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IGM Constraints and the Intracluster Medium at z=3 from X-ray Spectra of High Redshift Quasars

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Abstract. ROSAT has allowed the study of high redshift (z=3) quasars in X-rays. Using these quasars as a background light source enables us to 'X-ray' the intervening space and so search for photoelectric absorption by both an Intergalactic Medium (IGM) and any Intracluster medium around the quasar. We present our first results on both topics.

1. Introduction

The possibility of detecting diffuse matter at large redshifts has always been enticing. George Field in his 1972 review of the subject noted many possibilities for the detection of both a diffuse Intergalactic Medium (IGM) and matter clumped around clusters and galaxies. These possibilities concentrated on ionized material, especially thermal material at X-ray temperatures. X-ray astronomy should then be in the thick of studies of diffuse hot media at early epochs. However, a first explanation of the diffuse X-ray background as being due to thermal bremsstrahlung emission the diffuse IGM (Field & Perrenod 1977) has been ruled out by COBE (Mather et al. 1993). Otherwise the highest redshift to which diffuse X-ray emission has been studied in X-rays is 0.55 (for the cluster of galaxies CL0016+16, Yamashita 1994).

Meanwhile optical studies of absorption toward high redshift quasars have long been a tool for investigating intergalactic space and non-luminous material at early epochs. X-ray technology had until recently been hopelessly inadequate to apply similar methods at high energies. The ROSAT and ASCA mission have provided a just sufficient increase in collecting area, spectral resolution and sensitivity to begin to open up this field of inquiry. Here we report on our first efforts in this area: a search for the IGM and the possible detection of intracluster material at z=3.

2. The 'X-ray Gunn-Peterson Test' for the Intergalactic Medium

For some time there has been indirect evidence which indicates the existence of a diffuse intergalactic medium (IGM): observationally, the detection of X-ray emitting gas in galaxy clusters, and the Ly-α forest clouds seen in the spectra of high redshift quasars demonstrate that there is a significant amount of matter not condensed into galaxies; theoretically, studies of galaxy formation generally predict that the process is inefficient ($\geq$20% uncollapsed, Shapiro et al. 1994).

Despite the evidence that a diffuse IGM should exist, there still has been no unequivocal detection (but see Jakobsen et al 1994), nor have the basic properties of this medium such as temperature, density, and chemical composition been strongly constrained. The most sensitive tests for an IGM to date are the high temperature limit based on the distortion of the cosmic microwave background spectrum (the Compton y parameter) as measured by the COBE satellite (Mather et al. 1993), and the low temperature limit based on the absence of a trough due to Ly-α bluewards of the Ly-α emission line, the 'Gunn-Peterson test' (Giallongo, Cristiani, & Trevese 1992; Gunn & Peterson 1965; Shklovski 1964; Sheuer 1965). These limits (figure 1) in IGM temperature vs. density (in terms of Ω) space show large unexplored areas.

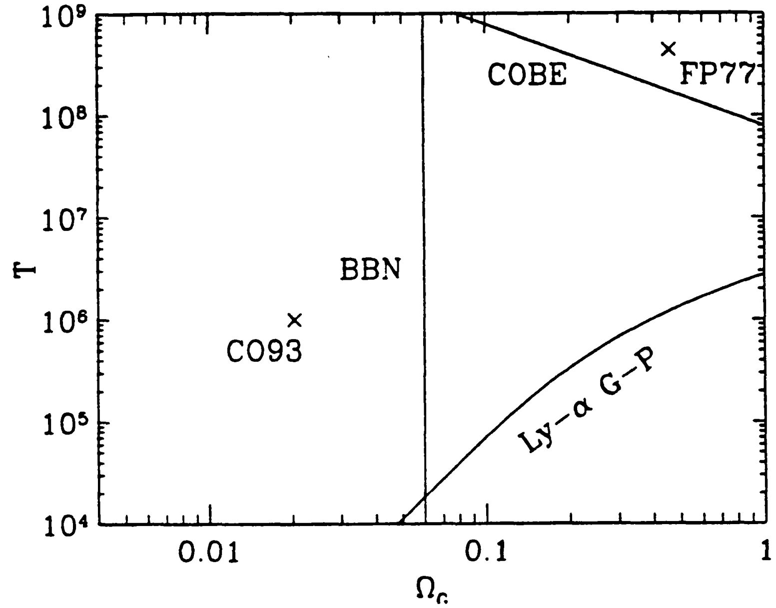

Figure 1. Non-X-ray constraints on the IGM temperature and density

It was realized when quasars were detected in the X-ray band that a Gunn-Peterson test using the X-ray transitions in heavy elements might constrain the IGM at higher temperatures than the original Ly-α Gunn-Peterson test (SB; Sherman & Silk 1979; Sherman 1979). This depends on the IGM not being of primordial composition, and indeed the IGM could have been enriched by the injection of processed gas from supernovae (e.g. Sarazin 1988) as in clusters of galaxies. The same process could re-ionize the IGM (Cen & Ostriker 1993).

Only with the launch of ROSAT (Trümper 1983) has an observational application of this IGM test become feasible. We report on its first application here. (The full details are given in Aldcroft et al 1994).

Since the early calculations of Shapiro & Bahcall (1982) and Rees and Sciama (1967) the importance of the diffuse ionizing radiation, due at a minimum to the integrated light of quasars , has been recognized (Bajtlik et al. 1988 and refs. therein). For a standard 'hard' quasar-like spectrum this radiation ionizes the helium in the IGM and reduces its optical depth at z=3 from a peak at 1/4 keV of τ ~5, to τ ~0.3 (Figure 2). This greatly weakens the X-ray Gunn-Peterson test. Nevertheless it is valuable to examine its potential.

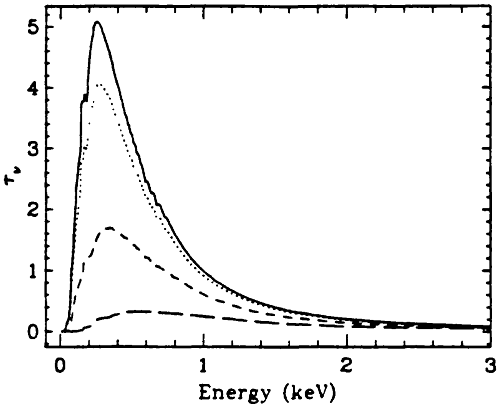

Figure 2. Optical depth of the IGM at z=3 for factor 10 changes ionizing background radiation, J_{21}.

Good signal-to-noise observations of high-redshift quasars with the ROSAT PSPC have revealed that some of these quasars can be well fitted in the soft X-ray band with only a single power-law and Galactic absorption (Elvis et al 1994). This lack of observed X-ray absorption in the IGM can be used to constrain the temperature, density, and heavy-element abundance of the IGM via the X-ray Gunn-Peterson test. IGM absorption produces a broad low-contrast dip in the soft X-ray spectra of high z quasars around 0.4–1 keV (Figure 3). Currently, we know of three quasars which are at $z > 2$ and have an unabsorbed PSPC spectrum with at least 300 counts: PKS 0237-233 (927 counts), Q0420-388 (363 counts), and Q1445+101 (OQ172; 656 counts).

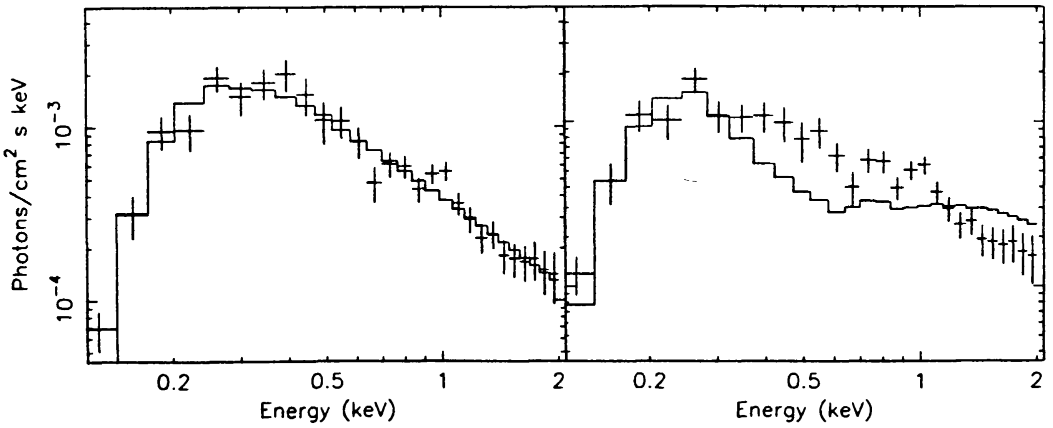

Figure 3. Model PSPC spectrum with and without IGM Absorption

We constructed absorption models using CLOUDY (Ferland 1993). The temperature of the gas is fixed and no attempt is made to balance heating and cooling. Instead, the gas is assumed to be heated by some unspecified mechanism to the given temperature. (CLOUDY is numerically unable to do calculations at the very low densities of the IGM. The actual computations in CLOUDY are all made at a fixed density of $10^{-4}\,\mathrm{cm}^{-3}$, which is equivalent because of a homology relation for all densities below $10^{3}\,\mathrm{cm}^{-3}$.)

We included an ultraviolet background ionizing spectrum with a power-law form:

$$J_\nu(z) = 10^{-21} J_{21} \left(\frac{1+z}{1+z_q}\right)^{\beta} \left(\frac{\nu}{\nu_{LL}}\right)^{-\alpha} \mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}\,sr^{-1}}. \qquad (1)$$

Here J_{21} is the dimensionless strength, z_q is the redshift at which the proximity effect is observed, ν_{LL} is the frequency at the hydrogen Lyman limit, and β characterizes the redshift evolution. Based on the range of parameter values found in the literature (which are generally in rough agreement but often formally inconsistent), we use the values $\beta = 4$, $\alpha = 1.5$, and $z_q = 2.5$. The strength J_{21} of the background radiation is uncertain by about a factor of 10, so we do all calculations for two values, $J_{21} = 1.0$ and $J_{21} = 0.1$.

An important assumption which is implicit in our calculation is that ionization equilibrium is established at all epochs. At the very low densities characteristic of the IGM, this assumption requires careful evaluation. Although it is well known that at typical IGM densities and temperatures, the HII recombination time scale can easily exceed the Hubble time (e.g. Ikeuchi & Ostriker 1986), for our purposes we only need to know that the hydrogen is very nearly 100% ionized, and so the assumption of ionization equilibrium for the heavy elements rests only on their recombination rate coefficients. Radiative recombination and dielectronic recombination dominate, and figure 4 shows that for the combinations of (Ω, T) that we can constrain, ionization equilibrium is a good approximation.

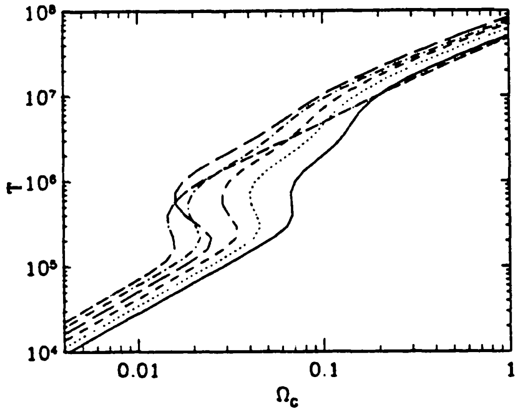

Figure 4. Regions of the T_{IGM}, Ω_{IGM} plane for which ionization equilibrium is applicable.

The final result is illustrated in figures 5. The unrealistic case of solar abundances gives quite restrictive limits even for $J_{21} = 1.0$. A more reasonable reference value of 0.1 Solar abundance allows the current X-ray Gunn-Peterson test to better the Lyman-α Gunn-Peterson limits only for $J_{21} = 0.1$, setting

$\Omega \leq 0.3$ for any temperature below 10^7 K. Although these results do set new limits on the IGM, they are disappointing in that they lie well below the region of present theoretical interest and depend upon several unknown parameters ($J_\nu(z)$, abundances).

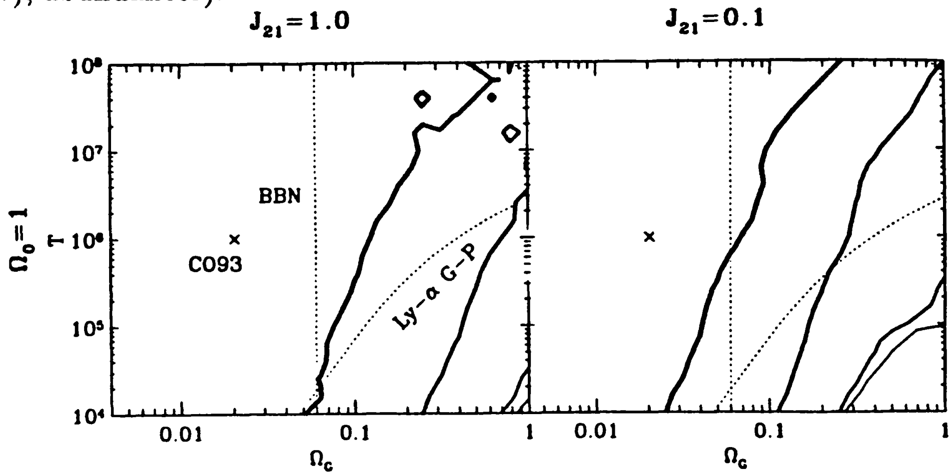

Figure 5. X-ray Temperature-Density Constraints for the IGM. (a) J_ν=1.0, (b) J_ν=0.1

A more direct test might be possible at low z where individual absorption lines and edges have not become blended together, thus yielding a more characteristic spectrum (Figure 6).

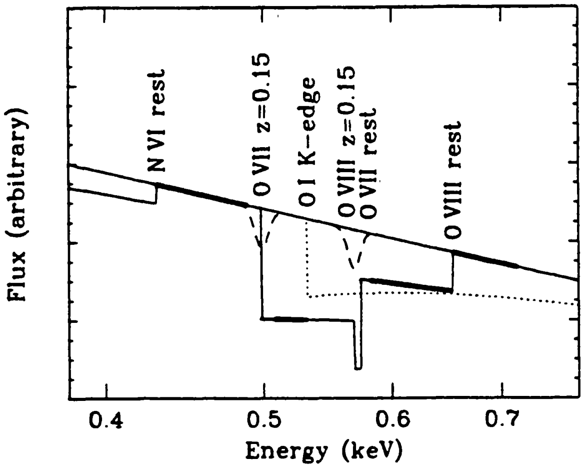

Figure 6. Characteristic absorption shapes produced by redshifted absorption lines and edges at moderate redshifts (z=0.15).

Surprisingly our simulations show that the extra spectral resolution (E/ΔE~10) afforded by X-ray CCD detectors (e.g. the SIS on ASCA) is insufficient. Grating spectrometers offer E/ΔE~1000, and this is sufficient. However the much reduced pathlength (a factor of 46 at z=0.15 compared with 3, Ω_0=0) leads to small IGM opacities and so requires long integrations to achieve sufficient signal-to-noise. Fortunately every extragalactic observation can be appropriated for this measurement, so that the low energy gratings on AXAF will accumulate sufficient signal over a few years (Figure 7).

The outlook may be more promising than the above discussion leads one to expect. Absorption of higher energy photons by the numerous Lyman limit clouds will reduce the ionization of the IGM (Meiksin & Madau 1993), rendering the X-ray Gunn-Peterson test more sensitive. Should also the background spectrum turn out to be 'soft', i.e. more rapidly falling to high energies (as suggested by Jakobsen et al 1994) then the X-ray Gunn-Peterson test will become more powerful again. This would be fortunate since then, with the possible detection of the HeII Gunn-Peterson effect in Q0302−003 by Jakobsen et al (1994) many of the unknowns in the X-ray problem drop out and allow quite direct limits to be set on abundances in the IGM.

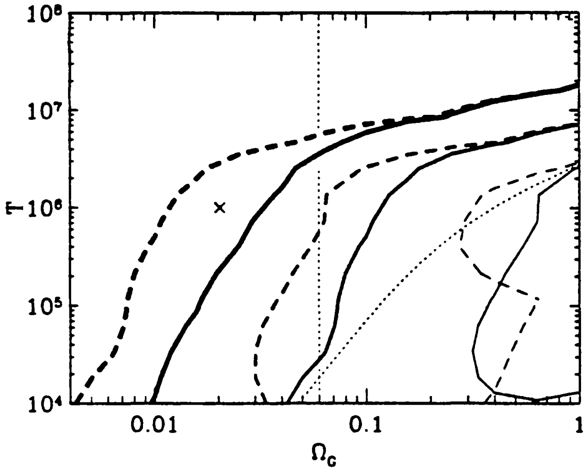

Figure 7. Model X-ray Temperature-Density Constraints for the IGM, using Absorption lines and edges in a low redshift (z=0.15) quasar. $2000 cm^2$, 10^5s exposure.

3. Intracluster Medium at z=3

Low energy cut-offs are common in the soft X-ray spectra of radio-loud quasars at z∼3. (They are seen in 3 out of 4 ROSAT spectra of z∼3 quasars, Figure 8, Elvis et al 1994). This is most easily interpreted as being due to photoelectric absorption by enriched material somewhere between us and the quasar. If the material is cold and has solar abundances then it requires a column density of $\sim 10^{22}$ atoms cm^{-2} at z=3. Because the cut-offs are not universal absorption by the diffuse IGM is ruled out

The PSPC X-ray spectra have far too poor a resolution to directly determine redshifts so the absorber could be anywhere: either randomly placed along the line of sight (an 'intervening' absorber), or physically associated with the quasar (an 'intrinsic', or 'associated', absorber). Radio-quiet quasars at similar redshifts, do not seem to show these cut-offs (Fiore et al. in preparation). Since an absorber cannot know whether the background quasar is a bright radio source or not, the absorbers must be intrinsic. Abundances in high redshift quasars may be enhanced by factors $\sim 3-14$ (Hamman & Ferland 1992), which would decrease the implied N_H from the X-ray cut-offs by the same factors.

A site within the quasar nucleus seems unlikely. Absorption by cold material at the distance of the broad emission line region is common at low luminosities

(Elvis & Lawrence 1982, Turner & Pounds 1989), but the absorbers tend to become ionized as luminosity increases and are not seen in high luminosity AGN (Elvis et al. 1994). For these to re-appear at the highest luminosities implies some change in the structure of the quasar nucleus, which seems unlikely. So does absorption in a jet. Absorption has been seen in one or more BL Lac objects (Canizares & Kruper 1984, Madejski et al. 1991). However two of the quasars showing strong cut-offs (PKS2126−158 and S4 0636+680) are Gigahertz Peaked Spectrum (GPS) radio sources. Beaming is not believed to be important in GPS sources because of their low radio polarization, steep high frequency spectra, and lack of strong variability (O'Dea, Baum and Stanghellini 1991).

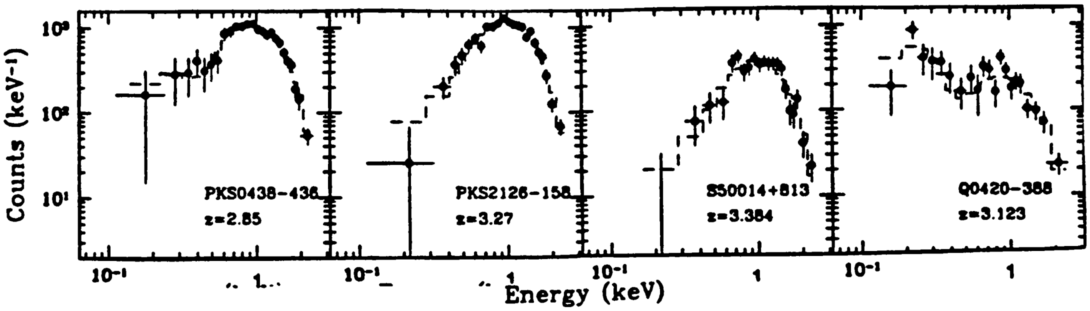

Figure 8. (a)-(c) PSPC X-ray spectra of high z quasars showing large low energy cut-offs. (d) similar spectrum with no cut-off.

We are thus forced to examine other absorption sites, further from the nucleus. An origin related to cluster environment is plausible, since all the observed quasars are radio-loud, and at z>0.7 radio-loud quasars tend to be found in rich galaxy environments (Ellingson, Yee and Green 1991). The presence of GPS sources in our sample suggests an intriguing possibility for the site of the absorbers in these high redshift quasars. GPS sources are unusually compact (~ 100pc, Pearson and Readhead 1984), implying a dense confining medium for the radio sources.

Further, a cooling flow around the quasar provides a plausible mechanism and could also explain the X-ray absorbing columns. At low redshifts X-ray absorption associated with cooling flows has column densities up to a few 10^{21}atoms cm^{-2} (White et al. 1991), within a factor of a few as large as those seen in the high redshift quasars. Clumping in front of the small X-ray source, and abundance enhancements could raise the observed column densities in high z quasars to the values we observe. Low redshift radio-loud AGN seen at the centers of cooling flows do in fact have similarly large X-ray column densities (NGC1275, Fabian et al. 1981; M87 Schreier et al. 1982; Cygnus A, Arnaud et al. 1987). Of course, many AGN not in cooling flows also show similar absorption.

The absence of a damped Lyman-α or Lyman limit systems near the quasar emission redshift (Sargent, Steidel and Boksenberg 1990, Morton, Savage and Bolton 1978), suggests that the quasar continuum photoionizes a region around the quasar, encompassing the cooling flow region. The low-energy cut-off is confirmed in one case by ASCA spectra (Serlemitsos et al. 1994). However the absorption does not fit simple high z absorption models with cold material at solar abundances. Special conditions of abundance or ionization need to be investigated, employing simultaneously constraints from the limits on high ionization UV absorption lines (as in Mathur et al 1994). By determining the distance and density of the absorbers we shall be able to locate the material definitively within or outside the nuclear region, and study its physical conditions.

The fact that our quasars were selected to be among the most luminous known could bias us toward objects in strong cooling flows. Fabian and Crawford (1990) have pointed out that the quasar continuum emission will Compton cool the material in a cooling flow, and so may increase the quasar accretion rate in a feedback that enhances the quasar luminosity. The most luminous quasars may thus be found in the strongest cooling flows.

We conclude that the X-ray absorption we see in high redshift quasars may represent the detection of intracluster material at z$\sim$3. Direct imaging of these clusters at the sub-arcsecond level by AXAF should be able to separate easily the cluster from the bright quasar at its center.

4. Conclusions

Absorption in the X-ray spectra of quasars at high redshift has now demonstrated a potential to investigate novel questions - the abundances in the IGM and the formation of clusters and cooling flows at early epochs. The present generation of X-ray spectroscopy detectors can only make a first order cut at these problems. Fortunately missions with far more area, spectral resolution and spatial resolution are approaching launch (AXAF, Spectrum-X and XMM). With these, X-ray spectroscopy will become a normal tool for investigating hot, ionized matter at high redshifts.

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