Where are the missing cosmic metals ?

Andrea Ferrara[1], Evan Scannapieco[2] & Jacqueline Bergeron[3]

ABSTRACT

The majority of the heavy elements produced by stars 2 billion years after the Big Bang (redshift $z \approx 3$) are presently undetected at those epochs. We propose a solution to this cosmic 'missing metals' problem in which such elements are stored in gaseous halos produced by supernova explosions around star-forming galaxies. By using data from the ESO/VLT Large Program, we find that: (i) only 5%-9% of the produced metals reside in the cold phase, the rest being found in the hot ($T = 10^{5.8-6.4}$ K) phase; (ii) 1%-6% (3%-30%) of the observed C IV (O VI) is in the hot phase. We conclude that at $z \gtrsim 3$ more than 90% of the metals produced during the star forming history can be placed in a hot phase of the IGM, without violating any observational constraint. The observed galaxy mass-metallicity relation, and the intergalactic medium and intracluster medium metallicity evolution are also naturally explained by this hypothesis.

Subject headings: (galaxies:) intergalactic medium – supernovae: general – galaxies: stellar content – stars:early-type

1. Motivation

In its original formulation (Pettini 1999), the 'missing metals' problem was stated as follows. Studies of the comoving luminosity density of distant galaxies allow us to trace the cosmic star formation density (or history, SFH), $\dot\rho_\star(z)$, up to redshift $z_{max} \approx 7$. Assuming an initial mass function of such stars (IMF), one can compute the specific fraction of heavy elements ('metals') they produce, y, and derive the metal production rate $\dot\rho_Z(z) = y\dot\rho_\star(z)$, whose integral from z_{max} gives the density of cosmic metals in units of the critical density, Ω_Z^{sfh}, at any given z. Early searches in cosmic structures for which the metal/baryon mass ratio[1] (metallicity, $Z = \Omega_Z/\Omega_b$) can be derived either via intergalactic gas quasar absorption line experiments (Damped Lyα Absorbers [DLAs] or the Lyα 'forest') or through direct spectroscopic studies (Lyman Break Galaxies [LBGs]) have

[1]SISSA/International School for Advanced Studies, Via Beirut 4, I-34914, Trieste, Italy.

[2] Kavli Institute for Theoretical Physics, Kohn Hall, UC Santa Barbara, Santa Barbara, CA 93106.

[3]Institut d'Astrophysique de Paris - CNRS, 98bis Boulevard Arago, 75014 Paris, France.

[1]When necessary, we use the following cosmological parameters $(\Omega_\Lambda, \Omega_m, \Omega_b, n, \sigma_8, h) = (0.7, 0.3, 0.044, 1, 0.9, 0.71)$, consistent with *WMAP* results (Spergel et al. 2003), a solar metallicity $Z_\odot = 0.0189$ by mass, and adopt the notation $Y_x = Y/10^x$

found that only $\Omega_Z^{obs} \lesssim 0.20\Omega_Z^{sfh}$ is stored in these components, *i.e.,* the large majority of the metals are 'missing'. An analogous missing metal problem is also found by considering in a self-consistent manner the star formation rates and metallicities of DLAs alone (Wolfe et al. 2003, Prochaska et al 2003). Newly available high-quality data allow a more precise analysis of the problem.

2. Stating the problem

To re-evaluate Ω_Z^{sfh} we use the most recent SFH compilation (Bouwens et al. 2004) corrected upwards for the effects of dust obscuration by the prescribed (Reddy & Steidel 2004) value of 4.5 at $z \gtrsim 3$ and adopt $y = 1/42$. Integration of $\dot\rho_Z(z)$ to $z = 2.3$ yields $\Omega_Z^{sfh} = 1.84 \pm 0.34 \times 10^{-5}$. Where should we look for these metals ?
The most obvious locations are the galaxies used to derive the SFH, *i.e.,* LBGs. These are characterized (Reddy & Steidel 2004) by a mean comoving number density of $6 \times 10^{-3} h^3$ Mpc^{-3} and $Z = 0.6 Z_\odot = 0.0113$. Stellar masses can be constrained only by assuming a range of star formation histories of the form $SFR(t) \propto \exp(-t/\tau)$ and therefore they are somewhat uncertain. According to Shapley et al. 2005, they should be in the range $0.6 - 6 \times 10^{10} M_\odot$. Assuming the best fit value $M_\star = 2 \times 10^{10} M_\odot$, we get $\Omega_Z^{lbg} = 3.4 \times 10^{-6} M_{\star,10} \approx 0.18\Omega_Z^{sfh}$. If metals are not in LBG stars or gas, they could be in DLAs or the IGM. The metal content of DLAs is derived by noting that (Rao & Turnsheck 2000, Prochaska & Wolfe 2000) at $z \approx 3$ their neutral ($\approx$ total) gas density $\Omega_g^{dla} = 10^{-3}$ and metallicity $Z = 3.8 \times 10^{-4}$ combine to give $\Omega_Z^{dla} = 3.8 \times 10^{-7} < \Omega_Z^{obs} \ll \Omega_Z^{sfh}$; we can therefore neglect their contribution. In the following, we correct for LBG contribution by (re)defining the cosmic density of missing metals $\Omega_Z^{sfh} \equiv \Omega_Z^{sfh} - \Omega_Z^{lbg}$.
Hence, the missing metals should be found outside the main body of galaxies or DLAs. There are essentially two possibilities: (a) they could reside in the Lyα forest, or (ii) in the halos of the galaxies that have produced and ejected them. Note that the distinction between these two components is somewhat ambiguous. Our working definition is that galactic halos are gravitationally bound structures around galaxies; they are special sites affected by galactic winds.

The most widely studied tracers of Lyα forest metallicity are C IV and O VI absorption lines. The fraction of the critical density ρ_c contributed by a given element ion, E_i, of mass m_E residing in the Lyα forest is given by

$$\Omega_{E_i}^{ly\alpha} = \frac{H_0}{\rho_c c} \frac{\sum N_{E_i}}{\sum \Delta X} m_E \tag{1}$$

where $\Delta X(z_+, z_-) = \int_{z_-}^{z_+} dz (1+z)^2 E(z)^{-1}$ is the absorption distance (Bahcall & Peebles 1969), with $E(z) = [\Omega_\Lambda + \Omega_m (1+z)^3]^{1/2}$; sums are performed over all the redshift intervals $z_- < z < z_+$ over which an ion column density N_{E_i} is detected. To determine $\Omega_{\rm OVI}^{ly\alpha}$ and $\Omega_{\rm CIV}^{ly\alpha}$, we use data from the ESO VLT Large Program[2] (Bergeron et al. 2002) which provides high S/N, high resolution

[2]http://www2.iap.fr/users/aracil/LP/

spectra of an homogeneous sample of 19 QSOs in $1.7 < z < 3.8$; $\Omega^{ly\alpha}_{\rm OVI}$ is currently available for four LP lines of sight (Bergeron et al. 2002, Bergeron & Herbert-Fort 2005), for which we find $\Omega^{ly\alpha}_{\rm OVI} = 1.3 \times 10^{-7}$; two other recent estimates (Simcoe, Sargent & Rauch 2004, Carswell, Schaye & Kim 2002), give $\Omega^{ly\alpha}_{\rm OVI} = (1.1, 0.9) \times 10^{-7}$. We adopt the sightline–weighted mean of the three values allowing for the largest error, $\Omega^{ly\alpha}_{\rm OVI} = 1.1 \pm 0.3 \times 10^{-7}$. From the C IV absorber distribution (Aracil et al. 2004, Scannapieco et al. 2005) in the column density range $12 < \log N_{\rm CIV} < 16$ we obtain $\Omega^{ly\alpha}_{\rm CIV} = 7.5 \pm 2.2 \times 10^{-8}$ (statistical error). This value is about two times higher than previous determinations (Songaila 2001; Simcoe, Sargent & Rauch 2004, Schaye et al 2003) which could not account for the contribution of strong ($\log$ C IV > 14) absorption systems. Combining the average measured $N_{\rm CIV}$–N_{HI} and $N_{\rm OVI}$–N_{HI} correlations (Aracil et al. 2004) with the measured distribution of weak HI absorbers (Petitjean et al 1993), we have checked that systems with $\log N_{\rm CIV} < 12$ contribute less than 1%, well within the quoted error. For a (meteoritic) solar carbon logarithmic abundance (in number) $A_C = 8.52$ with respect to hydrogen ($A_H = 12$), we conclude that only a fraction $\Omega^{ly\alpha}_{\rm CIV}/\Omega^{sfh}_C = 2.4 \times 10^{-2}$ of the produced carbon is observed in the C IV state. Repeating the procedure for O ($A_O = 8.83$), gives a ratio $\Omega^{ly\alpha}_{\rm OVI}/\Omega^{sfh}_O = 1.3 \times 10^{-2}$. To account for all uncertainties above, we will consider values in the range $1.4 \times 10^{-2} < \Omega^{ly\alpha}_{\rm CIV}/\Omega^{sfh}_C < 4.0 \times 10^{-2}$ and $8.1 \times 10^{-3} < \Omega^{ly\alpha}_{\rm OVI}/\Omega^{sfh}_O < 2.1 \times 10^{-2}$.

We now determine the physical conditions of the gas hiding the missing C and O. Numerical simulations (Davé et al. 2001) suggest that the intergalactic medium [IGM] might be a two-phase system made by a cool ($T_c \approx 10^{4-4.5}$ K), photoionized phase, and a hot, collisionally ionized one. We impose the following conditions separately for each ion (C IV ,O VI) and element (C,O): (1) the observed ionic abundance is the sum of the abundances in the two phases; (2) the SFH-produced element abundance is the sum of the element abundances in the two phases; (3) the elements are in the same abundance ratios in the two phases. More explicitly, these conditions can be mathematically expressed as

$$f^c_C\Omega^c_C + f^h_C\Omega^h_C = \Omega^{ly\alpha}_{\rm CIV} \tag{2}$$

$$f^c_O\Omega^c_O + f^h_O\Omega^h_O = \Omega^{ly\alpha}_{\rm OVI} \tag{3}$$

$$\Omega^c_C + \Omega^h_C = \Omega^{sfh}_C \tag{4}$$

$$\Omega^c_O + \Omega^h_O = \Omega^{sfh}_O \tag{5}$$

$$\Omega^c_C - A\Omega^c_O = 0 \tag{6}$$

$$\Omega^h_C - A\Omega^h_O = 0 \tag{7}$$

After some simple algebra, the above equations reduce to:

$$\frac{\Omega^{ly\alpha}_{\rm CIV}/\Omega^{sfh}_C - f^h_C}{f^c_C - f^h_C} = \frac{\Omega^{ly\alpha}_{\rm OVI}/\Omega^{sfh}_O - f^h_O}{f^c_O - f^h_O}, \tag{8}$$

where $f^j_i \equiv f^j_i(\Delta_j, T_j, \mathcal{U}_j)$ is the ionization correction for the considered ion (C IV or O VI) of a given element ($i = C, O$) in the cold or hot phase, ($j = c, h$), respectively; the overdensity, Δ_j and temperature, T_j, of the two phases are the unknowns of the problem; finally, A is the abundance ratio of the two elements. We complement these conditions by further imposing that the pressure of the cool phase does not exceed that of the hot one and assuming a temperature-density relation for the cold phase $T = T_0 \Delta_c^\gamma$, (with $T_0 = 2 \times 10^4$ K and $\gamma = 0.3$), as inferred from the Lyα forest data. The value of the photoionization parameter, $\mathcal{U}_j = n_\gamma / n_j$, is fixed by the ionizing photon density n_γ of the assumed UV background spectrum (Haardt & Madau 1996) shifted so that the intensity at 1 Ryd is $J_\nu = 0.3 \times 10^{-21}$ erg s^{-1} Hz^{-1} = 0.3 J_{21}, corresponding to a hydrogen photoionization rate $\Gamma = 0.84 \times 10^{-12}$s^{-1} = 0.84 Γ_{12}, in agreement with Bolton *et al.* 2005. Finally, we warn that deviations from solar abundances might be possible, and indeed there are hints that oxygen might be overabundant (Telfer et al. 2002; Bergeron et al. 2002); here we neglect this complication.

3. A possible solution

By solving eq. 8, we obtain the results plotted in Fig. 1. The hot phase is characterized by a wide density range, $\log \Delta_h > 0.4$ and a restricted temperature range $5.8 < \log T_h < 6.4$. We find that: (i) only 5%-9% of the produced metals reside in the cold phase, the rest being found in the hot phase; (ii) 1%-6% (3%-30%) of the observed C IV (O VI) is in the hot phase. We conclude that more than 90% of the metals produced during the star forming history can be placed in a hot phase of the IGM, without violating any observational constraint. To further constrain the hot phase parameter range, we have searched in the LP C IV line list for components with large Doppler parameters. We find no lines with $b_{\rm CIV} \geq 26.5$ km s^{-1}, corresponding to $\log T_h > 5.7$; this result seems to exclude the high density and temperature region of the allowed parameter space in the middle panel of Fig. 1. We checked that the above findings are insensitive to variations of Γ_{12} of $\pm 50\%$; however, O VI /C IV ratios in the cold phase might depend on the UVB shape around 4 Ryd.

The derived values of T_h and Δ_h are suggestive of regions likely to be found around galaxies; moreover, 10^6 K gas temperature would have a scale height of > 10 kpc, hence it cannot be confined in the disk. To test this hypothesis we resort to cosmological simulations. As an illustration, Fig. 2 shows the temperature and velocity structure in a 2D cut through the center of a simulated galaxy (we used the multiphase version [Marri & White 2003] of the GADGET2 code to simulate a comoving $10h^{-1}$ Mpc^3 cosmic volume) at redshift $z = 3.3$; its total (dark + baryonic) mass is $2 \times 10^{11} M_\odot$, the star formation rate $\approx 20 M_\odot$ yr^{-1}. This galaxy has been selected to match LBG properties, but it is not unusual in the simulation volume. As often observed in LBGs, a strong galactic wind is visible, whose expansion is counteracted by energy losses due to cooling and gravity, and ram pressure exerted by the infalling gas. Infall is particularly effective at confining the wind into a broadly spherical region of physical radius ≈ 300 kpc, into which cold infalling streams of gas penetrate. Inside such wind-driven bubble the temperature (Fig. 2) is roughly constant $T \approx 10^6$ K, whereas the density spans values of $0 < \log \Delta < 5$ [$\Delta(z = 3.3) = 1$ corresponds to $\approx 2 \times 10^{-5}$ cm^{-3}]. The cool phase is evident in the outer boundary of the bubble, where cooling interfaces arise from the interaction with infalling streams. Hence halos of LBGs seem to meet the requirements as repositories of missing metals.

Additional support for this conclusion comes from studies of the correlation properties of C IV and O VI absorbers (Pichon et al 2003, Aracil et al. 2004, Bergeron & Herbert-Fort 2005), which conclude that: (i) O VI absorption in the lowest density gas is usually (about 2/3 of the times) located within $\approx 300 - 400$ km s^{-1} of strong H I absorption lines; (ii) the C IV correlation function is consistent with metals confined within bubbles of typical (comoving) radius $\approx 1.4h^{-1}$ Mpc in halos of mass $M \geq 5 \times 10^{11} M_\odot$ at $z = 3$. If each such objects hosts one bubble, the cosmic volume filling factor of metals is $f_Z = 11\%$; it follows that halo metallicity is $\Omega_Z^{sfh}/f_Z\Omega_b = 0.165 Z_\odot$. A temperature of $\log T_h = 5.8$ corresponds to H I (O VI) Doppler parameters $b_{\rm HI} = 102$ ($b_{\rm OVI} = 25.5$) km s^{-1} and to $N_{\rm OVI}/N_{\rm HI} = 3$; absorbers with $\log N_{\rm OVI} = 13$ are detectable for $b_{\rm OVI} = 25.5$ km s^{-1} but the corresponding $\log N_{\rm HI} = 12.4$ ones for $b_{\rm HI} = 102$ km s^{-1} are not. This raises the possibility of finding O VI absorbers without associated H I .

4. Implications

The scenario proposed leads to several interesting consequences. First, metals produced by LBGs do not seem to be able to escape from their halos, due to the confining mechanisms mentioned above. This is consistent with the prediction (Ferrara, Pettini & Shchekinov 2000) that galaxies of total mass $\mathcal{M} > 10^{12}(1+z)^{-3/2} M_\odot$ do not eject their metals into the IGM. Interestingly, the metallicity-mass relation recently derived from the SDSS (Tremonti et al. 2004) shows that galaxies with *stellar* masses above $3 \times 10^{10} M_\odot$ (their total mass corresponds to $\mathcal{M}$ for a star formation efficiency $f_\star = 0.2$) chemically evolve as "closed boxes," *i.e.,* they retain their heavy elements. Second, the nearly constant ($2 \leq z \leq 5$, $Z \approx 3.5 \times 10^{-4} Z_\odot$) metallicity of the low column density IGM (Songaila 2001) is naturally explained by the decreasing efficiency of metal loss from larger galaxies. Early pollution from low-mass galaxies allows a sufficient time for metals to cool after ejection; however, the majority of metals in LBG halos at lower redshifts are still too hot to be detected. Hence their contribution to the metallicity evolution of the IGM cannot be identified by absorption line experiments, which mostly sample the cool phase of the forest. Third, the rapid deceleration of the wind results either in a quasi-hydrostatic halo or in a 'galactic fountain' if radiative losses can cool the halo gas. In both cases this material is very poorly bound and likely to be stripped by ram pressure if, as it seems reasonable, the galaxy will be incorporated in the potential well of a larger object (galaxy group or cluster) corresponding to the next level of the hierarchical structure growth. Turbulence and hydrodynamic instabilities associated with this process are then likely to efficiently mix the metals into the surrounding gas within approximately a sound crossing time of ~ 1 Gyr, or $\Delta z \approx 0.5$. If metals produced and stored in LBG halos by $z = 2.3$ end up in clusters, than the average metallicity of the intracluster medium is $Z_{ICM} = \Omega_Z^{sfh}/\Omega_{ICM} = 0.31 Z_\odot$, having assumed (Fukugita, Hogan & Peebles 1998) $\Omega_{ICM} = 0.0026 h_{70}^{-1.5}$. Not only is this number tantalizingly close to the observed value at $z = 1.2$ (Tozzi et al. 2003), but we also predict that little evolution will be found in the ICM metallicity up to $z \approx 2$ as essentially all the metals that could have escaped galaxies during cosmic evolution had already done so by this epoch.

We thank P. Rosati for discussions and A. Fangano for help with data analysis. We acknowledge partial support from the Research and Training Network 'The Physics of the Intergalactic Medium' set up by the European Community under the contract HPRN-CT2000-00126 RG29185. This work has been completed during the KITP Program "Galaxy-IGM Interactions", funded by NSF Grant PHY99-07949, whose support is kindly acknowledged.

REFERENCES

Aracil, B., Petitjean, P., Pichon, C. & Bergeron, J. 2004, A&A, 419, 811

Bahcall, J. & Peebles, J. 1969, ApJ, 156, L7

Bergeron, J., Aracil, B., Petitjean, P. & Pichon, C. 2002, A&A, 396, L11

Bergeron, J. & Herbert-Fort, S. 2005, astro-ph/0506700

Bolton, J. S., Haehnelt, M. G., Viel, M., Springel, V. 2005, MNRAS, 257, 1178

Bouwens, R. J. et al. 2004, astro-ph/0409488 (2004)

Carswell, B., Schaye, J. & Kim, T.-S. 2002, ApJ, 578, 43

Davé et al. 2001, ApJ, 552, 473

Ferrara, A., Pettini, M. & Shchekinov, Y. 2000, MNRAS, 319, 539

Fukugita, M., Hogan, C. J. & Peebles, P. J. E. 1998, ApJ, 503, 518

Haardt, F. & Madau, P. 1996, ApJ, 461, 20

Marri, S. & White, S. D. M. 2003, MNRAS, 345, 561

Petitjean, P., Webb, J. K., Rauch, M., Carswell, R. F., & Lanzetta, K. 1993, MNRAS, 262, 499

Pettini, M. *ESO Workshop, Chemical Evolution from Zero to High Redshift*, 233-247 (1999)

Pichon, C., Scannapieco, E., Aracil, B., Petitjean, P., Aubert, D., Bergeron, J. & Colombi, S. 2003, ApJ, 597, L97

Prochaska, J. X. & Wolfe, A. M. 2000, ApJ, 533, L5

Prochaska, J. X., Gawiser, E., Wolfe, A. M., Castro, S. & Djorgovski, S. G. 2003, ApJL, 595, L9

Rao, S. M. & Turnshek, D. A. 2000, ApJS, 130, 1

Reddy, N. A. & Steidel, C. C. 2004, ApJ, 603, L13

Savage, B. D. & Semback, K. R. 1996, ARA&A, 34, 279

Scannapieco, E. et al., preprint, 2005

Schaye, J., Aguirre, A., Kim, T.-S., Theuns, T., Rauch, M. & Sargent, W. L. W. 2003, ApJ, 596, 768

Shapley, A. E., Steidel, C. C., Erb, D. K., Reddy, N. A., Adelberger, K. L., Pettini, M., Barmby, P., Huang, J. 2005, ApJ, 626, 698

Simcoe, R. A., Sargent, W. L. W. & Rauch, M. 2004, ApJ, 606, 92

Songaila, A. 2001, ApJ, 561, L153

Spergel, D. N. et al. 2003, ApJ, 148, 175

Telfer, R. C., Kris, G. A., Zheng, W., Davidsen, D. A. & Tytler, D. 2002, ApJ, 579, 500

Tozzi, P., Rosati, P., Ettori, S., Borgani, S., Mainieri, V. & Norman, C. 2003, ApJ, 593, 705

Tremonti, C. A. et al. 2004, ApJ, 613, 898

Wolfe, C. A., Gawiser, E. & Prochaska, J. X. 2003, ApJ, 593, 235

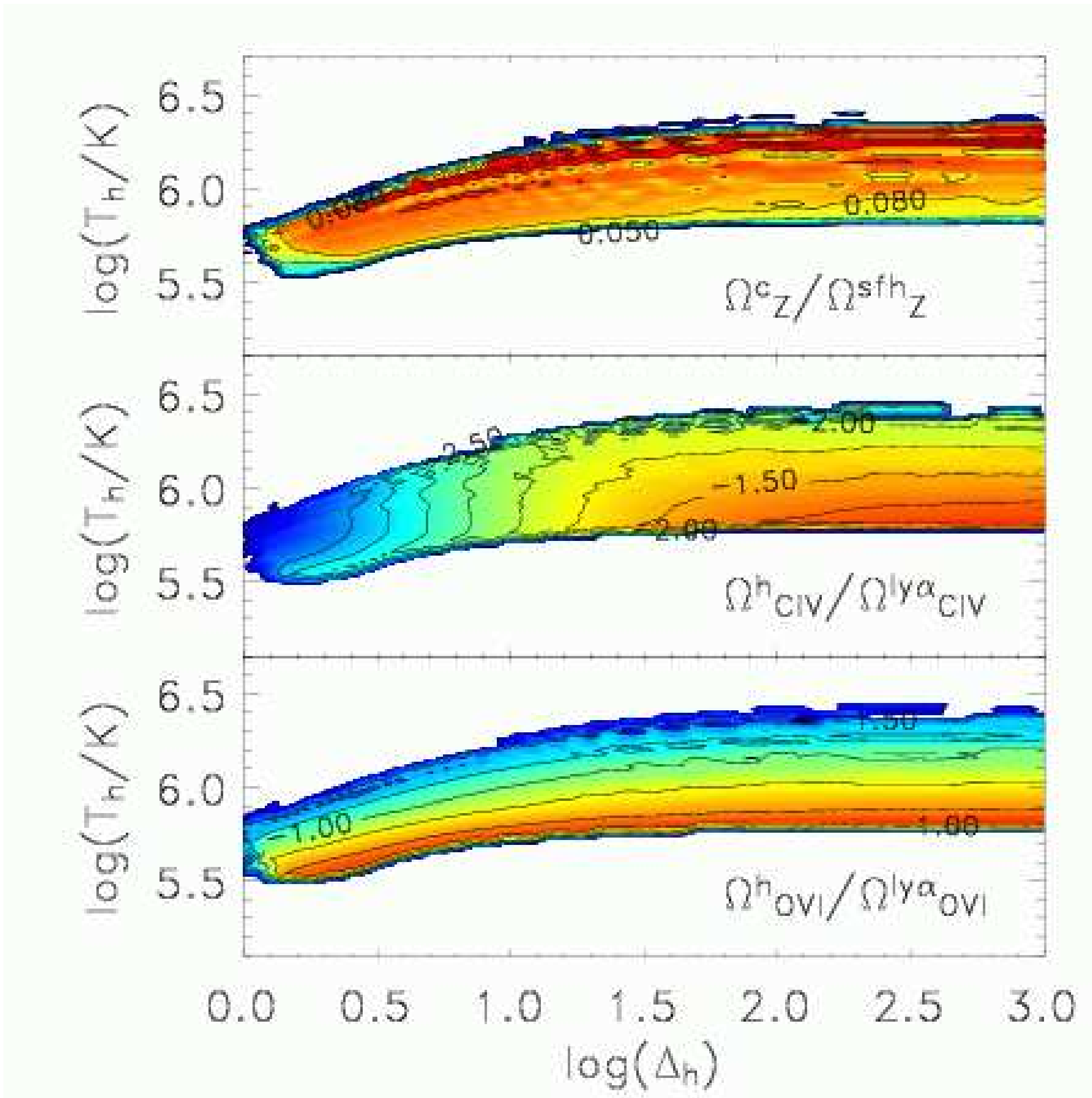

Fig. 1.— Allowed hot phase gas temperature, T_h, and overdensity, Δ_h, regions. Also shown are the corresponding isocontours of the $\Omega_Z^c/\Omega_Z^{sfh}$ (*upper panel*), $\Omega_{\rm CIV}^h/\Omega_{\rm CIV}^{ly\alpha}$ (*middle panel*) and $\Omega_{\rm OVI}^h/\Omega_{\rm OVI}^{ly\alpha}$ (*bottom panel*).

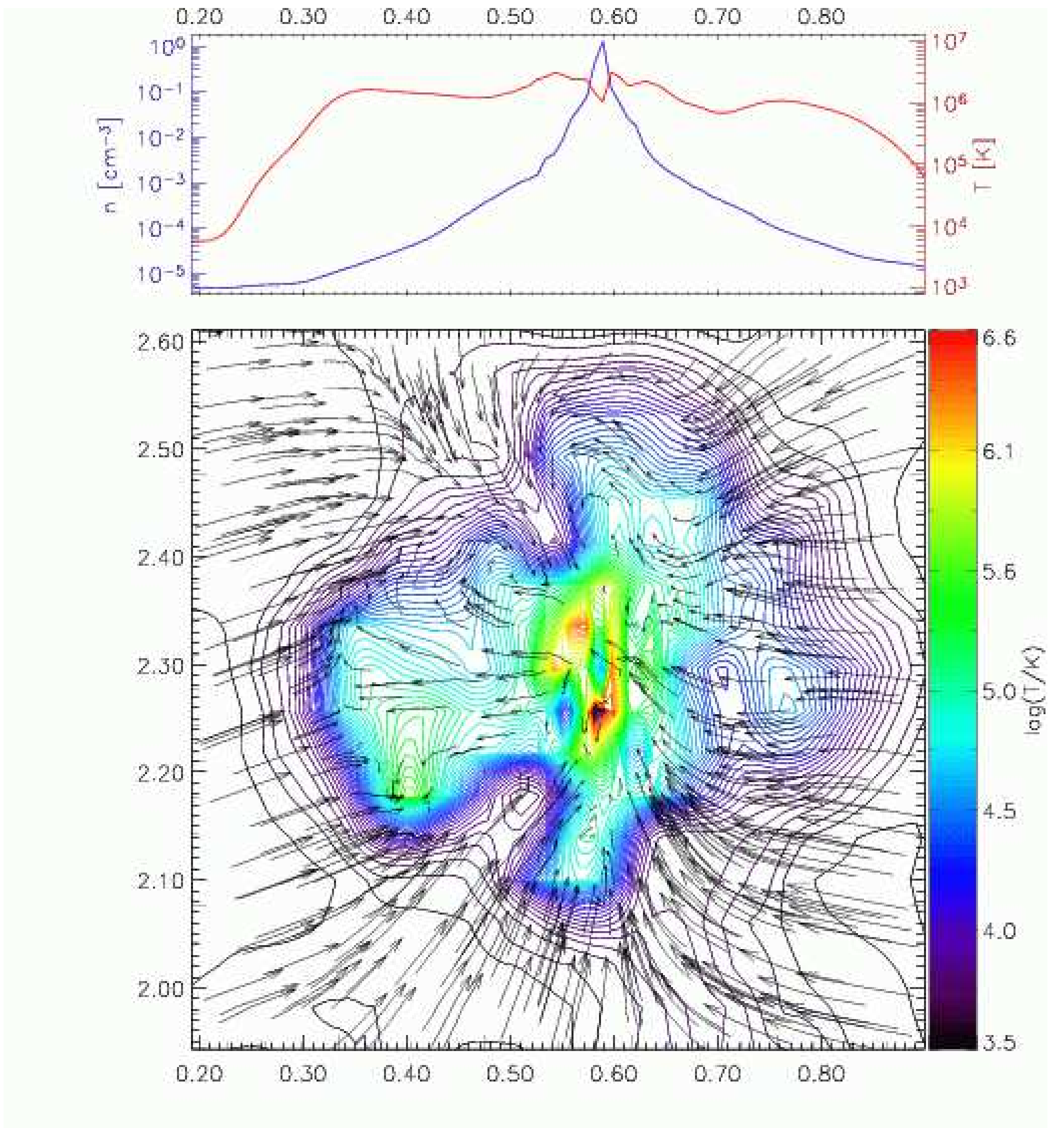

Fig. 2.— *Bottom panel:* Temperature map (physical Mpc units) of a plane through the center of a simulated starburst galaxy at $z = 3.3$ with properties typical of Lyman Break Galaxies; longest velocity vectors correspond to $v = 150$ km s^{-1}. *Upper panel:* 1D cuts parallel to the horizontal axis and passing through the center of the map in the bottom panel showing the gas density (blue) and temperature (red)