WHERE ARE THE BARYONS? II. FEEDBACK EFFECTS

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ABSTRACT

Numerical simulations of the intergalactic medium have shown that at the present epoch, a significant fraction (40%–50%) of the baryonic component should be found in the \( T \sim 10^6 \) K warm-hot intergalactic medium (WHIM)—with several recent observational lines of evidence indicating the validity of the prediction. We here recompute the evolution of the WHIM with the following major improvements: (1) galactic superwind feedback processes from galaxy and star formation are explicitly included; (2) major metal species (O vi to O ix) are computed explicitly in a nonequilibrium way; and (3) mass and spatial dynamic ranges are larger by factors of 8 and 2, respectively, than in our previous simulations. Here are the major findings: (1) Galactic superwinds have dramatic effects, increasing the WHIM mass fraction by about 20%, primarily through heating of warm gas near galaxies with density \( 10^{1.5} \)–\( 10^4 \) times the mean density. (2) The fraction of baryons in the WHIM is increased modestly from the earlier work but is still \( \sim 40\%–50\% \). (3) The gas density of the WHIM is broadly peaked at a density 10–20 times the mean density, ranging from underdense regions to regions that are overdense by \( 10^3 \)–\( 10^4 \). (4) The median metallicity of the WHIM is 0.18 \( Z_{\odot} \) for oxygen, with 50% and 90% intervals being (0.040, 0.38) and (0.0017, 0.83).

Subject headings: cosmology: observations — intergalactic medium — large-scale structure of universe

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1. INTRODUCTION

Cosmological hydrodynamic simulations have strongly suggested that most of the previously “missing” baryons may be in a gaseous phase in the temperature range \( 10^5 \)–\( 10^7 \) K and at moderate overdensity (Cen & Ostriker 1999, hereafter CO99; Davé et al. 2001), called the warm-hot intergalactic medium (WHIM), with the primary heating process being hydrodynamic shocks from the formation of large-scale structure at scales currently becoming nonlinear. The reality of the WHIM has now been quite convincingly confirmed by a number of observations from the Hubble Space Telescope, the Far Ultraviolet Spectroscopic Explorer, Chandra, and XMM-Newton (Tripp et al. 2000; Tripp & Savage 2000; Oegerle et al. 2000; Scharf et al. 2000; Tittley & Henriksen 2001; Savage et al. 2002; Fang et al. 2002a, 2002b; Nicastro et al. 2002; Mathur et al. 2003; Kaasstra et al. 2003; Finoguenov et al. 2003; Sembach et al. 2004; Nicastro et al. 2005).

In addition to shock heating, feedback processes following star formation in galaxies can heat gas to the same WHIM temperature range. What is lacking theoretically is a satisfactory understanding of the known feedback processes on the WHIM and how the WHIM may be used to understand and calibrate the feedback processes. Another unsettled issue is how the predicted results will change if one has a more accurate, nonequilibrium calculation of the major metal species, such as O vi, O vii, and O viii, since the timescales for ionization and recombination are not widely separated from the Hubble timescale. We have investigated these important processes. Additional improvements include significantly larger dynamic ranges in the simulation, a cosmological model normalized to measurements from the Wilkinson Microwave Anisotropy Probe (WMAP), and an improved radiative transfer treatment. Our current work significantly extends previous theoretical works by our group and others (CO99; Davé et al. 2001; Cen et al. 2001; Fang et al. 2002a, 2002b; Chen et al. 2003; Furlanetto et al. 2004, 2005a, 2005b; Yoshikawa et al. 2003; Suto et al. 2004; Fang et al. 2005; Ohashi et al. 2006). In this paper, we focus on the feedback effects due to star formation, and in a companion paper (Cen & Fang 2006), we present additional effects due to nonequilibrium treatments of metal species and observables of the WHIM. The outline of this paper is as follows: the simulation details are given in § 2, in § 3 we give detailed results and discussion, and conclusions are presented in § 4.

2. SIMULATIONS

The numerical methods of the cosmological hydrodynamic code and input physical ingredients have been described in detail in an earlier paper (Cen et al. 2003). Briefly, the simulation integrates five sets of equations simultaneously: the Euler equations for gas dynamics in comoving coordinates, time-dependent rate equations for different hydrogen and helium species at different ionization states, the Newtonian equations of motion for dynamics of collisionless (dark matter) particles, the Poisson equation to obtain the gravitational potential field, and the equation governing the evolution of the intergalactic ionizing radiation field, all in cosmological comoving coordinates. Note that the cosmological (frequency dependent) radiation field is solved for self-consistently, rather than being a separate input to the modeling. The gas dynamical equations are solved using the TVD (total variation diminishing) shock-capturing code of Ryu et al. (1993) on a uniform mesh. H i, He i, and He ii are separately followed as different species in non-LTE rate equations for each cell at every time step. Oxygen in various states of ionization is also followed as separate species (see the companion paper, Cen & Fang 2006), and in total, seven species are followed in a non-LTE way. The rate equations are treated using subcycles within a hydrodynamic time step because of the much shorter ionization timescales (i.e., the rate equations are very “stiff”). Dark matter particles are advanced in time using the standard particle-mesh scheme. A leapfrog integration scheme is used. The gravitational potential on a uniform mesh is solved for using the fast Fourier transform method.

The initial conditions adopted are those for Gaussian processes, with the phases of the different waves being random and
Cooling and heating processes due to all the principal line and continuum atomic processes for a plasma of primordial composition with additional metals ejected from star formation (see below), Compton cooling due to the microwave background radiation field, and Compton cooling and heating due to the X-ray and high-energy background are computed in a time-dependent, nonequilibrium fashion. The cooling due to metals is computed using a code based on the Raymond-Smith code (Raymond et al. 1976), assuming ionization equilibrium (Cen et al. 1995a).

We follow star formation using a well-defined prescription employed in our earlier work (Cen & Ostriker 1992, 1993) and similar to that of other investigators (Katz et al. 1992, 1996; Steinmetz 1996; Gnedin & Ostriker 1997). A stellar particle of mass \( m_* = c_e m_{gas} \Delta t/\tau_{cs} \) is created (the same amount is removed from the gas mass in the cell) if the gas in a cell at any time meets the following three conditions simultaneously: (1) contracting flow, (2) cooling time less than dynamical time, and (3) Jeans-unstable. Here \( \Delta t \) is the time step, \( \tau_{cs} = \text{max} (t_{dynam}, 10^7 \text{yr}) \), \( t_{dynam} = [3\pi/(32G\rho_{\text{crit}})]^{1/2} \) is the dynamical time of the cell, \( m_{gas} \) is the baryonic gas mass in the cell, and \( c_e = 0.07 \) is the star formation efficiency.

Each stellar particle is given a number of other attributes at birth, including formation time \( t_\text{f} \), initial gas metallicity, and the free-fall time in the birth cell \( t_{dynam} \). The typical mass of a stellar particle in the simulation is about 1 million solar masses; in other words, these stellar particles are like coeval globular clusters, whose evolution can be computed with standard stellar evolution codes such as that of Bruzual & Charlot (1993). Changing the numerical coefficient \( c_e \) to higher or lower values can change the time dependence of star formation, making it more smooth or more “bursty,” but it has little effect on the total mass in stars/galaxies or in the overall simulation. All variations of this commonly adopted star formation algorithm essentially achieve the same goal: in any region where gas density exceeds the stellar density, gas is transformed into stars on a timescale longer than the local dynamical time and shorter than the Hubble time. Since these two timescales are widely separated, the effects, on the longer timescale, of changing the dimensionless numbers (here \( c_e \)) are minimal. Since nature does not provide us with examples of systems that violate this condition (systems that persist over many dynamical and cooling timescales in having more gas than stars), this commonly adopted algorithm should be adequate even though our detailed understanding of star formation remains primitive.

Stellar particles are treated dynamically as collisionless particles subsequent to their birth. But feedback from star formation is allowed in three forms: ionizing UV photons, the effects of the cumulative supernova explosions and the output from active galactic nuclei known as galactic superwinds (GSWs), and metal-enriched gas, all being proportional to the local star formation rate. The temporal release of all three feedback components at time \( t \) has the same form: \( f(t, t_\text{f}, t_{dynam}) \equiv (1/\tau_{dynam})[(t - t_{dynam}) \exp \left[ -(t - t_{dynam})/\tau_{dynam} \right]. \)

Within a time step \( dt \), the GSW energy released to the intergalactic medium (IGM), ejected mass from stars into the IGM, and escaping UV radiation energy are \( \epsilon_{\text{GSW}} f(t, t_\text{f}, t_{dynam}) m_c c^2 dt \), \( \epsilon_{\text{mass}} f(t, t_\text{f}, t_{dynam}) m_c c^2 dt \), and \( f_{\text{esc}}(Z) \epsilon_c Z(t, t_\text{f}, t_{dynam}) m_c c^2 dt \). We use the Bruzual-Charlot population synthesis code (Bruzual & Charlot 1993; Bruzual & Charlot 2003) to compute the intrinsic metallicity-dependent UV spectra from stars with a Salpeter initial mass function (with lower and upper mass cutoffs of 0.1 and 125 M\(_\odot\)). Note that \( \epsilon_{\text{UV}} \) is no longer just a simple, normal coefficient but a function of metallicity. The Bruzual-Charlot code gives \( \epsilon_{\text{UV}} \) values of \( 1.2 \times 10^{-4}, \ 9.7 \times 10^{-5}, \ 8.2 \times 10^{-5}, \ 7.0 \times 10^{-5}, \ 5.6 \times 10^{-5}, \ 3.9 \times 10^{-5}, \ 1.6 \times 10^{-6} \) at metallicities \( Z \) of \( 5.0 \times 10^{-3}, \ 2.0 \times 10^{-2}, \ 2.0 \times 10^{-1}, \ 4.0 \times 10^{-1}, \ 1.0, \ 2.5, \ 5.0 \ Z_\odot \), respectively. We also implement a gas metallicity-dependent ionizing photon escape fraction from galaxies, in the sense that galaxies with higher metallicity, and hence higher dust content, are assumed to allow a lower escape fraction; we adopt escape fractions \( f_{\text{esc}} \) of 2% and 5% (Hurwitz et al. 1997; Deharveng et al. 2001; Heckman et al. 2001; Steidel et al. 2001; Shapley et al. 2006) for solar and 1/10 solar metallicity, respectively, and interpolate or extrapolate using a loglinear form for metallicity. In addition, we include the emission from quasars using the spectral form observationally derived by Sazonov et al. (2004), with a radiative efficiency in terms of stellar mass of \( e_{\text{GSW}} = 2.5 \times 10^{-5} \) for \( h \nu > 13.6 \text{ eV} \). This number, \( e_{\text{GSW}} \), convolves together the ratio of black hole to stellar masses, \( \sim 1 \times 10^{-3} \) (Kormendy & Gebhardt 2001), the radiative efficiency of black holes, 0.1 (Yu & Tremaine 2002), and the fraction of the radiative energy emitted beyond the Lyman limit, 0.25 (Sazonov et al. 2004). Finally, hot, shocked regions (such as clusters of galaxies) emit ionizing photons due to bremsstrahlung radiation, which are also included. The UV component is simply averaged over the box, since the light-propagation time across our box is small compared with the time steps. The radiation field (from 1 eV to 100 keV) is followed in detail with allowance for self-consistently produced radiation sources and sinks in the simulation box and for cosmological effects; that is, radiation transfer for the mean field \( J_e \) is computed with stellar, quasar, and bremsstrahlung sources and sinks due to LyC clouds, etc. (eq. [7] of Cen 1992). In addition, a local optical depth approximation is adopted to crudely mimic the local shielding effects: each cubic cell is flagged with six hydrogen “optical depths” on the six faces, each equal to the product of neutral hydrogen density, hydrogen ionization cross section, and scale height, and the appropriate mean from the six values is then calculated; equivalent one for neutral helium and singly ionized helium are also computed. In computing the global sink terms for the radiation field, the contribution of each cell is subject to the shielding due to its own “optical depth.” In addition, in computing the local ionization and cooling-heating balance for each cell, the same shielding is taken into account to attenuate the external ionizing radiation field.

It is very difficult to accurately model the effects of GSWs. A proper treatment would include allowance for a multiphase medium having most of the mass in clouds or filaments occupying a small fraction of the volume. Significant progress has been made recently to provide a better treatment of the multiphase interstellar medium (Yepes et al. 1997; Elizondo et al. 1999a, 1999b; Hultman & Pharasyn 1999; Ritchie & Thomas 2001; Springel & Hernquist 2003), but the generation of GSWs is far from being adequately modeled. Clearly, a combination of both high resolution and a detailed treatment of the multiphase medium (including magnetic fields and cosmic rays) is requisite before our understanding of the interactions between galaxy formation and the IGM can be considered to be truly satisfactory. This problem is too difficult for us to address with our code, so we have chosen not to attempt to calculate the causes and generation of GSWs but, instead, to simply assume an input level of mass, energy, and metals and carefully compute the consequences of a GSW on the surrounding medium. For this purpose our code is very well designed.

Thus, GSW energy and ejected metals are distributed into 27 local gas cells centered at the stellar particle in question, weighted by the specific volume of each cell. We fix \( \epsilon_{\text{mass}} = 0.25 \), that is, 25% of the stellar mass is recycled. GSW energy injected into the
IGM is included with an adjustable efficiency (in terms of restmass energy of total formed stars) of $e_{\text{GSW}}$, which is normalized to observations for our fiducial simulation with $e_{\text{GSW}} = 3 \times 10^{-6}$. If the ejected mass and associated energy propagate into a vacuum, the resulting velocity of the ejecta would be $(e_{\text{GSW}}/\epsilon_{\text{mass}})^{1/2} c = 1470$ km s$^{-1}$. After the ejecta has accumulated an amount of mass comparable to its initial mass, it may slow down to a few hundred kilometers per second. We find that this velocity roughly corresponds to the observed outflow velocities of Lyman break galaxies (e.g., Pettini et al. 2002). We also performed a simulation with no GSWs to investigate the effects of GSWs on the IGM. In the “no GSW” run, we set $e_{\text{GSW}} = 0$ but fixed all the parameters, including $\epsilon_{\text{mass}} = 0.25$; in other words, ejected mass enriched with metals from supernovae is deposited in the neighboring cells as before, but the driving GSW is removed. Thus, all the uncertainties concerning how much of the energy that is generated by feedback can escape into the surrounding IGM is encapsulated into one parameter, $e_{\text{GSW}}$. We note that this has been a known problem in cosmological simulations (more notably in smoothed particle hydrodynamics simulations), where feedback energy from star formation deposited in high-density regions is highly effective in driving a blast wave, and often clever techniques are designed to circumvent this problem, such as delayed cooling (e.g., Brook et al. 2004). The primary difference between our work and previous works is that we have a multiphase medium by design, in the sense that we condense out star-forming gas into “stellar particles” while leaving the underlying gas component relatively diffuse. Our adopted method of distributing feedback energy weighted by specific volume is able to account for the fact that blast waves tend to preferentially propagate along the lowest density gradients. As a result, we find that adequate feedback energy on the IGM is obtained for reasonable choices of parameters, which are ultimately normalized to match observations, producing a self-consistent picture.

The results reported here are based on new simulations of a WMAP-normalized (Spergel et al. 2003; Tegmark et al. 2004) cold dark matter model with a cosmological constant, $\Omega_m = 0.31$, $\Omega_b = 0.048$, $\Omega_{\Lambda} = 0.69$, $\sigma_8 = 0.89$, $H_0 = 100 \, h \, \text{km s}^{-1} \, \text{Mpc}^{-1} = 69 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, and $n = 0.97$. The adopted box size is $85 \, h^{-1} \, \text{Mpc}$ comoving and with a number of cells of $10^{23}$; the cell size is $83 \, h^{-1} \, \text{kpc}$ comoving, with dark matter particle mass equal to $3.9 \times 10^2 \, h^{-1} \, M_{\odot}$. Given a lower bound of the temperature for almost all the gas in the simulation of $T \sim 10^4 \, K$, the Jeans mass is $\sim 10^{10} \, M_{\odot}$, which is comfortably larger than our mass resolution.

3. RESULTS

As in CO99, in our analysis we divide the IGM into three components by temperature: (1) $T > 10^7 \, K$ (the normal X-ray-emitting gas, predominantly in collapsed and virialized clusters of galaxies); (2) $10^7 \, K > T > 10^5 \, K$, which is defined as WHIM and exists mainly in unvirialized regions; and (3) $T < 10^5 \, K$ warm gas, which is mostly in low-density regions. A last component is (4) the cold gas that has been condensed into stellar objects, which we designate “galaxies” and which will contain stars and cold gas. After reionization at $z \sim 6$ (e.g., Gnedin & Ostriker 1997; Fan et al. 2002; Cen & McDonald 2002), driven by the absorption of UV photons from the early generation of stars and quasars, the photoionized IGM is left in the “warm” component with $T \sim 10^{10} - 10^{13} \, K$. Then, as larger and larger scale structure forms, the breaking waves of wavelength $\lambda_{\text{NL}}(t)$ cause gas to shock-heat to temperatures $kT/\mu m_p = A(\lambda_{\text{NL}}(t)/H(t))^2$, which increases monotonically with time, where $H(t)$ is the Hubble constant at time $t$. Details of this fit are provided in CO99 ($A \sim 3/16$). Thus, warm gas is increasingly shock-heated, removed from that category, and added to the WHIM category, with the shocks forming the observed filamentary network seen in Figure 2 below. By redshift $z \sim 2$, $\lambda_{\text{NL}}$ has increased to the point at which, at the
nodes, where filaments intersect, gas has been shocked into the “hot” X-ray-emitting gas category, as we begin to see the formation of the great clusters of galaxies in these regions. While not expected to be the primary heater of the IGM, GSWs from star-forming galaxies are observed to blow winds at speeds of several hundred kilometers per second and will heat up the IGM in the vicinity.

Figure 1 shows the evolution of these four components. We note that 49% of all baryons are in the WHIM by the time $z = 0$, which is consistent with our previous findings (CO99). Without galactic superwinds, the mass fraction in the WHIM is reduced from $\sim 50\%$ to $\sim 40\%$, which may partially explain the lower WHIM mass fractions in other simulations without GSWs, such as found by Davé et al. (2001). The bottom line is this: while GSWs are less dominant than gravitational heating caused by the collapse of large-scale density waves, they nevertheless make about a 20% contribution to the overall WHIM mass. Other components are consistent with our earlier results and approximately in agreement with observations with regard to low-redshift $\text{Ly}_\alpha$ cloud gas (Penton et al. 2004) and X-ray clusters of galaxies and stellar mass (Fukugita et al. 1998). Convergence tests indicate that this result is robust, simply because contributions from small galaxies (see, e.g., Kay et al. 2002) not resolved in our simulations are small, given that our resolution is adequate for galaxies significantly below the knee of the galaxy luminosity function.

The hot-component gas reached 11% in this simulation by $z = 0$, which is somewhat smaller than the 19% found in our previous work (CO99). The difference is due partly to differences in the model parameters and partly to cosmic variance. This component is not greatly affected by GSWs (see Fig. 13 below). As noted, our attention will be focused in this paper on the WHIM (\textit{filled circles}) in Figure 1$b$: the warm-hot gas rises dramatically in abundance with increasing time and dominates the mass balance by $z = 0$, reaching 49% of the total baryons. Therefore, our new simulations with a host of improved physical treatments and numerical details confirm our previous results: the long-sought missing baryons (those not seen in the more easily observed warm and hot components) should be found in the WHIM. The primary purpose of this paper is, in addition, to provide a more quantitative description of the observable properties of the WHIM, to better test this prediction.

All subsequent results are focused on redshift zero. The characteristic spatial distribution of the WHIM is shown in Figure 2.
We see a filamentary structure (green), as found previously (CO99), in which, at the high-density nodes (red), “galaxies” as well as very hot gas have been collected to form X-ray–bright clusters of galaxies. This “cosmic web” is traced out by moderate-density gas (the green filaments); galaxies and other virialized objects are beads threading the filaments. The vast volume between the filaments is mostly underdense in gas and is also relatively devoid of galaxies (Peebles 2000).

Figure 3 shows the gas distribution in the density-temperature plane. The gas in this phase space can be best described using the four baryon components defined at the beginning of this section. First, one sees a cooling feature at $T \sim 10^4$ K and overdensity of $\sim 10^{3.5} - 10^{5.0}$, where the gas is cooling rapidly to form stars. Second, the lower left corner of the plot ($\rho \leq 1$ and $T < 10^4$ K) represents cold-warm gas in the voids, which does not cool efficiently by means of radiative processes but cools adiabatically because of the expansion of the universe after initial photoionization and photoheating. This gas was heated up to 10,000 K when it was first reionized. Subsequently, since the recombination time becomes significantly longer than the Hubble time, further heat input to the gas becomes small, and it cools roughly adiabatically with the expansion of the universe. Third, both WHIM and hot gas are heated up, primarily by shocks formed during large-scale structure formation. Initially, this heated gas tends to occupy the upper right corner of the phase space, representing relatively dense regions that have attained high temperature due to of shocks, some of which are in virialized regions corresponding to groups and clusters of galaxies. With time, the shocks continue to expand and propagate into lower density regions as matter continues to infall toward these regions, resulting in the mass concentration contours in Figure 3 moving to the left in the displayed phase space and filling up the upper left quarter of the plot. We provide a fitting formula that traces the locus of the ridge line in the $T$-$\rho$ plane for the WHIM:

$$\log T = 8 - \frac{1}{4\log (\rho_\parallel / \bar{\rho})} \log \bar{\rho} \, ,$$

where $T$ is in the range $10^5 - 10^7$ K, $\rho_\parallel$ is the gas density, and $\bar{\rho}$ is the mean gas density at $z = 0$.

Comparing the top and bottom panels of Figure 3, we see that while the overall effect of GSWs on the IGM is significant, as shown in Figure 1b, it is not easily discernible here quantitatively. However, one feature is very noticeable even to the eye: it can clearly be seen that in the simulation with galactic superwinds, some gas in the IGM is being pushed toward the left (near the upper left corner) in the WHIM temperature range in the plot. This suggests that GSWs visibly propagate into lower density regions.

Before presenting detailed quantitative calculations of the GSW effects, we provide a more pictorial view of the GSW processes. Figures 4–6 provide a close-up view of a region, of size $21.2 \times 21.2$ h$^{-2}$ Mpc$^2$ and thickness $1.75$ h$^{-1}$ Mpc, that has had significant GSW activity in the recent past, in the sense that it contains significant hot bubbles produced by GSWs. We note that, as shown in Cen et al. (2005b), GSW effects tend to be more vigorous at higher redshifts, when the star formation rate was higher. Nevertheless, the effects of GSWs on the surrounding IGM are strongly visible even at $z = 0$. Figure 4 compares the gas density and temperature distributions in the two simulations without and with GSWs. Overall, the effect on the appearance of large-scale density structure (Fig. 4, left) by GSWs is small, and their effect on low-density regions (blue and purple) is negligible, simply because GSWs do not reach there, or turn very weak even if they do. The effect on high-density regions ($>10^2$; yellow) is quite visible, in the sense that GSWs tend to suppress the gas density concentration in these regions and disperse gas outward; note that some of the yellow spots in the simulation without GSWs are significantly suppressed; examples include the features at $(8, 5), (13, 8),$ and $(6, 13)$ h$^{-1}$ Mpc. This effect is quantified more precisely in subsequent figures.

From the temperature slices (Fig. 4, right), we see that shocks induced by large-scale gravitational collapse tend to center on dense regions; these are virialization and infall shocks due to gravitational collapse of high-density peaks. Some of the larger...
peaks are enclosed by shocks of temperature in excess of $10^7$ K (note that the displayed picture is inevitably subject to smoothing by projection, and thus the higher temperature regions have their temperatures somewhat underestimated). A few shock structures are clearly caused by GSWs, however, because they appear prominent only in the simulation with GSWs; for example, in the upper left quarter, the gravitational shock feature oriented northwest-southeast near $(6, 14) h^{-1}$ Mpc, which is aligned with a high-density filament, is significantly enlarged by GSW shocks propagating approximately in the direction (northeast-southwest) perpendicular to the filament. The resulting shock temperature is in the WHIM temperature range of $10^5$–$10^7$ K. Another large feature is seen in the lower right quarter near $(18, 5) h^{-1}$ Mpc in the simulation with GSWs but is nearly invisible in the simulation without GSWs; this feature is most likely produced by a GSW shock originating from a galaxy not centrally located in the displayed slice, since there is no significant density concentration at that location. These regions affected by GSWs clearly are heating up the warm gas and its surroundings seen in Figures 4 and 5 and adding this gas to the WHIM; more quantitative results are given below.

Figure 5 shows the total density of metals and the non-LTE–computed $\text{O} \text{vi}$ density distributions in the same slice for the simulations without and with GSWs. The most visible difference in the total metal density distributions (Fig. 5, left) between simulations with and without GSWs is that the high-metallicity (yellow) regions in the close vicinity of galaxies are substantially extended by GSWs. This is because metals in the case of no GSWs are concentrated in regions of about our grid size, and the GSWs cause these extremely dense metal nuggets to appear on the IGM scale. The predicted effect has perhaps received dramatic confirmation in the $\text{O} \text{vi}$ absorption measurements of Stocke et al. (2006), who find that $\text{O} \text{vi}$ absorbers are invariably found within $800$ kpc of galaxies. The affected regions have a size ranging from a few hundred kiloparsecs to about $1$ Mpc, suggesting that this is the range of influence of GSWs in transporting metals to the IGM. We note that the shocks, seen in Figure 5, tend to propagate farther out to scales of $1–2 h^{-1}$ Mpc, while apparently leaving metals significantly behind; that is, the energy of the GSWs is, as expected, transported more efficiently than metals. As we show quantitatively below, heating metal-rich warm gas and significant dispersal of heated-up WHIM gas to significant...
distances from galaxies is the most dramatic role played by GSWs. Most spectacularly, a GSW reduces the total amount of metals in cold-warm gas in the close vicinity of galaxies by a factor of 3 compared with the case without GSWs and adds all this metal-enriched gas to WHIM. From the right panels of Figure 5 one can see that the visibly discernible difference caused by GSWs is that GSWs tend to disperse concentrations of O\textsuperscript{vi} density, in accordance with overall metals dispersal in dense regions seen in the total metals distribution (left), and tend to create typically nonspherical features in the immediate regions surrounding galaxies on scales of less than 1 Mpc.

The differences caused by GSWs on O\textsuperscript{vii} density, shown in the left panels of Figure 6, appear to be somewhat larger than those for O\textsuperscript{vi} density, suggesting that GSW-heated regions around galaxies are more often in the range of 10\textsuperscript{6}–10\textsuperscript{7} K, higher than the optimal temperature of 10\textsuperscript{5.5} K for O\textsuperscript{vi}, which seems to be consistent with Figure 4. This is confirmed by the right panels of Figure 6, where O\textsuperscript{vii} density is shown for the simulations without and with GSWs. The overall results from Figures 4–6 indicate that the effects of GSWs on the abundances of individual species cannot be easily described and that the only means to compare models and observations is through direct simulations. This is because the relative abundance of an individual species depends on the temperature and density history of the gas, which in turn would depend on the shock (i.e., GSW) strengths and environments, which are too complicated to be characterized by simple analytically tractable relations.

Clearly, the regions where differences caused by GSWs are visible to the eye in Figure 3 do not contain a significant amount of IGM mass. More dense regions must have been affected by GSWs to account for the effect indicated in Figure 1b, which is visually confirmed by the pictures shown above. We quantify this further to have a better understanding. Figures 7–9 show the concentration of gas mass of the three IGM components, warm, WHIM, and hot, respectively, in the dark matter density–gas density plane. Comparing the simulations with (solid contours) and without (dotted contours) GSWs reveals some important information. From Figure 7 we see that there are two separate mass concentrations for the warm IGM component, one centered at about the mean density and the other at about 10\textsuperscript{3} times the mean density. The physical nature of these two separate concentrations is quite clear, as noted earlier: the peak at lower density is primarily photoheated gas in the voids, whereas the peak at high density is the cooled gas reservoir for star formation. The effect

**Fig. 5.—** Left: Spatial distribution of log (metal density) in the same slice as in Fig. 4 without (top) and with (bottom) GSWs. The gas metallicity is in units of solar metallicity. Note the slightly greater extent of metal-rich regions with GSWs. Right: Spatial distribution of log (O\textsuperscript{vi} density) in the same slice without (top) and with (bottom) GSWs. The density is in units of the global mean gas density. The significantly greater volume of O\textsuperscript{vi} reflects both temperature and metallicity effects of GSWs. In collisionally ionized gas, the O\textsuperscript{vi} fraction peaks at a temperature around 10\textsuperscript{5.5} K (see Cen & Fang 2006).
of GSWs seems to be to push the peak at lower density to the left; that is, some gas at low to moderate density is being pushed to slightly lower (dark matter) density regions by GSWs. This is quite understandable. The peak at high density, however, appears to move both left and downward with GSWs. This may be understood as two cases that may be occurring simultaneously. First, as in the previous case, gas is simply blown out of high-density regions, causing it to move left. Second, for some regions where the gas density has become comparable to or larger than the dark matter density as a result of gas cooling and condensation, a reduction in gas density due to GSWs would have dynamic effects on both the remaining gas and the dark matter, resulting in a gravitational potential change, which may explain the downward-left movement of the contour peak. Since the high-density regions provide the gas reservoir for star formation, GSWs are explicitly shown here to have a major effect on reducing and regulating star formation, which is verified by the reduced (but adequate) star formation in the simulation with GSWs.

The effect of GSWs on the WHIM is shown in Figure 8. Since most of the mass in the WHIM is in regions with moderate density (10–20 times the mean density), the dark matter dominates the gravitational potential. Therefore, the primary effect of GSWs on the WHIM is in moving gas into somewhat lower density regions and heating up gas in regions with a wide range of densities, as shocks sweep through them in the direction of negative density gradient. The same effect is seen for the hot component (Fig. 9), although the overall effect is somewhat diminished, simply because the incremental increase in energy due to GSWs in these regions is less dominant than the gravitational potential energy released in strong shocks.

Figure 10 summarizes more quantitatively the trends in Figures 7–9 in a slightly different way, showing the probability distribution of each of the three gas components as a function of the gas density. The most dramatic difference is seen for the warm component (dotted curves, top) between simulations with (thick dotted curve) and without (thin dotted curve) GSW. One can see that a substantial fraction of the warm gas at density $\rho / \rho_c = 10^{13} - 10^{14.5}$ is removed by GSWs. This gas removed from the warm component is primarily added to the WHIM gas, as clearly indicated.
by the difference for WHIM components (Fig. 10, middle) between simulations with (thick solid curve) and without (thin solid curve) GSWs. There is also an overall shift of this component to lower densities, at which radiative cooling would be less efficient. The effect of GSWs on the hot component is rather small, as can be seen from the nearly overlapping thick dashed curve and thin dashed curve in the bottom panel. Figure 11 demonstrates in a different way the same point: the gain in WHIM fraction is at the expense of warm gas, heated up by GSWs.

Metals that originate in galaxies are transported by GSWs and other hydrodynamic and gravitational processes. The role that GSWs actually play to affect the distribution of metals in the IGM is complex. Figure 12 shows the distribution of metals in each of the three IGM components as a function of metallicity. The warm component displays a bimodal distribution, with one peak at high metallicity corresponding to the star formation
regions while the other peak at very low metallicity corresponds to the uncontaminated, predominantly low-density, regions that are remote from late-time star formation regions, which are a relic from very early low-mass galaxy formation. We stress that the exact metallicity value of the lower metallicity peak is very uncertain, being significantly subject to resolution effects; it is likely that our still relatively poor resolution must have underestimated star formation at high redshift in quite small galaxies that are not well resolved by our numerical resolution, which may otherwise have enriched the IGM with metals to a higher floor level. In addition, the metals produced by the very first generation of stars (see, e.g., Cen 2003; Ricotti & Ostriker 2004) may also have helped to raise the metallicity floor in the IGM. Overall, the effect of GSWs is to reduce the amount of metals in the high-metallicity peak (Z > 0.3–1.0 Z⊙) of the warm gas, and it is likely that a significant amount of this metal-rich gas is dispersed to mix with other, lower metallicity warm gas in the metallicity range Z ~ 0.003–0.3 Z⊙. More importantly here, a significant amount of warm, metal-rich gas is heated to the WHIM temperature range, accounting for the differences seen at Z ~ 0.01–1.0 Z⊙ between the simulations without and with GSWs shown in the middle panel of Figure 12. At the same time, it is also clearly seen that some of the WHIM gas at low metallicity (Z ≤ 0.01 Z⊙) is substantially enriched and hence removed from that section and added to the section with Z ≥ 0.01 Z⊙. We find that the median metallicity of the WHIM is 0.18 Z⊙ for oxygen, with 50% and 90% intervals being (0.040, 0.38) and (0.0017, 0.83). Finally, the effect of GSWs on hot, cluster X-ray gas is rather minimal, as shown in the bottom panel of Figure 12. The metallicity of the cluster gas is robustly peaked at Z ~ 0.3 Z⊙ in terms of iron abundance, as observed (Arnaud et al. 1994; Tamura et al. 1996; Mushotzky et al. 1996; Mushotzky & Loewenstein 1997; Tozzi et al. 2003); in fact, this is how we normalize our metal yield (the sole parameter to determine the amount of metal output from stars) in order to construct a self-consistent picture. In our simplest, one-parameter model for metal yield, there is no adjustable free parameter that can alter the distribution of metals, and our predictions as presented in the next section are completely deterministic and falsifiable.

Figure 13 shows the cumulative metal mass fraction as a function of gas density for each of the three IGM components. Overall, we find that in the simulation without GSWs, 36%, 48%, and 16% of all metals in the IGM are respectively in the warm, WHIM, and hot components. The distribution among the IGM components is altered to (warm, WHIM, hot) = (12%, 71%, 17%) in the simulation with GSWs. This shows that GSWs reduce the metal mass in the warm IGM component by a factor of 3, while the hot IGM component is virtually unaffected by GSWs. All the metals when a part of the warm IGM component is heated up are added to the WHIM component. This is the most dramatic effect that GSWs have on one single physical component or process. As is also quite clear from the top panel of Figure 13, most of the metals that are heated and removed from the warm component are in relatively overdense regions, at ρgas ≥ 200. However, most of the metals that are added to the WHIM can be seen, from the middle panel of Figure 13, to be in regions spanning a significant range in density, from 1 to 300 times the mean density. At the same time, as the middle panel of Figure 13 indicates, some WHIM gas in the high-density region (ρ > 300) is affected oppositely, in the sense that their metallicity appears to be reduced by GSWs (the thick solid curve falls below the thin solid curve); however, a more correct interpretation is that the thin solid curve is pushed to the left to become the thick solid curve, that is, GSWs reduce the density of this already metal-rich gas that is located in the very close vicinity of galaxies.

Figure 14 further illustrates the effect of GSWs on metal transport in a “phase” space, where we show average gas metallicity in the density-temperature phase space for the simulations with (top) and without (bottom) GSWs. Let us examine this closely.
First, in the bottom panel, we see a concentration of high-metallicity gas ($Z/C_21 > 1 > Z/C_12$) at $(T/C_24 = 10^4 K)$, within the thick solid contours, which clearly is the gas within the galaxy that has been enriched by metals but remains cold-warm in the absence of GSW shocks. We note that the original gravitational shocks caused this gas to cool and condense to that phase-space domain. Then, in the top panel this contour has vanished; this concentration of high-metallicity gas is essentially "blown away" by the GSWs, as there remains little high-metallicity gas in that phase-space domain in the simulation with GSWs (top), but this gas reappears at low density and high temperature within the thick solid contour in the upper left corner. Specifically, as GSWs propagate to lower density regions (cf. Figs. 4–6), the metals transported there weigh relatively more importantly than in high-density regions, creating high-metallicity gas there. We see that in the WHIM temperature range of $10^5 – 10^7$ K there is a concentration of solar-metallicity gas in the density range of 1–30 times the mean density, which can be easily probed by metal absorption line observations (see Cen & Fang 2006). We note that what is displayed here is the average metallicity and that there is a very large dispersion in metallicity for gas elements in the same phase-space location. Third, a significant fraction of WHIM gas in moderate- to high-density regions of $\rho = 50 – 10^5$ is now significantly enriched to an average metallicity of $0.1 – 0.3 Z_\odot$.

From these results, we expect that one of the most sensitive tests of GSWs’ effect may lie in the properties of metal-rich gas in the vicinity of galaxies and groups of galaxies, where density ranges from moderate to high and GSWs are most energetically relevant. These dramatic effects caused only by GSWs, not gravitational shocks, can then be used to provide important tools to understand GSWs. Observationally, we expect that metal lines, both absorption and emission, may serve as an excellent diagnostic for probing GSWs, as will be shown in the companion paper (Cen & Fang 2006). The absorption lines may be most efficient to probe the moderate-density regions, while the emission lines may mostly concentrate on the high-density regions.

4. DISCUSSION AND CONCLUSIONS

Numerical simulations of the intergalactic medium have shown that at the present epoch, a significant fraction (40%–50%) of the
baryonic component should be found in the \((T \sim 10^2-10^7 \, \text{K})\) warm-hot intergalactic medium—with several recent observational lines of evidence indicating the validity of the prediction. We here recomputed the evolution of the WHIM with the following major improvements: (1) galactic superwind feedback processes from galaxy and star formation are explicitly included; (2) major metal species (O iv to O ix) are computed explicitly in a nonequilibrium way; and (3) the mass and spatial dynamic ranges are larger by factors of 8 and 2, respectively, than our previous simulations.

Our significantly improved simulations confirm previous conclusions based on earlier simulations: nearly half of all baryons at the present epoch should be found in the WHIM—a filamentary network in the temperature range of \(10^2-10^7 \, \text{K}\).

Here are the major findings: (1) Overall, the fraction of baryons in the WHIM is slightly increased from the earlier work but consistent with a value of \(\sim 40\%-50\%.\) (2) Galactic superwinds have three significant effects, first to increase the WHIM mass fraction by about \(20\%\), through shock-heating of photoionized gas adjacent to filaments, second to contaminate nearby gas with extra metals and additional heating, and third to disperse much of the metals within galaxies. (3) The gas density of the WHIM is broadly peaked at a density \(10^{-10} \text{Mpc}\) times the mean density, ranging from underdense regions to regions overdense by \(10^3-10^6\). (4) The median metallicity of the WHIM is \(0.18 \, \text{Z}_\odot\) for oxygen, with 50% and 90% intervals being \((0.040, 0.38)\) and \((0.0017, 0.83)\).

The physics behind this robust conclusion is largely dictated by the dominance of gravitational heating when large-scale structures began to collapse in the recent past in cosmic history. Simply put, the average temperature of the IGM at any epoch is determined by the mass scale that goes nonlinear at that epoch, which, at the present time, is close to the \(8 \, \text{h}^{-1} \, \text{Mpc}\) scale that fixes the abundance of rich clusters. This explains the relative insensitivity of the computed mass fraction in the WHIM to cosmological parameters, so long as each model is properly normalized to reproduce the well-determined abundance of observed rich clusters of galaxies today; only a very small extrapolation is needed to go from this well-observed scale to the nonlinear scale, so the estimated temperature of collapsed regions that we find will be common to all models based on the gravitational growth of structure—as normalized to local cluster observations.

It was not entirely clear how important feedback processes from galaxy formation on the IGM are based on comparisons of our early simulations with simulations by others (Davé et al. 2001). In this work we have demonstrated quantitatively, for the first time, this effect. We find that galactic superwinds generated collectively by supernova explosions in galaxies, while still less dominant than gravitational heating from large-scale structure formation, have important effects on the WHIM as well as other components of the IGM. The mass fraction of the WHIM is increased by about 20% when GSWs are included. We show that this increase in the WHIM mass fraction comes largely at the expense of the warm IGM phase over a broad range of \(10^3-10^4\) times the mean density, which is often independently invoked to suppress star formation and alleviate the overcooling problem. A perhaps more important effect of GSWs is to transport metals to the IGM from inside galaxies to a distance of from several hundred kiloparsecs up to about 1 Mpc, a necessary process to enrich the IGM. It is therefore likely that detailed, joint analyses and comparisons with observations of the detailed structure of the WHIM density, temperature, and metal abundances should be able to provide useful information on GSWs, which currently can only be modeled crudely. Nevertheless, with the adopted approximate treatment, we are able to show the significant effects on many observables, including the properties of major absorption and emission lines in the UV and soft X-rays (see Cen & Fang 2006).

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