PROBING THE INTERGALACTIC MEDIUM WITH THE O VI FOREST

TAOTAO FANG AND GREG L. BRYAN

Department of Physics and Center for Space Research, Massachusetts Institute of Technology, NE80-6081, 77 Massachusetts Avenue, Cambridge, MA 02139

Received 2001 July 20; accepted 2001 September 26; published 2001 October 9

ABSTRACT

Recent Space Telescope Imaging Spectrograph and Far Ultraviolet Spectroscopic Explorer observations have detected O vi absorption lines at low redshift that are not clearly associated with any galactic system. In this Letter, we argue that these lines are due to metal-enriched hot gas in the intergalactic medium. Using numerical simulations of a cosmological constant–dominated cosmology, combined with reasonable assumptions about the metallicity distribution, we show that the number density and internal characteristics of these lines are correctly predicted. We find that the O vi is primarily produced by collisional ionization from gas at a few times $10^5$ K for lines with equivalent widths larger than 40 mA, while weaker lines can also be produced by photoionization. The absorption occurs in diffuse gas in filaments at moderate overdensity ($\delta \sim 5–100$).

Subject headings: intergalactic medium — large-scale structure of universe — methods: numerical — quasars: absorption lines

1. INTRODUCTION

The census of baryons in the local universe (Fukugita, Hogan, & Peebles 1998) indicates that a substantial fraction of the baryonic density predicted by primordial nucleosynthesis remains to be detected. Numerical simulations (Cen & Ostriker 1999a; Davé et al. 2001) predict that a large fraction of this is in the form of a moderately warm/hot ($10^5 < T < 10^7$ K) component (warm-hot intergalactic medium [WHIM]). The WHIM is hard to detect directly because of both the difficulty in UV observations as well as its relatively low intrinsic density. A promising direction is to look for its signature in absorption lines from background quasars (see Hellsten, Gnedin, & Miralda-Escudé 1998; Perna & Loeb 1998; Fang et al. 2001b).

Recently, a number of groups have reported detecting the Li-like O vi resonance doublet in far-UV quasi-stellar object spectra at $z < 2$ (Bergeron et al. 1994; Burles & Tytler 1996; Lopez et al. 1999; Churchill & Charlton 1999; Reimers et al. 2001). Savage, Tripp, & Lu (1998) also detected an O vi absorber at $z = 0.225$ without any C iv or N v absorption, indicating that it was either collisionally ionized with a temperature $T \sim 5 \times 10^5$ or photoionized with a low density. Tripp & Savage (2000) and Tripp, Savage, & Jenkins (2000) report O vi absorption systems at $0.12 < z < 0.27$. Adopting reasonable assumptions, these authors argued that the total number of baryons associated with these absorbers was significant, comparable to the combined mass in stars, cool gas, and cluster gas.

In this Letter, we explore the connection between these two ideas in more detail. In particular, we posit that the O vi absorption arises, in large part, in collisionally ionized gas that resides in the sheets, filaments, and low-density clumps that are naturally produced by gravitational collapse in hierarchical cosmology. The gas is shock-heated to a range of temperatures, while O vi is significantly produced only in a relatively narrow range around $3 \times 10^5$ K. This is near the peak of the cooling curve (e.g., Sutherland & Dopita 1993) and so places a constraint on the density if the gas is not to cool in the Hubble timescale. For gas with 10% solar metallicity at $3 \times 10^5$ K, the density must be less than $n_H \lesssim 10^{-5}$ cm$^{-3}$. Assuming an O vi ionization fraction of 0.15, this requires a path length of 100 kpc to generate a column density of $N_{\alpha} = 4 \times 10^{13}$ cm$^{-2}$, typical of observed values. While this is a relatively large path length, the Hubble expansion if undisturbed would be only $\sim 7$ km s$^{-1}$, which is well within the observed line widths. Therefore, we expect that thermal broadening should dominate and $b \sim 20$ km s$^{-1}$ for most lines. As we will show, however, colder, photoionized gas can also give rise to O vi absorption. For these lines, which tend to have lower column densities, the predicted line width is considerably smaller. Very recently, a preprint by Cen et al. (2001) has appeared, which examines this issue using different simulation techniques; where there is overlap, our results agree reasonably well.

2. METHOD

We use numerical simulations to generate predictions for the observed O vi distribution. In particular, we use a grid-based adaptive mesh refinement method (Bryan 1996; Norman & Bryan 1999) that provides both good shock capturing as well as relatively high resolution in dense regions. We simulate a cube $20 h^{-1}$ Mpc on a side with gas and dark matter mass resolution of $6 \times 10^7$ and $5 \times 10^8 M_\odot$, respectively. The smallest grid cell (i.e., the best resolution) is 9.8 kpc and occurs in the densest regions. We assume a cosmological model with a matter density $\Omega_m = 0.3$, baryon density $\Omega_b = 0.04$, Hubble constant $h = 0.67$ (in units of 100 km s$^{-1}$ Mpc$^{-1}$), and cosmological constant $\Omega_k = 0.7$. The initial density field is drawn from an adiabatic cold dark matter power spectrum as approximated by the formula of Eisenstein & Hu (1998).

We include dark matter and gravity but not radiative cooling or energy/metal injection from supernova-driven galactic winds. By comparing a set of hydrodynamic simulations, Davé et al. (2001) concluded that radiative cooling plays a minor role in the evolution of WHIM gas at $z \sim 3$ due to its low density. However, these processes can play an important role in metal enrichment of the intergalactic medium (IGM). The Far Ultraviolet Spectroscopic Explorer has detected O vi absorption in the galactic wind from the prototypical dwarf galaxies (see, e.g., Heckman et al. 2001). Since we do not know the distribution of oxygen a priori in this simulation, we adopt a density-dependent metallicity model as derived in the sim-

1 Hubble Fellow.
ulations of Cen & Ostriker (1999b). While this is reasonable, we plan to revisit this issue in a future paper using a simulation that self-consistently includes both radiative cooling and metal/energy injection.

To analyze the results, we generate artificial spectra as described in Fang, Bryan, & Canizares (2001a) and Zhang et al. (1997), both for the 1032 Å O vi line and the 1216 Å H i Lyα line. To compute the f(O vi/O) and f(H i/H) fractions, we adopt two models to investigate the effect of collisional ionization and photoionization mechanisms. In model A, we use collisional ionization only, with ionization fractions from Mazzotta et al. (1998). In model B, we use CLOUDY (version 90.04; Ferland et al. 1998) to generate a grid of temperatures (10^3 K < T < 10^7 K) and densities [10^{-4} < n(cm^{-3}) < 10^{-1}]. We included a background radiation field as computed by Haardt & Madau (1996) at z = 0 due to the observed quasar distribution. We adopt a mean specific intensity at the Lyman limit of J_0 = 2 \times 10^{-22} ergs s^{-1} Hz^{-1} sr^{-1}. Since the simulation did not include radiative heating/cooling, the unshocked IGM gas has a temperature that is unrealistically low. For these low-temperature (and generally low-density) regions, we adopt the relation between temperature and density that has been found in simulations of the Lyα forest: T = T_0(1 + \delta)^{-1}, where T_0 \sim 5000 K and \gamma = 1.4 (see, e.g., Zhang et al. 1997; Ricotti,
Figure 2.—Physical properties along one random LOS. (a) Baryon number density; (b) peculiar velocity; (c) temperature; (d) O\textsc{vi} number density (model A: solid line; model B: dashed line); (e) synthesized spectra for O\textsc{vi} and H\textsc{i} (dot-dashed line). In (d) and (e), model B is shifted down by 5% for visual clarity. The dashed line in (a) indicates the mean baryon density. The lines at $z \sim 0.0019$ are produced by gas at $z \sim 0.0044$.

Figure 3.—Cumulative number of O\textsc{vi} absorption lines per unit redshift vs. line EW. Dashed line: model A; solid line: model B. Lines produced by collisionally ionized gas dominate at EW $> 40$ mA. Observational data are plotted with 1 $\sigma$ error bars (Tripp & Savage 2000; Tripp, Savage, & Jenkins 2000).

$\sim 750$ km s$^{-1}$ corresponds to a shift of $\Delta z \sim 0.0025$. Parenthetically, we note that this means the total number of lines may be underestimated because the peculiar velocities can shift lines out of the simulated regions; however, we estimate that this would change our predicted number density by only about 10%. Fitting the observed line in Figure 2e gives an equivalent width (EW) of $\sim 185$ mA and a Doppler $b$-parameter of $\sim 21$ km s$^{-1}$, which is roughly consistent with thermal broadening [$b = 0.129(T/A)^{1/2}$ km s$^{-1}$; $A$ is the atomic mass number]. Tripp & Savage (2000) suggested that a broad, hot H\textsc{i} Ly\textsc{α} component may coexist with the O\textsc{vi} absorbers and such a broad component could be easy to miss with current observations. To demonstrate this, they showed that a fit to the multicomponent Ly\textsc{α} profile including a broad component (due to H\textsc{i} coexisting with the O\textsc{vi} in hot gas) is indistinguishable from a fit that does not contain such a broad component, at the signal-to-noise ratio level of their data. In Figure 2e, we display the H\textsc{i} Ly\textsc{α} spectrum (dot-dashed line) from our simulation. A broad component is clearly identified at the position of the strongest O\textsc{vi} absorption line. Spectral fitting shows this line has a column density of $3.2 \times 10^{13}$ cm$^{-2}$ and a Doppler $b$-parameter of $\sim 76$ km s$^{-1}$. Both parameters are consistent with those from the missing H\textsc{i} Ly\textsc{α} absorption line in Tripp & Savage (2000). The Doppler $b$-parameter is also consistent with thermal broadening by a hot gas of $\sim (3-4) \times 10^5$ K.$^2$

By applying the spectral fit procedure to a total of 3000 LOSs, we obtain the cumulative number per unit redshift ($dN/dz$) as a function of O\textsc{vi} EW. Figure 3 displays the $dN/dz$ for both models. We also plot two observational results from Tripp & Savage (2000) for PG 0953+415 and Tripp, Savage, & Jenkins (2000).

A recent observation of the low-redshift quasar E1821+643 (Tripp et al. 2001) reveals that in addition to a narrow H\textsc{i} Ly\textsc{α} line, a relatively broad component appears with $b \approx 85$ km s$^{-1}$ in the $z = 0.1212$ O\textsc{vi} absorption systems.

Gnedin, & Shull 2000; Davé & Tripp 2001 for observational support). Here overdensity $\delta = \rho_b / \langle \rho_b \rangle - 1$ and $\langle \rho_b \rangle$ is the mean baryon density of the universe. To fit the simulated spectra, we adopt the method developed by Zhang et al. (1997), which should work well for these relatively isolated lines.

3. RESULTS

Figure 1 displays the projected baryon overdensity (Fig. 1a), O\textsc{vi} column density (Fig. 1b; based on model B), and temperature ($10^7$–$10^8$ K in Fig. 1c; $10^3$–$10^6$ K in Fig. 1d). Comparing Figures 1b and 1a, we find that most of the high column density O\textsc{vi} lines come from regions with overdensities of $\delta \sim 5$–100. Collisional ionization is dominant in many of these regions, given their temperatures in the range $10^5$–$10^6$ K (Fig. 1d), but some systems are clearly photoionized, particularly at the low-density end. Note that big clusters and groups are too hot to produce O\textsc{vi}.

In Figure 2, we show the properties of the simulated region along one random line of sight (LOS). From top to bottom, we display the baryon number density, peculiar velocity, temperature, O\textsc{vi} number density, and transmission spectrum [$F = \exp(-\tau)$, where $\tau$ is the optical depth] for O\textsc{vi} in model A (solid line) and model B (dashed line) and for H\textsc{i} (dot-dashed line). Note that at high densities and warm temperatures, both models agree well, while for low-temperature regions, model B (which includes both photoionization and collisional ionization) produces substantially more O\textsc{vi}.

Figure 2e shows that both models generate a strong O\textsc{vi} absorption line at around $z \sim 0.0019$ along this LOS. Notice that no strong peak appears in the $n$ and $n_{O\textsc{vi}}$ distributions at the corresponding redshift. This absorption line is actually produced by the $n_{O\textsc{vi}}$ peak at $z \sim 0.0044$. It is the peculiar velocity that shifts the line to a lower redshift: a peculiar velocity of $\sim 750$ km s$^{-1}$ corresponds to a shift of $\Delta z \sim 0.0025$. Parenthetically, we note that this means the total number of lines may be underestimated because the peculiar velocities can shift lines out of the simulated regions; however, we estimate that this would change our predicted number density by only about 10%. Fitting the observed line in Figure 2e gives an equivalent width (EW) of $\sim 185$ mA and a Doppler $b$-parameter of $\sim 21$ km s$^{-1}$, which is roughly consistent with thermal broadening [$b = 0.129(T/A)^{1/2}$ km s$^{-1}$; $A$ is the atomic mass number]. Tripp & Savage (2000) suggested that a broad, hot H\textsc{i} Ly\textsc{α} component may coexist with the O\textsc{vi} absorbers and such a broad component could be easy to miss with current observations. To demonstrate this, they showed that a fit to the multicomponent Ly\textsc{α} profile including a broad component (due to H\textsc{i} coexisting with the O\textsc{vi} in hot gas) is indistinguishable from a fit that does not contain such a broad component, at the signal-to-noise ratio level of their data. In Figure 2e, we display the H\textsc{i} Ly\textsc{α} spectrum (dot-dashed line) from our simulation. A broad component is clearly identified at the position of the strongest O\textsc{vi} absorption line. Spectral fitting shows this line has a column density of $3.2 \times 10^{13}$ cm$^{-2}$ and a Doppler $b$-parameter of $\sim 76$ km s$^{-1}$. Both parameters are consistent with those from the missing H\textsc{i} Ly\textsc{α} absorption line in Tripp & Savage (2000). The Doppler $b$-parameter is also consistent with thermal broadening by a hot gas of $\sim (3-4) \times 10^5$ K.$^2$

By applying the spectral fit procedure to a total of 3000 LOSs, we obtain the cumulative number per unit redshift ($dN/dz$) as a function of O\textsc{vi} EW. Figure 3 displays the $dN/dz$ for both models. We also plot two observational results from Tripp & Savage (2000) for PG 0953+415 and Tripp, Savage, & Jenkins (2000). A recent observation of the low-redshift quasar E1821+643 (Tripp et al. 2001) reveals that in addition to a narrow H\textsc{i} Ly\textsc{α} line, a relatively broad component appears with $b \approx 85$ km s$^{-1}$ in the $z = 0.1212$ O\textsc{vi} absorption systems.
from photoionized gas. However, overall we predict more \ovi absorption lines.

We find the Doppler \(b\)-parameter of the \ovi absorption line can provide important clues in distinguishing photoionization and collisional ionization. The distribution of the line widths can be well approximated by a lognormal: \( f \propto \exp \left[ - \log^2 (b/b_0)/2 \sigma_n^2 \right] \). In Figure 4, we plot \( b_0 \) against EW cutoff for our two models. In the collisional ionization case (model A), the distribution is nearly constant with \( b_0 \sim 20 \) km s\(^{-1}\). On the other hand, when we include a photoionizing background (model B), the distribution depends on the strength of the line. For lines with EW > 70 mA, the value of \( b_0 \) is still around 20 km s\(^{-1}\) but drops quickly for smaller lines. This reflects the fact that more photoionized lines contribute for EW < 70 mA.

A statistically complete sample does not yet exist to compare against these predictions. Recently, Tripp (2001) compiled the first batch of \(~15\) \ovi absorption lines detected in a total of five quasars. They found that the majority of the \ovi lines have \( b\)-values of \(~22\) km s\(^{-1}\), implying a collisional ionization origin. If this result continues to hold for low-EW lines, it may be telling us something about either the strength of the photoionizing background or the metallicity of the low-temperature filaments. Either case (lower background or lower metallicity in the cold gas) would produce fewer photoionized lines relative to collisionally ionized.

4. CONCLUSIONS

In this Letter, we have studied the properties of \ovi absorption lines via hydrodynamic simulation. Our main conclusions are as follows:

1. The projected \ovi number density distribution shows that the majority of \ovi absorption comes from filaments that connect virialized intersections or groups of galaxies. These regions typically have an overdensity of \(~5–100\).
2. Spectral fits show that collisional ionization dominates in high-density, high-temperature regions, while photoionization dominates in low-density, low-temperature regions.
3. The predicted cumulative distribution of \ovi absorption lines fits the observations remarkably well, given the uncertainties due to limited resolution and the assumed metallicity distribution. At EW > 40 mA, \ovi absorption lines produced by collisionally ionized gas start to outnumber lines produced by photoionized gas, while at EW > 80 mA essentially all the \ovi absorption lines are produced by collisionally ionized gas.
4. We find that the \ovi absorption lines produced by collisionally ionized gas have a characteristic Doppler \(b\)-parameter of \(~20–23\) km s\(^{-1}\), and lines due to the photoionized gas typically have narrower \(b\)-parameters.

T. F. thanks the MIT/CXC team for support. This work is supported in part by contracts NASA-38249 and SAO SV1-61010. Support for G. L. B. was provided by NASA through Hubble Fellowship grant HF-01104.01-98A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS6-26555.

REFERENCES

Bergeron, J., et al. 1994, ApJ, 436, 33
Bryan, G. 1996, Ph.D. thesis, Univ. Illinois, Urbana-Champaign
Burles, S., & Tyler, D. 1996, ApJ, 460, 584
Cen, R., & Ostriker, J. P. 1999a, ApJ, 514, 1
Cen, R., & Ostriker, J. P. 1999b, ApJ, 519, L109
Cen, R., Tripp, T. M., Ostriker, J. P., & Jenkins, E. B. 2001, ApJ, 559, L5
Churchill, C. W., & Charlton, J. C. 1999, AJ, 118, 59
Dave, R., et al. 2001, ApJ, 552, 473
Dave, R., et al. 2001, ApJ, 552, 473
Fig. 4.—Peak of the Doppler \(b\)-distribution \((b_0)\) for lines with an EW larger than the corresponding value. The value of \(b_0\) is obtained by fitting each distribution with a lognormal functional form (dashed line: model A; solid line: model B). The \ovi absorption lines that are produced by collisionally ionized gas have a mean \(b\)-value of \(~20\) km s\(^{-1}\). After including photoionized gas, the characteristic \(b\)-value drops as low as \(~5\) km s\(^{-1}\).
Dave, R., & Tripp, T. M. 2001, ApJ, 553, 528
Eisenstein, D. J., & Hu, W. 1998, ApJ, 498, 137
Fang, T., Bryan, G. L., & Canizares, C. R. 2001a, ApJ, in press (astro-ph/0108495)
Fang, T., Marshall, H. L., Bryan, G. L., & Canizares, C. R. 2001b, ApJ, 555, 356
Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, PASP, 110, 761
Fukugita, M., Hogan, C. J., & Peebles, J. P. E. 1998, ApJ, 503, 518
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Heckman, T. M., Sembach, K. R., Meurer, G. R., Strickland, D. K., Martin, C. L., Calzetti, D., & Leitherer, C. 2001, ApJ, 554, 1021
Hellsten, U., Gnedin, N. Y., & Miralda-Escudé, J. 1998, ApJ, 509, 56
Lopez, S., Reimers, D., Baade, R., Hagen, H.-J., & Lopez, S. 2001, A&A, 374, 871
Reimers, D., Baade, R., Hagen, H.-J., & Lopez, S. 2000, ApJS, 130, 1
Reimers, D., & Loeb, A. 1998, ApJ, 503, L135
Rao, S. M., & Turnshek, D. A. 2000, ApJS, 130, 1
Savage, B. D., Tripp, T. M., & Lu, L. 1998, AJ, 115, 456
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Tripp, T. M. 2001, in Extragalactic Gas at Low Redshift, ed. J. S. Mulchaey & J. Stocke (San Francisco: ASP), in press (astro-ph/0108278)
Tripp, T. M., & Savage, B. D. 2000, ApJ, 542, 42
Yang, Y., Anninos, P., Norman, M. L., & Meiksin, A. 1997, ApJ, 485, 496
Zhang, Y., Anninos, P., Norman, M. L., & Meiksin, A. 1997, ApJ, 485, 496
