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THE ABSORPTION LINES IN QUASI-STELLAR OBJECTS

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ABSTRACT

The gas producing the absorption lines seen in the spectra of some high-redshift QSOs can be physically related to the QSO or it can be located by chance on the line of sight to the quasar. If it is physically adjacent to the quasar, it will be photoionized and the observed pattern of absorption lines can be produced. However, an ejection model has great difficulty explaining the sharpness of the observed absorption features compared with the large difference between absorption and emission redshift. A model in which the gas is part of the intergalactic medium or the extreme outer parts of galaxies is discussed. In this case, the gas may be collisionally ionized. To produce the observed ions C IV, N V, and O VI in absorption, the temperature must be about 10^5 ° K. For solar metal abundance, it is then surprising that Lα is the strongest line in absorption. An attempt to enhance the Lα absorption by adding a cool region in which hydrogen is predominantly neutral fails as this region is photoionized by radiation from the hot region. Therefore, the metal abundance in the absorbing gas must be less than solar if the gas is not photoionized.

Subject headings: abundances — intergalactic medium — quasi-stellar sources or objects

I. INTRODUCTION

There are two hypotheses for the location of the gas producing the absorption lines observed in the spectra of several high-redshift QSOs. The gas may be physically related to the QSO, perhaps ejected from it, or it may be in the intergalactic medium, far from the QSO, in which case it is only coincidence that it is in the line of sight to the quasar. Although very little is known about the physical properties of the absorbing clouds, certain inferences can be made about these regions from the line spectra which they produce when illuminated by a quasar. Little reliance can be placed on the presence or absence of any particular weak absorption feature in a particular QSO because of the difficulty of identifying such features. However, in § II we use the general pattern of lines which are present to place constraints on the density and ionization of the absorbing region. We show in § III that if photoionization prevails, then the absorbing region must be located within 1 Mpc of the source of ultraviolet radiation. Since the radiation-density requirement is very high, this source cannot be an energetic galaxy, but rather must be the QSO itself. Several lines of evidence suggest that the close proximity required to photoionize the absorbing region leads to other difficulties with such a model. In § IV we consider a model in which the absorbing regions are located far from the QSO. We show that under these circumstances, where the region is collisionally ionized, the fact that Lα is in general the strongest absorption line observed in QSO spectra places a significant upper limit on the metal abundance of the absorbing region. This requirement that the metal abundance in such a region be less than solar is an important datum in understanding the chemical evolution of the Universe.

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II. THE GENERAL PATTERN OF LINES OBSERVED IN QSOS

Bahcall and Joss (1973) have summarized the redshifts that have been found in the five QSOs with multiple absorption redshifts. In each QSO up to eight redshift systems have been identified. In accordance with the search procedure used by Bahcall and Joss, each redshift system contains Lα and Lβ, when they are redshifted into the observable wavelength region. In addition, the resonance lines of the ions of the more astrophysically abundant atoms such as C II, C III, C IV, N V, O VI, Si II, and Si IV are present. Often a wide range of ionization is observed within any one redshift system, and also the general degree of ionization of each system $\{z_{\mathrm{abs},}\}_i$ can be characterized as high (C IV, N V, O VI present) or low. There is no correlation between $\{z_{\mathrm{em}} - z_{\mathrm{abs},i}\}$ and the degree of excitation of the absorption system $z_{\mathrm{abs},i}$ when the redshift systems of each individual QSO are considered as a group. The emission redshift is always greater than the absorption redshift, and there are no known absorption systems that are blueshifted with respect to the observer. The largest value of $z_{\mathrm{em}} - z_{\mathrm{abs}}$ given by Bahcall and Joss (1973) is 1.6 for PHL 938.

The most surprising feature of the absorption spectra is the sharpness of many of the lines. The observations of Morton and Morton (1972) show that when the lines observed with the Princeton television system are fitted by Voigt profiles, the total velocity is less than 80 km s^{-1} in all cases, which corresponds to a temperature of about 4×10^5 ° K, if the dispersion velocity is zero. Therefore V(dispersion)/V(recession) $\leqslant 10^{-3}$. If we assume that the velocity dispersion is an upper limit to the cosmological expansion over the absorbing region, then using a Hubble constant of 50 km s^{-1} Mpc^{-1} we obtain a maximum size of 1 Mpc for the region. Furthermore, the cores of the narrow lines are very deep, almost reaching zero residual intensity, so that the absorbing region must completely cover the emitting QSO as seen by the observer. No detectable variations of the strengths and wavelengths of the absorption lines have been seen over a time span of at least a year.

No lines originating from excited fine-structure states or metastable states have been seen. This places an upper limit on n_e of 10^2 per cm^3 (Bahcall and Wolf 1968). Furthermore, no neutrals aside from hydrogen have been observed. Morton and Morton (1972) derive column densities for the absorption lines of PHL 957 which we may take as typical; $N_{\mathrm{H\,I}} \simeq 5 \times 10^{14} - 5 \times 10^{15}$ per cm^2 (with the exception of the extremely broad Lα for $z = 2.3099$, a low-ionization absorption system), $N_{\mathrm{C\,IV}} \simeq 10^{14}$ per cm^2; $N_{\mathrm{Si\,IV}} \simeq 5 \times 10^{13}$ per cm^2; $N_{\mathrm{N\,V}} \simeq 10^{14}$ per cm^2. We also have an upper limit to $N_{\mathrm{H\,I}}$, since for the very high redshift QSOs, we can see beyond the Lyman limit, and know that the optical depth in the Lyman continuum is not large. Hence we have an upper limit on the column density of neutral hydrogen of about 5×10^{17} per cm^2.

Thus our final set of constraints for the high ionization absorbing regions are:

$$5 \times 10^{14} < N_{\mathrm{H\,I}} < 5 \times 10^{15} \text{ per cm}^2\,, \qquad n_e < 10^2 \text{ per cm}^3\,,$$

$$N_{\mathrm{C\,IV}} \approx 10^{14} \text{ per cm}^2\,, \qquad N_{\mathrm{Si\,IV}} \approx 5 \times 10^{13} \text{ per cm}^2\,, \qquad N_{\mathrm{N\,V}} \approx 10^{14} \text{ per cm}^2\,.$$

Note that the total mass of the gas per absorbing region is approximately

$$M = \frac{10^{18}}{(n_e/10^2)^2} \cdot \left(\frac{n_{\mathrm{H\,II}}}{n_{\mathrm{H\,I}}}\right)^3 \text{ grams}\,.$$

Unless $n_e < 10^{-4}$ per cm^3, this is an insignificant mass with regard to the problem of closing the universe. In § IV we derive a lower limit to n_e of 10^{-5}–10^{-6} per cm^3, so that we cannot rule out the possibility that the clouds are rather massive.

III. A PHOTOIONIZATION MODEL

Williams (1967) and Tarter, Tucker, and Salpeter (1969) have calculated the photoionization produced by a strong ultraviolet source with varying spectral energy distribution. Tarter (1972) kindly repeated this calculation for a synchrotron source with spectral index of -1.0. In both cases, in order to produce a reasonable amount of C IV, ζ must be about 0.1, where $\zeta = L/nr^2$, and L is the luminosity (ergs s^{-1}) beyond the Lyman limit, n (cm^{-3}) is the total number density, and r (cm) the distance from the source. At that ζ, $n_{\mathrm{H\,I}}/n_{\mathrm{H}} = 0.005$. This means that the ratio of the strength of absorption of Lα to the C IV doublet will be given by

$$\frac{R_{\mathrm{L}\alpha}}{R_{\mathrm{C\,IV}}} = \frac{gf_{\mathrm{L}\alpha}}{gf_{\mathrm{C\,IV}}}(5 \times 10^{-3})\frac{n_{\mathrm{H}}}{n_{\mathrm{C}}},$$

which for solar C/H is about 25. Thus a photoionization model can easily explain the observed fact that Lα is the strongest absorption line. Furthermore, the range in ionization observed over the absorption spectra can be produced by slight variations in the spectral energy distribution of the QSO and in the gas distribution around it.

Let us consider the value of r which this implies for a QSO as the ionizing source. An energetic QSO emits 10^{56} photons s^{-1} in the Lyman continuum (Oke, Neugebauer, and Becklin 1970), or 10^{45} ergs s^{-1} in the ultraviolet. Using a value of 10^{-3} for n (which implies a diameter of the absorbing region of about 2 kpc for solar C/H, and 10 percent of C being C IV) we obtain

$$r_{\mathrm{max}} = 1\ \mathrm{Mpc}\,(n/10^{-3})^{1/2}\,.$$

The luminosity of a typical Seyfert galaxy is about 10^{-4} that of a QSO; hence r becomes 10 kpc. This means that a Seyfert galaxy cannot reach the necessary level of photoionization except within the galaxy itself. As Seyfert galaxies are rather rare, the probability that a line of sight to a distant QSO passes through the outer parts ($r \approx 10$ kpc) and not the nucleus of even one Seyfert galaxy is very low. Therefore, if the gas producing the absorption lines in QSO spectra is to be photoionized, it must be located in the immediate vicinity of a QSO ($r \lesssim 1$ Mpc), and has probably been ejected from the QSO.

The principal difficulty with such an ejection model as proposed by Mushotzsky, Solomon, and Strittmatter (1972) is the sharpness of the lines, and the lack of correlation of degree of ionization of the redshift system with ($z_{\mathrm{em}} - z_{\mathrm{abs}}$). Without ejection from the QSO, it is difficult to see how all the absorbing gas can be constrained to within 1 Mpc of a QSO, and any gas farther away is not sufficiently photoionized that the ions seen in its absorption spectrum will not agree with those observed in the highly ionized absorption redshifts seen in QSOs.

Arons (1972) and Arons and Wingert (1972) have recently considered the time dependent photoionization of the intergalactic medium by QSOs. Because the recombination time is greater than the probable lifetime of QSOs, they are able to significantly photoionize the intergalactic medium. It is not yet clear whether such photoionization can be produced in the denser absorbing clouds. If so, this represents an alternative hypothesis which may be able to explain many of the observed properties of the highly ionized absorption redshifts seen in QSOs.

IV. A COLLISIONAL IONIZATION MODEL

Calculations of ionization equilibrium in low-density plasmas including dielectronic recombination have been made by Weymann (1967), Allen and Dupree (1969), and Cox and Tucker (1969). Using these calculations, we require a region with temperature of 10^5 °K in order to ionize carbon sufficiently that 10 percent of the atoms are in the form of C IV. At such a high temperature, only 10^{-5} of the hydrogen is neutral. Assuming solar abundances and the absolute oscillator strengths given by Smith (1972), we may construct the ratio of the expected absorption-line strength R of a resonance line of a given ion i of an atom x to that of Lα, namely,

$$R_{x,i}^{(T)} = \frac{N_{x,i}(T)}{N_x} \frac{gf_x}{gf_{\mathrm{L}\alpha}} \frac{n_x}{n_{\mathrm{H}}} \frac{N_{\mathrm{H}}}{N_{\mathrm{H\,I}}(T)} . \tag{IV.1}$$

Table 1 displays $R_{x,i}(T)$ for the ions most commonly seen in absorption in QSOs. Note that at the higher temperatures, which are required to produce the observed high stages of ionization of C, N, and O, Lα is no longer expected to be the strongest line. For solar abundances, the resonance lines of C IV, C III, and N V will dominate Lα at temperatures near 10^5 °K. With a single temperature and solar abundances, it is impossible to reproduce the observed ratios of Lα to the resonance lines of C IV, C III, N V, and O VI.

In only five of the 16 redshift systems seen in the multiple-redshift QSOs in which Lα is in the observable wavelength range is Lα not the strongest line. There is no pattern to these five cases; they range from the redshift system $z = 2.8751$ in 4C 05.34, where O VI is the strongest line, to the redshift system $z = 2.1819$ in the same object, with Si IV being the strongest line. In the spectrum of Ton 1530 as analyzed by Bahcall, Osmer, and Schmidt (1969), there is a redshift system with Si II stronger than Lα. These cases may result from mistaken identifications or anomalous ionization conditions. However, in general it is clear that Lα is the strongest absorption line. The calculations of table 1 show that if collisional ionization predominates, then in a single-temperature region with solar metal abundances, Lα will not be the strongest line.

To avoid this problem, one may imagine a collisionally ionized region with an inhomogeneous temperature distribution. The hotter region $1(T \approx 10^5$ °K) would contribute predominantly to the absorption in the highly ionized C, N, O, and Si lines, whereas Lα absorption would occur in the cooler region $2(T \approx 10^4$ °K). Because the abundances of C, N, and O are much less than that of H, the cool region will not produce detectable absorption lines of any element except hydrogen. We now proceed to show that such a model is untenable. We assume that regions 1 and 2, with diameters R_1 and R_2, respectively, are physically adjacent, i.e., that n is a monotonic nonzero

TABLE 1

PREDICTED LINE STRENGTHS WITH RESPECT TO Lα

A. COOL REGIONS

log T	log R (N II)	log R (C II)	log R (C III)	log R (O I)	log $(n_{\mathrm{H\,I}}/n_{\mathrm{H}})$
4.0............	−7.6	−4.5	< −7	−3.8	0.0
4.6............	−1.6	−1.0	−0.9	−3.6	−3.1
4.8............	−0.4	+0.0	+0.9	−2.4	−4.5

B. HOT REGIONS

log T	log R (C III)	log R (C IV)	log R (N V)	log R (Si IV)	log R (O VI)	log $(n_{\mathrm{H\,I}}/n_{\mathrm{H}})$
5.0....	+0.7	+0.5	−2.6	−0.5	−2.9	−4.8
5.5....	−0.5	−0.5	+0.0	−0.5	+1.1	−5.8
6.0....	...	...	−0.9	...	+0.6	−6.5

function from regions 1 to 2. For simplicity we take n to be constant within each region. The size of region 1 is then given by the mean value of

$$R_1 = \left\langle \frac{N_{x,i}}{n_e} \left(\frac{n_x}{n_{x,i}}\right)_1 \left(\frac{n_{\rm H}}{n_x}\right) \right\rangle , \tag{IV.2}$$

where $N_{x,i}$ are the column densities given in § II for Si IV, C IV, and N V. Then

$$R_1 \approx 5 \times 10^{17}(10^2/n_e)\frac{1}{Z}\,\mathrm{cm}\,, \tag{IV.3}$$

where Z is the ratio of C, N, and O abundance in the absorbing region to that of the Sun.

Note that because $R_1 + R_2$ must be less than 1 Mpc, and N_1 (the total column density of the hot region) is about $10^{19}/Z\ \mathrm{cm}^2$, we may obtain a lower limit to n_e of $10^{-5}\,Z\ \mathrm{cm}^{-3}$.

Consider the radiation emitted by region 1 with $T = 10^5\ ^\circ$ K. Cox and Tucker (1969) find that the radiative power loss P is about $10^{-21}n_e n_{\rm H}$ ergs cm^3 s^{-1} at $T \approx 10^5\ ^\circ$ K. P is strongly peaked at this temperature, and arises mainly from resonance line emission of the ions O III–O VI. These lines have wavelengths 832 Å (O III), 787 Å (O IV), 629 Å (O V), and 1033 Å (O VI), conveniently close to the Lyman limit. Therefore, unlike the case of photoionization by a synchrotron spectrum, or a hot blackbody, there are not enough energetic photons ($\lambda < 500$ Å) to significantly ionize C, N, and O more than once or twice at the most, while hydrogen will be almost completely photoionized. Furthermore, P is proportional to Z.

Let us calculate the distance $r_{\rm max}$ from the hot region within which photoionization by radiation from the hot region is sufficient that $n_{\rm H\,I}/n_{\rm H} \leq 10^{-3}$. If we can keep the hydrogen that ionized without more than once ionizing the metals, the dominant line from the cool region will be C II rather than Lα. We use the standard formula for ionization equilibrium of a medium with negligible optical depth in a dilute radiation field $F(\nu)$,

$$\frac{n_p n_e}{n_{\rm H\,I}} = \frac{4\pi W}{\alpha_t - \alpha_1}\int_{\nu_c}^{\infty}\frac{a_1(\nu)F(\nu)}{h\nu}\,d\nu\,. \tag{IV.4}$$

The recombination coefficient, $\alpha_t - \alpha_1$, has the value $2.6 \times 10^{-13}(10^4/T)^{0.8}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ (Kaplan and Pikel'ner 1970) and the absorption coefficient $a_1(\nu)$ is independent of temperature. We assume that the integral can be approximated by $a_1(912\ \text{Å})PR_1/(2.2 \times 10^{-11})$ since most of the emitted photons have energies just greater than 1 rydberg. The dilution factor W is given by $R_1{}^2/4r^2$, so that r$_{\rm max}$ is given by

$$r_{\rm max}{}^2 = R_1{}^2(n_{e_1}/n_{e_2})50\,. \tag{IV.5}$$

If we now use the very crude requirement of pressure equilibrium between the two regions, and assume that within the cool region $n_e/n \geq 10^{-3}$, we find that $10^2 \geq n_{e_1}/n_{e_2} \geq 0.1$. Hence $r_{\rm max}$ is greater than R_1. We now integrate to find the total column density of neutral hydrogen in regions 1 and 2. That of region 1 is

$$\begin{aligned}(N_{\rm H\,I}) &= \tfrac{1}{2}10^{-5}R_1(n_{e_1})\\ &= \frac{2 \times 10^{14}}{Z}\ \mathrm{cm}^{-2}\,.\end{aligned} \tag{IV.6}$$

Note that, as expected, this is too little hydrogen to produce the observed column densities given in § III. The column density of region 2 within the radius $r_{\max}$ using the equation (IV.4) is

$$(N_{\mathrm{H\,I}})_2 = \int_{R_1}^{r_{\max}} n_{e,2}\left(\frac{n_{\mathrm{H\,I}}}{n_e}\right)_2 dr = \frac{1}{Z}\left(\frac{n_{e_2}}{n_{e_1}}\right)^{1/2} 10^{17}\ \mathrm{cm}^{-2}\,. \qquad \text{(IV.7)}$$

Since $0.1 \leq n_{e_1}/n_{e_2} \leq 10^2$, this column density of neutral hydrogen is greater than that permitted by the observed strength of Lα. Therefore, we cannot produce just Lα in a cool region physically adjacent to the hot region, because if we are far enough away from the hot region for the ionization equilibrium to make Lα the strongest line, the permitted column density of H I is exceeded. It seems physically unreasonable to have a model with a region of zero density in the range from R_1 to $r_{\max}$, then some density comparable to n_1, at $r > r_{\max}$. This tenuous argument suggests that it would be difficult to arrange a region which is collisionally ionized with a nonuniform temperature distribution which will reproduce the observed pattern of absorption line strengths for solar metal abundances.

The easiest way to remedy the situation is to decrease Z. Then according to equation (IV.6) a reduction of Z to 0.1 will make the hot region alone able to have a sufficiently large column density of H I to explain the observed strength of Lα. Therefore a collisionally ionized hot region with $0.1 < Z < 1$ will produce the column densities inferred from the observations of high ionization redshift systems in QSOs.

V. CONCLUSIONS

The present observational data on the highly ionized absorption redshifts in QSOs suggest that a photoionization model will produce the observed spectral features only if the absorbing material is very close to the QSO. If an ejection model can be rejected on other grounds (such as the sharpness of the lines), we are forced to a model where the ionization is collisional. In this case, we show that Lα is not predicted to be the strongest absorption line in a single-temperature gas cloud. An attempt to enhance the strength of Lα absorption by adding a cool region fails, as the cool region is photoionized by line radiation from the hot region, unless there is a region of zero gas density between the cool and the hot region. Therefore, in the collisionally ionized case, we require $0.1 < Z < 1$ to obtain an absorption spectrum which matches that observed for the redshift systems which are highly ionized in QSOs.

These arguments are necessarily crude, and the limits on Z thus derived are highly inaccurate, as there is very little quantitative information available on the absorption lines in QSOs. Further measurements of line strengths and derived column densities in more QSOs over all the lines of a given redshift system would be very useful. It is interesting that even with the paucity of present observational data and the uncertainty as to where these absorption lines are formed, some conclusions as to the physical parameters of the absorbing gas can be derived if the gas is collisionally ionized.

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