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THE GALACTIC ENVIRONMENT OF THE Ne viii ABSORBER TOWARD HE0226 − 4110

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ABSTRACT

We report the discovery of a small galaxy system in the vicinity of the Ne viii absorber at \( z = 0.20701 \) toward HE0226 − 4110. The galaxy system consists of two 0.25 \( L_\odot \) disk galaxies and a 0.05 \( L_\odot \) galaxy all within \( \Delta v < 300 \text{ km s}^{-1} \) and \( \rho < 200 \text{ h}^{-1} \text{ physical kpc} \) of the absorber. We consider various scenarios for the origin of the Ne viii absorption, including photo-ionized gas from an active galactic nucleus, a starburst-driven wind, a hot intragroup medium, hot gas in a galaxy halo, and a conductive front produced by cool clouds moving at high speed through a hot medium. We argue that the conductive front scenario is most likely responsible for producing the Ne viii feature, because it is consistent with the observed galactic environment around the absorber and because it naturally explains the multi-phase nature of the gas and the kinematic signatures of the absorption profiles. Although our preferred scenario suggests that Ne viii may not be directly probing the warm-hot intergalactic medium, it does imply the existence of an extended hot confining medium around a disk galaxy that may contain a significant reservoir of baryons in the form of hot gas.

Key words: cosmology; observations – galaxies: halos – intergalactic medium – quasars: absorption lines

1. INTRODUCTION

A census of the observed baryons in the local universe falls far short of the amount required by Big Bang Nucleosynthesis and the cosmic microwave background (Fukugita et al. 1998). Cosmological simulations suggest that most of the missing baryons are in the form of \( 10^5–10^7 \text{ K} \) gas that resides in low-density regions such as groups and filaments (Cen & Ostriker 1999; Davé et al. 2001). Considerable effort has been made in recent years to locate this “warm-hot intergalactic medium” (WHIM; Bregman 2007), but such gas has largely eluded detection. Ultraviolet absorption lines in the spectra of background quasars are considered a sensitive probe of the WHIM (Verner et al. 1994; Mulchaey et al. 1996). The most commonly used feature is the O vi \( \lambda\lambda 1031.926,1037.617 \) A absorption doublet. While many O vi systems have now been identified (Tripp et al. 2000, 2008; Savage et al. 2002; Danforth & Shull 2005; Thom & Chen 2008a, 2008b), recent observations (Tripp et al. 2008; Thom & Chen 2008b) suggest that \( \sim 30\%–50\% \) of the observed O vi absorbers may result from photo-ionized gas and therefore may not be probing the WHIM.

The presence of other high-ionization lines may help distinguish between photo-ionized and collisionally ionized systems. In particular, the ultraviolet lines of Ne viii \( \lambda\lambda 770.5,780.3 \) are potentially powerful tracers of hot collisionally ionized gas because of the high-ionization potential required to produce the ions (207.28 eV). However, only one intergalactic Ne viii absorber has been reported to date (Savage et al. 2005; Lehner et al. 2006). The observed Ne viii absorption is accompanied by lower ionization features. A detailed ionization analysis shows that the Ne viii is best explained by collisionally ionized warm gas, while the low-ionization features most likely result from photo-ionization (Savage et al. 2005). The relationship between the collisionally ionized and photo-ionized components is unclear. The galactic environment of the Ne viii absorber is also unknown. Here, we report the results of a galaxy survey in the vicinity of the Ne viii absorber that allows us to better understand the nature of this system and to examine the effectiveness of Ne viii as a probe of the WHIM. We adopt a lambda cold dark matter (ΛCDM) cosmology, \( \Omega_M = 0.3 \) and \( \Omega_\Lambda = 0.7 \), with a dimensionless Hubble constant \( h = H_0/(100 \text{ Mpc s}^{-1} \text{ km}^{-1}) \) throughout this Letter.

2. THE NE viii ABSORBER AT \( z = 0.20701 \) TOWARD HE0226 − 4110

Using high-resolution Far Ultraviolet Spectroscopic Explorer (FUSE) and Space Telescope Imaging Spectrograph (STIS) observations with respective spectral resolutions of FWHM \( \sim 25 \text{ km s}^{-1} \) and 7 km s\(^{-1}\), Savage et al. (2005) reported the first detection of intergalactic Ne viii \( \lambda\lambda 770,780 \) absorption at \( z = 0.20701 \) toward HE0226 − 4110, together with detections of absorption transitions due to H i, C iii, O iii, O iv, O vi, N iii, Si iii, S vi, and possibly S v. Different ionization species exhibit different kinematic signatures in the absorption-line profiles, suggesting a multi-phase medium nature of the underlying absorbing gas. Specifically, the absorption transitions due to low-ionization species such as H i, C iii, and O iii are resolved into two relatively narrow components (Doppler parameter \( b \approx 15 \text{ km s}^{-1} \)) separated by \( \Delta v \approx 30 \text{ km s}^{-1} \) (see also Thom & Chen 2008b). The observed H i column densities of the absorbing gas are \( \log N (\text{H} i) = 15.06 \pm 0.04 \) for the blueshifted component and \( \log N (\text{H} i) = 14.89 \pm 0.05 \) for the redshifted component. The O vi absorption doublet shows a broad component of \( \log b_{\text{O} vi} = 31 \pm 2 \text{ km s}^{-1} \) that centers roughly between the two components found in the low-ionization lines with \( \log N (\text{O} vi) = 14.37 \pm 0.03 \), while the Ne viii (and S vi) absorption lines appear to be blueshifted by \( \approx 7–18 \text{ km s}^{-1} \) with respect to the O vi absorption doublet with \( \log N (\text{Ne viii}) = 13.9 \pm 0.1 \) (log \( N (\text{S} vi) = 12.8 \pm 0.1 \)) and \( \log b_{\text{Ne viii}} = 23 \pm 15 \text{ km s}^{-1} \) (\( \log b_{\text{S} vi} = 39 \pm 20 \text{ km s}^{-1} \)).

Savage et al. (2005) conducted an extensive ionization analysis of the absorbing gas. Using the observed absorption strengths of C iii, O iii, N iii, and Si iii assuming a mean background radiation field of \( J_{912} = 1.9 \times 10^{-23} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \) at \( z = 0.2 \) from Haardt & Madau (1996), the authors found...
that the relative abundances of these low-ionization species are characterized by a photo-ionized cloud of metallicity ≈ 1/3 solar, temperature $T \sim 2 \times 10^4$ K, density $n_{\text{H}} = 2.6 \times 10^{-5}$ cm$^{-3}$, neutral fraction $f_{\text{H}_0} = 2.5 \times 10^{-3}$, and size $\approx 57$ kpc. But applying a photo-ionization model to explain the observed large column densities of O vi and Ne viii with the same assumed radiation field would require the gas density to be still lower, $n_{\text{H}} = 4.5 \times 10^{-7}$ cm$^{-3}$ and the inferred total path length near $\approx 11$ Mpc. Such a scenario was ruled out by Savage et al. (2005), because the Hubble flow broadening of the absorption over such a large path length would be much larger than that found in the observed line widths.

Savage et al. (2005) further considered a collisional ionization scenario, adopting the 1/3 solar metallicity inferred for the low-ionization species under the photo-ionization model. The authors derived a gas temperature of $T = 5.4 \times 10^4$ K, assuming the gas is under collisional ionization equilibrium. At this temperature, the observed line widths of Ne viii and O vii would imply a turbulent velocity field of $b_{\text{turbulent}} \sim 20$ km s$^{-1}$. At $T \lesssim 6 \times 10^5$ K, however, cooling efficiency approaches a maximum. The gas is therefore expected to be in nonequilibrium conditions, undergoing rapid cooling at somewhat lower temperature (e.g., Gnat & Sternberg 2007).

In summary, Savage et al. (2005) concluded that the $z = 0.20701$ absorber toward HE0226 – 4110 is part of a multiphase system. In their preferred model, the low-ionization features originate in a photo-ionized component of $T \sim 2 \times 10^4$ K, while the Ne viii and most of the O vi absorption originate in collisionally ionized gas of $T \sim 5 \times 10^5$ K. However, the connection between the photo-ionized cool component and the collisionally ionized hot gas is unclear.

3. THE GALAXY SYSTEM AT $z = 0.207$.

To help determine the nature of the $z = 0.20701$ absorption system, we have performed a spectroscopic survey of the galaxies in the field around HE0226 – 4110. Complete details of our observing program can be found in Chen & Mulchaey (2009). Here, we provide a brief summary of the galaxy survey. Spectroscopic candidates were selected from optical images covering a $\sim 28 \times 28$ arcmin$^2$ region centered on the quasi-stellar object (QSO). Candidate galaxies were observed at the Magellan telescopes using the IMACS and LDSS-3 spectrographs. The spectra were reduced using the COSMOS software package and redshifts measured by cross-correlating the extracted spectra and galaxy templates. The mean redshift measurement uncertainty is $\Delta z \approx 0.0003$. Our survey is nearly 100% complete for galaxies brighter than $R = 23$ at angular distances $\Delta \theta \lesssim 2'$ (corresponding to projected distances of $\rho \lesssim 285$ h$^{-1}$ physical kpc at $z = 0.20701$) and approximately 50% complete at $\rho \lesssim 22$ out to $\Delta \theta \lesssim 10'$ ($\rho \lesssim 1.4$ h$^{-1}$ physical Mpc at $z = 0.20701$).

Our spectroscopic survey revealed a small association of three galaxies in the vicinity of the Ne viii absorber. These galaxies are all within $|\Delta v| < 300$ km s$^{-1}$ and $\rho < 200$ h$^{-1}$ physical kpc of the absorber. A summary of their properties is presented in Table 1. The optical spectra and an R-band image are presented in Figure 1.

Table 1 shows that the galaxy with the smallest projected distance from the QSO (A) is an underluminous disk galaxy of luminosity $\sim 0.05 L_*$ (adopting $M_\text{R} = -5 \log h = -20.4$ from Blanton et al. 2003). The projected distance between A and HE0226 – 4110 is $\rho = 26.5$ h$^{-1}$ physical kpc. The two other objects are more luminous disk galaxies of $\sim 0.25 L_*$ These galaxies have impact parameters of $\rho = 76.5 h^{-1}$ physical kpc (B) and $\rho = 197.3 h^{-1}$ physical kpc (C), respectively. Galaxies A and B have emission-line spectra consistent with normal star-forming galaxies, while C exhibits absorption-dominated spectral features that indicates a more evolved underlying stellar population.

We note that based on the completeness of our survey, we can rule out the presence of additional galaxies near the redshift of the absorber down to $M_R = -5 \log h = -16.1$ (roughly 0.02 $L_*$) within $\rho = 285$ h$^{-1}$ kpc of the QSO. Four additional galaxies of $M_R = -5 \log h = -17.2$ to $M_R = -5 \log h = -20.45$ are found within $|\Delta v| < 300$ km s$^{-1}$ of the absorber but these galaxies are located at $\rho < 802 - 1500$ h$^{-1}$ physical kpc from the QSO line of sight (Chen & Mulchaey 2009). They are therefore unlikely to host the absorbing gas found in the QSO absorption-line data.

4. THE ORIGIN OF THE NE viii ABSORBER

The combination of the results of our galaxy survey in the field around HE0226 – 4110 and the known properties of the absorbing gas from Savage et al. (2005) provides a unique opportunity to examine the relationship between the highly ionized warm gas and the galaxy environment. Below we consider whether the absorber is produced in individual galactic halos, intragroup medium in a galaxy group, or outflows from either a starburst galaxy or active galactic nucleus (AGN). The close proximity of the Ne viii absorber to multiple galaxies is similar to what is found for some O vi absorbers (e.g., Stocke et al. 2006; Wakker & Savage 2009). It suggests that the absorbing gas is unlikely to originate in underdense filamentary regions, but is likely to be gravitationally bound to galaxies.

4.1. Intragroup Medium

To assess whether the absorber is likely to be associated with an intragroup medium or a halo around a galaxy, we first estimate individual halo sizes of the galaxies based on their intrinsic luminosities. Previous halo occupation studies of field galaxies have shown a monotonic relationship between halo mass $M_h$ and galaxy luminosity for galaxies fainter than $L_*$ and
located at the centers of their dark matter halos. Adopting the $M_h$ versus $M_R$ relation of Tinker & Conroy (2009), we estimate that galaxies $A$, $B$, and $C$ reside in halos of $M_h = 10^{11}$, $10^{11.5}$, and $10^{11.5} h^{-1} M_\odot$, respectively. The corresponding halo radii $R_h \equiv R_{200}$ are $R_h = 93$, 137, and $137 h^{-1}$ kpc for $A$, $B$, $C$, respectively. The expected halo radii of these galaxies together with the projected separations between one another indicate that galaxies $B$ and $C$ do not share a common halo, whereas galaxies $A$ and $B$ (separated by $\approx 50 h^{-1}$ projected physical kpc and $\approx 300$ km s$^{-1}$) are likely to share a common halo (based on the two-point correlation function, the probability of having two unrelated galaxies at this separation is $\approx 0.5$%; Zehavi et al. 2005). Analogous to the Local Group, it is probably more appropriate to consider $B$ and $C$ as two separate halos, instead of a single virialized “group.” With this interpretation of the mass distribution, it seems unlikely that the Ne VIII absorber would be associated with a diffuse intragroup medium.

4.2. Extended Hot Gaseous Halo

Given the projected distances from the QSO and the $R_{200}$ estimates above, only $A$ and $B$ are viable hosts for the Ne VIII absorber. Here, we consider the possibility that the absorber originates in an extended hot halo around one of these galaxies. Hot halos around individual galaxies are expected in the hierarchical galaxy formation paradigm. While such halos are commonly found around early-type galaxies (Fabbiano et al. 1992), the presence of extended hot halos around disk galaxies has not been confirmed (Rasmussen et al. 2009) with the exception of the Milky Way for which an extended hot halo is implied from several observations (Sembach et al. 2003; Fang et al. 2006; Bregman & Lloyd-Davies 2007).

We first consider the more massive galaxy $B$. The estimated halo mass of galaxy $B$ would imply a virial temperature of $T_{\text{vir}} \sim 4 \times 10^5$ K, similar to the gas temperature ($T = 5.4 \times 10^5$ K) derived for the Ne VIII absorber under the assumption of a collisional ionization equilibrium (Savage et al. 2005). It is therefore possible that the absorber originates in an extended hot halo around galaxy $B$.

If the Ne VIII absorption is produced by an extended hot halo, we can use the observed properties of the absorption to estimate the mass of the hot gas. Savage et al. (2005) derive a total hydrogen column density of $\log N(H) = 19.9$ for the absorber under the assumptions of collisional ionization equilibrium and metallicity $[Z/H] = -0.5$. Assuming a gaseous radius equal to $R_{200}$, the total path length is $l \sim 227 h^{-1}$ kpc at the impact distance of $\rho = 76.5 h^{-1}$ kpc. This path length combined with the inferred column density, suggests that the total hydrogen density is $n(H) \sim 1.1 \times 10^{-4}$ cm$^{-3}$. For a uniform density, the total mass in the hot gas within the virial radius is $M_{\text{gas}} \sim 4 \times 10^{10} h^{-2} M_\odot$. This mass is significantly greater than the mass in stars $M_* \sim 4 \times 10^9 h^{-2} M_\odot$ as inferred by the broadband spectral energy distribution of the galaxy. The difference would suggest that the hot gas revealed by the Ne VIII absorption is the dominant baryonic component.

We have argued based on the mean space density of dwarf galaxies (see Section 4.1) that galaxies $A$ and $B$ share a common halo. If instead $A$ is at a cosmological distance from $B$ and responsible for the absorption, the virial temperature is $T_{\text{vir}} \sim 2 \times 10^5$ K for its host halo, somewhat lower than the temperature derived by Savage et al. (2005). The gas mass in this case would be $M_{\text{gas}} \sim 9 \times 10^9 h^{-2} M_\odot$. This mass is approximately a factor of 10 times larger than the stellar mass, so as is the case for galaxy $B$, the hot gas would be the dominant baryonic component if the Ne VIII absorption was due to a hot gas halo.

However, the notion of Ne VIII arising in an extended hot halo is difficult to reconcile with the relatively narrow line width observed for the Ne VIII absorption feature, $b_{\text{Ne VIII}} = 23 \pm 15$ km s$^{-1}$, which corresponds to a velocity dispersion of $\sigma_v = 16$ km s$^{-1}$. This is smaller than the velocity dispersion expected from virial motion along the line of sight ($\sigma_v \equiv \sqrt{3/2} \approx 62$ km s$^{-1}$ and 42 km s$^{-1}$ in a uniformly distributed hot gas in a halo of $M_h = 10^{11.5} h^{-1} M_\odot (B)$ and $M_h = 10^{11} h^{-1} M_\odot (A)$, respectively. We therefore do not favor this scenario.

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3 We adopt $R_{200}$ to represent the size of a dark matter halo, which corresponds to the radius within which the enclosed mean density is 200 times the background matter density.
4.3. Photo-Ionized Halo Gas

Next, we consider the possibility that the Ne VIII absorber originates in individual clouds that are photo-ionized by both the intergalactic radiation field and local ionizing sources. Recall that Savage et al. (2005) ruled out a photo-ionization origin of the Ne VIII absorber because the implied path length given a mean intergalactic radiation field of $J_{012} = 1.9 \times 10^{-21}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at $z = 0.2$ was $\approx 11$ Mpc, too large for the observed line widths. The required path length would be smaller if the absorber was exposed to a more intense radiation source such as a local AGN. Here, we examine whether our galaxy data can rule out the presence of such an ionizing source for producing the Ne VIII absorber.

To reduce the path length to a more reasonable size ($\sim 100$ kpc) requires the intensity of the radiation to increase by approximately two orders of magnitude (up to $\sim 2 \times 10^{-21}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$). Assuming a flat $f_\nu$ spectrum (appropriate for an AGN) and adopting a $r^{-2}$ scaling law, we estimate that an AGN would need to be as luminous as $M_R = -5 \log h = -17.5$ at 38 kpc (A) or $M_R = -5 \log h = -19.8$ at 110 kpc (B) away in order to provide sufficient ionizing photons for producing the Ne VIII absorber. The expected AGN luminosity already exceeds the observed luminosity for either of the two galaxies. In addition, there is a lack of AGN spectral features in the optical spectra. We therefore conclude that galaxies A and B are unlikely to host a powerful enough AGN to produce the observed absorption with photo-ionization.

While photo-ionization cannot explain the observed Ne VIII absorber, we note that additional ionizing photons from galaxies A and B may contribute substantially to the ionizations of H I, C II, O II, and Si II. Adopting a flat UV spectrum for star-forming galaxies and assuming 2% escape fraction of ionizing photons, we estimate the absorbing cloud is illuminated by additional ionizing radiation intensities of $J_{012} = 1.3 \times 10^{-22}$ and $0.3 \times 10^{-22}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ from galaxies A and B, respectively. The inferred gas density and size of the H I absorbing cloud are then $n_H = 2.2 \times 10^{-4}$ cm$^{-3}$ and $\approx 4.7$ kpc. By assuming a spherical cloud, we obtain a mass of $M_{\text{cl}} \approx 6 \times 10^5 M_\odot$. However, the mass could be larger with other assumed geometries.

4.4. Outflows

Next, we consider the possibility that the absorption arises in a starburst-driven wind from the dwarf galaxy (A). Based on the optical spectrum presented in Figure 1, we find that galaxy A is forming stars at a rate ($\sim 0.1 M_\odot$ yr$^{-1}$) that is typical of dwarf galaxies at low redshift. With a rest-frame H$\alpha$ equivalent width of $EW \approx 13$ Å, however, the galaxy would not be considered a starburst by most definitions adopted in the literature (Lee et al. 2009). Combining the estimated total stellar mass for galaxy A of $M_* \approx 8 \times 10^8 h^{-2} M_\odot$ and the observed star formation rate, we derive a characteristic star formation timescale of $\tau \approx 8$ Gyr. This is much longer than the characteristic timescale for typical starburst galaxies (Brinchmann et al. 2004). We also note that the major axis of the galaxy is oriented along the direction to the QSO. As an outflowing wind is expected to be predominantly along the minor axis, the bulk of the wind is unlikely to pass in front of the QSO sightline for the observed geometry. Given the modest star formation rate in galaxy A and the disk alignment, a starburst-driven wind would seem incapable of producing the observed absorption $26.5 h^{-1}$ kpc from the disk of the galaxy.

4.5. Conduction Front

Finally, we consider the idea that the Ne VIII absorption is produced at the turbulent boundary layers of cooler clouds moving at high speed through a hot medium. This scenario has been proposed to explain the O VI absorption associated with high-velocity clouds and the Magellanic Stream in the Milky Way (Sembach et al. 2003). The redshift difference between galaxy B and the Ne VIII absorber leads to a relative velocity of nearly 200 km s$^{-1}$, roughly twice the sound speed for an ionized warm-hot medium of $T \sim 5 \times 10^5$ K. Although the clouds are expected to suffer from the Kelvin–Helmholtz instability, the inferred gas density and cloud size discussed in Section 4.3 suggest that the cloud may be massive enough to counterbalance such instabilities (Maller & Bullock 2004).

A natural consequence of this scenario is that both low- and high-ionization species would be expected with a moderate velocity offset between the two components ($\sim 20$ km s$^{-1}$), similar to what is observed in the absorber at $z = 0.20701$. Therefore, the conductive front idea is both consistent with the observed galactic environment and the multi-phase nature of the gas.

5. Conclusions

Combining the results of our galaxy survey with the absorption-line analysis of Savage et al. (2005), we have considered many possible origins for the $z = 0.20701$ absorber toward HE0226 $-$ 4110. We find that the absorber is best explained by a cool cloud moving through a hot medium. Although our study suggests that the Ne VIII absorption may not be directly probing the WHIM in this system, it does imply the existence of hot gas at least 76.5 $h^{-1}$ kpc from a 0.25 $L_\odot$ galaxy (B). The existence of extended hot gas halos around disk galaxies is a key ingredient in most semianalytic models of disk galaxy formation (White & Frenk 1991; Cole et al. 2000; Bower et al. 2006). However, there has been very little direct observational evidence for such halos in quiescent galaxies. Perhaps the best evidence for an extended hot corona comes from the Milky Way, where the presence of hot gas has been inferred from many different observations (Sembach et al. 2003; Fang et al. 2006; Bregman & Lloyd-Davies 2007). Our observations provide evidence for a similar halo around galaxy B. Given the large extent of the halo, a significant fraction of the baryons in the system are likely contained in hot gas.

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