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Analysis of Ly α absorption lines in the vicinity of QSOs

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Abstract. Recent evidence suggesting that at least some of the Lyman alpha forest absorbers are not primordial and are indeed associated with galaxies is discussed. Proximity effect, which deals with the change in the distribution of Lyman alpha forest lines near the quasi-stellar objects (QSO) due to the radiation from the QSO is described. Results of calculations of the background UV intensity based on the proximity effect, for a large, homogeneous sample of lines, collected from the literature, are presented. It is shown that blending of lines in the intermediate resolution observations is responsible for an overestimation of the background UV flux in earlier calculations. Independent evidence is provided for the presence of dust in damped Lyman alpha absorbers. Causes for the occurence of the Lyman alpha forest lines with redshifts greater than the quasar redshift are investigated.

1. Introduction

Narrow absorption lines in the spectra of QSOs have proved extremely useful for understanding various components of the universe at high redshifts (Z). The 'heavy element or metal line systems' to which most of the lines on the longer wavelength side of the Lyman alpha emission line belong, are most likely produced by halos and disks of galaxies lying along the line of sight to the QSO. Details of their classification, and origin can be found in Khare (1995a, 1995b).

Most of the large number of lines on the short wavelength side of the Lyman alpha emission line cannot be identified with any heavy element lines and are believed to be Lyman alpha lines at different redshifts, forming what is called the Lyman alpha forest. Until a couple of years ago the Lyman alpha forest lines (LAFLs) were believed to be produced by intergalactic clouds as (i) their number is too large to be produced by galaxies (ii) the clouds producing these lines did not appear to have metals in them and therefore have not been processed through stars, (iii) they are not found to cluster as strongly as the galaxies (iv) their neutral hydrogen column densities are smaller than the column densities in metal systems. This belief has recently changed to some extent after observations in the UV (with HST) and with high signal to noise ratio (with Keck telescope) became available.

HST observations made it possible to observe the LAFLs at lower ($z \leq 1$) redshifts. Remember that ground based observations can only see Lyman alpha at redshifts beyond 1.6. It is now possible to detect galaxies close to the QSO line of sight having the same redshifts as the LAFLs. Such studies (Lazetta 1995) indicate that about 30% of the LAFLs (mostly having rest equivalent width ≥ 0.3 Å) are produced by galaxies and that most galaxies at $z \leq 1.0$ are surrounded by halos of radius $\simeq$160 Kpc with a covering factor of the order of unity.

High S/N observations from the Keck telescope (Tytlar 1995) have shown that 60% of the LAFLs with neutral hydrogen column densities greater than $10^{14.5}$ do have accompanying CIV lines. The abundance of Carbon has been found to be about two orders of magnitude below the solar value (Cowie *et al.* 1995), similar to that observed in some of the metal line systems. The LAFL material is thus not pristine and has been processed through stars.

There has also been increasing evidence for clustering of Lyman alpha lines (Srianand and Khare 1994, Srianand 1996). Evidence for strong clustering has been recently found by Soto *et al.* (1996) from a study of the accompanying C IV lines.

These new observations have led to the suggestion that there are likely to be two distinct populations of LAFLs. One, associated with galaxies, has metals and clusters at velocities of up to 1000 km s^{-1} and another, weaker, not associated with galaxies and probably has no metals.

2. Distribution of LAFLs

The number of these clouds per unit redshift interval per line of sight, n(z), is seen to increase with redshift. An analysis of a large intermediate resolution sample of ground based observations, collected from the literature by Srianand and Khare (1996) shows that for $3.2 \geq z \geq 1.7$, $n(z) \propto (1+z)^{1.724\pm0.228}$ for lines with $W \geq 0.3$ Å. This result however holds only for the clouds at $z \geq 1.7$. HST observations have revealed that there are many more clouds at low z than that given by the above formula. It has been suggested that the clouds at low redshifts belong to the first population (associated with galaxies), whose number may have been increasing with time at the cost of the clouds of the second population (truly intergalactic). The higher number at low redshifts could also partly be a result of the decrease in the background UV field at low redshifts which is expected due to the decline in the QSO number density at these redshifts.

Intermediate resolution observations of the LAFLs have yielded an equivalent width distribution, $n(w) \propto \exp(-w/w_*)$. The value of w_* typically being 0.28 (Srianand and Khare 1996). High resolution observations of these lines allow the determination of the column density and velocity dispersion parameter for individual components in lines, by profile fitting analysis. The column density distribution if found to be a powerlaw with a slope of $\simeq -1.7$. Note that high resolution observations take much longer time and need bigger telescopes. Large number of QSOs have been observed to date at intermediate resolution resulting in a large, statistically meaningful data set for the study of the forest lines. The high resolution data are comparatively scarce, and though increasing rapidly, are still not sufficient for the purpose of statistical analysis, regarding the distribution of the lines.

Note that in all these analyses only lines which are sufficiently far away from the QSOs (with distances greater ≥ 8 Mpc) are used, as the properties and distribution of lines close to the QSOs are likely to be modified by the QSOs.

3. Proximity effect

It was first noted by Carswell *et al.* (1988) that there exists an inverse trend in the distribution of LAFLs close to the QSOs, in the sense that the number of lines, n(z), which shows an increase with redshift, as noted above, starts to decrease with redshift at distances within a few Mpc from the QSO. This was later confirmed by various statistical tests performed by different groups. The Lyman alpha clouds are most likely ionised by the intergalactic UV background radiation field (IGBR). This field is the integrated field from various UV sources, in particular the QSOs. The fraction of neutral hydrogen in a cloud is decided by the intensity of the UV field falling on it and for optically thin clouds like the Lyman alpha clouds, is inversely proportional to this intensity. Sufficiently close to a particular QSO, it's own UV radiation dominates over the IGBR. The neutral fraction of hydrogen in a cloud close to the QSO is therefore expected to be smaller than that in a similar cloud away from the QSO. As a result the number of clouds per unit redshift interval, n(z), having neutral hydrogen column density above a minimum column density, N_{min}, will be smaller near the QSO compared to it's value away from the QSO. The inverse effect mentioned above is therefore interpreted as the decrease in the number of clouds having column density of neutral hydrogen above a cutoff value, near a QSO, due to the increased ionization of clouds by the QSO radiation field. This effect, called the proximity effect, was first used by Bajtlik *et al.* (1988), to obtain the intensity of background UV ratdiation field. Their model assumes the shape of the ionizing background radiation and that of the QSO continuum to be same. For a given cloud near QSO, the H I column density is then given by

$$N_{HI} = N_O (1 + \omega)^{-1} \tag{1}$$

where N_O is what the column density would have been if there had been no nearby QSO and

$$\omega = \frac{F_\nu^Q}{4\pi J_\nu(z)} . \tag{2}$$

$J\nu(z)$ is the IGBR at the Lyman limit, at redshift z, and

$$F_\nu^Q = \frac{L\nu}{4\pi r_L^2} \tag{3}$$

is the local Lyman limit flux density due to the QSO, r_L being the luminosity distance of the cloud from the QSO. As noted before, the distribution of neutral hydrogen column density,

N_{HI} in individual clouds is a power law with index β, so that the number density of clouds above a threshold column density N_O, is given by

$$N\,(N_{HI}) \propto N_O^{1-\beta} \tag{4}$$

Hence, for a sample limited by lower column density or corresponding minimum equivalent width, the distribution of lines with redshift in the spectra of a single QSO, after accounting for the proximity effect is

$$n(z) \propto (1+z)^{\gamma}\,[(1+\omega(z))]^{1-\beta}. \tag{5}$$

Note that γ and β are obtained, as seen in the last section, from analysis of lines away from the QSO. Comparing this distribution with the observed distribution near the QSOs one can obtain $\omega(z)$ and thereby the UV background intensity as a function of redshift. Bajtlik *et al.* (1988) obtained the IGBR to be, $J\nu = 10^{-21.0 \pm 0.5}$ ergs cm^{-2} s^{-1} Hz^{-1} Sr^{-1} by analysing an intermediate resolution data sample. Recently Bechtold (1994) obtained $J_\nu = 10^{-20.5}$ ergs cm^{-2} s^{-1} Hz^{-1} Sr^{-1} with her intermediate resolution data sample. For our sample we get a value of $J_\nu = 10^{-20.22}$ ergs cm^{-2} s^{-1} Hz^{-1} Sr^{-1} . All these values are much larger than the values obtained from the known distribution of the QSOs and it has been proposed that the number of QSOs producing the UV background may be much larger than the observed number, most of the QSOs being invisible to us due to the obscuration by dust in the intervening galaxies.

3.1 *Effect of line blending*

As noted above, the samples used for the proximity effect analysis are of intermediate resolution. Most of the lines observed at this resolution are actually blends of narrow lines. It has been noted (Barcons and Webb 1990) that the column density distribution and velocity dispersion parameters obtained from the high resolution observations do not yield the observed (at intermediate resolution) equivalent width distribution. This has been attributed to the blending of lines, due to the large number of these lines per unit redshift interval as well as due to the enhanced blending due to clustering of these lines. We have argued that it is necessary to use a column density distribution describing the column densities in blends in the proximity effect calculations. This distribution can be obtained from the observed equivalent width distribution by using an effective velocity dispersion parameter describing the width of the blends and performing a curve of growth analysis. The slope of this distribution was found to be 1.4-1.6. Using this values of β in the proximity effect calculation reduces the background intensity by factors of upto 3. We thus conclude that the values of background field obtained previously from the intermediate resolution data are overestimates due to the blending effects which are not accounted for in these studies. We however note that accounting for this effect does not eliminate the discrepancy between the background radiation intensity obtained from the proximity effect calculations and the background from the known QSOs. The former still being several times the latter.

3.2 Evidence for dust in damped Lyman alpha absorbers

It has been shown (Fall and Pei 1995) that the damped Lyman alpha absorbers contain dust. The F_ν values calculated for these QSOs may thus be underestimates. IGBR calculations from proximity effect, considering only QSOs having damped Ly α absorbers are therefore expected to yield smaller values for the background radiation field compared to the values obtained using the whole sample. This was confirmed for the subsample of 16 QSOs having damped Lyman alpha systems in their spectra, for which we obtain J_ν to be 10^{-21} ergs cm^{-2} s^{-1} Hz^{-1} Sr^{-1} . This is smaller than the value obtained for the whole sample by a factor of 3. Our results thus provide an independent evidence for the presence of dust in damped Lyman alpha absorbers.

4. Properties of NVLs

More than 50% of the QSO sight lines in our sample show narrow absorption features in the red wing of the Ly α emission which cannot be attributed to any strong UV absorption belonging to previously known absorption systems. These are believed to be Ly α lines redshifted with respect to the QSO, and therefore have a negative velocity with respect to the QSOs (here after NVLs).

In order to determine if the occurrence of the NVLs depends on any of the QSO properties, we looked for possible correlation between the occurence of these lines and observed QSO properties. We did not find any correlation with the QSO flux at the Lyman limit, radio loudness or optical spectral index. The probability of occurence of these lines is, however, found to be larger for QSOs with associated metal line systems. Also the probability is higher for QSOs with higher redshifts.

In the framework of cosmological redshifts as distance indicators, we consider two possible origins for these lines, (1) The emission redshift of the QSOs used here may be wrong and may actually be higher than the values used here, (2) The redshifts are not the correct indicators of distance and peculiar velocities of the Ly α clouds or the QSOs can be the cause for NVLs. For both these possibilities we have estimated the IGBR by performing the proximity effect calculations, described above, this time including the NVLs in the line sample.

4.1 Higher QSO systemic redshift

A discrepancy between the redshifts of different emission lines in the spectra of a QSO is often present. Tytler and Fan (1992) have worked out recipes to calculate the systemic redshift of a QSO from the redshifts of it's emission lines. These have been incorporated in our calculations described above. Here we consider the possibility that the corrections given by Tytler and Fan (1992) underestimate the systemic redshifts of QSOs which may be even higher (see Srianand and Khare 1996 for further details), so that the absorption redshifts exceed the emission redshifts by, a velocity v_s, and calculated the expected number of LAFLs in various relative velocity bins for $W_r^{min} = 0.3$Å. The best fit values of J_ν for various values of v_s and the probability for various values of v_s to describe the observations are given in Table 1. It appears that v_s has to be less than 1500 kms^{-1} in order to reproduce the observed distribution of Ly α clouds near the QSOs. There are, however, Ly α lines redshifted with respect to QSOs by more than 2500 kms^{-1}, which implies that at least in few QSOs the correction to the emission redshift may be much higher than the upper limit obtained from our analysis.

Table 1. Results of proximity effect calculations taking into account possible shift in systemic redshifts.

v_s	$\log J_\nu^*$	χ^2 (prob)
0	–20.2	0.68
500	–20.6	0.97
1000	–21.0	0.91
1500	–21.4	0.86
2000	–21.6	0.61

* J_ν is in units of ergs cm^{-2} s^{-1} Hz^{-1} Sr^{-1}

4.2 Peculiar velocities of absorbers

Another explanation for NVLs may be the presence of large peculiar velocities of the intervening Ly α clouds on top of the general Hubble flow. These peculiar velocities may either be due to the gravitation induced clustering of clouds associated with collapsed density peaks as in the models of Rees (1986) or due to the origin of clouds in the fragmenting shells as in the models proposed by Ikeuchi and Ostriker (1986). If Ly α clouds are present in the extended galactic halos, in extended disks or in dwarf galaxies, one would expect them to have some peculiar velocity on top of the Hubble flow. We have performed the proximity effect analysis by assuming that the distribution of the line of sight component of the peculiar velocities of Ly α clouds is gaussian, given by,

$$f(v) = \frac{1}{\sqrt{\pi} v_d} \exp\left[-\left(\frac{v}{v_d}\right)^2\right], \qquad (6)$$

Table 2. Results of proximity effect calculations taking into account the effect of peculiar velocities.

		c^2 probability for	
v (Km S^{-1})	$J_\nu^* = 10^{-2-}$	$J_\nu^* = 10^{-20.5}$	$J_\nu^* = 10^{-21}$
1000	0.0000	0.0000	....
1500	0.0036	0.1527	....
2000	0.7468	0.6032	0.0009
2500	0.6578	0.5733	0.0096
3000	....	0.5044	....

* J_ν is in units of ergs cm^{-2} s^{-1} Hz^{-1} Sr^{-1}

where v_d is the dispersion in peculiar velocity. Taking the value of $\beta = 1.7$ we calculated the expected number of lines in bins with different relative velocities with respect to QSOs for various values of v_d and J_ν. Considering only bins between -2500 and 6000 km s^{-1} w.r.t. the QSO, the χ^2 probability that the predicted number of lines is consistent with the observed values given in Table 2. It is clear from the table that J_ν has to be higher than $10^{-20.5}$ ergs cm^{-2} s^{-1} Hz^{-1} Sr^{-1} with v_d around 2000 km s-1 in order to fit the observed distribution. This value of peculiar velocity is very large compared to the observed values of 600 km s^{-1} for galaxies (Dressler 1987). However, the peculiar velocities of clusters of galaxies are around 2000 km s^{-1} (Bahcall, 1988).

One can consider the possibility that the QSOs themselves have peculiar velocities of ~ 2000 km s^{-1} on top of the Hubble flow. The values of J_ν and v_d obtained above will be valid for this case also. In order to have such a high velocity, QSO host clusters should have a mass of about $\sim 10^{16} M_\odot$. and more than 50% of the QSOs should form in such massive cluster environments. The formation of such massive structures at redshifts as early as z = 4 is difficult in the currently favored models of structure formation. We can thus rule out the possibility that NVLs are produced due to peculiar velocities of Ly α clouds or those of QSOs. Also if this scenario is correct, it will widen the discrepancy between the calculated background and that expected from the QSO counts alone.

It is clear from the above analysis that there is no unique mechanism by which one can explain the presence of NVLs. However a systemic offset of 1000-15000 km s^{-1} of the QSO emission redshifts along with a peculiar velocity dispersion of 500 km s^{-1} may explain the NVLs. The background intensity calculated in such a model will be similar to the values obtained by considering proximity effect for lines with $z_{abs} < z_{em}$ alone and the discrepancy between the background intensity calculated by using proximity effect and from QSO counts will persist.

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