Imprint of Inhomogeneous Hydrogen Reionization on the Temperature Distribution of the Intergalactic Medium

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

Citation
Trac, Hy, Renyue Cen, and Abraham Loeb. 2008. “Imprint of Inhomogeneous Hydrogen Reionization on the Temperature Distribution of the Intergalactic Medium.” The Astrophysical Journal 689 (2): L81–84. https://doi.org/10.1086/595678.

Citable link
http://nrs.harvard.edu/urn-3:HUL.InstRepos:41417373

Terms of Use
This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Open Access Policy Articles, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP
We study the impact of inhomogeneous hydrogen reionization on the thermal evolution of the intergalactic medium (IGM) using hydrodynamic + radiative transfer simulations where reionization is completed either early (z ~ 9) or late (z ~ 6). In general, we find that low-density gas near large-scale overdensities is ionized and heated earlier than gas in the large-scale, underdense voids. Furthermore, at a later time the IGM temperature is inversely related to the reionization redshift because gas that is heated earlier has more time to cool through adiabatic expansion and Compton scattering. Thus, at the end of reionization the median temperature-density relation is an inverted power-law with slope γ ≈ −0.2 in both models. However, at fixed density, there is up to order unity scatter in the temperature due to the distribution of reionization redshifts. Because of the complex equation-of-state, the evolved IGM temperature-density relations for the redshift range 4 ≤ z ≤ 6 can still have significant curvature and scatter. These features must be taken into account when interpreting the Lyα and Lyγ absorption in high redshift quasar spectra.

Subject headings: cosmology: theory – large-scale structure of universe – intergalactic medium – methods: numerical – hydrodynamics – radiative transfer
spacing, in order to model radiation sources and sinks. With a particle mass resolution of $2.68 \times 10^6 M_\odot h^{-1}$, we can reliably locate all dark matter halos with virial temperatures above the atomic cooling limit ($T \sim 10^4$ K) with a minimum of $\sim 40$ particles (Heitmann et al. 2007), and half of this collapsed mass budget is resolved with $> 400$ particles per halo. Our halo mass functions are in very good agreement with other recent work (e.g. Reed et al. 2007; Łukić et al. 2007; Cohn & White 2008).

The second component of the work produces a series of hydrodynamic + RT simulations with moderate resolution, but incorporating subgrid physics modelled using the high-resolution information from the large N-body simulation. For the first two simulations in the series, we consider basic models where reionization is completed early ($z \sim 9$) and late ($z \sim 6$) to roughly reflect our current state of knowledge on the details of the reionization process (e.g. Cen 2003; Wyithe & Loeb 2003; Haiman & Holder 2003; Fan et al. 2006a). Radiation sources are prescribed and star formation rates calculated using the halo model described in Trac & Cen (2007). Here we consider only Population II stars from starbursts (Schaerer 2003) as contributing to the ionizing photon budget. We also neglect subgrid clumping and self-shielding of dense absorbers such as minihalos or Lyman limit systems, but will study their effects in ongoing work.

Each simulation utilizes equal numbers ($N = 1536^3$) of dark matter particles, gas cells, and adaptive rays, where for the latter, we track 5 frequencies above the hydrogen ionizing threshold of 13.6 eV. The photo-ionization and photo-heating rates for each cell are calculated from the incident radiation flux and used in the non-equilibrium solvers for the ionization and energy equations. The initial conditions are generated with a common white noise field and a linear transfer function calculated with CAMB (Lewis et al. 2000). The simulations were run using the NASA Columbia Supercomputer.

3. RESULTS

3.1. The Redshift of Reionization

Over the course of each simulation we track when a gas cell first becomes more than 99% ionized, enabling us to construct a 3D reionization-redshift field $z_{\text{reion}}(x)$ in parallel to the gas density $\rho(x)$ and temperature $T(x)$ fields. In Fig. 1 we show a slice from the late reionization simulation box to illustrate the inhomogeneity of the reionization process and the large-scale correlations. The fields have been smoothed on cells of comoving length $130 \text{kpc} h^{-1}$, which is close to the Jean’s or filtering scale (Gnedin & Hui 1998; Gnedin 2000). In general, $z_{\text{reion}}$ is highly correlated with the large-scale density field, as HII regions originate around biased, overdense sources and final overlap occurring in the large-scale, underdense voids. We find that the strong and positive correlation extends down to scales $\sim 1 \text{ Mpc} h^{-1}$.

The temperature field at the end of reionization shows considerable complexity with some interesting characteristics. First, we note the presence of cool ($T \sim 10^4$ K), low-density gas just outside the shock-heated filamentary and halo gas. Second, the low-density gas gets progressively warmer ($T \sim 10^4$ K) as one moves away from sources and towards the voids. It is apparent from the maps that the temperature is inversely related to $z_{\text{reion}}$ for the low-density IGM and we will quantify this relation in the next section.

3.2. The Temperature-Density Relation

Fig. 2 shows the gas temperature-density relations at the end of reionization and at redshift $z = 4$ for the early and late reionization models. For each density bin of width 0.05 dex, we plot the median temperature and the 2-$\sigma$ spread around it. At the end of reionization, the two models have complex but similar $T-\rho$ relations, driven by photo-heating, shock-heating, and cooling. For the low-density IGM where photo-heating dominates over shock-heating, we find that the median temperature approxi-
Fig. 2.— Gas temperature-density relations at the end of reionization (left) and at a redshift $z = 4$ (right) for the early (red, thick lines) and late (blue, thin lines) reionization models. For each density bin of width 0.05 dex, we plot the median temperature (solid lines) and the 2-$\sigma$ spread (dashed lines). At the end of reionization, the two models have similar inverted power-law $T$-$\rho$ relations for the low-density IGM, with slopes $\gamma - 1 \sim -0.2$ and order unity scatter. By $z = 4$, the early model has settled into a rising power-law with only small scatter. However, the late model is closer to yielding an isothermal equation-of-state with still significant scatter of thousands of kelvins.

Fig. 3.— End-of-reionization temperature as a function of the reionization redshift for low-density ($\delta = -0.5 \pm 0.05$) gas, for the early (red, thick lines) and late (blue, thin lines) models. The two contours specify the 1-$\sigma$ (solid lines) and 2-$\sigma$ (dashed lines) boundaries for the cumulative probability distributions.
We have studied the photo-ionization and photo-heating of the IGM from hydrogen reionization using two hydrodynamic + RT simulations. We considered two basic models in which reionization is completed early \((z \sim 9)\) and late \((z \sim 6)\) and found for both models that the temperature of a low-density region at a later time is inversely related to the redshift of reionization of that region. Low-density gas near large-scale overdensities is ionized and heated earlier than gas in the large-scale, underdense voids. As a result, at the end of reionization the median temperature-density relation is an inverted power-law with slope \(γ \sim −0.2\). There is up to order unity scatter in the temperature at fixed density due to the distribution of reionization redshifts. We expect that both the slope and scatter will depend on the reionization history, especially its duration. Furthermore, it is known that radiative transfer effects from Lyman limit systems can modify the temperature distribution (e.g. Abel & Haiman 1999), although more for helium rather than hydrogen reionization because for the latter, the UV spectrum from stellar sources is relatively soft and only weak spectral filtering can occur.

We conclude that at the high redshift range \(4 \leq z \leq 6\), the equation-of-state of the IGM is more complicated than the commonly assumed forms (isothermal or a tight power-law relation). It is important to keep this result in mind when interpreting the Lyα absorption in quasar spectra (e.g. Fan et al. 2002, 2006b; Lidz et al. 2006; Gallerani et al. 2008). In fact, a recent analysis by Becker et al. (2007) has already suggested that adopting an inverted temperature-density relation instead of an isothermal model may have profound implications on the interpretation of the reionization process based on the high redshift Lyα forest. We will study the observational signatures of inhomogeneous hydrogen reionization in an upcoming paper.

We thank C.-A. Faucher-Giguère, L. Hernquist, A. Lidz, M. McQuinn, and M. Zaldarriaga for many stimulating discussions. We also thank J. Chang at NASA for invaluable supercomputing support, N. Gnedin for his compilation of ionization and recombination rates, and D. Schaerer for the Pop II SEDs. This work is supported in part by NASA grants NNX08AL43G and NNG06GI09G, NSF grant AST-0407176, FQXi, and Harvard University funds. Computing resources were in part provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center.

REFERENCES

Abel, T., & Haehnelt, M. G. 1999, ApJ, 520, L13
Becker, G. D., Rauch, M., & Sargent, W. L. W. 2007, ApJ, 662, 72
Cen, R. 2003, ApJ, 591, 12
Cohn, J. D., & White, M. 2008, MNRAS, 385, 2025
Dunkley, J., Komatsu, E., Nolta, M. R., Spergel, D. N., Larson, D., Hinshaw, G., Page, L., Bennett, C. L., Gold, B., Jarosik, N., Weiland, J. L., Halpern, M., Hill, R. S., Kogut, A., Limon, M., Meyer, S. S., Tucker, G. S., Wollack, E., & Wright, E. L. 2008, ArXiv e-prints, 803
Fan, X., Carilli, C. L., & Keating, B. 2006a, ARA&A, 44, 415
Fan, X., Narayanan, V. K., Strauss, M. A., White, R. L., Becker, R. H., Pentericci, L., & Rix, H.-W. 2002, ApJ, 123, 1247
Fang, T., & White, M. 2004, ApJ, 606, L9
Furlanetto, S. R., & Oh, S. P. 2008, ApJ, 681, 1
Furlanetto, S. R., Zaldarriaga, M., & Hernquist, L. 2004, ApJ, 613, 1
Gallerani, S., Ferrara, A., Fan, X., & Choudhury, T. R. 2008, MNRAS, 386, 359
Gnedin, N. Y. 2000, ApJ, 542, 535
Gnedin, N. Y., & Hui, L. 1998, MNRAS, 296, 44
Haiman, Z., & Holder, G. P. 2003, ApJ, 595, 1
Heitmann, K., Lukic, Z., Fasel, P., Habib, S., Warren, M. S., White, M., Ahrens, J., Ankeny, L., Armstrong, R., O’Shea, B., Ricker, P. M., Springel, V., Stadel, J., & Trac, H. 2007, ArXiv e-prints, 706
Hui, L., & Gnedin, N. Y. 1997, MNRAS, 292, 27
Hui, L., & Haiman, Z. 2003, ApJ, 596, 9
Lee, K.-G., Cen, R., Gott, J. R. L., & Trac, H. 2008, ApJ, 675, 8
Lewis, A., Challinor, A., & Lasenby, A. 2000, ApJ, 538, 473
Lidz, A., Oh, S. P., & Furlanetto, S. R. 2006, ApJ, 639, L47
Loeb, A. 2008, ArXiv e-prints, 804
Lukič, Z., Heitmann, K., Habib, S., Bashinsky, S., & Ricker, P. M. 2007, ApJ, 671, 1160
McDonald, P., Miralda-Escude, J., Rauch, M., Sargent, W. L. W., Barlow, T. A., & Cen, R. 2001, ApJ, 562, 52
McQuinn, M., Lidz, A., Zaldarriaga, M., Hernquist, L., Hopkins, P. F., Dutta, S., & Faucher-Giguere, C. . 2008, ArXiv e-prints, 807
Miralda-Escude, J., & Ostriker, J. P. 1990, ApJ, 350, 1
Miralda-Escude, J., & Rees, M. J. 1994, MNRAS, 266, 343
Reed, D. S., Bower, R., Frenk, C. S., Jenkins, A., & Theuns, T. 2007, MNRAS, 374, 2
Ricotti, M., Gnedin, N. Y., & Shull, J. M. 2000, ApJ, 534, 41
Schaerer, D. 2003, A&A, 397, 527
Theuns, T., Schaye, J., & Ostriker, J. P. 1990, ApJ, 350, 1
Theuns, T., Schaye, J., & Zaldarriaga, M. 2000, MNRAS, 318, 817
Theuns, T., Schaye, J., & Haehnelt, M. G. 2000, MNRAS, 315, 600
Theuns, T., Schaye, J., Zaroubi, S., Kim, T.-S., Tzanavaris, P., & Carswell, B. 2002, ApJ, 567, L103
Trac, H. 2004, PhD thesis, University of Toronto (Canada), Canada
Trac, H., & Cen, R. 2007, ApJ, 671, 1
Trac, H., & Pen, U.-L. 2004, New Astronomy, 9, 443
—. 2006, New Astronomy, 11, 273
Viel, M., Haehnelt, M. G., & Springel, V. 2004, MNRAS, 354, 684
Withey, J. S. B., & Loeb, A. 2003, ApJ, 586, 693
—. 2004, Nature, 432, 194
Zaldarriaga, M., Hui, L., & Tegmark, M. 2001, ApJ, 557, 519.