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THE TEMPERATURE STRUCTURE OF THE WARM-HOT INTERGALACTIC MEDIUM

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ABSTRACT

We study the temperature structure of the intergalactic medium (IGM) using a large cosmological N -body/SPH simulation. We employ a two-temperature model for the thermal evolution of the ionized gas, in which we include explicitly the relaxation process between electrons and ions. In the diffuse, hot IGM, the relaxation time is comparable to the age of the Universe and hence the electron temperature in post-shock regions remains significantly smaller than the ion temperature. We show that, at the present epoch, a large fraction of the warm/hot intergalactic medium (WHIM) has a well-developed two-temperature structure, with typical temperature differences of order a few. Consequently, the fraction of metals in various ionization states such as OVI, OVII, and OVIII, as well as their line emissivities, can differ locally by more than an order of magnitude from those computed with a single-temperature model, especially in gas with $T \sim 10^7$ K. It is thus necessary to follow the evolution of the electron temperature explicitly to determine absorption and emission by the WHIM. Although equipartition is nearly achieved in the denser intracluster medium (ICM), we find an appreciable systematic deviation between the gas-mass weighted electron temperature and the mean temperature even at half the virial radii of clusters. There is thus a reservoir of warm ($T_e < 1$ keV) gas in and around massive clusters. Our results imply that relaxation processes need to be considered in describing and interpreting observational data from existing X-ray telescopes as well as from future missions designed to detect the WHIM, such as the *Diffuse Intergalactic Oxygen Surveyor* and the *Missing Baryon Explorer*.

Subject headings: cosmology: theory - intergalactic medium

1. INTRODUCTION

The distribution of baryons in the Universe remains one of the puzzling issues in modern cosmology. At the present epoch, the total amount of baryons inferred from a census of H I absorption, gas and stars in galaxies, and X-ray emission from hot gas in galaxy clusters is far smaller than that predicted by nucleosynthesis calculations (Persic & Salucci 1992; Fukugita, Hogan & Peebles 1998) and by measurements of the cosmic microwave background radiation (Spergel et al. 2003). Hence, it is believed that a large fraction of the baryons lies in an as yet undiscovered *dark* state.

Three dimensional hydrodynamic simulations of cosmic structure formation (e.g., Cen & Ostriker 1999; Davé et al. 2001; Croft et al. 2002) predict that about 30–40% of the baryons reside in the so-called warm-hot intergalactic medium (WHIM) at the present epoch. This gas is mostly shock-heated to a temperature of $\sim 10^5$ – 10^7 K during large scale structure formation, and this relatively low temperature makes its thermal emission difficult to detect with conventional X-ray probes.

A variety of observational approaches have been considered for studying the WHIM, including both ultraviolet (e.g., Furlanetto et al. 2003, 2004) and X-ray lines. With respect to the latter possibility, there have been several tentative claims that the WHIM has been detected locally in absorption (e.g., Nicastro et al. 2002) and in emission (Finoguenov et al. 2003). Moreover, Yoshikawa et al. (2004) have proposed using OVII/OVIII lines to examine

the WHIM in detail with high spectral resolution X-ray detectors. They argue that, under a variety of assumptions, about half of the WHIM (by mass) can be detected via oxygen line emission (see also Fang et al. 2004). While the proposed missions appear promising, the detectability depends crucially on the assumed metallicity and the relative abundances of particular ions.

Previous theoretical studies used a single-temperature model for the WHIM, under the assumption that equipartition is fully achieved. However, the outskirts of galaxy clusters may actually have a two-temperature structure (e.g., Fox & Loeb 1997; Takizawa 1998; Courty & Alimi 2004). Near galaxy clusters, infalling gas shock-heats to roughly the virial temperature as kinetic energy is converted into thermal energy. Because the infalling ions carry nearly all of the bulk kinetic energy (exceeding that contained in electrons by a factor $\sim m_p/m_e$), the post-shock electrons can gain thermal energy only via collisions with ions. If collisional relaxation takes a time comparable to or longer than the age of the Universe, the two temperatures, i.e. those of the electrons and ions, remain different. One can easily show that the relaxation time is rather long for diffuse warm-hot gas around clusters and in large-scale filamentary structures. Since the relative abundance of metal ions and their emissivities are sensitive to the electron temperature, this has important implications for future observations of the WHIM, particularly for the hotter component.

In this *Letter*, we study the thermal evolution of the intergalactic medium (IGM) using a large hydrodynamic

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FIG. 1.— The distribution of baryons (left), the warm/hot component with $10^6 < T < 10^7$ K (middle), and gas with $T_e < 0.5T_i$ (right) in a slab of $100 \times 100 \times 20$ $(h^{-1}\text{Mpc})^3$ at $z = 0$. The vertical bar in the middle panel indicates a ‘super-cluster’ region, for which we compute the soft X-ray intensity (see section 4 and Figure 5).

simulation of structure formation. We show that a considerable fraction of the WHIM indeed has a two-temperature structure, particularly in and around rich clusters. In these regions, the electron temperature is typically smaller than the ion temperature by a factor of a few, substantially modifying estimates of the abundances of ions and their emissivities.

2. THE N -BODY/SPH SIMULATIONS

For our simulations, we use the parallel Tree-PM/SPH code GADGET2 (V. Springel, in preparation), which employs a fully conservative scheme for integrating the equations of motion (Springel & Hernquist 2002). We implement non-equipartition processes between ions and electrons following Fox & Loeb (1997) and Takizawa (1998). Equilibrium in an electron-proton plasma is achieved in the following manner. After passing through a shock, electrons and ions thermalize into (separate) Maxwellian distributions on equilibration timescales t_{ee}, t_{ii} , with $t_{ii}/t_{ee} \sim (m_i/m_e)^{1/2} \sim 43$ (Spitzer 1962). Here, m_e and m_i are the electron and ion masses and we have assumed protons dominate the ionic component. Equipartition between protons and electrons is achieved on an even longer timescale $t_{ei} \sim (m_i/m_e)t_{ee}$. Hence, we assume that electrons and ions quickly achieve Maxwellian distributions with temperatures T_e and T_i , respectively, and consider only the non-equipartition effect. Spitzer (1962) showed that the appropriate timescale is given by

$$t_{ei} = \frac{3m_em_i}{8(2\pi)^{1/2}n_iZ_i^2e^4\ln\Lambda} \left(\frac{kT_e}{m_e} + \frac{kT_i}{m_i} \right)^{3/2}, \quad (1)$$

where e is the electric charge, Z_i is the charge of an ion, n_i is the ion number density, and $\ln\Lambda$ is the Coulomb logarithm, which is given by

$$\ln\Lambda = 37.8 + \ln\left(\frac{T_e}{10^7\text{K}}\right) - \frac{1}{2}\ln\left(\frac{n}{10^{-5}\text{cm}^{-3}}\right). \quad (2)$$

For a hot, fully ionized plasma,

$$t_{ei} = 6.3 \times 10^8 \text{yr} \frac{(T_e/10^7\text{K})^{3/2}}{(n/10^{-5}\text{cm}^{-3})(\ln\Lambda/40)}, \quad (3)$$

and this timescale can be comparable to the Hubble time in regions with $T \gtrsim 10^7$ K and overdensities $10 - 100$ with respect to the cosmic mean. The evolution of the electron temperature is given by

$$\frac{dT_e}{dt} = \frac{T_i - T_e}{t_{ei}} + (\gamma - 1) \frac{T_e}{n} \frac{dn}{dt}. \quad (4)$$

We do not consider heat conduction on the assumption that it will be suppressed by tangled magnetic fields. Some other electron heating processes driven by plasma instabilities have also been proposed (Laming 2000), but detailed calculations in the context of supernova remnants suggest that these mechanisms convert less than 20% of the bulk kinetic energy to electron thermal energy (e.g., Cargill & Papadopoulos 1988), so we neglect these effects. Our treatment therefore maximizes the possible offset between T_e and T_i .

We work with a flat Λ -dominated cold dark matter cosmology with matter density $\Omega_0 = 0.3$, cosmological constant $\Omega_\Lambda = 0.7$ and expansion rate at the present time $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We set the baryon density $\Omega_b = 0.04$ and the normalization parameter $\sigma_8 = 0.9$. Our simulation employs 324^3 cold dark matter particles and the same number of non-radiative gas particles in a cosmological volume $100 h^{-1} \text{ Mpc}$ on a side. The mass per gas particle is $3.26 \times 10^8 h^{-1} M_\odot$, and the nominal gas mass resolution is about $10^{10} h^{-1} M_\odot$ for our choice of the number of SPH neighbors, $N = 32$. We note that the CDM initial conditions and the large simulation volume allow us to correctly model the merging process during the formation of filamentary structures and the assembly of massive halos which contribute to heating of the IGM as well as the intracluster medium (ICM; e.g., Keshet et al. 2003).

3. RESULTS

Figure 1 shows the baryon distribution at $z = 0$ in a slice $20 h^{-1} \text{ Mpc}$ thick (top), the hot component with temperature $10^6 < T < 10^7$ K (middle), and gas in which $T_e < 0.5T_i$. The latter two components are quite similar, suggesting that much of the hotter WHIM has a two-temperature structure. The distribution of the two-temperature gas appears quite complex even in clusters,

FIG. 2.— Electron temperature plotted against the mean gas temperature. The number density of gas particles is shown in grey-scale. The rectangular box indicates the so-called WHIM which we define to have $10^5 < T_e < 10^7$ K.

indicating that shocks induced by mergers during hierarchical assembly propagate and leave two-temperature gas within clusters. We have checked the time variation of the specific entropy of the gas elements and verified that the two-temperature regions have recently been shock-heated. In the gas around large-scale structure, *continuous* shock-heating disturbs equipartition sufficiently close to the shock, while more distant gas is often relaxed.

Figure 2 shows the electron temperature T_e plotted against the mean temperature $\bar{T} = (n_e T_e + n_i T_i) / (n_e + n_i)$, which is the temperature we would obtain in a single temperature model. Interestingly, the two-temperature deviation is largest in the WHIM regime (indicated by the rectangular box). Note that there are some gas elements with $T_e \ll \bar{T}$. This is because our simulation does not include electron heating processes other than Coulomb collisions.

Figure 3 shows the radial distribution of T_e (solid line) and $\bar{T}$ (dashed line) for one of the most massive halos in our simulation. We used a friends-of-friends group-finder to locate dark matter halos and define the virial radius such that the mean matter density within this radius is 200 times the critical density. The halo we consider here has a virial mass of $3 \times 10^{14} h^{-1} M_\odot$ and a virial radius of $1.1 h^{-1}$ Mpc. In Figure 3, the difference between the two temperatures is large at $r > 1 h^{-1}$ Mpc and appreciable even at $r < 1 h^{-1}$ Mpc. The overall profile looks similar to those found in simulations of single clusters by Takizawa (1998) and Chieze et al. (1998). Owing to the difference in relaxation time (see eq. [3]) in the dense central part and in the low density outer regions, the electron temperature profile appears steeper than that of the mean temperature at $r > 0.1 h^{-1}$ Mpc. The bottom panel of Figure 3 shows the baryonic mass fraction as a function of both T_e and $\bar{T}$ (thick and thin histograms, respectively). We selected gas particles within $5 h^{-1}$ Mpc of the cluster center. The distribution of T_e is skewed significantly to smaller values. The total gas mass contained in this region ($r < 5 h^{-1}$ Mpc) is $1.0 \times 10^{14} h^{-1} M_\odot$, and nearly 50% of it has $T_e < 1$ keV; i.e., the mass of the warm

FIG. 3.— Radial distribution of the electron temperature (solid line) and the mean temperature (dashed line) in one of the most massive clusters in our simulation (top panel). Bottom panel shows the mass fraction of gas within $5 h^{-1}$ Mpc from the cluster center in temperature bins, using the electron temperature (thick histograms) and the mean temperature (thin histograms).

component surrounding the cluster is greater than the gas mass within the cluster itself.

4. COSMOLOGICAL IMPLICATIONS

The two-temperature structure of the WHIM and ICM has many important implications. For example, the relative fractions of metal ions are of considerable interest for WHIM observations. Figure 4 shows the fraction of OVI, OVII, and OVIII ions as a function of temperature assuming collisional ionization equilibrium.⁴ Clearly the abundances have a strong dependence on *electron* temperature, because the populations are primarily determined by electron collisions (photo-ionization is unimportant for these high-level ions unless $T \ll 10^{5.5}$ K or the incident X-ray intensity is high). The bottom panel indicates the possible errors caused by assuming a single temperature for the WHIM. A factor of two systematic shift in temperature, typical of the offsets we find between $\bar{T}$ and T_e near shocks, can lead to significant over/under-estimates of the abundances.

We further quantify the importance of non-equipartition with a model oxygen line emission map. We put the super-cluster region indicated in Figure 1 at $z = 0.03$ and compute the surface brightness of OVII emission following the procedure of Yoshikawa et al. (2004). We adopt a simple relation between the gas metallicity and the local gas density of the form $Z = 0.02(\rho_{\text{gas}}/\bar{\rho})^{0.3} Z_\odot$, where $\bar{\rho}$ is the mean baryon density. We then compute the surface brightness for both T_e and $\bar{T}$. Figure 5 shows the

⁴The assumption of collisional ionization equilibrium may not be strictly valid in the WHIM. We nevertheless adopt this commonly-made assumption to compute the line emissivities in a post-processing manner.

FIG. 4.— Relative abundance of oxygen ions f_{OVI} (solid), f_{OVII} (dashed), and f_{OVIII} (dotted) as a function of electron temperature. The bottom panel shows the ratio $f(T)/f(T/2)$ which indicates the error induced by a factor of two shift (misestimate) in T_e .

derived profiles. While the overall results appear similar in the two cases, there are substantial local deviations. In particular, around some bright spots, the emissivity is greater by up to an order of magnitude when computed using the electron temperature. The ratio of the surface brightness $S(T_e)/S(\bar{T})$ is shown in the bottom panel of Figure 5. There, we mark the regions with $S(T_e) > 10^{-11} \text{ ergs}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$, which is the nominal detection limit of the proposed DIOS mission (Yoshikawa et al. 2003).

Similar considerations may also apply to efforts to study the WHIM using UV observations (e.g., Furlanetto et al. 2004), although the steep temperature dependence of t_{ei} implies that equipartition is more accurate in this regime (see Fig. 2). In principle, one can measure the degree of equilibration using various line intensities from far UV to soft X-rays (e.g., Ghavamian et al. 2001; Raymond et al. 2003) as well as the metal line Doppler widths. Measuring the age of the WHIM from the degree of equilibration will put a stringent constraint on theoretical models of large-scale *baryonic* structure formation.

FIG. 5.— Surface brightness of OVII emission for the region indicated in the middle panel of Figure 1 using T_e (solid line) and $\bar{T}$ (dot-dashed line). Bottom panel shows the ratio $S(T_e)/S(\bar{T})$. Dots in the bottom panel indicate the region where $S(T_e)$ is greater than $10^{-11} \text{ ergs}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$.

Although our simulation does not include radiative cooling, we note that the lower electron temperature can have a significant impact on the radiative cooling efficiency in dense regions. The gas cooling rate has a very steep temperature dependence at $10^5 < T < 10^6 \text{ K}$ regardless of the metallicity (Sutherland & Dopita 1993). As shown in Figure 2, recently shock-heated gas with $\bar{T} \sim 10^6 \text{ K}$ may have an electron temperature $T_e \sim 10^5 \text{ K}$. Such gas should cool rapidly and in a highly non-equilibrium manner. This warrants further study of the effect of the two-temperature structure on the IGM using a simulation with radiative cooling.

Overall, our simulation suggests that theoretical studies of the WHIM and correct interpretation of the observational data from current and future X-ray missions requires explicit consideration of these relaxation processes.

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REFERENCES

- Cargill, P. J. & Papadopoulos, K. 1988, ApJ, 329, L29
Cen, R. & Ostriker, J. P. 1999, ApJ, 519, L109
Chieze, J.-P., Alimi, J.-M., & Teyssier, R. 1998, ApJ, 495, 630
Courty, S. & Alimi, J. M. 2004, A&A, 416, 875
Croft, R.A.C. et al. 2002, ApJ, 581, 20
Davé, R., Cen, R., Ostriker, J. P., Bryan, G. L., Hernquist, L., Katz, N., Weinberg, D. H., Norman, M. L., & O'Shea, B. 2001, ApJ, 552, 473
Fang, T. et al. 2004, ApJ in press
Finoguenov, A., Briel, U. G., & Henry, J. P. 2003, A&A, 410, 777
Fox, D. C. & Loeb, A. 1997, ApJ, 491, 459
Fukugita, M., Hogan, C. J. & Peebles, P. J. E. 1998, 503, 518
Furlanetto, S.R., Schaye, J., Springel, V. & Hernquist, L. 2003, ApJ, 599, L1
Furlanetto, S.R., Schaye, J., Springel, V. & Hernquist, L. 2004, ApJ, 606, 221
Ghavamian, P. et al. 2001, ApJ, 547, 995
Keshet, U., Waxman, E., Loeb, A., Springel, V. & Hernquist, L. 2003, ApJ, 585, 128
Laming, J. M. 2000, ApJS, 127, 409
Majumdar, S. & Mohr, J. J. 2004, ApJ, 613, 41
Nicastro, F. et al. 2002, ApJ, 573, 157
Persic, M. & Salucci, P. 1992, MNRAS, 258, 14
Raymond, J. C., et al. 2003, ApJ, 584, 770
Spergel, D.N., et al., 2003, ApJS, 148, 175
Spitzer, L., Jr. 1962, Physics of Fully Ionized Gases (New York: Wiley)
Springel, V. 2004, in preparation
Springel, V. & Hernquist, L. 2002, MNRAS, 333, 649
Sutherland, R. & Dopita, M. 1993, ApJS, 88, 253
Takizawa, M. 1998, ApJ, 509, 579
Yoshikawa, K. et al. 2003, PASJ, 55, 879
Yoshikawa, K. et al. 2004, PASJ in press [astro-ph/0408140]