ABSORPTION LINES IN THE SPECTRA OF DISTANT OBJECTS

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I shall discuss studies that can be carried out with the Space Telescope (ST) of absorption-line systems which may be expected to occur in the spectra of distant objects.

Absorption-line systems with redshifts very different from the emission-line redshift have so far been observed only in the spectra of quasars and BL LAC objects. However, the fact that quasars exhibit rich absorption spectra and galaxies have not yet been observed to do so may be explained by two selection effects. Galaxies are by definition fainter than quasars and most of the strong absorption lines occur in the far ultraviolet. Thus galaxies at the redshifts sufficient to shift the absorption systems into the visible region are too faint to be studied at the high resolution necessary to detect narrow absorption lines.

ST observations of galaxies (with, e.g., $0.1 \lesssim z_{em} \lesssim 0.5$) may be expected to reveal quasar-like absorption lines *if* many of the absorption systems observed in quasar spectra are due to absorption by material along the line of sight at cosmologically significant distances from the quasar.

For convenience only, I shall describe all of the proposed observations as if the continuum sources were only quasars. The listener will easily recognize that many of the suggested observations could be carried out with distant galaxies (irrespective of the origin of the already-observed quasar absorption lines). Galaxies are more numerous per square degree than are quasars. For some observations (see § VI and VII), the advantage of being able to choose galaxies behind specified regions may outweigh the disadvantage of their relative faintness.

Most of the absorption systems have been observed in the spectra of quasars with large emission-line redshifts. How-

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ever, one may anticipate some general advantages in studying the small absorption redshifts, $z_{abs} < 1$, that are accessible with ST. Relatively bright quasars can be used. Also the spectra may be less crowded (see equation (1) below) than is the case when large values of z_{abs} are considered. The observed region between 1100 Å and 1200 Å will be especially interesting since it is both accessible to the ST spectographs and free of confusion due to Ly-α absorption lines.

In § I, I describe the phenomenology of quasar absorption-line systems. In § II, I summarize the principal explanations that have been suggested. I also add one new proposal, i.e., that the numerous Ly-α systems are caused by "extremely large" hydrogenic halos around galaxies or clusters of galaxies. In Tables 2 and 3 of § III, I list the absorption lines that are likely to be strongest. In § IV, I describe two tests for the origins of known absorption systems. In § V, I discuss observations in which distant sources of ultraviolet radiation can be used as continuum probes to search for gas in previously-known, relatively-nearby systems. I describe four special projects in § VI. Finally, I present a sample observing program in § VII.

1. PHENOMENOLOGY

The main characteristics of the absorption lines observed in quasar spectra are summarized in Table 1. The properties listed are described in greater detail in several recent review articles [see for example Bahcall 1978; Boksenberg 1977, 1978; Burbidge 1978; Sargent 1977; Weymann and Williams 1978]. It is an encouraging augury for the ST program that participants in this colloquium [especially Boksenberg, Burbidge, Lynds, Morton, Sargent, and Weymann] have accomplished most of the crucial, ground-based observational work on quasar absorption lines that is summarized in the above-cited reviews.

Quasar ultraviolet spectra have many absorption lines. There are typically of order 0.05 absorption lines per Å with rest equivalent widths $\gtrsim$ 0.3Å for wavelengths, in the rest frame of the quasar, in the approximate range 1600 Å to 1216 Å ($\equiv$ Ly-α). For wavelengths shortward of the Ly-α emission line, the number of absorption lines rises dramatically to of order 0.2 absorption lines per Å. This increase in the density of absorption lines below the Ly-α emission line was explained by Lynds (1971) as being due to many Ly-α lines. The metal lines and the higher members of the Lyman series are mostly too weak to be detectable with present techniques [see also Lynds and Oemler 1975 and Young et al. 1979].

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Table I. CHARACTERISTICS OF OPTICAL ABSORPTION LINES

This table summarizes the main characteristics of the optical absorption lines that have been observed in QSO spectra.

General Property	Detailed Characterisitics
Many Lines	~ 0.2 per Å, $\lambda_{quasar} < $ Ly-α 0.05 per Å, $\lambda_{quasar} >$ Ly-α
Many Redshifts	~ $10^{1\pm0.5}$ per spectrum mostly $z_{abs} < z_{lim}$
Distribution in Redshifts (may be homogeneous)	More detected at large z(~2.5) than small z(~0.7). Requires great care in avoiding selection effects.
Variety of Ionization Stages (HI and HII)	HI, CII, CIV, NII, N V, OI, OVI, MgI, MgII, AℓII, AℓIII, SiII - SiIV, MnII, FeII, FeIII ($T \sim 10^{4.5\pm1}$ °K)
Mostly narrow lines	$\frac{\Delta\lambda}{\lambda} \sim 10^{-3.5\pm0.5}$, most lines $\frac{\Delta\lambda}{\lambda} \sim 10^{-1.5}$, in a few cases with $z_{abs} \sim z_{lim}$
Line Splittings	~ 10^2 km/sec (metal lines) (some cases of ~ 10^3 km/sec)
Excited Fine Structure States mostly absent	$n_e \lesssim 10^3$ cm^{-3}
No established transitions from metastable states	CIII λ 1175.7 absent
Wavelengths are constant in Time	$\left\lvert \frac{1}{\lambda}\frac{d\lambda}{dt} \right\rvert \lesssim 10^{-5}$ yr^{-1}

There are many independent absorption-line redshifts in each (large redshift) quasar spectrum. For the systems containing heavy elements, this conclusion was established shortly after the discovery of rich absorption spectra by a detailed statistical analysis [Bahcall 1968]. Subsequent work, cited above, validated the identification with separate Ly-α systems (by Lynds) of most of the many lines shortward of the Ly-α emission line.

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A well-defined technique for analyzing spectra is required in order to establish the existence of multiple redshifts, because of the many degrees of freedom that are available in fitting the data. Typically [Bahcall 1968] one tabulates a predetermined set of standard lines that are expected, on the basis of some hypothesis about the nature of the absorbing region, to appear in the absorption spectrum. One also formulates a set of rules for determining whether a candidate redshift is physically reasonable (e.g., the weaker component of a doublet is successfully identified only if the stronger component can also be present). The actual redshifts are determined by a systematic search (with a computer) for acceptable redshifts. Finally, a Monte-Carlo simulation is made using nonsense spectra (or some other statistical estimate is carried out) in order to establish the level of statistical significance. Only if the number, N_{obs}, of redshifts identified in the real spectrum is large compared to the average number of spectra identified in the Monte-Carlo simulation (or found by another statistical estimator), $N_{nonsense}$, can one conclude that there are indeed a multiplicity of redshifts produced by the standard lines in the observed spectrum. In the computer analysis of many moderate dispersion spectra, $N_{obs} \gg N_{nonsense}$. The precise value of $N_{nonsense}$ that should be associated with a given set of rules depends on the distribution of lines that is assumed for the nonsense spectra. It has become clear [Bahcall and Joss 1973; Aaronson, McKee, and Weisheit 1975; Colvin 1975; Joss and Ruffa 1977; Young et al. 1979; Roberts 1979] that the original prescription of a uniform distribution underestimates the value of $N_{nonsense}$ by a factor that may be of order of fifty percent, but which is still uncertain. However, as long as one uses only identifications for which $N_{obs} \gg N_{nonsense}$, the precise value of N_{obs} is not crucial. One must be very cautious about making inferences based on individual lines since only the total pattern of identifications is shown to be statistically significant.

There are now in use a number of computer programs that differ in varying degrees from the original identification procedure (Bahcall 1968). Some of these (e.g., Boksenberg and Sargent 1975; Young et al. 1979) are described by the authors as essentially the same as the original procedure and some make rather far-reaching modifications (e.g., Joss and Ruffa 1977; Roberts 1979). In any event, the software that will be appropriate for analyzing ST observations will differ in some details from all of the above since it will depend upon the quality of the data that is obtained and on the as yet unknown character of high resolution quasar spectra in the region $1100\ \text{Å} \leq \lambda_{observed} \leq 3200\ \text{Å}$.

The distribution of absorption redshifts can be predicted

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(Bahcall and Peebles 1969) as a function of the standard cosmological parameters q_o and Λ/ρ_o, if one assumes that most of the absorption lines arise in material that is randomly distributed along the line of sight between us and cosmologically distant quasi-stellar sources. We shall refer to this assumption as the "cosmological hypothesis." The probable number of absorption lines in a redshift range between z and z + dz is then

$$dP = \frac{\pi R^2(0)N(0)c(1+z)\left[\left(R(z)/R(0)\right)^2\left(\frac{N(z)}{(1+z)^3N(0)}\right)\right]}{H_o\left[1+2q_oz-(\Lambda/3)\left\{(1+z)^2q_o^{-1}+z^2+2z\right\}\right]^{1/2}}\,dz \quad ,(1)$$

where $\pi R^2(0)N(0)$ is the suitably averaged product of projected surface area and present number density of absorbing regions, H_o the present Hubble constant; q_o the acceleration parameter, and Λ, the cosmological constant. For simplicity, we assumed that the absorbers did not evolve with redshift [i.e. the bracketed quantity in the numerator of equation (1) was unity], although the possibility of evolution was recognized as an important factor determining the observed distribution (see especially Bahcall 1971).

Two tests of the cosmological hypothesis were proposed (Bahcall and Peebles 1969) that are based on equation (1). The first test expresses the fact that the total number of absorption redshifts in each quasar should be given by the integral $\int dP(z)$ over the allowed range of z. If all of the objects are studied in the same way over the same range of z, then the number of absorption redshifts in each quasar should be Poisson distributed with a mean given by the integral of the right hand side of equation (1). The second test does not require a constant detection efficiency for each object. The observed distribution of redshifts, $\frac{dP(z)}{dz}$ dz, can be determined by counting all the redshifts found in just one object. The simplest application of the second test is to ask whether the observed function, dP(z), can be represented by equation (1). It may be necessary to average dP(z) over large enough bins of z to eliminate peaks due to several correlated absorbers, e.g., galaxies in a rich cluster, cf. Boksenberg (1978).

There has been a more or less continuous controversy over whether or not these tests are satisfied in the ten years since they were first proposed. Only very recently, Boksenberg (1978) and Burbidge (1978) reached opposite conclusions on this question in successive review talks that were given at the same conference. My own opinion has been [Bahcall 1971, 1978], until very recently, that the required observational material, sufficiently free of selection effects, was not available. Most recently, Sargent, Young, Boksenberg, and

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Tytler (1979) have applied both tests described above to high resolution data obtained for six quasars. They have constructed well defined samples from the Ly-α absorption lines observed in these objects and have paid scrupulous attention to possible selection effects. They have carried out a rigorous statistical analysis that, in my opinion, will constitute a standard of excellence for years to come. Sargent et al. (1979) conclude that the results in each object are consistent with equation (1) (test 1 above) and that the intercomparison of the spectra of different objects is also consistent with spatial homogeneity (test 2 above).

Both of these results were obtained assuming no evolution of the absorbers (bracketed quantity in the numerator of equation (1) set equal to unity). Ellis (1978) earlier reached a similar conclusion regarding test 1 which he made by taking account of the selection effects in inhomogeneous data.

Quasar absorption spectra show lines from a wide variety of ionization stages. The ions that contribute the most prominent lines are shown in Table I; they range from ions characteristic of HI regions (HI, OI, MgI) to highly ionized atoms (CIV, NV, and OVI). The observed lines arise primarily from ground-state transitions (see below) of the elements with the largest solar abundances. The lines that are observed were predicted [Bahcall and Salpeter 1966; Bahcall 1968] to be the strongest lines that would be seen in quasar spectra on the basis of atomic physics considerations, solar abundances and the hypothesis that absorption systems are low-density gases. The strong lines are essentially the same as those observed by Copernicus to be produced in the instellar medium of our Galaxy (see Boksenberg 1978 for a discussion of this similarity).

Most of the observed optical absorption lines are very narrow; in many cases they are unresolved at the highest resolution available ($\Delta\lambda \sim 1$ Å). [Observations of some systems at 21 cm even show velocity widths of individual components that are only 20 km/sec or less wide (see, e.g. Brown and Roberts 1973)]. In a few cases, very broad optical absorption lines are present. Such features were first seen in the spectrum of PHL 5200 [Lynds 1967], which exhibits absorption troughs shortward of Ly-α, NV, SiIV, and CIV, extending over a range of 12,500 km/sec. One of the most extreme examples of this phenomenon is seen in the spectra of Q1246 - 057 [Boksenberg 1978], which shows a broad absorption system of width ~ 5000 km/sec separated by ~ 1500 km/sec from the emission lines. Most observers have interpreted the broad-line systems in terms of material flowing out of the quasar [see Boksenberg 1978 and Burbidge 1978].

Absorption line systems, when studied at high resolution, are frequently observed to be split into separate subsystems [see, especially, Boksenberg and Sargent 1975; Morton and Morton 1972; Wingert 1975]. These splittings are often of the order of 10^2 km/sec. Boksenberg and Sargent (1975) originally suggested that the numerical value of these splittings, $\Delta z \cong 0.0012$ or 141 km/sec might be a constant with special significance. It was proposed instead (Bahcall 1975) that the observational results could be explained by a velocity dispersion of less than or of order of 10^2 km/sec among individual absorbing clouds and a comparable instrumental resolution. A specific model was suggested in which the splittings were supposed due to absorption in clouds in halos surrounding galaxies or small groups of galaxies. This interpretation implied that there are many absorption redshifts that are split with velocity separations less than 10^2 km/sec, a prediction that has been confirmed recently with very high resolution spectra by Boronson, Sargent, Boksenberg, and Carswell (1978). It was also proposed [Bahcall 1975] that splittings of order 10^3 km/sec might be expected from absorption in the halos of galaxies that are themselves in clusters of galaxies. A splitting of order 10^3 km/sec has in fact been observed in some cases [see, e.g., the results of Strittmater et al. 1973 on 1331 + 170 and Boksenberg and Sargent 1975 on Pks 0237 - 23].

Transitions originating on excited fine structure states of Si II, CII, and NII are usually weak and undetectable. However, they have detected in a few cases and occasionally are strong [see, e.g. Stockton and Lynds 1966; Boksenberg 1978; Roberts 1979]. The absence of excited fine structure transitions implies that the electron density must be relatively small [Bahcall and Wolf 1968; Bahcall 1967]. Typical limits on the ambient electron density are $n_e \lesssim 10^3$ cm^{-3} [Bahcall 1967; Burbidge and Burbidge 1969], although in one case (B2 1225 + 31.7) a much more stringent limit ($n_e \lesssim 2$ cm^{-3}) has been deduced (Boksenberg 1978) using the absence of a line from CII*. The absence of excited fine structure states can also be used to establish a lower limit on the separation, D, between the continuum source (the quasar) and the absorbing system. Typical limits are (Bahcall 1967) D $\gtrsim$ 1 kpc, as long as the transitions that populate the excited fine structrue states are optically thin (Sarazin, Flannery, and Rybycki 1979). Direct infrared transitions are presumably optically thin for clouds close to a quasar, but this condition may not be satisfied for the lines that might provide ultraviolet pumping.

Absorption lines originating on metastable states have not been identified in recent spectroscopic analyses of quasar spectra [see Bahcall 1978 for a detailed discussion of this point]. Such lines (e.g., CIII λ1175.5) are observed in the solar corona and, with P Cyni profiles, in all hot galactic supergiants earlier than BO [Snow and Morton 1976]. The obvious inference, consistent with the results cited above for the fine structure transitions, is that the ambient electron densities are much less in the quasar absorption systems than in the stellar atmospheres or winds in which CIII λ1175.7 is observed.

There are no confirmed observations of variations in the wavelengths (or strengths) of quasar absorption lines. The strongest limit on wavelength variations has been given by Boksenberg and Sargent (1975) who find, for 28 strong lines in PKS 0237-23, individual rms upper limits of $|\lambda^{-1}d\lambda/dt| \lesssim 2\times10^{-5}\text{yr}^{-1}$.

2. THEORETICAL MODELS

A number of theoretical suggestions have been made for explaining the absorption lines observed in quasar spectra. However, the question of where the observed lines originate remains controversial.

E. M. Burbidge (1978) and G. R. Burbidge (1978) have recently reviewed arguments which they believe suggest that many or nearly all of the observed lines arise in material associated with the quasar. They cite especially evidence for an inhomogeneous distribution of redshifts, including "line-locking" and a peak in the redshift distribution at z = 1.95.

I have been an advocate for a long time (see Bahcall and Salpeter 1965; 1966; Bahcall 1971) of the opposite point of view, i.e., that many or nearly all of the observed lines (with $z_{absorption} < z_{emission} - 0.01$) originate in material not associated with the quasar. In this interpretation, absorption arises in material distributed along the line between us and the quasar at cosmologically significant distances from the quasar. The implied (Bahcall and Peebles 1969 and equation 1) smooth redshift distribution can be reconciled with the evidence of apparent redshift inhomogeneit: cited by E. M. Burbidge (1978) and G. R. Burbidge (1978) by noting (see Bahcall 1971) that the reported redshift distribution is sensitive to observational selection effects and the identification procedures.

Many explanations have been advanced of specific sources that might produce absorption at cosmological distances from the quasar. The first such suggestion (made just before absorption lines in quasars were discovered) was that absorption lines would be formed in clusters of galaxies [Bahcall and Salpeter 1965, 1966]. This model was abandoned as incorrect as soon as quasar absorption lines were discovered and the narrowness of the observed lines became apparent. I think this conclusion was premature. Recent discoveries, discussed above, of redshift splittings in optical observations have taught us that the absorption lines may be formed in individual clouds and hence need not have widths comparable to the total velocity dispersion in a cluster. Moreover, recent x-ray observations of Fe emission lines have shown that the intracluster gas is rich in iron and presumably other heavy elements (Mitchell, Culhane, Davison, and Ives 1976; Serlemitsos, Smith, Boldt, Holt, and Swank 1977).

Other absorbers at cosmological distances from the continuum source that have been suggested include the discs of spiral galaxies [Wagoner 1967], dead galaxies [Peebles 1968], large galactic halos [Bahcall and Spitzer 1969], intergalactic hydrogen clouds [Arons 1972; Sargent, Young, Boksenberg, and Tytler 1979], and protogalaxies [Roser 1975].

It is useful in discussing the various theoretical models to rewrite equation (1) in a form that makes explicit the average cross section times number density that is required to produce the observed absorption-line density.

One has:

$$R^2(0)\ N(0) = \left[(1+2q_o z)^{1/2}\ \mathcal{N}(z) \big/ \pi(1+z)\ C/H_o\right] , \qquad (2a)$$

or in convenient units:

$$\left(\frac{R(0)}{100\text{kpc}}\right)^2 \left(\frac{N(0)}{0.003h_{50}^3\text{Mpc}^{-3}}\right) \sim 3h_{50}^{-2}\ \mathcal{N}(z) \big/ 5 \quad . \qquad (2b)$$

Here $\mathcal{N}(z)\Delta z$ is the number of redshifts in the interval Δz from independent absorbers [i.e., counting split redshifts from different clouds in the same absorber as one system]. I have set $\Lambda = 0$ and abbreviated (H_o/50 km/sec Mpc^{-1}) as h_{50}. I use illustrative reference values for the radius (from Bahcall and Spitzer's hypothesis of large galactic halos), for the number density of absorbers (the local number density of observed galaxies from Felten's 1977 renormalization of Scheter's 1976 luminosity function), and $z_{abs} \sim 2.5$, with, for systems containing metal lines, $\mathcal{N}(2.5) \sim 5$ [see, e.g., Young et al. 1979]. In deriving equation (2), I assumed that the effective radius is independent of the observed luminosity of the individual absorbers. This assumption is plausible if, as supposed by Bahcall and Spitzer (1969), the low-density gas that produces the absorption

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lines extends to much greater distances than does the boundary of the region producing detectable optical or radio emission. [Radii that depend upon luminosity are more appropriate if the gas is related to visible stars, see the discussions of models of this kind by Wagoner (1967), Burbidge, O'Dell, Roberts, and Smith (1977), and Weymann, Williams, Peterson, and Turnshek (1979), all of whom scale the effective radius with visible luminosity.]

The original estimate of $R \sim 10^2$ kpc still seems to be of the right order to explain the observed number of absorption systems that produce detectable lines from heavy elements, if we adopt for N(0) the observed number density of (reasonably bright) galaxies.

The Lyman-alpha systems, however, are much more numerous. For them (using the number densities reported by Sargent et al. 1979):

$$\left(\frac{R_{Ly-\alpha}(2.5)}{100\ \text{kpc}}\right)^2\left(\frac{N_{Ly-\alpha}(0)}{0.003\text{Mpc}^{-3}}\right) \sim 35\ h_{50}^{-2} \quad . \tag{3}$$

Arons (1972) and Sargent et al. (1979) have suggested that the Ly-α systems are due to intergalactic hydrogen clouds.

I would like to propose a different interpretation of the Ly-α systems, i.e., extremely large hydrogen halos. These halos may be associated with either galaxies or clusters of galaxies. It is possible that essentially all galaxies, even those not luminous enough today to appear in the observed local samples of galaxies, once had large gaseous halos composed largely of hydrogen. This may require, in the above notation, $R_{Ly-\alpha} \sim 200$ kpc and $N_{Ly-\alpha}(0) \sim 0.01\ \text{Mpc}^{-3}$. Many other combinations of R^2 and N are, of course, possible, since only R^2N is determined at present from the observations.

It is also possible that the Ly-α halos are associated with clusters of galaxies. Illustrative parameters not inconsistent with available observations (N. Bahcall 1977) are: $R_{\text{cluster}}(0) \sim 30$ Mpc and $N_{\text{cluster}}(0) \sim 7 \times 10^{-7}\ \text{Mpc}^{-3}$.

Both of the "large Ly-α halo" hypotheses described above can be tested by ST observations that are discussed in § V. Both suggestions are consistent with the observation (Sargent et al. 1979) that the Ly-α systems exhibit less small-scale splitting than do the metal (i.e., CIV) lines. In the explanations proposed here, the Ly-α lines arise in a region outside that which produces the metal lines. This picture is also consistent with the idea (see Sarazin 1979; Bahcall 1975) that the heavy elements in the halo are produced by

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supernova remnants in the Galaxies.

3. EXPECTED STRONG LINES

The ST observatory will make possible high resolution spectroscopic observations, a region that is inaccessible with ground-based telescopes, from 1100 Å to 3200 Å. This wavelength range is particularly important because many of the strongest absorption lines have rest wavelengths in this region. In addition, one will be able to observe for the first time very short wavelength absorption lines (300 Å $\lesssim \lambda \lesssim$ 900 Å) in the spectra of very large redshift objects ($z \gtrsim 3$).

Table II shows the strongest lines that may be expected to occur. This list is essentially the same as was used by Bahcall (1968) to identify absorption-line systems of large redshift quasars (with the addition of the MgI λ 2852.97 and MnII λ 2576.88 lines that have been observed in some small-redshift quasars). (The original line list was constructed by determing which transitions would be strongest assuming: solar abundances; estimated transition probabilities; and equilibrium populations of initial states in a low density gas. The fact that this list accounts well for the observed lines indicates that the initial assumptions are not grossly incorrect.)

Table III lists some important short wavelength lines that can be searched for in the spectra of objects with appreciable emission redshifts. The lines in this table have been selected in much the same way as were the longer wavelength lines in Table II.

4. COSMOLOGICAL VERSUS INTRINSIC HYPOTHESES

The cosmological and intrinsic hypotheses for the origins of the absorption lines predict spectra with qualitatively different appearances.

The cosmological hypothesis predicts (Bahcall 1971, 1978) that there will be many fewer absorption lines in the far ultraviolet spectrum ($\lambda \lesssim$ 2300 Å) of nearby quasars ($z_{em} \ll 1$) than in the spectra of large redshift quasars <u>observed at the same rest wavelengths</u>. Table II shows that the strongest lines that have been observed in the visible spectra of large redshift quasars can be studied conveniently with ST in the spectra of small redshift quasars in the far ultraviolet (1100 Å $\lesssim \lambda \lesssim$ 2300 Å).

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Table II. Lines Most Likely to Appear in the Range 1100 Å ≤ $\lambda_{\text{observed}}$ ≤ 3200 Å.

Ion	λ_{Vacuum} (Å) (λ>1215.67Å)	Ion	λ_{Vacuum} (Å) (λ≤1215.67Å)
Mg I	2852.97	Si III	1206.51
Mg II(1)	2803.53	Si II	1193.28
Mg II(2)	2796.35	Si II	1190.42
Fe II	2600.18	Fe II	1144.95
Mn II	2576.88	Fe III	1122.53
Fe II	2586.64	N II	1083.99
Fe II	2382.76	O VI(1)	1037.63
Fe II	2374.46	C II	1036.34
Fe II	2344.21	O VI(2)	1031.95
Aℓ III(1)	1862.78	H I(0.2)	1025.72
Aℓ III(2)	1854.72	Si II	989.87
Aℓ II	1670.81	C III	977.03
C IV(1)	1550.77	H I(0.07)	972.54
C IV(2)	1548.20	H I(0.03)	949.74
Si II	1526.72	Some Excited State Fine Structure Lines	
Si IV(1)	1402.77		
Si IV(2)	1393.76	Si II	1533.45
C II	1334.53	C II	1335.70
Si II	1304.37	O I	1304.86
O I	1302.17	Si II	1264.76
Si II	1260.42	Si II	1194.50
N V(1)	1242.80	N II	1084.58
N V(2)	1238.82	N II	1085.55
H I(1)	1215.67	N II	1085.70

The number of absorption redshifts expected in the spectrum of a quasar with $z_{\text{emission}} \ll 1$ can be computed simply on the basis of the cosmological hypothesis. The predicted number is $\mathcal{N}(0)z_{\text{em}}$, where $\mathcal{N}(z)dz$ is (as defined earlier) the number of redshifts in the interval Δz. The value of $\mathcal{N}(z\sim2.5)$ has been determined by the many available observations of large redshift quasars and is, for the Ly-α systems, $\mathcal{N}_{\text{Ly-}\alpha}(z\sim2.5) \sim 60$ (see, e.g., Sargent et al. 1979). Note $\mathcal{N}(0) \sim (1+2q_0z)^{1/2}\,\mathcal{N}(z)/(1+z)$. For 3C 273, one expects $\lesssim$ 4 Ly-α absorption systems on the basis of the cosmological hypothesis. If the product NR^2 was larger, as seems likely, at earlier times [i.e., the bracketed term in equation (1) is less than unity for large z], then the inequality applies.

On the other hand, if most of the absorption occurs in material intrinsic to the quasars, then a similar number of absorption systems ought to be present in the spectra of both small and large redshift quasars. In many cases, the observed number of Ly-α systems is of order 10^2. Thus the intrinsic hypothesis requires more than an order of magnitude more absorption systems for small emission-line redshift quasars than the cosmological hypothesis predicts.

There is another qualitative difference between the cosmological and intrinsic hypotheses. No blueshifts ($z_{abs} < 0$) are possible on the cosmological hypothesis. Blueshifts are natural and expected, in quasar spectra with z_{em} relatively small, on the intrinsic hypothesis. Let $R \equiv (1+z_{em})/1+z_{abs})$, where z_{em} and z_{abs} are, respectively, emission and absorption redshifts. The apparent ejection velocity is $\frac{V_{ejection}}{c} = \frac{R^2-1}{R^2+1}$.

The maximum ejection velocity that can be achieved for positive z_{abs} is given by substituting $R_{crit} = (1+z_{em})$ in this relation:

$$\frac{v_{ejection}(z_{abs}\geq 0)}{c} \leq \frac{(1+z_{em})^2 - 1}{(1+z_{em})^2 + 1} \quad . \tag{4}$$

For 3C 273, equation (4) yields $v_{ejection} \leq 0.15c$ for $z_{abs} \geq 0$. Thus for nearby quasars like 3C 273, the intrinsic hypothesis implies that many or most of the absorption lines (all with $v_{ejection} \gtrsim 0.2c$) should be blueshifted!

The decision between the intrinsic and cosmological hypotheses can be made definitively with high-resolution, far ultraviolet observations of nearby quasars using the Space Telescope High Resolution Spectrograph. An appropriate complete sample can be defined as follows: all 3CR quasars with $z_{em} < 0.4$, $m_V < 18^m$, $\delta > -5^o$, and with intrinsic brightnesses one magnitude or more brighter than the brightest cluster galaxy (with $q_o = 0$ evaluated at $\lambda_o = 2500$ Å). There are six members of this sample: 3C 48, 3C 249.1, 3C 273, 3C 277.1, 3C 323.1 and 3C 351.

A search for Lyman-alpha halos can provide a different test for the origin of quasar absorption lines. The basis for this test has been discussed by Goldreich and Sargent (1976), Davidson (1977), Sargent and Boroson (1977), and Davidson (1979); these authors have also presented observational results on the absence of halos for some large redshift quasars.

The basic idea may be stated simply. Many high-redshift quasars show appreciable absorption of the Lyman continuum (see Osmer 1979), often at the redshift corresponding to an absorption system. If the absorption occurs locally (i.e., the absorption is "intrinsic"), then of the order of one

Lyman-alpha photon will be reemitted for each absorbed Lyman continuum photon. These reemitted photons may be detected as a "halo" if the absorbing clouds are located at observable distances from the quasar. Estimates of the expected fluxes are given in the above-cited references.

Abortive searches for Lyman-alpha halos have been carried out for several large redshift quasars on distance scales that correspond to between 10 kpc and 500 kpc at the quasar. Space Telescope observations will allow much smaller radii, r_o, to be explored:

$$r_o \approx 0.46\left(\frac{\theta}{0.1''}\right)\left(\frac{z_{QSO}}{0.16}\right) h_{50} \text{ kpc} \quad . \tag{5}$$

The relatively small sky-correction will represent an additional advantage (for this problem) of ST observations over ground-based experiments.

It will be particularly interesting to observe at the smallest possible distances, r_o , quasars that have broad absorption lines (analogous to PHL 5200 and Q 1246-057), which most observers have interpreted in terms of material flowing out of the quasar.

The crucial instrumental requirement will be appropriate interference filters for the cameras so that redshifted Lyman-alpha lines can be observed.

5. ABSORPTION SPECTROSCOPY

Distant sources of ultraviolet radiaion can be used as continuum probes to search for gas in known relatively - nearby systems. If any appreciable amount of gas is present (column density of HI $\gtrsim 10^{13}$ cm^{-2}), absorption lines will be produced by the resonant transitions listed in Table II and will be observable in the ultraviolet with ST spectrographs. I discuss next several classes of objects whose gaseous content we would very much like to study in this way.

5.1 Clusters of Galaxies

Rich Abell clusters may have halos with radii as large as 10 Mpc and a local number density of order 6×10^{-7} Mpc^{-3} (N. Bahcall, 1977). Thus the product $R^2N(0)$ may be as big for Abell clusters as it is for the postulated large galactic halos (cf. equation 2b). Independent of the contribution of clusters of galaxies to the known large-redshift absorption line systems, (see section 2 for a discussion of this possibility), one would like to study the distribution, composition, extent, and physical characteristics of moderate-temperature gas in clusters of galaxies.

Lists of quasars behind clusters of galaxies have been compiled, for this purpose, by Bahcall (1969a,b). More recently, Peterson (1978) has searched unsuccessfully for 21 cm absorption in the radio spectra of quasars behind Abell clusters. ST observations should permit searches for Ly-α lines that are of order 10^7 times more sensitive than the 21 cm studies. Moreover, one can also investigate the presence of moderately-ionized heavy elements using the lines listed in Table II.

5.2 Large Galactic Halos

Quasars can be used also to study the gaseous content of large ($\gtrsim$ 100 kpc) galactic halos of nearby galaxies. There are many galaxies within 10 Mpc distance of our Galaxy for which the postulated large galactic halos would subtend at earth full angles of several degrees or more. It will be easy therefore to locate by standard techniques relatively bright quasars behind the supposed large galactic halos and test for the present existence of gas in these halos. The strong ultraviolet lines listed in Table II will produce observable absorption lines at the redshifts of the nearby galaxies if the corresponding ions are, as postulated (Bahcall and Spitzer 1969), present in large halos.

The galactic halos that may be observed in nearby galaxies might be different in size, chemical composition, and ionization characteristics from the corresponding galactic halos at large redshifts. For example, the evolution of massive stars may have polluted the nearby halos. Also, the recombination time at the illustrative temperatures and densities considered by Bahcall (1975) is less than the Hubble time. In the model proposed by Sarazin (1979), supernovae remnants produced during the formation of a galaxy, absorption systems are much more likely at large redshift than small redshift.

Fortunately, the study of the gaseous content of large halos of nearby galaxies is interesting in its own right, irrespective of its possible connection with the observed absorption lines in large redshift quasars. The physical conditions in the gas of the halos may be an important clue in the study of galaxy formation. The composition of the gas will indicate to what extent stellar evolution and supernova explosions have contributed processed material to the halos.

5.3 Ly-α Systems

The ST spectrographs can be used to study the absorption systems shortward of the Ly-α emission line in relatively bright, small (emission-line) redshift quasars. The observed spectra may be somewhat less crowded than for large redshift quasars.

It should be possible to test directly the Lynds' (1971) interpretation of large redshift spectra (in terms of Ly-α lines) by searching for the other members of the Lyman series in the spectra of relatively bright quasars (e.g., 3C 273). It will also be important to test whether or not the observed Ly-α lines are "split" into subsystems separated by $\sim 10^2$ to 10^3 km/sec.

The Ly-α clouds may correspond to objects with observable radio or optical counterparts. Sensitive radio and optical studies of small-redshift Ly-α absorption systems will be of great diagnostic value.

6. SPECIAL PROJECTS

In this section, I will discuss five special projects, each (I believe) of great interest.

6.1 The D/H - ratio

The D/H - ratio is of cosmological importance (see Wagoner 1973) if it can be demonstrated that the observed ratio is a constant (or the variation can be understood in terms of local environmental effects). The conventional Big Bang cosmology predicts that D/H is independent of redshift for all measurable redshifts.

It should be possible to observe the D/H ratio at absorption redshifts that are sufficiently large so that several Lyman lines are observable (for consistency checks). Thus for $z_{abs} \gtrsim 0.15$, Lyman lines through Ly-δ are redshifted into the region accessible with ST spectrographs ($\lambda \gtrsim 1100$ Å). The separation of the Lyman lines for deteurium and hydrogen is $\Delta\lambda_{rest} \cong 0.3$ Å. In principle, it is possible and important to try to measure the D/H ratio with ground-based observations at large z_{abs}, but small z_{abs} offer advantages that include the possibility of using brighter sources and less crowded spectra.

The small z_{abs} analogues of the Ly-α systems observed at large z_{abs} may be especially suited to the determination of D/H. For these systems, the saturation of the Lyman lines, the contamination by other lines, and the disentaglement of the separate cloud complexes may produce relatively few complication. One will want also to try to measure the D/H - ratio

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in gas within clusters of galaxies and in large galactic halos.

Many of the appropriate procedures and complications have already been discussed by Vidal-Madjor et al. (1977) and Rogerson and York (1973) in connection with their determinations of D/H in interstellar gas illuminated by nearby bright stars.

6.2 He/H

In large redshift quasars, the helium resonance lines will be observable, He I λλ 584.3, 537.0, 522.2 Å at $z \gtrsim 1.1$ and He II λ 303.9 Å (and 256.4 Å) at $z \gtrsim 2.6$ (and 3.3). It may be possible, therefore, to determine the helium to hydrogen ratio in some large-z objects by studying absorption systems that show He I and He II absorption as well as several of the hydrogen Lyman lines. The ionization of hydrogen can be estimated approximately from the relative strengths of observed lines from other elements, e.g. lines from O I, O II, and O III (see Tables 2 and 3) or N I λ 1134.6 Å and N II 1084 Å. Studies of systems with $z_{abs} \gtrsim 2.6$ will be especially interesting since for them one may be able to measure the strengths (or upperlimits) of lines from H I, He II, O I, O II, and O III (as well as N I and N II).

6.3 Other Short Wavelength Lines in Large z_{abs} Systems

Table III suggests a number of other important projects that can be accomplished by studying the very short-wavelength lines in large z_{abs} systems. The C IV resonance line at 312.4 Å is of special interest. C IV doublets at λλ = 1548.2 Å, 1550.8 Å have been used as the basis for identifying many of the absorption systems containing metals in known large redshift quasars. The line at 312.4 Å is the 2s to 3 p transition corresponding to the 2s to 2 p doublet at 1549 Å (the 312.4 line is actually a doublet with a splitting of 0.04 Å). Searches for the C IV line at 312 Å in large redshift quasars ($z_{em} > 2.5$) will be of great importance in testing the validity of the many identifications based on the longer-wavelength C IV doublet.

Note also that one will be able to study the detailed ionization structure of several important elements by combining observations of the lines in Tables 2 and 3. In large z_{abs} systems, this will be possible by observing lines in Table II with ground-based instruments and lines in Table III with ST spectrographs. Of special interest are systems containing N I - N V, O I - O VI, and Ne I - Ne VIII.

Table III. Some Shortwavelength (300 Å < λ < 950 Å) Absorption Lines That Are Expected To Be Strong

Ion	λ_{vacuum} (Å)	Ion	λ_{vacuum} (Å)
He I	584.33, 537.03, 522.21	Ne IV	543.88, 542.08, 541.12
He II	303.80	Ne V	586.42, 480.41, 357.196 (+ ex. f.s.)
C IV	312.43		
N II	915.60, 644.62 (+ ex. f.s.)	Ne VI	558.59, 433.18, 401.14, 399.82, (+ ex. f.s.)
N III	989.79, 763.34, 685.00, 451.87, 374.20 (+ ex. f.s.)	Ne VII	465.22
		Ne VIII	770.40, 780.32
N IV	765.14	Na II	376.38, 372.07
O II	834.46, 833.33, 832.75, 539.09, 539.55, 539.85, 430.1	Na III	378.14
		Na IV	410.37, 408.68
		Na V	463.3, 461.05, 451.9
O III	832.93, 702.33, 507.39, 305.60 (+ ex. f.s.)	Na VI	489.57, 414.35, 311.93
		Mg IV	321 (+ ex. f.s.)
O IV	787.71, 608.40, 554.07, 553.33 (+ ex. f.s.)	Mg. V	353.09, 351.09
		Mg. VI	403.32, 400.68, 399.29
O V	629.73	S V	786.48
Ne I	743.70, 735.89	Fe V	536.4 (+ ex. f.s.)
Ne II	460.73 (+ ex. f.s.)		
Ne III	489.50, 488.10 313.05 (+ ex. f.s.)		

6.4 Astrophysical Analyses

ST observations will make possible detailed studies of the characteristics of the gas that produces the known absorption systems, as well as the gas that will (hopefully) be identified with the large halos of galaxies and clusters of galaxies. The wide range of elements and ion states that are accessible to ST spectrographs is evident from the lists given in Tables II and III.

Chemical abundances, ionization conditions, densities, and column densities can all be derived by standard models of analysis. New insights into the evolution of galaxies and clusters of galaxies should result from the study of gas that (I expect) will be discovered in the halos of galaxies and clusters of galaxies. The techniques that have proven valuable in the study of interstellar gas in the Galaxy will be of great importance for studies of the intergalactic gas accessible to ST. The existence of "splitting" among known redshift systems suggests that multi-cloud models of the absorption systems will be necessary in the analysis. An exemplary multi-cloud study has been described recently by Boksenberg, Carswell, and Sargent (1979), in their analysis of (necessarily limited) ground-based observations of a $z = 0.4$ absorption system in the spectrum of Pks 0735 + 178.

There may well be molecular hydrogen bands (Lyman bands ~ 1108 Å and Werner bands ~ 1008 Å), or dust absorption features in some cooler absorption systems. It will be important to search for H_2 and dust features in order to delimit further the physical processes and conditions.

6.5 Evolution of Absorption Systems

The evolution of absorption systems can be measured by comparing the spectra of a representative sample of large-redshift quasars observed in the visible with ground-based telescopes to the spectra of a similar sample of small-redshift quasars observed in the ultraviolet with ST. The observations should be carried out by observing for both the small and large redshift samples the same lines at the same resolution and sensitivity in equivalent width in the rest frame of the quasars. These studies will provide unique information about the evolution of the gas revealed by quasar absorption studies.

VII. A SAMPLE OBSERVING PROGRAM

An illustrative observing program based on the discussions of § 5 and § 6 is shown in Table IV. In compiling Table IV, I have assumed that all spectroscopic observations were carried out at a resolution of $R = \lambda/\Delta\lambda = 2 \times 10^3$, unless specified otherwise. At this res-lution, it will take (see Bahcall and O'Dell 1979 and references quoted there) of order 20 minutes to obtain a spectrum of a $V = 17^m$ object, with $F_\nu \propto \nu^{-1}$, at a signal to noise ratio of 10. The total telescope time required to complete the initial phases of all the projects listed is of order 17 days, if the time spent integrating on an astronomical object is of order one-third the allocated time on the telescope. Most of the time would be spent using the HRS. A resolution of $R = 2 \times 10^3$ for a small z_{em} object corresponds to resolution in quasar frame of order 1.8 Å. This is to be compared with the highest-resolution ground based studies, which are typically 1 Å in the observed frame or of order 0.3 Å in the quasar's frame. Thus the best FOS resolution, $R = 1.2 \times 10^3$, is not sufficient for a number of the projects that I have described.

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Table IV. A Sample Observing Proposal

(Telescope time = 3 × Observing Time, 1 = 2 hr. for $V = 17^m$, $R = 2 \times 10^3$, S/N = 10)

Observation	Instrument	Initial Number of Objects	Total Telescope Time (days)
Number of Absorption Systems in Small $z_{emission}$ Spectra	HRS (FOS)	6	1 1/2
Lyman-α Halos	FOC	10	6
Halos of Cluster of Galaxies	HRS, FOS	15	4 1/2
Galactic Halos	HRS	20	6
Ly-α Systems			
Other Lines	HRS, FOS	3	3
Splitting	HRS ($R = 2 \times 10^4$)	3	12
D/H	HRS ($R = 2 \times 10^4$)	5	48
He/H	FOS, HRS	5	3
Astrophysical Analyses	HRS ($R = 2 \times 10^4$)	3	12
Evolution	FOS, HRS	5	3
Total			99

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My own guess is that the above estimate of the total required telescope time is probably optimistic by a factor of two or more. I have not taken account of the fact that, among other things, many instruments perform in space less well than their design specifications.

Nevertheless, the amount of important science that potentially can be performed in a few months of telescope time using the Space Telescope is awesome.

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DISCUSSION

Boksenberg (Discussion leader): I would like to make some supporting comments to Bahcall's excellent presentation.

First, we may distinguish between the absorption systems which clearly are intrinsic to the QSO or Seyfert galaxy and the others. The intrinsic systems are either very broad in velocity profile (PHL 5200 and Q1246-057 are interesting examples of this class) or show narrow-lined absorption from metastable levels which may also be variable (Markarian 231, NGC 3516 and particularly NGC 4151 - note these are all Seyferts). In no QSO yet observed is there absorption other than from levels of the ground state and in no case is variability observed. Again, unlike the bulk of the narrow-lined QSO absorption systems, these intrinsic systems are relatively close to the parent objects and there is no problem of enormous mass or energy requirements to explain their presence.

Next, we may identify those of the other systems which clearly are not intrinsic to the QSOs. Such a case is the absorption system observed in 3C232 at the same redshift as the nearby galaxy NGC 3067 in the plane of the sky. This system contains not only hydrogen (21-cm observations) but CaII (optical observations) and MgII, FeII (UV observations with IUE). The fact that the line of sight passes far outside the optical extent of the galaxy demonstrates that the effective cross-section of galaxies as manifested by absorption lines in QSO spectra is very large and indeed this is consistent with the observed frequency of such systems. That another similar case has now been observed (PKS 2020-370 and galaxies in Klemola 31) considerably strengthens this case. Yet another case of very direct support for this comes from the observation of an absorption system due to an intervening galaxy in the IUE spectrum of 3C273. In this case, the galaxy is our own. What is particularly interesting, and indicative, is that no other absorption lines are observed than those at zero redshift and that CIV is strong. The latter fact and the deduction that the absorption must be produced in the outer galactic halo, is then in conformity with the common observation of CIV in QSO spectra because the relatively large cross-section presented by such haloes of galaxies in line to the QSOs would give strong emphasis to its detection (CIV is not observed to be strong in the disc of the Galaxy).

Finally, I would like to touch on the question of the Lyman-α absorption lines. In the work by Sargent et al. described by Bahcall in his talk, we find a clear distinction between those absorption systems containing heavy elements and those showing only hydrogen lines. The heavy element systems show fine velocity structure, generally up to a few 100 km s^{-1} as might be expected for galactic haloes, but the "pure" hydrogen systems do not. We also find that the hydrogen systems are

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identical in their properties among all QSOs we have studied and show no evidence at all of clustering such as is demonstrated for galaxies. We conclude that these hydrogen systems, in contrast to the heavy element systems, represent cosmologically distributed primordial material, unassociated with intervening galaxies and are probably intergalactic clouds.

Savage: Our high resolution IUE observations of bright stars in the Magellanic clouds enable us to study the details of the absorption lines produced in the Galactic halo with 70 times the spectral resolution of the IUE spectrum of 3C273. We find broad strong absorption components having velocities $0 \lesssim v \lesssim 150$ km s^{-1} associated with ions of low (OI, SiII, CII) and high (SiIV, CIV) ionisation. NV absorption with the same profile has not been observed. These absorption features bear a remarkable resemblance to what one sees in QSO absorption spectra.

Burbidge: The OI absorption is very strong in those spectra, much stronger relative to CIV, for example, than in any QSO spectrum I've seen. Is it equally strong in all your Magellanic Cloud stellar spectra ? In QSO absorption spectra at high redshifts, CIV is the most characteristic and most frequently seen feature.

Savage: All stars we have looked at in the Magellanic Clouds show strong OI. Our interpretation of the coexistence of the different stages of ionisation is that there is a hot medium embedded in which there are clouds of cooler material.

Sargent: A possible explanation of the point noted by Dr Burbidge is that at large redshifts, the haloes of galaxies are more highly ionised than they are at the present epoch because of the very much greater intergalactic flux of ionising radiation due to quasars. The increase in ionising flux is roughly $(1+z)^9$, 6 powers for the evolution of the quasar population and three powers for the volume factor. Thus, haloes are expected to be much more highly ionised at redshifts of 2 than they are now.

Burbidge: I shall not present any results or describe any programs underway with ground-based telescopes because I'd like to mention two specific kinds of observations needing ST. I'll not get into the discussion of location and origin of absorption features in QSO spectra because I'd rather hear Ray Weymann say something about the results of the survey by Weymann, Williams, Peterson, and Turnshek. This survey contains many objects, with homogeneous material.

The first ST observation I'd like to mention is to observe Ly α absorption in the lower-redshift lower-ionization systems showing MgII and FeII from the ground, where Ly α is only reachable by ST, and where Arthur Wolfe and colleagues are searching for 21-cm absorption.

Comparison of the strengths of Ly α and 21-cm can yield the spin temperature of the absorbing cloud, and hence bear on its location with respect to the energy source. The only case so far where he's been able to detect 21-cm absorption in such a system is 1331+170, and the spin temperature is high, 1000 K. I'd like this to be done for as many of the MgII/FeII absorption systems as possible.

Second, I'd like to comment on the QSOs with supernova-like absorptions, very broad, which Alex Boksenberg referred to. These are turning out to be more frequent than thought previously. They are characteristically high ionization systems; in the prototype PHL 5200 the continuum drops right down to essentially zero shortward of Ly α absorption, yet somewhere the continuum must pick up and provide high-energy photons, if photoionization is the mechanism. With ST we can follow these out into the UV, and also look to see what happens at the HeI resonance line.

Weymann: It seems very clear to me now that we are dealing with several different classes of absorption lines. Which class dominates depends upon the spectral and redshift ranges in which one looks. I identify 4 classes of absorption systems: (i) The supernova-type of absorption profile which is characterised by the absorption troughs seen in PHL 5200, (ii) halo-type absorption systems which are characterised by the presence of metal-enriched material, (iii) "primordial" Lyman-α absorption systems which appear to be relatively uncontaminated by heavy elements and (iv) absorption systems with small blue and redshifts with respect to the redshift of the quasar. This last class is most often seen as absorption features superimposed on the CIV emission line. These features are seen just as often to the red as to the blue of the line centre. i.e. literally interpreted the material is just as likely to fall in as be ejected from the quasar. My preferred explanation is that these absorption systems are clouds moving backwards and forwards with velocity dispersion which can be measured from the observations. Typically velocity dispersions of 700-1000 km s^{-1} are found which are typical of rich clusters of galaxies and not of small groups and this is a difficulty. One would like now to measure these features in low redshift quasars, to measure the very much weaker CII lines as well and directly see if we can see these features in objects which are close enough to make direct studies of their environments.

Morton: How many cases are there where halo absorption of QSO radiation at either 21 cm or CaII H and K has been searched for and not found ?

Boksenberg: I have been involved in searches in the spectra of 3QSOs and we have had success in two cases. The third case is not yet fully analysed.