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

Th. Boller,^{1*} A. C. Fabian,² W. N. Brandt³ and M. J. Freyberg¹

¹Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, 85748 Garching, Germany

²Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

³Department of Astronomy and Astrophysics, Penn State, 525 Davey Lab, University Park, PA 16802, USA

Accepted 2000 April 28. Received 2000 April 5; in original form 2000 February 21

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 ± 8 per cent is detected on a time-scale of 6500 s in the rest frame. The X-ray variation requires an unusually high radiative efficiency η 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, because 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 cut-offs, 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 1.3×10^{47} erg s⁻¹ as well as variability of a factor of 2 on a time-scale of about 2.4 d in the rest frame.

The ASCA observations did not allow tight constraints to be placed on X-ray absorption, owing 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 1998 December, employing the excellent low-energy sensitivity of the PSPC detector to constrain the intrinsic X-ray absorption in GB 1428+4217 as well as to search for flux and associated spectral variability.

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

2 THE *ROSAT* PSPC OBSERVATIONS FROM 1998 DECEMBER

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 ($MV < 35 \text{ count s}^{-1}$). 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) might not be reached. Finally, a gain hole in the PSPC detector began to develop, which currently cannot be corrected for; this 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 count s^{-1} and durations exceeding 100s (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 K α line. Additionally, we wanted to ensure that residual gain uncertainties do not affect the data quality. We have checked the onboard Al K α measurements that were taken at spacecraft clock times (approximate seconds after launch) SCC = 269147793 - 269148181 (1998 Dec 12, 00:23-00:29 UT) and at 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

^{*} E-mail: bol@mpe.mpg.de

Table 1.Observationlogof180308p (selected period).

Start UTC	1998 Dec 11 17:17
Start SSC	269122244
End UTC	1998 Dec 12 09:35
End SCC	269180932
Exposure	9446 s
Average MV	$114.9 \text{count s}^{-1}$
Eff.gain	102.7

resulting from gain uncertainties dominate at higher pulse height amplitudes and our analysis concentrates on the softer energy range. Nevertheless, we reprocessed 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, Jordan & Koester 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 RA (2000) = $14^{h}30^{m}22^{\circ}0 \pm 0^{\circ}72$, Dec. (2000) = $42^{\circ}04'41'' \pm 11''$. The internal PSPC position error is about 20 arcsec. The total exposure spent on the source was 9446 s. 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 centred at RA (2000) = $14^{h}28^{m}59^{\circ}7$, Dec. (2000) = $42^{\circ}09'41''$ (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 count 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. Fig. 1) with the neutral absorption column density constrained to be consistent with the Galactic value of $N_{\rm H,Gal} = (1.4 \pm 0.4) \times 10^{20} \, {\rm cm}^{-2}$ (Dickey & Lockman 1990; Elvis, Lockman & Fassnacht 1994b). While this fit is statistically acceptable [$\chi^2 = 120$ for 114 degrees of freedom (d.o.f.)], it shows clear systematic residuals at low energies (upper panel of Fig. 1), 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). While we cannot statistically rule out a flattening of the intrinsic continuum at low energies, such flattenings are not usually seen in active galaxies, and the intrinsic continuum would need to be exceptionally hard.



Figure 1. Upper panel: power-law plus Galactic column fit to the *ROSAT* PSPC observations obtained in December 1998 of the z = 4.72 radio-loud quasar GB 1428 + 4217. The column density was allowed to vary within its measurement error $N_{\rm H,Gal} = (1.4 \pm 0.4) \times 10^{20} \, {\rm cm}^{-2}$. 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). Lower panel: 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 χ^2 distribution.

Furthermore, we note that *ROSAT* versus *ASCA* calibration discrepancies cannot easily explain a systematically flatter *ROSAT* continuum (*ROSAT* slopes, if anything, appear to be systematically steeper than *ASCA* slopes; see Iwasawa, Fabian & Nandra 1999). If we require the photon index to lie within the *ASCA* range of 1.29 ± 0.05 and the column density to lie within the range consistent with the Galactic value, the fit can be statistically rejected with a probability of 98.7 per cent ($\chi^2 = 150$ for 114 d.o.f.; lower panel of Fig. 1). We conclude that plausible power-law models absorbed by the Galactic column density cannot provide an adequate fit to the *ROSAT* data.

A simple power-law fit where the absorption column density and the photon index are allowed to be free parameters provides a better statistical fit to the *ROSAT* PSPC data ($\chi^2 = 100$ for 113 d.o.f.; cf. Fig. 2). Using the *F*-test for the addition of one free parameter, one obtains $\Delta \chi^2 / \chi_{\nu}^2 = 22.7$ (cf. equations 11.50 of Bevington & Robinson 1992). According to Table C.5 of Bevington & Robinson (1992), this corresponds to a highly significant improvement (>99.9 per cent) in the fit quality. Most important, the soft X-ray absorption of $N_{\rm H,fit}^{z=0} = (3.14 \pm 0.35) \times 10^{20} \,{\rm cm}^{-2}$ is larger than the Galactic column towards GB 1428+4217 at the 5 σ level. The photon index is $\Gamma = 1.40 \pm 0.20$, in agreement with the



Figure 2. Power-law fit to the *ROSAT* PSPC observations obtained in 1998 December of the z = 4.72 radio-loud quasar GB 1428 + 4217. In the observer's frame the neutral absorbing column density is $N_{\rm H,fit}^{z=0} = (3.14 \pm 0.35) \times 10^{20} \,\rm cm^{-2}$. Assuming intrinsic X-ray absorption, the absorbing column is $N_{\rm H,fit}^{z=4.72} = (1.52 \pm 0.28) \times 10^{22} \,\rm cm^{-2}$.



Figure 3. Contour plot of χ^2 as a function of the absorbing column $N_{\rm H,fit}^{z=0}$ (*x*-axis) and the photon index Γ (*y*-axis) for five confidence levels of 68.3, 95.4, 99.7, 99.99 and 99.9999 per cent. The absorbing column is given in units of $10^{21} \,{\rm cm}^{-2}$. The Galactic column (dashed vertical line) is $N_{\rm H,Gal} = 1.4 \times 10^{20} \,{\rm cm}^{-2}$. The 90 per cent confidence upper limit to the column density of $5.3 \times 10^{20} \,{\rm cm}^{-2}$ and the corresponding *ASCA* photon index of $\Gamma = 1.29 \pm 0.05$ obtained by Fabian et al. (1998) is marked by the left arrow.

ASCA value. These results are robust to changes in the number of data points included in the fit. A contour plot of χ^2 as a function of the absorbing column in the observer's frame and the photon index is shown in Fig. 3. The displayed contour levels of 68.3, 95.4, 99.7, 99.99 and 99.9999 per cent clearly demonstrate the detection of excess absorption above the Galactic column towards the high-redshift quasar GB 1428+4217. This excess low-energy cut-off translates into an intrinsic X-ray absorption of



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 $N_{\rm H,fit} = (1.50 \pm 0.17) \times 10^{20} \, {\rm cm}^{-2}$. This value is significantly below the value of $(3.14 \pm 0.35) \times 10^{20} \, {\rm cm}^{-2}$ found for GB 1428+4217, further supporting the presence of significant soft X-ray absorption in GB 1428+4217.

 $N_{\rm H,fit}^{z=4,72} = (1.52 \pm 0.28) \times 10^{22} \, {\rm cm}^{-2}$ for neutral gas and solar abundances. With the current data we are unable to constrain the ionization level of the absorbing gas precisely; 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 modelled the influence of different gain values on the soft X-ray absorption. In Fig. 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 (Fig. 4) results in $N_{\rm H,fit}^{z=0} = (1.50 \pm 0.17) \times 10^{20} \, {\rm cm}^{-2}$, 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 Fig. 5).

GB 1428+4217 is clearly detected in the *ROSAT* All-Sky Survey with a detection likelihood of 35 (see Cruddace, Hasinger & Schmitt 1988 for the definition of the detection likelihood). The *ROSAT* PSPC count rate is 0.046 ± 0.011 count s⁻¹. The exposure time is 639 s. 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. Fig. 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 K α 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



Figure 5. Upper panel: *ROSAT* PSPC light curve of GB 1428+4217 obtained between 1998 December 11 and December 12. Variability is about 25 ± 8 per cent on a time-scale of about 37 000 s is detected in the observer's frame. Lower panel: *ROSAT* PSPC light curve of CSO 0454. The count rate variations detected in the observer's frame in GB 1428+4217 do not occur in CSO 0454.

features may therefore only be the result of 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 data set. *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 (HeII) 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 HeII absorption in some detail. The analytic fit to the absorption cross-section presented by Verner et al. (1996) and values of $\Omega_{\rm b} = 0.06$ and $\Omega_0 = 0.3$ were used. Unfortunately the effect of HeII 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 Fig. 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 $N_{\rm H}$ at the Galactic value provided that the oxygen abundance in the IGM has almost the solar value down to z = 3 (setting $N_{\rm H}$ to the upper limit of 1.8×10^{20} 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 the result of 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} 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 reasonably be 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 α feature). This means that the absorbing material must be enriched but relatively dust-free, and that the hydrogen in it must be ionized.

4 TIMING PROPERTIES OF GB 1428+4217

Fig. 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 $\leq 2 \times 10^{-3}$.

Using the mean of the first six data points and comparing it with the mean of the last two data points results in a variability amplitude of 25 ± 8 per cent. No significant spectral variability is detected upon examination of the appropriate hardness ratios. Using the spectral parameters for GB 1428+4217 as displayed in Fig. 2, the count rate variations translate into a 0.1-2.4 keV flux change in the observer's frame of $\Delta F = 5.9 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. The corresponding change in luminosity in the quasar rest frame (0.6-13.7 keV) is $\Delta L = 5.7 \times 10^{46} \text{ erg s}^{-1}$ (using the best-fitting) spectral parameters and the cosmology given in Section 1) within $\Delta t = 37\,000\,\mathrm{s}$, 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 $\eta \ge 4.2$. 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 $F = 2.7 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, corresponding to an isotropic luminosity in the quasar rest frame of $L = 2.6 \times 10^{47} \text{ erg s}^{-1}$. 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 $F = 9.0 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ 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 $F = 1.3 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (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 $N_{\rm H,fit}^{z=0}$ = $(3.14 \pm 0.35) \times 10^{20} \text{ cm}^{-2}$ is larger than the Galactic column of $N_{\text{H,Gal}} = (1.4 \pm 0.4) \times 10^{20} \text{ cm}^{-2}$ towards GB 1428+4217 at the 5σ level. The inferred intrinsic column density is $N_{\rm H,fit}^{z=4.72} =$ $(1.52 \pm 0.28) \times 10^{22} \text{ cm}^{-2}$. 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 $\eta \ge 4.2$ is remarkably large and further supports the blazar nature of the object.

ACKNOWLEDGMENTS

We thank the anonymous referee for helpful and constructive suggestions for further improvements of the paper. We thank J. Trümper, P. Predehl and D. Grupe for helpful discussions. The *ROSAT* Project is supported by the Bundesministerium für Bildung und Forschung (BMBF/DLR) and the Max-Planck-Gesellschaft (MPG). We gratefully acknowledge the support of the Royal Society (ACF) and NASA LTSA grant NAG5-8107 (WNB).

REFERENCES

- Aldcroft T., Elvis M., McDowell J., Fiore F., 1994, ApJ, 437, 584
- Bevington P. R., Robinson D. K., 1992, Data Reduction and Error Analysis for the Physical Sciences, 2nd edn. McGraw-Hill, New York
- Brandt W. N., Boller Th., Fabian A. C., Ruszkowski M., 1999, MNRAS, 303, L53
- Cruddace R. G., Hasinger G., Schmitt J. H. M. M., 1988, in Murtagh F., Heck A., eds, ESO Conf. Workshop Proc. 28, Astronomy from Large Databases: Scientific Objectives and Methodological Approaches. ESO Press, Garching, p. 177
- Dickey J. M., Lockman F. J., 1990, ARA&A, 28, 215
- Elvis M., Fiore F., Wilkes B., McDowell J., Bechtold J., 1994a, ApJ, 422, 60
- Elvis M., Lockman F., Fassnacht C., 1994b, ApJS, 95, 413
- Elvis M., Fiore F., Giommi P., Padovani P., 1998, ApJ, 492, 91
- Fabian A. C., 1979, Proc. R. Soc. London, Ser. A, 366, 449
- Fabian A. C., 1999, MNRAS, 308, L39
- Fabian A. C., Brandt W. N., McMahon R. G., Hook I. M., 1997, MNRAS, 291, L5
- Fabian A. C., Iwasawa K., Celotti A., Brandt W. N., McMahon R. G., Hook I., 1998, MNRAS, 295, L25
- Fiore F., Elvis M., Giommi P., Padovani P., 1998, ApJ, 492, 79
- Hook I. M., McMahon R. G., 1998, MNRAS, 294, L7
- Iwasawa K., Fabian A. C., Nandra K., 1999, MNRAS, 307, 611
- Miralda-Escude J., 2000, ApJ, 528, L1
- Rees M. J., 1988, MNRAS, 231, 91
- Verner D. A., Ferland G. J., Korista K. T., Yakovlev D. G., 1996, ApJ, 465, 487 Wolff B., Jordan S., Koester D., 1996, A&A, 307, 149
- Zimmermann H. U., Becker W., Belloni T., Döbereiner S., Izzo C., Kahabka P., Schwentker O., 1994, MPE Report 275. MPE, Garching



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.

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. In Fig. A1 we demonstrate that, even in the case of unusual gain values, the excess absorption above the Galactic column is still present.

This paper has been typeset from a TEX/LATEX file prepared by the author.