1990ApJ...349..437T

THE ASTROPHYSICAL JOURNAL, 349:437–442, 1990 February 1

GRAVITATIONAL LENSING AND EVOLUTION IN QUASAR ABSORPTION SYSTEMS

PETER A. THOMAS AND RACHEL L. WEBSTER
Canadian Institute for Theoretical Astrophysics, University of Toronto
Received 1989 February 21; accepted 1989 August 5

ABSTRACT

We present tests of both evolution and the bias due to gravitational lensing in the number density of metal absorption-line systems in quasar spectra. No evidence is found for evolution except perhaps in the high equivalent width systems, where gravitational lensing may affect the statistics. We propose a model in which the distribution of high equivalent width systems reflects clustering of an unevolving low equivalent width population.

Subject headings: gravitational lenses — quasars

I. INTRODUCTION

Absorption-line systems of heavy elements are thought to arise in gas associated with galaxies and their halos. Thus the detection of absorption-line systems at high redshift may provide a tracer for the evolution of both number density and the chemical composition of galactic halos over redshift ranges not accessible by other means. Statistical studies of absorption-line systems may also measure large-scale structure in the universe, and the evolution of this structure.

Over the last 10 years, a number of groups have compiled samples of metal line absorption systems. In this paper, we use the data from these groups, and in particular the extensive compilations of Sargent, Boksenberg, and Steidel (1988, hereafter SBS), Sargent, Steidel, and Boksenberg (1988, hereafter SSB1), and Sargent, Steidel, and Boksenberg (1989, hereafter SSB2) to test the various hypotheses for the evolution of comoving number density with redshift.

We also investigate distortions which gravitational lensing may introduce into the counts of absorption-line systems. The effects of gravitational lensing in a sample of absorption-line systems are difficult to disentangle from evolution in the number counts; however, in some cases it is possible to test the hypothesis that a substantial fraction of absorption-line systems are observed only because the quasar is lensed.

It is often assumed that metal line absorption systems are actually galaxies (including their halos) or protogalaxies. There is strong evidence that the absorption systems are associated with galaxy complexes. Since large galactic cross sections are required, and the correlation length between absorption systems is large, the absorption-line clouds are likely to be associated with gravitational potentials containing galaxies, rather than with simple isolated galactic potentials (see discussion for more details). These gravitational potentials may cause gravitational lensing.

In order for gravitational lensing to affect absorption-line studies, two distinct criteria must be met:

1. The quasar must be intrinsically fainter than the cutoff in apparent magnitude for selection into the sample. It must be amplified into the sample by gravitational lensing. An example might be the inclusion of 0142−100 in the SBS sample. This quasar is probably intrinsically several magnitudes fainter than it appears (Surdej *et al.* 1988) and therefore would not normally be included in the sample.

2. Second, the object responsible for the lensing must contribute an absorption line in the redshift interval observed. In the case of 0142−100, the primary cause of the lensing is a galaxy at $z \sim 0.49$. Thus the two C IV lines at $z = 1.94$ and 2.36 included in the SBS sample may still represent an unbiased line of sight over the redshift interval $1.92 < z < 2.73$.

Identification of lensed quasars can be difficult; micro-lensed quasars will not show multiple images and although the frequency of multiply imaged quasars is relatively well known, the percentage of bright quasars which might be micro-lensed is not (Webster *et al.* 1988). From points (1) and (2) above, it can be seen that little correlation is expected between the absolute magnitude of the quasar and the number of absorbers (as was suggested by SBS). Gravitational lensing resulting from two or more independent systems is unlikely (as total flux is conserved by gravitational lensing, the fraction of the observed sky which can be significantly amplified is small). If the mean number of absorbers per quasar is $\gg 1$, then most of these absorption-line systems cannot be significantly lensing the quasar. Even if such a quasar is lensed by one absorption-line system, so long as that system is uncorrelated with all others, the absorption lines defined by the quasar may be treated as selected from a random line of sight. In practice this means that if the number of absorbers is large ($\gg N_l$—see eq. [7]), then lensing is not important; for example, the sample of C IV systems with rest equivalent widths $W_0 > 0.15$ from the SBS sample will not be strongly biased by gravitational lensing.

In § II, suitable statistical tests for both evolution and gravitational lensing are discussed. These tests are applied to various data samples in § III, and the results are discussed in § IV.

II. STATISTICAL TESTS OF THE DATA

a) Evolution of Number Density with Redshift

Here we are concerned with measuring the apparent evolution in comoving number density as a function of redshift. We take as our null hypothesis that the absorption lines are randomly drawn from some probability function, $p(z)$, within the redshift window, $Z = [z_{\min}, z_{\max}]$, in which they could have been detected; i.e., the set of absorption-line redshifts, $\{z_a\}$, is randomly drawn from the distribution

$$P(z) \propto \sum_q \theta[z - z_{\min}(q)]\theta[z_{\max}(q) - z]p(z) , \qquad (1)$$

where $\theta(z) = 0$ for $z < 0$ and 1 for $z \geq 0$ (Heaviside step function). The value of p depends upon our model for the density evolution and is normalized to match the total number of lines. In this section p is taken to be independent of the properties of the quasar—this is not true of the lensing models considered below. If the optical depth of absorbers per unit redshift is proportional to $(1 + z)^{\delta}$, where δ gives the rate of evolution, we have

$$p(z) = \frac{c n_0 \sigma_0}{H_0} \frac{(1 + z)^{1+\delta}}{(1 + 2q_0 z)^{1/2}} , \tag{2}$$

where c is the speed of light, H_0 is Hubble's constant, q_0 is the deceleration parameter, n_0 is the current number density of absorption line systems and σ_0 is their cross section. The quantity p is normally expressed as $\propto (1 + z)^{\gamma}$ where, for $q_0 = 0$, $\gamma = 1 + \delta$, and for $q_0 = 0.5, \gamma = 0.5 + \delta$.

If our model for the density evolution is incorrect, then this will show as a trend with redshift, for which the most obvious, nonparametric test is that of Kolmogorov and Smirnov (K-S; described in Press *et al.* 1986). Alternatively we can group the lines into redshift bins $Z_i = [z_i, z_{i+i}]$ and compare the observed number, $N_i = \sum_a \theta(z_a - z_i)\theta(z_{i+1} - z_a)$, with the expected number $E_i = \int_{z_i}^{z_{i+1}} P(z)dz$. Within each bin we have a Poisson distribution—the probability of having N or fewer lines, Prob $\{N_i \leq N\}$, or N or more lines, Prob $\{N_i \geq N\}$, when the expected number is E_i, is given by

$$\begin{aligned} \text{Prob}\, \{N_i \leq N\} &= \exp\, \{-E_i\} \sum_{n=0}^{N_i} \frac{(E_i)^n}{n!} , \\ \text{Prob}\, \{N_i \geq N\} &= 1 - \exp\, \{-E_i\} \sum_{n=0}^{N_i - 1} \frac{(E_i)^n}{n!} . \end{aligned} \tag{3}$$

Note that the numbers involved here are not large enough for the distribution to be well approximated by a Gaussian. This is a two-sided test since we will reject both small and high numbers of lines. In practice both of these tests give similar constraints. The K-S is perhaps to be preferred since it is parameter-free (the redshift intervals have to be chosen carefully to make best use of the Poisson test) and is less subject to systematic errors.

b) Gravitational Lensing

We wish to test the hypothesis that the sample of absorption-line systems is biased by gravitational lensing. We assume that 100% of quasars in the sample are intrinsically fainter than the apparent magnitude limit of the sample, and that a single compact object associated with one absorption line system is responsible for amplifying each quasar into the sample. Then the probability distribution of these particular lines is given by (Turner, Ostriker, and Gott 1984):

$$p(z; z_q, f) = f^2 \Omega_0 \times \begin{cases} \dfrac{3}{4} \dfrac{[(1 + z_q)^2 - (1 + z)^2][(1 + z)^2 - 1]}{[(1 + z_q)^2 - 1](1 + z)^{2-\delta}} , & q_0 = 0.0 ; \\ \dfrac{3}{5} \dfrac{[(1 + z_q)^{5/2} - (1 + z)^{5/2}][(1 + z)^{5/2} - 1]}{[(1 + z_q)^{5/2} - 1](1 + z)_{7/2-\delta}} , & q_0 = 0.5 , \end{cases} \tag{4}$$

where Ω_0 is the cosmological density in lensing systems and f is a function of the quasar amplification which is unknown. It would be possible to estimate an expected value of f as a function of the line equivalent width and quasar luminosity but this is both model-dependent and difficult; we will not pursue this here.

One way to revise the test of § II*a* is to consider only detected lines—how are these distributed within the redshift interval, Z, in which they reside? Since the intervals, Z, are often small any one observation carries little weight and we must bin them all together. We do this as follows: across each Z we hypothesize a model $p(z; z_q)$ as in equation (4) above. Then we define the weighted path length

$$s(z_{\min}, z_{\max}; p) = \int_{z_{\min}}^{z_{\max}} p\, dz \tag{5}$$

and the "y-parameter"

$$y_a = \left(\int_{z_{\min}}^{z_a} p\, dz)\right) \Big/ s(z_{\min}, z_{\max}) \tag{6}$$

which measures the position of the absorption line within Z. The term s is a generalization of the redshift path density used by Lanzetta, Turnshek, Wolfe 1988, hereafter LTW) and y is a generalization of the function Y in SBS. Our null hypothesis is that the $\{y_a\}$ are uniformly distributed over [0, 1]. This test complements that of § II*a*. It makes no use of null detections and therefore has less power to discriminate evolution in number density. On the other hand, it is independent of system parameters and can be applied to a more general range of models.

We note in passing that the expected value of the maximum number of lines which can be introduced into the sample by gravitational lens biasing (assuming one lens per quasar) is

$$N_l = \sum_q s(z_{\min}, z_{\max})/s(0, z_q) . \tag{7}$$

III. APPLICATION TO OBSERVATIONS

a) Data

There now exist many data sets of both C IV (SBS; Young, Sargent and Boksenberg 1982; hereafter YSB; Foltz *et al.* 1986, hereafter F86) and Mg II (SSB1; SSB2; Tytler *et al.* 1987, hereafter T87; LTW) absorption lines. Steidel, Sargent, and Boksenberg (1988) have used these data sets to support claims of an increasing comoving number density with redshift of magnesium absorption-line systems (for $z \lesssim 1$) and decreasing comoving number density of carbon line systems (for $z \gtrsim 1$). In this section we reexamine the evidence for evolution and investigate the hypothesis that any observed evolution arises from a bias due to gravitational lensing.

To proceed we need an unbiased sample of quasar absorption-line systems. For each quasar, q, we must determine the redshift interval, $Z(q, W_0)$, over which absorption lines with a given test equivalent width, W_0, could have been detected. The exact value of the S/N required is not important provided that it is sufficient to ensure the detected lines are real—most of the above authors use a conservative 5 σ detection criterion. The most useful of the above data sets in this respect is that of T87 who give Z as a function of W_0. LTW do not specify redshift ranges, and so we have used the entire redshift interval of their observations. The other authors give redshift ranges for a single equivalent width. In such cases it is correct to use the same interval for higher equivalent width cuts and to ignore lines which fall outside this interval (though this may not make full use of the data).

Evidence has been presented for an excess of metal absorption-line systems near the quasar redshift (F86). Following SBS we exclude that part of the redshift interval which would correspond to a recession speed relative to the quasar,

1990ApJ...349..437T

$\sim (z_q - z_a)/(1 + z_q)c$, of less than 5000 km s^{-1}. In addition, care has been taken in the selection of absorption lines by equivalent width. Large equivalent width systems often break up into multiple components in higher resolution data. Thus the observed number density at a given equivalent width depends on the resolution used in the observations and reduction. Also at a given spectral resolution and signal-to-noise ratio, high-redshift lines are generally observed at higher resolution, and in principle this could lead to spurious evolutionary effects. Since we are interested only in the distribution underlying the absorption-line systems, we combine lines whose velocity separation $\Delta v \sim c\,\Delta z/(1 + z)$ is less than 2000 km s^{-1}. The mean redshift of such systems and the sum of the individual equivalent widths is used. A velocity of 2000 km s^{-1} corresponds to a $\Delta\lambda$ of >20 Å, and so the problem of lines with subcomponents is eliminated. Lines should be merged before selection of the complete subsample as a function of equivalent width. Part of the difference between our subsamples and those of SBS, SSB1, and SSB2 arises because of the order in which these procedures were undertaken; the rest is due to the slightly different selection criterion.

Since most data sets do not contain enough quasars or cover a sufficient redshift range to give strong constraints on evolution models, it is tempting to combine samples in order to improve statistics. However, different samples cover different redshift intervals, and so differences in normalization can lead to spurious evolutionary effects. In Tables 1 and 2 we compare the relative numbers of absorption-line systems found in the same redshift intervals for each of the data sets listed above. The mean line density is calculated for a volume-weighted ($q_0 = 0.5$) redshift interval (the results are not sensitive to the choice of weighting here). From Table 1, YSB and F86 appear to have a smaller normalization than SBS. In addition, when the equivalent widths of lines detected in the seven quasars which were observed by both YSB and SBS are compared, the equivalent widths of YSB are found to be systematically 10%–15% lower. A similar comparison for the only quasar with lines which is in both the F86 and SBS sample gave a discrepancy of $\sim$50%. If the samples were concatenated, these differences would tend to bias the C IV samples towards showing less evolution than really exists. In Table 2, little difference is detected between the SSB1 and SSB2 samples; however, both LTW and T87 may have smaller normalizations (the LTW normalization is a lower limit because we have used the full redshift interval). Also, in at least one case—0848 + 163, there are two Mg II doublets recorded in SSB1 which were not found by T87, although they should have been if the quoted equivalent widths are correct. The only samples which we consider can be confidently combined, are SSB1 and SSB2.

TABLE 1

RELATIVE NORMALIZATION OF C IV DATA SETS

	$z = 1.2$–1.6		$z = 1.6$–2.0		$z = 2.0$–2.4	
SAMPLE	Number[a]	dN/dz[b]	Number[a]	dN/dz[b]	Number[a]	dN/dz[b]
F86	6	0.53	5	0.85	...	...
YSB	8	0.89	12	0.87	1	0.33
SBS	12	1.30	24	1.30	13	1.02

[a] Number of absorption lines ($W_0 > 0.3$ Å) in each redshift interval.

[b] Number of lines per unit volume-weighted path length (as described in § II*b*).

TABLE 2

RELATIVE NORMALIZATION OF Mg II DATA SETS

	$z = 0.4$–0.8		$z = 0.8$–1.2		$z = 1.2$–1.6	
SAMPLE	Number[a]	dN/dz[b]	Number[a]	dN/dz[b]	Number[a]	dN/dz[b]
T87	5	0.21	2	1.01	...	...
SSB1	10	0.50	6	0.53	1	0.39
SSB2	...	...	13	0.65	9	0.56
LTW	...	...	...	...	6	>0.36

[a] Number of absorption lines ($W_0 > 0.6$ Å) in each redshift interval.

[b] Number of lines per unit volume-weighted path length (as described in § II*b*). This is a lower limit for LTW as we do not know the correct redshift intervals.

b) C IV *Systems*

We analyze the SBS data set which is the largest homogeneous sample and contains 55 quasars. The results of the test for evolution (§ II*a*) are shown in Table 3. In this table, confidence levels for the rejection of the hypothesis that the absorption lines are distributed with $dN/dz \propto (1 + z)^{\gamma}$ are given as a function of γ and equivalent width. This means, for example, that for $W_0 \geq 0.6$ Å and $\gamma = 0$, the difference between the data and the model would be exceeded in 10% of samples. The lower equivalent widths of the samples are defined by requiring both lines be greater than the specified level. The upper equivalent width cutoff requires that the mean of the lines be lower than the given level. There are 60 absorption lines in which both C IV lines (1548 Å and 1550 Å) have a rest equivalent width, W_0, exceeding 0.3 Å. The best-fit evolution model has $\gamma \sim -1$, but the 95% confidence range extends to include $\gamma = 0.5$ (i.e., no evolution and $q_0 = 0.5$). As the equivalent width cut is raised, the best-fit value of γ decreases, although the confidence range expands due to the decreasing number of lines. This suggests that it is the highest W_0 systems which drive the apparent evolution; if we restrict our sample to the 40 lines with 0.3 Å $\leq W_0(1548)$, $W_0(1550)$, and $W_0(1548) + W_0(1550) \leq 2 \times 0.9$ Å, then we find that both $\gamma = \frac{1}{2}$ and $\gamma = 1$ (i.e., no evolution for $q_0 = 0.5$ and $q_0 = 0.0$) are easily acceptable, with a best-fit value of $\gamma \sim 0$. In Figure 1, which

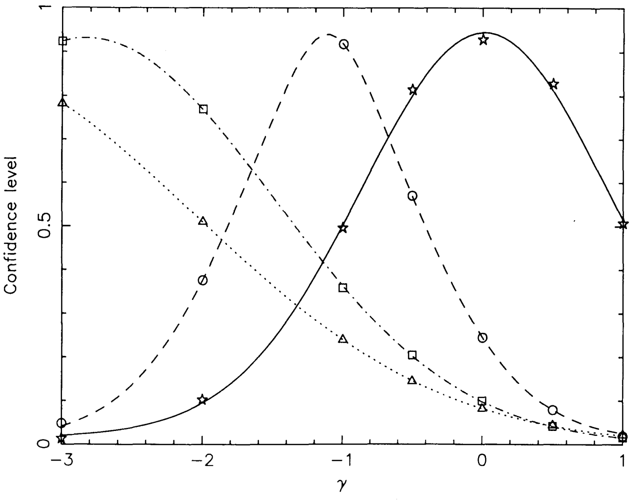

FIG. 1.—Confidence level as a function of γ for the subsamples detailed in Table 3. The dashed line is the sample with $W_0 \gtrsim 0.3$ Å; the dot-dash line, $W_0 \gtrsim 0.6$ Å; the dotted line, $W_0 \gtrsim 0.9$ Å; the solid line, $0.9 \gtrsim W_0 \gtrsim 0.3$ Å.

TABLE 3

KOLMOGOROV-SMIRNOV CONFIDENCE LEVELS FOR REJECTION OF C IV EVOLUTION MODELS

		γ						
EQUIVALENT WIDTH	NUMBER	−3.0	−2.0	−1.0	−0.5	0.0	0.5	1.0
≥0.3 Å	60	0.048	0.376	0.918	0.570	0.245	0.079	0.019
≥0.6 Å	28	0.923	0.770	0.359	0.205	0.100	0.042	0.016
≥0.9 Å[a]	13	0.782	0.510	0.240	0.145	0.082	0.044	0.022
0.9 Å ≥ W_0 ≥ 0.3 Å	40	0.013	0.102	0.496	0.814	0.928	0.828	0.507

NOTE.—Confidence levels for rejection of the hypothesis that the absorption-line samples are distributed with $dN/dz \propto (1+z)^\gamma$. Also given is the number of absorption lines in each subsample. The selection by equivalent width is described in the text.

[a] The confidence levels given here are slightly too high (less than 10%) as we applied the asymptotic, large number formula to work out the Kolmogorov-Smirnov probabilities.

plots the confidence level as a function of γ, the trend with equivalent width is clearly apparent. In the discussion which follows, we shall refer to this subset as LEW (low equivalent width) systems, and those with $W_0 > 0.9$ in both lines as HEW (high equivalent width) systems. The HEW lines show either strong evolution or reflect a bias due to gravitational lensing.

Table 4 gives the confidence levels for the rejection of the hypothesis that the distribution of absorption lines, as measured by the y-parameter (§ II*b*) fits the various models described. The equivalent width samples are as described in Table 3. This test confirms that the LEW lines are consistent with a constant comoving density in both open and closed cosmologies. The HEW systems are better fitted by lensing solutions although strong evolution is not ruled out at the 5% level. The redshift intervals over which we could detect lines contribute a fraction 0.098 to the total lens-weighted path length (for $q_0 = 0.5$). Thus even if all of the 55 quasars in the SBS data set are lensed into the sample we should expect to see only about five absorption lines related to the lensing objects. This number represents an upper limit to the number of absorption lines which can be added to the sample due to the effects of gravitational lensing. There may be a mixture of effects contributing to the observed distribution of HEW lines.

When combined with the data from YSB and F86 the evidence for comoving number density evolution of HEW lines is decreased. We believe that this is due to the difference in normalization mentioned in § III*a*.

c) Mg II *Systems*

Here we concentrate upon the data sets of SSB1 and SSB2 which appear to have similar normalizations (see § III*a*) and which comprise a total of 99 quasars. The test results are given in Tables 5 and 6. In line with previous authors we only require the 2796 Å line to exceed the lower equivalent width cut. Once again there is no evidence for evolution in the LEW systems as is clearly shown in Figure 2, where the confidence levels are

TABLE 4

KOLMOGOROV–SMIRNOV CONFIDENCE LEVELS FOR REJECTION OF C IV LENSING MODELS

		NO LENSING		LENSING, $q_0 = 0$		LENSING, $q_0 = \frac{1}{2}$	
EQUIVALENT WIDTH	NUMBER	$\gamma = -2.0$	0.5	$\delta = -3.0$	0.0	$\delta = -2.5$	0.0
≥0.3 Å	60	0.799	0.424	0.010	0.134	0.006	0.071
≥0.6 Å	28	0.404	0.138	0.324	0.470	0.264	0.393
≥0.9 Å	13	0.075	0.028	0.643	0.319	0.704	0.414
0.9 Å ≥ W_0 ≥ 0.3 Å	40	0.978	0.770	0.006	0.059	0.004	0.035

NOTE.—Confidence levels for rejection of the hypothesis that the distribution of absorption lines within the redshift interval in which they could have been observed, as measured by the "y-parameter" described in § II*b*, fits various models. Parameters as defined in Table 3.

[a] The confidence levels given here are slightly too high as we applied the asymptotic, large number formula to work out the Kolmogorov-Smirnov probabilities.

TABLE 5

KOLMOGOROV-SMIRNOV CONFIDENCE LEVELS FOR REJECTION OF Mg II EVOLUTION MODELS

		γ						
EQUIVALENT WIDTH	NUMBER	−0.5	0.0	0.5	1.0	1.5	2.0	3.0
≥0.6 Å	38	0.106	0.259	0.511	0.803	0.918	0.620	0.155
≥0.9 Å	26	0.075	0.166	0.318	0.528	0.755	0.925	0.934
≥1.2 Å	16	0.060	0.109	0.188	0.309	0.474	0.671	0.971
1.2 Å ≥ W_0 ≥ 0.6 Å	25	0.274	0.501	0.709	0.443	0.243	0.120	0.024

NOTE.—As for Table 3 except that the lower equivalent width limits are defined by requiring only that the 2796 Å line exceed the specified level.

[a] The confidence levels given here are slightly too high as we applied the asymptotic, large number formula to work out the Kolmogorov-Smirnov probabilities.

1990ApJ...349..437T

TABLE 6

KOLMOGOROV-SMIRNOV CONFIDENCE LEVELS FOR REJECTION OF Mg II LENSING MODELS

		NO LENSING		LENSING, $q_0 = 0$		LENSING, $q_0 = \frac{1}{2}$	
EQUIVALENT WIDTH	NUMBER	$\gamma = 0.5$	3.0	$\delta = 0.0$	2.0	$\delta = 0.0$	2.5
≥0.6 Å	38	0.413	0.672	0.331	0.953	0.202	0.809
≥0.9 Å	26	0.209	0.701	0.161	0.452	0.100	0.369
≥1.2 Å	16	0.123	0.393	0.102	0.249	0.068	0.211
1.2 Å ≥ W_0 ≥ 0.6 Å	25	0.987	0.327	0.997	0.711	0.923	0.864

NOTE.—As for Table 4 with equivalent width sample defined as in Table 5.

[a] The confidence levels here are slightly too high as we applied the asymptotic, large number formula to work out the Kolmogorov-Smirnov probabilities.

plotted against γ for each of the subsamples. Although the distribution of HEW systems does not deviate significantly from that expected with no evolution, the best-fit models do show an increase in comoving number density with redshift. In contrast to the C IV systems this cannot be explained in terms of a simple lensing model since there is little difference between these and no-evolution models over the redshift range in which most of the absorption lines fall. The total lens-weighted path length (for $q_0 = 0.5$) is 0.31, and thus if 100% of the 99 quasars in the combined magnesium data set were lensed into the sample then we might expect about 31 of the lines to be related to lensing systems.

Combining the above data with that of LTW leads to virtually identical results. However, if the data of T86 are also used, then strong evolution is required—this is probably due to a difference in normalization between the two data sets.

IV. DISCUSSION

We have specifically addressed two questions:

1. Is there evidence for evolution in the number redshift counts for any of the metal absorption-line systems?

2. Could gravitational lensing be biasing the numbers of absorption line systems detected?

In the process of examining these questions, the following general conclusions were established:

1. Concatenating samples of different groups is problematic, since the normalizations appear to differ significantly. Evolution can only be verified within a single homogeneous sample. Unfortunately most samples are small and cover a limited redshift range; thus, the statistics of one sample are not very good.

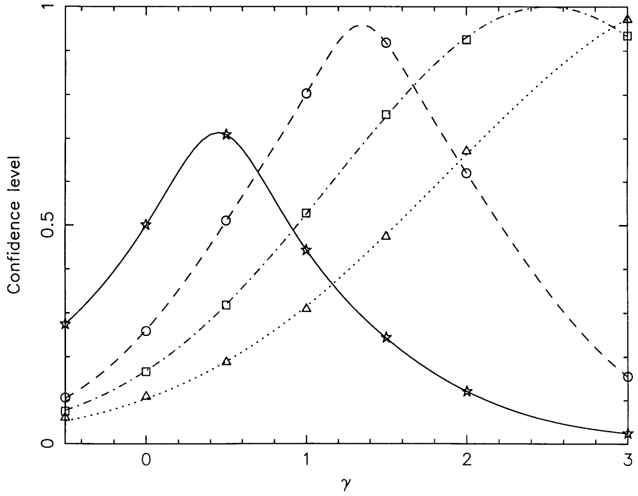

FIG. 2.—Confidence level as a function of γ for the subsamples detailed in Table 5. The dashed line is the sample with $W_0 \gtrsim 0.6$ Å; the dot-dash line, $W_0 \gtrsim 0.9$ Å; the dotted line, $W_0 \gtrsim 1.2$ Å; the solid line, $1.2 \gtrsim W_0 \gtrsim 0.6$ Å.

2. The fact that a quasar is gravitationally lensed does not necessarily invalidate its contribution to a random sample of absorption-line systems. A bias will only arise if the object responsible for lensing the quasar into the sample also contributes a related absorption-line system.

3. By calculating the lensed-weighted path length, we can work out the maximal contamination in the sample, equation (7). The mean lens-weighted path length in the complete C IV sample is ~0.1 and for the Mg II is ~0.3. This means that the C IV sample is unlikely to be seriously contaminated.

When we examine the specific C IV and Mg II samples, the following conclusions are reached:

4. For C IV, the only evidence for evolution is in the high equivalent width systems. The evolution of these systems is well fitted by a gravitational lens model; however, nearly every quasar would need to be lensed into the sample for this explanation to be viable.

5. For Mg II, it is not necessary to invoke evolution to account for the distribution of lines. Gravitational lensing would have little effect on the expected distribution of the lines.

Identifying tracers for gravitational lensing relies on weak assumptions, such as objects which lens will also produce metal absorption lines. Of 10 multiply imaged quasars in the literature which are claimed to be lensed, galaxies are seen in four cases. In only two cases, Mg II absorption associated with the galaxy is redward of the Lyman-α emission line, and in neither case is it observed. In all four cases, C IV associated with the galaxies would fall in the Lyman-α forest and thus be difficult to detect. Thus not every lens is associated with Mg II absorption, and the covering factor of Mg II must be less than 1.

Bergeron (1988) has found galaxies at the appropriate redshift in at least 10 out of the 13 cases of quasars with Mg II absorption which she observed. Using an argument similar to Webster *et al.* (1988), one can estimate the number of expected associations between a galaxy and a quasar as

$$N_{\rm assoc} \sim 3.6\left(\frac{R}{12''}\right)^2\left(\frac{N_g}{10^{3.9}}\right)\left(\frac{N_q}{13}\right), \qquad (8)$$

where R is the radius searched for galaxies, N_g is the number of galaxies per square degree to the search limit, and N_q is the number of quasars in the sample. The estimate of N_g is taken from Tyson's (1988) of R differential number counts, suitably corrected for the change of color, where the limiting magnitude $m_r \sim 22.2$ for the galaxies is assumed. There are two possible explanations for this result. The first and perhaps most plausible is that Mg II lines are caused by gas clouds around the galaxy. In this case, the quasars with absorption lines at $z \lesssim 0.55$ as selected by Bergeron are a biased subsample of a larger sample of quasars. A correction factor is $f_{\rm bias} \sim 2.5$ estimated from Table 5 should be applied to the counts, giving $N_{\rm assoc} \sim 9$ as observed. A second possibility is that the quasars are biased into the sample by gravitational lensing by the galaxies. Since a total of 38 absorption lines with $W_0 \gtrsim 0.5$ Å are observed in 99 quasars, and only ~ 0.3 of the mean path length has been searched for Mg II absorption, each quasar will actually have ~ 1 absorption line. In this case, $f_{\rm bias} \sim 1$, and if the estimate for the galaxy number counts is correct, then the majority of bright quasars are lensed. We are obtaining more data with controls in order to clarify this issue.

In this paper we have obtained results which are independent of the identity of the absorption-line systems. By way of contrast with the chemical evolution model discussed by Steidel, Sargent, and Boksenberg (1988), we now consider whether the observed distribution might instead be consistent with a model for the evolution of clustering.

6. Although the allowed parameter range is very large, we tentatively conclude that the comoving number density of LEW absorption lines is constant over a large range of redshifts ($0.5 \lesssim z \lesssim 2.5$). This would strongly suggest that the clouds in which the absorption lines arise are not pressure-confined by the intergalactic medium but rather exist in potential wells whose number density changes little between $z \sim 2.5$ and the present.

It is often assumed that the absorption lines are associated with normal ($L \sim L_*$) galaxies. Unfortunately, the cross section of the luminous part of these galaxies is too small to give the observed number of absorption lines, and thus galactic halos with average radii of 50–100$h^{-1}f^{-0.5}$ kpc are postulated, where f is the covering factor of clouds. In our model, the clouds containing the absorption line gas are smaller than a typical galactic size; thus, the number density is not prescribed, and constraints which apply for galaxy halos are not relevant. This model is consistent with the results of Bergeron (1988), discussed above, who found galaxies associated with most but not all of a sample of Mg II lines.

7. We postulate that the HEW systems (with $W_0 > 0.9$ Å) are merely projections of LEW systems which happen to lie close together in redshift (in the data analysis, we bin together lines which have separations less than 2000 km s^{-1}; here we consider the raw data). We note that the HEW lines do appear to break up into subcomponents when observed at higher resolution. SBS give the number of line pairs as a function of velocity separation and from this we estimate that all the lines in their sample with $W_0 > 0.9$ Å can be explained by the merging of LEW lines with a velocity separation smaller than their resolution limit. This means that the high tail of the equivalent width distribution is an artifact of the resolution, and that the number distribution of equivalent widths may be better fitted by a linear relation, rather than an exponential one.

The clouds which give rise to the LEW lines will cluster in the potential, and it is this which results in the large number of pairs with small velocity separation. In cases where absorption is detected in two lines of sight which are close together on the sky, the velocity difference is ~ 200 km s^{-1} (SBS) and may well be caused by two different clouds in a single potential. The velocity correlations on separations less than 600 km s^{-1} (SBS) also confirm this view.

We have considered the possibility that HEW lines are more likely to be associated with gravitational lensing. One possible link is that HEW lines are associated with clustering clouds and thus a substantial potential, and that the high mass density this implies provides a large cross section for lensing.

8. In our picture some of the evolution in number density of HEW systems (for which the evidence is not conclusive) would reflect the evolution in clustering of these systems of small clouds. The turnaround and collapse of clusters would lead to significant reduction of the separation of lines in redshift space. In order to reduce the effect of internal cluster evolution on our statistical results we choose to merge lines with velocity separations less than 2000 km s^{-1}. This gives 13 HEW C IV systems, whereas before merging there were only four. Also, in one example, eight lines merged to form one system. Thus it is important to define carefully the procedure by which these lines are selected.

The value of 2000 km s^{-1} used here was chosen as it is the largest size of velocity correlations between absorption lines (SBS) and corresponds to the virial velocity of a large cluster. While this should eliminate most of the evolutionary effects it is possible that (1) the increase in density of small clouds as the clusters collapse could lead to the an apparent increase in number density of HEW systems with decreasing redshift, as in the C IV data; and (2) the disruption of clouds during cluster virialization may lead to a decrease in the number density of HEW clouds at late times, as may be observed in the Mg II data.

Although the above arguments are tentative, they suggest to us that any evolution in HEW systems may reflect an evolution in the clustering properties of clouds rather than an internal change in these clouds.

REFERENCES

Bergeron, J. 1988, in *IAU Symposium 130, Evolution of Large-Scale Structures in the Universe*, ed. J. Audouze, M.-C. Pelletan, and A. Szalay (Dordrecht: Kluwer), p. 343.

Foltz, C. B., Weymann, R. L., Peterson, B. M., Sun, L., Malkan, M. H., and Chaffee, F. H. 1986, *Ap. J.*, **307**, 504 (F86).

Lanzetta, K. M., Turnshek, D. A., and Wolfe, A. M. 1988, *Ap. J.*, **322**, 739 (LTW).

Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T. 1986, *Numerical Recipes* (Cambridge: Cambridge University Press), p. 472.

Sargent, W. L. W., Boksenberg, A., and Steidel, C. C. 1988, *Ap. J. Suppl.*, **68**, 539 (SBS).

Sargent, W. L. W., Steidel, C. C., and Boksenberg, A. 1988, *Ap. J.*, **334**, 22 (SSB1).

Sargent, W. L. W., Steidel, C. C., and Boksenberg, A. 1989, *Ap. J. Suppl.*, **69**, 703 (SSB2).

Steidel, C. C., Sargent, W. L. W., and Boksenberg, A. 1988, *Ap. J.* (*Letters*), **333**, L5.

Surdej, J., *et al.* 1988, *Astr. Ap.*, **198**, 49.

Turner, E. L., Ostriker, J. P., and Gott, J. R., III. 1984, *Ap. J.*, **284**, 1.

Tyson, J. A. 1988, *A.J.*, **96**, 1.

Tytler, D., Boksenberg, A., Sargent, W. L. W., Young, P. J., and Kunth, D. 1987, *Ap. J. Suppl.*, **64**, 667 (T87).

Young, P., Sargent, W. L. W., and Boksenberg, A. 1982, *Ap. J. Suppl.*, **48**, 455 (YSB).

Webster, R. L., Hewett, P. C., Harding, M. E., and Wegner, G. A. 1988, *Nature*, **336**, 358.

PETER A. THOMAS: School of Mathematics and Physical Sciences, University of Sussex, Falmer, Brighton, BN1 9RH, UK

RACHEL L. WEBSTER: C.I.T.A., 60 St. George Street, Toronto, Ontario, Canada M5S 1A1