ABSORPTION-LINE SIGNATURES OF GAS IN DARK MATTER MINIHALOS

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ABSTRACT

Recent observations and theoretical calculations suggest that some QSO absorption-line systems may be due to gas in small dark matter halos with circular velocities on the order of 30 km s⁻¹. Kepner, Babul & Spergel have shown that gas in these “minihalos” can readily be in a multiphase state. Additional observational evidence suggests that, in general, many absorption-line systems may also be multiphase in nature. Thus, computing the absorption lines of minihalos, in addition to providing signatures of small halos, is a natural way to explore multiphase behavior. The state of gas in minihalos is strongly affected by the background UV radiation field. To address this issue, a code was developed that includes many of the chemical and radiative processes found in CLOUDY and also incorporates spherically symmetric multiwavelength radiative transfer of an isotropic field, nonequilibrium chemistry, heating, cooling and self-consistent quasi-hydrostatic equilibrium gasdynamics. With this code detailed simulations were conducted of gas in minihalos using different types of background spectra: power-law, power-law + He II break, Haardt & Madau, and O-star. From these simulations, the absorption-line signatures of the gas were computed and compared with a variety of observations: high-redshift metal lines, He lines, and low-redshift metal-line systems. Based on these results, the minihalo model absorption-line signatures appear to be consistent with many current observations, given a sufficiently soft spectrum. Thus, in any given instance it is difficult to either rule in or rule out a minihalo, and in most cases additional data (e.g., optical counterparts or the lack thereof) or contextual information (e.g., evidence of significant star formation, which would disrupt gas in a minihalo) are necessary to break this degeneracy. Finally, the minihalo model is a useful tool for analyzing absorption-line data in a multiphase context and should become even more applicable as new space-based observations become available.

Key words: galaxies: evolution — galaxies: formation — galaxies: fundamental parameters — galaxies: halos — quasars: absorption lines

1. INTRODUCTION

Quasar absorption lines due to metals are sensitive probes of physical conditions and chemical abundances. With current instrumentation, they can be detected from z = 0 to z > 4 and therefore can be used to track the chemical and physical evolution of galaxies and the intergalactic medium over most of the history of the universe. Metals are now routinely detected in all types of QSO absorption-line systems over most of the history of the universe. Metals are able.

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intensity of the UV background radiation. As the intensity of the UV background decreases, the core passes through three stages characterized by the predominance of ionized, neutral, and molecular hydrogen (see Figs. 1–3). The model includes full radiative transfer, gasdynamics, and nonequilibrium chemistry and produces physically self-consistent hydrostatic gas density and temperature radial profiles. Given the extragalactic UV background as input, the model can track the properties of the minihalos from $z \gg 4$ to $z = 0$. Since previous papers have shown the detailed dependencies of the metal-line ratios on the assumed shape of the UV background (see, e.g., Giroux & Shull 1997; Songaila 1998), the primary goal of this paper is to explore the effects of the two-phase core-envelope structure on the metal ratios and to determine if minihalos have any distinctive absorption signatures.

Observationally, there is evidence that the minihalo model is a plausible model for some QSO absorbers. Abel & Mo (1998) have suggested that if density perturbations collapse to form minihalos before reionization, then owing to their high densities, the minihalos will remain largely neutral when the UV background turns on in a population of objects with $N(H\ I) \gtrsim 10^{17} \text{ cm}^{-2}$, which can explain the number density of Lyman limit (LL) absorbers observed at high redshifts. Likewise, the simulations of Bond & Wadsley (1997) predict large numbers of minihalos with $v_c \sim 30 \text{ km s}^{-1}$. If the minihalos form after reionization, then they will be substantially more ionized. This is the model considered in this paper—the objects begin fully ionized and subsequently develop self-shielded cores as the background intensity decreases. One objection to the minihalo model is that it cannot explain the complex component structure and velocity spread usually observed in QSO heavy element absorption profiles. However, in the hierarchical model of galaxy formation, ensembles of dwarflike objects coalesce to form larger galaxies, and in this case the individual components in the coalescing object may be well described as minihalos. Rauch et al. (1996) have shown that the two-point correlation function of high-$z$ IV absorbers is consistent with the hierarchical formation scenario. In this scenario, the number of minihalos should decrease with redshift as they merge into larger systems. Nevertheless, some of the minihalos may survive down to $z = 0$, and Blitz et al. (1999) have recently suggested that the more distant high-velocity clouds in the vicinity of the Milky Way are in fact minihalos that have not yet accreted onto the galaxy.

Some higher column density QSO absorbers may also be due to minihalo-like objects. For example, Steidel et al. (1997) have been unable to identify the damped Ly$\alpha$ system at $z_{abs} = 0.656$ in the spectrum of 3C 336 despite an exhaustive galaxy redshift survey and deep Hubble Space Telescope (HST) and ground-based IR imaging. They conclude that this absorber is probably due to a dwarf galaxy with $L < 0.05L_* \text{ very close to the QSO. This damped system has } N(H\ I) \approx 2 \times 10^{20} \text{ cm}^{-2}$, and a wide variety of metals are detected in this absorber in the HST Faint Object Spectrograph and ground-based spectra of the QSO obtained by Steidel et al. (1997), but unfortunately none of their spectra have adequate resolution to compare the absorption-line kinematics to the minihalo model. On a different sight line, Rao & Turnshek (1998) have identified two low-redshift damped Ly$\alpha$ absorbers in the spectrum of QSO OI 363, and they note that “none of the galaxies visible in the vicinity of the quasar is a luminous gas-rich spiral with low impact parameter,” again raising the possibility that these high column density systems are due to dwarflike objects. Kepner et al. (1997) have shown that when a minihalo attains a self-shielded H I core, the H I column density in the core can exceed $10^{20} \text{ cm}^{-2}$. However, if the damped absorbers are due to several clustered minihalos that will eventually coalesce, then the $N(H\ I)$ of the individual minihalos may be lower while the total H I column (integrated along the line of sight) is sufficient to produce a damped absorber.

Finally, as suggested by Rees (1986) and Miralda-Escudé & Rees (1993), it is possible that some of the Ly$\alpha$ clouds may be due to minihalos, and Mo & Morris (1994) have shown that the observed number density of Ly$\alpha$ clouds at various redshifts can be reproduced by the minihalo model. Rees (1988) points out that owing to merging of minihalos in the hierarchical galaxy formation model, at low redshifts surviving minihalos will be less likely to be found in regions of large-scale overdensity. Some of the recent studies of the relationship between Ly$\alpha$ clouds and galaxies have found Ly$\alpha$ clouds apparently in galaxy voids (see, e.g., Morris et al. 1993; Stocke et al. 1995; Tripp, Lu, & Savage 1998); these may be minihalos that have survived to low $z$ by virtue of their location in regions of low galaxy density.

After the minihalo model was introduced, it was criticized because a huge number of halos per unit redshift would be required to reproduce the observed density of absorption lines since the minihalos have small spatial cross sections. Also, observations of double sight lines to QSO pairs indicate that some Ly$\alpha$ absorbers have very large spatial extents (see, e.g., Dinshaw et al. 1995, 1997). It now seems clear that all of the absorbers cannot be attributed to minihalos. However, recent hydrodynamic simulations of cosmological structure growth suggest that a variety of phenomena cause QSO absorption lines ranging from very large gaseous filaments to minihalo-like objects. Furthermore, large numbers of minihalos are found within the large filamentary structures in simulations at high redshift (see, e.g., Bond & Wadsley 1997) as well as simulations pushed to $z = 0$ (Dave et al. 1999). Interestingly, recent H I 21 cm imaging has revealed this predicted type of structure at very low redshift: Hoffman et al. (1999) have discovered three minihalo-like objects embedded in the much larger gas envelope that surrounds the Sm galaxies NGC 4532 and DDO 137 in Virgo. These objects have the expected masses of minihalos and show no traces of star formation in deep CCD images in B and R.

Given these observational and theoretical motivations, we have revisited the minihalo model for QSO absorption lines. The rest of this paper is organized as follows. Section 2 presents the basic physical model behind the minihalo. Section 3 describes the code used to compute properties of minihalos. Section 4 discusses the various input spectra and presents comparisons of observations with the minihalo absorption signatures. Section 5 discusses the results, and § 6 gives our conclusions.

## 2. MINIHALO MODEL

The simulations attempt to follow the evolution of the gas in a fixed halo potential. For these purposes, the dark matter halo is specified by two parameters: the circular velocity $v_c$ and the virialization redshift $z_{vir}$, which can be translated into a halo radius $r_{halo}$ and halo mass $M_{halo}$ by assuming that the overdensity at virialization is $\delta = 18\pi^2$.
\[ v^2 = \frac{GM_{\text{halo}}}{r_{\text{halo}}} + \frac{4\pi^2}{3} \frac{r^3}{h} \delta \rho(z) = M_{\text{halo}}, \] (1)

where the mean density is given by the usual expressions for a \( \Omega = 1 \) CDM cosmological model: \( \rho(z) = (1 + z)^2 \rho^0 \), where \( 6\pi G \rho H_{\text{hubble}} = 1, H_{\text{hubble}} = 2/3H_0 \).

The dark matter halo profile is taken from Burkert (1995) and is based on fits of dwarf galaxy rotation curves,

\[ \rho_{\text{DM}}(r) = \frac{\rho_0}{1 + x} = \frac{r}{r_0}, \] (2)

which in turn can be related to the halo radius and mass by

\[ r_{\text{halo}} = 3.4r_0, \]
\[ M_{\text{halo}} = M_{\text{DM}}(r_{\text{halo}}), \]
\[ M_{\text{DM}}(r) = \int_0^r \rho_{\text{DM}}(r)4\pi r^2 dr. \] (3)

While recent numerical work suggests that the halo density profiles of large galaxies are proportional to \( r^{-1} \) in the centers and \( r^{-3} \) at the edges (Navarro, Frenk, & White 1996), these profiles do not fit the dwarf galaxy observations (Moore 1994; Flores & Primack 1994).

The ultraviolet background is able to heat the gas to a temperature of roughly \( 10^6 \) K. In large halos, where \( v_t > 50 \) km s\(^{-1} \), the gas pressure is relatively unimportant, and the gas content is determined by the global value of \( \Omega_b: M_{\text{gas}} = \Omega_b M_{\text{halo}} \) (assuming \( \Omega = 1 \)). However, for smaller halos collapsing out of a hot IGM, the gas pressure resists the collapse (Thoul & Weinberg 1996) and \( M_{\text{gas}} < \Omega_b M_{\text{halo}} \). A simple estimate as to where this transition occurs and how much gas should reside in the halo can be made using the Jeans mass and Bondi accretion limits. If the gas mass in the uncollapsed halo is greater than the Jeans mass, then the gas should collapse of its own accord. This provides an upper limit to amount of gas in the halo

\[ M_{\text{gas}} = \Omega_b M_{\text{halo}}, \quad \Omega_b M_{\text{halo}} > M_{\text{Jeans}} \] (4)

where \( M_{\text{Jeans}} = \Omega_b \rho_0 (2\pi c_{\text{IGM}} H_{\text{hubble}})^3, f = 3/\pi\sqrt{2}, c_{\text{IGM}}^2 = 1.5k_B T_{\text{IGM}}/\mu \). For \( M_{\text{halo}} < M_{\text{Jeans}} \) an upper limit can be computed for \( M_{\text{gas}} \) by estimating the amount of mass that could be accreted via Bondi accretion in a Hubble time. Thus

\[ M_{\text{gas}} = M_{\text{Bondi}}, \quad \Omega_b M_{\text{halo}} < M_{\text{f}} \] (5)

where \( M_{\text{Bondi}} = \frac{1}{2} \frac{H_{\text{hubble}}^2 M_{\text{halo}} M_{\text{Bondi}} = \pi G^2 M_{\text{halo}}^2 \rho_0 / c_{\text{IGM}}^3 \). Note, the \( O(1) \) factor \( f \) has been included in \( M_{\text{Jeans}} \) and \( M_{\text{Bondi}} \) so that \( M_{\text{Jeans}} = M_{\text{Bondi}} \) when \( \Omega_b M_{\text{halo}} = M_{\text{Jeans}} \).

3. SIMULATING MINIHALOS

Calculating the absorption signatures is significantly complicated by the large effect a background UV radiation field can have on gas in small halos (Dekel & Silk 1986; Efstathiou 1992; Quinn, Katz, & Efstathiou 1996; Kepner et al. 1997). To address this issue, a code was developed that includes many of the chemical and radiative processes found in CLOUDY (Ferland et al. 1998) and also incorporates multiwavelength radiative transfer, nonequilibrium chemistry, and gasdynamics. The full details of the code are given in Kepner et al. (1997) and are briefly summarized here.

The code computes the quasi-hydrostatic equilibrium states of gas in spherically symmetric dark matter halos (roughly corresponding to dwarf galaxies) as a function of the amplitude of the background UV field. The code integrates the full equations of radiative transfer, heating, cooling, and nonequilibrium chemistry for nine species of H and He including H\(_2\), as well as all the ionization states of the metals C, O, Mg, and Si. These metals were chosen because they are commonly observed in absorption-line systems. The density and temperature profiles are evolved through an iterative procedure. The initial gas density profile is specified by hydrostatic equilibrium and by our assumption that the gas is in thermal equilibrium with the background radiation field. At each redshift a new equilibrium temperature profile is computed for the current value of the background radiation field, which evolves with redshift. For a given temperature profile, DM potential, and total gas mass, it is then a simple matter to compute the density profile necessary to maintain hydrostatic equilibrium.

The important role of the detailed chemistry of primordial gas (in particular the formation of H\(_2\)) has been known and studied since it was first proposed as a mechanism for the formation of globular clusters (Peebles & Dicke 1968). The potential number of reactions in this simple mixture of H and He is enormous (Janev et al. 1987). Abel et al. (1997) have selected a subset of these reactions to model the behavior of primordial gas for low densities (\( n < 10^4 \) cm\(^{-3} \)) over a range of temperatures (\( 1 \text{ K} < T < 10^8 \text{ K} \)). Among the processes included in this model are the photoattachment of neutral hydrogen, the formation of molecular hydrogen via \( H^- \), charge exchange between \( H_2 \) and \( H^+ \), electron detachment of \( H^- \) by neutral hydrogen, dissociative recombination of \( H_2 \) with slow electrons, photodissociation of \( H_2^+ \), and photodissociation of \( H_2 \). In addition, these species have been supplemented with the appropriate chemical and radiative processes for four commonly detected metals: C, O, Mg, and Si. For the metals, this required obtaining additional collisional ionization rate coefficients (Vorontsov 1997), radiative recombination rates (Verner & Ferland 1996), dielectronic recombination rates (Aldrovandi & Pequignot 1973; Shull & Van Steenberg 1982; Arnaud & Rothenflug 1985; Nussbaumer & Storey 1983), charge exchange rates (Kingdon & Ferland 1996), and photoionization cross sections (Verner et al. 1996; Verner & Yakovlev 1995).

Fully three-dimensional radiative transfer requires estimating the contribution to the flux at every point from every other point along all paths for each wavelength. At the minimum this is a six-dimensional problem. However, in most instances, symmetries can be introduced that result in a more tractable situation. The simplest situation occurs when the gas can be assumed to be optically thin throughout. This approximation is sufficient in the majority of cosmological situations. The next simplest geometry is that of a slab (or a sphere under the assumption of a radially perpendicular radiation field), which leaves an intrinsically two-dimensional problem. Although this approach may not be a bad approximation for a sphere in an isotropic radiation field, this code accounts for all the different paths that penetrate a given spherical shell, which leaves an inherently three-dimensional problem. Taking into account the differ-
ent paths effectively “softens” the optical depth, smoothing out transitions from optically thin to optically thick regimes.

Perhaps the most important aspect of the model is the balance between the heating and cooling processes. This balance is what allows the establishment of a quasi-static temperature profile for a specific radiative flux. If the balance between the heating and cooling is not established, then the hydrostatic equilibrium solution to the gas profile will evolve too rapidly. Fortunately, this situation comes about only when the gas in the halo becomes dense and a large amount of H$_2$ is formed. This point presumably marks the onset of star formation, which would dramatically alter the situation, and so the calculation is halted when H$_2$ cooling dominates. The temperature profile is evolved via the heating and cooling functions found in Anninos et al. (1997), which includes photoionization heating and cooling due to collisional excitation, collisional ionization, recombination, molecular hydrogen, bremsstrahlung, and Compton cooling.

The microphysical processes couple to the larger scale density profile primarily through radiative heating, which sets the temperature profile. The rate of radiative heating (primarily due to H I, He I, and He II) is in turn strongly dependent on the column densities of each species, which is set by the temperature. Thus, the resulting system is described by differential equations on the small scale with integral constraints on the large scale. The difficulty of solving such a system is the large variety of timescales involved. Solving the entire set simultaneously is prohibitive. The approach taken here has been to use code modules that solve for each of the processes independently. Iterating between the modules then provides an adequate approximation to the true solution (see Kepner et al. 1997 for a more complete discussion).

For a given input spectrum (e.g., power-law with $\alpha = -1.5$), as the amplitude of the UV background is decreased, the gas in the core of the dwarf goes through three stages characterized by the predominance of ionized...
(H II), neutral (H I), and molecular (H₂) hydrogen. The last stage (H₂) marks the onset of runaway cooling and presumably star formation. Figures 1, 2, and 3 show this evolution as illustrated by the H I density, H I column density, and gas temperature profiles. Figures 4 and 5 show the number density profiles and computed column density profiles of several species for a minihalo in the neutral (H I) phase.

Although these calculations include C, O, Mg, and Si for computing the strengths of absorption lines, metals are ignored in the cooling of the gas. Metals can have a number of important effects on the chemistry and dynamics of gas clouds: dust grains will absorb ionizing radiation and serve as formation sites for molecular hydrogen; atomic lines of C and other heavy elements can be important coolants. Are these processes important in dwarf galaxies at high redshift? Observations of QSO Lyman forest clouds suggest that the metal abundances in metagalactic gas are $Z \sim 0.001$–0.01 times the solar value at $z \sim 3$ (Songaila & Cowie 1996). At these abundances, heavy element cooling is unimportant (Bohringer & Hensler 1989). An upper limit on the mass in dust grains can be obtained by assuming that most of the carbon at high redshift is incorporated into dust grains. If the size distribution of the grains is similar to the local ISM, then this suggests a cross section per hydrogen atom of $\sigma_{\text{dust}}(1000 \, \AA) \approx Z(2 \times 10^{-2}) \, \text{cm}^2$ (Draine & Bertoldi 1996).

In the minihalo model, the maximum column density occurs when the cloud is most centrally condensed, which occurs just before the onset of H₂ formation and is roughly $N(\text{H I}) \sim 10^{21} \, \text{cm}^{-2}$ (see Fig. 1). Thus, the maximum optical depth at these wavelengths is approximately $\tau_{\text{dust}} \sim Z \sim 0.01$. The contribution of dust to H₂ formation in our galaxy can be approximated by a $\dot{n}_{\text{H}_2} \approx R n_{\text{H}_2}$, where $R = 6 \times 10^{-18} \, T^{1/2} \, \text{cm}^3 \, \text{s}^{-1}$ (Draine & Bertoldi 1996). If we scale $R$ by the metallicity, then the dust term will be negligible in comparison to the other terms contributing to H₂ formation whenever $n_{\text{H}_2} \sim 10^{-9} \, \text{cm}^{-3}$, which is nearly always the case in the neutral H core.

As a test of the accuracy of the chemistry and radiative parts of the code, an optically thin static gaseous halo illuminated by simple power-law spectrum was tested. Figure 6 compares the number densities of various species computed with the minihalo code with the results of a similar calculation performed with CLOUDY. The two codes are in good agreement.

### 4. COMPARISON WITH OBSERVATIONS

Having laid the groundwork for the minihalo model, it is possible to proceed with several observational comparisons.
Heavy element absorption lines in the higher column density QSO absorbers have been measured and studied intensively for some time. With the advent of the echelle spectrograph on the Keck telescope (Vogt et al. 1994), it has become routine to also detect metals in high-redshift Lyα absorbers. For example, Songaila & Cowie (1996) have reported that C IV is detected in 75% of Lyα clouds with $N(H\alpha) \gtrsim 3 \times 10^{14}$ cm$^{-2}$.

Based on single-phase photoionization models constructed with CLOUDY, Giroux & Shull (1997) and Songaila (1998) have shown that Si IV/C IV column density ratios at high redshift require an overabundance of Si relative to C by factors of 2–3 and/or an ionizing spectrum that is softer than expected based on detailed calculations of the background owing to QSOs and AGNs. This can be achieved by a strong contribution to the ionizing spectrum from local hot stars (Giroux & Shull 1997) or by putting a large break in the ionizing spectrum at the He II edge (Songaila 1998). In addition, Songaila & Cowie (1996) and Songaila (1998) have suggested that the Si IV/C IV ratio decreases rapidly at $z \sim 3$ (note: other observations do not show this change; e.g., Boksenberg 1997), which can be interpreted as evidence that the ionizing spectrum changes abruptly at this redshift perhaps owing to the completion of intergalactic He reionization (see also Heap et al. 1999).

It has also become possible to detect helium absorption in the spectra of QSOs. Absorption due to He II has now been detected in the spectra of several high-z QSOs with HST (Jakobsen et al. 1994; Tytler et al. 1995; Hogan, Anderson, & Rugers 1997; Reimers et al. 1997; Heap et al. 1999) as well as the Hopkins Ultraviolet Telescope [Davidson, Kriss, & Zheng 1996]). In some cases voids in the H I Ly$\alpha$ forest closely match voids in the He II absorption (Reimers et al. 1997; Heap et al. 1999), which suggests that a substantial portion of the He absorption is due to unresolved discrete He II lines corresponding to the H I Ly$\alpha$ forest. If many of the Ly$\alpha$ clouds are due to minihalos, then the He absorption lines due to minihalos should be consistent with the observed He absorption. Also, He II absorption lines have been reported in some Lyman limit absorbers (Reimers & Vogel 1993).

By stacking the spectra of low-redshift Lyα clouds in the rest frame, Barlow & Tytler (1998) have shown that low-$z$ clouds also contain metals with apparently higher metallicities than their high-redshift counterparts (however, see Shull et al. 1998 for a counterexample of a rather low metallicity absorber at low redshift). Therefore, observations of low-$z$ QSOs with the Space Telescope Imaging Spectrograph (STIS) should enable detailed studies of abundances and physical conditions in the low redshift clouds whose optical counterparts are more readily observable.

In this section, these observations are compared to the predicted properties of the minihalo model. Section 4.1 summarizes the various input spectra assumed for the model. The resulting metal-line ratios are presented in § 4.2. The observed high-redshift metal-line ratios are compared with the minihalo metal-line ratios in § 4.3. In § 4.4 a similar comparison is made with He lines. Finally, as an example of the kind of comparisons that will be possible in the future, the model is applied to a low-redshift O VI absorber in § 4.5. For the calculations in this section the metallicity is fixed at 1/10 solar. The metal-line ratios are independent of metallicity as long as the metallicity is low enough so that radiative cooling by heavy elements is not important, in which case the metal column densities directly scale with $N(H\alpha)$ and metallicity.

### 4.1. Input Ionizing Spectra

Several spectral shapes are used as inputs: (1) a power law with spectral index $\alpha = -1$ (i.e., $f_\nu \propto \nu^{-1}$), (2) a power law with $\alpha = -1.5$ and a factor of $50$ break at the He II edge, (3) an O star with $T_{\text{eff}} = 50,000$ K from the ATLAS9 models computed and distributed by R. L. Kurucz, and (4)–(6) the UV background due to QSOs and AGNs calculated by Haardt & Madau (1996) at redshifts $z = 0, 2, \text{and 4}$. The power-law and power-law + He II break spectra are standard approximations of the UV background due to QSOs and AGNs but neglect much of the radiation reprocessing that occurs in intervening gas; the detailed effects of intervening absorption and reemission are included in the Haardt & Madau (1996) models. The O-star spectrum is not particularly realistic for a real QSO absorber but is useful for illustrating the differences between a minihalo ionized by UV radiation predominantly from local hot stars and a minihalo photoionized by the background radiation from distant quasars. The shapes of these spectra are shown in Figure 7. The spectra have been normalized so that $J_\nu(h\nu = 13.6 \text{ eV}) = 1.0$. The minihalo model evolves the spectra by decreasing its overall amplitude, beginning high and slowly dropping off. This is meant to approximate crudely the evolution of the amplitude of the radiation field with redshift. As the amplitude of the radiation field drops, the gas in the core of the minihalo enters the H I phase, while the outer parts are still ionized. The various column

![Figure 7](https://example.com/fig7.png)

**Fig. 7.**—Shape of the six different types of background spectra used to heat gas in minihalos. The spectra have been normalized so that $J_\nu(h\nu = 13.6 \text{ eV}) = 1.0$. The top panel shows an $\alpha = -1$ power-law spectrum (solid line), an $\alpha = -1.5$ power-law spectrum with a factor of $50$ drop at $54.4 \text{ eV}$ (dotted line), and an O-star spectrum (dashed line). The bottom panel shows three spectra computed by Haardt & Madau (1996) at $z = 0$ (solid line), $z = 2$ (dotted line), and $z = 4$ (dashed line).
densities computed from the minihalo that are shown in the subsequent sections are done so during the H\textsc{i} phase, which provides the best example of a multiphase absorber.

### 4.2. Minihalo Metal-Line Ratios

Figures 8 and 9 show the metal-line column density ratios predicted by the minihalo model for all six spectra shown in Figure 7. Various ions of C, O, Si, and He are selected with transitions that can be detected from the ground, with the exception of the He lines at $\lambda \leq 912$ Å, which must be observed from space. (Note: See Table 4 in Morton, York, & Jenkins 1988 for transition wavelengths. Oscillator strengths for these lines are found in Morton 1991, and some important recent $f$-value revisions are summarized by Tripp, Lu, & Savage 1996.) The ratio $N$(C\textsc{ii})/$N$(C\textsc{iv}) is chosen as the standard abscissa in this type of plot because the C\textsc{ii} and C\textsc{iv} lines are extremely strong and therefore can be detected in low-metallicity gas. However, these lines are also prone to saturation and must be used cautiously.

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**Fig. 8.**—The $N$(Si\textsc{iv})/$N$(C\textsc{iv}), $N$(Si\textsc{iv})/$N$(Si\textsc{iii}), and $N$(Si\textsc{iv})/$N$(Si\textsc{ii}) column density ratios vs. $N$(C\textsc{ii})/$N$(C\textsc{iv}) as predicted by the minihalo model for the spectra shown in Fig. 7. The left-hand panels plot the ratios corresponding to the $z = -1$ (solid line), $z = -1.5$ w/break (dotted line), and O-star spectra (dashed line). The right-hand panels plot the ratios from using the spectra generated by Haardt & Madau (1996) at three redshifts: $z = 0$ (solid line), $z = 2$ (dotted line), and $z = 4$ (dashed line).
The model ratios are primarily a function of the ionization parameter $U$, the ratio of the H ionizing photon density to the total hydrogen density, which decreases as $N(C\,\Pi)/N(C\,\IV)$ increases. The value of $U$ for the six input spectra is shown as a function of $N(C\,\Pi)/N(C\,\IV)$ in Figure 10. In terms of the minihalo model depicted in Figures 1–5, low $N(C\,\Pi)/N(C\,\IV)$ corresponds to the outer part of the halo, and high $N(C\,\Pi)/N(C\,\IV)$ corresponds to the inner part.

For the ratios shown in Figures 8 and 9, $U$ ranges from $10^{-1}$ to $10^{-4}$. Figure 8 shows that over this range of $U$, the metal ratio differences resulting from the different input spectra (in particular the $\alpha = -1.5$ with a He II break and the Haardt & Madau 1996 spectra) are usually within a factor of 3, which is typically less than the scatter in the observed ratios (see below). Notable exceptions are the O-star ratios, which not surprisingly are quite different, even from the $\alpha = -1.5$ w/break spectra, and the O\,VI/C\,IV and the Si\,IV/C\,IV ratios, which in some cases differ by two orders of magnitude.

The right-hand panels of Figures 8 and 9 show the minihalo metal ratios at $z = 0, 2,$ and 4 based on the Haardt &
Madau (1996) modeling of the UV background, which show very little change in the metal ratios between $z = 4$ and $z = 2$, i.e., the abrupt change at $z = 3$ in the Si iv/C iv ratio reported by Songaila & Cowie (1996) is not expected in minihalos given the Haardt & Madau (1996) UV background. Again, the largest changes (greater than a factor of 3) from $z = 4$ to $z = 0$ are in the O vi/C iv and Si iv/C iv ratios; it seems that the other ratios do not change much over this entire redshift range if the ionizing UV background is predominantly due to QSOs and AGNs.

4.3. Metal-Line Ratios in High-Redshift Absorbers

In Figure 11, observed column density ratios from a sample of high-redshift ($z > 2.1614$) absorbers are plotted with the minihalo model ratios for three radiation fields: Haardt & Madau (1996) at $z = 2$, $\alpha = -1.5$ w/break, and O-star. The Si iv/C iv and Si ii/C iv ratios are plotted versus the C ii/C iv ratio. All of observed column densities in this figure were measured with the Keck 1 echelle spectrograph and include a mix of Lyman limit and Ly$\alpha$ forest absorbers (shown with open diamonds) from Songaila (1998) as well as four higher column density damped Ly$\alpha$ absorbers (filled squares) from Lu et al. (1996).

The damped absorbers are the four systems from the Lu et al. (1996) sample that have low enough H i column densities that the minihalo model still applies—their column densities range from log $N$(H i) = 20.20 to log $N$(H i) = 20.52. Most of these systems are complex multiple-component absorbers, so a single minihalo obviously cannot produce the observed absorption profiles. However, as noted in §1, if these absorption systems are collections of merging smaller objects as postulated in the hierarchical galaxy formation model, then the individual clumps may be well described by the minihalo model. Alternatively, some of the absorption may be due to minihalos accreting onto bigger galaxies. In either case, it would be useful to compare these models to the observed properties of the individual components, but unfortunately such data are not yet widely available. The large amount of data contained in Keck spectra makes it difficult to provide a full listing of each component. With a few exceptions (e.g., Ganguly, Churchill, & Charlton 1998), most Keck publications provide in tabular format only the total column densities integrated over all components. Nevertheless, these total column densities provide weighted averages of the column densities of the individual components and can be used to test the validity of photoionization models.

Figure 11 shows that the multiphase minihalo model developed here leads to many of the same conclusions reached by, among others, Giroux & Shull (1997) and Songaila (1998) on the basis of single-phase constant density slab models. Specifically, it appears that the models with the straight power-law and the Haardt & Madau (1996) ionizing radiation fields fall well below many of the observed ratios when $N$(C ii)/$N$(C iv) $\lesssim 10^{-1}$. This problem is alleviated by adopting the much softer O-star spectrum. The power law with a break at the He ii edge comes closer to the observed ratios but still falls short. Evidently in this model the flux must drop by substantially more than a factor of 50.
at the He II break or Si must be overabundant relative to C (compared to the solar ratio) in these high-z absorbers.

4.4. Helium Absorption Lines

Recently detected He II absorption has raised the question as to whether or not this absorption is entirely due to He II associated with the discrete H i Lyα clouds or whether a diffuse smoothly distributed IGM makes a contribution. A variety of calculations have been performed to try to reproduce the observed He II optical depth (see, e.g., Giroux, Fardal, & Shull 1995; Fardal, Giroux, & Shull 1998). These models are not completely constrained by the observations and require a variety of inputs (e.g., the amplitude, shape, and evolution of the background radiation field). These authors find that a radiation field similar to that of Haardt & Madau (1996) with \( \frac{N(\text{He} \, \text{II})}{N(\text{H} \, \text{I})} \sim 100 \) provides the best results. The minihalo model is consistent with this value (see Fig. 12) for absorbers with \( N(\text{H} \, \text{I}) < 10^{16} \), which are believed to dominate the discrete component of the He II optical depth.

He i absorption has also been claimed to be detected from space in four Lyman limit systems (Reimers et al. 1992; Reimers & Vogel 1993). These results have been used to try and provide additional constraints on the global He/H value. The limited number of observations makes detailed comparisons difficult, but the observed \( N(\text{He} \, \text{i})/N(\text{H} \, \text{i}) \) are consistent with the minihalo model if a harder \( (x = -1) \) spectrum is used (see Fig. 13), but this spectrum is unlikely to be consistent with the metal-line data. Interestingly, similar slab-based calculations were unable to match these observations (Reimers & Vogel 1993). These Lyman limit systems may correspond to a region along the core edge where the multiphase and geometric effects of the minihalo model are greatest (see Figs. 4 and 5). If these were true, one might expect to see a class of He i absorbers corresponding to LL systems. However, we note that the identification of the He i absorption lines in the Reimers et al. (1992) data is equivocal owing to the low resolution of the data and requires verification with higher resolution spectroscopy.

4.5. Low-Redshift Absorbers

Barlow & Tytler (1998) have recently shown that most low-z Lyα clouds do contain metals, and their metallicities are higher than the high-z clouds. STIS, the Cosmics Origins Spectrograph (COS—to be installed in HST in 2003), and to a lesser extent FUSE will provide a wealth of new data on metals in low-z absorbers. As an example of the type of analysis that will be possible, the minihalo is compared with the observations of the intervening absorber at \( z = 0.225 \) toward H1821 + 643 (Savage et al. 1998). This absorber has a good measurement of the O vi column density \( \log N(\text{O} \, \text{vi}) = 14.29 \pm 0.03 \) and upper limits on C iv, Si iv, and Si ii (see Table 3 in Savage et al. 1998).

Figure 14 shows these limits along with the minihalo model predictions. Comparing the minihalo O vi column density in the allowed region of Figure 14 for gas with 1/10 solar metallicity results gives a value of \( N(\text{O} \, \text{vi}) \sim 10^{12} \) indi-
cating that 10 minihalos would be needed to explain this absorber. This is not allowed because the high-resolution O vi absorption profile shown in Figure 3 of Savage et al. (1998) shows evidence of only one component. Furthermore, the good correspondence of the red wing of the O vi and H i Lyβ profiles in this absorber (again, see Fig. 3 in Savage et al. 1998) suggests that there is an appreciable amount of H i absorption that occurs in the same gas that produces the O vi absorption. The minihalo model will produce a negligible amount of H i absorption if it is required also to satisfy the above constraints on the metals. Therefore the minihalo model is unable to explain this absorber on two counts: (1) not enough O vi, and (2) not enough H i. The more likely explanation is a larger, more diffuse object.

5. DISCUSSION

The previous sections presented a variety of results comparing minihalos with absorption-line observations. This section considers the implication of a few of these results in more detail. Section 5.1 examines the overall abundance of minihalos. Section 5.2 looks at the implications of the metal-line comparisons and some possible alternative explanations. Section 5.3 looks at other possible probes of the minihalo model.

5.1. Abundance of Minihalos

The abundance of these minihalos can be roughly calculated with Press-Schechter formalism. Although, it is important to keep in mind that Press-Schechter theory is most accurate at the largest scales (i.e., clusters of galaxies) and becomes more uncertain for estimating the distribution of smaller objects. Following the calculation in Abel & Mo (1998), which uses the method of Lacey & Cole (1994) to account for merging of halos, it is possible to estimate the number of halos per unit redshift with \( v_c \sim 30 \text{ km s}^{-1} \) (see Fig. 15). These simple estimates assume column density profiles similar to those calculated in the previous section.

Although these calculations are far from definitive, they are consistent with the observations of Storrie-Lombardi et al. (1994) and Stengler-Larrea et al. (1995). It is not inconceivable that a significant fraction of absorption-line systems could be attributable to gas in minihalos. However, recent observations and cosmological simulations suggest that it is unlikely that all of the QSO absorption line systems are due to minihalos (see § 1).

If some of the present-day offspring of minihalos are high-velocity clouds like those believed to be falling into the Milky Way (Blitz et al. 1999), then the abundance of these clouds gives an idea of the likelihood of observing one of these objects near a large galaxy. Estimates of the covering fraction of high-velocity clouds around our own galaxy would suggest a probability of finding a minihalo within 1.5 Mpc of a larger galaxy is around 0.2.

5.2. Explaining the High-Redshift Absorbers

As shown in Figure 11, it appears that the models with the straight power-law and the Haardt & Madau (1996) ionizing radiation fields fall well below many of the observed ratios when \( N(\text{C II})/N(\text{C IV}) \lesssim 10^{-1} \). This problem is alleviated by adopting the much softer O-star spectrum. The power law with a break at the He ii edge comes closer to the observed ratios but still falls short. If the flux increases at energies higher than the He ii break, as might be expected owing to the decreasing He ii absorption cross section with increasing photon energy, then the observed ratios become even harder to fit with the power-law + He ii break spectrum (Rauch, Haehnelt, & Steinmetz 1997). The flux may not recover as rapidly as expected owing to smearing of the absorption by He at different redshifts along the line of sight, but nevertheless this scenario provides motivation for considering alternatives. Songaila (1998) suggests the power-law + He ii break ionizing spectrum provides a natural explanation for the change in the Si iv/C iv ratio at \( z \approx 3 \). At \( z > 3 \), He is not yet fully reionized, and consequently the universe has substantial opacity at the He break. At \( z < 3 \), He reionization is complete so the He break vanishes leading to smaller Si iv/C iv ratios.

An alternative is that the ionization of some of the absorbers is dominated by radiation from hot stars (Giroux & Shull 1997). Figure 11 shows that if the ionizing radiation can be approximately described by an O-star spectrum (dashed line in Fig. 11), then the observed ratios are reproduced by the model. In this respect, it is interesting to note that the highest Si iv/C iv ratios measured by Songaila (1998) are quite similar to the Si iv/C iv ratios observed in the ISM of the Milky Way. For example, Sembach, Savage, & Tripp (1997) have measured the C iv/Si iv ratio in the Galactic ISM using sight lines to 31 stars observed with HST and IUE, and they derive \( N(\text{C IV})/N(\text{Si IV}) = 3.8 \pm 1.9 \), close to the highest ratios in Figure 11. The high ionization of these Milky Way sight lines is probably produced by photoionization from hot stars or collisional ionization with additional photoionization from recombination in the hot gas (see § 8 in Sembach et al. 1997).

It is not entirely unreasonable to suggest that hot stars make a substantial contribution to the photoionization of high-z absorbers. At some point in the past, galaxies must have undergone widespread waves of star formation. Based on the apparent increase in the metallicity of damped Lyα absorbers at \( z \approx 3 \), Lu et al. (1996) have suggested that this redshift marks the first epoch of major star formation in
galaxies. This star formation will be accompanied by copious UV emission, and if this UV light is able to escape, then it could be a substantial source of photoionization.

In this scenario, what are some possible explanations for the change in the Si IV/C IV ratio at \( z = 3 \) reported by Songaila (1998)? One possibility is that the Si IV/C IV ratio is a function of absorber H I column density, and the portion of Songaila's sample with \( z > 3 \) has a larger fraction of systems with higher H I columns. In this case, the different Si IV/C IV ratios could be caused by self-shielding due to He and/or H in higher column density absorbers, for example. The Songaila (1998) sample contains Lyman limit \([N(H \text{ I})] \gtrsim 10^{17} \text{ cm}^{-2}\) and Ly\( \alpha \) forest absorbers, but H I column densities are not provided. However, the C II and Si II column densities can be used as rough proxies for the H I column since absorbers with higher \( N(H \text{ I}) \) will have higher C II and Si II column densities as well.

To check for a possible \( N(H \text{ I}) \) dependence, Figure 16 plots the C IV/Si IV column density ratio from the Songaila (1998) sample (diamond symbols) versus \( N(\text{Si II}) \) (left-hand panel) and versus \( N(\text{C II}) \) (right-hand panel). (Note: the Si II detections or limits are available for most of the absorbers in the Songaila 1998 sample, while C II measurements or limits are available for a fraction of the systems.) In addition, the four damped systems from Lu et al. (1996; square symbols) have also been added. In this figure, \( z > 3 \) absorbers are indicated with filled symbols, while \( z < 3 \) systems are marked with open symbols, and systems with only upper or lower limits are shown with arrows. Finally the Milky Way value of C IV/Si IV obtained by Sembach et al. (1997) is bracketed by the horizontal dashed lines.

Figure 11 suggests several interesting points:

1. As mentioned earlier, there appears to be a significantly larger fraction of systems with low \( N(\text{C IV})/N(\text{Si IV}) \) at \( z > 3 \).

2. Many of the high column systems have \( N(\text{C IV})/N(\text{Si IV}) \) ratios consistent with the ratios in our own Milky Way ISM.

3. There are almost no high column systems \([N(\text{Si II})] > 2 \times 10^{12} \) or \( N(\text{C II}) > 6 \times 10^{12} \) with high \( N(\text{C IV})/N(\text{Si IV}) \) at any redshift.

4. There appears to be a significantly larger fraction of high column systems \([N(\text{Si II})] > 2 \times 10^{12} \) or \( N(\text{C II}) > 6 \times 10^{12} \) at \( z > 3 \).

One hypothesis that is consistent with these points (the third and the fourth in particular) is that the lower column systems with higher \( N(\text{C IV})/N(\text{Si IV}) \) exist but were not detected at \( z > 3 \). However, for this hypothesis to be true, there must also be a dependence of \( N(\text{C IV})/N(\text{Si IV}) \) on column density. Thus, it would be useful to examine the dependence of the C IV/Si IV ratio on H I column density using direct measurements of \( N(\text{H I}) \).

5.3. Other Probes

The absorption signatures discussed so far are for species whose populations are dominated by the background radiation field. To probe the multiphase density and temperature structure of the minihalo fully requires examining other species that are involved in more complex chemistry, such as molecular hydrogen. So far, H\( _2 \) detections are rare, but as they become more common, the minihalo model can be used to make definite predictions. These may be particularly useful in higher column systems that correspond to the core of the minihalo where H\( _2 \) is most prevalent (see Figs. 4 and 5).

Another useful probe might be C II*. C II is a strong line that is often detected, and C II* has been detected in a few cases. For illustration purposes, the value of C II* is calculated assuming statistical balance between collisional deexcitation and collisional + radiative excitation between

![Observed column density ratios from a sample of high-redshift \( (z > 2.1614) \) absorbers. \( N(\text{C IV})/N(\text{Si IV}) \) ratio is plotted vs. \( N(\text{Si II}) \) (left-hand panel) and \( N(\text{Si IV}) \) (right-hand panel). The observed column densities in this figure include a mix of Lyman limit and Ly\( \alpha \) forest absorbers (diamonds; Songaila 1998) as well as four higher column density damped Ly\( \alpha \) absorbers (squares) from Lu et al. (1996). Open symbols correspond to absorbers with \( z < 3 \), while filled symbols indicate \( z > 3 \). The ratio computed for the Milky Way is shown between the two dashed lines.](image-url)
the level 0 (2P_{1/2}) and level 1 (2P_{3/2}) states:
\[
n(C \, n^*) = n(C \, n) = \frac{A_{10} + C_{10} + C_{01}}{A_{01} + C_{01}} ,
\]
\[
C_{10} = 1.81 \times 10^{-6} T^{-0.5} n(e^-) + 5.0 \times 10^{-10} [1 + 0.127 T^{0.5}] n(H \, I) + 4.86 \times 10^{-10} (0.01 T)^{0.11} [n(H_2) + 0.5 n(He \, I)] \times 2 \exp \left( \frac{-91.211}{T} \right) C_{10} ,
\]
\[
A_{10} = 2.4 \times 10^{-6} ,
\]
where the coefficients are computed as follows: H I (Harel et al. 1978), H_2 (Flower & Launay 1977), He (assumed to be 0.5 times H_2), e^- (Keenan et al. 1986), and A_{10} (Nussbaumer & Storey 1988). At maximum N(C n^*)/N(C n) \sim \sim 10^{-5}, which is unlikely to be detected and more importantly is swamped by C n^* excitation by the cosmic microwave background (Lu et al. 1996). In any case, additional diagnostics like these can be explored and tested with the minihalo model.

6. CONCLUSIONS AND FURTHER WORK

In this paper the absorption-line signatures of gas in dark matter minihalos were computed. The motivation for this comes from two perspectives. First, minihalos may exist in significant numbers and be the source of many absorption line systems. Second, absorption-line systems in general may be multiphase objects, and the minihalo model provides one means of exploring multiphase structures.

The minihalo model can be compared with a wide variety of observations, both ground- and space-based. A few such comparisons are made here: high-redshift metal-line systems, He absorption-line systems, and a low-redshift O vi absorber. It appears that the minihalo model is consistent with the high-redshift metal-line systems and leads to many of the same conclusions made with single-phase slab models. In particular, a very soft spectrum is required to fit the observed N(Si iv)/N(C iv) data. Likewise, the minihalo model N(He ii)/N(H i) is consistent with calculations by other researchers based on the observed He ii optical depth. Perhaps, one interesting result is that the minihalo model with a z = -1 spectrum is consistent with the He i observations in Lyman limit systems, where other models have had a more difficult time matching this result. Finally, a comparison with a single O vi absorber indicates that the minihalo is not a good explanation for this object and that a larger more diffuse system is more likely.

Based on these results, it appears that the minihalo model absorption-line signatures are consistent with most current observations. Thus, in any given instance, it is difficult either to rule in or to rule out a minihalo, and in most cases additional data (e.g., optical counterparts or the lack thereof) or a detailed examination of predicted line profiles may be necessary to break the degeneracy. There are a number of simplifications in the model presented here, and several issues should be explored in future studies. First, the effects of any star formation on the minihalos should be considered; even a very small number of supernovae could substantially affect the structure of a minihalo by driving a wind and blowing out gas. This may increase the likelihood that minihalos will cause QSO absorption lines by increasing their spatial cross sections. Second, the impact of shock heating on the minihalo absorption-line signatures should be evaluated. Shocks are generated by the collapse of initial density perturbations, and these are seen to cause substantial heating of gas in the vicinity of galaxies in cosmological hydrodynamic simulations (see, e.g., Davé et al. 1999; Cen & Ostriker 1999). Finally, the input radiation fields can be refined. For example, a considerably more sophisticated model for the radiation from a star-forming galaxy than the simple O-star spectrum should be developed. New hot star model atmospheres emit more ionizing continuum (see, e.g., Schaerer & de Koter 1997), and this may alter the metal-line ratios. The minihalo model is a useful tool for analyzing the absorption-line data in a multiphase context and should become even more applicable as new space based observations become available.

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