THE 3–53 keV SPECTRUM OF THE QUASAR 1508+5714: X-RAYS FROM z = 4.3

EDWARD C. MORAN
Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, L-413, Livermore, CA 94550

AND

DAVID J. HELFAND
Department of Astronomy, Columbia University, 538 West 120th Street, New York, NY 10027

Received 1997 March 21; accepted 1997 May 14

ABSTRACT

We present a high-quality X-ray spectrum in the 3–53 keV rest frame band of the radio-loud quasar 1508+5714, which is by far the brightest known X-ray source at z > 4. A simple power-law model with an absorption column density equal to the Galactic value in the direction of the source provides an excellent and fully adequate fit to the data; the measured power-law photon index \( \Gamma = 1.42^{+0.15}_{-0.10} \). Upper limits to Fe K\( \alpha \) line-emission and Compton-reflection components are derived. We offer evidence for both X-ray and radio variability in this object and provide the first contemporaneous radio spectrum (\( \alpha = -0.25 \)). The data are all consistent with a picture in which the emission from this source is dominated by a relativistically beamed component in both the X-ray and radio bands.

Subject headings: galaxies: active — quasars: individual (1508+5714) — X-rays: galaxies

1. INTRODUCTION

Surveys of the X-ray sky with the Einstein and ROSAT observatories have revealed that, over a broad range of fluxes, quasars are the most common extragalactic X-ray sources (Stocke et al. 1991; Boyle et al. 1993). Thousands of predominantly low-redshift quasars have now been observed with these instruments, providing a comprehensive picture of their soft X-ray properties (see, e.g., Ku, Helfand, & Lucy 1980; Zamorani et al. 1981; Avni & Tananbaum 1986; Wilkes & Elvis 1987; Wilkes et al. 1994; Laor et al. 1994; Green et al. 1995). But investigation of the hard X-ray spectra of quasars has, until recently, only been possible for the handful of nearby and exceptionally bright objects suitable for study with non-imaging instruments, such as those on board EXOSAT and Ginga (Lawson et al. 1992; Williams et al. 1992). Hence, comparatively little is known about the characteristics of quasars above a few keV, where most of their X-ray energy is emitted.

X-ray observations of high-redshift quasars provide access to their hard X-ray spectra and afford, through comparison to low-redshift objects, the opportunity to explore the evolution of their high-energy properties. Recent ROSAT observations of \( z \approx 3 \) quasars in the 0.1–2.4 keV band have served both functions, yielding spectra in the 0.5–10 keV rest frame energy range for objects that were emitting when the universe was roughly one-quarter its present age (Elvis et al. 1994a; Bechtold et al. 1994a; Pickering, Impey, & Foltz 1994). Many of the same objects observed with ROSAT have been studied with the ASCA satellite in order to examine their spectral properties up to rest energies of \( \approx 40 \) keV (Serlemitsos et al. 1994; Elvis et al. 1994b; Siebert et al. 1996; Cappi et al. 1997). Some preliminary conclusions have been drawn about the X-ray spectral evolution of quasars (see, e.g., Bechtold et al. 1994b), but to date just 25 objects with redshifts in excess of 3 have been detected in the X-ray band, and spectral information is available for only a fraction of these. Thus, each new high-\( z \) example provides a valuable datum for quasar evolution studies. In this Letter we present the results of deep ASCA observations of the \( z = 4.30 \) quasar 1508+5714, the brightest known quasar in the high-redshift universe.

We discovered 1508+5714 and its X-ray emission as part of our follow-up of unidentified radio-selected X-ray sources in the Einstein Two-Sigma Catalog (Moran et al. 1996). Despite the fact that we found the quasar to be a relatively strong X-ray source (detected at the 6 \( \sigma \) level in a \( \approx 2800 \) s exposure), it had apparently escaped notice in all previous analyses of the Einstein IPC image. Contemporaneous discovery of 1508+5714 was made by Hook et al. (1995) in their sample of flat-spectrum radio sources. Spurred by the Hook et al. report, Mathur & Elvis (1995) reanalyzed the Einstein image containing the quasar and also found that it was detected. The quasar 1508+5714 is nearly the most distant X-ray source known, second only to RX J1759.4+6638 at \( z = 4.32 \) (Henry et al. 1994), which is more than 50 times fainter. The only other \( z > 4 \) quasar detected at X-ray wavelengths is 0000–263 (\( z = 4.11 \); Bechtold et al. 1994a), which is 10 times fainter than 1508+5714. Thus, 1508+5714 currently provides the only opportunity to study quasar X-ray emission above a redshift of 4 in detail. We report here a measurement of its spectrum in the 0.5–10 keV ASCA bandpass, equivalent to the 3–53 keV band in the rest frame of the quasar.

2. X-RAY AND RADIO OBSERVATIONS

2.1. Broadband X-Ray Observations

The quasar 1508+5714 was observed with the ASCA satellite (Tanaka, Inoue, & Holt 1994) on two occasions, first on 1995 March 2 and then on 1995 December 15. Data collected with both sets of instruments on board ASCA, the Gas Imaging Spectrometers (GIS2 and GIS3) and the Solid-State Imaging Spectrometers (SIS0 and SIS1), were filtered following the guidelines described in The ABC Guide to ASCA Data.
To measure the GIS background, we collected counts within source-free regions at the same distance off-axis as the quasar and with twice the area of the source region. We estimated the background in the SIS spectra by extracting counts from the entire chip, omitting a region 4° in radius around the source. The total number of background-subtracted counts obtained in the SIS0, SIS1, GIS2, and GIS3 spectra of 1508+5714 in the 0.5–10 keV band are 1294, 1104, 808, and 1097, respectively. To improve the signal-to-noise ratios of the spectra for model fitting, we used the “addascaspec” program once more to combine the SIS0 spectrum with the SIS1 spectrum and the GIS2 spectrum with the GIS3 spectrum. These spectra, which are referred to as the SIS and GIS spectra below, were binned to have at least 100 counts (source plus background) per channel.

2.2. Radio Continuum Observations

Over the past two decades, 1508+5714 has been detected at a variety of radio frequencies, including 365 MHz ($S = 191$ mJy; Douglas et al. 1996), 1.4 GHz ($S = 149$ mJy; White & Becker 1992 and $S = 202$ mJy; Condon et al. 1997), 4.9 GHz ($S = 279$ mJy; Becker, White, & Edwards 1991), and 8.4 GHz ($S = 153$ mJy; Patnaik et al. 1992). Given the difference between the two 1.4 GHz measurements, it appears that the quasar is a variable radio source. To investigate its radio properties further, we observed 1508+5714 with the Very Large Array (VLA) in the A configuration on 1995 July 13. The source was observed at 1.46 and 8.41 GHz, for 5 minutes at each frequency. The quasar is unresolved at both frequencies, with measured flux densities of 234 mJy at 1.46 GHz and 152 mJy at 8.41 GHz. These observations confirm the radio variability of 1508+5714 and provide the first contemporaneous measurement of its radio spectrum, which is moderately flat: assuming $S_v \propto \nu^x$, $\alpha = -0.25$.

3. Results

3.1. The X-Ray Spectrum of 1508+5714

As Table 1 indicates, a simple model consisting of a single, absorbed power law provides an excellent fit to the ASCA spectrum of 1508+5714. The results obtained for separate and simultaneous fits to the SIS and GIS spectra are very similar. For the simultaneous fit, the derived photon index and column density, assuming the absorber is at $z = 0$, are $\Gamma = 1.42_{-0.13}^{+0.13}$ and $N_H = 1.4_{-1.4}^{+3.4} \times 10^{20}$ cm$^{-2}$. (All errors listed are at the 90% confidence level for two interesting parameters, unless otherwise noted.) This column density is consistent with the Galactic column in the direction of 1508+5714 of $1.6 \times 10^{20}$ cm$^{-2}$.
narrow Fe Kα emission line is 31 eV at an observed energy of 1.21 keV, which translates to 167 eV in the quasar frame.

3.2. X-Ray Variability

The two ASCA observations of 1508+5714, separated by 9 months, provide the opportunity to search for X-ray variability on a timescale of 54 days in the frame of this object. Using the “addascascpec” task, we combined the SIS0 spectrum with the SIS1 spectrum and the GIS2 spectrum with the GIS3 spectrum for both the March and December segments of the observation. To test for variability, we applied a power-law model to the spectra from the two epochs separately, fixing the absorption column density at the Galactic value. We find that the spectrum and intensity of 1508+5714 varied significantly between the two observations: a $\Gamma = 1.55_{-0.08}^{+0.06}$ power law with a 1 keV normalization of $1.39_{-0.10}^{+0.16} \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ fits the March spectrum, whereas a $\Gamma = 1.25_{-0.15}^{+0.14}$ power law with a normalization of $0.80_{-0.14}^{+0.09} \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ fits the December spectrum. The implied decrease in the 0.5–10 keV flux of 1508+5714 over the span between the two observations is 15%. Since we extracted the March and December spectra separately and determined the correct effective area for each, we are certain that the variability is not a consequence of the vignetting differences associated with the different off-axis positions of the quasar in the two exposures.

The X-ray variability of 1508+5714 could, in principle, allow us to place limits on the mass of the central black hole, which would be of interest for an object at such a high redshift. However, there are several lines of evidence that point to beaming as the origin of variability in 1508+5714. Not only is the quasar’s flat-spectrum radio variable, but there is also unresolved at a resolution of $<5$ mas in a 5 GHz VLBI observation (Frey et al. 1997). The compactness and high flux density (286 mJy) of the VLBI source, in addition to the radio variability, suggest that the radio emission from 1508+5714 is highly beamed. As discussed by Mathur & Elvis (1995), 1508+5714 appears to be considerably overbright in X-rays given its optical luminosity, which implies that a significant fraction of its X-ray emission is beamed as well. By extrapolating the mean unabsorbed ASCA spectrum and our optical spectrum (Moran et al. 1996) to rest frequencies corresponding to 2 keV and 2500 Å, respectively, we obtain a value of 0.93 for the two-point optical–to–X-ray spectral slope $\alpha_{ox}$ (Tananbaum et al. 1979), which confirms the extreme X-ray brightness of 1508+5714 (see Wilkes et al. 1994). Thus, the X-ray luminosities of 1508+5714 given above in § 3.1 are not likely to be isotropic values. A viewing geometry close to the axis of the radio jet might also explain why excess absorption is not observed in the X-ray spectrum of 1508+5714.

3.3. Implications for the X-Ray Background

The spectrum of the cosmic X-ray background (XRB) is well fitted by a $\Gamma = 1.4$ power law in the ASCA band (Gendreau et al. 1995) and by a $kT = 40$ keV thermal bremsstrahlung model in the 3–50 keV range (Marshall et al. 1980). It is now certain that the XRB arises from the integrated emission of discrete sources (Mather et al. 1990; Wright et al. 1994), even though a class of objects with an average spectrum similar to that of the XRB has yet to be identified; moderate-redshift quasars and Seyfert galaxies, the most numerous extragalactic sources at bright X-ray fluxes, have collective spectra that are...
generally far too steep to explain the background spectrum (Fabian & Barcons 1992). Interestingly, the application of redshifted thermal models to the ASCA spectra of $z \approx 3$ radio-loud quasars have revealed rest frame temperatures in the $34 - 45$ keV range (Serlemitsos et al. 1994; Elvis et al. 1994b; Siebert et al. 1996), suggesting to these authors that active galactic nuclei (AGNs) may produce the XRB after all. The similarity between the spectrum of 1508+5714 and the spectrum of the XRB might be cited to support this hypothesis. But, in addition to the obvious difficulties quasars have satisfying the integrated luminosity and areal surface density requirements imposed on the XRB-producing class of sources, a redshifted bremsstrahlung model for 1508+5714 (with $N_{\text{H}}$ fixed at the Galactic value) yields a rest frame temperature of 93 keV, with a 90% confidence range of 69–133 keV. A temperature of 40 keV is ruled out at greater than 99% confidence.

4. SUMMARY

Since sensitivity improvements of an order of magnitude over the best existing detectors (e.g., the X-Ray Timing Explorer) will be required to obtain high-quality spectra of a substantial sample of low-redshift AGNs in the 10–50 keV band, high-redshift quasars currently offer the only window on the XRB-producing class of sources. However, the properties of 1508+5714 are entirely consistent with those of other radio-loud X-ray quasars (see Fig. 3 of Cappi et al. 1997), which supports preliminary conclusions that radio-loud quasars exhibit no spectral evolution with redshift or luminosity (Cappi et al. 1997). Of course, additional examples of X-ray–bright, high-redshift quasars are needed to address this question fully. The advent of the Advanced X-Ray Astrophysics Facility and the X-Ray Multimirror Mission in the next few years will allow the extension of studies exploring the hard X-ray spectra of AGNs to many more such denizens of the high-z universe.

We are grateful to Leonid Gurvits for information about the VLBI observations of 1508+5714, to Sally Laurent-Muehleisen for illuminating discussions about relativistic beaming in AGNs, and to Bob Becker for assistance with the VLA data. This work has been supported at Columbia by a grant from NASA under the ASCA Guest Investigator Program (NAGS-3556) and at LLNL by the US Department of Energy under contract W-7405-ENG-48. This is contribution number 629 of the Columbia Astrophysics Laboratory.

REFERENCES

Avni, Y., & Tananbaum, H. 1986, ApJ, 305, 83
Bechtold, J., et al. 1994a, AJ, 108, 374
———. 1994b, AJ, 108, 759
Becker, R. H., White, R. L., & Edwards, A. L. 1991, ApJS, 75, 1
Boyle, B. J., Griffiths, R. E., Shanks, T., Stewart, G. C., & Georgantopoulos, I. 1993, MNRS, 260, 49
Cappi, M., Matsuoka, M., Comastri, A., Brinkmann, W., Elvis, M., Palumbo, G. G. C., & Vignali, C. 1997, ApJ, 476, 492
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1997, preprint
Day, C., Arnaud, K., Ebisawa, K., Gotthelf, E., Ingham, J., Mukai, K., & White, N. 1995, The ABC Guide to ASCA Data Reduction (Greenbelt, MD: NASA/GSFC)
Douglas, J. N., Bash, F. N., Boyzan, F. A., Torrence, G. W., & Wolfe, C. 1996, AJ, 111, 1945
Dressel, L. L., & Condon, J. J. 1976, ApJS, 31, 187
Elvis, M., Fiore, F., Wilkes, B., McDowell, J., & Bechtold, J. 1994a, ApJ, 422, 60
Elvis, M., Matsuoka, M., Siemiginowska, A., Fiore, F., Mihara, T., & Brinkmann, W. 1994b, ApJ, 436, L55
Fabian, A. C., & Barcons, X. 1992, ARA&A, 30, 429
Frey, S., Gurvits, L. I., Kellermann, K. I., Schilizzi, R. T., & Pauliny-Toth, I. I. K. 1997, A&A, in press
Gendreau, K. C., et al. 1995, PASJ, 47, L5
Green, P. J., et al. 1995, ApJ, 450, 51
Henry, J. P., et al. 1994, AJ, 107, 1270
Hook, I. M., McMahon, R. G., Patnaik, A. R., Browne, I. W. A., Wilkinson, P. N., Irwin, M. J., & Hazard, C. 1995, Nature, 328, 323
Laor, A., Fiore, F., Elvis, M., Wilkes, B. J., & McDowell, J. C. 1994, ApJ, 435, 611
Lawson, A. J., Turner, M. J. L., Williams, O. R., Stewart, G. C., & Saxton, R. D. 1992, MNRS, 259, 743
Lightman, A. P., & White, T. R. 1988, ApJ, 335, 57
Marshall, F. E., et al. 1980, ApJ, 235, 4
Mathur, J. C., et al. 1990, ApJ, 354, L37
Mathur, S., & Elvis, M. 1995, AJ, 110, 1551
Moran, E. C., Helfand, D. J., Becker, R. H., & White, R. L. 1996, ApJ, 461, 127
Nandra, K., & Pounds, K. A. 1994, MNRS, 268, 405
Patnaik, A. R., Browne, I. W. A., Wilkinson, P. N., & Wrobel, J. M. 1992, MNRS, 254, 655
Pickering, T. E., Impey, C. D., & Feltz, C. B. 1994, AJ, 108, 1542
Serlemitsos, P., Yaqoob, T., Ricker, G., Woo, J., Kunieda, H., Terashima, Y., & Iwasawa, K. 1994, PASJ, 46, L43
Siebert, J., Matsuoka, M., Brinkmann, W., Cappi, M., Mihara, T., & Takahashi, T. 1996, A&A, 307, 8
Stark, A. A., Gammie, C. F., Wilson, R. W., Bally, J., Linke, R. A., Heiles, C., & Hurwitz, M. 1992, ApJS, 79, 77
Stocke, J. T., et al. 1991, ApJS, 76, 813
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37
Tananbaum, H., et al. 1979, ApJ, 234, L9
White, R. L., & Becker, R. H. 1992, ApJS, 79, 331
Wilkes, B. J., & Elvis, M. 1987, ApJ, 323, 243
Wilkes, B. J., Tananbaum, H., Worrall, D. M., Avni, Y., Oey, M. S., & Flanagan, J. 1994, ApJS, 92, 53
Williams, O. R., & Elvis, M. 1992, ApJ, 399, 157
Worrall, D. M., & Wilkes, B. J. 1990, ApJ, 360, 396
Wright, E. L., et al. 1994, ApJ, 420, 450
Zamorani, G., et al. 1981, ApJ, 245, 357