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ON THE PHYSICAL STATE OF QSO LYMAN-α ABSORPTION CLOUDS

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ABSTRACT

Arguments are presented that QSO Lyman-α absorption lines might arise in denser environments than is usually thought, with a larger neutral fraction in the gas than in the usual models of rarefied intergalactic clouds, and a much smaller total mean mass density in Lyman-α clouds. A model is sketched in which collapse or collision of thermally unstable protogalactic clouds forms shocks which trigger the collapse of cool thin sheets. The statistical properties of absorption lines formed in this way are consistent with those of the observed Lyman-α forest.

Subject headings: galaxies: intergalactic medium — quasars

It is now widely believed that the large numbers of narrow absorption lines observed in all QSO spectra shortward of the Lyman-α emission line are caused by condensations of neutral hydrogen gas at various redshifts along the line of sight. However, the physical state of these condensations is still undetermined. Most often, they are thought to be large ($\gtrsim 10$ kpc), homogeneous, approximately spherical, rarefied clouds of highly photoionized gas, pressure-confined by a still more rarefied and ionized intergalactic medium (Sargent *et al.* 1980; Black 1981; Ostriker and Ikeuchi 1983; Ikeuchi and Ostriker 1986), or gravitationally confined by "mini-halos" of dark matter (Rees 1986), or perhaps just freely expanding. This *Letter* examines an alternative possibility, that the clouds may be at significantly higher pressure than in the models just cited, and therefore have smaller sizes, higher local densities, and a much larger neutral fraction. Clearly, an alternative interpretation of the lines may lead to significantly different conclusions about the history of the intergalactic medium and of galaxies themselves.

There are several reasons for preferring such a model. For example, Chaffee *et al.* (1983) in a detailed study of one narrow line with $N_{\mathrm{H\,I}} \approx 2 \times 10^{13}$ cm^{-2} showed that it arises in gas with temperature less than 17,000 K. Even for a diameter as small as 10^{19} cm (required to cover the QSO) a homogeneous spherical cloud of such small neutral column density in the known ionizing background would have a temperature of at least 25,000 K. To bring T down to the preferred value of 12,000 K would require increasing the gas density, shortening the line-of-sight cloud dimension to $\sim 10^{15}$ cm, more in line with the scale proposed below (the covering requirement being met by flattening clouds, or clustering them, or both). Tytler (1986*a*, *b*) brings up several other reasons for suspecting a larger than normal neutral fraction. For example, there is no apparent break in the column density distribution at $N_{\mathrm{H\,I}} \approx 10^{17}$ cm^{-2}, where clouds become self-absorbed in the Lyman continuum; the lack of observed metal lines in $N_{\mathrm{H\,I}} < 10^{17}$ cm^{-2} systems is easily explained (even for a normal spread of abundances) as observational selection if $N_{\mathrm{H\,I}} \approx N_{\mathrm{H}}$; and a strong dependence of line density on z_{em} might be most easily understood if the absorbing cloud population does indeed have structure on scales $\lesssim 10^{16}$ cm. In addition, Tytler argues that clouds over the whole range of column densities from 10^{13} cm^{-2} to 10^{22} cm^{-2} ought to belong to the same population. We have good reason to suspect that the high-$N_{\mathrm{H\,I}}$ end of this range are just galaxies at an early stage of evolution and it is natural to ask whether the low-$N_{\mathrm{H\,I}}$ systems could not arise from other effects associated with protogalaxy collapse. Such an environment naturally has higher mean pressure than the separate conditions usually postulated to explain intergalactic Lyman-α clouds.

Let us then investigate the theoretical plausibility of forming sufficient numbers of clouds in this relatively thin, cold, dense state, with appropriate correlations in angle and velocity to be consistent with observations. Begin by investigating the simple question of the mean mass density contributed by the clouds. Suppose that one has a population of gas condensations distributed throughout the universe, and that a fraction $P(z)$ of these systems at any given redshift z are detectable, say through absorption or emission lines. Let dN/dz denote the mean number of these systems detected along a line of sight per unit z. Then the contribution Ω_c of this population to the cosmic density parameter is determined by the mean baryonic column density N_b (in cm^{-2}) of each individual system through

$$\Omega_c = 0.1(dN/dz)(N_b/10^{22})(1+z)^{-1/2}h^{-1}P^{-1}, \quad (1)$$

where $\Omega = 1$ is assumed throughout and $h \equiv H_0/100$ km s^{-1} Mpc^{-1}. The component which by far dominates the total mass of H I actually seen in absorption is the population causing the damped Lyα lines such as those studied by Wolfe *et al.* (1986). For these systems, dN/dz is only about 0.2 but $N_{\mathrm{H\,I}} \approx 10^{21}$, indicating a density parameter (adopting $1+z = 4$) $\Omega_{\mathrm{H\,I}} \approx 2.5 \times 10^{-3} h^{-1} P^{-1}$, which may be comparable to the baryon density in spiral galaxy disks even if $P \approx 1$.

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The more frequent "Lyα forest" systems, on the other hand, have column densities of only $N_{\text{H I}} \approx 10^{14}$; clouds exceeding $N_{\text{H I}}$ have $(dN/dz) \approx 20(1+z)(N_{\text{H I}}/10^{14})^{-0.5}$ (by Tytler's 1986*a* reckoning), so that their contribution to the mean neutral hydrogen density is only $\Omega_{\text{H I}} \approx 4 \times 10^{-8} h^{-1} P^{-1} (N_{\text{H I}}/10^{14})^{0.5}$. This is just a "trace" component even by comparison to the small Ω_b in the damped systems. If the Lyα forest lines are formed in clouds with low ionization, they tell us directly about only a very small fraction of all the gas present, which encourages caution in model building as we are discussing essentially a rare phenomenon.

In the conventional interpretation, the Lyα forest clouds are not a minor constituent because they are highly ionized and most of their gas is not detected in H I. According to calculations of Black (1981),

$$\frac{n_{\text{H I}}}{n_b} \approx 4.6 \times 10^{-2} \left(I/3 \times 10^{-21} \right)^{-1.22} \left(n_b/1 \text{ cm}^{-3} \right)^{1.22}, \tag{2}$$

where I is the mean intensity of photoionizing radiation in ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}. For commonly adopted values of the mean density $n_b \approx 10^{-3}$, only $\sim 10^{-5}$ of the gas is neutral, so the Ω_b of the Lyα forest cloud population is comparable to that of damped Lyα disks and of galaxies. In these models the clouds provide a major constraint on scenarios for the evolution of the entire intergalactic medium (Ostriker and Ikeuchi 1983; Ikeuchi and Ostriker 1986) or the distribution of dark matter (Rees 1986). On the other hand it is clear that if some of the gas at any given time were to reach a much higher density (with larger $n_{\text{H I}}/n_b$), then the Lyα forest might be explained using a fraction of Galactic gas as low as 10^{-5}, or using short-lived transient effects in a larger fraction of the gas. This does not seem at all implausible. In what follows I sketch out one such scheme, at the same time addressing constraints arising from the observed correlations in angle and velocity.

Suppose that thermally unstable, protogalactic gas clouds are collapsing throughout the universe, as envisioned by Fall and Rees (1985). They suggested high-density condensations in such a collapse as the precursors of globular clusters, but smaller condensations would also occur which would be below the Jeans mass and would not collapse gravitationally after achieving pressure equilibrium. Let us work out first the dN/dz for these systems and then the H I column density expected in individual sheets cooling behind shocks formed in the collapse.

Assume that gas collapses into isothermal halos with circular velocity 100 V_{100} km s^{-1}, virial temperature $kT \approx 30\ V_{100}^2$ eV $= k \times 3.5 \times 10^5\ V_{100}^2$ K, and free-fall time from radius R, $\tau_{\text{ff}} = 1.2 \times 10^7\ R_{\text{kpc}}\ V_{100}^{-1}$ yr. Let β denote the ratio of τ_{ff} to the cooling time τ_{cool}. For the zero-metal cooling function adopted by Fall and Rees (1985), the gas density and radius of a uniform cloud of gas of mass M_g at the virial temperature are given by:

$$n_b = 0.2 \text{ cm}^{-3}\ \beta\ R_{\text{kpc}}^{-1}\ V_{100}^2, \tag{3a}$$

$$M_g = 2.4 \times 10^7\ M_\odot\ \beta\ R_{\text{kpc}}^2\ V_{100}^2, \tag{3b}$$

and

$$R_{\text{kpc}} = 220 \left(M_g/10^{12}\ M_\odot \right)^{1/2} \beta^{-1/2} V_{100}^{-1}. \tag{3c}$$

Thermally unstable collapse occurs at $\beta \approx 1$.

Suppose that gas everywhere is collapsing into such systems. If we fix the density parameter $\Omega_g h^2$ in protogalactic gas (rather than M_g or R_{kpc}), then the expression for dN/dz, the covering factor of thermally unstable clouds, becomes independent of the explicit mass or comoving number density n_g of galaxies:

$$R_{\text{kpc}} = 374 \beta^{-1/2} V_{100}^{-1} \left(\Omega_g h^2/0.1 \right)^{1/2} \left(n_g/10^{-2} \text{ Mpc}^{-3} \right)^{-1/2} \tag{4a}$$

$$\frac{dN}{dz} = 58 h^{-1} \beta^{-1} V_{100}^{-2} \left(\Omega_g h^2/0.1 \right) [(1+z)/4]^{1/2}. \tag{4b}$$

Note that galaxies cool efficiently at fairly large radii if the mean density of the gas is high. If each of these clouds produces a Lyα line over the range of epochs corresponding to observations of the Lyα forest, there might be enough to explain the whole forest, particularly if the typical value of V_{100} is not much greater than unity. If one feels uncomfortable with protogalaxies larger than 100 kpc, realize that the only assumptions in equation (4b) are the virial temperature of typical halos ($V_{100} \approx 1$–2) and the mean density of gas ($\Omega_g h^2 \approx 0.03$–$0.1$)—both of which are standard ingredients in any current recipe for galaxy formation.

From observations of the lensed QSO 2345+007A,B (Foltz *et al.* 1984), we know that the H I column density is highly correlated, and the dispersion in H I velocity must be less than 25 km s^{-1}, for lines of sight separated by as much as 10 kpc; this gives the minimum coherence scale of the gas velocity. The formation of Lyα absorbers would be this coherent in velocity if each protogalaxy is being assembled out of a small number of individually hydrostatic subunits, and Lyα absorbers form in shocks as they collide. I will now show that shocks in these conditions would naturally lead to coherent dense pancakes with column density appropriate for the Lyman-α clouds.

It is interesting that the column density N of gas in shock-induced pancakes is not sensitive to the ambient gas density n_0. Suppose gas approaches a shock with velocity $v \equiv 100 v_{100}$ km^2 s^{-1}. Behind the shock, gas cools on a time scale $\tau_{\text{cool}} \approx kT/\Lambda(T) n$, where Λ is the cooling function. The density n varies from $4n_0$ just behind the shock (for strong shocks) to $4n_0(T_s/T_c)$ when gas cools to its minimum temperature $T_c \approx 9000$ K from its immediate post-shock temperature $T_s \approx 2 \times 10^5 v_{100}^2$ K. A cool sheet forms after about a time $\tau_{\text{cool}}(T_s)$, during which time a column density of material

$$N_1 \equiv n_0 \tau_{\text{cool}}(T_s) v \approx 10^{17} v_{100}^3 \Lambda_{22}^{-1}(T_s) \text{ cm}^{-2} \tag{5}$$

has passed through the sheet—independent of n_0. The value of $\Lambda_{22} \equiv \Lambda/10^{-22}$ ergs cm^3 s^{-1} depends on the metallicity; for 10^4 K $< T < 10^5$ K, zero-metal gas has $0.3 \lesssim \Lambda_{22}(T) \lesssim 1$ (Fall and Rees 1985) and solar-metal gas has $1 \lesssim \Lambda_{22}(T) \lesssim 10$

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(Dalgarno and McCray 1972). It would be highly unnatural to form cool clouds with $N < N_1$ in any environment, although $N > N_1$ is no problem—cool gas will continue to accumulate as long as the supply lasts, which in real situations is the coherence timescale for the gas flow. This restriction on column density is more reliable than that imposed by conduction, $N > N_2$ with

$$N_2 \equiv (\kappa T/\Lambda)^{1/2} = 6 \times 10^{16} T_5^{7/4} \Lambda_{22}^{-1/2}\ \text{cm}, \qquad (6)$$

where we have adopted the conduction coefficient $\kappa = 1.2 \times 10^{-6} T^{5/2}$ ergs cm^{-1} s^{-1} K^{-1}. The conduction constraint requires no assumption about formation of clouds in shocks, but it only applies as long as any tangled magnetic fields are extraordinarily weak, a risky assumption in an astrophysical context since the hydrodynamic shock formulation itself relies on some such suppression of conduction (Spitzer 1978, p. 255).

Both of these limits on N apply equally well to shocks arising either from protogalaxy collapse or from explosions in the low-density intergalactic environment (Vishniac 1983; Ikeuchi, Tomisaka, and Ostriker 1983; Chernomordik and Ozernoy 1983). Very low neutral column density clouds formed in shocks must always, therefore, be photoionized to bring their $N_{\text{H I}}$ below expression (5); however, this does not preclude their having relatively "high" gas densities $n_0 \gtrsim 10^{-3}$ (i.e., $n_b \gtrsim 10^{-1}$ in the clouds), particularly if the ionizing flux is high (cf. eq. [2]).

Thus in principle, protogalactic shocks are able to produce the whole range of column density observed in Lyα lines. The actual details of the column density distribution depend on details of the gas flow on both large and small scales. Very rapid conversion of gas to cool phase would cause problems for the model since it would lead to a paucity of low-$N_{\text{H I}}$ systems, which as shown above involve a small fraction of the gas. But concurrent with this conversion is the collapse of systems, which reduces their cross sections. It is reasonable to suppose for example that the onset of thermal instability in a small fraction of gas might initiate pancake collapse with $N \approx 10^{17}$, $N_{\text{H I}} \approx 10^{14}$; as collapse ensues, the radius of a protogalaxy decreases from ~ 300 kpc to ~ 30 kpc, and the covering factor decreases from ~ 20 to about 0.2. Simultaneously, n_b increases (increasing the neutral fraction) and a progressively larger gas fraction is converted into cold H I phase producing in the end cool disks with $N_{\text{H I}} \gtrsim 10^{21}$. Qualitatively, this agrees with the observed run of dN/dz with $N_{\text{H I}}$: more gas occurs in high-$N_{\text{H I}}$ systems even though the covering factor is less. Whether the right quantitative behavior occurs depends on the particular theory of protogalaxy collapse. From another point of view, the efficiency of forming neutral absorbing pancakes can be regarded as an important constraint on models of galaxy formation at $z \approx$ 2–3, such as the "cold dark matter" model. If at the same time the coherence scale of gas flows within protogalaxies is suitable, the line correlations in 2345+007A,B can be reproduced. Thus it may be unnecessary to postulate a separate mechanism to create intergalactic Lyα clouds and their confining medium. A Lyman-α forest of some kind naturally arises as long as there is a substantial amount of gas present ($\Omega h^2 \approx 0.01$–0.1) at $z \approx 2$–3 and is being shocked at velocities ~ 100–200 km s^{-1}. Lyα pancakes formed in the collapse or collision of thermally unstable protogalaxies could have about the same column density and line density distribution that observed QSO lines require. They would be large-scale versions of the model of McCray, Stein, and Kafatos (1975) of sheets in the Vela supernova remnant.

The most interesting question is whether one can imagine a definitive test to choose between models of the cloud population with widely varying density, ionization state, and confinement mechanism. Velocity correlations of lines calculated in simple gravitational models of galaxy clustering reveal that protogalaxies could be weakly enough clustered at $z \gtrsim 2$ for their correlations to be undetected in present data (Salmon and Hogan 1986), but may appear in larger samples. In the present model, hydrodynamic velocities may, however, swamp gravitational ones, making detailed predictions very model-dependent. Low-temperature components within lines would be a signature suggestive of thin cool pancakes as advocated here; it would be valuable to have high signal-to-noise ratio, high-resolution spectra of more individual lines to strengthen the case made by Chaffee *et al.* (1983). But if these are not found then conclusive verification of the ionization state of the gas may only come with a comparison of He lines with H lines in the same system—observations which must await the launch of Space Telescope.

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