Part 5
HIGH REDSHIFT: THEORY AND OBSERVATIONS

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‘觀’ — *guān* — ‘*to observe*’

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Probing Galaxies through Quasar Absorption Lines
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Galaxies, intergalactic absorption lines, and feedback at high redshift

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Abstract. The galaxy-IGM part of the Lyman-break survey currently consists of measured redshifts for more than 1000 galaxies with redshift $1.5 \lesssim z \lesssim 3.5$ along the sight-lines to 25 background QSOs. One of the goals of the survey was to measure the influence on the intergalactic medium of energetic feedback from star and black-hole formation. This talk begins with a description of the observed correlations between galaxies and intergalactic absorption lines and ends with a discussion of whether any of the observations provide clear evidence for Mpc-scale superwinds. Although our own observations remain fairly ambiguous, other observations strongly disfavour a very high redshift ($z \sim 10$) for the creation of intergalactic metals.

1. Introduction

Fig. 1 illustrates the subject of this talk in a simple way. We would like to determine which cartoon resembles the Universe at high redshift more closely. The left panel shows data from Cen & Ostriker's numerical simulation of the evolving IGM. Gas settles into a filamentary pattern, streams into galaxies, and is peacefully converted into stars. The right panel is similar, except the energy released by each galaxy's supernovae and central black hole creates an enormous blast wave that sends metal-enriched gas back into its surroundings. Distinguishing between these possibilities is important, because standard models of galaxy formation cannot reproduce many basic observations† unless something heats and disrupts the gas near galaxies (although see Ari Maller's contribution for an alternate solution). Establishing or ruling out the existence of "superwinds" would have far-reaching implications.

One approach, taken by Rauch (this volume) and others, is to look for statistical differences between the observed intergalactic absorption in QSO spectra and the predictions of a windless scenario. A simple calculation shows the difficulty of this approach. Suppose every Lyman-break galaxy (LBG) at redshift $z \sim 3$ were surrounded by a spherical wind with a time-averaged radius of $1h^{-1}$ co-moving Mpc. This is the maximum radius allowed by even the most optimistic assumptions about the available energy (Adelberger 2002). Then the volume filling-fraction of winds would be only 1.7% for the observed LBG co-moving number density of $4 \times 10^{-3} h^3$ Mpc^{-3}. Galaxies too faint to be selected as LBGs would presumably increase the filling fraction somewhat, but still the impact of the tiny disturbed regions on the overall statistics of the IGM would be small and difficult to discern. This is especially true since absorption lines in the disturbed and undisturbed regions trace the same large-scale structure and are both produced by gas that has settled to similar temperatures of a few$\times 10^4$ K near the bottleneck in the

† Disk galaxies' sizes, the shape of the luminosity function, the fraction of baryons that have been crushed into stars, the X-ray cluster temperature-luminosity relationship, the existence of red galaxies at high redshift, etc.

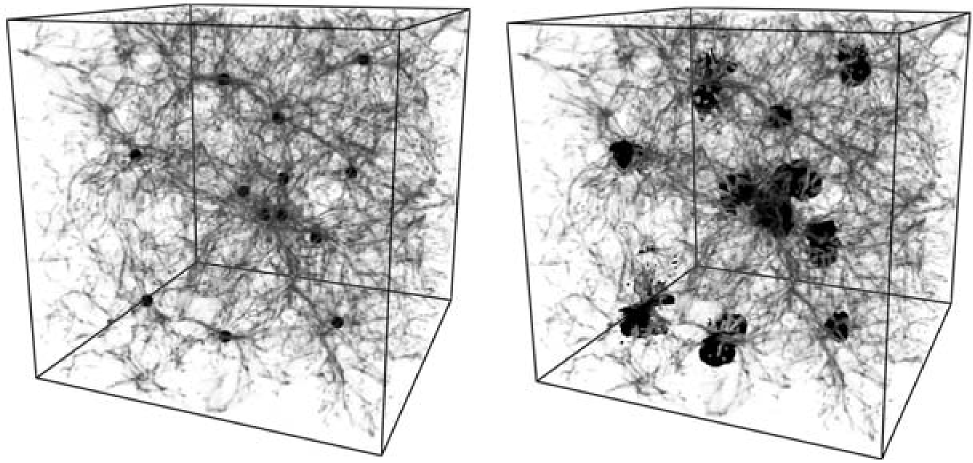

Figure 1. Cartoon illustration of the question that motivated us. The filaments in the boxes show the distribution of gas in a numerical simulation of Cen & Ostriker. Are galaxies (black spheres in left panel) surrounded by expanding superwinds, as illustrated by the large black regions in the right panel?

cooling curve; their power spectra will therefore have nearly indistinguishable shapes in the large k and small k limits.

We adopted an alternate approach. Since a weak signal is easier to detect if one knows where to look, we decided to measure the redshifts of galaxies near QSO sight-lines and focus our attention on the $\sim 2\%$ of the IGM that lies within 1 Mpc of LBGs. Our sample currently consists of spectroscopic redshifts for more than 1000 galaxies with $1.8 \lesssim z \lesssim 3.5$ that lie in fields containing 25 QSOs. Over 500 CIV systems were detectable in our QSO spectra.

A detailed analysis of the survey can be found in Adelberger *et al.* (2005c). Here is a brief summary of their main empirical results. The interpretation will be discussed afterwards.

• The gas that lies within 40 kpc of LBGs produces extremely strong absorption lines ($N_{\rm CIV} \gg 10^{14}$ cm^{-2}) in the spectra of background galaxies and QSOs. The large equivalent widths of the CIV absorption in low-resolution spectra imply that the absorbing material has a range of velocities of at least $\Delta v = 260$ km s^{-1}. The absorption produced by this gas is similar to the interstellar absorption seen in LBGs' spectra, suggesting the LBGs' outflowing "interstellar" gas may actually lie at radii approaching 40 kpc.

• For roughly half of the LBGs, CIV absorption lines with equivalent width $N \sim 10^{14}$ cm^{-2} are observed out to impact parameters of ~ 80 kpc. This implies that roughly one-third of all "intergalactic" absorption lines with $N \gtrsim 10^{14}$ cm^{-2} are produced by gas that lies within ~ 80 kpc of an LBG. Galaxies too faint to satisfy our selection criteria could easily account for the remainder. In some cases the absorbing gas has substructure on half-kpc scales.

• The cross-correlation function of galaxies and CIV systems with $N_{\rm CIV} \gtrsim 10^{12.5}$ cm^{-2} appears to be the same as the correlation function of galaxies. This implies that CIV systems and galaxies reside in similar parts of the Universe and is consistent with the idea that they are largely the same objects. We also find a strong association of OVI systems with galaxies (upper left panel, Fig. 2). On small scales the redshift-space cross-correlation function is highly anisotropic (right panel, Fig. 2). The metal-enriched gas must therefore have large velocities relative to nearby galaxies. The required velocities

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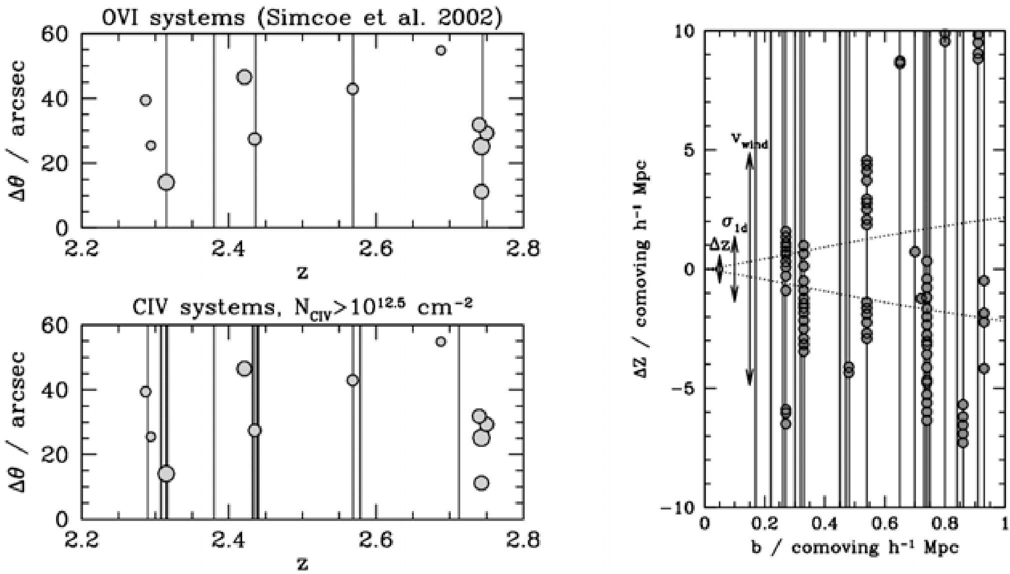

Figure 2. Left panel: redshifts of galaxies near the sight-line to QSO HS1700+6416 compared to the redshifts of CIV and OVI absorption systems in the QSO's spectrum. Circles mark galaxy redshifts and impact parameters. The area of each circle is proportional to the galaxy's apparent luminosity in the $\mathcal{R}$ band. Vertical lines mark the redshifts of OVI and CIV absorption. Thicker lines in the CIV panel mark systems with multiple components. OVI absorption redshifts are taken from Simcoe, Sargent & Rauch (2002). The absorption line catalogues are reasonably complete down to their limiting equivalent widths, but, owing to imperfect colour-selection criteria and limited time for follow-up spectroscopy, it is unlikely that the galaxy catalogues contain more than half of the galaxies brighter than $\mathcal{R} = 25.5$ at these redshifts. Right panel: the spatial separations of our sample's galaxy-CIV pairs in the angular (b) and redshift (ΔZ) directions. Vertical lines show the projected distance between each galaxy in the NIRSPEC sample and its nearest QSO. The QSO spectra allow us to detect any CIV-absorbing gas along these lines. Circles show the actual locations of detected CIV absorption. Owing to the power-law shape of the galaxy-CIV correlation function, half of the circles (on average) would lie inside the dotted triangular envelope if there were no peculiar velocities. In fact 65 of 81 lie outside. The uncertainty in each galaxy-CIV pair's redshift separation (i.e. in each circle's vertical position) is too small to account for this (~ 60 km s^{-1} or $0.6h^{-1}$ co-moving Mpc). Peculiar velocities must therefore be substantial. If the CIV systems were orbiting in the galaxy's halo, their observed redshift separations would be displaced relative to their true separations by a random amount comparable to their galaxy's velocity dispersion σ_{1d} (140 km s^{-1} or $1.4h^{-1}$ co-moving Mpc). If the CIV were infalling, one would expect the CIV systems' observed (i.e. redshift space) positions to be artificially compressed towards the x axis by an amount comparable to σ_{1d}. If it were flowing out-wards, the observed positions would be displaced away from the x axis by an amount that depends on the wind speed (~ 500 km s^{-1} or $4.9h^{-1}$ co-moving Mpc).

appear to exceed the galaxies' velocity dispersions but are similar to the galaxies' observed outflow speeds.

- In contradiction to the earlier result of Adelberger *et al.* (2003), we find that the gas within $1h^{-1}$ co-moving Mpc of LBGs usually produces strong Ly-α absorption in the spectra of background galaxies. The absorption is weak (mean transmitted flux within $1h^{-1}$ Mpc of $\bar{f}_{1\mathrm{Mpc}} > 0.7$) in only about one case out of three. Even so, the weakness of the absorption in these cases remains difficult to understand. Since high-redshift galaxies reside in dense parts of the Universe, with large amounts of hydrogen and short recombination times, one would expect them to be surrounded by large amounts of HI—unless something had disrupted the nearby material. One might imagine that the HI has

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collapsed into clouds and that the sight-lines to the background QSOs occasionally miss every cloud near a galaxy, but the SPH simulations of Kollmeier *et al.* (in preparation) suggest that the chance of this is very low.

2. Discussion

Galaxies would presumably be associated with QSO absorption lines even if there were no winds. I thought it might be useful to spend some time discussing how strongly (or weakly) the different observations support the superwind scenario. Table 1 presents my views in the form of a report card. Each observation is graded on two criteria: (a) how certain we are, statistically, that the observation is correct, and (b) how cleanly the observation would support the wind scenario if it were correct. I am adopting the Harvard grading system, in which 'A' is the highest grade you can get and everyone gets it unless they are completely abject.

Although it was not the subject of my talk, I'll begin with the blueshifted absorption and redshifted Lyman-α emission that has been detected in hundreds of high-redshift galaxies (e.g. Pettini *et al.* 2001; Shapley *et al.* 2003; Erb *et al.* 2005, in preparation). This is expected in a wide range of models in which the stars are surrounded by outflowing gas (e.g. Tenorio-Tagle *et al.* 1999; Zheng & Miralda-Escude 2002) and (as far as I know) is not expected in any other class of realistic models. Since it also cannot be a statistical fluctuation, I give it an A in both columns. There is a significant caveat, however: it tells us only that outflowing gas lies somewhere outside the stellar radius, not that the outflow will spill out of the galaxy's halo and qualify as a superwind.

The strength of CIV absorption at $b = 40$ kpc may suggest that the outflows have normally advanced to this radius, but even so this is only about half way to the virial radius. The minimum allowed velocity range of the gas at $b = 40$ kpc (~ 300 km s^{-1}) is not large enough to guarantee escape. In any case the similarity of the CIV absorption strength in LBGs' spectra and at impact parameter $b = 40$ kpc could just be a coincidence; it does not rule out the idea that the gas at 40 kpc is falling into or orbiting within the galaxy's potential. Anisotropies in the galaxy/CIV-system correlation function disfavour infall and seem to favour rapid outflows for the origin of the CIV, but the small number of distinct galaxy-CIV pairs leaves the situation unclear. All of these results are based on only a handful of galaxies and their statistical significance merits only a C+. In a larger sample they could prove to be powerful diagnostics, however, especially the correlation-function anisotropies and the changes in CIV mean velocity and velocity width as a function of impact parameter. That is the justification for the B+ in the interpretation column.

Measuring the spatial correlation of galaxies and metals on large (Mpc) scales provides a powerful way to distinguish between different scenarios for intergalactic metal enrichment. If the metals were produced in LBGs, they should have a spatial bias similar to the galaxies' bias of $b \sim 2.5$ at $z = 3$ (Adelberger *et al.* 2005). They would have $b = 1$ if they were produced at any redshift by the numerous dwarf galaxies that are 1σ fluctuations, and $b \sim 1.9$ at $z = 3$ if (as envisioned by Madau, Ferrara & Rees 2001) they were produced at $z = 9$ by galaxies that were 2σ fluctuations. These estimates of the bias exploit Mo & White's (1996) high-redshift (i.e. $\Omega \sim 1$) approximation $b = 1 + (\nu^2 - 1)(1 + z)[1.69(1 + z_i)]^{-1}$ for the bias at redshift z of objects that were ν-sigma fluctuations at the earlier redshift z_i. The galaxy-metal cross-correlation length would therefore be equal to the galaxy-galaxy correlation length if the metals were produced by LBGs and smaller for the other two cases. Unfortunately we have measured the galaxy-CIV correlation length, not the galaxy-metal correlation length. Understanding

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Table 1. Report card

Observation	Statistical Significance	Interpretation
Blueshifted ISM, redshifted Lyα	A	A
Metals at $r \lesssim 100$ kpc	C+	B+
Metals at large separations	B	C
Lack of HI near some galaxies	C+	C+

the relationship between the two will likely require sophisticated numerical simulations that may not be available for many years. Since our galaxy-CIV clustering measurements will not sway the sceptical until that time, I have assigned them a C for their interpretive value. They merit no more than a B for significance since our 2σ confidence intervals would allow galaxy-CIV clustering to be considerably weaker than the galaxy-galaxy clustering.

Although there are now 9 galaxies in our sample with precise (near-IR nebular line) redshifts and little HI within $1h^{-1}$ co-moving Mpc, their statistical significance is worth only a C+ in my opinion. There are two reasons. First, the measurement is difficult. To determine whether a galaxy lies within $\lesssim 1h^{-1}$ Mpc of a narrow absorption line in a QSO spectrum, one needs a good understanding of many possible sources of random and systematic error in the estimated redshifts. In about half the cases there is no absorption line anywhere near the galaxy redshift, but in the remainder the galaxies could conceivably be associated with nearby absorption lines if redshift errors were somewhat larger than we estimate. Reducing the number of galaxies with little nearby HI by 50% would begin to make our observations consistent with the predictions of windless SPH simulations. Second, 5 of the 9 galaxies lie within a single field, Q1623, which contains one of the largest known concentrations of QSOs with $2 \lesssim z \lesssim 3$. This is a consequence of the dense spectroscopic sampling we obtained in the field, but it raises the possibility that our result might have been different had we surveyed a more representative part of the Universe. The spatial clustering strength of the high-redshift galaxies in this field is certainly not typical, for example see Adelberger *et al.* (2005b).

Interpreting the result is difficult because of the complexity of any interaction between winds and galaxies' inhomogeneous surroundings. This cannot be modelled analytically, and existing numerical simulations are unable to resolve either the shock fronts or the instabilities that result when the hot wind flows past cooler intergalactic material. As a result it is difficult to know whether winds would destroy the HI near galaxies. Other effects that simulations do not resolve (e.g. cooling instabilities) might reduce the covering fraction of HI near galaxies. Even if there were low-density regions near galaxies in SPH simulations, they might not be recognised since the density is generally estimated by smoothing over the few dozen nearest particles, particles which (by definition) are likely to lie outside of any local under-density. It therefore remains uncertain whether the lack of HI near some galaxies is necessary or sufficient to establish the existence of superwinds. The lack of any correlation between galaxy properties and the strength of nearby intergalactic HI absorption (Adelberger *et al.* 2005c) makes me suspect that the weak observed HI absorption is probably unrelated to winds. I have given this observation a "C+" for interpretative value, but that is generous.

3. Concluding remarks

It is easy to measure the relative spatial positions of galaxies and the gas that produces QSO absorption lines, but difficult to find conclusive evidence for superwinds around galaxies. This is partly because our sample is still small, but mostly, I think, because theorists have been unable to work out the observational consequences of superwinds. It is entirely possible, for example, that our measured galaxy-CIV correlation function rules out every explanation except superwinds, but we would not know since the necessary simulations do not exist.

Although I have emphasised the weaknesses in the superwind interpretation, I should point out that in my opinion the weaknesses in the alternate scenario are far worse. The left panel of Fig. 3 illustrates the major problem faced by those who believe that intergalactic metals were created in early episodes of star formation at $10 \lesssim z \lesssim 15$: they must assume that the metals produced at $z \sim 10$ escape from their galaxies with ease while almost none of the metals produced at $z \sim 3$ are able to do so. In order for 90% of the intergalactic metals observed at $z \sim 3$ to have been produced at $z \sim 10$, for example, supernovae ejecta would have to be at least 100 times more likely to escape their galaxy at $z = 10$ than at $z = 3$. (See the caption to Fig. 3 for the derivation of this number.) It is widely believed that high-redshift supernovae ejecta escape more easily because galaxy masses are lower at high redshift, and that they pollute the IGM more readily because they need to reach only a comparatively small physical radius to enrich a large co-moving volume. Scannapieco (2005) argues that these two effects cause the co-moving filling fraction of the ejecta Q (or, more formally, the porosity) to depend on mass and redshift as $Q \propto M^{-2/5}(1+z)^{6/5}$. (Similar equations have been derived by Madau *et al.* 2001 and dozens of other papers.) This equation predicts that metals from $10^9 M_\odot$ galaxies at $z = 10$ should have a filling fraction ~ 20 times larger than those from the $10^{11} M_\odot$ galaxies observed at $z \sim 3$. It is not clear to me whether this is enough to explain the left panel of Fig. 3, but the question is moot: in my view, Scannapieco's (2005) formula vastly overstates the actual advantage of very high-redshift galaxies.

There are two reasons. First, it assumes that small galaxies at high redshift convert their baryons into stars exactly as efficiently as more massive galaxies at $z \sim 3$. This assumption is probably wrong by an order of magnitude. Star-formation efficiencies in massive galaxies at $z \sim 3$ appear to be far higher, as is easily seen by comparing the ratio of stellar to baryonic mass in LBGs ($M_*/M_b \sim 0.1$, Adelberger *et al.* 2004) to the global average at $z = 3$, $\Omega_*/\Omega_b \simeq 0.01$ (Dickinson *et al.* 2003; Rudnick *et al.* 2003). Since every baryon at $z = 3$ was part of a low-mass halo at higher redshift, at least in the Press-Schechter picture, and only $\sim 1\%$ of them had been turned into stars by $z = 3$, the mean star-formation efficiency in low mass halos at high redshift is evidently ~ 10 times lower than the mean efficiency in LBGs. A more realistic comparison would omit the halos with masses $M \lesssim 10^5 M_\odot$ that are too small to host star formation and would note that Ω_*/Ω_b is an order of magnitude lower at $z \sim 10$ than $z \sim 2$ for realistic cosmic star-formation histories. This leads to a similar conclusion. The high efficiency of star-formation in massive galaxies at $z \sim 2$ removes the low-mass halos' supposed advantage in enriching the IGM. Second, only a fraction of the metals released into the IGM at $z \sim 10$ will remain in the IGM at $z \sim 2-3$. This is a simple consequence of hierarchical structure formation: the material that lies near galaxies at higher redshift (e.g. any metal-enriched ejecta) will lie *inside* galaxies at lower redshift. Because they neglect this, standard treatments seriously overestimate the intergalactic volume that metals produced at $z \sim 10$ will occupy at $z \sim 2$. To illustrate the point, I calculated the distance to the nearest halo of mass $M \gtrsim 10^{11} M_\odot$ at $z = 2.12$ for every particle in the GIF-LCDM simulation (Kauffmann *et al.* 1999) that lay within $1h^{-1}$ co-moving Mpc of a galaxy (i.e. halo) at $z = 10$ or $z = 5$. The result, shown in the right hand panels of Fig. 3, is stark: the overwhelming majority of these particles end up inside the virial radius of a galaxy at $z \sim 2$. Since the stalled ejecta of galaxies at $z = 10$ or $z = 5$ will be swept

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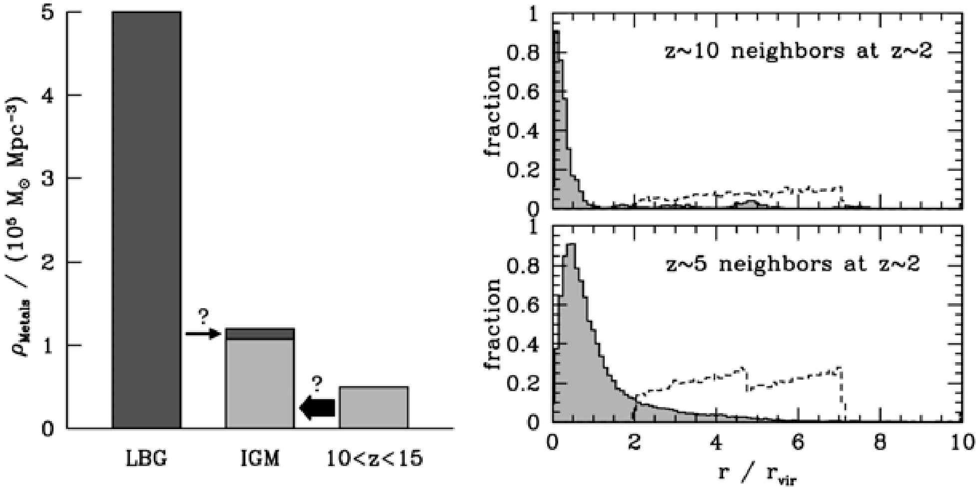

Figure 3. *Left panel:* the amount of metals produced in massive galaxies at $z \sim 2$ (LBG) compared to the amount of metals in the IGM at $z \sim 2$ and to the amount of metals produced at $10 < z < 15$. The amount of metals produced by massive galaxies at $z \sim 2$ was calculated by assuming that each $100 M_\odot$ of star formation produced $1 M_\odot$ of metals and scaling from the $z \sim 2$ stellar-mass density measured by Dickinson *et al.* (2003). An upper limit to the amount of metals produced at $10 < z < 15$ was derived by assuming a constant co-moving star-formation density at all redshifts $2 < z < 15$. This implies that $\sim 10\%$ of the stars that exist at $z = 2$ were formed at $10 < z < 15$. It is an upper limit because the actual star-formation density at $z \gg 2$ appears to be significantly lower than the star-formation density at $z \sim 2$. The amount of metals in the IGM was calculated by multiplying the critical density by the estimated intergalactic metal density at $z \sim 2$, $\Omega_{\rm met} \sim 4.4\Omega_C$ with $\Omega_C \sim 2 \times 10^{-7}$ (Schaye *et al.* 2003). If 90% of the intergalactic metals at $z \sim 2$ were produced at $10 < z < 15$, the fraction of metals that escape into the IGM would have to be ~ 100 times higher at $10 < z < 15$ than at $z \sim 2 - 3$. *Right panels:* distance to the nearest massive ($M \gtrsim 10^{11} M_\odot$) halo at $z \sim 2$ for all GIF-LCDM simulation particles whose distance r to the nearest halo satisfied $2r_{\rm vir} < r < 1h^{-1}$ co-moving Mpc at $z = 10$ (top) or $z = 5$ (bottom). Dashed lines show the particles' original (higher redshift) distribution of $r/r_{\rm vir}$; the solid shaded histograms show the distribution at $z \sim 2$. These particles initially lie at larger radii than those expected for the metals ejected by very high redshift winds, yet they mostly end up inside halos by $z \sim 2$. This implies that the metals ejected at $z \sim 5$ and $z \sim 10$ will generally also lie in massive halos at $z \sim 2$, not in the IGM.

along by the movements of the material that surrounds the galaxies, it should largely end up inside galaxies at $z \sim 2$ as well. This exercise may be slightly misleading, since the GIF-LCDM simulation only resolves halos of mass $M \gtrsim 10^{11} M_\odot$, not the smaller halos believed to be most responsible for polluting the IGM at $z \sim 10$. However, a simple calculation shows that a significant fraction of the metals from the lower-mass progenitors should also end up inside galaxies at $z \sim 2$. The estimated stalling radius for winds from small galaxies at $z \sim 10$ is ~ 100 co-moving kpc (e.g. Madau *et al.* 2001), which is the Lagrangian radius for a halo of mass $1.6 \times 10^8 M_\odot$. If these galaxies' typical descendants at $z \sim 2$ have masses significantly larger than this, the metals will likely have been swept inside them. According to the extended Press-Schechter formalism, $\sim 85\%$ of the galaxies at $z = 2$ that descended from 2σ fluctuations at $z = 10$ will have masses that exceed this threshold by an order of magnitude (see, e.g. Eq. 2.16 of Lacey & Cole 1993). A substantial fraction of the metals produced at $10 \lesssim z \lesssim 15$ should therefore be locked inside galaxies by $z \sim 2$. Once there, some of the metals are likely to cool further, fall towards the centre, and disappear from view. Since the total metal production at

$10 \lesssim z \lesssim 15$ is at best comparable to the observed metal content of the IGM at $z \sim 2$ (left panel, Fig. 3), this suggests that the intergalactic metallicity at $z \sim 2$ must receive a significant contribution from some other source. A corollary is that the metal content of the IGM would drain into galaxies and *decrease* over time if it were not continually replenished. The observed constancy of the IGM metallicity (e.g. Schaye *et al.* 2003) therefore also seems to require metals to escape from galaxies at lower redshifts.

In addition, a host of indirect arguments point towards superwinds from relatively massive galaxies at $z \sim 3$. Clustering measurements show that galaxies that were forming star rapidly at $z \sim 3$ are no longer forming stars by $z \sim 1$ (Adelberger *et al.* 2004). What physical process is responsible for this, if not energetic feedback that strips away the galaxies' gas and slows subsequent accretion? If winds are only able to escape from dwarf galaxies, how come so large a fraction of metals in the local Universe are found in the intra-cluster medium, near the largest galaxies? I could carry on but my allotted time is up. Although we have not yet found unequivocal evidence that intergalactic metals at $z \sim 2$–3 are often produced by galaxies at similar redshifts, the burden of proof surely falls on the other camp. Theirs is the preposterous claim.

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References

Adelberger, K. L., 2002, PhD thesis, California Institute of Technology, Pasadena.
Adelberger, K. L., Steidel, C. C., Shapley, A. E., Pettini, M., 2003, ApJ, 584, 45
Adelberger, K. L., *et al.*, 2005a, ApJ, 619, 697
Adelberger, K. L., *et al.*, 2005b, ApJ, 620, L75
Adelberger, K. L., *et al.*, 2005c, ApJ, in press
Dickinson, M., Papovich, C., Ferguson, H. C., Budavári, T., 2003, ApJ, 587, 25
Kauffmann, G., Colberg, J. M., Diaferio, A., White, S. D. M., 1999, MNRAS, 303, 188
Lacey, C., Cole, S., 1993, MNRAS, 262, 627
Madau, P., Ferrara, A., Rees, M. J., 2001, ApJ, 555, 92
Mo, H. J., White, S. D. M., 1996, MNRAS, 282, 347
Pettini, M., *et al.*, 2001, ApJ, 554, 981
Rudnick, G., 2003, ApJ, 599, 847
Scannapieco, E., 2005, ApJL, in press (astro-ph/0504081)
Schaye, J., Aguirre, A., Kim, T., Theuns, T., Rauch, M., Sargent, W., 2003, ApJ, 596, 768
Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., 2003, ApJ, 588, 65
Simcoe, R. A., Sargent, W. L. W., Rauch, M., 2002, ApJ, 578, 737
Tenorio-Tagle, G., Silich, S., Kunth, D., Terlevich, E., Terlevich, R., 1999, MNRAS, 309, 332
Zheng, Z., Miralda-Escudé, J., 2002, ApJ, 578, 33

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