the iron Kα line. The spectral energy resolution of the PSPC detector is not able to resolve any iron emission line shifted into the ROSAT energy band. These features may therefore occur in CSO 0454 (see Section 4 and Figure 5).

The residuals of the power-law fit to GB 1428+4217 (cf. Figure 2) results in $N_{\text{H,fit}} = (3.10 \pm 0.28) \times 10^{20}$ cm$^{-2}$ for neutral gas and $N_{\text{H,fit}} = (3.35 \pm 0.20) \times 10^{20}$ cm$^{-2}$ for neutral gas and solar abundances. With the current data we are unable to precisely constrain the ionization level of the absorbing gas; our only constraint is that oxygen must not be completely stripped. However, we note that increasing the gas' ionization level will require even larger column densities than the substantial one already derived for neutral gas.

In the Appendix we have modeled the influence of different gain values on the soft X-ray absorption. With Figure A1 in the Appendix we demonstrate that even in the case of unusual gain values the excess absorption above the Galactic column is still present.

Interestingly, there is another bright X-ray source (the blazar CSO 0454 = 1H 1430+423, $z = 0.129$) in the field of view, which can be used to demonstrate that there is not a relevant systematic effect in determining the excess absorption. The source is outside the gain hole and no other effects prevented the reliable analysis of the data for this source. A power-law fit combined with absorption by neutral matter (Figure 4) results in $N_{\text{H,fit}} = (1.50 \pm 0.17) \times 10^{20}$ cm$^{-2}$, in good agreement with the Galactic column density. In addition, the X-ray variability found in GB 1428+4217 does not occur in CSO 0454 (see Section 4 and Figure 5).

GB 1428+4217 is clearly detected in the ROSAT All-Sky Survey with a detection likelihood of 35 (see Cruddace et al. 1988 for the definition of the detection likelihood). The ROSAT PSPC count rate is $0.046 \pm 0.011$ counts s$^{-1}$. The exposure time is 639 seconds. The number of source photons detected during the survey observations do not allow precise spectral fitting and the soft X-ray absorption cannot be well constrained.

The residuals of the power-law fit to GB 1428+4217 (cf. Figure 2) indicate the presence of peculiar ‘wiggles’ between about 0.8 and 1.4 keV. Their origin is presently unclear. The dip at 1.2 keV is near the observed frame energy for the iron Kα line. The spectral energy resolution of the PSPC detector is not able to resolve any iron emission line shifted into the ROSAT energy band. These features may therefore
Figure 4. Power-law fit to the ROSAT PSPC observations obtained in December 1998 of CSO 0454. The column density resulting from the fit is \( N_{\text{Hfit}} = (1.50 \pm 0.17) \times 10^{20} \text{ cm}^{-2} \). This value is significantly below \((3.14 \pm 0.35) \times 10^{20} \text{ cm}^{-2}\) found for the GB 1428+4217 further supporting the presence of significant soft X-ray absorption in GB 1428+4217.

only be due to noise. Neither the ASCA data (Fabian et al. 1998) nor the ROSAT All-Sky Survey data can rule out the presence of intrinsic residuals at the level seen in the present dataset. XMM-Newton observations of GB 1428+4217 may help to solve the origin of these peculiarities.

3 ORIGIN OF THE EXCESS ABSORPTION

Miralda-Escude (2000) has discussed the possibility that absorption by singly ionized helium (He II) in the intergalactic medium (IGM) might be detectable in the soft X-ray spectra of distant quasars. As GB 1428+4217 is the most distant X-ray loud quasar known, we have studied the effect of He II absorption in some detail. The analytic fit to the absorption cross-section presented by Verner et al. (1996) and values of \( \Omega_0 = 0.06 \) and \( \Omega_\Lambda = 0.3 \) were used. Unfortunately the effect of He II absorption is completely swamped by that of Galactic absorption in the direction of GB 1428+4217 which almost completely absorbs all 100 eV X-rays and considerably depletes them at 200 eV. If all the helium in the IGM is He II down to redshift 3, then it only causes a further 30 per cent drop in the observed flux at 200 eV which is quite insufficient to explain our observed spectrum (see Figure 2). In order to use soft X-ray absorption to measure intergalactic helium, a bright quasar, preferably a blazar, at \( z > 4 \) in the Lockman Hole is required.

Another, speculative, possibility is that we have detected absorption by intergalactic oxygen. As an example we have replaced He II with O VII in the above model and find a good fit with \( N_{\text{H}} \) at the Galactic value provided that the oxygen abundance in the IGM has almost the solar value down to \( z = 3 \) (setting \( N_{\text{H}} \) to the upper limit of \( 1.8 \times 10^{20} \text{ cm}^{-2} \) requires that the abundance of oxygen, all in the form of O VII, must exceed 40 per cent of the solar value). The abundance at least in oxygen must therefore be similar to that of the intracluster medium at low redshifts. This hypothesis can be tested by a search for the resonance absorption lines of oxygen in distant quasars (see Aldcroft et al. 1994).

The most probable explanation is that the downturn is due to absorbing material intrinsic to the host galaxy of the blazar. This material needs to be metal-rich (or very high column densities are required); our result of about \( 10^{22} \text{ cm}^{-2} \) assumes solar metallicity. An interesting possibility is that this gas is connected with the youth and possible formation of the host galaxy. Large column densities may be reasonably expected in such young objects (see e.g. Rees 1988; Fabian 1999). We note that the optical spectrum (Hook & McMahon 1998), which covers the rest-frame ultraviolet band of the object, indicates little dust along our line of sight or any large intrinsic absorption by hydrogen (i.e. any very large damped Lyman \( \alpha \) feature). This means that the absorbing material must be enriched but relatively dust free, and that the hydrogen in it must be ionized.

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4 TIMING PROPERTIES OF GB 1428+4217

Figure 5 (upper panel) displays the ROSAT PSPC light curve obtained for GB 1428+4217 between 1998 December 11 and 12. A constant model fit to the data points can be rejected with > 99 per cent confidence. Similarly, if we work out the Poisson probability of obtaining the last two data points given the mean of the first six data points, we obtain a probability of ≤ 2 × 10⁻³.

Using the mean of the first six data points and comparing it with the mean of the last two data points results to a variability amplitude of 25 ± 8 per cent. No significant spectral variability is detected upon examination of appropriate hardness ratios. Using the spectral parameters for GB 1428+4217 as displayed in Figure 2 the count rate variations translate into a 0.1–2.4 keV flux change in the observer’s frame of ∆F = 5.9 × 10⁻¹³ erg cm⁻² s⁻¹. The corresponding change in luminosity in the quasar’s rest frame (0.6–13.7 keV) is ∆L = 5.7 × 10⁴⁶ erg s⁻¹ (using the best-fitting spectral parameters and the cosmology given in Section 1) within ∆t = 37000 s, corresponding to about 6500 s in the rest frame. Applying the efficiency limit (Fabian 1979; Brandt et al. 1999), we derive a remarkable efficiency of η ≥ 4.2. The efficiency is significantly larger than even that obtained for the narrow-line quasar PHL 1092 (Brandt et al. 1999). Such a large derived efficiency strongly supports the evidence for relativistic flux boosting in the source and its blazar nature, previously discussed by Fabian et al. (1998).

The mean 0.1–2.4 keV flux obtained from the ROSAT observations of GB 1428+4217 between 1998 December 11 and 12 is F = 2.7 × 10⁻¹² erg cm⁻² s⁻¹, corresponding to an isotropic luminosity in the quasar’s rest frame of L = 2.6 × 10⁴⁷ erg s⁻¹. The ROSAT PSPC flux value is somewhat larger than the mean flux values previously reported for GB 1428+4217. Fabian et al. (1997) give a mean 0.1–2.4 keV flux of F = 9.0 × 10⁻¹³ erg cm⁻² s⁻¹ based on a ROSAT HRI observation on 1996 July 30. The ASCA 2–10 keV flux obtained on 1997 January 17 translates into an 0.1–2.4 keV flux of F = 1.3 × 10⁻¹² erg cm⁻² s⁻¹ (Fabian et al. 1998).

5 SUMMARY

In this paper we report on the detection of significant soft X-ray absorption in the most distant X-ray detected object, the highly X-ray luminous quasar GB 1428+4217, obtained during the last ROSAT observations in December 1998. The low-energy sensitivity of the PSPC detector was employed to constrain the intrinsic X-ray absorption. The soft X-ray absorption of N_{H,fit} = (3.14 ± 0.35) × 10²⁰ cm⁻² is larger than the Galactic column of N_{H,Grand} = (1.4 ± 0.4) × 10²⁰ cm⁻² towards GB 1428+4217 at the 5 sigma level. The inferred intrinsic column density is N_{H,fit} = (1.52 ± 0.28) × 10²⁰ cm⁻². The most probable explanation for the soft X-ray absorption is intrinsic absorption in GB 1428+4217. An interesting possibility is that this gas is connected with the youth and possible formation of the host galaxy. Absorption by intergalactic singly ionized helium (He ii), ionized oxygen (O vii) or an intrinsic break in the spectrum of GB 1428+4217 are found to be unlikely explanations for the soft X-ray absorption. X-ray flux variability by 25 ± 8 per cent is detected on a time scale of about 6500 s in the rest frame. The derived efficiency limit of η ≥ 4.2 is remarkably large and further supports the blazar nature of the object.

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APPENDIX A: DEPENDENCE OF GAIN VALUES ON THE X-RAY ABSORPTION

The nominal gain during the ROSAT PSPC observation of GB 1428+4217 is 102.7. With Figure A1 we demonstrate that even in the case of unusual gain values the excess absorption above the Galactic column is still present.
Figure A1. Influence of different gain corrections on the soft X-ray absorption. We demonstrate that even in the case of unusual gain corrections (101.5, 102.1, 103.3, and 103.9) the excess absorption above the Galactic column density is still present. A simple power-law fit where the absorption column density and the photon index are allowed to be free parameters is used to create the residuals.