COSMOLOGICAL CONDUCTIVE/COOLING FRONTS AS Lyα FOREST CLOUDS

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ABSTRACT

We propose a simple model for the origin and evolution of Lyα forest clouds based on cosmological conductive/cooling fronts. In this model the Lyα forest arises in the interfaces between the intergalactic medium and cold clouds that could be tentatively identified with protogalaxies. Most of the properties of the Lyα forest absorbers are reproduced with a very restricted number of assumptions. Among these are the correct range of H i column density, cloud sizes, and redshift, and H i column density distributions for the absorbers. Several predictions and implications of the model are briefly discussed.

Subject headings: intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The remarkable observational advances made in the last few years allow us to tackle the problem of the origin and evolution of Lyα forest clouds in a firmer and more quantitative manner. In brief, the available observational constraints that every model for the Lyα forest clouds should fulfill are the following. The typical range of hydrogen column density is $10^{12}$ cm$^{-2}$ to $10^{16}$ cm$^{-2}$ (Dobrzycki & Bechtold 1996). Doppler parameters are typically $b = 30$ km s$^{-1}$, even if some claims of much smaller values of $b$ have been made (Pettini et al. 1990; Carswell et al. 1991; Rauch et al. 1993; Giallongo et al. 1993). Lower limits on the sizes are provided by a small number of experiments using quasar pairs (Dinshaw et al. 1994; Bechtold et al. 1994) which generally agree that transverse sizes should be $\approx 100$ kpc.

Here we propose an alternative view of the origin and evolution of Lyα forest absorbers, based on the theory of conductive/cooling fronts described by Ferrara & Shchekinov (1993) (hereafter FS93). The basic idea is that Lyα forest clouds may represent the interface region between the intergalactic medium (IGM) and cold clouds that could be tentatively identified with protogalaxies. Since the IGM is in a thermally unstable state, the joint action of thermal conduction and radiative instabilities drives a cooling wave into the hot IGM. Thus, contrary to the common view in which thermal conduction should eventually lead to the evaporation and destruction of the cold phase, we argue that protogalaxies initiate the condensation process in gas which can be subsequently accreted by the galaxy itself. The relatively rarefied transition layer between the two phases represents a suitable environment for the formation of the Lyα forest absorption lines. Although very simple, the model is able to reproduce most of the properties of Lyα forest clouds with a very restricted number of assumptions.

2. CONDUCTIVE/COOLING FRONTS

In this section we describe briefly some results concerning conductive/cooling (CC) fronts following FS93 and Ferrara & Shchekinov (1996). We define a CC front as the interface between a hot and cold gas phase, whose structure is governed by the combined effects of thermal conduction and radiative cooling. As shown by FS93, dynamical effects (i.e., shocks) can be important at the initial stages of the front evolution when the conductive timescale is shorter than the dynamical timescale of the system. However, after this transient phase the evolution relaxes to a quasi-isobaric regime. We will therefore consider only evolved stages for which pressure equilibrium holds approximately. For the same reason, we consider only “classical” Spitzer conductivity, since saturation effects are important only in the initial evolutionary phases (FS93). We neglect magnetic fields, mostly because their existence and strength at high redshift are far from being established.

In the isobaric approximation, the hydrodynamic equations describing a CC front reduce to the energy equation, which could be cast in Lagrangian form as

$$ \frac{\partial T}{\partial t} + c_p^{-1} \mathcal{F} - \frac{\partial}{\partial q} \left( \chi \frac{\partial T}{\partial q} \right) = 0, \quad (2.1) $$

where $T$ is the gas temperature, $\mathcal{F}$ is the net cooling rate per unit mass, $c_p$ is the specific heat at constant pressure; $\chi = \kappa \rho / c_p$, where $\kappa = \eta T^{3/2}$ is the classical thermal conduction coefficient, is the reduced thermal conduction coefficient. The Lagrangian mass variable is

$$ q = \int_{x_0}^{x} dx \rho(x, t), $$

where for all $t$ the coordinate of a “reference” particle $x_0(t)$ is determined by the condition $v(x_0, t) = 0$. In equation (2.1) lengths are normalized to the Field length (Field 1965) (Lagrangian formulation), $q_0 = (\chi T c_p / \mathcal{F})^{1/2}$, and time to the cooling time $t_c = c_0 \sqrt{T / \mathcal{F}}$, both calculated for the hot medium.

The cooling function depends on the details of the microscopic processes responsible for the heating and cooling of the gas; for our purposes, however, it will be sufficient to consider a general form of $\mathcal{F}$ reproducing a two-phase medium with a cold stable, and a hot unstable, equilibrium. This assumption closely resembles the IGM, supposedly constituted by cold clouds in pressure equilibrium with a surrounding, thermally unstable, hot diffuse gas. The simplest analytical function that retains such characteristics is $\mathcal{F}(T) = T(1 - T)$; the point $T = 1$ is thermally unstable $(\partial \mathcal{F} / \partial T = -1)$, while $T = 0$ represents the thermally stable phase. In addition to the equilibrium points, this function also correctly mimicks the

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negative slope of the actual cooling function in the range $10^4$ K $\lesssim T \lesssim 10^6$ K.

Figure 1 shows the temporal evolution of the CC front, as obtained from the numerical solution of equation (2.1) with the above cooling function. Initially a cold cloud at $t = 0$ is immersed in the hot gas at $T = 1$. The evolution of the CC front induces a thermal wave in the cold medium and a cooling wave into the hot medium; the temperature profile is very steep because of the strong nonlinearity of the thermal wave propagation; the temperature profile is very steep because of the strong nonlinearity of the thermal wave propagation.

At about $t \approx t_c$, the thermal wave propagation is inhibited by radiative losses (see FS93), and the cloud now acts as a finite perturbation for the unstable hot gas, whose only possible fate is to condense. As the CC front moves away from the origin, a cooling wave develops ($t \approx 2t_c$); the profile of the wave becomes stationary and its shape corresponds to a quasi-linear thermal conductivity, in that $(\partial T/\partial q)^2 \ll |T(\partial^2 T/\partial q^2)|$. This fact suggests comparison of the numerical results with an analytical traveling wave solution of equation (2.1) obtained for linear conductivity ($\chi = \text{constant}$). Making the position $T(q, t) = T(\xi = q + 5Ut)$, substitution in equation (2.1) yields the solution

$$T(\xi) = 1 - \frac{1}{(1 \times e^{-\xi})^2}, \quad (2.2)$$

where $U$ is the propagation speed of the wave. In Figure 1 we have fitted the curve of equation (2.2) to the cooling wave, adjusting the parameter $U$ to take into account the fact that the exact solution is only quasi-linear; the agreement is remarkable for $U = 4/3 = \epsilon^{-1}$. Of course, it is not surprising that the value of $U$ is close to unity, since it can be seen from dimensional analysis that it must be $U \sim q_c/t_c = 1$, in our units. The evolution depends rather weakly on the detailed shape of $F$ as long as an unstable point does exist. We will use this approximation to study the interface between Ly$\alpha$ forest clouds and the IGM in the next section.

3. CONDUCTIVE/COOLING MODEL FOR Ly$\alpha$ FOREST ABSORBERS

To model Ly$\alpha$ forest clouds as cosmological CC fronts, it is necessary to adopt a model for the IGM. Ikeuchi & Ostriker (1986) (and more recently Giroux & Shapiro 1995) have studied in detail the thermal history of the IGM from the era of the reheating to the present; they conclude that the most plausible scenario requires that both photoionization and bulk mechanical heating (i.e., shocks) contribute to the heating. The IGM reionization epoch is still uncertain, but the limits on the Gunn-Peterson effect (Webb et al. 1992) suggest that it must have occurred at $z \approx 5$. Ikeuchi & Ostriker (1986) show that, if the reionization occurred at $z = 10$, for example, the IGM had already entered the adiabatic expansion phase at $z \approx 4$. Since we will mostly concentrate on the $z \lesssim 4$ epoch, we will assume in what follows that the IGM is adiabatic, and therefore temperature and pressure are $T(z) = T_0(1 + z)^{-2}$, $p(z) = p_0(1 + z)^{3/2}$; the local values are $T_0 = 3 \times 10^4$ K and $p_0 = 3 \times 10^{-2}$ cm$^{-3}$ K; we use the cosmology $\Omega = 1$ and $h_{100} = 0.5$; in addition, $\Omega_b = 0.03$.

Since the heat transport relies on the presence of a hot IGM, it is likely that CC fronts were generated immediately after the reionization epoch. Next, they propagate away from the cloud with velocity decreasing rapidly with redshift: $U \approx q_c/t_c \propto (1 + z)^{-3}$, assuming that IGM cooling is dominated at early epochs by inverse Compton scattering on the microwave background. A stationary cooling wave profile, similar to the one given in equation (2.2), will form after a few cooling times, as demonstrated in Figure 1; this requires that the Hubble time be larger than $t_c$, a condition satisfied for $z \geq 4$. If reionization occurred at $z = 10$, the distance traveled by the cooling wave at $z = 4$ is

$$d = (m_{H}m_{h})^{-1} \int_{4}^{10} dz \left(1 + z\right)^{-5/2} U^{-1}n_{-1}^{-1} = 60 \text{ kpc};$$

the cool material behind the wave is accreted by the parent protogalaxy at a rate $M_{\text{in}} \sim \rho_{\text{in}} t_{H} v_{\text{in}} n_{\text{in}} = 5 \times 10^{7} M_{\odot} \text{ Gyr}^{-1}$, where $t_{H}$ is the Hubble time at $z = 4$. As the front has reached the steady state, its width (of the order of $q_c$) is regulated only by the changes of the IGM parameters due to Hubble expansion; since $q_c \propto (1 + z)^{-2}$, the front shrinks as $z$ decreases (it can be shown that the interface reacts almost instantaneously to external changes).

The neutral hydrogen column density of the Ly$\alpha$ forest cloud, $N_{\text{H}_1}$, will be in general a function both of the impact parameter, $b$, at which the interface is intersected by the line of sight, and of redshift. Assuming spherical symmetry, with radial coordinate $r(q)$, the expression for $N_{\text{H}_1}$ is

$$N_{\text{H}_1}(b, z) = \frac{2}{m_{\text{H}}} \int_{\text{gph}} dq \left[1 - x(T(q, z), n(q, z))\right] r(q) \left(\frac{r(q)}{\sqrt{r^2(q) - b^2}}\right)^{1/2}, \quad (3.1)$$

The hydrogen ionization fraction $x$ has been derived under the assumption that ionization equilibrium is due to photo- and collisional ionizations and that the time variation of the diffuse UV flux is $J(z) = 10^{-35}[(1 + z)/3.5]^{2}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$.
The temperature profile follows from equation (2.2) and \( n(q) = p/kT(q) \); we have neglected geometrical corrections in the solution \( T(q) \) due to spherical geometry. The lower integration limit is the Lagrangian impact parameter implicitly defined by \( m_{\text{HI}} q(q) dq/n(q) = b - d \), while the upper limit is the characteristic size of the interface. The size of the central cold core is determined by the distance \( d \approx 60 \) kpc traveled by the front in the early stages of evolution; however, the value of the integral depends very weakly on any reasonable choice for \( d \). A sketch of the geometry is given in Figure 2. Impact parameters \( b \geq d \) are not considered because of the negligible contribution of the Ly\( \alpha \) forest cloud to the central damped Ly\( \alpha \) system.

Figure 3 shows the curves for \( N_{\text{HI}} \) from equation (3.1) as a function of \( q(b) \) for different redshifts. Therefore, \( q(b) = 0 \) corresponds in physical units to an impact parameter \( b = d \), and \( q(b) = 1 \) corresponds to \( b = d + \Delta r \), where \( \Delta r = q_{\text{HI}}/m_{\text{HI}} n \) is the Field length in physical units; \( \Delta r \) depends on redshift as

\[
l_{r} = \sqrt{\frac{\chi T_{\nu}}{T_{\nu}^{2}}} = 333(1 + z)^{-1} \text{ kpc} \tag{3.2}
\]

for the adopted IGM parameters.

The hydrogen column density is a rather flat function of \( q(b) \) for values \( q(b) \lesssim 0.1 \), i.e., close to the central cold cloud, and decreases roughly as \( q(b)^{-4} \) for \( z = 4 \) and less steeply for smaller values of \( z \). The values of \( N_{\text{HI}} \) are in the range \( 10^{12} \text{ cm}^{-2} \leq 3 \times 10^{16} \text{ cm}^{-2} \) for \( 0 \leq z \leq 4 \). An useful analytical approximation to the curves shown in Figure 3 between \( z = 0 \) and \( z = 3 \) is

\[
N_{\text{HI}}(q) = N_{\text{HI}}^{0} \left[ \frac{(1 + z)^{5}}{1 + (q/a)^{1+2}} \right], \tag{3.3}
\]

with \( N_{\text{HI}}^{0} = 7 \times 10^{12} \text{ cm}^{-2} \) and \( a = 0.1 \).

4. IMPLICATIONS

In the present model \( N_{\text{HI}} \) is a function both of redshift and of the impact parameter for the cloud; it decreases with decreasing \( z \) and with increasing \( b \); the variation range is \( 10^{12} \text{ cm}^{-2} \leq N_{\text{HI}} \approx 3 \times 10^{16} \text{ cm}^{-2} \) for \( 0 < z < 4 \). Therefore, below \( N_{\text{HI}} = 10^{12} \) we expect a turnoff in the distribution of the clouds; this prediction awaits an observational test from oncoming high-sensitivity observations with the Keck telescope.

The temperature is a function of the depth inside the cloud along the line of sight (see Fig. 2), with radial dependence as described by equation (2.2). Its range is bracketed by the temperature of the cold cloud (here assumed to be \( T_{c} = 10^{4} \text{ K} \)) and the temperature of the IGM, \( T(z) \) (roughly \( 10^{5} \text{ K} - 7 \times 10^{5} \text{ K} \)). For a given Ly\( \alpha \) forest cloud, the temperature is anticorrelated with \( N_{\text{HI}} \), since the inner regions are colder than the external ones. However, since this cold material is far from hydrostatic equilibrium in the gravitational field of the parent protogalaxy, it will be accelerated toward the center, acquiring bulk velocity that could reverse the sign of the \( T-N_{\text{HI}} \) correlation. This conclusion must be substantiated by fully hydrodynamical calculations.

An interesting feature of the model is the presence of a natural scale for the size of the clouds, the Field length \( l_{r} \) (eq. [3.2]). Thus, the size of Ly\( \alpha \) forest clouds is constrained directly by physical arguments. For the adopted model of the IGM, typical transverse sizes are \( \sim 50 \text{ kpc} \) and \( \sim 150 \text{ kpc} \), for \( z = 4 \) and \( z = 1 \), respectively. Hence, for a constant number of absorbers per comoving volume, the probability to detect a Ly\( \alpha \) forest cloud in a quasar pair should be higher at low redshifts if the signal-to-noise ratio is infinite (see below).

The expected redshift distribution of absorbers can be calculated as follows. The number of absorbers between \( z \) and \( z + dz \) is

\[
dN = N_{\text{sc}} dt \int_{b_{\min}}^{b_{\max}} db 2\pi b \frac{\pi N_{\text{sc}}}{H_{0}} (1 + z)^{1/2} b_{\min}^{a} dz, \tag{4.1}
\]

where \( N_{\text{sc}} = N_{0} (1 + z)^{5} \) is the density of absorbers. The maximum impact parameter, \( b_{\min} \), is determined by the observational threshold for detection of Ly\( \alpha \) forest absorption:
\( b_n = b(N_{HI}^{th}) \). For example, from Figure 3, at \( z = 3 \) and for \( N_{HI}^{th} = 10^{13} \text{ cm}^{-2} \), which represents a typical threshold for current observations, the maximum value of \( q(b) \) sampled is \( \sim 0.4 \) [there is an almost linear relation between \( q(b) \) and \( b \)]. For the previous value of \( N_{HI}^{th} \), a fit to the numerical results gives \( b_n \propto l_q(1 + z)^{\alpha} \). In \( 1 \leq z \leq 4 \) the best-fit value is \( \alpha = 1.4 \). For a higher value of \( N_{HI}^{th} \), the corresponding value of \( \alpha \) increases, i.e., the distribution becomes steeper. Upon substitution in equation (4.1), with \( \alpha = 1.4 \), we obtain \( dN/\ dN_{HI} \propto (1 + z)^{-1.3} \).

The index of the distribution is slightly smaller than the one found by Bechtold (1994) \((\gamma = 1.32 \pm 0.24)\) for a sample of lines complete to equivalent width \( W_{th} = 0.16 \text{ Å} \). According to her curves of growth, depending on the adopted Doppler parameter, this corresponds to \( 6 \times 10^{13} \text{ cm}^{-2} \equiv N_{HI} \approx 10^{14} \text{ cm}^{-2} \), about an order of magnitude larger than \( N_{HI}^{th} \). Since Bechtold has also noted a decreasing trend for \( \gamma \) with decreasing \( W_{th} \), it is reasonable to expect that for lower \( W_{th} \), the distribution flattens to a value similar to the one we have found. However, this physical effect can be difficult to disentangle from spurious line-blending effects (Trevese, Giallongo, & Camurani 1992).

The column density distribution for the absorbers is

\[
\frac{dN}{dN_{HI}} = 2\pi N_0 \int_0^{z_{th}} dz \frac{db}{dq}(N_{HI}, z) \frac{db}{dq}(N_{HI}, z) \frac{dt}{dz}.
\]

Using the definition of the Lagrangian coordinate \( q \) to eliminate \( b \), and equation (3.3) to eliminate \( q \), we get \( dN/dN_{HI} \propto N_{HI}^F f(N_{HI}, z_m) \).

Numerical integration shows that the function \( f(N_{HI}, z_m) \) depends very weakly on \( N_{HI} \), and can be approximated by a power law with index \(-0.1\). Therefore, from equation (4.3) we find that the column density distribution for the \( \text{Ly} \alpha \) forest clouds is also a power law with index \( \beta = -2.1 \). The value of \( \beta \) is independent of \( z_m \) and somewhat higher than the one \((\beta = -1.4)\) obtained by Dobrzycki & Bechtold (1996).

Two additional consequences of our model can be outlined: (1) \( \text{Ly} \alpha \) forest clouds should be quite often associated with damped \( \text{Ly} \alpha \) clouds, from which they originate, at least at high \( z \). At low \( z \), damped \( \text{Ly} \alpha \) systems can be destroyed by violent episodes of star formation (Salpeter 1995) and isolated “fossil” \( \text{Ly} \alpha \) forest clouds remain; (2) metal abundances at the level detected by Tytler (1995) could be easily reproduced by our model if part of the \( \text{Ly} \alpha \) forest gas is coming from a metal-rich protogalaxy, or if the IGM is polluted by metals associated with the same blast waves responsible for its bulk heating.

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REFERENCES

Bechtold, J. 1994, ApJS, 91, 1
Bechtold, J., Crotts, A. P. S., Duncan, R. C., & Fang, Y. 1994, ApJ, 437, L83
Carswell, R. F., Lanzetta, K. M., Parnell, H. C., & Webb, J. K. 1991, ApJ, 371, 36
Dinshaw, N., Impey, C. D., Foltz, C. B., Weymann, R. J., & Chaffee, F. H. 1994, ApJ, 437, L87
Dobrzycki, A., & Bechtold, J. 1996, ApJ, 457, 102
Ferrara, A., & Shchekinov. Yu. 1993, ApJ, 417, 595 (FS93)
———. 1996, MNRAS, submitted
Field, G. B. 1965, ApJ, 142, 531
Giallongo, E., Cristiani, S., Fontana, A., & Trevese, D. 1993, ApJ, 416, 137
Giroux, M., & Shapiro, P. R. 1995, ApJS, 102, 191
Ikeuchi, S., & Ostriker, J. P. 1986, ApJ, 301, 522
Pettini, M., Hunstead, R. W., Smith, L. J., & Mar, D. P. 1990, MNRAS, 246, 545
Rauch, M., Carswell, R. F., Webb, J. K., & Weymann, R. J. 1993, MNRAS, 260, 589
Salpeter, E. E. 1995, in ASP Conf. Ser. 80, The Physics of the Interstellar and Intergalactic Medium, ed. A. Ferrara, C. F. McKee, C. Heiles, & P. R. Shapiro (San Francisco: ASP), 264
Tetreve, D., Giallongo, E., & Camurani, L. 1992, ApJ, 398, 491
Tytler, D. 1995, in Proc. ESO QSO Absorption Line Workshop, ed. G. Meylan (Garching: ESO), 299
Webb, J. K., Barcons, X., Carswell, R. F., & Parnell, H. C. 1992, MNRAS, 255, 319