THE C IV ABSORPTION–Mg II KINEMATICS CONNECTION IN ⟨z⟩ ~ 0.7 GALAXIES

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ABSTRACT

We have examined Faint Object Spectrograph data from the Hubble Space Telescope archive for C IV λ1548, 1550 absorption associated with 40 Mg II λλ2796, 2803 absorption–selected galaxies at 0.4 ≤ z ≤ 1.4. We report a strong correlation between Mg II kinematics, measured in ~6 km s⁻¹ resolution HIRES/Keck spectra, and W(1548); this implies a physical connection between the processes that produce “outlying velocity” Mg II clouds and high-ionization galactic/halo gas. We found no trend in ionization condition W(1548)/W(2796) with galaxy-QSO line-of-sight separation for 13 systems with confirmed associated galaxies, suggesting no obvious ionization gradient with galactocentric distance in these intermediate-redshift galaxies. We find tentative evidence (2 σ) that W(W(1548))/W(2796) is anticorrelated with galaxy B–K color; if further data corroborate this trend, in view of the strong C IV–Mg II kinematics correlation, it could imply a connection between stellar populations, star formation episodes, and the kinematics and ionization conditions of halo gas at z ~ 1.

Subject headings: galaxies: evolution — galaxies: halos — quasars: absorption lines

1. INTRODUCTION

The central and complex role of galactic gas in the star formation, dynamical, and chemical evolution of galaxies is well established. Evidence is mounting that, at the present epoch, multiphase gaseous halos are a physical extension of their host galaxy’s interstellar medium (ISM); their physical extent, spatial distribution, ionization conditions, and chemical enrichment are intimately linked to the energy density rate infused into the galaxy’s ISM by stellar winds, ionizing radiation, and supernovae shock waves (e.g., Dahlem 1998 and references therein). One long-standing question is how halos and ISM of earlier epoch galaxies compare or relate, in an evolutionary sense, to those of the present epoch.

Normal (~L*) galaxies at intermediate redshifts (0.5 ≤ z ≤ 1.0) are seen to give rise to low-ionization Mg II λλ2796, 2803 absorption with W(W(2796)) ≥ 0.3 A out to projected distances of ~40 h⁻¹ kpc (e.g., Steidel 1995). A key question is whether low-ionization gas at large galactocentric distances is due to infall (i.e., satellite accretion, minor mergers, intragroup or intergalactic infall) or to energetic processes in the ISM (galactic fountains, chimneys). Using high-resolution Mg II profiles, Churchill, Steidel, & Vogt (1996) found no suggestive trends between low-ionization gas properties and galaxy properties at ⟨z⟩ = 0.7. A next logical step toward addressing this question is to explore the high-ionization gas in Mg II absorption–selected galaxies at these redshifts.

The C IV λ1548, 1550 doublet is a sensitive probe of higher ionization gas. Using C IV and Mg II, Bergeron et al. (1994) inferred multiphase ionization structure around a z = 0.79 galaxy. Churchill & Charlton (1999) incorporated the Mg II kinematics and found high-metallicity, multiphase absorption in a possible group of three galaxies at z = 0.93. In a survey of the SC 336 field (Q1622+238), Steidel et al. (1997) reported that W(W(1548))/W(2796) appeared to be correlated with galaxy-QSO impact parameter, as expected if halo gas density decreases with galactocentric distance.

In this Letter, we present a study of C IV absorption associated with 0.4 ≤ z ≤ 1.4 Mg II absorption–selected galaxies using Faint Object Spectrograph (FOS) data available in the Hubble Space Telescope (HST) archive. We compare the C IV strengths to the Mg II strengths and kinematics and (when available) to the galaxy properties.

2. THE DATA

The Mg II absorbers are selected from the HIRES/Keck sample of Churchill (1997) and Churchill et al. (1999b). The HIRES resolution is ~6 km s⁻¹ (Vogt et al. 1994). The data were processed using IRAF4 as described in Churchill et al. (1999b). The redshifts of the individual Mg II subcomponents were obtained using MINFIT (Churchill 1997), a Voigt profile fitter that uses χ² minimization. For 36 of the Mg II absorbers, FOS/HST (resolution ~230 km s⁻¹) spectra covering C IV were available from the HST archive. For four absorbers, C IV was taken from ground-based spectra of Steidel & Sargent (1992) and Sargent, Boksenberg, & Steidel (1988). The FOS spectra were processed using the techniques of the HST QSO Absorption-Line Key Project (Schneider et al. 1993; Jannuzi et al. 1998). For 13 systems, the absorbing galaxy impact parameters, rest-frame K and B luminosities, and B–K colors are available from Steidel, Dickinson, & Persson (1994), Churchill et al. (1996), and Steidel et al. (1997). We will present a more detailed account in a companion paper (Churchill et al. 1999a).

3. RESULTS

In Figure 1, we present the Mg II and C IV data for each of the 40 systems (note that the velocity scale for Mg II is 500 km s⁻¹ and for C IV is 3000 km s⁻¹). Ticks above the HIRES spectra give the velocities of the multiple Voigt profile Mg II subcomponents, and ticks above the FOS data give the expected location of these components for both members of the C IV doublet. The Mg II profiles are shown in order of

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increasing kinematic spread from the upper left to lower right. The kinematic spread is the second velocity moment of the apparent optical depth of the Mg II λ2796 profile, given by \( \omega_z^2 = \int \tau_z(v) v^2 dv / \int \tau_z(v) dv \), where \( \tau_z(v) = \ln [I_z(v)/\bar{I}(v)] \) and \( \bar{I}(v) \) and \( I_z(v) \) are the observed flux and the fitted continuum flux at velocity \( v \), respectively. The zero-point velocity is given by the optical depth median of the Mg II λ2796 profile. The kinematic spreads range from a few to \( \sim 120 \) km s\(^{-1}\).

In Figure 2a, we present \( W_i(1548) \) versus \( W_i(2796) \), which exhibits considerable scatter. Solid data points are damped Lyα absorbers (DLAs) and candidate DLAs, based upon \( W_i(\text{Ly} \alpha) \geq 8 \) Å or \( W_i(\text{Mg II} \lambda2796) = W_i(\text{Fe II} \lambda2600) \geq 1.0 \) Å (Boissé et al. 1998).

As seen in Figure 2b, \( W_i(2796) \) correlates with \( \omega_z \). Significant scatter arises because \( \omega_z \) is sensitive to the line-of-sight chance presence and equivalent width distribution of the smaller \( W_i(2796) \), “outlying velocity” clouds (see Charlton & Churchill 1998). The DLAs define a “saturation line”; profiles with \( W_i(2796) > 0.3 \) Å along this line have saturated cores. As seen in Figure 2c, there is a tight correlation between \( \omega_z \) and \( W_i(1548) \). A Spearman-Kendall test incorporating limits (LaValley, Isern, & Feigelson 1992) yielded a greater than 99.99% confidence level. A weighted least-squares fit to the data (dotted line through the origin and with upper limits excluded) yielded a slope of \( \omega_z = 65 \) km s\(^{-1}\) per 1 Å of \( W_i(1548) \). The data exhibit a scatter of \( \sigma_{\omega_z}(1548) = 0.22 \) Å about the fit. An essentially identical maximum likelihood fit is shown as a dashed line.

Over the interval \( 35 \leq \omega_z \leq 55 \) km s\(^{-1}\), there are four absorbers that lack the higher ionization phase typical for their Mg II kinematic spread; they are “C iv deficient.” These systems—Q0117+213 at \( z = 1.0479 \), Q1317+277 at \( z = 0.6606 \), Q0117+213 at \( z = 0.7290 \), and Q1329+274 at \( z = 0.8936 \) (in order of decreasing \( \omega_z \))—lie 3.3, 2.9, 2.5, and 2.3 \( \sigma \) from the correlation line, respectively. As compared to other DLAs with similar \( \omega_z \)’s, the DLA at \( z = 0.6561 \) in the field of Q1622+238 (3C 336) also appears to have a slight C iv deficiency.

4. DISCUSSION

Three important observational facts are (1) the scatter in \( W_i(1548) \) versus \( W_i(2796) \) indicates that the strength of C iv absorption is not driven by the strong “central” Mg II component that dominates \( W_i(2796) \), (2) \( \omega_z \) is sensitive to the presence of small \( W_i(2796) \), outlying velocity clouds, and (3) the scatter of \( W_i(2796) \) versus \( \omega_z \) is large, whereas the scatter of \( W_i(1548) \) versus \( \omega_z \) about the correlation line is only 0.22 Å. These facts imply that, independent of the overall Mg II line-of-sight kinematics, the existence and global dynamics of smaller, kinematic “outliers” are intimately linked to the presence and physical conditions of a higher ionization phase.

It would appear that C iv is governed by the same physical processes that give rise to kinematic outlying Mg II clouds. The C iv absorption could arise because of the ionization balance in the Mg II clouds, ionization structure in the clouds, or due to multiphase structure. In most cases, multiphase structure is the likely explanation because the small \( W_i(2796) \), single-
Fig. 2.—(a) $W_r(2796)$ vs. $W_r(1548)$. (b) $W_r(2796)$ vs. the Mg ii kinematic spread $\omega_r$. (c) $W_f(1548)$ vs. $\omega_r$. Errors are on the order of the data point sizes. Filled points are DLAs and candidate DLAs. The dotted and dashed curves (c) are from linear fits, excluding the upper limits (see text).

If the Mg ii clouds are accreted by infall and/or minor mergers, such that the energetics originated gravitationally (e.g., Mo & Miralda-Escudé 1996), multiphase structure could arise from shock heating and/or merger-induced star formation (e.g., Hernquist & Mihos 1995). If, on the other hand, the absorbing gas is mechanically produced by winds from massive stars, OB associations, or from galactic fountains and chimneys, a dynamic multiphase structure could arise from shock-heated ascending material that forms a high-ionization layer (corona) and supports a descending lower ionization layer, which then breaks into cool, infalling clouds (see Avillez 1999 and references therein). Both scenarios imply a link between galaxy star formation histories, in particular multiple episodes of elevated star formation (but not necessarily bursting; Dahlem 1998), and the presence of outlying velocity Mg ii clouds and strong C iv.

Infall models predict increasing cloud densities with decreasing galactocentric distance (e.g., Mo & Miralda-Escudé 1996), resulting in an ionization gradient (clouds further out are more highly ionized). In Figure 3a, we show $W_r(1548)/W_r(2796)$ versus impact parameter for 13 absorbing galaxies. There is no obvious evidence for an ionization gradient (95% confidence). However, $W_r(1548)/W_r(2796)$ could be sensitive to halo mass (e.g., Mo & Miralda-Escudé 1996), to the presence of satellite galaxies (York et al. 1986), or to the sampling of discrete clouds over a range of galactocentric distances along the line of sight. In Figure 3b, we show $W_r(1548)/W_r(2796)$ versus galaxy $B-K$ color for 11 galaxies. There is a suggested trend (2 $\sigma$) for red galaxies (those dominated by late-type stellar populations) to have small $W_r(1548)/W_r(2796)$. If such a trend is confirmed in a larger data sample, it would not be incompatible with a dynamical multiphase scenario in which absorbing gas properties are linked to the host galaxy stellar populations and, therefore, to star formation history.
The tight correlation between Mg~II kinematics and C~IV absorption may imply a self-regulating process involving both ionization conditions and kinematics in the halos of higher redshift, ~\(L^*\) galaxies (e.g., Lanzetta & Bowen 1992), as explored by Norman & Ikeuchi (1989) and Li & Ikeuchi (1992). Perhaps outflow energetics from supernovae during periods of elevated star formation are balanced by the galactic gravitational potential well, resulting in a fairly narrow range of kinematic and multiphase ionization conditions. Such a balance might set up a high-ionization Galactic-like “corona” (Savage, Sembach, & Lu 1997) in proportion to the kinematics of gravitationally bound, cooling material. All this would imply that galaxy “coronae” have been in place since \(z \sim 1\), that their nature primarily depends upon the host galaxy’s star formation history, and therefore upon morphology, environment, and stellar populations (as seen locally, e.g., Dahlem 1998). Detailed observations of the stellar content and galactic morphologies and space-based UV high-resolution spectroscopy of high-ionization absorption lines would be central to establishing the interactive cycles between stars and gas in intermediate-redshift galaxies.

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