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THE TEMPERATURE OF THE LYMAN-α CLOUDS AND THE ULTRAVIOLET IONIZING BACKGROUND AT HIGH REDSHIFTS

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ABSTRACT

It is shown that it is possible to account for low temperatures in diffuse photoionized clouds using ionization arguments in a manner independent of the structure and confinement of the clouds. We emphasize that cooling by inverse Compton scattering of cosmic microwave background photons by electrons and the effect of a strong but progressive decrease of the UV ionizing background at wavelengths shorter than the He II edge can allow for temperatures as low as 20,000 K for gas in photoionization equilibrium. Using recent determination of H I column densities and temperatures from profile fitting of QSO Lyα absorption lines, it is shown that the total density of these high-redshift clouds lies in a narrow range around $n \sim 10^{-4}$ cm^{-3}. The sizes are larger than 20 kpc. The observed temperature distribution is explained in terms of space fluctuations in the ionizing UV background at energies larger than the He II edge.

Subject headings: cosmology: observations — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

Most of the information on the space distribution and physical state of the intergalactic medium (IGM) up to redshift $z \simeq 5$ is derived by studying the absorption spectra of high-redshift quasars.

The optical depth observed shortward of the QSO Lyα emission is due to the presence of neutral hydrogen along the line of sight. Numerous narrow absorption lines are observed and interpreted as H I Lyman-α absorptions from intervening clouds (Sargent et al. 1980). Absorption from an additional continuous intergalactic medium has been searched for (Gunn & Peterson 1965) with no success up to now and only upper limits on the optical depth are derived, $\tau < 0.02 \pm 0.03$ at $\langle z \rangle = 2.6$ (Steidel & Sargent 1987), $\tau < 0.02 \pm 0.03$ in the range $z = 3$–4.5 (Giallongo, Cristiani, & Trevese 1992; Giallongo et al. 1994). Moreover, Webb et al. (1992) have shown that if the H I column density distribution is flattening below $N(\text{H I}) \sim 10^{13.75}$ cm^{-2}, which seems to be confirmed by recent analysis (Petitjean et al. 1993b; Giallongo et al. 1993), then data are compatible with no Gunn-Peterson effect.

The knowledge of the Lyα absorber physical and cosmological properties relies on a few parameters (redshift, column density, Doppler width of individual components) which can be derived from high-resolution spectroscopy and line profile fitting of blended absorption features.

At the typical resolution of 20–30 km s^{-1} used in the past decade, the derived average value of the Doppler width was $b = 30$ km s^{-1} and the column density distribution was found to conform to a single power law of the type $f(N_{\rm H\,I}) \propto N_{\rm H\,I}^{-1.7}$ for $N_{\rm H\,I} \geq 10^{13.7}$ cm^{-2} (Carswell 1988, and references therein). The inferred average temperature $T \lesssim 5 \times 10^4$ K was considered consistent with what is expected for clouds in photoionization equilibrium with the general UV ionizing background (UVB) produced by quasars and/or high z galaxies. Models of highly ionized clouds have been proposed where the ionization ratio is $n_{\rm H}/n_{\rm H\,I} \sim 10^4$. These models predict total densities of the order of $n_{\rm H} = 10^{-3}$–10^{-4} cm^{-3} and sizes in the range 1–20 Kpc regardless of the kind of confinement assumed for the clouds, namely pressure confinement by the diffuse intergalactic medium (Sargent et al. 1980; Ikeuchi & Ostriker 1986; Baron et al. 1989) or gravitational confinement by nonbaryonic dark matter (Rees 1986; Ikeuchi 1986).

However narrow absorption lines ($b < 20$ km s^{-1}) are observed in data of higher spectral resolution. Long-slit spectra at FWHM ~ 12 km s^{-1} covering 38 Å of the Lyα forest in PHL 957 revealed one line with $b \simeq 14.5$ km s^{-1} ($T \simeq 13{,}000$ K; Chaffee et al. 1983). More recently echelle data at 10 km s^{-1} resolution reveal a large fraction of narrow lines with $b \lesssim 20$ km s^{-1} (Pettini et al. 1990; Carswell et al. 1991; Hunstead & Pettini 1991; Rauch et al. 1992, 1993; Giallongo et al. 1993). Even excluding lines with $b \lesssim 10$ km s^{-1}, which could be either spurious because of the limited S/N ratio of the data or unidentified metal lines, the fraction of lines with $10 < b < 20$ km s^{-1} is ~15%–20% of the overall sample.

It has been pointed out by Pettini et al. (1990) that low temperatures can be obtained by increasing the gas density. Consequently, however, the cloud sizes are very small for typical column densities (~1 pc). This is in contrast with the observational constraints derived from observation of coincident absorptions in the spectra of two images of a gravitationally lensed QSO. An upper limit on the cloud sizes $S < 800$ h_{50}^{-1} kpc has been given by Shaver & Robertson (1983) in the pair Q0307 − 195. On the other hand, Foltz et al. (1984) derive a lower limit to the transverse sizes in the range 5–25 h_{50}^{-1} kpc from the gravitationally lensed pair Q2345+0007. Using the one to one coincidence for all the lines but two and the good correlation between equivalent widths along both line of sights of the QSO pair UM 673, Smette et al. (1992) give lower limits in the range 12–50 h_{50}^{-1} kpc for the diameters of spherical clouds. Moreover, recent results on a new QSO pair (Wisotzki et al. 1994) by Smette and collaborators (P. A. Shaver 1993, private communication) seem to imply a lower limit $S > 30$ h_{50}^{-1} kpc.

Interesting solutions to the problem of explaining low temperatures together with large sizes can be obtained allowing for adiabatic cooling due to cloud expansion against the external pressure of a diffuse intergalactic medium (Duncan, Vishniac, & Ostriker 1991). A detailed description of such clouds shows however that it is difficult to reproduce the global characteristics (Doppler parameter and H I column density distributions) of the entire population of Lyα absorbers (Petitjean et al. 1993a). In the latter models the lower temperature compared to standard models is the consequence of an increased cooling rate. A similar result is obtained if the heating rate can be made smaller. This led Sciama (1990) to the speculation that Lyα clouds could be ionized and heated by photons with energy exceeding the hydrogen ionization potential by only a few percent. Miralda-Escudé & Ostriker (1992) have shown however that in this case He I λ584 absorption features should be conspicuous and give rise to a "He I forest" which is not observed in HS 1700+6416 (Reimers & Vogel 1993).

The aim of this *Letter* is to show that it is possible to account for these low temperatures using ionization arguments in a manner independent of detailed models for the structure (i.e., density profile) and confinement of the clouds. We emphasize that inverse Compton cooling of the electrons on the cosmic microwave background and a strong decrease of the UVB flux just shortward of the He II edge could allow for temperatures as low as 20,000 K even for clouds with large sizes of greater than 20 kpc and in photoionization equilibrium.

2. THE MODEL

Both standard photoionization codes NEBULA (Péquignot et al. 1978; Petitjean et al. 1990) and CLOUDY (Ferland 1991) are used for modeling the ionization state of a plane-parallel slab illuminated on one side by an ionizing flux J_ν. The flux at the Lyman limit (1 ryd) is $J = 10^{-21} J_{-21}$ ergs s^{-1} cm^{-2} Hz^{-1} sr^{-1} and the spectrum is taken to be characterized by a power law of index α from 1 to 4 ryd (the He II ionization potential), a break at 4 ryd of variable amplitude $B = J(4\text{ ryd})/J(4.5\text{ ryd})$, a constant value from 4.5 ryd to the energy at which the spectrum recovers the original power-law. The shape is consistent with what is expected for the UVB (Miralda-Escudé & Ostriker 1990). We thus vary the two important parameters J_{-21} and B.

A primordial abundance of hydrogen and helium is assumed with a ratio He/H ∼ 0.08.

The results are obtained under the assumption of photoionization and thermal equilibrium. Heating processes are photoionization and Compton heating, cooling includes contributions from recombination, free-free radiation, collisional ionization and excitation and Compton cooling. Given an ionizing flux, the ionization parameter and thus the temperature and ionization state of the cloud are fully determined by the total density. The size along the line of sight is then directly proportional to the H I column density.

The assumption of thermal equilibrium in low density, low temperature clouds can be marginally accepted at high redshifts. Indeed the recombination cooling time is smaller than the recombination time by a factor $1/(1 + 1/kT)$ where kT is in ryd (see, e.g., Collin-Souffrin 1991). For $T = 20{,}000$ K, then $t_{\rm coolrec} \lesssim t_{\rm rec}$, where

$$t_{\rm rec} = [\alpha(T) n_e]^{-1} = 7.6 \times 10^8 \text{ yr} \quad T_4 (n_e/10^{-4})^{-1} \tag{1}$$

and $T = 10^4 T_4$ K. This value should be compared to the Hubble cosmic time $t_{\rm H}$ at $z = 3$ which is for the $q_0 = 0.5$ and $H_0 = 50$ km s^{-1} Mpc^{-1} cosmological model used throughout the paper:

$$t_{\rm H} = (2.4 \times 10^9 \text{ yr})/[(1+z)/4]^{3/2} \,. \tag{2}$$

Thus, for temperatures $T_4 = 2$–4, $t_{\rm rec} \lesssim t_{\rm H}$ at $z \sim 3$.

At $z > 2$ inverse Compton scattering of the cosmic microwave background (CMB) photons on electrons becomes an important source of cooling for clouds with $n < 10^{-3.5}$ cm^{-3}. The characteristic cooling time is defined as $t_c \equiv nkT/L_c$, where $L_c = 5.4 \times 10^{-32}(1+z)^4 n_e T_4$ ergs cm^{-3} s^{-1} (see, e.g., Ikeuchi & Ostriker 1986). This yields

$$t_c = (3.2 \times 10^9 \text{ yr})/[(1+z)/4]^4 \tag{3}$$

and t_c is not appreciably longer than the cosmic time at $z = 3$. Moreover, it should be noted that $t_c/t_{\rm H} \propto (1+z)^{-2.5}$ becomes rapidly smaller than 1 for $z > 3$.

Since the timescale for net supply of neutral hydrogen is $n_{\rm H\,I}/n_{\rm H\,II} \sim 10^{-4}$ times the recombination time, ionization equilibrium is also adequate as a first approximation.

The solid lines in Figures 1*a* and 1*b* show the change in temperature and size $S \equiv N_{\rm H}/n_{\rm H}$ of clouds with different densities and without including inverse Compton cooling. The results are obtained assuming $J_{-21} = 1$, a power-law index $\alpha = -1.5$, no break at 4 ryd and a column density $N_{\rm H\,I} = 3 \times 10^{13}$ cm^{-2}. It is clear that the temperature increases monotonically as the density decreases. Temperatures lower

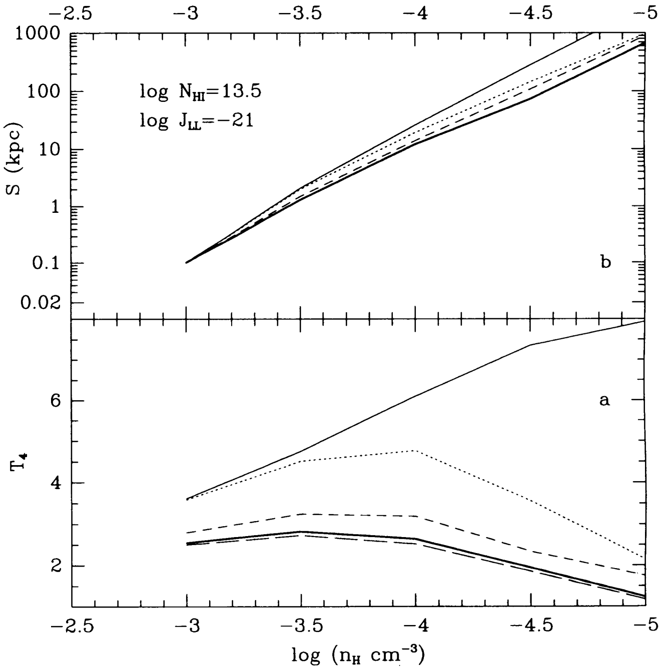

FIG. 1.—(*a*) Temperature in units of 10^4 K as a function of total density for clouds with log $N_{\rm H\,I} = 13.5$ photoionized by a UVB of intensity at the Lyman limit $J_{\rm LL} = 10^{-21}$ ergs s^{-1} cm^{-2} Hz^{-1} sr^{-1}. Continuous curve is for models with no inverse Compton cooling included and no break in the shape of the ionizing flux at 4 ryd. Other models include inverse Compton cooling; dotted line is for models with no break in the ionizing flux. Dashed, thick, and long-dashed curves are for models with a break at 4 ryd of increasing amplitude $B = 10^2$, 10^3, and 10^4 respectively. (*b*) Size vs. total density as in Fig. 1*a*.

than $T_4 = 4$ are obtained for $\log n > -3$, but the sizes of the clouds are less than 100 pc and are therefore ruled out by the observations (as already pointed out by Foltz et al. 1984 and Pettini et al. 1990).

In Figures 1*a* and 1*b* dotted lines show the change in temperature and size when Compton cooling is taken into account. For $\log n_{\rm H} < -3.5$ the temperature levels off and then decreases. This is because the ratio between the cooling and heating rates is proportional to $n_e/n_{\rm H\,I}$ when Compton cooling is dominant. A value $T_4 = 3.5$ is obtained for both $\log n_{\rm H} \simeq -3$ and $\log n_{\rm H} \simeq -4.5$ but in the latter case the sizes are 1000 times larger, i.e., ∼100 kpc. It is clear however that even in the most favorable case it is not possible to explain temperatures lower than 30,000 K for clouds with sizes exceeding 10 kpc.

To achieve lower temperatures a way must be found to reduce the heating rate. In the case where the power-law spectrum has no break at 4 ryd, helium is mostly ionized by hard photons and contributes about half the heating. To significantly reduce the heating due to helium two approaches can be thought of (1) either consider that there is a sharp break at 4 ryd *and* no photons of energy larger than 4 ryd (Miralda-Escudé & Rees 1984); He is then mostly in the form of He II (2) or that there is a *smooth* break at 4 ryd; He II is then completely ionized in He III but by photons with energy exceeding the helium ionization potential by only a few percent. This allows for a residual flux in the soft X-ray band.

Indeed, a break with a strong decrease of the ionizing flux just beyond 4 ryd has been predicted by Miralda-Escudé & Ostriker (1990) mainly because of the He II absorption by the same Lyα clouds and because of the possible dominant contribution to the *UVB* by galaxies whose spectrum does not extend beyond the He II edge.

Following an empirical approach we introduce a smooth break in the power-law ionizing flux between 4 and 4.5 ryd. Results obtained for different amplitude of the break are shown in Figures 1*a* and 1*b*. Beyond the break the spectrum is flat until it recovers the original power-law in the soft X-ray band.

A global trend toward lower temperatures is apparent in Figure 1*a* as the amplitude of the break increases from $B = 10^2$ (*short-dashed line*) to 10^4 (*long-dashed line*). In all the cases where the break amplitude is large, the size is nearly constant for a given total density and the $S - n_{\rm H}$ relation is shown by the thick line in Figure 1*b*.

It is clear that temperatures $T \lesssim 22{,}000$ K can be obtained with total densities $\log n_{\rm H} \lesssim -4$ and with an amplitude of the break $B = 10^3$ (*thick line*, Fig. 1*a*). Note that amplitudes greater than $B = 10^4$ do not change the cloud temperature any more.

If we change the ionizing flux at the Lyman limit by a factor of 10 in the case $B = 10^3$, then there is no appreciable change in the cloud temperature for densities $\log n_{\rm H} \lesssim -4$. However, the sizes can vary by more than one order of magnitude, being $S \simeq 1$ kpc, 100 kpc for $\log n_{\rm H} = -4$ and $J_{-21} = 0.1$, 10, respectively. Indeed, higher fluxes ($\log J_{\rm LL} \gtrsim -21$) are compatible with large sizes ($S > 10$ kpc) within a wider density interval.

3. COMPARISON WITH THE DATA AND DISCUSSION

It is important to check the model against samples of Lyα observed at high spectral resolution. For this purpose, we use the $z \sim 3$ data obtained by Giallongo et al. (1993) at a spectral resolution of 14 km s^{-1}.

This Lyα sample has a considerable fraction of narrow lines, 22% with $10 < b < 20$ km s^{-1}. The column density distribution has a two power-law shape with a somewhat flat index -1.5 below $\log N_{\rm H\,I} = 14.5$–15 and a steeper one, less than -2, for larger column densities. Such a break is expected in a scenario where gravitation controls the structure of the gaseous clouds (Duncan et al. 1991; Rees 1993). Indeed Jeans instability takes place for clouds with large sizes and column densities.

In order to constrain the model parameters, we have averaged the observed column densities and Doppler parameters, i.e., average temperatures, in five bins (Fig. 2*a*). We have limited the sample to lines with $10 \leq b \leq 40$ km s^{-1} to avoid possible contamination by metal lines and blends of lines. These average values are not representative of the exact intrinsic properties of the clouds because of selection effects which favor detection of narrower lines at very low column densities $\log N_{\rm H\,I} < 13.3$. Nevertheless they correspond to the range of physical conditions any model should explain.

Results from the photoionization codes are shown in Figure 2*b* where filled dots represent sizes and masses of clouds having temperatures and neutral column densities shown in Figure 2*a*. It turns out that all the clouds have about the same density $\log n_{\rm H} \simeq -4.2$. To explain the observed range of temperature, $22{,}000 < T < 46{,}000$ K, we are forced to vary the amplitude of the break at 4 ryd by a factor of 10^3. Indeed the high temperature in clouds with $\log N_{\rm H\,I} > 13.5$ can be reproduced using a featureless power-law *UVB* spectrum, while temperatures such as $T \simeq 35{,}000$ and 22,000 K result from the presence of a break at 4 ryd with increasing amplitude, $B = 10^{1.5}$, 10^3, respectively. Very low temperatures, $T \sim 15{,}000$ K, which are 1 σ below the average value in the $\log N_{\rm H\,I} = 13$–13.25 bin, can be obtained only with densities $\log n_{\rm H} = -5$ and sizes $S \simeq 210$ kpc. But the assumption of ionization equilibrium is then questionable.

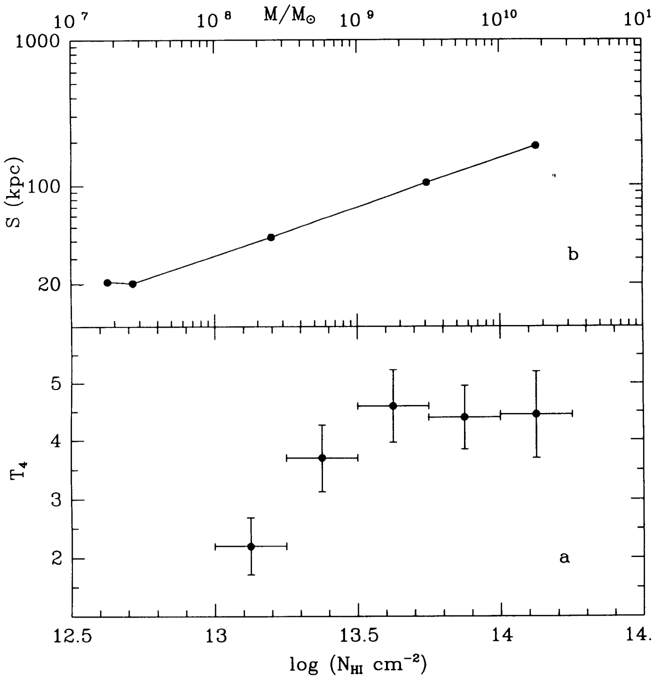

FIG. 2.—(*a*) Temperature vs. H I column density for the Lyα lines in PKS 2126−158. The data have been arbitrarily binned. (*b*) Size vs. mass of cloud models with temperatures and H I column densities as in Fig. 1*a*.

In this scenario lines with $\log N_{\rm H\,I} > 13.5$ and $T \sim 45{,}000$ K correspond to clouds of sizes $S > 40$ kpc. The fact that the whole range of column density and temperature can be reproduced in clouds with large radii suggests that the contribution of bulk motions to the Doppler width is negligible.

The observed temperature distribution is explained in terms of space fluctuations in the ionizing UV background at energies higher than the He II edge. High T ($T > 40{,}000$ K) clouds are present in regions where the ionizing *UVB* is dominated by a QSO like spectrum. The filling factor of these clouds is proportional to $S\,dN/dz$, where N is the number of lines along the line of sight, and is of the order of $\simeq 0.05$. Low T ($T < 35{,}000$ K) clouds are present in regions where the spectrum is very steep beyond 4 ryd because of strong absorption by intervening Lyα clouds and/or because of a dominant galaxy-like spectrum (see, e.g., Miralda-Escudé & Ostriker 1990). The filling factor of these clouds is 0.01. Assuming the clouds are randomly distributed, this implies that the volume shielded from photons of energy larger than the He II edge represents about 20% of space at $z \sim 3$.

The mass of the corresponding spherical clouds are given in Figure 2*b*. The Jeans length $S_{\rm J} = 150$ kpc $(T_4/n_{-4})^{1/2}$ ranges from 320 to 400 kpc, with Jeans masses $M_{\rm J} \sim 10^{11}\ M_\odot$, to be compared with the cloud sizes in the range 20–200 kpc. For the same ionization and thermal states, the column densities beyond which the clouds are unstable ($S > S_{\rm J}$) are $\log N_{\rm H\,I,J} \sim 14.3$ for the lowest $N_{\rm H\,I}$ bin, and $\log N_{\rm H\,I,J} \sim 14.6$ for $\log N_{\rm H\,I} \gtrsim 13.3$. The clouds with larger densities disappear in a timescale much shorter than the cosmic time at $z = 3$ explaining the observed break in the column density distribution. Moreover, the break predicted by the model depends on the cloud temperature. Indeed, in the extreme case where $\log n_{\rm H} = -5$ and $T = 12{,}000$ K, clouds with $\log N_{\rm H\,I} > 13.4$ are gravitationally unstable. This is consistent with the deficit of lines with $b < 20$ km s^{-1} and $\log N_{\rm H\,I} > 13.5$ found by Giallongo et al. (1993) in their sample. In the framework of this model, objects with masses in the range expected for dwarf galaxies $M > 10^8\ M_\odot$ are Jean stable (Efstathiou 1992).

The amplitude of the break at 54.5 eV can be observationally tested since in the case there is a large break, C IV is not ionized and all carbon is in the form of C IV. Consequently, even for abundances of the order of 10^{-3} the solar value, the C IV column density could be as large as 10^{12} cm^{-2} for N(H I) = $10^{13.5}$ cm^{-2} which is marginally detectable in good S/N ratio intermediate resolution data.

A further prediction of the model is the relevant contribution of Lyα clouds with $\log N_{\rm H\,I} > 13.5$ to the cosmological baryon density $\Omega_{{\rm Ly}\alpha} = f n_{\rm H}/n_{\rm H\,crit}$ where $n_{\rm H\,crit}$ is the closure hydrogen density, $n_{\rm H}$ is the average density of the clouds and f is the volume filling factor. Given the observed number density of lines in each bin of Figure 2*b*, we estimate a total contribution $\Omega_{{\rm Ly}\alpha} \simeq 0.03$ in agreement with the findings of Petitjean et al. (1993b). On the other hand, the contribution by diffuse IGM has been found to be $\Omega_{\rm IGM} \lesssim 0.01$ through measures of the Gunn-Peterson optical depth in the range $z = 3$–4.5 (Giallongo et al. 1992, 1994). Optically thick systems as Lyman Limit and Damped systems could give a contribution $\Omega_{\rm LL+D} \simeq 0.01$ (Steidel 1990; Lanzetta et al. 1991; Petitjean et al. 1993b). Thus, Lyα clouds in our model provide the required value needed to explain the nucleosynthesis constrained baryon density $\Omega_b \simeq 0.05$ (Walker et al. 1991).

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