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Title of research: OPTIMAL EXTRACTION OF QUASAR LYMAN LIMIT ABSORPTION SYSTEMS FROM THE IUE ARCHIVE

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ABSTRACT

The IUE archive contains a wealth of information on Lyman limit absorption systems (LLS) in quasar spectra. QSO spectra from the IUE data base have been optimally extracted, coadded, and analyzed to yield a homogeneous sample of LLS at low redshifts. This sample comprise 36 LLS, twice the number previously analyzed low z samples. These systems are ideal for the determination of the origin, redshift evolution, ionization, velocity dispersions and the metal abundances of absorption systems. Two of them are also excellent targets for the determination of the primordial Deuterium to Hydrogen ratio.

1. INTRODUCTION

The study of quasar absorption systems is an inherently statistical endeavor because a large sample of systems will include absorption from all the different types of extended gaseous objects in the universe. The study of absorption systems complements the study of luminous objects because the latter are condensed, while absorption systems are most readily detected in highly extended structures which present the biggest cross-sections. Going back in time the importance of absorption increases because a larger fraction of the mass of the universe was in an extended gaseous form.

Key questions to be addressed are the determination of the types of objects which cause the majority of the absorptions, and the investigation of the physical properties of those objects. The absorbers can either be intervening material unassociated with the quasar, or gas in the immediate vicinity of the quasar, which may have been accelerated by the quasar itself. The primary way to distinguish between these two alternatives is the statistical analysis of unbiased samples of systems.

Intervening systems should satisfy each of the following three constraints (Bahcall and Peebles 1969).

1. They should have a wide-spread cosmological distribution. Except for (gravitational) clustering near to the quasars, there should not be any excess of systems at velocities similar to that of the quasar.

2. The number of intervening absorbers seen in a given redshift range in the spectra of different quasars should fit a Poisson distribution. In particular, the number of absorbers observed per unit redshift should not depend on any properties of the quasars themselves.

3. The density of systems per unit redshift should be a function of only the cosmological evolution of the absorbers, and rate of expansion of the universe.

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In contrast, material associated with the quasars might be seen predominantly at redshifts similar to those of the quasars, and the number of systems observed might vary widely from quasar to quasar depending on the properties of the quasars.

To apply these tests one must construct unbiased samples of systems, as Sargent and co-workers originally stressed. Such samples include only those spectral regions in which one is certain that all systems with equivalent widths above a threshold could be detected.

BAL systems. Most dramatic of all systems are the broad absorption line (BAL) systems which have strong lines of highly ionized species. They occur in about 5% of quasars and are interpreted as gas accelerated away from the quasars (Turnshek 1987).

Extensive existing data show that nearly all systems with narrow lines (≤ 100 kms^{-1}) are dominated by one of four different spectral features.

Ly-α systems. Sargent *et al.* (1980) showed that these systems are intervening. Later work revealed that they evolve rapidly, and that there is a significant lack of systems at $z_{abs} \simeq z_{em}$ (Carswell *et al.* 1982, Hunstead *et al.* 1987, Tytler 1987a, Bajtlik, Duncan and Ostriker 1988), perhaps because of the intense ionizing radiation near to the quasar.

C IV systems. Young, Sargent and Boksenberg (1982), and Sargent, Boksenberg and Steidel (1988) have shown that most of these system are intervening. However Weymann *et al.* (1979), Foltz *et al.* (1986), and Anderson *et al.* (1987) have established that the strongest C IV absorbers are often associated with the quasars. These associated systems seem to occur only at velocities within 5000 kms^{-1} of the quasars.

Mg II systems. Tytler *et al.* (1987), Lanzetta *et al.* (1987), Sargent, Steidel & Boksenberg (1988a), and Steidel & Sargent (1992) all find that these systems are intervening, and that most also show C IV lines. With a few exceptions, there is no evidence for any associated Mg II systems.

Lyman limit systems (LLS). These absorption systems which show strong Lyman continuum absorption are the subject of this work. They are mostly metal line systems (C IV and especially Mg II), although some 15% are those Lyα systems with the largest H I column densities. Tytler (1982), Bechtold *et al.* (1984) and Sargent, Steidel and Boksenberg (1988b) all find that the Lyman limit systems (LLS) are intervening. As with the Mg II systems, associated systems have not been found.

Published information on the properties of these systems, from the references given above, are listed below. The density of absorption systems, denoted N(z), is the number of systems per unit redshift. The redshift dependence is parameterised by the index γ in the function $N(z) \propto (1+z)^{\gamma}$. Values given in the top part of the table are from previous data, while the bottom part includes the new IUE results.

TABLE 1

DENSITY OF SYSTEMS

ION	NUMBER of QUASARS	RANGE of REDSHIFT	NUMBER of SYSTEMS	DENSITY N(z)	INDEX γ

	Previous	Data	Only		
H I Ly-α	31	1.68-3.7	639	36^a	2.30 ± 0.38
C IV	55	1.30-3.4	86	2.4^a	-1.2 ± 0.7
Mg II	103	0.16-2.1	111	1.3^a	0.78 ± 0.42
H I LLS	150	0.25-4.5	64	1.4^a	0.68 ± 0.54
H I LLS	52	0.25-2.5	13	0.8	–
	Including	New	Data		
H I LLS	201	0.25-4.5	87	1.3^a	0.82 ± 0.30
H I LLS	103	0.25-2.5	36	1.0	–

[a] At $z = 2$.

In the absence of evolution the γ parameter would be 0.5 for $q_o = 0$, or 1.0 for $q_o = 0.5$. Clearly evolution has been detected for both the Lyα and the C IV systems, but not for Mg II systems or LLS. The most interesting result is that the rates of evolution differ by large amounts, clearly showing that the samples contain different types of systems. The Ly-α systems are normally regarded as a separate population of intergalactic clouds because their number density is so large, they do not cluster strongly and they lack metal lines (but see Tytler 1987a for counter arguments). However the three remaining categories of systems are all believed to be associated with galaxies. Why then do they evolve differently? The different redshift ranges sampled in each case do not fully account for the differences.

2. DATA PROCESSING

The goal of this investigation was to determine the frequency of occurrence of LLS in the IUE archival quasar spectra.

2.1. Object Selection.

A quasar must have a redshift in excess of 0.3 for the Lyman limit to occur at above 1200Å in the observed frame. All such quasars were considered. Kinney et al. (1991) have optimally extracted 69 QSOs and Seyfert galaxies which were observed three or more times each. These spectra were not re-extracted. In total there are 137 QSOs with $z_{em} \geq 0.3$.

2.2 Data Processing

It is extremely important that the data be processed in a homogeneous manner which maximizes the signal to noise ratio. When more than one spectrum exists of a given quasar, which is often the case, they were coadded. Extinction corrections were not applied.

Two different algorithms have been developed which lead to a dramatic increase in the signal to noise ratio of underexposed spectra (Kinney, Bohlin and Neill 1988). Both the routines conserve total flux which is important because we be are looking for abrupt changes in the continuum flux.

We used procedures similar to those employed by Kinney et al. 1991: the optimal extraction algorithms described by Kinney, Bohlin & Neill 1991. The spectra were inspected and an attempt was made to remove all cosmic rays, blemishes saturated regions and microphonic noise defects, though this could not always be done completely. The extractions and sample construction was done by Kenneth Lanzetta, Jennifer Sandoval and David Turnshek.

2.3. Construction of an Unbiased Sample

For each spectrum we determine the range of wavelengths over which LLS with optical depths in excess of 1.0 could be detected. Of the 137 QSOs with $z \geq 3$, only 80 had sufficient SNR for the detection of such LLS. Of these 80 QSOs, 68 are suitable for $z_{LLS} \geq 0.3617$ (i.e. $912(1+z) \geq 1242$ Å), 11 are suitable for $z_{LLS} \geq 1.1786$ (i.e. $912(1+z) \geq 1987$ Å), and one with low SNR is complete to $z_{LLS} \geq 1.6144$ (i.e. $912(1+z) \geq 2384$ Å). The maximum z_{LLS} is equal to z_{em} in all cases.

The sample includes 27 LLS. Seventeen of these have $\tau \geq 3$, and fourteen were included in prior analyses.

3. USES OF THE IUE LLS DATA

The above steps yield an unbiased sample of LLS in the IUE spectra. The statistical methods required to analyse these data were introduced and described by Tytler (1982), and have subsequently been used by Bechtold *et al.* (1984), and Sargent, Steidel and Boksenberg, A. (1989). These methods make maximal use of the data.

3.1. Evolution

The IUE data sample LLS over the large redshift range 0.25 to 2.5. Figure 1 shows the redshift distribution of the density of LLS using the IUE data at $z \leq 2.5$ and data collected by Tytler (1982a,b), Bechtold (1984), Sargent, Steidel & Boksenberg (1989). A total of 87 systems were found towards 201 quasars. The three bins on the left of each plot show the IUE data. The line is the function $N(z) = 0.538(1+z)^{0.82}$ which provides an acceptable fit to the data. The evolution index γ was determined to be 0.82 ± 0.3 using the usual maximum likelihood fit to the unbinned data. This index is indistinguishable from that for Mg II systems (0.78 ± 0.42), as is expected from the similar ionization levels of the two types of system. We also note that the Mg II systems, which have $W_r(2796) \geq 0.3$Å have exactly the same density at $z = 2$ as the LLS with $\tau \geq 1$, which also indicates that these are essentially the same systems. For both types of system, the data are compatible with no evolution for any $0 \leq q_o \leq 0.5$ at the one sigma level.

It is clear from Figure 1 that the IUE data are absolutely essential to the determination of the evolution of the systems. Evolution is important in itself as one of the few characteristics of the systems which can readily be determined. It is also a strong constraint on possible models for the systems. Systems which do not evolve by more that 50% over some 12 Billion years, which seems to be the case for the LLS, must be highly stable structures, or in some stable equilibrium of births and deaths.

The rate of change of time with redshift (dt/dz) is a maximum at the current epoch; the time interval from z =0 to 1 is 64% of the age of the universe for $q_o = 0.5$. The IUE LLS data (z =0.3 – 2.4) sample 51% of the age of the universe, compared to the mere 6% (z =2.5 – 4) which is accessible at optical wavelengths.

Comparison with the evolution of other types of systems leads to a clearer understanding of their similarities and differences. Sargent, Steidel and Boksenberg (1988) suggest that the differences in the evolution of the Mg II and the C IV systems are due to the combined effects of abundance evolution and the expansion of the universe. The LLS are the obvious sample of absorbers with which to explore these possibilities because they are selected without bias by metal abundance. For example, any difference in the evolution of the Mg II systems and the LLS would probably be the result of abundance evolution. Ionization changes are unlikely to be important because the LLS and most Mg II systems are optically thick and self shielding in the Lyman continuum. On the other hand differences between the evolution of the LLS and the Lyα and the C IV systems could easily be the result of differing ionizations.

Since the Mg II systems track the LLS, and many weak Mg II systems have large doublet ratios, so that a reduction in Mg II column density would lead to fewer visible systems, we conclude that the Mg II abundance in halo gas does not evolve significantly at $z \leq 2$.

3.2. Finding Low z LLS

Fifteen of the IUE LLS are at $z \leq 1$, low enough for a direct imaging search for the absorbing galaxy. All five at $z \leq 0.5$ are previously known systems.

They are interesting because we can search directly for the absorbing objects in optical images. Bergeron (1988) has applied this technique most successfully for Mg II systems, finding galaxies in 80% of the cases examined. We will be able to apply this technique to the IUE LLS, some of which are already known to be devoid of strong metal lines (Bechtold 1984). Do these large column density systems Lyα systems also arise in galaxies, despite their lack of metal lines? We do not yet know whether column density or metal abundance is a better indication that a system is located in a galaxy as opposed to being a part of the presumably intergalactic Lyα cloud population.

3.3. Metal abundances

The IUE quasars include the brightest objects in which absorption systems can been found. This makes them the ideal candidates for follow up ground-based and HST observations to determine the physical conditions in the absorbing clouds. The LLS are also the ideal sample for the determination of metal abundances because they are selected only on the basis if the H I column density. Systems detected on the basis of strong lines will naturally be biased to above average abundances. Indeed the fact that metal lines are found with most LLS shows that abundances are not commonly very low.

The LLS sample also includes all systems with very large column densities which show sufficient metal lines for accurate abundance determinations. Those LLS lacking metal lines with the largest H I column densities are the best systems in which to establish extremely low limits on metal abundances.

3.4. Optical Depth in the Lyman Continuum

High quality optical spectra exist for many of the quasars observed by the IUE. If an absorption systems found in the optical is associated with LLS in the IUE spectra at the same redshift, it is optically thick in the Lyman continuum. Otherwise it must be optically thin. This difference is believed to have a profound effect on the ionization of the absorbing gas cloud because the systems are known to be photoionized and Lyman continuum radiation is exceedingly important.

It has not proven possible to check whether the systems in question are actually optically thin or thick because they must be at $z_{abs} \leq 2.2$ for the Mg II line to appears in the optical, and they are generally too faint to be observed by the IUE. However this sample of LLS is ideally suited to construct samples of systems which are optically thin and thick.

3.5. The column density distribution function

The H I column densities of the LLS can be determined from the amount of residual flux below the Lyman limit. Upper bounds on the residual flux give lower limits on the column density of about $5 \times 10^{17}\mathrm{cm}^{-2}$. The column density of these systems can be determined from the profile of the Ly-α line measured in high (about 1Å) resolution spectra.

It is a remarkable fact that the distribution of the column densities of a representative sample of both Ly-α and LLS systems can be approximated as a single power law extending over 9 orders of magnitude in the H I column density N(HI) (Tytler 1987a, Sargent, Steidel and Boksenberg 1988). Many of the LLS have column densities similar to 10^{17} which is a particularly interesting part of the column density distribution for two reasons.

At column densities near to 10^{17} the dominant type of system changes from the presumably intergalactic Ly-α systems to the metal line systems which are presumably associated with galaxies. It is most surprising that there are no conspicuous features in the distribution at this junction. The IUE data on the LLS will help us understand this critical junction because they sample redshifts below 2.5 which can not be observed in the optical. The evolution of the absorption systems might be detected as a change in the column density distribution. Higher resolution observations are needed to obtain HI column densities.

3.6. Velocity Dispersions

The LLS are selected without being biased to high velocity dispersions which lead to larger line equivalent widths. Thus they are the best sample for the determination of the distribution of system velocity dispersions. High resolution spectra are needed for this.

3.7. Primordial Deuterium abundances

The LLS are the only absorption systems in which one can hope determine the primordial deuterium abundance. Column densities above about $10^{17}\mathrm{cm}^{-2}$ are necessary for H I to ensure that a D/H ratio of 10^{-5} would give a detectable D line. On the other hand the H I column density should not exceed about $10^{18}\mathrm{cm}^{-2}$ or the Ly-α line will be too wide and blend with that of D only 0.25Åto the blue. Ground based observations have so far been unsuccessful in large part because the density of the Ly-α forest systems is so high at moderate and high redshifts. LLS at low z in the bright IUE quasars are the ideal hunting ground. Ideally one would hope for an LLS in which the limits on the metal abundances were very low, guaranteeing minimal, and hopefully no stellar processing.

Only two of the LLS are in QSOs which are bright enough for follow up observations with the HST GHRS. We applied for time to observe both in 1991.

3.8. Associated systems

Associated systems with $z_{abs} \simeq z_{em}$ have been identified amongst the C IV systems, but not in the Mg II systems or the LLS. For the sample of 204 QSOs at all z, we find no excess of systems at low velocities: we observe 20 systems at $v \leq 6000$ kms^{-1} (including 4 at negative velocities) where 17.1 are expected. The nominal excess of 2.9 is not significant. Thus these is no statistically significant excess of associated systems. There could still be a few associated systems in the sample, which might be revealed through strong C IV lines in HST spectra.

3.9. Emission line covering factor

Smith et al. (1981) noted that the lack of LLS with $z_{abs} \simeq z_{em}$ implied that the emission line covering factor must be less than about 10% . The IUE data allows us to estimate this limit at low z. The limit is in principle better than that at high z because there fewer low z intervening systems which happen to lie near to the QSOs.

There are no known systems which must arise in the emission line region. From the numbers given in §3.8, the 95% upper limit on the number of systems at $v \leq 6000$ kms^{-1} is 28.9, which is an excess of 11.9 over the expectation of 17.1 systems. The 95% upper limit on the emission line region covering factor is then 11.9/204 = 5.8%. The corresponding one sigma upper limit is 3.6%, and the one sigma lower limit includes zero.

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