X-RAYS AND HIGH REDSHIFT QUASARS

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ABSTRACT

X-ray observations of high redshift (z∼3) quasars have yielded a wealth of surprises, both in their emission spectra, and in their absorption properties. The same observations can place limits on a hot diffuse IGM (the "X-ray Gunn-Peterson test"), and on physical conditions in damped Lyman-α absorbers. This paper reviews the current status of the ROSAT observations, and looks forward to the diagnostics that will be provided by ASCA and other spectroscopy missions, such as AXAF.

1. The Moving Frontier

At the Nagoya meeting on 'Frontiers of X-ray Astronomy' in 1991 I showed the X-ray frontier for quasars in several observable dimensions, e.g. α_{OX}, redshift (Elvis 1991), and speculated on how our ideas of what was true for quasars in general may be biased by our limited observing capabilities.

Since then we have pursued a strategy with ROSAT that explores the whole parameter space of quasars - high redshift, X-ray quiet (Fiore et al 1993, Mathur et al 1994), optically-quiet (Elvis et al 1994a, Mathur 1994), IR-quiet and radio-silent (Aldcroft et al 1994 in preparation), high signal-to-noise (Fiore et al 1994), and low Galactic N_H (Laor et al 1994). Figure 1 shows the 1991 frontier projected into (α_{OX}, z) space. Our new ROSAT PSPC points are superposed, showing how far we have reached beyond our knowledge of 3 years ago.

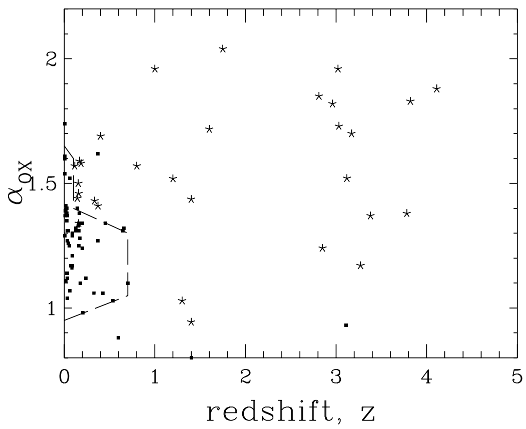

Figure 1: Observed regions in (α_{OX},z) space. Stars show our ROSAT points, filled squares the IPC spectral observations, defining the 1991 'frontier'- approximated by the dashed line.

Our strategy has successfully found surprises. Here I describe only our results on high redshift quasars and note where ASCA will do better, and where it can not.

2. A ROSAT Program

We observed 14 high z quasars between z=2.85 and z=4.11. yielding 25 – 1000 PSPC counts per quasar. Only radio-loud quasars, which are relatively X-ray bright, gave enough counts to allow well-constrained spectral fits. Radio-quiet quasars give only an X-ray color, which nevertheless turned out to be valuable.

An altered perspective is needed when thinking about ROSAT observations of high redshift quasars. First, in the quasar frame ROSAT observes 0.5–10 keV. This is the same *rest* energy range as Ginga observes for z$\sim$0 quasars, thus enabling simple comparisons to be made. Next, optical evolution studies show that the typical quasar at z=3 is $\sim$50 times more luminous than at z=0: $L^*_Q(z=3) \sim 50\ L^*_Q(z=0)$ (Boyle et al 1990). By coincidence the quasars which are observable with ROSAT at z=3 are also $\sim$50 times more luminous than those Ginga could observe, so we are investigating the same relative position on the quasar luminosity function at both epochs. These luminosities are large, $L_X = 10^{47-48}$ erg s^{-1}, compared with 10^{46} erg s^{-1} for 3C273. In black hole models these luminosities require central masses of $\sim10^{10} M_\odot$ in order not to exceed the Eddington limit, i.e. of order 1/10 the Milky Way mass. Finally, z=3 corresponds to a look back time of $\sim$75% the age of the Universe (Ω_0=0). This leaves plenty of room for evolution of both the quasars and their environment.

3. Absorption: Radio-Loud High z Quasars

Low energy cut-offs are seen in 3 out of 4 ROSAT spectra of z$\sim$3 quasars and so are common (Elvis et al 1994b), but are not universal, so a diffuse intergalactic medium (IGM) is not responsible.

The simplest interpretation is that these cut-offs are due to photoelectric absorption. If so, the column densities implied are $\sim 10^{21-22}$ atoms cm^{-2}. The higher values apply if the absorption is close to the quasar, the lower values if the absorption is local to us. These values also assume solar abundances, which may well not apply. Abundances for intervening absorbers are likely to be lower (Pei, Fall & Bechtold 1991) implying larger N_H by up to a factor 4. Abundances in the quasar may be enhanced by factors $\sim 3-14$ (Hamman & Ferland 1992), decreasing N_H by the same factors.

A site within the quasar broad line region seems unlikely, as does absorption in a jet (Elvis et al. 1994), so a new absorption site is required. The ROSAT spectra give no X-ray redshift so this could be anywhere on the long path between us and the quasar. This path length is more than 20 times greater than that toward the previously studied quasars at z$\leq$0.4 (from *Einstein* (Wilkes & Elvis 1987) and Ginga (Williams et al 1993)), suggesting that *intervening* explanations are likely. Probability arguments show that the population of "damped Lyman-α" absorbers provide a plausible location. [1] These systems have column densities of 10^{19}-10^{22} atoms cm^{-2} (Wolfe 1988) and are often considered to be the disks of protogalaxies. For the quasars

[1] 'damped' refers to being on the 'damping wing' of the 'curve-of-growth, i.e. the relation between line width and column density (Spitzer 1978). The damping wing is caused by the 'natural' line width due to Heisenberg Uncertainty Principle broadening. This simple point can be hard to track down in textbooks.

we observe they would be located at z<2 in order for the damped Lyman-α absorption line not to be detectable. The probability argument is good, if no evolution in damped Lyman-α density occurs for z<2. However, such evolution is expected since protogalaxies are rare today. Other explanations should not be dismissed therefore.

An *intrinsic* origin, i.e. one physically related to the quasar, must be considered. To find a new site we probably need to look on a larger scale than for low redshift absorbers. The host galaxy or its environment are obvious locations to consider.

At z>0.7 radio-loud quasars tend to be found in rich galaxy environments (Yee and Green 1984, Ellingson, Yee and Green 1991). Half of all z$\sim$3 radio-loud quasars are highly compact ($\sim$ 100pc) and show low frequency radio cut-offs in the GHz range (the 'GPS' or "GigaHertz Peaked Sources", O'Dea 1990). These symptoms strongly suggest a confining medium (leading to either free-free absorption or synchrotron self-absorption in the radio). If high z clusters are similar to low z clusters then many of them will contain cooling flows (Edge & Stewart 1991) many of these will exhibit X-ray absorption (White et al 1991, Allen, these proceedings). Thus in the X-ray absorption of high z quasars we may be detecting the intracluster medium at z$\sim$3.

The key input needed to answer the ambiguities in the PSPC data is an X-ray redshift. It is unlikely that ASCA can give this because the oxygen edge is the strongest feature to search for, and this is rapidly redshifted out of the SIS band. Nevertheless it is worth attempting (Yaqoob et al these proceedings). A direct redshift requires fair spectral resolution (E/ΔE $\geq$20) over the 0.1-0.6 keV band. AXAF and XMM will provide this. In the meantime indirect approaches are promising (Stewart et al, these proceedings), e.g. if the absorption is limited to radio-loud objects, esp. the GPS, then it must be intrinsic.

4. Absorption: X-Ray Limits on the Intergalactic Medium (IGM)

Not all z=3 quasars show cut-offs. One such has known damped Lyman-alpha absorbers. The X-ray column limits the ionization state and, given a background ionizing flux, the density and size of the absorber. The present limit indicates low ionization and is unrestrictive on size (<25 Mpc, Elvis et al 1994b). However an achievable limit of 1/10 the column density would give a size limit comparable with a galaxy (<25 kpc) so that this method is a highly promising tool (Elvis et al 1994b).

The absence of absorption toward some high z quasars can also be used to put limits on the possible cosmological density, Ω_{IGM}, of a hot diffuse IGM: an 'X-ray Gunn-Peterson test' (Shapiro and Bahcall 1982) using both edge and line, rather than just line, opacity in the soft X-rays. The K-edges of oxygen, neon, silicon and the L-edge of iron produce the absorption, which is spread out by the redshift of the source. For an assumed thermal history the optical depth of this absorption can be calculated, with some other assumptions.

This test is restrictive (Aldcroft et al 1994) for a somewhat enriched IGM at temperatures intermediate between those ruled out by COBE (Mather et al 1993), and the cold IGM ruled out by the traditional Lyman-alpha Gunn-Peterson test (Gunn and Peterson 1965, Giallongo et al 1992), i.e. 10^{5-6}K.

The PSPC data for three z$\sim$3 quasars limit an IGM of solar abundance quite well (Ω_{IGM} <0.2 for T_{IGM} < 5×10^6, for 0.2< Ω <1.0) (figure 2a), although a more plausible abundance of 1/10 solar is not better constrained than by the Lyman-α

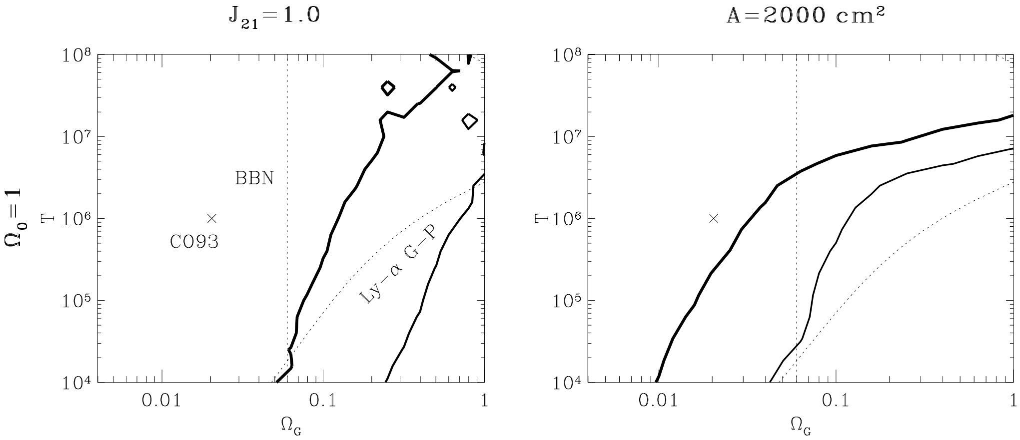

Figure 2: (a) ROSAT limits to Ω_{IGM} versus the Temperature of the IGM . (b) Potential limits for E/ΔE=200, A=2000 cm^2, t=10^5s. Solar abundances, heavy line, 1/10 solar, medium line. Regions to top and left are disallowed.

test (assuming an isothermal thermal history.) Photoionization of the IGM by the integrated quasar light, $J_{\nu 21}$ (Bajtlik et al 1988), has a large effect (Aldcroft et al 1994), making early estimates too optimistic (Shapiro & Bahcall 1982, Rees & Sciama 1967). Even for a $J_{\nu 21}$ 1/10 the nominal value, the limits are an order of magnitude above the limits on Ω from big bang nucleosynthesis (BBN, Kolb & Turner 1990).

Somewhat surprisingly simulations show that the improved energy resolution of the SIS detectors on ASCA do not improve these limits significantly. At high z this is because all spectral features are spread by a factor four due to redshifting. At low redshift one should gain by being able to discriminate individual absorption lines. The SIS do not do this both because their spectral resolution is not high enough, and because the main edges are due to redshifted Oxygen, which lies at the extreme low energy end of the SIS bandpass.

A resolution of E/ΔE$\geq$100 is needed to cleanly resolve lines. The low energy gratings on AXAF (Brinkman et al 1987) easily have this. On 3C273 a 10^5s exposure will bring the X-ray Gunn-Peterson limits close to the BBN limits (Aldcroft et al 1994). Since all quasar observations contribute to an IGM limit we can expect that over the course of the AXAF lifetime sufficient exposure will accumulate to bring the sensitivity of the test into an interesting regime (Figure 2b, Cen & Ostriker 1993).

5. Emission: X-ray loudness (a$_{OX}$ vs. z, L)

A basic characteristic of quasars is the scale-free nature of their emission. From the lowest luminosity AGN (e.g. M81) to the highest redshift, most luminous quasars, the quasar continuum and emission lines scale almost linearly with luminosity, regardless of redshift (e.g. Netzer 1990; Blandford 1990). This is true within both the radio-loud and the radio-quiet classes of quasar. There are small deviations from this pattern, e.g. the Baldwin effect (Baldwin 1977), and the slowly decreasing X-ray loudness for higher luminosity quasars (Worrall et al. 1987). Even these, however, are continuous changes in the sense that there is no characteristic redshift or luminosity at which they occur. This is somewhat surprising because the Eddington luminosity provides

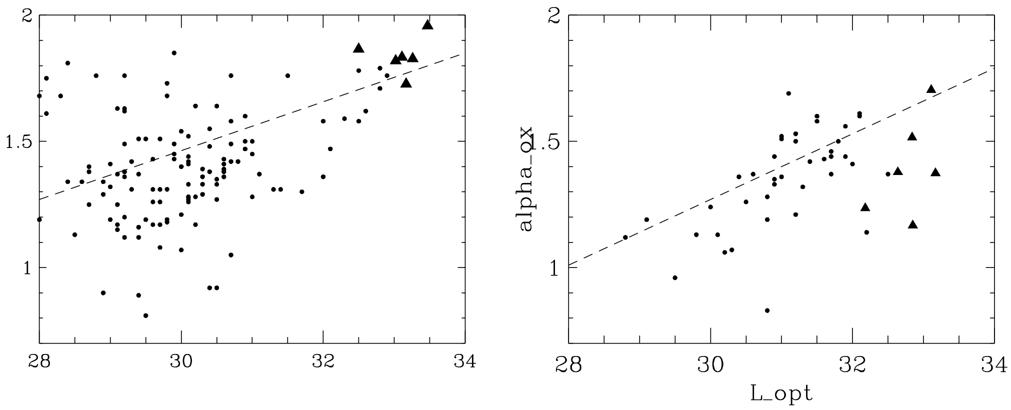

Figure 3: X-ray loudness (α_{OX}) versus optical luminosity (L_{opt}) for (a) radio-quiet quasars, (b) steep spectrum radio-loud quasars.

a natural break point in the standard black hole model for AGN.

Breaks in the scaling laws for quasars may now be beginning to appear (Elvis et al 1994, Bechtold et al 1994 a, b):
(1) Steep spectrum radio-loud quasars do not continue to follow the well-established correlation (e.g. Worrall & Wilkes 1990) of α_{ox} increasing with L_{opt} at high redshift [2] ; they are too X-ray bright (Figure 3b). Radio-quiet quasars instead continue to follow the correlation of α_{ox} increasing with increasing L_{opt} seen at lower redshift (Figure 3a).
(2) Radio-loud quasars become strongly X-ray absorbed between z=0.5 and z=3, whereas radio-quiet quasars probably do not (section 6, Bechtold et al 1994a, b).
These characteristic luminosities and/or redshifts can be used to limit the physics of the emission for steep spectrum radio-loud quasars. For example, since L_X ceases to be proportional to L_{opt} it is likely that the source of the X-ray power ceases to be proportional to the central mass and accretion rate. A second source, e.g. the extraction of black hole spin energy (Blandford 1990) may become important. If we identify the break luminosity as where the spin-derived luminosity becomes comparable to accretion luminosity (Bechtold et al 1994b) then, since the two luminosities depend differently on central mass (Blandford 1990) they define a critical mass, $\sim 10^{9-10} M_{\odot}$, assuming an Eddington limited source. The efficiency with which spin energy is converted into X-rays also comes out of this analysis and is small, $\sim$1% .

6. Emission: X-ray Spectral Evolution

Radio-quiet quasars are fainter in X-rays than radio-loud quasars for a given optical luminosity, a situation that is made worse at high luminosities by the breaking of the scaling law described in the preceding section. This makes it hard to obtain high signal-to-noise detections of radio-quiet quasars at high redshifts. We have found that even a simple hardness ratio gives useful information on their X-ray properties, even though we have as few as 25 counts in individual detections (Bechtold et al 1994).

Figure 4 is a plot of the hardness ratio R , for the quasars in our sample. (R=(H-S)/(H+S), where H = PI channels 11-40, 0.11-0.40 keV, S = PI channels 41-245, 0.41-

[2] $\alpha_{OX} = -\log(f_{opt}(2500)\AA/f_X(2\mathrm{keV}))/2.605$. Larger α_{OX} equals more X-ray quiet.

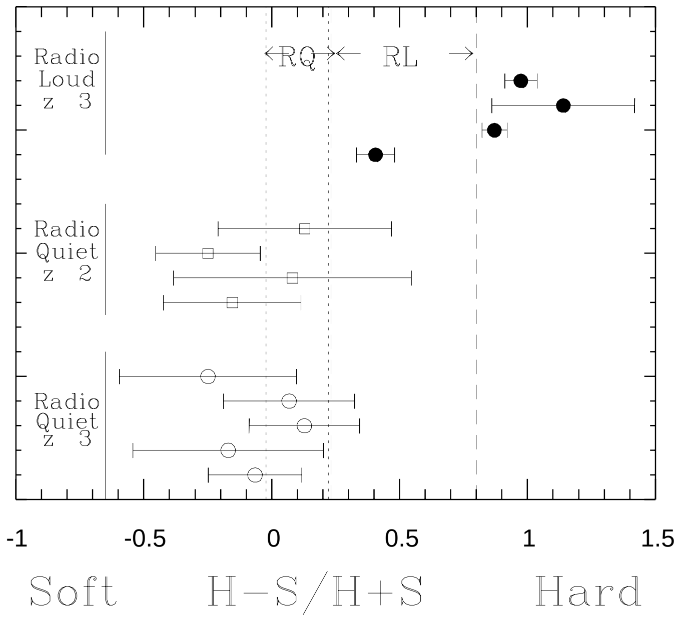

Figure 4: X-ray hardness ratio, R, from the ROSAT PSPC for high z quasars. Ginga predicted ranges of R for radio-quiet (RQ) and radio-loud (RL) are shown.

2.48 keV, in the observed frame). We also plot the R of four intermediate redshift, radio-quiet quasars (1.5 $<$z$<$ 2.2) from the PSPC field of Q0130-403 (Bechtold et al 1994b). Note the systematic difference between the radio-loud and radio-quiet quasars.

The difference in R between low and high redshift radio-loud quasars, can be interpreted in different ways. The two most simple and extreme possibilities are:
(A) a difference in emitted power law index, in the sense that the high-redshift quasars are flatter than the low redshift ones, or
(B) a difference in absorbing column density, in the sense that the high z quasars have a larger absorbing column than at low z.

ASCA observations can easily determine whether radio-quiet quasars change their slopes radically at z$\sim$2, and so will quickly remove many of the ambiguities from the present situation. The results of Stewart et al (these proceedings) are suggestive.

7. Conclusions: Scaling Laws and High Redshift Quasars

Expanding the frontier over which we know quasars' X-ray spectra has led us to two ways in which the scaling laws for quasars break down at high luminosities and/or redshifts. These breakdowns occur for radio-loud quasars, which become strongly X-ray absorbed between z=0.5 and z=3, whereas radio-quiet quasars probably do not; also steep spectrum radio-loud quasars do not follow the well-known correlation of α_{ox} increasing with L$_{opt}$ at high redshift- they are too X-ray bright; Radio-quiet quasars instead continue to follow the correlation of α_{ox} increasing with increasing L$_{opt}$ seen at lower redshift. These breaks in the scaling laws may be related to the origin of the quasar power output from either accretion or spin energy.

We have also made new calculations for the X-ray 'Gunn-Peterson' test for an

IGM, and made the first observational use of this test.

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8. References

Aldcroft T.L., Elvis M., McDowell J. & Fiore R., 1994, Ap.J., submitted.
Baldwin, J. 1977, MNRAS, 178, 67P.
Bajtlik S., Duncan R. C., Ostriker J. P., 1988, Ap.J.,327, 570.
Bechtold, J., Elvis, M., Fiore, M., Kuhn, O., Cutri, R.M., McDowell, J.C., Rieke, M., Siemiginowska, A., & Wilkes, B.J., 1994a, A.J., in press.
Bechtold, J., Elvis, M., Fiore, M., Kuhn, O., Cutri, R.M., McDowell, J.C., Rieke, M., Siemiginowska, A., & Wilkes, B.J., 1994b, A.J., submitted.
Blandford, R. D., 1990, in "Active Galactic Nuclei", Saas-Fee Advanced Course 20 [Berlin: Springer-Verlag] eds. T.J.-L. Courvoisier and M. Mayor.
Boyle B.J., Fong R., Shanks T., and Peterson B.A. 1990, MNRAS, 243, 1.
Edge A.C., & Stewart G.C., 1991, MNRAS, 252, 414.
Ellingson E., Yee H.K.C. and Green R.F., 1991, Ap.J.s, 76, 455.
Elvis M., 1991, "Frontiers of X-ray Astronomy",
Elvis, M., Fiore, F., Mathur S. & Wilkes, B., 1994a, Ap.J., 425, 103.
Elvis, M., Fiore, F., Wilkes, B., McDowell, J., & Bechtold, J. 1994b, Ap.J.,422,60.
Fiore F., Elvis M., Mathur S., Wilkes B.J., and McDowell, 1993, ApJ, 415, 129.
Fiore, F., Elvis, E., Siemiginowska, A., Wilkes, B.J., & McDowell, J.C., 1994, ApJ, submitted.
Giallongo, E., Cristiani, S., & Trevese, D. 1992, Ap.J.lett, 398, L9.
Gunn J.E. and Peterson B. A., 1965, Ap.J., 142, 1633.
Hamman F. & Ferland G., 1992, Ap.J., 391, L53.
Kolb, E.W. & Turner,M.S. 1990, The Early Universe, (New York:Addison-Wesley)
Laor, A., Fiore, F. Elvis, E., Wilkes, B.J., & McDowell, J.C. 1994, Ap.J., submitted
Brinkman A.C., van Rooijen J.J., Bleeker J.A.M., Dijkstra J.H., Heise J., De Korte P.A.J., Mewe R., and Paerels F., 1987, Ap. Letters & Comm., 26, 73.
Mather, J. C., et al., 1993, COBE preprint no. 93-01
Mathur, S., 1994, Ap.J., submitted.
Mathur, S., Wilkes, B., & Elvis, M. 1994, Ap.J., in press.
Netzer, H. 1990, in "Active Galactic Nuclei", Saas-Fe Advanced Course 20 [Berlin: Springer-Verlag] eds. T.J.-L. Courvoisier and M. Mayor.
O'Dea C.P., 1990, MNRAS, 245, 20P.
Pei Y., Fall M., Bechtold J., 1991, Ap.J., 378, 6.
Shapiro P.R. and Bahcall J.N., 1980, Ap.J., 241, 1.
Spitzer L., 1978, 'Physical Processes in the Interstellar Medium, [Wiley-Interscience].
White D.A., Fabian A.C., Johnstone R.M., Mushotzky R.F., and Arnaud K.A., 1991, MNRAS, 252, 72.
Wilkes B.J. and Elvis M., 1987, ApJ, 323, 243.
Wilkes B.J., Elvis M., Fiore F., McDowell J.C., Tananbaum H. and Lawrence A. 1992, ApJ (Lett), 393, L1.
Williams O.R. et al., 1992, ApJ, 389, 157.
Wolfe A.M., 1988, in "QSO Absorption Lines", eds. J.C. Blades, D. Turnshek, and C.A. Norman [Cambridge:CUP], p.297.
Worrall D.M., and Wilkes B.J., 1990, Ap.J., 360, 396.
Worrall, D.M., Giommi, P., Tananbaum, H. & Zamorani G., 1987, ApJ, 313, 596.
Worrall D.M., and Wilkes B.J., 1990, Ap.J., 360, 396.