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IR TO X-RAY SPECTRAL ENERGY DISTRIBUTIONS OF HIGH REDSHIFT QUASARS

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ABSTRACT

We have observed 13 quasars having $z > 2.8$ with the ROSAT PSPC, and detected 12 of them, including the z=4.11 quasar 0000-263. For the radio quiet quasars with $z > 2.5$, the mean $< \alpha_{ox} > \sim 1.8$. Thus, the high redshift quasars are relatively more X-ray quiet than quasars with $z < 2.5$. However given their high optical luminosities, they are consistent with the extrapolation of the dependence of $< \alpha_{ox} >$ on l_{opt} seen at low redshift. For the radio-loud quasars, $< \alpha_{ox} > \sim 1.4$, independent of redshift. This is smaller than the expected value for the optically luminous, high redshift objects, if they are comparable to steep-spectrum, compact radio sources at low redshift.

For 6 of the quasars, there are sufficient counts detected to provide meaningful constraints to the X-ray spectrum. For the others, a PSPC hardness ratio is used to constrain the X-ray spectral properties. The observations imply that at $z \approx 3$, the X-ray spectra of radio-loud and radio-quiet quasars are different. Implications for the interpretation of the evolution of the luminosity function of quasars are discussed. Models where quasars are numerous and short-lived are favored.

1. Introduction

We have observed a sample of bright, high redshift quasars with the PSPC. Most of these quasars were discovered since the demise of the Einstein Observatory and EXOSAT, and so had not been previously studied in the X-rays. The objects in the sample were chosen because they are very bright at optical wavelengths; 6 are radio-loud and 7 (including the one not detected) are radio-quiet. While this sample is clearly heterogeneous, there seemed to be no other way to get a comparable data set to study the X-ray properties of high redshift quasars: the ROSAT all-sky survey is generally too shallow to detect many z>3 quasars, and the deep pointed PSPC surveys cover too little of the sky to expect many of these rare objects. Also, these quasars are bright at all wavelengths, and so it was relatively easy to construct the spectral energy distributions for these quasars from the radio to X-rays.

For the objects in this sample we obtained near-IR spectrophotometry with the GESPEC at the Multiple Mirror Telescope, optical spectrophotometry with the B&C Spectrograph at the Steward Observatory 2.3 meter, and IR photometry at the MMT. This work is discussed in greater detail in Bechtold et al. 1994a,b, and in Fiore (1994, these proceedings). The X-ray spectral properties of 4 of the quasars were discussed in Elvis et al. (1994). The infrared data is also discussed by Kuhn (1994).

2. Optical to X-ray Spectral Index

The mean spectral index between the optical and X-ray bands, α_{ox}, has been studied extensively for low redshift quasars, based on observations with the Einstein IPC (Zamorani et al 1981; Avni & Tananbaum 1982, 1986; Kriss & Canizares 1985; Worrall et al. 1987). For optically selected, and presumably mostly radio quiet quasars, the ratio of X-ray to optical flux decreases with increasing optical luminosity, and is only weakly dependent on redshift. Radio loud quasars were found to have larger X-ray to optical flux ratios compared to radio quiet objects of the same optical luminosity, implying that an extra component to the X-ray emission is present that is associated with the radio emission. No significant dependence on redshift is seen for this effect. Since our sample extends the redshift range observed, we re-examined these trends.

We computed α_{ox} for the quasars in our sample, where

$$\alpha_{ox} = \frac{-log(l_x/l_{opt})}{log(\nu_x/\nu_{opt})}.$$

Here logν_x is the frequency corresponding to 2 keV and logν_{opt} corresponds to 2500 Å; all quantities are in the rest frame of the quasar. Note that we have measured the flux at 2500 Å directly from the GESPEC data at an observed wavelength of ~1 μm. We assume that the X-ray spectra are power laws with $\alpha_E = 0.5$ and absorption by the known Galactic N(HI) only. For a comparison low redshift sample, we used the results from the Einstein Quasar and Seyfert 1 Galaxy Database by Wilkes et al. (1994) as obtained from the Einline on-line service. To investigate the radio properties of the sample, we cross-correlated this list with the QCAT database, which is based on the Veron-Cetty & Veron (1989) and Hewitt & Burbidge (1987) catalogs. In addition we have included several serendipitously detected quasars at z≈1.5 from the PSPC image of 0130-403, and 2 other high redshift quasars discussed by Henry et al. (1994) and Fink and Briel (1993).

In Figure 1, we plot α_{ox} as a function of redshift for the radio quiet and radio loud quasars. The high-redshift radio quiet objects appear to be significantly more X-ray quiet (i.e. larger α_{ox}) than their low redshift counterparts. The 7 objects with z > 2.5 have a mean $< \alpha_{ox} > = 1.80 \pm 0.01$, compared to $< \alpha_{ox} > = 1.38 \pm 0.05$ for the 111 quasars detected in the IPC with z < 2.5. The radio loud objects, instead, appear to have nearly constant α_{ox} with redshift, with a mean of ~1.4. If we extrapolate the dependence of α_{ox} on l_{opt} for the radio quiet quasars given by Worrall et al. (1987), then for log $l_{opt} = 33$ ergs sec^{-1} Hz^{-1} (typical of the quasars in our sample), the expected α_{ox} is 1.78, which is consistent with the observed mean $< \alpha_{ox} > \sim 1.8$. At the same l_{opt}, the radio loud, steep spectrum quasars are expected to have α_{ox} =1.66; the radio-loud, flat spectrum sources, $\alpha_{ox} = 1.45$; and the radio-loud, steep-spectrum, but compact sources, $\alpha_{ox} \approx 1.6$. Thus, given the dependence of α_{ox} on l_{opt}, it appears that the radio quiet quasars at z> 2.5 show no evolution of α_{ox} with z. On the other hand, the radio loud quasars at high redshift may be more X-ray loud than expected, if they are similar in nature to the steep spectrum compact radio sources at low z.

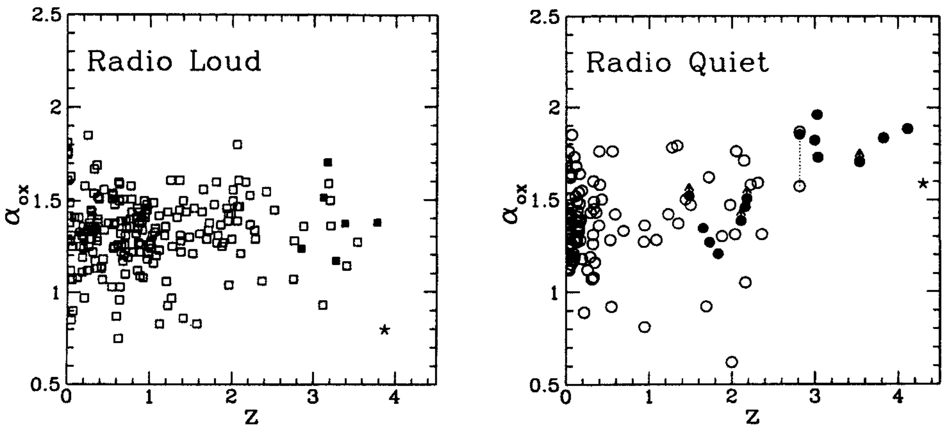

Figure 1: α_{ox} as a function of redshift for radio quiet and radio loud quasars. Open symbols are IPC results and closed symbols are ROSAT PSPC results presented here. The IPC and PSPC values for 0207-389 are connected by a dashed line. The z=4.3 quasar of Henry et al. (1993) and the z=3.87 quasar of Fink and Briel (1993) are shown as 5 pointed stars. Upper limits for the IPC sample are not shown for clarity, but were included in the analysis described in the text.

3. PSPC X-ray Spectra of High Redshift Quasars

Elvis et al. (1994) presented the PSPC spectra of 4 radio-loud quasars, and found that two showed evidence for soft X-ray absorption in excess of the Galactic HI column density. This is different from the situation at low redshift, where few high luminosity quasars show absorption. Since the spectral resolution is not high enough to measure the redshift of the absorbing material, it's location could be almost anywhere along the line of sight. Elvis et al. (1994) give a discussion of the possibilities: it could be related the radio source, in the host galaxy, or originate in an intervening galaxy along the line of sight. To begin to disentangle these possibilities, we have obtained spectra of two radio quiet quasars, 1946+76 at z=3.03 and 0000-263 at z=4.11. Neither show absorption in excess of the Galactic value, with 3σ upper limits of $1.3\text{x}10^{22}$ cm^{-2} and $5.6\text{x}10^{22}$ cm^{-2} respectively, assuming the absorption is at the emission line redshift. However, these upper limits only marginally rule out the absorption seen by Elvis et al. (1994) in 2126-158 (z=3.27, $N_H=1.4\text{x}10^{22}$ cm^{-2}) and are larger than the absorption seen in 0438-436 (z=2.85, $N_H=0.9\text{x}10^{22}$ cm^{-2}). Interestingly, 1946+76 and 0000-263 have damped Lyα absorbers in their optical spectra, as does the radio loud 0420-388 which also has no absorption (z=3.12, $N_H < 1\text{x}10^{22}$ cm^{-2} 3σ). Therefore, since no soft X-ray absorption is seen in 3 quasars that are known to have intervening galaxies, it is more likely that the absorption is intrinsic to the quasars and may well be related to the radio source.

To study the X-ray spectral properties of the quasars in our sample with less than 100 photons detected, we have computed an X-ray color, or hardness ratio, R =

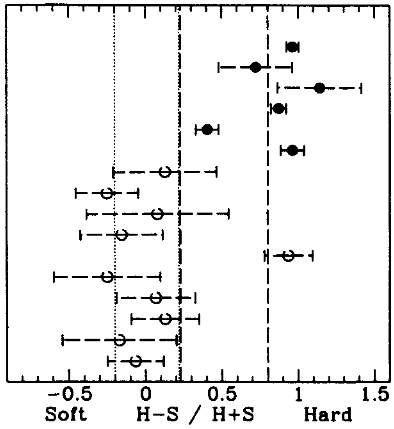

Figure 2: The X-ray hardness ratio R for high redshift radio quiet quasars (open symbols) and radio loud quasars (filled symbols). The dashed and dotted lines show the expected R for radio-loud and radio quiet quasars respectively, using the mean spectral index found at low redshift by GINGA (Williams et al. 1992) and the minimum and maximum Galactic N_H values in our samples.

(H-S)/(H+S), where H = the number of photons between 0.44 and 2.48 keV and S = the number of soft photons between 0.11 and 0.44 keV (c.f. Maccacaro et al. 1988). This hardness ratio is shown in Figure 2. Clearly the radio loud quasars are harder than the radio quiet ones. The mean $< R >$ =-0.018 $\pm$ 0.110 for the radio quiet quasars, whereas $< R > = 0.740 \pm 0.030$ for the radio loud quasars, a 6.6σ difference.

If the radio quiet quasars have no soft absorption in excess of the Galactic column, then their power law indices are $< \alpha_E > \approx 1.0$, similar to the low redshift quasars observed in the same rest energy range by GINGA (Williams et al. 1992). If they do have absorption, then their hardness ratios imply $< \alpha_E > >> 1$, in which case the intrinsic power law spectrum has evolved significantly with redshift.

On the other hand, the hardness ratios of the radio loud quasars imply that if they have no soft absorption in excess of the Galactic value, then $\alpha_E < 0$, much flatter than the $< \alpha_E >$ =0.7 average observed in the GINGA sample. In this case, their intrinsic spectra have evolved with redshift. Of course, in 2 cases there is clear evidence from the X-ray spectra for absorption, and the hardness ratios are consistent with absorption being present in all the high redshift radio loud objects, with an unabsorbed $< \alpha_E > = 0.7$.

4. Discussion

One would like to relate the changes in the spectral properties of individual quasars with redshift to the changes in the ensemble properties of the quasars, that is, the evolution of the luminosity function of quasars at high z. The X-rays in particular probably originate close to the central engine in the quasars and so may give direct clues to the nature of the evolution of the black hole and accretion. If the soft X-ray absorption seen by Elvis et al. (1994) originates outside the central engine, then the X-ray colors imply that the intrinsic X-ray spectra of radio loud quasars does not evolve with z. On the other hand, the radio quiet objects have steeper X-ray power laws at high z than at low z.

This may be interpreted in the context of recent models for the X-ray emission of quasars by Haardt and Maraschi (1993). In their models, the 2-20 keV X-rays are inverse compton emission from a hot corona above a colder accretion disk. More massive black holes would be expected to have steeper X-ray spectra than less massive ones. If quasars are long-lived and rare, so that the evolution of the luminosity function is the result of the slow increase of black hole mass with decreasing redshift, then one expects flatter X-ray spectra at high z. This is inconsistent with our results for radio quiet objects. On the other hand, if quasars are numerous and short-lived, they may be better understood in the hierarchical collapse of CDM halos described by Haehnelt and Rees (1993). More massive fluctuations collapse at high z than at low z, so one expects quasars at high z to have more massive black holes. In this case, the X-ray spectra would be steeper at high z, as is seen for the radio quiet quasars. The radio loud quasars on the other hand, may have a significant fraction of their X-ray emission from some other source.

Acknowledgements

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