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The *ASCA* spectrum of the $z = 4.72$ blazar GB 1428+4217

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ABSTRACT

The X-ray-luminous quasar GB 1428+4217 at redshift 4.72 has been observed with *ASCA*. The observed 0.5–10 keV flux is $3.2 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. We report here on the intrinsic 4 – 57 keV X-ray spectrum, which is very flat (photon index 1.29). We find no evidence for flux variability within the *ASCA* data set or between it and *ROSAT* data. We show that the overall spectral energy distribution of GB 1428+4217 is similar to that of lower redshift MeV blazars, and present models that fit the available data. The Doppler beaming factor is likely to be at least 8. We speculate on the number density of such high-redshift blazars, which must contain rapidly formed massive black holes.

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

1 INTRODUCTION

The distant radio-loud quasar GB 1428+4217 at redshift $z = 4.72$ (Hook & McMahon 1998) is so X-ray-bright that its X-ray emission dominates the observed spectral energy distribution (Fabian et al. 1997). This property, together with its flat spectrum and compact radio appearance (Patnaik et al. 1992), suggests that it is a blazar that is beamed toward us.

The *ROSAT* flux from GB 1428+4217, after a small correction for Galactic absorption, corresponds to $\sim 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the observed 0.1–2.4 keV band, which is bright enough for a good spectrum to be obtained with *ASCA*. We report here on that spectrum, which is flat and indicates that the overall spectrum peaks in the hard X-ray or gamma-ray band. The flux of GB 1428+4217 in the 0.5–10 keV *ASCA* band is $\sim 3.2 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, more than three times brighter than the next brightest quasar at $z > 4$, GB 1508+5714 (Hook et al. 1994; Moran & Helfand 1997), which has similar properties to GB 1428+4217.

2 THE *ASCA* SPECTRUM

GB 1428+4217 was observed with *ASCA* (Tanaka, Inoue & Holt 1994) on 1997 January 17. The Solid state Imaging Spectrometers (SIS: S0 and S1) were operated in Faint mode through the observation using the single standard CCD chip for each detector. The lower level discriminator was set at 0.47 keV for the SIS. The spectral resolution of the SIS at the time of the observation had FWHM ~ 300 eV at 6 keV owing to degradation in the performance of the CCDs (Dotani et al. 1997). Nominal PH mode was used for the Gas Imaging Spectrometers (GIS: G2 and G3).

Standard calibration and data reduction methods were employed using FTOOLS provided by the *ASCA* Guest Observer Facility at Goddard Space Flight Center. The net exposure time was 40.2 ks for each detector. During the one-day observation, no significant flux variation (greater than 30 per cent) was observed. Background data were taken from a blank part of the field in the same detector. Spectral fits were performed jointly for the background-subtracted data from all detectors using XSPEC. The normalizations of the spectra for the SIS and GIS detectors were allowed to be slightly (12 per cent) different (see Gendreau & Yaqoob 1997 for a discussion of *ASCA* calibration issues).

The data are well fitted by a hard power-law spectrum (Fig. 1). Assuming only the Galactic column density of 1.4×10^{20} (Dickey & Lockman 1990), the photon index $\Gamma = 1.29 \pm 0.05$ (χ^2/d.o.f. = 383/380). A 90 per cent confidence upper limit to the column density is $5.3 \times 10^{20}\mathrm{cm}^{-2}$ in the observed frame or $4.5 \times 10^{22}\mathrm{cm}^{-2}$ at $z = 4.72$. The limit on a joint fit of Γ and intrinsic absorption ΔN_H is shown in Fig. 2. There is no obvious break seen in the spectrum (see Fig. 1); a broken power-law fit to the data constrains the allowable difference in spectral index to be ± 0.1 at 3 keV, increasing to ± 0.2 at 1.7 keV and greater than ± 0.4 below 1.2 keV.

We note that the SIS data alone do suggest the presence of some excess absorption, corresponding to $\Delta N_\mathrm{H} = 1.3 \pm 0.6 \times 10^{23}\mathrm{cm}^{-2}$ at $z = 4.72$. The photon index is then $\Gamma = 1.43 \pm 0.12$.

No obvious emission or absorption features arising from iron are evident in the spectrum. The 90 per cent confidence limit on the equivalent width of a narrow emission line from either cold (6.4 keV) or ionized (6.7 keV) iron is about 17 eV or just under 100 eV in the quasar frame. This last limit rises to about 170 eV if the line width has a dispersion of 0.5 keV, instead of 0.1 keV. Some marginal structure in the SIS spectrum is observed around 1 keV in the observed frame (~5.9 keV in the rest frame of the quasar).

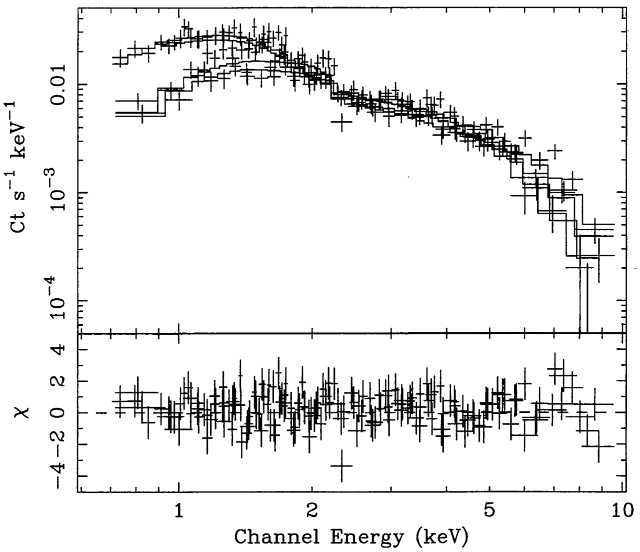

Figure 1. *ASCA* spectrum for GB 1428+4217. The SIS and GIS spectra are the upper and lower ones below 2 keV, respectively.

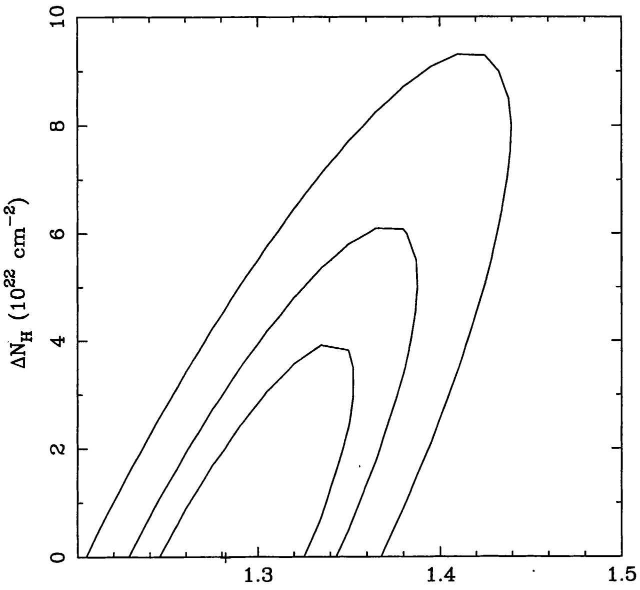

Figure 2. Excess absorption column density $\Delta N_{\rm H}$ (at $z = 4.72$) plotted against photon index for the joint SIS and GIS fits. The contours correspond to confidence levels of 68, 90 and 99 per cent. Note that cosmic abundances are assumed, which may not be relevant for such a young object.

The flux of GB 1428+4217 in our 2–10 keV band (after correction for Galactic absorption and using the best-fitting model) is 2.5×10^{-12} erg cm^{-2} s^{-1}, and in the 0.1–2.4 keV *ROSAT* band it is 1.29×10^{-12} erg cm^{-2} s^{-1}. These translate to a rest-frame, 2–10 keV luminosity of 1.4×10^{47} erg s^{-1} (assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$), rising to 6.4×10^{47} erg s^{-1} in the rest-frame 4–57 keV band which we observed. The *ASCA* flux in the 0.1–2.4 keV *ROSAT* band is consistent, within the uncertainties, with that detected during the pointed *ROSAT* observations. The flux reported from the *ROSAT* All-Sky Survey (see table 2 of unidentified sources in Brinkmann et al. 1997) is marginally weaker.

3 AN MeV BLAZAR?

Here we consider the *ASCA* results in the wider context of the broad-band energy distribution and examine possible interpretations of the properties of this source.

As discussed by Fabian et al. (1997), the flat X-ray and radio spectra, the remarkable spectral energy distribution (SED) peaking in the X-ray band, and the radio polarization of GB 1428+4217 all suggest that it is a blazar candidate, the observed emission of which is therefore dominated by relativistic beaming. Although, owing to the sparse data coverage, this cannot be established uniquely, we consider it to be the most likely possibility and therefore interpret here the properties of GB 1428+4217 within this scenario.

In particular, the flat radio spectrum indicates that the source is a potentially strong gamma-ray emitter. Blazar SEDs are characterized by two broad components, peaking in the IR–UV and gamma-ray bands, most likely produced as synchrotron and inverse Compton emission, respectively. It has also been recognized, through a study of the spectral indices of the gamma-ray-loud sample (Comastri et al. 1997), that the position and the relative intensities of these two peaks are correlated (see also Ghisellini et al., in preparation).

The X-ray spectrum of GB 1428+4217 is among the flattest measured in gamma-ray-loud blazars, suggesting that the source emission peaks in the inverse Compton component at ~ MeV energies. If one proceeds by considering the similarities with lower redshift sources, the seed photons for the Comptonization are most likely provided, at least in radio-loud quasars for which there is strong evidence of an intense quasi-thermal radiation field, by photons produced externally to the relativistically moving plasma. Indeed, the extremely flat IR–optical spectrum (see Fig. 3) could represent the seed photon field.

The (non-simultaneous) broad-band distribution (in νL_ν) is shown in Fig. 3, where, together with the radio (see Fabian et al. 1998), IR–optical (Hook & McMahon 1998; Hoenig et al., in preparation), *ROSAT* and *ASCA* spectra, *IRAS* and *CGRO*/EGRET upper limits are also plotted. In particular, GB 1428+4217 has not been detected by EGRET (Thompson et al. 1995); the gamma-ray limit reported in the figure corresponds to a sensitivity level of $\sim 10^{-7}$ photon cm^{-2} s^{-1} above 100 MeV.

Despite the sparse coverage of the total SED of GB 1428+4217, we now examine the predictions of plausible emission models.

3.1 Emission models

In the simplest hypothesis, the emission region is assumed to be a homogeneous sphere, moving with bulk velocity βc along a direction close to the line of sight. The region, of dimension R, is filled with a tangled magnetic field of intensity B. Here relativistic electrons are continuously injected with a power-law spectrum extending in energy to $\gamma_{\rm max} m_{\rm e} c^2$, at a rate per unit volume corresponding to an injection compactness parameter $\ell_{\rm inj}$.

The (stationary) equilibrium particle distribution is obtained by solving the continuity equation, balancing the rates of particle injection, radiative cooling and electron–positron pair production through photon–photon collisions. In particular, the cooling is dominated by the synchrotron and inverse Compton processes, where the latter allows for contribution to the radiation field both by photons produced inside the emitting region and by any external photon field (described for simplicity as blackbody radiation at optical–UV frequencies). Further details on the precise

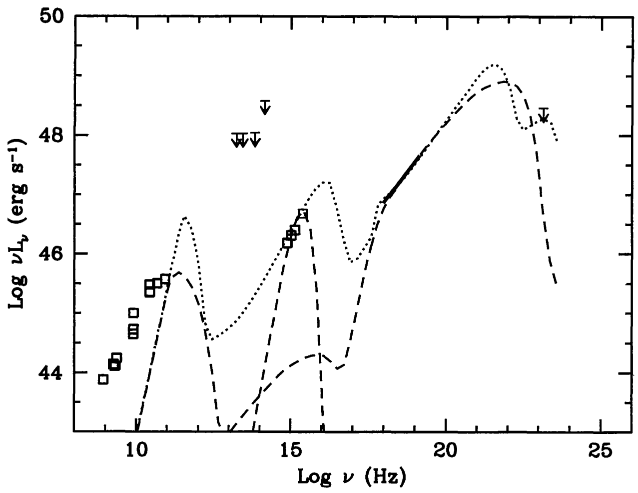

Figure 3. Broad-band SED (rest frame in νL_ν) with possible blazar model spectra. The three peaks in the continua are due to: (a) $\sim 10^{11}$ Hz, self-absorbed synchrotron radiation; (b) $\sim 10^{16}$ Hz, first-order SSC radiation; and (c) $\sim 10^{22}$ Hz, Comptonization of the radiation field dominating in the optical/UV band. This field is either external (EC, blackbody) or internal (SSC) radiation, or some combination of them (SSC/EC). Shown here is an EC model (dashed), with the external blackbody radiation field peaking in the UV (it can of course peak at slightly higher frequencies), and an SSC/EC model (dotted). The parameters of these and a pure SSC model are given in Table 1.

Table 1. The input parameters for the EC, SSC/EC and SSC models: (1) model; (2), (3) compactnesses in injected particles and external radiation field, respectively; (4) maximum energy of the injected particles; (5) magnetic field intensity (G); (6) relativistic Doppler factor.

Model (1)	$\ell_{\rm inj}$ (2)	$\ell_{\rm ext}$ (3)	$\gamma_{\rm max}$ (4)	B (5)	δ (6)
EC	0.1	1	400	0.1	12
SSC/EC	0.3	4.5e-3	250	0.1	22
SSC	0.5	0.	350	0.03	22

assumptions of the code can be found in the paper by Ghisellini et al. (1998; see also Ghisellini 1997).

A complete exploration of the possible parameter space of the model is beyond the scope of this paper. In Fig. 3 we superpose on the SED of GB 1428+4217 the predictions of this homogeneous model. In particular, the broad-band energy distribution represented by the dashed line has been computed by assuming that the external photon field mainly contributes the seed photons scattered to high (X- and gamma-ray) energies through the inverse Compton effect. This external field could also be observable in the optical band, as shown in Fig. 3 (dashed blackbody component peaking at $\sim 10^{15}$ Hz).

Indeed, the extremely flat near-IR–optical spectrum cannot be simply interpreted as synchrotron emission, as is usually considered (e.g. Ghisellini 1997). Here we examine an alternative possibility, namely that the near-IR–optical radiation is dominated by SSC emission. The low equivalent width of the UV emission lines (Hook & McMahon 1998) supports the presence of the boosted UV continuum then predicted. The X-ray/gamma-ray component can now be dominated by the Comptonization of either this same SSC radiation or an external field. The SED predicted under the last hypothesis (i.e. a hybrid synchrotron self-Compton/external Comptonization, SSC/EC, model) is shown by the dotted line in Fig. 3; a satisfactory model can also be found for the pure SSC case. The parameters for all these models are reported in Table 1.

If our interpretation of GB 1428+4217 is correct, two main points have to be stressed: (i) the set of parameters adopted here are consistent with those analogously derived for a sample of gamma-ray-loud blazars by Ghisellini et al. (in preparation); no evidence has been found so far of any peculiar properties of this $z = 4.7$ source compared with the low-redshift counterparts; (ii) the observed luminosity of the source is expected to be completely dominated by high-energy radiation and copious gamma-ray emission, at a level corresponding to an isotropic luminosity of 10^{49} erg s^{-1}.

We have also considered the predictions of an inhomogeneous SSC model (Ghisellini & Maraschi 1989) which can effectively account for the X-ray and radio emission (produced in the less compact region of the jet). However, as already pointed out, the near-IR–optical spectrum cannot be reproduced as synchrotron emission and has then to be ascribed to a different spectral component.

3.2 Cosmological and statistical consequences

If GB 1428+4217 is an MeV blazar, independently of the details of the emission model, it is possible to derive general constraints by assuming a typical dimension for the emitting source. In fact, the requirement of transparency to internal photon–photon absorption (to the process of pair production) implies $\delta \gtrsim 8$, for $R \sim 2 \times 10^{16}$ cm. This dimension is similar to those of lower redshift objects, and corresponds to an observed variability time-scale of $t_{\rm var} \sim 6$ d ($\delta \propto t_{\rm var}^{0.22}$).

Even assuming that the radiation observed from GB 1428+4217 is amplified by relativistic beaming with, say, a bulk Doppler factor of $\delta \sim 10\delta_1$, the intrinsic source luminosity would amount to about $10^{45}\delta_1^{-4}$ erg s^{-1}, requiring a $\sim 10^7$-M$_\odot$ black hole radiating at the Eddington rate to be formed in less than 10^9 yr.

Gamma-ray emission from high-redshift sources can be a very powerful tool with which to study the background radiation fields. However, if this source is indeed an 'MeV blazar', despite the intense emission and great distance, we do not expect to detect signs of absorption owing to the optical–UV stellar background radiation, as this mostly affects photons at energies $\gtrsim$ GeV (Salamon & Stecker 1998).

The number density of sources at $z \gtrsim 4$ is clearly critical to the determination of the evolution of active nuclei (and the radio phenomenon) and the inference of constraints on the formation or cycle of activity of these systems. A minimum comoving number density has been estimated from the three $z > 4$ radio-loud quasars discovered by Hook & McMahon (1998). Alternatively, one can consider the number of sources expected by statistical arguments based on the random orientation of the beaming pattern in the sky to obtain a maximum number. If objects are classified as flat-spectrum, radio-loud quasars for angles to the line of sight smaller than $\lesssim 14°$ (e.g. Padovani & Urry 1992), then given at least one within a search area, about $6\delta_1^2$ such quasars are expected in total (with different luminosities). For the assumed cosmological parameters, the resulting comoving number density of very powerful flat-spectrum radio quasars is $1.2 - 4 \times 10^{-10}$ Mpc^{-3} at $4 < z < 5$.

Many more objects ($\sim 200\delta_1^2$) that are not beamed in our direction at $4 < z < 5$ are predicted to be in the search area. They may appear as powerful radio galaxies and steep-spectrum radio sources, if the current unification models are correct (Padovani & Urry 1992), giving a comoving space density for the host galaxies of $\sim 10^{-7}\,\mathrm{Mpc}^{-3}$, comparable to that of the brightest cD galaxies today. The high energy density in the microwave background and the density of the intergalactic medium may, however, seriously affect the size and brightness of radio lobes (Dunlop & Peacock 1992: this could explain the lack of any resolved radio component to GB 1428+4217).

4 CONCLUSIONS

We report the results of *ASCA* observations of the $z = 4.72$ quasar GB 1428+4217, the most distant X-ray source known. The observed energies correspond to emission up to ~57 keV in the source rest frame. The flat X-ray spectrum, as well as the radio properties, indicates that the source is a flat-spectrum radio-loud blazar, dominated by relativistic beaming from non-thermal plasma in a jet. The slope of the X-ray emission is among the flattest seen in blazars and suggests that GB 1428+4217 is emitting most of its power in the MeV band.

The sparse spectral information does not allow us to constrain uniquely the emission model. However, it is important to note that plausible models do not require parameters significantly different from those of similar low-redshift blazars.

The properties of GB 1428+4217 are also similar to those of another radio-loud quasar at $z \gtrsim 4$, GB 1508+5714 (Moran & Helfand 1997). In both sources the X-ray emission dominates the (observed) radiative output, and they show no sign of absorption in excess of the Galactic value, contrasting with that seen in the high-z radio-loud quasar sample presented by Cappi et al. (1997). Although two sources do not allow us to derive statistically significant results, there is so far no sign of evolution either in the spectrum or in the other properties for this class of objects. Low abundances in such young objects could of course contribute to the lack of any detectable absorption or emission features in their X-ray spectra.

Clearly, further information on the SED (in particular, the millimetre and MeV spectral bands) and especially on the variability properties of GB 1428+4217 will allow us to constrain the models further. It should be noted that, owing to cosmological time dilation, variability on the shortest time-scale (probably weeks) could be temporally resolved.

General statistical arguments predict that a significant source population could be present at redshift $\gtrsim 4$, with masses in excess of $10^7\,\mathrm{M}_\odot$.

It is remarkable that such a young object as GB 1428+4217 has very similar properties to lower redshift sources. This emphasizes that the formation of relativistic jets is a ubiquitous phenomenon.

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