Absorption Line Signatures of Gas in Mini Dark Matter Halos

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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 (1997) have shown that gas in these "mini-halos" can readily be in a multi-phase state. Additional observational evidence suggests that, in general, many absorption line systems may also be multi-phase in nature. Thus, computing the absorption lines of mini-halos, in addition to providing signatures of small halos, is a natural way to explore multi-phase behavior. The state of gas in mini-halos 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 multi-wavelength radiative transfer of an isotropic field, non-equilibrium chemistry, heating, cooling and self-consistent quasi hydro-static equilibrium gas dynamics. With this code detailed simulations were conducted of gas in mini-halos using different types of background spectra: power-law, power-law + HeII break, Haardt & Madau (1996) 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 mini-halo 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 mini-halo, 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 mini-halo) is necessary to break this degeneracy. Finally, the mini-halo model is a useful tool for analyzing absorption line data in a multi-phase context and should become even more applicable as new space based observations become available.

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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 with HI column densities ranging from $\sim 10^{14}$ to $\gg 10^{20}$ cm^{-2}. Typically these absorption systems are analyzed using idealized single-phase photoionization models where the absorber is treated as a constant density plane-parallel slab illuminated from one side (e.g., Bergeron & Stasińska 1986; however, see Donahue & Shull 1991; Giroux, Sutherland & Shull 1994). Recently these models have considered rather detailed and realistic ionizing radiation fields including reprocessing of the radiation as it propagates through intervening absorption systems and intergalactic space (e.g., Giroux & Shull 1997; Khare & Ikeuchi 1997), but they still usually assume a single-phase medium. However, by analogy with the ISM in our own galaxy, it seems more probable that QSO absorption lines arise in multi-phase media, and there is observational evidence which suggests that this is indeed the case in some absorbers. For example, in some absorbers the single-phase slab models cannot reproduce all of the observed metal column densities (Giroux, Sutherland & Shull 1994; Petitjean, Riediger, & Rauch 1996; Tripp, Lu, & Savage 1997; Churchill & Charlton 1999). It is also readily apparent in some absorbers that high resolution profiles of low and high ionization stages do not have identical component structure in velocity space; some components are strong in high ion profiles and are weak or not detected in low ion profiles (see, e.g., Figures 2-21 in Lu et al. 1996). This suggests the presence of multiple absorbing phases similar to those observed in the Milky Way ISM. Not surprisingly, the densities are also not constant within a given absorber component; by observing common absorption lines toward closely-spaced images of a gravitationally lensed QSO, Rauch (1997a) has shown that the metal densities vary on the scale of a few hundred parsecs or less (see his Figure 5). Therefore it now seems worthwhile to consider more sophisticated photoionization models which allow for multiple absorbing phases and changing densities along the line of sight.

In this paper the absorption line signatures are calculated for gas in small dark matter halos (i.e., mini-halos) with small circular velocities ($v_c \sim 30$ km s^{-1}). Kepner, Babul & Spergel (1997) have shown that gas in this type of potential can be a multi-phase absorber with a core and an ionized envelope, and the character of the core depends on the 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 Figures 1–3).

The model includes full radiative transfer, gas dynamics, and non-equilibrium 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 mini-halos 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 (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 mini-halos have any distinctive absorption signatures.

Observationally, there is evidence that the mini-halo model is a plausible model for some QSO absorbers. Abel & Mo (1998) have suggested that if density perturbations collapse to form mini-halos before reionization, then due to their high densities, the mini-halos will remain largely neutral when the UV background turns on resulting in a population of objects with N(HI) $\gtrsim 10^{17}$ 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 mini-halos with $v_c \sim 30$ km s^{-1}. If the mini-halos 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 mini-halo 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 dwarf-like objects coalesce to form larger galaxies, and in this case the individual components in the coalescing object may be well-described as mini-halos. Rauch et al. (1996) have shown that the two-point correlation function of high z C IV absorbers is consistent with the hierarchical formation scenario. In this scenario, the number of mini-halos should decrease with redshift as they merge into larger systems. Nevertheless, some of the mini-halos may survive down to $z = 0$, and Blitz et al. (1998) have recently suggested that the more distant high velocity clouds in the vicinity of the Milky Way are in fact mini-halos which have not yet accreted onto the galaxy.

Some higher column density QSO absorbers may also be due to mini-halo-like objects. For example, Steidel et al. (1997) have been unable to identify the damped Lyα system at $z_{\rm abs} = 0.656$ 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 $L < 0.05L^*$ very close to the QSO. This damped system has N(HI) $\approx 2 \times 10^{20}$ 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 mini-halo model. On a different sight line, Rao & Turnshek (1998) have identified two low redshift damped Lyα 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 dwarf-like objects. Kepner, Babul & Spergel (1997) have shown that when a mini-halo attains a self-shielded H I core, the H I column density in the core can exceed 10^{20} cm^{-2}. However, if the damped absorbers are due to several clustered mini-halos which will eventually coalesce, then the N(H I) of the individual mini-halos 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 Lyα clouds may be due to mini-halos, and Mo & Morris (1994) have shown that the observed number density of Lyα clouds at various redshifts can be reproduced by the mini-halo model. Rees (1988) points out that due to merging of mini-halos in the hierarchical galaxy formation model, at low redshifts surviving mini-halos will be less likely to be found in regions of large-scale overdensity. Some of the recent studies of the relationship between Lyα clouds and galaxies have found Lyα clouds apparently in galaxy voids (e.g., Morris et al. 1993; Stocke et al. 1995; Tripp, Lu & Savage 1998); these may be mini-halos which have survived to low z by virtue of their location in regions of low galaxy density.

After the mini-halo 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 mini-halos have small spatial cross-sections. Also, observations of double sight lines to QSO pairs indicate that some Lyα absorbers have very large spatial extents (e.g., Dinshaw et al. 1995, 1997). It now seems clear that *all* of the absorbers cannot be attributed to mini-halos. 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 mini-halo-like objects. Furthermore, large numbers of mini-halos are found within the large filamentary structures in simulations at high redshift (e.g., Bond & Wadsley 1997) as well as simulations pushed to $z = 0$ (Davé 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 mini-halo-like objects embedded in the much larger gas envelope which surrounds the Sm galaxies NGC 4532 and DDO 137 in Virgo. These objects have the expected masses of mini-halos 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 mini-halo model for QSO absorption lines. The rest of this paper is organized as follows. §2 presents the basic physical model behind the mini-halo. §3 describes the code used to compute properties of mini-halos. §4 discusses the various input spectra and presents comparisons of observations with the mini-halo absorption signatures. §5 discusses the results and §6 gives our conclusions.

2. Mini-halo 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_v, which can be translated into a halo radius $r_{\rm halo}$ and halo mass $M_{\rm halo}$ by