

# Analysis of low $z$ absorbers in the QSO spectra

R. Srianand

Inter-University Centre for Astronomy and Astrophysics

Post Bag 4, Ganeshkhind, Pune 411 007, India,

email anand@iucaa.ernet.in

Received August 13, 1995; accepted November 15, 1995

(To appear in Ap-J)

## ABSTRACT

We present the results of reanalysis of low redshift Mg II absorption line sample compiled by Steidel and Sargent. We constructed grids of photoionization models for various cloud parameters. The conditions on cloud parameters to produce  $N(\text{Fe II}) \geq N(\text{Mg II})$  are obtained using single cloud curve of growth. Properties of Mg II absorbers with  $W(\text{Fe II})/W(\text{Mg II})$  (defined as  $R$ )  $\geq 0.5$  and with  $R < 0.5$  are analysed separately. Contrary to the whole Mg II sample, the clouds with  $R < 0.5$  show a steep increase in number density with redshift. These systems also show clear increase in  $W(\text{Mg II})$  and doublet ratio of Mg II with redshift. However there is no correlation between  $W(\text{Mg II})$  and doublet ratio. In the case of  $R \geq 0.5$  clouds  $W(\text{Mg II})$  and doublet ratio are not correlated with redshift. However there is a clear anticorrelation between doublet ratio of Mg II and  $W(\text{Mg II})$ . We find a clear decrease in the ratio of  $W(\text{Fe II } 2383)$  and  $W(\text{Mg II } 2796)$  with redshift. The number density of Fe II lines selected absorbers are not evolving with redshift, consistent with Mg II results. We are also not finding any dependence of  $W(\text{Fe II } 2382)$  and the ratio of  $W(\text{Fe II } 2382)$  and  $W(\text{Fe II } 2600)$  with redshift. This implies no evolution for the average Fe II column density with redshift. Based on the available data of Lyman limit systems (LLS) in the literature, we are not finding any dependence of optical depth ( $\tau_{\text{LLS}}$ ) on redshift in the range  $z = 0.3-2.0$ . We collected the LLS information for 53 QSO sight lines, from the literature, for which details of Mg II absorption are available. There are 4 Mg II absorption systems which are not LLS at redshifts which are lower than the mean redshift of the sample ( $z \simeq 1.1$ ). In the higher redshifts, where one expect to see  $2.5 \pm 1.4$  such absorbers, we do not find any nonLLS Mg II absorbers.

Individual systems with  $\tau_{\text{LLS}} < 3.0$  are analysed with an aim to constrain the ionization parameter and metallicity. Our results imply some of the absorbers

at  $z \simeq 0.6$  have reached metallicity roughly around solar value, indicating the chemical enrichment in some of the absorbers are similar to our Galaxy, as  $z \sim 0.6$  is roughly the formation epoch of sun in our Galaxy. The required ionization parameters for these systems are less than 0.001 in most cases. Comparison of our results with results obtained for intermediate and high redshift absorbers confirms that mean ionization state of metal rich absorbing clouds falls with redshift.

*Subject headings:* QSO: absorption lines-QSO:general

## 1. INTRODUCTION

Absorption lines seen in the spectra of QSOs provide an indirect mean by which the formation and evolution of galaxies can be studied. Latest observations of bright galaxies at the redshifts of the previously known Mg II absorbers (Bergeron (1988); Steidel (1993)) strengthen the idea that the absorbers are the gas clouds present in the extended halo regions of the luminous galaxies. Results obtained by studying the redshift evolution of these absorbers can be utilized to understand the evolution of the gas content of these galaxies.

Properties of the metal line absorption systems can be analysed with photoionization models to get the estimates of metal abundance and intensity of metagalactic ionizing flux. (eg. Bergeron and Stasinska 1986; Srianand and Khare 1994, etc.). These studies use high redshift observations to get constraints on various model parameters, as most of the ultra violet transitions produced at higher redshifts alone can be observed using ground based telescopes.

In the low  $z$  range (i.e  $z = 0.2-2.0$ ) Mg II lines together with Fe II lines fall in the observable window of the ground based telescopes. In order to get other UV transitions of the abundant elements, in this redshift range, one has to go for space telescope observations. Another way of understanding the nature of the low  $z$  absorbers is to image and study the properties of actual galaxies which are responsible for absorption. Steidel(1993) and his collaborators surveyed all the galaxies that are responsible for Mg II absorption (for  $z < 1.5$ ). Based on optical and IR imaging and spectroscopy they concluded that the galaxies producing Mg II absorption lines are similar to the normal galaxies at the present epoch. They did not find any evolution in B-K colour, space density and luminosity of the galaxies selected based on Mg II absorption. Their study showed on an average Mg II absorbing galaxies appear to be consistent with a normal  $0.7 L_B^* S_b$  galaxy having a roughly constant star formation rate since  $z \simeq 1$ .

It is known that the look back time corresponding to the epoch of formation of our sun is  $z \simeq 0.692$  (for  $H_0 = 75 \text{ kms}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5$  with the age of the sun taken to be 4.6 Gyr). Thus if the absorbing galaxies are similar to normal galaxies, one would expect to see some of the absorbers to have metal abundances almost that of sun. If the QSOs and other AGNs are the main contributors of the intergalactic ionizing UV background then the ionizing flux at the Lyman limit is expected to decrease with decreasing redshift. (Miralda-Escude and Ostriker 1990; Madau 1992) and one would expect to see more domination of low ionization lines at low redshifts.

Statistical studies of Mg II absorption lines by Steidel and Sargent (1992), with their homogeneous high signal to noise data, show there is a differential evolution in the number density of Mg II absorbers with redshift. Strong lines show more redshift evolution compared to weak lines. This together with the nonevolving Mg II doublet ratio are interpreted as the evolution in number of subcomponents producing the Mg II absorption lines.

Recent HST observations indicate the decrease in number density of C IV systems with decreasing redshift (for  $z < 1.0$ ) (Bahcall et al 1993). This together with the finding of low neutral hydrogen optical depth low ionization systems (Bergeron et al 1994) show that the mean ionization of the metal rich optically thin absorbing clouds falls with the redshift.

In this work we study the properties of low  $z$  absorbers using the data of Steidel and Sargent (1992) considering the ratio of equivalent widths of Fe II(2382) and Mg II (2796) lines rather than considering Mg II lines alone. We have performed several grids of photoionization models and using standard single cloud curve of growth we obtained conditions for clouds to have various equivalent width ratios of Fe II(2382) and Mg II(2796) lines, which are described in section 2. In section 3 redshift evolution in number density of Mg II, Fe II lines and LLS are analysed. In section 4 we present the results of correlation tests performed on equivalent width distributions. In section 5 we analyse the properties of LLS which are also having Mg II observations. Discussion and results are presented in

section 6.

## 2. CURVE OF GROWTH AND PHOTOIONIZATION MODELS

We performed standard single cloud curve of growth to calculate the column densities of Fe II, for various values of  $N(\text{Mg II})$ , required to produce different values of  $R$ . Figure 1 shows the expected relationship between Fe II and Mg II column densities for different values of equivalent width ratios and velocity dispersion parameters. We used the atomic parameters given in Morton (1992) for these calculations. It is clear from the figure that the  $N(\text{Fe II})$  will be greater than or equal to  $N(\text{Mg II})$  when the  $R$  is greater than 0.5.

One can get the conditions on cloud parameters, to produce  $N(\text{Fe II}) \geq N(\text{Mg II})$ , by constructing photoionization models. We constructed several grids of photoionization models using the code "CLOUDY" kindly given to us by Prof. Ferland. In these calculations we assumed the cloud to be a plane parallel slab, photoionized by the powerlaw background radiation. The ratios of various elements are assumed to be solar ratios. The calculations are performed for various values of ionization parameter,  $\Gamma$ , metallicity,  $Z$ , and neutral hydrogen column density. Figure 2 shows the  $N(\text{Fe II})/N(\text{Mg II})$  as a function of neutral hydrogen column density for various cloud parameters. It is known from the standard curve of growth that in order to produce observable equivalent width (i.e.  $> 0.2 - 0.3 \text{\AA}$ ) the Fe II column density should be greater than  $10^{13} \text{ cm}^{-2}$ .

In table 1 we give the minimum neutral hydrogen column densities needed to produce  $N(\text{Fe II}) > 10^{13} \text{ cm}^{-2}$  for various cloud parameters. Also given in the table are the minimum values of  $N(\text{H I})$  to produce  $N(\text{Fe II}) \geq N(\text{Mg II})$ , and the expected minimum Mg I column density for this value of  $N(\text{H I})$ . It is clear from the table that the cloud has to be a damped Lyman alpha cloud, when  $(\Gamma)$  is greater than 0.001, in order to produce  $R > 0.5$ , when  $Z < 0.5Z_{\odot}$ . Also Fe II lines will be observable only in the case of high optical depth Lyman limit clouds. If the value of  $(\Gamma)$  is less than 0.001, higher optical depth LLS as well as

damped Lyman alpha clouds will produce  $R > 0.5$ . Thus if the cloud is photoionized by the background radiation then it can produce  $R > 0.5$  only when the optical depth of hydrogen is very high or the metallicity is very high when  $N(\text{H I}) < 10^{19} \text{ cm}^{-2}$ . Also in these high metallicity cases Fe II lines can be produced even by the clouds with hydrogen Lyman limit optical depth less than 1.

We know that oscillator strength of Mg I is large and a cloud can produce a line with  $W(\text{Mg I } 2852) > 0.3$  when  $N(\text{Mg I}) > 10^{12.5} \text{ cm}^{-2}$ . Thus from the table it is clear that for  $(\Gamma) > 0.001$  whenever  $R > 0.5$  one should see Mg I(2852) line also. Thus absence of Mg I line when  $R > 0.5$  will indicate low neutral hydrogen optical depth and hence low ionization parameter.

Thus it is clear, from this analysis, that studying the evolution of  $W(\text{Fe II } 2382)/W(\text{Mg II } 2796)$  with redshift will enable one to study the evolution of ionization parameter and neutral hydrogen optical depth. Motivated by this idea in the following sections we perform various statistical tests using the Mg II sample compiled by Steidel and Sargent (1992) and low  $z$  LLS samples (Lanzetta, Wolfe, Turnshek, 1995; Bahcall et al. 1993).

### 3. NUMBER DENSITY DISTRIBUTION OF ABSORBERS

It is customary to parameterise the redshift distribution of absorption line systems as

$$N(z) = N_0(1 + z)^\gamma, \quad (1)$$

where  $N_0$  and  $\gamma$  are constants that are to be determined by fitting the observed distribution. Steidel and Sargent (1992) used maximum likelihood analysis to calculate the values of  $N(z)$  and  $\gamma$  for various subsamples. Their results are given in table 2. For the same subsamples, considering same redshift path for each QSO, we have calculated the value of  $\gamma$  and  $N(z)$  considering only lines with  $R < 0.5$ . This based on our curve of growth results implies that  $N(\text{Fe II})$  to be less than  $N(\text{Mg II})$ . Whenever the Fe II equivalent widths are not available

we have taken the  $5\sigma$  uncertainties as the upper limits. The values obtained using the maximum likelihood analysis are given in Table 2. It is clear from the table that, contrary to the whole Mg II sample considered by Steidel and Sargent (1992), Number density of absorption systems with total Mg II column density greater than total Fe II column density show a sharp increase with redshift. This implies at higher redshifts, most often, the Mg II lines tend to be much stronger compared to Fe II lines.

We considered all the Fe II lines irrespective of Mg II equivalent widths and performed maximum likelihood method to get the evolutionary index. In these calculations we used only regions where one can detect Fe II lines with equivalent width greater than the cutoff equivalent width used for different samples. The results obtained are also given in table 2. Like Mg II sample the results are consistent with nonevolving absorbers for  $0.0 \leq q_o \leq 0.5$ . However the small number of Fe II lines involved in these calculations prevent us from making any conclusions regarding differential redshift evolution.

IUE observations of low redshift Lyman limit systems are available in Lanzetta, Wolfe, Turnshek(1995). We combined their data set with the HST observations obtained from the literature (Bahcall et al. 1993) and performed maximum likelihood analysis to study the redshift evolution of LLS in the low redshifts (i.e  $< 2.0$ ). The observed value of  $\gamma$  for the whole sample with  $\tau_{LLS} > 1.0$  is  $1.30 \pm 0.65$ . When we consider only strong LLS with  $\tau_{LLS} > 3.0$  the obtained value of  $\gamma$  is  $1.56 \pm 0.84$  and  $\gamma$  is  $0.90 \pm 1.30$  for LLS with  $\tau_{LLS} < 3.0$ . There seems to be no change in the value of  $\gamma$  with the strength of the LLS. The changes, if at all, are within  $1\sigma$  uncertainty. Thus the available data is consistent with no change in the Lyman limit optical depth with redshift, in the redshift range 0.2 to 2.0. We performed generalised Kendall rank correlation test (described in Isobe, Feigelson & Nelson, 1986) to see any correlation between  $\tau_{LLS}$  and redshift. The null hypothesis that the two quantities are uncorrelated can be rejected only at 55% confidence level. Thus optical depth of the neutral hydrogen in LLS is not seem to be correlated with redshift.

#### 4. REST EQUIVALENT WIDTH DISTRIBUTION

The equivalent width distribution of any absorption line system can be parameterised as

$$f(W)dW = \left(\frac{N_*}{W_*}\right)\exp(-W/W_*)dW, \quad (2)$$

where the parameters  $N_*$  and  $W_*$  are determined using maximum likelihood analysis. The values of  $W_*$  for Mg II lines with  $R > 0.5$  are consistent with the  $W_*$  values of Mg II absorption lines obtained for the whole sample (table 2). This implies that presence of Fe II lines with equivalent width greater than  $0.5 \times W(\text{MgII})$  is not correlated with the equivalent width of the Mg II lines. The values of  $W_*$  obtained for Fe II lines are less than that for Mg II systems. This clearly shows that the average Fe II equivalent width is less than that of the Mg II equivalent width.

It is known for the case of Mg II systems, that the average equivalent width increases with increasing redshift (Steidel and Sargent, 1992). We performed Spearman correlation test to search for any possible dependence of  $W(\text{Fe II } 2382)$  on redshift. The result is given in table 3. Contrary to the Mg II systems there is no correlation between  $W(\text{Fe II})$  and redshift, and the null hypothesis that the two quantities are uncorrelated can be rejected only at 37% confidence level. We also do not find any correlation between  $W(\text{Fe II } 2382)/W(\text{Fe II } 2600)$  and redshift. This implies that total column densities of Fe II lines are not changing with redshift. This with nonevolving Mg II doublet ratio ( $dr$ ) with  $z$  suggest that the relative column density of Mg II and Fe II lines are not changing with redshift. This result also implies the decrease in the equivalent width ratios of  $W(\text{Fe II } 2382)$  and  $W(\text{Mg II } 2796)$  with redshift.

In fig 3. we have plotted  $R$  as a function of redshift. The open squares in the figure represent the observed values and the closed one represent the upper limits. The lines with  $R$  greater than  $0.6\text{\AA}$  are rare in the higher redshift (say  $z > 1.1$ ). To illustrate this point we have plotted the histogram of  $R$  in two different redshift bins (Fig 4). It is clear from the

figure that the distribution of  $R$  is changing with redshift. The Spearman correlation test shows a  $1.9\sigma$  anticorrelation between  $R$  and redshift. If we include the upper limits also the null hypothesis that the two quantities are uncorrelated can be rejected at 94% confidence level using the generalised Kendall rank correlation tests. Thus various analysis performed with the Steidel and Sargent (1992) data indicates an increase in the number of lines, with  $R < 0.5$ , with increasing redshift.

We looked for the correlation between doublet ratio of Mg II lines and  $R$ . This is similar to looking for the correlation between the column density of Mg II lines and the column density ratios of Fe II and Mg II lines. We do not find any correlation between the two quantities and the null hypothesis that the two quantities are uncorrelated can be rejected only at 49% confidence level. We also do not find any correlation between  $W(\text{Fe II } 2382)/W(\text{Fe II } 2600)$  and Mg II doublet ratio. The null hypothesis that the two quantities are uncorrelated can be rejected only at 72% confidence level. This is consistent with the nonevolving Mg II doublet ratio and the ratio of  $W(\text{Fe II } 2382)$  and  $W(\text{Fe II } 2600)$  with redshift.

The change in the Mg II equivalent width with  $z$  is mainly interpreted as due to the change in the number of components comprising the line (Sargent and Steidel 1992). Our results indicate that there is no change in the Fe II column density with redshift. Thus the change in  $R$  can be understood as the change in the relative number of clouds producing Fe II and Mg II lines. While number of clouds (i.e.  $W(\text{Fe II})$ ) and the average column density of Fe II are not changing with redshift, the number of clouds producing Mg II changes with redshift. As the presence of Fe II with Mg II lines imply the presence of high  $\tau_{\text{LLS}}$  then this results imply that there are more highly ionized component compared to low ionization components at higher redshift. Thus in all cases when  $W(\text{Fe II } 2382)$  is much less than  $W(\text{Mg II})$  one should see  $W(\text{C IV}) > W(\text{Mg II})$ . Table 6 of Steidel and Sargent (1992), with the available Fe II observations, reveal that in most of the cases when  $W(\text{C IV})$  is greater than  $W(\text{Mg II})$  the Fe II lines are absent.

Another surprising result of the analysis of Steidel and Sargent (1992) is the significant anti-correlation between Mg II doublet ratio and  $W(\text{Mg II } 2796)$ , at approximately 98% confidence level. This correlation is paradoxical considering the fact that  $W(\text{Mg II } 2796)$  is increasing with increasing redshift and doublet ratio of Mg II is independent of redshift. They argued that this apparent correlation is mainly due to the strong lines which tend to have doublet ratios near one, while the weak lines have a wide range of doublet ratios. In order to understand this correlation we performed rank correlation test between different parameters considering the Mg II lines with  $R$  less than 0.5 and greater than 0.5 separately. The results of Spearman correlation tests are given in table 3.

For systems with  $R > 0.5$  there is no strong tendency of Mg II equivalent width as well as Mg II doublet ratio to show any change with redshift. This result is consistent with the results obtained for Fe II lines. However there is a clear anti-correlation between Mg II equivalent width and doublet ratios. Thus the very high optical depth systems do not show any change in Mg II or Fe II column density with redshift. Most probably the Mg II equivalent width is a measure of column density rather than the number of clouds in these systems.

For systems with  $R < 0.5$  there is a clear tendency of equivalent width of Mg II lines to increase with redshift. There is also a weak correlation between Mg II doublet ratio with redshift. The null hypothesis that the two quantities are uncorrelated can be rejected at roughly 93% confidence level. This indicates the decrease in total column density of Mg II with increasing redshift. This result is similar to the one seen for C IV absorbers for  $z > 2.0$ . We do not find any significant correlation or anti-correlation between Mg II doublet ratios and equivalent widths.

Thus in the total Mg II sample the correlation between  $W(\text{Mg II})$  and redshift is mainly due to clouds with  $R$  is less than 0.5, which are also showing increase in Mg II doublet ratio with redshift. The correlation seen between  $W(\text{Mg II})$  and doublet ratios of Mg II is due to clouds with  $R > 0.5$ , which are not showing any correlation between  $W(\text{Mg II})$

II) and  $z$ , and redshift and doublet ratio of Mg II lines. In this way we can understand the paradoxical correlation seen by Steidel and Sargent (1992).

## 5. LOW REDSHIFT LYMAN LIMIT SYSTEMS

There are 53 sight lines for which Mg II observations as well as low redshift Lyman limit observations are available in the literature (Steidel & Sargent (1992); Aldcroft, Bechtold & Elvis (1994); Boisse et al. (1993); Lanzetta, Wolfe & Turnshek (1995) & Bahcall et al. (1994)). Twenty eight LLS are with  $\tau_{\text{LLS}} > 1.0$  are detected in these spectra. Out of these 28 systems 7 systems do not show Mg II or Fe II absorption lines and rest of them show metal line absorption at the same redshift. Four Mg II systems which are not LLS are also in our sample. Out of 19 Mg II systems which are LLS 5 systems have observed  $\tau_{\text{LLS}} < 3.0$ . Thus Lyman limit optical depth is known for these systems and presence of Fe II lines with Mg II lines in these low optical depth systems can be used to put bounds on the physical conditions.

All the nonLLS systems in our sample are at redshifts which are less than the average redshift of the sample (i.e  $z = 1.1$ ). We calculated the number density per unit redshift of the nonLLS absorbers, for  $z < 1.1$ , to be 0.28. If we assume the number density of such absorbers are not changing with redshift one should expect to see  $2.5 \pm 1.4$  absorbers for  $z > 1.1$  in our sample. Our failure to detect any such absorbers at high redshift suggests the decrease in the ionization parameter and/or increase in the metal abundance in the Mg II absorbers with decreasing redshift. The number per unit redshift of LLS which are not showing Mg II or Fe II lines in the two redshift bins are  $0.33 \pm 0.16$  and  $0.32 \pm 0.19$  respectively. The values are consistent with one another suggesting no evolution for such systems with redshift. If these LLS are highly ionized metal line systems, (i.e with observable C IV), then our results suggest that very high ionization metal poor clouds are present even at low redshifts.

As seen in the previous section the presence of Fe II with the Mg II lines in the low neutral hydrogen optical depth clouds will reflect very high metallicity and low ionization parameter. In what follows we try to get the column densities of metal lines assuming single cloud curve of growth. Then these column densities together with the results of photoionization models are used to get an estimate of the metal abundance and the ionization structure of the clouds.

As we know almost all the metal lines are produced by the ensemble of clouds rather than by a single cloud as assumed here. However Jenkins (1986) showed that if the components forming the blends are not heavily saturated, the column density obtained using doublet ratios and single cloud curve of growth will be equal to the actual total column density and the obtained effective velocity dispersion will reflect the number of clouds rather than the kinematics of the clouds. Also in the photoionization models, we are using the shape of the ionizing background to be a single powerlaw. In the realistic case the continuum will be altered by the intervening material in the intergalactic medium. However in the redshift range we are interested in, the absorption due to intergalactic material will be less pronounced and our assumption of powerlaw will be a reasonable one. Thus our analysis will not give the exact values of the metallicity and background radiation however one can get a bound on these values.

In what follows we analysis the 9 low optical depth systems one by one to get a rough estimate of the background radiation and the metallicity.

### 5.1. Systems with $\tau_{LLS} < 1.0$

(a) 1115+080 ( $z_{abs} \simeq 1.0430$ )

IUE spectrum of this QSO is clean (Lanzetta, Turnshek & Sandoval, 1992) and does not show any break in the expected position. Steidel and Sargent (1992) identified this weak Mg II system. The rest equivalent widths of the Mg II doublets are 0.31 and 0.18

Å respectively. The high doublet ratio indicates that Mg II lines are in the linear portion of the curve of growth. Single cloud curve of growth gives  $N(\text{Mg II}) = 9 \times 10^{12} \text{ cm}^{-2}$  with the effective velocity dispersion,  $b_{\text{eff}} = 40 \text{ km s}^{-1}$ . The absence of break in the continuum at the expected position of the Lyman limit gives an upper limit on the neutral hydrogen column density to be  $8 \times 10^{16} \text{ cm}^{-2}$  ( $\tau_{\text{LLS}} < 0.5$ ). Young, Sargent and Boksenberg (1982) did not detect Fe II lines for this system. The observed  $5\sigma$  upper limits on the Fe II(2382) and Fe II(2600) lines (0.10 and 0.15 Å respectively) give the value of  $N(\text{Fe II}) \leq 7 \times 10^{12} \text{ cm}^{-2}$  for  $b_{\text{eff}} = 40 \text{ km s}^{-1}$ . Upper limit on Mg I line give  $N(\text{Mg I}) < 10^{12} \text{ cm}^{-2}$ . Absence of Fe II lines and weak Mg II unsaturated lines prevent us from getting any stringent constraints on the radiation field and metallicity. For the metallicity to be around  $0.1Z_{\odot}$  the ionization parameter for this system should be less than  $10^{-3}$ . Along the same line of sight, Young, Sargent and Boksenberg (1982) observed five other absorption systems ( at redshifts 1.6998, 1.7283, 1.7304, 1.7322, and 1.7535). No Mg II absorption lines are seen for these systems (Steidel & Sargent 1992). This with non-detection of LLS show that these systems are highly ionized with ionization parameter greater than  $10^{-2}$ .

(b) 1206+457 ( $z_{\text{abs}} \simeq 0.9277$ )

IUE spectrum of this QSO show no sign of break in the expected position (Lanzetta, Turnshek & Sandoval, 1992). However a very strong Ly  $\alpha$  with rest equivalent width 7.5 Å is observed for this system (Lanzetta, Wolfe, Turnshek 1995). This clearly indicates a complex blend with very high effective velocity dispersion (Since  $N(\text{H I})$  is small). Mg II lines were identified by Steidel and Sargent (1992). Mg II lines are also strong (with equivalent widths 1.0 and 0.79 Å) and saturated. The single cloud curve of growth gives the total Mg II column density to be greater than  $7 \times 10^{13} \text{ cm}^{-2}$  for  $b_{\text{eff}} = 40 \text{ km s}^{-1}$ . Upper limits on the Mg I equivalent width gives  $N(\text{Mg I}) < 10^{12} \text{ cm}^{-2}$ . Fe II(2382) line is observed with rest equivalent width 0.27 Å. This with the  $5\sigma$  upper limits on the equivalent width of Fe II(2600) line give  $N(\text{Fe II}) \simeq 2 \times 10^{13} \text{ cm}^{-2}$ . These values imply the ionization parameter to be less than  $3 \times 10^{-4}$  and the metallicity to be greater than  $0.5 \times Z_{\odot}$ . Very strong Ly  $\alpha$

line with  $\tau_{\text{LLS}} < 1$  indicates Ly  $\alpha$  effective velocity dispersion to be more than that for Mg II lines. This imply that there are Ly  $\alpha$  clouds which do not produce appreciable amount of Mg II lines. If the absorbing region consists of two components, one is highly ionized and the rest is a low ionized region, then most of the Ly  $\alpha$  absorption seen in this system may be due to the high ionization phase. In such case HST observations should show a broad C IV line for this system. If the observed C IV lines are also narrow then the high Ly  $\alpha$  equivalent width will reflect the clustering of Ly  $\alpha$  forest lines with this metal line system.

(c) 1338+416 ( $z_{\text{abs}} \simeq 0.6213$ )

This system is analysed in detail by Bergeron et al (1995). This systems has  $R \simeq 0.5$ , which implies  $N(\text{Fe II}) \simeq N(\text{Mg II})$ . This with  $\tau_{\text{LLS}} < 1.0$  indicate high metallicity and low ionization for this system.

(d) 1040+122 ( $z_{\text{abs}} \simeq 0.6591$ )

Aldcroft, Bechtold, & Elvis (1994) reported this systems for the first time. However they suggested the identification to be marginally significant with the disagreement in the redshift matching of the doublet around 0.0006. The fit to the Mg II doublets showed a clear wavelength ratio problem, however the fit had  $\chi_{\nu}^2 = 1$ . If this identification is real this is also a system with very low Lyman limit optical depth. Bahcall et al. (1993) do not find any break in the expected position of this redshift. The equivalent width of Mg II doublets are 0.58 and 0.42  $\text{\AA}$  respectively. Mg I line is not observed and the  $5\sigma$  upper limit is 0.19 $\text{\AA}$ . Fe II lines are absent and the observed  $5\sigma$  limit on the equivalent width is 0.40 $\text{\AA}$ . The single cloud curve of growth gives the  $N(\text{Mg II}) \geq 3 \times 10^{13} \text{ cm}^{-2}$ . This high column density of Mg II with low values of  $\tau_{\text{LLS}}$  imply ionization parameter  $\Gamma < -3.5$  and metallicity  $> 0.1Z_{\odot}$

## 5.2. $1 < \tau_{\text{LLS}} < 3$ systems

(a) 1017+280 ( $z_{\text{abs}} \simeq 1.9230$ )

This system has  $\tau_{\text{LLS}} \simeq 1.0$  (Lanzetta, Turnshek & Wolfe(1995), which implies  $N(\text{H I}) = 1.6 \times 10^{17} \text{ cm}^{-2}$ . Fe II lines are not observed for this system. C IV doublet lines are observed for this system with equivalent widths 0.37 and 0.25 Å implying  $N(\text{C IV}) \simeq 2 \times 10^{14} \text{ cm}^{-2}$  and  $b_{\text{eff}} \simeq 30 \text{ km s}^{-1}$ . Based on the observed C II lines one can get  $N(\text{C II}) \simeq 6 \times 10^{13} \text{ cm}^{-2}$ . Absence of Si II lines give an upper limit in the column density  $N(\text{Si II}) \leq 10^{12} \text{ cm}^{-2}$ . Si IV lines are observed for this system and single component curve of growth gives  $N(\text{Si IV}) \simeq 4 \times 10^{13} \text{ cm}^{-2}$ . Steidel and Sargent (1992) observed very weak Mg II lines, with equivalent width 0.11 and 0.12 Å respectively. This gives Mg II column density to be  $8 \times 10^{12} \text{ cm}^{-2}$ . Absence of Fe II lines with  $W(\text{Si IV}) > W(\text{Si II})$  and  $W(\text{C IV}) > W(\text{C II}) > W(\text{Mg II})$  imply a high ionization. This system is analysed in detail with a more realistic multicomponent photoionization models by Srianand & Khare (1994). Their results show (see their table 5) the required ionization parameter for this systems is  $\simeq 10^{-2}$  and the average metallicity of the clouds producing the absorption is roughly around  $0.014Z_{\odot}$ .

(b) 1317+277 ( $z_{\text{abs}} \simeq 0.6601$ )

This system has  $\tau_{\text{LLS}} \simeq 2.7$  (Lanzetta, Wolfe & Turnshek 1995) implying that the  $N(\text{H I}) = 4 \times 10^{17} \text{ cm}^{-2}$ . The equivalent widths of the Mg II doublets are 0.49 and 0.33 Å respectively. The strong Mg II lines with doublet ratio  $\sim 1.5$  give  $N(\text{Mg II}) > 2.2 \times 10^{13} \text{ cm}^{-2}$  for the effective velocity dispersion parameter  $25 \text{ kms}^{-1}$ . Fe II lines are observed with  $W(\text{Fe II } 2382)$  as strong as that for Mg II lines (0.42 Å) indicating  $N(\text{Fe II}) > N(\text{Mg II})$ . This together with low neutral hydrogen optical depth imply the ionization parameter to be less than  $3 \times 10^{-4}$ . The metallicity in this absorber may very well be higher than solar metallicity.

(c) 1354+19 ( $z_{\text{abs}} \simeq 0.4591$ )

This system is discussed in detail in Bergeron et al.(1995) This system has  $\tau_{\text{LLS}} = 1.2\text{Å}$ . The equivalent widths of the Mg II doublets are 0.89 and 0.82. The Mg II line is saturated and  $N(\text{Mg II}) > 4 \times 10^{13} \text{ cm}^{-2}$ . The observed equivalent width of Fe II(2600) = 0.32 Å and the  $5\sigma$  upper limit on  $W(\text{Fe II } 2382)$  implies saturation for Fe II lines and the  $N(\text{Fe II})$

values for this will be  $> 1.5 \times 10^{14} \text{cm}^{-2}$ . The Mg I line is observed with equivalent width  $0.16 \text{ \AA}$ . Assuming Mg I to be optically thin one can get  $N(\text{Mg I}) = 1.5 \times 10^{12} \text{cm}^{-2}$ . High values of Mg II and Fe II column densities together with low  $N(\text{H I})$  imply metallicity above solar and very low ionization parameter, less than  $(10^{-4.0})$ . Bechtold & Ellingson (1992) found the galaxy which is responsible for producing the Mg II absorption lines. The impact parameter with the QSO line of sight from the system is  $27.2 h_{100}^{-1} \text{ kpc}^{-1}$ .

(d) 1634+706 ( $z_{\text{abs}} \simeq 0.9903$ )

This system has  $\tau_{\text{LLS}} \simeq 1.1$  which implies  $N(\text{H I}) = 1.76 \times 10^{17} \text{ cm}^{-2}$ . The observed Mg II equivalent widths for this system is  $0.58$  and  $0.42 \text{ \AA}$  respectively. Fe II and Mg I lines are not detected. Single component curve of growth gives  $N(\text{Mg II}) \geq 3 \times 10^{13} \text{ cm}^{-2}$ . The lack of Fe II lines implies the ionization parameter in the range  $-3.0$  to  $-4.0$  for the metallicity greater than  $0.1 Z_{\odot}$ .

(e) 1038+063 ( $z_{\text{abs}} \simeq 0.458$ )

This system is analysed by Bergeron et al (1995) in detail. This system has  $\tau_{\text{LLS}} = 1.2$  with a saturated Mg II doublet similar to  $z_{\text{abs}} \simeq 1.0384$  absorber in the spectra of 1634+706. This system also implies metallicity more than  $0.5 Z_{\odot}$  and ionization parameter in the range  $10^{-3.0}$  to  $10^{-4}$  (Bergeron et al. 1995). The galaxy causing these absorption lines is identified at a projected radial separation of  $35 h_{100}^{-1} \text{ kpc}$  from the QSO sight line (Bergeron & Boisse 1991).

It is known that most of the iron in our interstellar medium is in the form of dust. Thus if the absorbers discussed here have similar dust content then the obtained metallicity estimates are very well be lower limits.

## 6. Results and discussion

(1) We performed standard single cloud curve of growth to calculate column densities of Fe II required to produce different values of  $R$ . It is shown that when  $R \geq 0.5$ , the column density of Fe II will be equal to column density of Mg II. Simple photoionization models show when the ionization parameter is more than 0.001 such absorbers are possible only in the damped Lyman alpha clouds. If the absorbers are with low Lyman limit optical depth (say  $\tau_{\text{LLS}} < 3.0$ ) then the presence of Fe II lines, with  $R$  greater than equal to 0.5, will imply very low ionization parameter and high metallicity.

(2) The redshift distribution of Mg II, Fe II and Lyman limit systems are analysed using maximum likelihood analysis. Contrary to whole Mg II sample considered by Steidel and Sargent (1992) the number density of absorption systems with  $R < 0.5$  are showing clear increase in number density with redshift. The redshift distribution of Fe II lines are consistent with non evolving population of absorbers. The number densities of low  $z$  LLS are also consistent with the no evolution in redshift. The evolutionary index  $\gamma$  is independent of the optical depth cutoff.

(3) Equivalent width distribution of subsamples of Mg II systems are analysed using maximum likelihood analysis. The values of  $W_*$  obtained for lines with  $R$  greater than 0.5 are consistent with the  $W_*$  values obtained for whole Mg II sample. This implies the presence of strong Fe II lines are not correlated with equivalent width of Mg II lines.

(4) We do not find any trend of  $W(\text{Fe II } 2382)$  and the ratio of  $W(\text{Fe II } 2382)$  and  $W(\text{Fe II } 2600)$  with redshift.

(5) There is a clear increase in  $R$  with decreasing redshift.

(6) We find no correlation of Mg II doublet ratio with the equivalent width ratios  $R$  and  $W(\text{Fe II } 2382)/W(\text{Fe II } 2600)$ . This clearly indicate that the average column density of Fe II and column density ratios of Fe II and Mg II are independent of Mg II column density.

(7) For systems with  $R > 0.5$  there is no strong tendency of Mg II equivalent width as well as Mg II doublet ratios to show any change with redshift. However there is a clear

anti-correlation between Mg II equivalent width and doublet ratio.

(8) For systems with  $R < 0.5$  there is a clear tendency of equivalent width and doublet ratio of the Mg II lines to increase with increasing redshift. This indicates there are large number of low Mg II column density clouds at higher redshift compared to lower redshift. The doublet ratio and equivalent widths of Mg II lines are not correlated in these systems.

(9) Analysis of absorbers along the lines of sight searched for LLS and Mg II absorption lines show no change in the number density of LLS which do not show Mg II absorption. However the Mg II absorbers which are nonLLS are seen only in the low redshifts.

(10) Nine individual metal line systems with  $\tau_{\text{LLS}} < 3.0$  are analysed with photoionization models to get an estimate of the metallicity and ionization parameters. Some of the absorbers in low redshifts show metallicity almost that of sun. The required ionization in most of the absorbers are less than 0.001.

The inferred ionization parameters for the high redshift absorbers are high ( $\sim 0.01-0.001$  at  $z \simeq 1.5$  (Srianand & Khare 1994);  $> 3 \times 10^{-3}$  at  $z \sim 3.0$  (Steidel 1990)). Thus the cloud will have column density of Fe II comparable to that of Mg II only when it is a damped Lyman alpha cloud. Thus our results of more Mg II clouds with  $R < 0.5$  at high  $z$  is consistent with high ionization parameters at high redshift. The rough estimate of nonLLS Mg II systems show at low redshifts 25% of the Mg II systems are not LLS ( $\frac{dN}{dz} = 0.28$  compared to 0.96 for the whole sample). This together with the increase in the number of systems with  $R$  less than 0.5 with decreasing redshift suggest a decrease in the mean ionization parameter. However there are LLS which do not show Mg II or Fe II absorption even at low redshifts, with same number density as in high redshifts. Also available LLS data in low redshifts do not show any change in  $\tau_{\text{LLS}}$  with redshift.

The number density per unit redshift of C IV systems decreases with redshift for  $z < 2.0$ , contrary to what is seen in very high redshifts Bahcall et al. (1993). The values of  $(\frac{dN}{dz})_{\text{C IV}} \simeq 0.87 \pm 0.43$  at average redshift 0.3 and  $1.76 \pm 0.33$  at an average redshift 1.50.

The ratio of number density of C IV and Mg II (defined as R1) at  $z = 1.5$  is  $1.6 \pm 0.57$  and at  $z = 0.3$  the value of R1 is  $1.16 \pm 0.73$  (Bergeron et al. 1995). The two values are consistent with one another within  $1\sigma$  uncertainty. They found the systems with  $W(\text{C IV})/W(\text{Mg II}) < 1$  contains 38% of the absorbers at  $z = 0.53$ , whereas the fraction is only 17% at  $z = 1.7$ . As metagalactic radiation field is lower at  $z = 0.50$  than at  $z = 1.7$  by an order of magnitude, this suggests that if the gas is photoionized by the background radiation, the mean gas density of the high ionization systems falls with decreasing redshift. Their results show even at low redshifts the high ionization absorbers are the dominant over low ionization absorbers.

Pettini et al. (1994) also noted that both distribution and typical metallicity measured in the damped Lyman alpha clouds are more in line with the values found in the halo. They also showed the observed metallicities have a very large spread, and on an average the damped Lyman alpha clouds at  $z \simeq 2.0$  have metallicity roughly 1/10th of the solar value. Comparison of metallicity estimates obtained here with the results of Pettini et al. (1994) suggests that on an average there is an increase in the metallicity between  $z \sim 2$  to  $z \sim 0.6$ . Our analysis of individual low optical depth LLS show that there are at least few systems which are enriched to solar metallicity at the look back time corresponding to the formation epoch of sun in our Galaxy. There are also few LLS which do not show Mg II or Fe II absorption indicating the existence of low metallicity clouds also in the same epoch.

Steidel & Dickinson (1994) showed based on the color distribution, the Mg II line selected galaxies are undergoing constant star formation in the whole redshift range studied ( $z < 1.5$ ). It is known that if the star formation is continuous then one would expect that  $[\text{O}/\text{Fe}]$  would be over solar, as well as  $[\text{Mg}/\text{Fe}]$  and  $[\text{Si}/\text{Fe}]$ . In addition  $[\text{C}/\text{Fe}]$  should be close to solar whereas  $[\text{N}/\text{Fe}]$  would be subsolar. If the star formation in the absorbers are not continuous then the abundance pattern will be different from those expected for continuous star formation. Thus studying the abundance pattern in the redshift range 0.5 to 2.0, where most of the enrichment seems to have occurred, will give the clear picture of

the chemical evolution of the galaxies.

Steidel & Dickinson (1994) also showed that the star formation rate is not correlated with the properties of the halo. They concluded that this result clearly rules out the possibility that the halo clouds are originated from the disk of galaxies (fountain models), and the halo gas may be due to satellite accretion. If the halo gas are due to satellite accretion then the evolution of metallicity in the halo as well as the disk will be very different with redshift. Studying the metallicity distribution of damped Lyman alpha systems (which are believed to be similar to galactic disks) and other metal line systems (most probably originate in halos) will enable one to understand the origin and evolution of halo gas. It is also possible that the halo clouds which are seen at  $z \simeq 2.0$  can undergo collision which induces star formation and enrich the halo. The star formation also helps in keeping the clouds in the halo for a long time. There are also indications for the recent star formation in the halo of our galaxy. Brown et al. (1989) have showed few halo stars in our Galaxy have flight time to reach its present  $z$ -position, if ejected from the disk, much more than their evolutionary age, implying that they must have formed in the halo. Future detailed studies with extended UV data in the low redshift range can discriminate between various alternatives.

## REFERENCES

- Aldcroft, T. L., Bechtold, J., & Elvis, M. 1994, Ap. J, 93, 1.
- Bahcall et al. 1993, ApJS, 87, 1
- Bergeron, 1988, QSO absorbing lines: Probing the Universe, ed. J. C. Blades, D. A. Turnshek. & C. A. Norman (Cambridge)275
- Bergeron, J., & Boisse. 1991, A&A, 243, 344.
- Bergeron et al. 1994, Ap. J.,436, 33.
- Bergeron, J., & Stasinska, G. 1986, A&A, 169, 1.
- Bechtold, J., & Ellingson, E. 1992, Ap. J, 392,20.
- Boisse, P., Boulade, O., Kunth, D., Tytler, D., & Vigroux, B. 1992, A&A, 262,401.
- Brown, P. J. F., Dufton, P. L., Keenam, F. P., Bokesenberg, A., King, P. L., & Pettini, M. 1989, Ap. J, 339, 397.
- Isobe, Feigelson, & Nelson, 1986, Ap. J, 306, 490.
- Jenkins, E. B. 1986, Ap. J, 322,96.
- Lanzetta, K. M., Turnshek, D. A., & Sandoval, J. 1992, ApJS, 84, 109.
- Lanzetta, K. M., Wolfe, A. M., & Turnshek, D. A. 1995, Ap. J, 440,435.
- Madau, P. 1992, Ap. J, 376, L33.
- Miralda-Escude, J. & Ostriker, J. P. 1990, AP. J, 350, 1.
- Pettini, M., Smith, L. J., Hunstead, R. W., King, D. L. 1994, Ap. J, 426,79
- Srianand, R. & Khare, P. 1994, Ap. J, 428, 82.

Steidel, C. C. 1990b, ApJS, 74,37

Steidel, C. C. 1993, in the Evolution of Galaxies and Their Environment. Proc. of the  
3rd Tetons Summer Astrophysics Conf., ed. J. N. Shull & H. A. Thronson, Jr.  
(Dordrecht:Kluwer), in press.

Steidel, C. C. & Dickinson., 1994, Preprint

Steidel, C. C. & Sargent, W. L. W. 1992, ApJS, 80, 1

Young, P. J., Sargent, W. L. W. & Boksenberg, A. 1982, Ap. J, 252, 10

---

This manuscript was prepared with the AAS L<sup>A</sup>T<sub>E</sub>X macros v3.0.

### Figure captions

**Figure 1:** Relation between the  $N(\text{Mg II})$  and  $N(\text{Fe II})$ , obtained based on single cloud curve of growth, required to produce different values of  $R$  for different velocity dispersion parameters (30, 40, 50, 60, 70  $\text{kms}^{-1}$ ).

**Figure 2:** Results of photoionization models for different values of ionization parameter and metallicity ( $Z = 0.001, 0.01, 0.1, 0.5 Z_{\odot}$ ).

**Figure 3:** Plot showing  $R$  as a function of redshift. The filled squares represent the upper limits.

**Figure 4:** Histogram of  $R$  in two different redshift bins.

**Table 1**  
**Results of photoionization models**

log $\Gamma$	$Z/Z_{\odot}$	Minimum log N(H I) for		
		$N(\text{Fe II}) > 10^{13}$	$N(\text{Fe II}) \geq N(\text{Mg II})$	log N(Mg I)
-2.0	0.01	19.00	21.00	12.56
	0.10	18.40	20.60	13.40
	0.50	18.00	20.40	13.87
-2.5	0.01	19.00	20.40	12.33
	0.10	18.20	20.40	13.32
	0.50	17.60	20.00	13.72
-3.0	0.01	19.00	20.00	12.04
	0.10	18.00	19.80	12.93
	0.50	17.20	19.60	13.42
-3.5	0.01	19.20	19.60	11.70
	0.10	17.60	19.40	12.58
	0.50	16.80	19.00	13.00
-4.0	0.01	19.20	19.00	11.14
	0.10	17.60	19.00	12.13
	0.50	16.80	18.20	12.34

**Table 2**  
**Results of Maximum likelihood analysis**

$W_r^{\min}$	Number	$\langle z \rangle$	$N(z)$	$\gamma \pm d\gamma$	$W_* \pm dW_*$
Steidel&Sargent 92					
0.30	111	1.12	0.97	$0.78 \pm 0.42$	$0.57 \pm 0.06$
0.60	67	1.17	0.52	$1.02 \pm 0.53$	$0.66 \pm 0.08$
1.00	36	1.31	0.27	$2.24 \pm 0.76$	$0.66 \pm 0.11$
for $R < 0.5$ systems					
0.30	43	1.29	0.38	$2.27 \pm 0.71$	$0.74 \pm 0.11$
0.60	39	1.41	0.31	$3.09 \pm 0.78$	$0.69 \pm 0.11$
1.00	22	1.49	0.17	$4.24 \pm 1.13$	$0.68 \pm 0.15$
for Fe II lines					
0.30	32	1.18	0.28	$1.14 \pm 0.77$	$0.44 \pm 0.07$
0.60	20	1.24	0.15	$1.60 \pm 0.99$	$0.36 \pm 0.08$
1.00	9	1.09	0.06	$0.43 \pm 1.38$	$0.21 \pm 0.06$

**Table 3**  
**Results of Spearman correlation test**

Test variables	$\rho$	$\rho/\sigma$	significance
W(Fe II),z	0.11	0.76	0.450
$\frac{W(\text{FeII}2382)}{W(\text{FeII}2600)},z$	0.07	0.48	0.625
R,z	-0.27	-1.91	0.055
R,dr(Mg II)	-0.09	-0.69	0.515
$\frac{W(\text{FeII}2382)}{W(\text{FeII}2600)},\text{dr}(\text{Mg II})$	0.15	1.01	0.286
when $R < 0.5$			
W(Mg II),z	0.37	2.72	0.005
dr(Mg II),z	0.25	1.83	0.067
dr(Mg II),W(Mg II)	-1.63	-1.19	0.239
when $R > 0.5$			
W(Mg II),z	0.09	0.45	0.657
dr(Mg II),z	-0.26	-1.32	0.189
dr(Mg II),z	-0.51	-2.58	0.007

figure 1

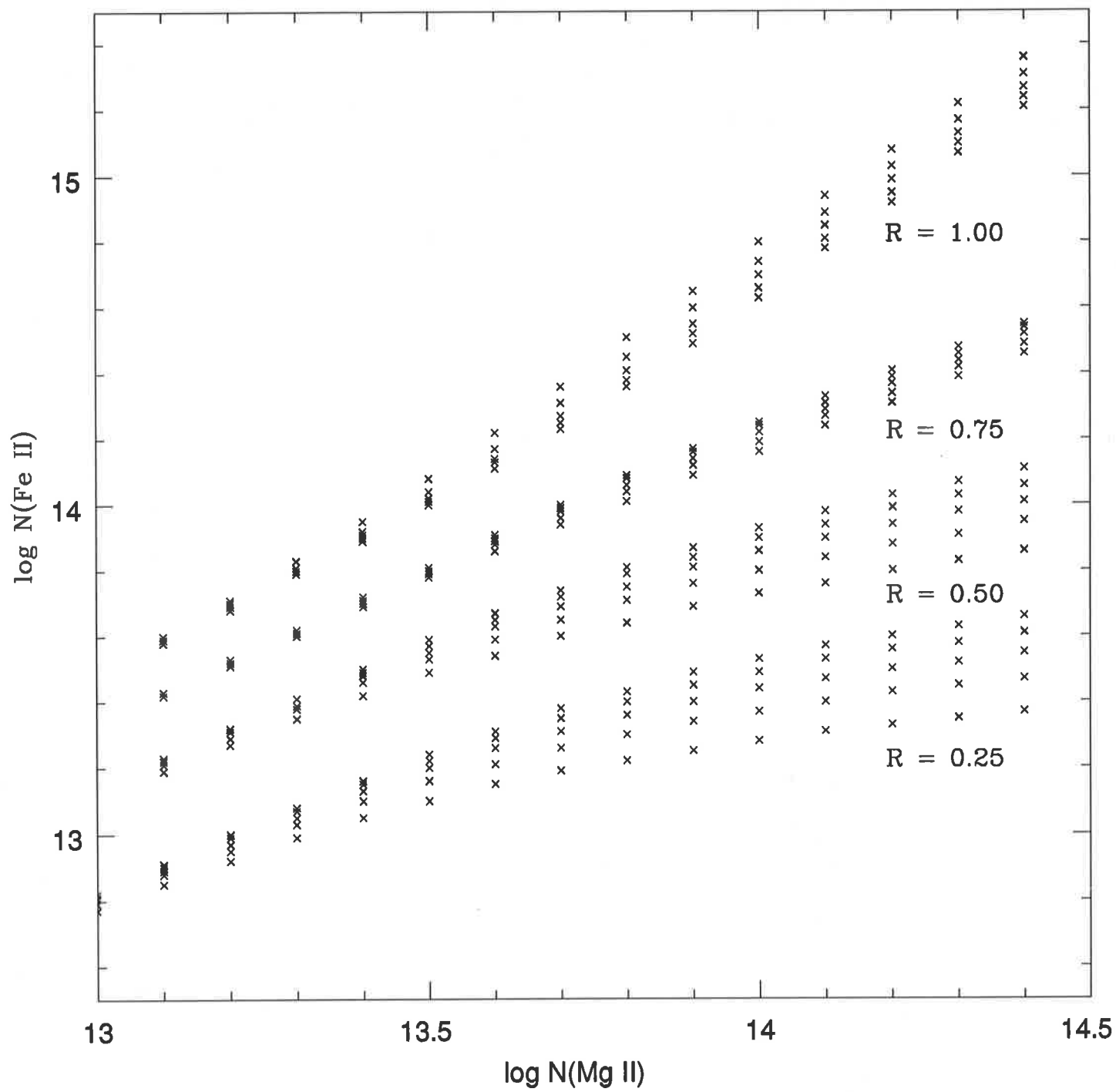


figure 2

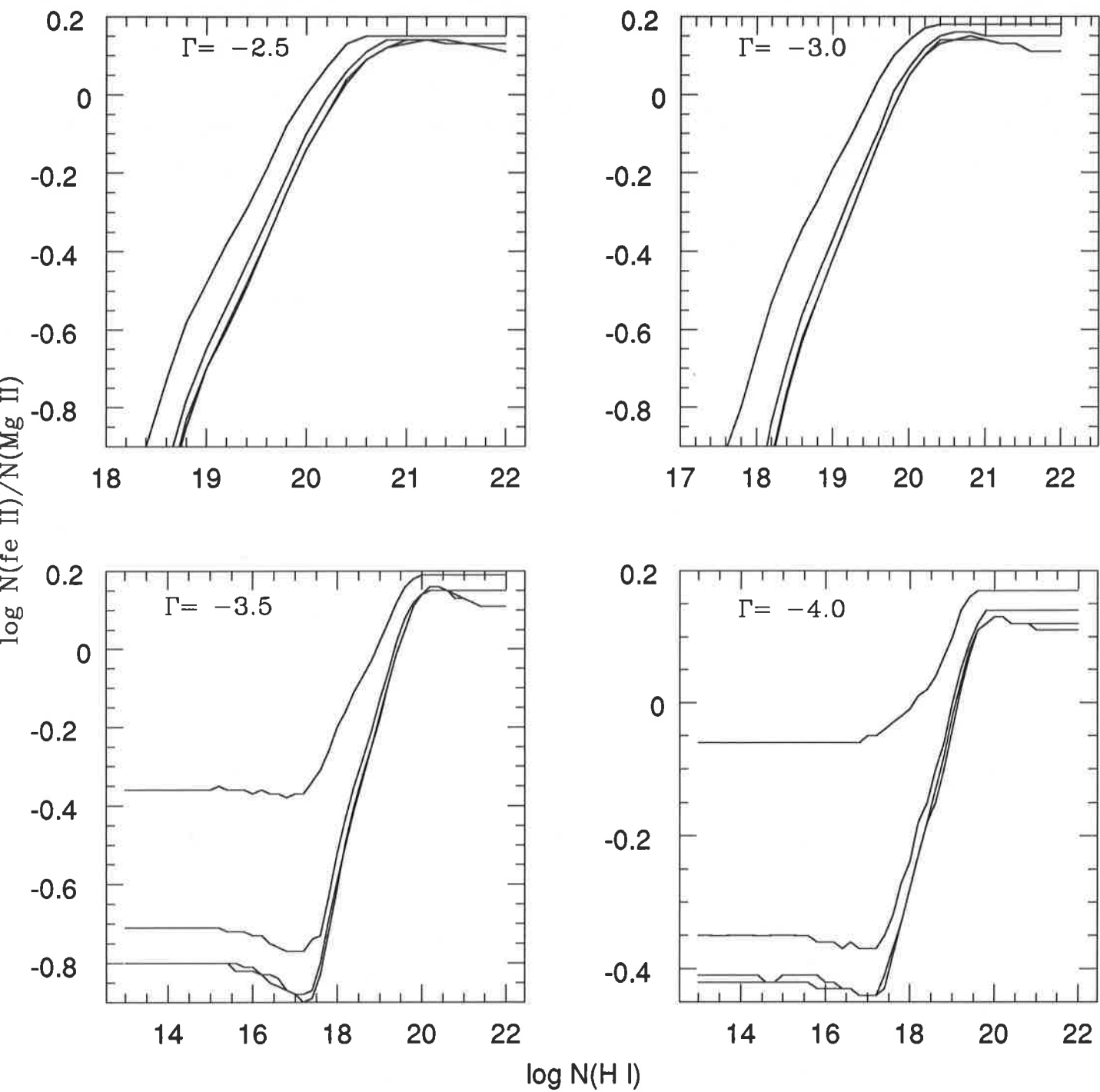


figure 3

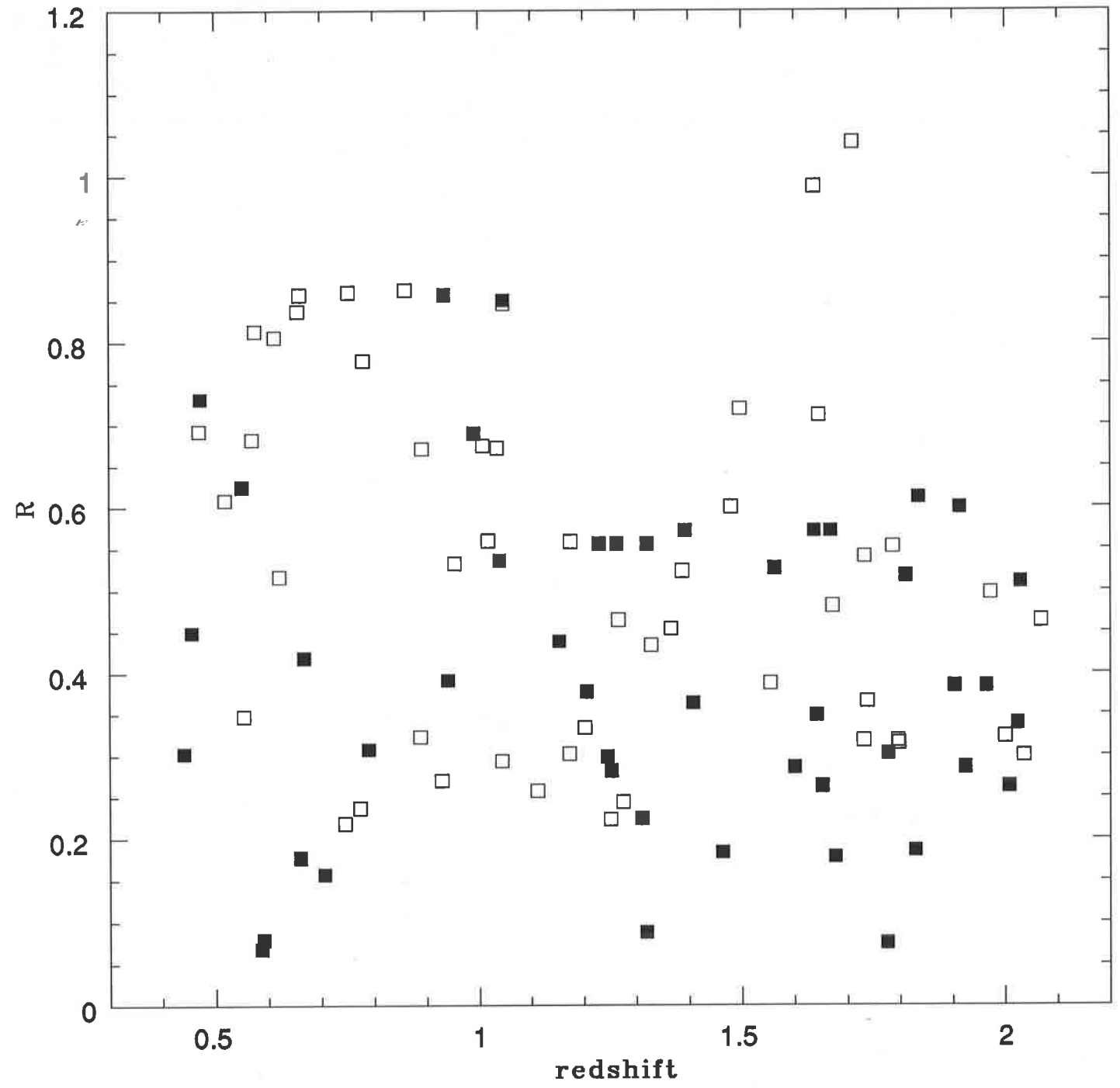


figure 4

