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GALACTIC WINDS IN THE INTERGALACTIC MEDIUM[1]

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ABSTRACT

We have performed hydrodynamical simulations to investigate the effects of galactic winds on the high-redshift ($z = 3$) universe. Strong winds suppress the formation of low-mass galaxies significantly, and the metals carried by them produce C IV absorption lines with properties in reasonable agreement with observations. The winds have little effect on the statistics of the H I absorption lines, because the hot gas bubbles blown by the winds fill only a small fraction of the volume and because they tend to escape into the voids, thereby leaving the filaments that produce these lines intact.

Subject headings: cosmology: observations — cosmology: theory — galaxies: formation — intergalactic medium — quasars: absorption lines

On-line material: color figure

1. INTRODUCTION

Feedback from star formation is thought to play an important role in the formation of galaxies. For example, theoretical models require feedback in order not to overproduce the number of low-mass galaxies (White & Rees 1978) and the fraction of baryons that cools (e.g., Balogh et al. 2001). Models without feedback also predict disk galaxies that are too small (e.g., Navarro & Steinmetz 1997) and an X-ray background that is too strong (e.g., Pen 1999).

Observations of galactic winds indicate that strong feedback processes do indeed occur. Observations in X-rays, and of optical and UV lines, indicate that most local starbursts (e.g., Heckman 2001), as well as high-redshift Lyman break galaxies (e.g., Pettini et al. 2001), drive winds with a mass-loss rate comparable to their star formation rate. The wind speeds are high, 100–1000 km s^{-1}, and so the conversion of supernova (SN) energy into kinetic energy must be quite efficient. This process is currently not well understood because of the complications that arise from the multiphase nature of the interstellar medium (ISM; e.g., McKee & Ostriker 1977; Efstathiou 2000). Simulations that take some of these complications into account have shown that SNe can indeed plausibly power a wind (e.g., Mac Low & Ferrara 1999).

Although successful models of galaxies appear to require feedback, the same is not true for models of the high-redshift ($z \gtrsim 2$) intergalactic medium (IGM). The IGM can be studied in great detail from the properties of the hydrogen absorption lines, seen in the spectra of background quasars (see Rauch 1998 for a review). Hydrodynamical simulations of the IGM (see Efstathiou, Schaye, & Theuns 2000 for a recent review) as well as semianalytic (Bi & Davidsen 1997; Viel et al. 2002) and analytic (Schaye 2001) models, have been very successful in reproducing the statistical properties of the observed H I lines. These models, which generally do *not* take feedback into account (but see Cen & Ostriker 1999), suggest that the Lyα forest absorption arises in a network of voids and filaments, with the higher column density absorbers located at the intersections of filaments. The low column density absorbers are extended structures with densities around the cosmic mean, which contain a large fraction of the baryons in the universe.

Although feedback has so far largely been ignored in models of the IGM, the detection of metals in the IGM suggests that it *does* play a role. The higher column density ($N_{\rm H\,I} \gtrsim 10^{14.5}$ cm^{-2}) Lyα absorption systems generally have detectable absorption by C IV (Cowie et al. 1995) and, at least at $z \lesssim 2.5$, O VI (Carswell, Schaye, & Kim 2002). Furthermore, there is statistical evidence that metals are also present at somewhat lower densities (Cowie & Songaila 1998; Ellison et al. 2000; Schaye et al. 2000a). Simple photoionization models indicate that the absorbers have a metallicity of order 0.1%–1% solar (e.g., Cowie et al. 1995; Rauch, Haehnelt, & Steinmetz 1997; Hellsten et al. 1997; Carswell et al. 2002).

If galactic winds are ubiquitous and able to transport mass to large distances, then they may be responsible for enriching the IGM with metals. Indeed, numerical simulations of galactic winds in a cosmological setting (e.g., Gnedin 1998; Cen & Ostriker 1999; Aguirre et al. 2001a, 2001b; Thacker, Scannapieco, & Davis 2002; Springel & Hernquist 2002) suggest that winds could enrich a substantial volume fraction of the IGM to the inferred levels.

Therefore, both observational and theoretical considerations suggest that some fraction of galaxies may undergo an episode in which they blow a strong wind into their surroundings. This may have observational effects on the Lyα forest in quasar spectra (Theuns, Mo, & Schaye 2001; Croft et al. 2002), which may have already been detected (Rauch, Sargent, & Barlow 2001; Adelberger et al. 2002). In this Letter, we use hydrodynamical simulations to investigate whether galactic winds that strongly influence the properties of small galaxies, and are effective in enriching the IGM with metals, can do so without undermining the success of current models of the IGM.

2. HYDRODYNAMICAL SIMULATIONS

We have performed simulations of vacuum energy–dominated, cosmologically flat cold dark matter models, with

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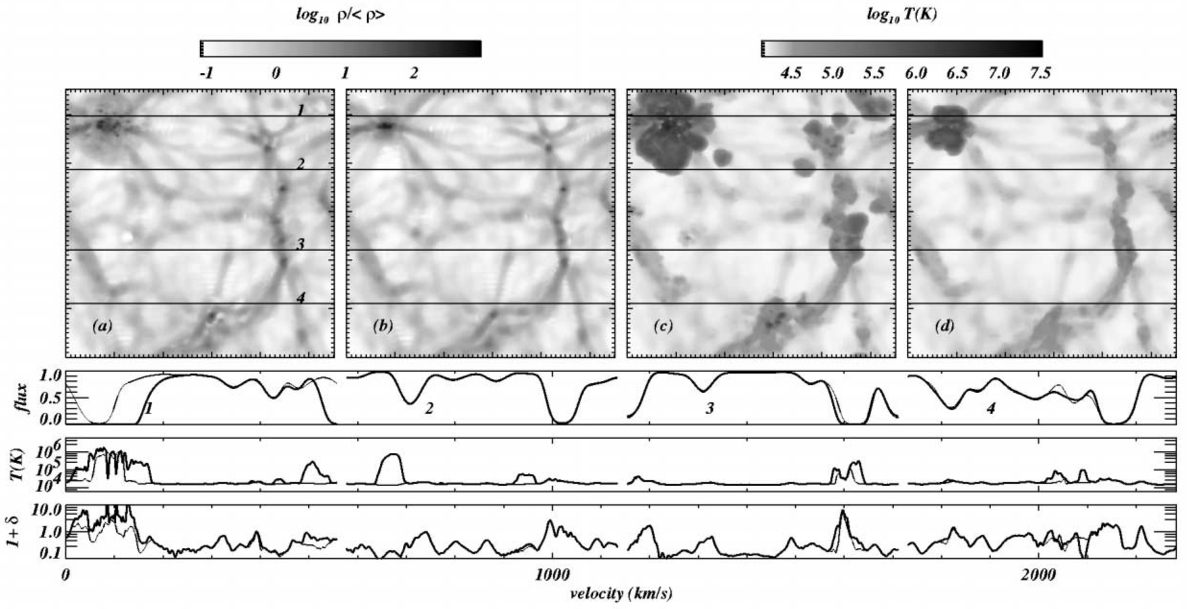

FIG. 1.—*Top panels*: Density (*a*, *b*) and temperature (*c*, *d*) for a slice through the simulation with feedback (*a*, *c*) and the simulation without feedback (*b*, *d*), at redshift $z = 3$. The simulation box is 5.0 h^{-1} (comoving) Mpc. The slice is chosen to go through the most massive object in the simulation. In the feedback simulation, hot bubbles of gas surround the galaxies. These tend to expand into the voids, thereby leaving the filamentary network of higher density regions unaffected. The four numbered horizontal lines (*from top to bottom*) are sight lines for which the Lyα spectrum, temperature, and density are shown in the bottom panel (*from left to right*, offset for clarity). The feedback and no feedback cases are shown as thick and thin lines, respectively (*blue and red*). Only the strongest lines are significantly affected by feedback. [*See the electronic edition of the Journal for a color version of this figure*.]

cosmological parameters (Ω_m, $\Omega_b h^2$, h, σ_8, Y) = (0.3, 0.019, 0.65, 0.7, 0.24). The lower value of σ_8 was chosen in view of the recent results from the Two-Degree Field survey (Lahav et al. 2002). The simulations are performed using a modified version of HYDRA (Couchman, Thomas, & Pearce 1995; Theuns et al. 1998), in which the gas is photoheated by an imposed uniform UV background that evolves with redshift and reionizes H I and He I at $z \sim 6$ and He II at $z \sim 3.2$. The photoheating rates were adjusted in order to match the temperature measurements of Schaye et al. (2000b), where the current simulation is referred to as the "designer" simulation. Nonequilibrium rates for photoionization, cooling, and heating are computed using the fits in Theuns et al. (1998). The particle masses for dark matter and baryons are 6.5 and 1.1 × 10^6 $M_\odot$, respectively, and the simulation box (which has periodic boundary conditions) is 5.0 h^{-1} (comoving) Mpc on a side. The Plummer softening is 5 h^{-1} (comoving) kpc.

Star formation and feedback are implemented using the prescription described in detail in Kay et al. (2002). Briefly, cold gas with density $\rho/\langle\rho\rangle > 1000$ and temperature $T < 50{,}000$ K is converted into collisionless stars. Each star particle heats the nearest gas particle using equation (3) of Kay et al. (2002), with a given efficiency parameter (we use $\epsilon = 1$). Reheated gas is prohibited from cooling for 10^7 yr to crudely account for the multiphase nature of the ISM. This simple feedback prescription has the desired effect of blowing hot bubbles around star-forming regions. The heated gas is also enriched with metals. A yield of 3 times solar matches the metal line data well (see below).

We make no attempt to model the transition from SN bubble to galactic wind correctly, since our simulations lack both in resolution and input physics. We do not include cooling due to metal transitions, which could be important. Our primary aim in this preliminary investigation is to test whether strong feedback in the form of galactic winds can coexist with the Lyα forest as we know it from simulations without feedback. We use the galaxy mass function and the properties of the C IV forest to demonstrate that the implemented feedback is indeed significant. We have performed two simulations with identical initial conditions, one with and one without feedback, so that we can examine its effect directly.

3. RESULTS

Figure 1 illustrates the effect of feedback from star formation on the density and temperature of the IGM. In the simulation without feedback, the density structure displays the usual filamentary pattern of mildly overdense regions, mostly at temperatures ~10^4 K, although accretion shocks have also generated some significantly hotter gas. In the simulation with feedback, galaxies are surrounded by hot, windblown bubbles; in particular, the most massive object in the slice is embedded in a halo of ≈1 Mpc comoving size, of temperature up to 10^7 K.

Except for the very strong absorption lines, the Lyα spectra are not significantly affected by these hot bubbles (Fig. 1, *bottom panel*). In contrast, feedback has a very strong effect on the stellar masses of the galaxies (Fig. 2). The hot bubbles disrupt or prevent inflow of cold gas, which reduces the star formation rate dramatically.

We have created absorption spectra along random sight lines through the simulations at $z = 3$ and fitted them with Voigt profiles using VPFIT (Webb 1987), mimicking a high signal-to-noise ratio, high-resolution spectrum (see Theuns, Schaye, & Haehnelt 2000 for details of the procedure). We imposed a power-law ionizing background $J_\nu \propto \nu^\alpha$ with spectral slope $\alpha = -1.5$ and a break at the He II Lyman limit (4 ryd) such that the softness parameter (i.e., the ratio of the H I and He II ionization rates) $\Gamma_{\rm H\,I}/\Gamma_{\rm He\,II} = 10^3$. Such a soft spectrum may be appropriate for $z \gtrsim 3$, when He II reionization was incomplete (e.g., Theuns et al. 2002 and references therein). The amplitude

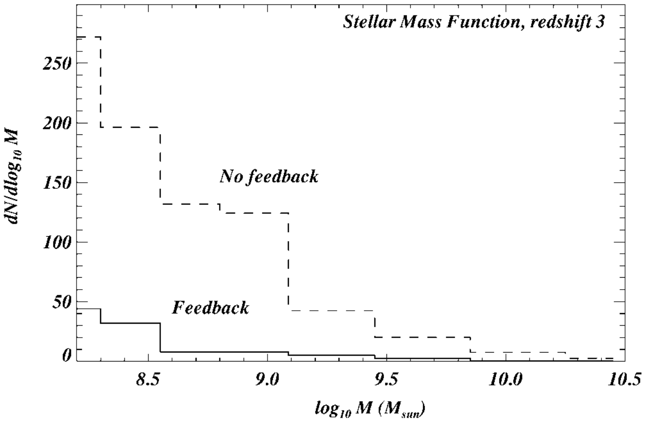

FIG. 2.—Stellar mass function of galaxies at redshift $z = 3$, for the simulation with feedback (*solid line*) and without feedback (*dashed line*). The feedback scheme has a dramatic effect on the masses of the galaxies.

of the ionizing flux is scaled to give the simulations the observed mean Lyα absorption. The required flux differs by around 10% between the two simulations, with the simulation with feedback requiring more ionizing photons because the density in voids is enhanced by the winds. (Note that this ionizing background differs from the one imposed during the simulation; see Theuns et al. 1998 for tests of such rescaling.)

The Lyα column density distribution functions (CDDFs; the number of absorption lines per unit column density, per unit redshift) for the two simulations are compared in Figure 3*a*: they are nearly indistinguishable and fit the observations well.[7] The same is true for the distribution of absorption line widths (*b*-parameters; Fig. 4). This is the main result of this Letter: even though the galaxies in the feedback simulation drive strong winds, there is no discernible effect on the Lyα forest. Closer examination of the properties of the hot bubbles reveals why this is so: the winds expand preferentially into the lower density regions (Fig. 1) and so keep the filaments that produce the hydrogen lines intact. Only very strong lines differ noticeably between the two simulations, but this does not affect the statistics significantly.

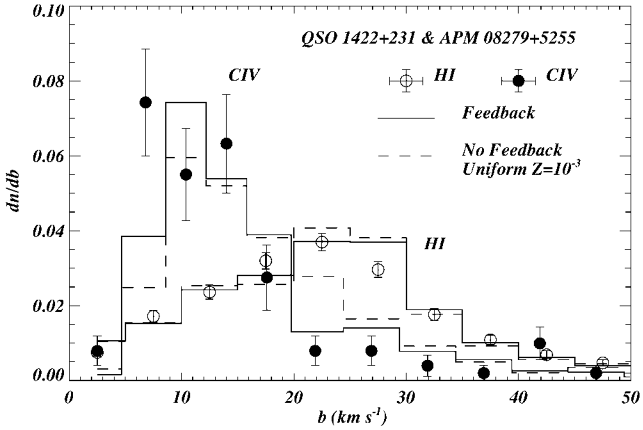

FIG. 4.—Line width distributions from the combined line lists of quasars Q1422+231 (Ellison et al. 2000; $z_{\mathrm{em}} = 3.6$) and APM 08279+5255 ($z_{\mathrm{em}} = 3.91$) for C IV (*filled circles*) and H I (*open circles*). Solid lines are the corresponding results for the feedback simulation. Dashed lines are the H I and C IV line width distributions for the simulation without feedback (and uniform enrichment). (Only lines for which $12 < \log N_{\mathrm{C\,IV}} < 13.2$ and errors in $N_{\mathrm{C\,IV}}$ and $b_{\mathrm{C\,IV}}$ less than 0.3 dex are included.) The feedback simulation matches both distributions well, and feedback has little influence on the H I distribution.

Another way to demonstrate that our feedback implementation *does* influence the IGM is by examining the C IV forest. The hot gas surrounding the galaxies has been enriched with metals and produces C IV absorption. We used CLOUDY (version 94; Ferland 2000) to solve the ionization balance equations, computed mock C IV spectra (see Aguirre, Schaye, & Theuns 2002 for details), and analyzed them with VPFIT. Figure 3*b* shows that the feedback simulation reproduces the observed C IV CDDF very well. In contrast, the low and high end of the CDDF cannot be matched simultaneously by imposing a uniform metallicity (*hatched region*).

The metal distribution is very inhomogeneous in the simulation, since metals are deposited by the winds predominantly in the surroundings of galaxies. This causes a scatter in the C IV column density for a given Lyα column density. We have proceeded as follows to quantify this effect. Find the strongest

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[7] The discrepancy between the simulations and the observations for $N_{\mathrm{H\,I}} > 10^{15.5}$ cm^{-2} is caused mainly by the missing large-scale power due to the finite size of the simulation box.

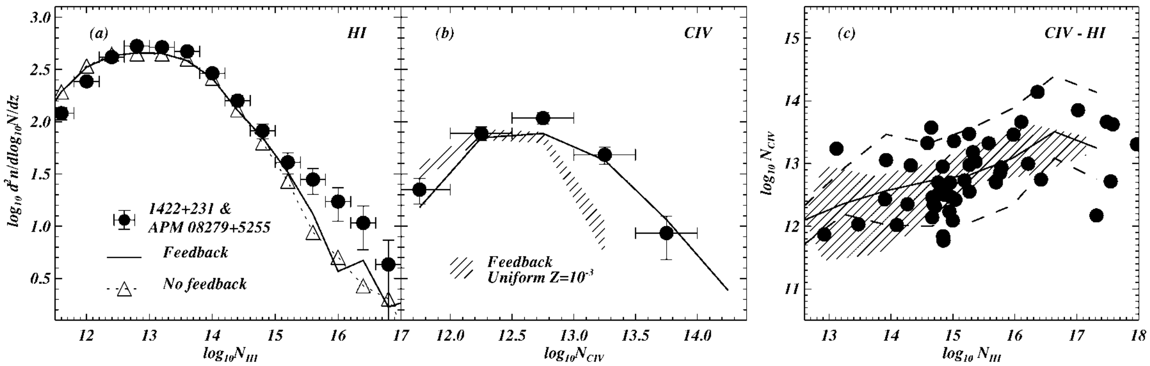

FIG. 3.—CDDFs of (*a*) H I, (*b*) C IV, and (*c*) the C IV vs. H I column density of systems. Filled circles refer to the combined line lists of quasars Q1422+231 (Ellison et al. 2000; $z_{\mathrm{em}} = 3.6$) and APM 08279+5255 ($z_{\mathrm{em}} = 3.91$), and the solid line indicates the results for the feedback simulation at $z = 3$. (*a*) The H I CDDF of the feedback simulation is nearly identical to that of the simulation without feedback (*dotted line and triangles*), and both fit the observations very well for $\log N_{\mathrm{H\,I}} \lesssim 15$. (*b*) The feedback simulation matches the observed C IV CDDF, but imposing a uniform metallicity ($Z = 10^{-3}\ Z_{\odot}$, *hatched region*) does not work so well. (*c*) C IV vs. H I column density, for systems identified on a smoothing scale of ± 150 km s^{-1}. The median for the feedback simulation is indicated with the solid line, with dashed lines indicating 5% and 95%. The hatched region is the corresponding range for the uniform metallicity case. The feedback simulation reproduces the observed median and scatter better than the uniform Z case.

Lyα line in the line list and sum up the column densities of all H I lines, as determined by VPFIT, of which the center falls within $\pm\Delta$ km s^{-1}. This is the H I column density of that "system." Use the same algorithm to compute the C IV column density at the corresponding wavelength. Remove all lines that have contributed to the column density from the line list, and start again. Figure 3*c* plots C IV versus H I column density for $\Delta = 150$. The feedback simulation reproduces the median and scatter in the observations relatively well, whereas the uniform metallicity case underpredicts the scatter (see also Davé et al. 1998).

However, some caution is appropriate. Given that in the observations $N_{\rm C\,IV}/N_{\rm H\,I} \approx 10^{-2.6}$, with no evidence for a trend with $N_{\rm H\,I}$ (e.g., Ellison et al. 2000), the lack of strong C IV lines for the uniform metallicity case may be caused in part by the fact that the simulation underpredicts the number of strong H I lines. Using a harder UV background would increase the metallicity required to match the observations. On the other hand, including metal cooling would increase the C IV fraction (and thus strengthen the C IV lines) considerably for the feedback simulation. With our choice of parameters, the feedback simulation reproduces the C IV data well. However, other choices of parameters might do equally well.

In the feedback simulation, most of the intergalactic metals reside in hot ($T \sim 10^{4.5}$–$10^{6.5}$ K), relatively metal-rich ($Z \sim 0.1$–$1.0\ Z_\odot$) gas, and collisional ionization has a significant effect on the strength of metal lines such as C IV, N V, and O VI. Consequently, the temperature of the gas that dominates the absorption in one transition, e.g., C IV, can be different from that of another transition, e.g., H I or O VI. In such a scenario, one would expect the metal line widths (or *b*-parameters) to be higher than in the simulation without feedback (and uniform enrichment). This is in fact not obvious from Figure 4, because the lines also have a significant nonthermal component. At present, both distributions seem to be in reasonable agreement with the data (*filled circles with error bars*). Again, some caution is appropriate: metal cooling (which was not included) could reduce both the line widths and the importance of collisional ionization in the feedback simulation. A more detailed investigation of the metal lines is beyond the scope of this Letter. Here we merely conclude that the feedback simulation predicts a (highly inhomogeneous) metal distribution that appears to be in reasonable agreement with the current data but differs significantly from the uniform metallicity models considered previously (e.g., Rauch et al. 1997).

In summary, galactic winds that are strong enough to strongly suppress galaxy formation and to pollute the IGM with enough metals to reproduce the data do not have a significant effect on the Lyα forest. The reason is that the winds fill only a small fraction of the volume and tend to expand into the voids, leaving the filaments that produce the hydrogen lines intact.

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