

# HALO GAS AND GALAXY DISK KINEMATICS OF A VOLUME-LIMITED SAMPLE OF Mg II ABSORPTION-SELECTED GALAXIES AT $z \sim 0.1$

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## ABSTRACT

We have directly compared Mg II halo gas kinematics to the rotation velocities derived from emission/absorption lines of the associated host galaxies. Our  $0.096 \leq z \leq 0.148$  volume-limited sample comprises 13  $\sim L_*$  galaxies, with impact parameters of 12–90 kpc from background quasar sight lines, associated with 11 Mg II absorption systems with Mg II equivalent widths  $0.3 \text{ \AA} \leq W_r(2796) \leq 2.3 \text{ \AA}$ . For only 5/13 galaxies, the absorption resides to one side of the galaxy systemic velocity and trends to align with one side of the galaxy rotation curve. The remainder have absorption that spans both sides of the galaxy systemic velocity. These results differ from those at  $z \sim 0.5$ , where 74% of the galaxies have absorption residing to one side of the galaxy systemic velocity. For all the  $z \sim 0.1$  systems, simple extended disk-like rotation models fail to reproduce the full Mg II velocity spread, implying that other dynamical processes contribute to the Mg II kinematics. In fact 55% of the galaxies are “counter-rotating” with respect to the bulk of the Mg II absorption. These Mg II host galaxies are isolated, have low star formation rates (SFRs) in their central regions ( $\lesssim 1 M_\odot \text{ yr}^{-1}$ ), and SFRs per unit area well below those measured for galaxies with strong winds. The galaxy Na I D (stellar+ISM) and Mg I b (stellar) absorption line ratios are consistent with a predominately stellar origin, implying kinematically quiescent interstellar media. These facts suggest that the kinematics of the Mg II absorption halos for our sample of galaxies are not influenced by galaxy–galaxy environmental effects, nor by winds intrinsic to the host galaxies. For these low-redshift galaxies, we favor a scenario in which infalling gas accretion provides a gas reservoir for low-to-moderate SFRs and disk/halo processes.

**Key words:** galaxies: halos – galaxies: kinematics and dynamics – intergalactic medium – quasars: absorption lines

*Online-only material:* color figures

## 1. INTRODUCTION

Absorption lines detected in the spectra of background quasars and gamma-ray bursts provide powerful probes of the intervening universe. In particular, it was predicted that discrete metal lines, produced in the clumpy metal-enriched gas distribution arising from intervening groups and isolated galaxies, should be detected as absorption in quasar spectra (Bahcall & Salpeter 1965, 1966; Bahcall & Spitzer 1969). Since the Mg II  $\lambda\lambda 2796, 2803$  doublet arises in metal-enriched low-ionization gas, with neutral hydrogen column densities of  $10^{16} \text{ cm}^{-2} \lesssim N(\text{H I}) \lesssim 10^{22} \text{ cm}^{-2}$  (Churchill et al. 2000; Rigby et al. 2002), it should be a dominant absorption feature detected in quasar spectra. In fact, Mg II absorption was indeed detected along quasar sight lines within close proximity to, and with similar redshifts as, foreground galaxies (Bergeron 1988; Bergeron & Boissé 1991).

Since then, the association of Mg II with normal, bright, field galaxies is now well established (see Churchill et al. 2005, and references therein). It has been demonstrated that galaxy Mg II halos extend out to  $\sim 120$  kpc and have gas covering fractions of 50%–80% (Tripp & Bowen 2005; Kacprzak et al. 2008; Chen & Tinker 2008; Chen et al. 2010a). However, despite the recent progress on the galaxy–halo connection, the origins of this extended halo gas are still widely debated.

Host galaxy environment has been demonstrated to play some role in determining the gas covering fraction and extent of their halos from studies of galaxy close pairs, galaxy groups, and galaxy clusters associated with Mg II absorption (Nestor et al.

2007; Lopez et al. 2008; Padilla et al. 2009; Chen et al. 2010a; Kacprzak et al. 2010a, 2010c). Although the bulk of the evidence supports that Mg II absorption detected along quasar sight lines is a result of outflowing gas (e.g., Bond et al. 2001; Ellison et al. 2003; Bouché et al. 2006; Bouché 2008; Ménard et al. 2009; Nestor et al. 2010), several studies are now emerging that support infalling gas as the source of the absorption (Chen & Tinker 2008; Chen et al. 2010a; Kacprzak et al. 2010a, 2010b; Stocke et al. 2010) or a combination of both inflow and outflow (Chen et al. 2010b; Chelouche & Bowen 2010). In fact, Kacprzak et al. (2010b) have suggested that different mechanisms may be responsible for different equivalent width regimes: low equivalent width systems ( $\lesssim 1 \text{ \AA}$ ) may be dominated by inflow and the strong equivalent width systems may be dominated by outflows.

It is difficult to isolate separate dynamic processes, such as inflow and outflow, responsible for producing the Mg II absorption by only studying statistically large samples of absorbers. However, it may be possible to further understand these individual dynamic processes by studying galaxy–absorber pairs on a case-by-case basis. Furthermore, studying a direct comparison of the galaxy disk kinematics and absorbing Mg II halo gas kinematics may yield a more in depth understanding of these processes.

A direct comparison of the galaxy disk kinematics and absorbing Mg II halo gas kinematics has been performed for 19  $z \sim 0.6$  systems (Steidel et al. 2002; Ellison et al. 2003; Chen et al. 2005; Kacprzak et al. 2010a). The galaxy halos were probed over a range of impact parameters,  $8 \text{ kpc} \leq D \leq$

110 kpc. Kacprzak et al. (2010a) studied 10 host galaxy/absorber pairs and found that the absorption was fully to one side of the galaxy systemic velocity and usually aligned with one arm of the rotation curve in most cases. These results are consistent with earlier studies of five galaxies by Steidel et al. (2002), one galaxy by Ellison et al. (2003), and three galaxies of Chen et al. (2005). In only 5/19 cases, the absorption velocities span both sides of the galaxy systemic velocity. These observations are highly suggestive that Mg II halos obey “disk-like” rotation dynamics, given the alignment of the absorption and the velocity offsets of the absorbing gas relative to the galaxy.

Steidel et al. (2002) applied simple disk-halo models and concluded that a large fraction of the Mg II halo gas velocities could be explained by an extension of the disk rotation with some lag in velocity. However, the models were not able to account for the full velocity spread of the gas. This was also confirmed by Kacprzak et al. (2010a) where a large fraction of the Mg II could not be explained by disk-halo rotation alone and the observed additional velocities were consistent with infalling gas as demonstrated by their study of hydrodynamical galaxy simulations within a cosmological context.

With the increasing blue sensitivity of CCDs, a new redshift window has recently opened, enabling us to detect photons down to the atmospheric cutoff of around 3050 Å. This provides a lower Mg II absorption detection redshift of  $z = 0.09$ . Only a few studies have taken advantage of this new regime to explore the evolution of covering fractions, halo sizes, and kinematics as a function of redshift (Barton & Cooke 2009; Chen et al. 2010a, 2010b).

We have obtained the rotation curves of 13  $\sim L_*$  galaxies, at  $0.096 \leq z \leq 0.148$ , that also have Keck/LRIS quasar absorption profiles of Mg II. In this paper, we perform a kinematic comparison of these galaxies and their associated halo Mg II absorption. We compare our data with a simple rotating disk-halo model, implemented in Kacprzak et al. (2010a) and Steidel et al. (2002), and examine the maximum absorption velocities that could be attributed to the halo gas as disk rotation alone. We further examine the host galaxy environments and also study the intrinsic host galaxy properties, such as star formation rates (SFRs), Mg Ib and Na I D line ratios, and Na I D and H $\alpha$  velocity offsets, that are used to identify and quantify strong outflows. The paper is organized as follows. In Section 2, we present our sample and explain the data reduction and analysis. In Section 3, we present the results of our galaxy-Mg II absorption kinematic observations, and in Section 4, we compare the observed Mg II absorption velocities with a simple disk kinematic halo model. In Section 5, we evaluate and discuss the potential mechanisms that produce the observed Mg II absorption detected near these galaxies. We end with our discussion and conclusions in Sections 6 and 7, respectively. Throughout we adopt an  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0.7$  cosmology.

## 2. DATA AND ANALYSIS

Our sample consists of 11 Mg II absorption systems detected in the spectra of background quasars that are associated with 13 foreground galaxies at similar redshifts. Six of the 11 Mg II absorption systems were selected from Barton & Cooke (2009) who performed a volume-limited survey targeting  $\sim L_*$  galaxies at  $z \sim 0.1$  with  $M_r + \log h \gtrsim -20.5$  that were in close proximity to quasar lines of sight. They detected six Mg II absorption systems that are at a similar redshift to seven foreground  $\sim L_*$  galaxies. We are in the process of expanding

this survey to a more luminous absolute magnitude limit ( $-21$ ) and, hence, a somewhat higher redshift (E. J. Barton et al. 2011, in preparation). Ultimately, the study will involve approximately 45 galaxies. Here, we add an additional five Mg II absorption systems, associated with six galaxies, discovered from the expanded survey. Here, we focus on the first kinematics study of the absorbing galaxies at  $z \sim 0.1$ . We do not include the non-absorbing galaxies identified in this survey in this study. Thus, our sample is composed of 11 absorption systems that are associated with 13 galaxies, two of which are double galaxy systems. The galaxy-quasar impact parameters range from  $12 \text{ kpc} \leq D \leq 90 \text{ kpc}$ . We discuss our data and the analysis in the next subsections.

### 2.1. Quasar Spectroscopy

In addition to the six quasar spectra obtained in Barton & Cooke (2009), we acquired an additional five quasar spectra between 2009 July 21 and 2010 January 12. Details of the additional observations are presented in Table 1. We used the LRIS-B/Keck 1200 lines  $\text{mm}^{-1}$  grating, blazed at 3400 Å, which covers a wavelength range of 2910–3890 Å. Using a 1"0 slit results in a dispersion of  $0.24 \text{ Å}$  per pixel and provides a resolution of  $\sim 1.6 \text{ Å}$  ( $\sim 150 \text{ km s}^{-1}$ ). Integration times of 600–2490 s were used, depending on the magnitude of the quasar, providing  $3\sigma$  detection limits of  $W_r(2796) \gtrsim 0.2 \text{ Å}$ .

The spectra were reduced using the standard IRAF packages.<sup>4</sup> Since neither the sky nor the quartz lamps provide substantial photon counts at  $\sim 3100 \text{ Å}$ , the data were not flat fielded and no sky background correction was applied. The spectra are heliocentric and vacuum-corrected.

The quasar continuum fit was obtained iteratively. First, low-order orthonormal polynomials were fitted to the low-frequency shape of the photon counts over the full wavelength range, then higher frequency features and emission lines were fit to localized wavelength regions using multiple Gaussian functions and orthonormal polynomials (see Sembach & Savage 1992).

The uncertainty spectrum was created post-reduction using a simple Poisson (counts plus background), flat field, and a read noise model appropriate for the sky conditions and instrument specifications. A small-scale factor was applied to ensure a reduced  $\chi^2$  about the continuum fit of unity within a tolerance of 0.1 (iteratively rejecting outlier pixels such as those associated with absorption features).

The Mg II  $\lambda\lambda 2796, 2803$  doublets were objectively searched for using the methods described by Churchill et al. (1999). Because of the low redshifts of the target systems, the redshift number density of interloping absorption lines in the spectra is negligible; as such, there was no confusion with blends or misidentifications. Significant ( $3\sigma$ ) corroborating transitions such as Mg I  $\lambda 2852$  and Fe II  $\lambda\lambda 2344, 2383, 2600$  were identified using the a posteriori knowledge of the Mg II absorption redshift.

Analysis of the absorption profiles was performed using graphic-based interactive software of our own design, which uses the direct pixel values to measure the equivalent widths, velocity moments, and the redshift of the Mg II  $\lambda 2796$  transition. Absorption system velocity widths were measured between the pixels where the equivalent width per resolution element

<sup>4</sup> IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

**Table 1**  
Keck-I/LRIS Quasar Observations

SDSS Quasar Name	Foreground Galaxy Name	R.A. (J2000)	Decl. (J2000)	Quasar $m_r$	$z_{em}$	Date (UT)	Exposure (s)
SDSS J005244.23–005721.7	J005244G1	00:52:44.23	–00:57:21.82	18.8	0.756	2009 Sep 18	$2 \times 940$
	J005244G2						
SDSS J111850.13–002100.7	J111850G1	11:18:50.14	–00:21:00.61	18.9	1.026	2010 Jan 12	$1 \times 1245$
SDSS J114518.47+451601.4	J114518G1	11:45:18.48	+45:16:04.45	18.7	0.612	2010 Jan 12	$2 \times 1245$
SDSS J161940.56+254323.0	J161940G1	16:19:40.57	+25:43:23.12	16.8	0.269	2009 Jul 21	$1 \times 600$
SDSS J225036.72+000759.4	J225036G1	22:50:36.74	+00:07:59.45	19.1	0.431	2009 Jul 21	$1 \times 700$

**Table 2**  
APO/DIS and Keck II/ESI Galaxy Observations

Galaxy Name	R.A. (J2000)	Decl. (J2000)	Galaxy $m_r$	Galaxy $M_r$	Date (UT)	Instrument /Telescope	Slit P.A.	Exposure (s)
J005244G1	00:52:43.92	–00:57:09.23	16.8	–20.8	2009 Nov 16	DIS/APO	35	$3 \times 1600$
J005244G2	00:52:44.02	–00:56:46.41	19.5	–19.7	2009 Nov 15	DIS/APO	–60	$3 \times 1600$
J081420G1	08:14:22.08	+38:33:49.32	16.7	–20.1	2008 Dec 1	DIS/APO	0	$3 \times 1700$
J091119G1	09:11:16.80	+03:12:10.69	16.8	–20.0	2009 Feb 2	DIS/APO	50	$4 \times 1700$
J092300G1	09:23:00.96	+07:51:05.11	16.4	–20.6	2009 Mar 2	DIS/APO	22	$3 \times 1800$
J102847G1	10:28:46.56	+39:18:42.78	17.1	–20.1	2008 May 8	DIS/APO	94	$3 \times 600$
J111850G1	11:18:49.68	–00:21:10.02	17.1	–20.4	2010 Jan 18	DIS/APO	126	$3 \times 1800$
J114518G1	11:45:19.92	+45:16:10.56	17.0	–20.5	2010 Jan 18	DIS/APO	45	$3 \times 1800$
J114803G1	11:48:03.84	+56:54:25.92	16.5	–20.5	2008 Dec 1	DIS/APO	30	$3 \times 1200$
J144033G1	14:40:35.52	+04:48:50.43	16.9	–20.3	2008 May 8	DIS/APO	50	$4 \times 960$
J144033G2	14:40:34.56	+04:48:25.10	17.2	–20.2	2010 Aug 7	ESI/Keck	110	$2 \times 500$
J161940G1	16:19:39.36	+25:43:33.60	18.1	–19.0	2010 Apr 7	DIS/APO	120	$4 \times 1400$
J225036G1	22:50:37.70	+00:07:45.02	15.9	–21.2	2009 Nov 16	DIS/APO	60	$3 \times 1600$

recover to the  $1\sigma$  detection threshold (Churchill et al. 1999). The redshift for each Mg II system is computed from the optical depth weighted mean of the absorption profile (see Churchill & Vogt 2001). The statistical uncertainties in the redshifts range between 0.00001 and 0.00009 ( $\sim 3$ – $30$  km s $^{-1}$  comoving). In addition, least-squares Gaussian deblending was performed (using the program FITTER; Churchill et al. 2000) to estimate the equivalent widths, velocity widths, and velocity centroids of component structures in the absorption profiles. We only display the Gaussian fits in Figures 1–7 to help the reader identify the Mg II absorption profiles and we only use the direct pixel-measured values for all quantitative values published here. Our equivalent widths published here differ from those of Barton & Cooke (2009) who choose to publish the Gaussian-fitted equivalent widths.

## 2.2. Galaxy Spectroscopy

The majority of the galaxy spectra were obtained during nine nights between 2008 May and 2010 February using the double imaging spectrograph (DIS) at the Apache Point Observatory (APO) 3.5 m telescope in New Mexico. Details of the observations are presented in Table 2. The total exposure time per target ranges from 1800 to 5400 s. For each galaxy, the slit position angle was selected to lie along the galaxy major axis.

The DIS spectrograph has separate red and blue channels that have plate scales of  $0''.40$  pixel $^{-1}$  and  $0''.42$  pixel $^{-1}$ , respectively. The B1200 grating was used for the blue channel resulting in a spectral resolution of  $0.62$  Å pixel $^{-1}$  with a wavelength coverage of  $1240$  Å. The R1200 grating was used for the red channel resulting in a spectral resolution of  $0.58$  Å pixel $^{-1}$  with a wavelength coverage of  $1160$  Å. Wavelength centers for each grating were selected to target  $z \sim 0.1$  galaxies having

either H $\alpha$  plus [N II] (red channel) and [O II] (blue channel) in emission or [Na I] (red channel) and Ca II H & K (blue channel) in absorption. We used a  $1''.5$  wide by  $6'$  long slit with no on-chip binning of the CCD. The spectral resolution is  $1.76$  Å ( $\sim 120$  km s $^{-1}$ ) and  $1.28$  Å ( $\sim 53$  km s $^{-1}$ ) FWHM in the blue and red channels, respectively. The observations were performed during good weather conditions with a typical seeing of  $1''$ – $2''$ .

The spectrum of galaxy J144033G2 was obtained using the Keck Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002) on 2010 August 7. Details of the ESI/Keck observations are presented in Table 2. The slit length is  $20''$  and  $1''$  wide and we used  $2 \times 1$  on-chip CCD binning in the spatial direction. Binning by two in the spatial directions results in pixel sizes of  $0''.27$ – $0''.34$  over the echelle orders of interest. The mean seeing was  $0''.8$  (FWHM) with clear skies. The total exposure time was 1000 s. The wavelength coverage of ESI is  $4000$ – $10000$  Å, which allows us to obtain multiple emission lines (such as [O II] doublet, H $\beta$ , [O III] doublet, H $\alpha$ , [N II] doublet, etc.) with a velocity dispersion of  $11$  km s $^{-1}$  pixel $^{-1}$  (FWHM  $\sim 45$  km s $^{-1}$ ).

All DIS and ESI galaxy spectra were reduced using IRAF. External quartz dome-illuminated flat fields were used to eliminate pixel-to-pixel sensitivity variations. Each DIS spectrum was wavelength calibrated using HeNeAr arc line lamps, and the ESI spectrum was calibrated using CuArXe arc line lamps. Again, galaxy spectra are both vacuum and heliocentric velocity corrected for comparison with the absorption line kinematics. The arc emission line vacuum wavelengths were obtained from the National Institute of Standards and Technology (NIST) database.

A Gaussian fitting algorithm (FITTER; see Churchill et al. 2000), which computes best fit Gaussian amplitudes, line centers, and widths, was used to obtain the galaxy redshifts from



**Table 3**  
Galaxy Redshifts and Mg II Absorption Properties

Galaxy Name	$D$ (kpc)	$z_{\text{gal}}$	$z_{\text{abs}}$	$\Delta v_r^a$ (km s $^{-1}$ )	$W_r(2796)$ (Å)	$W_r(2803)$ (Å)	$DR^b$	$\Delta V_-^c$ (km s $^{-1}$ )	$\Delta V_+^c$ (km s $^{-1}$ )
J005244G1	86.1 ± 1.2	0.13429 ± 0.00005	0.13460 ± 0.00002	−14.7	1.46 ± 0.04	1.23 ± 0.04	1.19 ± 0.05	−353.8	241.9
J005244G2	32.4 ± 0.2	0.13465 ± 0.00002		+82.2					
J081420G1	51.1 ± 0.3	0.09801 ± 0.00004	0.09833 ± 0.00001	+105.2	0.57 ± 0.05	0.28 ± 0.05	2.04 ± 0.37	21.7	178.5
J091119G1	72.1 ± 0.4	0.09616 ± 0.00004	0.09636 ± 0.00009	+66.3	0.82 ± 0.10	0.34 ± 0.07	2.41 ± 0.59	−336.6	454.0
J092300G1	11.9 ± 0.3	0.10385 ± 0.00005	0.10423 ± 0.00004	+127.1	2.25 ± 0.14	1.40 ± 0.12	1.61 ± 0.17	−186.3	418.2
J102847G1	89.8 ± 0.4	0.11348 ± 0.00002	0.11411 ± 0.00004	+168.3	0.30 ± 0.02	0.13 ± 0.02	2.23 ± 0.36	−54.9	329.5
J111850G1	25.1 ± 0.3	0.13159 ± 0.00001	0.13158 ± 0.00002	−4.8	1.93 ± 0.08	1.82 ± 0.07	1.06 ± 0.06	−253.2	227.7
J114518G1	39.4 ± 0.8	0.13389 ± 0.00004	0.13402 ± 0.00002	+46.0	1.06 ± 0.06	1.07 ± 0.05	0.99 ± 0.07	−188.8	247.8
J114803G1	29.1 ± 0.5	0.10451 ± 0.00011	0.10433 ± 0.00002	−62.1	1.59 ± 0.06	1.25 ± 0.05	1.27 ± 0.07	−341.0	217.3
J144033G1	67.1 ± 0.1	0.11277 ± 0.00005	0.11304 ± 0.00001	+90.7	1.18 ± 0.04	0.93 ± 0.03	1.28 ± 0.06	−115.0	293.4
J144033G2	24.9 ± 0.2	0.11271 ± 0.00001		+88.8					
J161940G1	45.7 ± 0.7	0.12438 ± 0.00006	0.12501 ± 0.00003	+211.8	0.32 ± 0.03	0.28 ± 0.03	1.12 ± 0.18	72.5	370.9
J225036G1	53.9 ± 0.7	0.14826 ± 0.00002	0.14837 ± 0.00002	+38.0	1.08 ± 0.07	1.11 ± 0.07	0.97 ± 0.09	−140.8	224.4

**Notes.**

<sup>a</sup>  $\Delta v_r$  is the rest-frame velocity offset between the mean Mg II  $\lambda 2796$  absorption line and the galaxy where,  $\Delta v_r = c(z_{\text{abs}} - z_{\text{gal}})/(1 + z_{\text{gal}})$  km s $^{-1}$ .

<sup>b</sup> Doublet ratio,  $DR \equiv W_r(2796)/W_r(2803)$ .

<sup>c</sup> Blue and red Mg II absorption velocity edges.

an emission or absorption line(s). The galaxy redshifts derived here are consistent with those derived by the Sloan Digital Sky Survey (SDSS). The galaxy redshifts are listed in Table 3; their accuracy ranges from 2 to 30 km s $^{-1}$ .

The rotation curve extraction was performed following the methods of Kacprzak et al. (2010a; also see Vogt et al. 1996; Steidel et al. 2002). We extracted individual spectra by summing three-pixel-wide apertures (corresponding to approximately one resolution element of 1''.20–1''.26 for DIS and 0''.81–1''.02 for ESI) at 1 pixel spatial increments along the slit. To obtain accurate wavelength calibrations, we extract spectra of the arc line lamps at the same spatial pixels as the extracted galaxy spectra. Fitted arc lamp exposures provided a dispersion solution accurate to  $\sim 0.15$  Å (6 km s $^{-1}$ ) and  $\sim 0.025$  Å (1 km s $^{-1}$ ) for DIS and ESI, respectively. Each galaxy emission line (or absorption line in some cases) was fit with a single Gaussian in order to extract the wavelength centroid for each line. The velocity offsets for each emission line in each extraction were computed with respect to the redshift zero point determined for the galaxy (see Table 3). The rotation curves for the 13 galaxies are presented in Figures 1–7.

### 2.3. Galaxy Images and Models

In Figures 1–7, we show combined *gri*-band SDSS color images of the galaxies and quasar fields. We used GIM2D (Simard et al. 2002) to model the galaxy morphologies. For each galaxy, the morphological parameters were quantified by fitting a two-component (bulge+disk) cospatial parametric model to its two-dimensional surface brightness distribution. We fit each galaxy surface brightness profile with a Sérsic bulge component (with  $0.2 \leq n \leq 4.0$ ) and an exponential disk component. GIM2D has been previously used to model  $z \sim 0.5$  Mg II absorption-selected galaxies (Kacprzak et al. 2007, 2010b). Here, we use GIM2D to acquire the quasar–galaxy impact parameters ( $D$ ), inclination angles ( $i$ ), and position angles (P.A.) of the galaxy major axes with respect to the quasar line of sight.

During the GIM2D modeling process, the models are convolved with a point-spread function (PSF) determined by the user. To determine the two-dimensional PSF, we selected 10 or more stars close to the absorbing galaxy in the Sloan *r*-band images and modeled them using DAOPHOT (Stetson 1987,

1999). We then used that PSF in combination with GIM2D to model SDSS *r*-band galaxy images to extract morphological properties. We chose to model the galaxies using *r*-band images since it has the best sensitivity and it also traces the H $\alpha$  emission at  $z \sim 0.1$ . The galaxy-modeled orientations are found in Table 4.

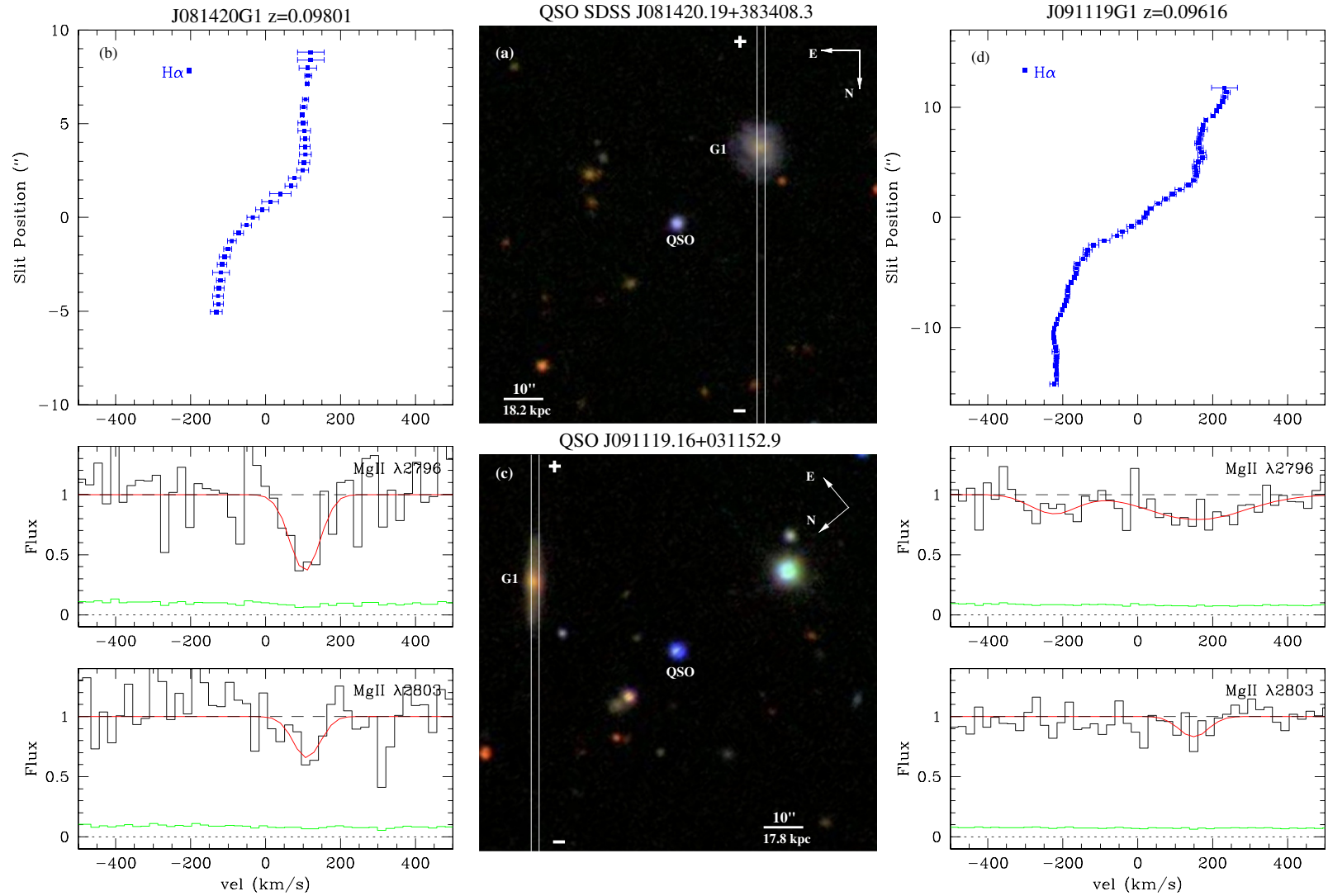
The magnitudes quoted in Table 2 are *k*-corrected and corrected for Galactic reddening (Blanton et al. 2005). Rest *r*-band luminosities were computed using  $M_r^* = -19.67$  derived for  $z \sim 0.1$  SDSS galaxies (Montero-Dorta & Prada 2009; Blanton et al. 2003).

## 3. DISCUSSION OF INDIVIDUAL FIELDS

Here we discuss the halo gas and galaxy kinematics of the 13 absorption-selected galaxies along 11 different quasar sight lines shown in Figures 1–7. In Table 3, we list all the galaxies in each field that have spectroscopically confirmed redshifts. The table columns are (1) galaxy name, (2) the quasar–galaxy impact parameter, (3) the galaxy redshift, (4) the Mg II absorption redshift, (5) the Mg II absorption and galaxy velocity offset, (6) the rest-frame Mg II  $\lambda 2796$  and (7) the Mg II  $\lambda 2803$  equivalent width, (8) the doublet ratio,  $DR$ , and the blue (9) and red (10) velocity limits of the Mg II  $\lambda 2796$  absorption profiles. The galaxy velocity offsets from the optical-depth-weighted mean Mg II absorption range from  $-14$  to  $+212$  km s $^{-1}$ . Galaxy redshifts will only be quoted to four significant figures from here on for simplicity. We will later discuss kinematic halo models in Section 4.

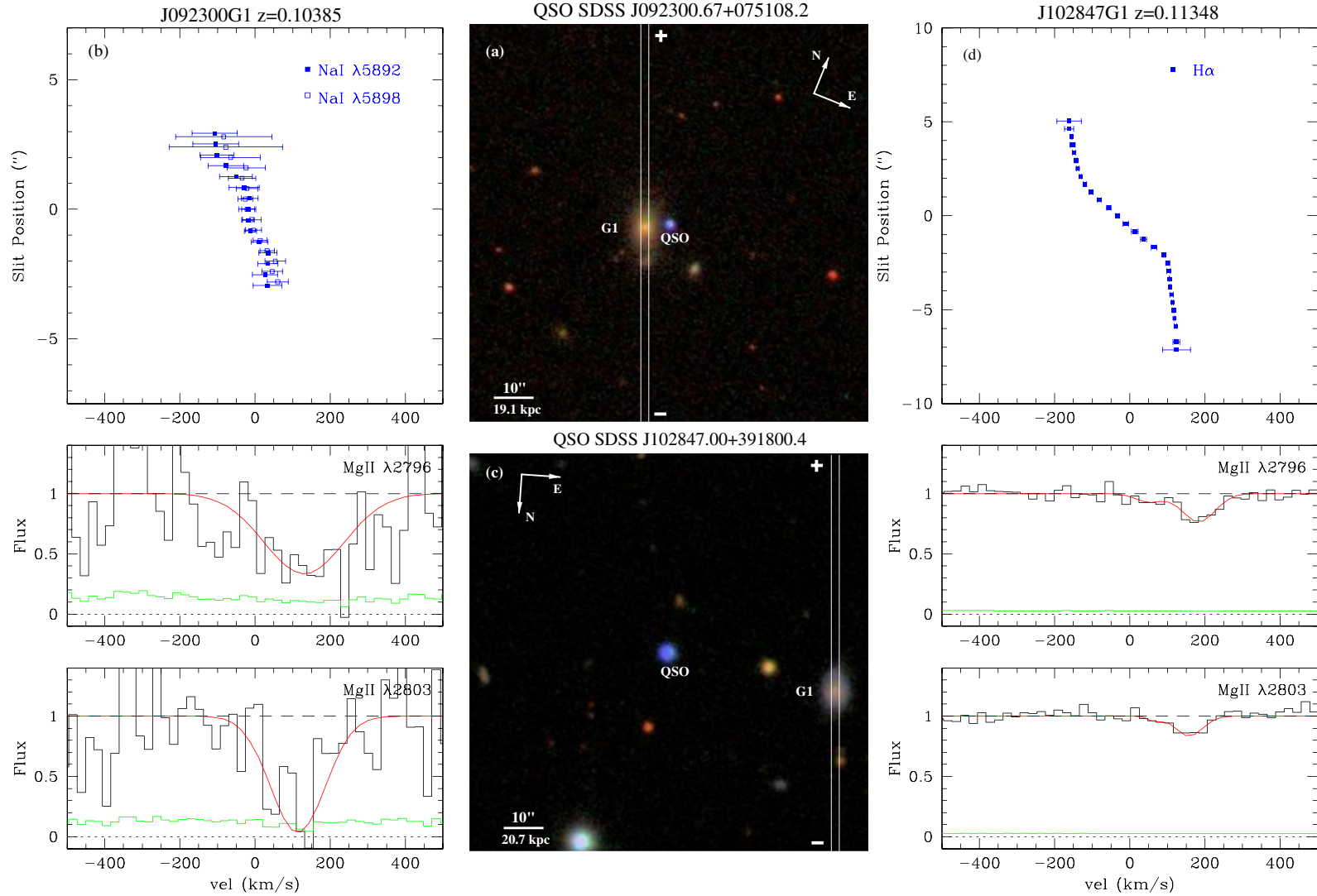
### 3.1. Mg II Absorption from Isolated Galaxies

In the following subsections, we discuss the nine galaxy–absorber pairs which appear to be isolated systems and do not have any major or minor companions within 100 kpc of the quasar line of sight. We discuss the remaining four absorbers in Section 3.2. In all Figures 1–7, we show a 100''  $\times$  100'' SDSS image of the field centered on the quasar. Below the rotation curve of each galaxy, the Mg II  $\lambda \lambda 2796, 2803$  absorption profiles are shown on the same velocity scale. For each galaxy, the slit position angle was selected to lie along the galaxy major axis.



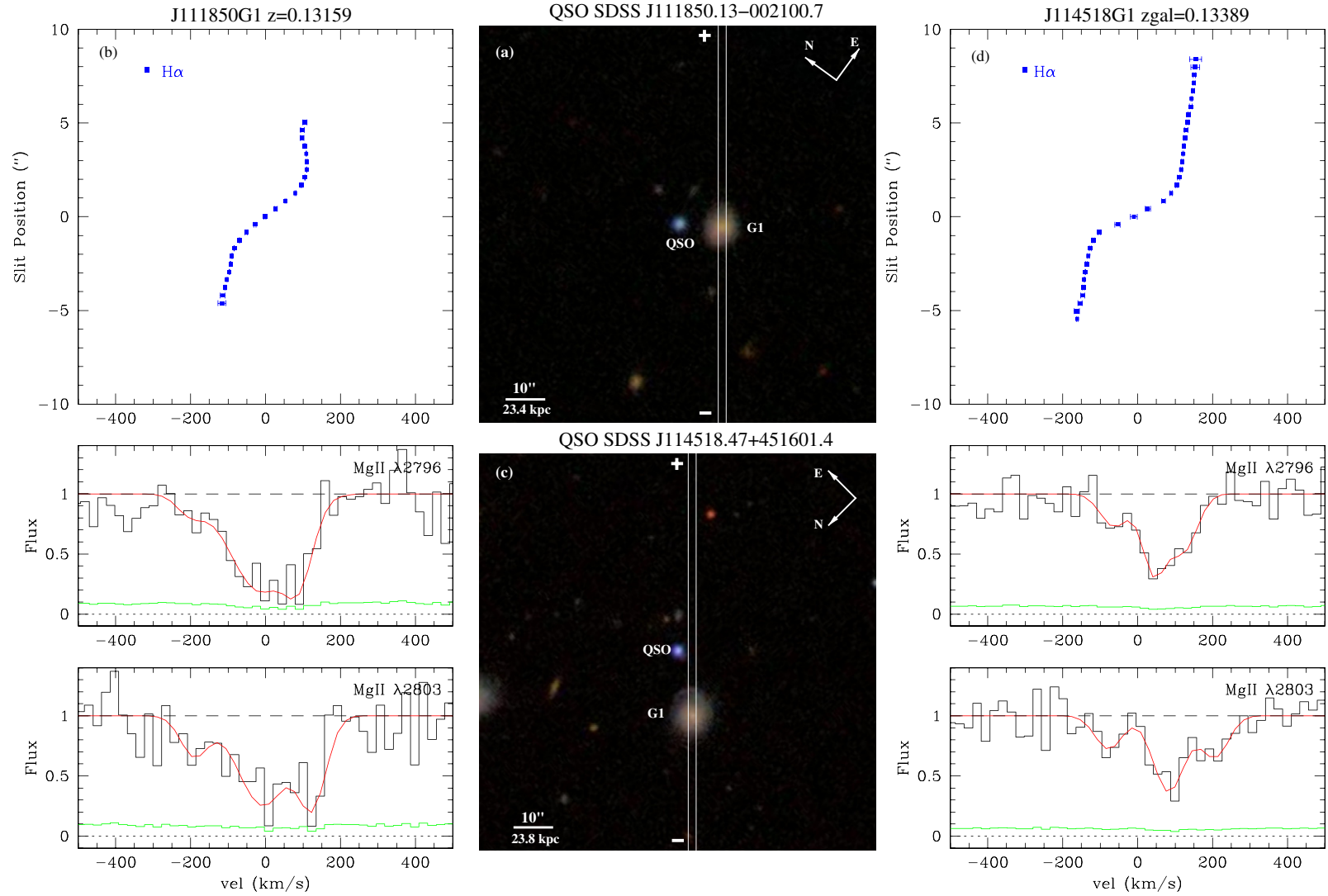
**Figure 1.** (a) A  $100'' \times 100''$  ( $181.8 \times 181.8$  kpc at the absorption redshift) Sloan *gri* color image of the SDSS J081420.19+383408.3 quasar field. The DIS/APO slit is superimposed on the image over the absorbing galaxy J081420G1. The “+” and “-” on the slit indicate the positive and negative arcseconds where 0'' is defined at the target galaxy center. (b) DIS/APO rotation curve of J081420G1 determined from the  $H\alpha$  emission line. Below, the LRIS/Keck absorption profiles of the  $Mg\ II\ \lambda\lambda 2796, 2803$  doublet which are aligned with the galaxy systemic velocity. The quasar continuum fit is indicated by the dashed line, and the solid line (red) shows the Gaussian fit to the absorption features. Below, the solid (green) line shows the sigma spectrum. (c) Same as (a) except for the J091119.16+031152.9 quasar field, and the physical size of the image at the absorption redshift is  $178.3 \times 178.3$  kpc. (d) Same as (b) except the DIS/APO rotation curve is for J091119G1.

(A color version of this figure is available in the online journal.)



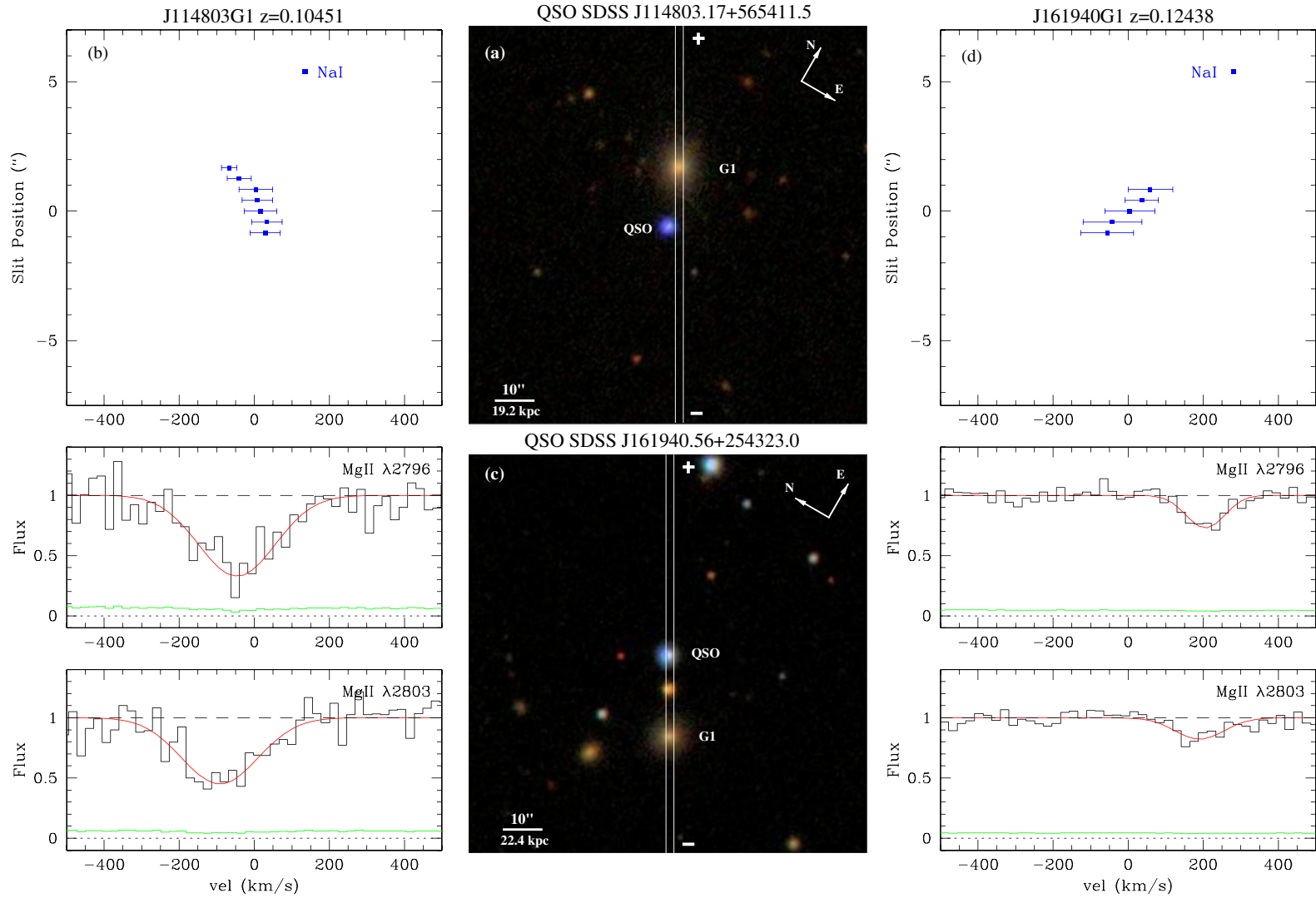
**Figure 2.** (a) A  $100'' \times 100''$  ( $191.4 \times 191.4$  kpc at the absorption redshift) Sloan *gri* color image of the SDSS J092300.67+075108.2 quasar field. The DIS/APO slit is superimposed on the image over the absorbing galaxy J092300G1. The “+” and “-” on the slit indicate the positive and negative arcseconds where  $0''$  is defined at the target galaxy center. (b) The DIS/APO rotation curve of J092300G1 determined from NaI D  $\lambda\lambda 5892, 5898$  absorption doublet. Below, the LRIS/Keck absorption profiles of the Mg II  $\lambda\lambda 2796, 2803$  doublet which are aligned with the galaxy systemic velocity. The quasar continuum fit is indicated by the dashed line, and the solid (green) line shows the sigma spectrum. (c) Same as (a) except for the J102847.00+391800.4 quasar field, and the physical size of the image at the absorption redshift is  $206.8 \times 206.8$  kpc. (d) Same as (b) except the DIS/APO rotation curve is for J102847G1 determined from H $\alpha$ .

(A color version of this figure is available in the online journal.)



**Figure 3.** (a) A  $100'' \times 100''$  ( $234.2 \times 234.2$  kpc at the absorption redshift) Sloan *gri* color image of the SDSS J111850.13–002100.7 quasar field. The DIS/APO slit is superimposed on the image over the absorbing galaxy J111850G1. The “+” and “–” on the slit indicate the positive and negative arcseconds where  $0''$  is defined at the target galaxy center. (b) The DIS/APO rotation curve of J111850G1 determined from the H $\alpha$  emission line. Below, the LRIS/Keck absorption profiles of the MgII  $\lambda\lambda 2796, 2803$  doublet which are aligned with the galaxy systemic velocity. The quasar continuum fit is indicated by the dashed line, and the solid line (red) shows the Gaussian fit to the absorption features. Below, the solid (green) line shows the sigma spectrum. (c) Same as (a) except for the J114518.47+451601.4 quasar field, and the physical size of the image at the absorption redshift is  $238.0 \times 238.0$  kpc. The galaxy directly to the left of the absorber, at the edge of the image, is at  $z = 0.0700$  and is not associated with the absorption system at  $z_{\text{abs}} = 0.13402$ . (d) Same as (b) except the DIS/APO rotation curve is for J114518G1.

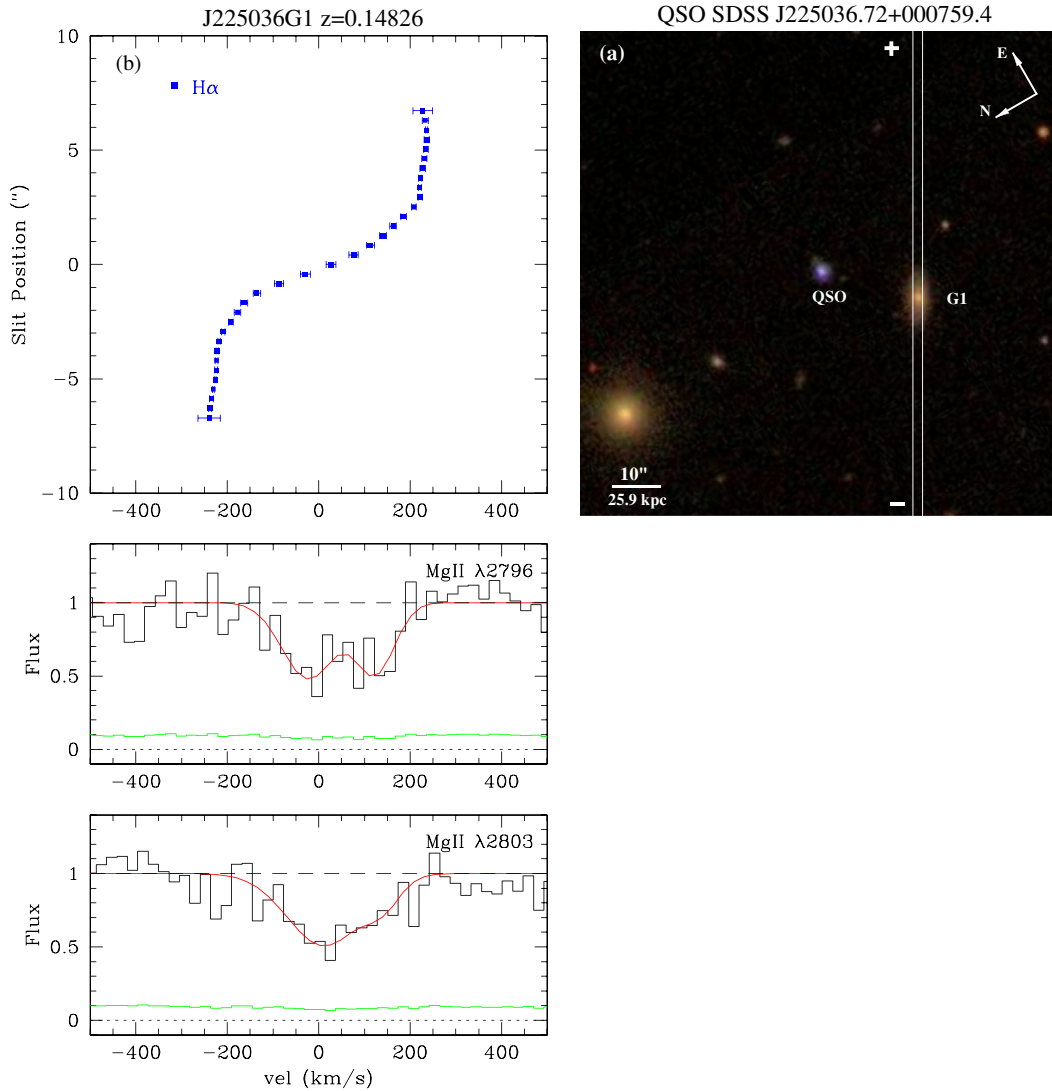
(A color version of this figure is available in the online journal.)



**Figure 4.** (a) A  $100'' \times 100''$  ( $191.6 \times 191.6$  kpc at the absorption redshift) Sloan *gri* color image of the SDSS J114803.17+565411.5 quasar field. The DIS/APO slit is superimposed on the image over the absorbing galaxy J114803G1. The “+” and “-” on the slit indicate the positive and negative arcseconds where 0'' is defined at the target galaxy center. (b) The DIS/APO rotation curve of J114803G1 determined from the Na I  $\lambda\lambda 58925898$  Å absorption doublet, which was fit with a single Gaussian. Below, the LRIS/Keck absorption profiles of the Mg II  $\lambda\lambda 2796, 2803$  doublet which are aligned with the galaxy systemic velocity. The quasar continuum fit is indicated by the dashed line, and the solid line (red) shows the Gaussian fit to the absorption features. Below, the solid (green) line shows the sigma spectrum. (c) Same as (a) except for the J161940.56+254323.0 quasar field, and the physical size of the image at the absorption redshift is  $224.2 \times 224.2$  kpc. (d) Same as (b) except the DIS/APO rotation curve determined from the H $\alpha$  emission line is for J161940G1.

(A color version of this figure is available in the online journal.)





**Figure 5.** (a) A  $100'' \times 100''$  ( $259.2 \times 259.2$  kpc at the absorption redshift) Sloan *gri* color image of the SDSS J225036.72+000759.4 quasar field. The DIS/APO slit is superimposed on the image over the absorbing galaxy J225036G1. The “+” and “-” on the slit indicate the positive and negative arcseconds where  $0''$  is defined at the target galaxy center. The galaxy directly north of the absorber, in the lower left corner of the image, is at  $z = 0.1117$  and is not associated with the absorption system at  $z_{\text{abs}} = 0.14837$ . (b) The DIS/APO rotation curve of J225036G1 determined from the H $\alpha$  emission line. Below, the LRIS/Keck absorption profiles of the Mg II  $\lambda\lambda 2796, 2803$  doublet which are aligned with the galaxy systemic velocity. The quasar continuum fit is indicated by the dashed line, and the solid line (red) shows the Gaussian fit to the absorption features. Below, the solid (green) line shows the sigma spectrum.

(A color version of this figure is available in the online journal.)

### 3.1.1. J081420G1

In Figure 1(a), we show that the absorption system detected in the spectrum of the background quasar is associated with a  $1.51 L_*$  galaxy located 51 kpc away from the quasar line of sight. This spiral galaxy is moderately inclined at  $40^\circ$ .

The rotation curve of G1, presented in Figure 1(b), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 130 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+105 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption is an apparent single kinematic component having a velocity spread of roughly  $200 \text{ km s}^{-1}$ . The doublet ratio suggests that this  $W_r(2796) = 0.57 \text{ \AA}$  system is not saturated. The Mg II absorption resides to one side of the galaxy systemic velocity and also aligns with the maximum rotation velocity of the galaxy.

### 3.1.2. J091119G1

In Figure 1(c), we show that the absorption system detected in the spectrum of the background quasar is associated with an almost edge-on ( $i = 82^\circ$ )  $1.38 L_*$  spiral galaxy located 72 kpc from the quasar line of sight.

The rotation curve of G1, presented in Figure 1(d), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 230 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+66 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption consists of two broad regions that span roughly  $790 \text{ km s}^{-1}$ . The doublet ratio suggests that this  $W_r(2796) = 0.82 \text{ \AA}$  system is not saturated. The galaxy velocities are consistent with most of the absorbing gas velocities with the two highest optical depth regions aligning with both sides of the galaxy rotation curve.

## 3.1.3. J092300G1

In Figure 2(a), we show that the absorption system detected in the spectrum of the background quasar is associated with a  $2.27L_r^*$  S0-like galaxy located only 12 kpc from the quasar line of sight. The galaxy has an inclination of  $56^\circ$ .

The dynamics of G1, presented in Figure 2(b), is derived from NaID absorption and exhibits a maximum projected rotation velocity of  $\sim 110 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+127 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption comprises a single component that spans roughly  $605 \text{ km s}^{-1}$ , with the bulk of the gas spanning  $\sim 200 \text{ km s}^{-1}$ . The doublet ratio suggests that this strong  $W_r(2796) = 2.25 \text{ \AA}$  system is partially saturated. The bulk of the absorption resides to one side of the galaxy rotation curve, although it tends to have slightly higher velocities than the maximum rotation.

## 3.1.4. J102847G1

In Figure 2(c), we show that the absorption system detected in the spectrum of the background quasar is associated with a  $1.49L_r^*$  spiral galaxy located 90 kpc from the quasar line of sight. The galaxy has an inclination of  $54^\circ$ .

The rotation curve of G1, presented in Figure 2(d), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 160 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+168 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption consists of a broad shallow and single narrower component that spans roughly  $385 \text{ km s}^{-1}$ . The doublet ratio suggests that this weak  $W_r(2796) = 0.30 \text{ \AA}$  system is saturated. The bulk of the absorption resides to one side of the galaxy systemic velocity and aligns with the maximum rotation of the galaxy.

## 3.1.5. J111850G1

In Figure 3(a), we show that the absorption system detected in the spectrum of the background quasar is associated with a  $1.91L_r^*$  spiral galaxy located only 25 kpc from the quasar line of sight. The galaxy has an inclination of  $30^\circ$ .

The rotation curve of G1, presented in Figure 3(b), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 120 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $-5 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption consists of a large broad component that spans roughly  $480 \text{ km s}^{-1}$ . The doublet ratio suggests that this strong  $W_r(2796) = 1.93 \text{ \AA}$  system is mostly saturated. The bulk of the absorption spans the entire velocity range of the galaxy rotation curve almost centered on the galaxy systemic velocity.

## 3.1.6. J114518G1

In Figure 3(c), we show that the absorption system detected in the spectrum of the background quasar is associated with a  $2.23L_r^*$  spiral galaxy located 34 kpc from the quasar line of sight. The galaxy has an inclination of  $34^\circ$ .

The rotation curve of G1, presented in Figure 3(d), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 160 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+46 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption consists of a large broad component that spans roughly  $437 \text{ km s}^{-1}$ . The doublet ratio suggests that this strong  $W_r(2796) = 1.06 \text{ \AA}$  system is mostly saturated. The bulk of the absorption resides primarily to one side of the galaxy systemic velocity and spans from the galaxy systemic velocity to the maximum rotation velocity of the galaxy.

## 3.1.7. J114803G1

In Figure 4(a) we show that the absorption system detected in the spectrum of the background quasar is associated with an  $2.17L_r^*$  elliptical galaxy located 29 kpc from the quasar line of sight.

The spatial radial velocity of G1, as derived from Na I, is presented in Figure 4(b). The data suggest that G1 exhibits more of a global shear than rotation and has a maximum observed shear velocity of  $\sim 67 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $-62 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption consists of a large broad component that spans roughly  $558 \text{ km s}^{-1}$ . The doublet ratio suggests that this strong  $W_r(2796) = 1.59 \text{ \AA}$  system is mostly saturated. The bulk of the absorption spans the entire velocity range of the galaxy rotation curve almost centered on the galaxy systemic velocity.

## 3.1.8. J161940G1

In Figure 4(c), we show that the absorption system detected in the spectrum of the background quasar is associated with a  $1.70L_r^*$  elliptical galaxy located 46 kpc from the quasar line of sight.

The spatial radial velocity of G1, as derived from Na ID, is presented in Figure 4(d). The data suggest that G1 exhibits more of a global shear than rotation and has a maximum observed shear velocity of  $\sim 70 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+212 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption consists of a single narrow component that spans roughly  $298 \text{ km s}^{-1}$ . The doublet ratio suggests that this weaker  $W_r(2796) = 0.32 \text{ \AA}$  system is mostly saturated. The absorption resides to one side of the galaxy systemic velocity.

## 3.1.9. J225036G1

In Figure 5(a), we show that the absorption system detected in the spectrum of the background quasar is associated with a  $4.27L_r^*$  elliptical galaxy located 54 kpc from the quasar line of sight.

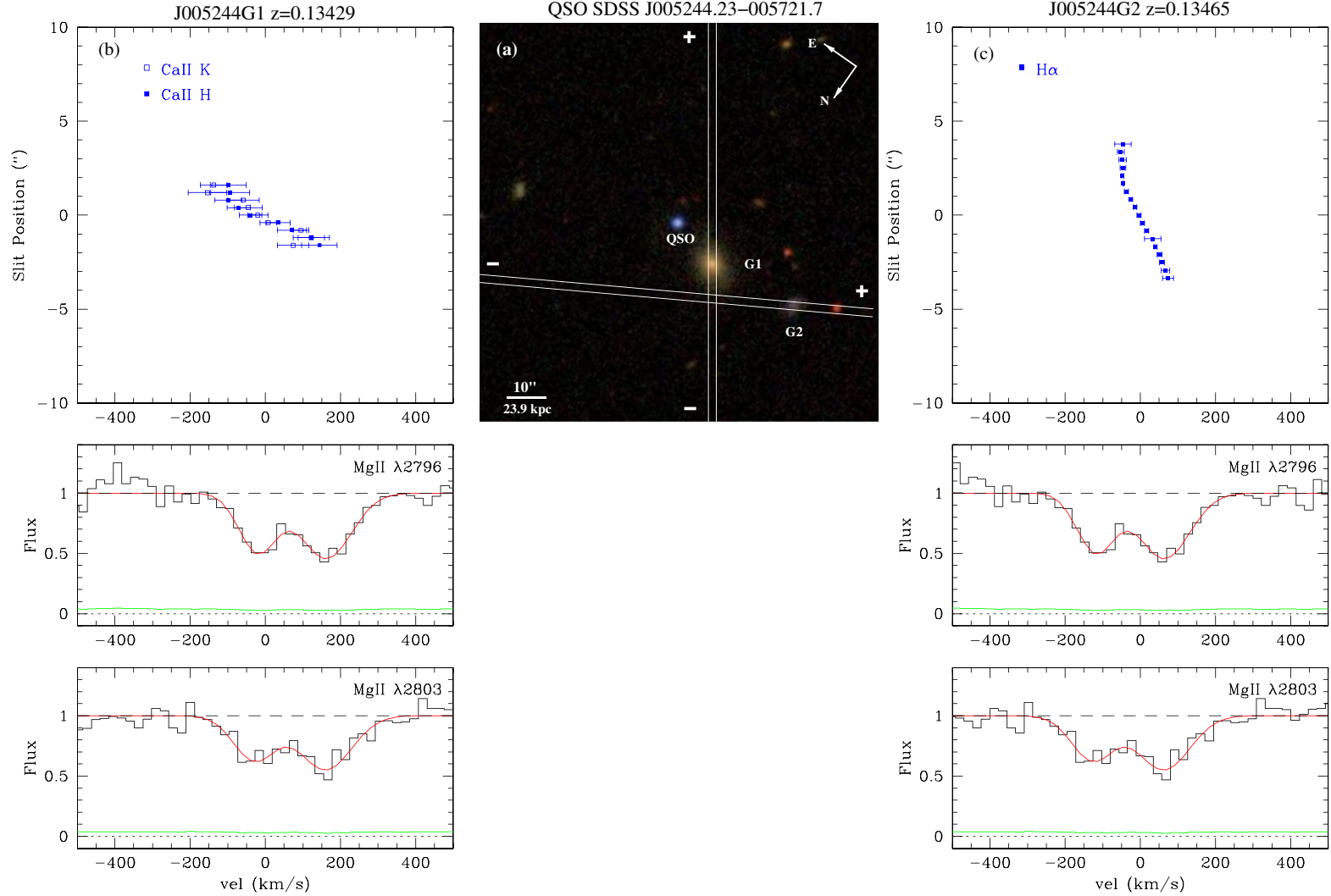
The rotation curve of G1, presented in Figure 5(b), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 240 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+38 \text{ km s}^{-1}$  from the galaxy systemic velocity. The Mg II absorption consists of a single narrow component that spans roughly  $365 \text{ km s}^{-1}$ . The doublet ratio suggests that this strong  $W_r(2796) = 1.08 \text{ \AA}$  system is mostly saturated. The absorbing gas spans both sides of the galaxy systemic velocity, however the bulk of the absorption resides to one side.

## 3.2. Mg II Absorption from Galaxy Pairs/Groups

Here we discuss galaxies in “group” environments which are typically defined by two or more galaxies within the standard halo size of  $\sim 120 \text{ kpc}$  (Chen & Tinker 2008; Kacprzak et al. 2008; Chen et al. 2010a). It has been suggested that group environments may give rise to Mg II absorption from a range of structures such as from tidal tails, streams, etc. (Bowen et al. 1995; Churchill & Charlton 1999; Whiting et al. 2006; Kacprzak et al. 2010a, 2010c). It has also been suggested that galaxy pairs/groups may not follow the same clear anti-correlation between  $D$  and  $W_r(2796)$  as seen for isolated galaxies (Chen et al. 2010a). Here we discuss the two absorbing pairs of galaxies.

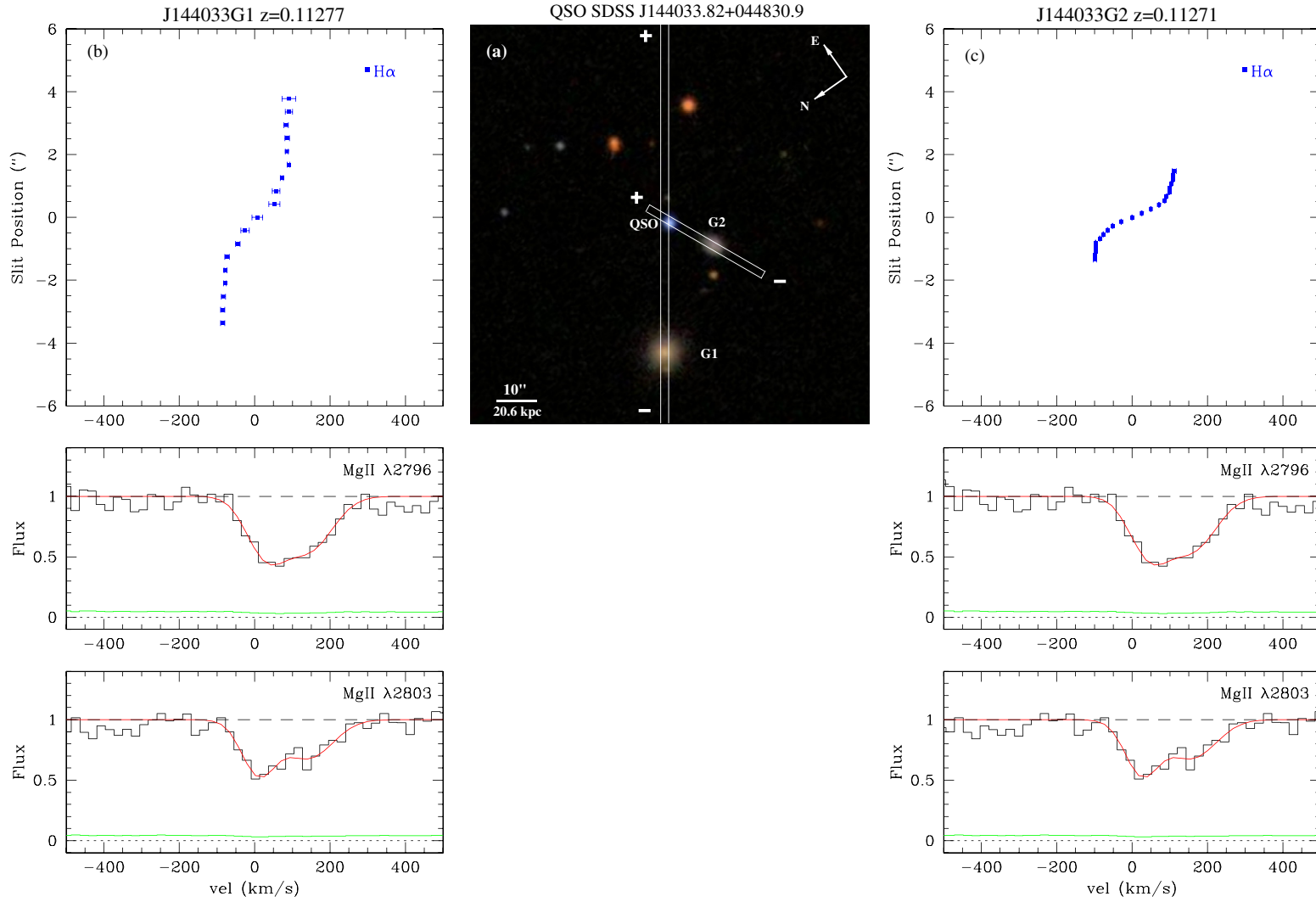
## 3.2.1. J005244G1 &amp; J005244G2

In Figure 6(a), we show that the absorption system detected in the spectrum of the background quasar may be associated with



**Figure 6.** (a) A  $100'' \times 100''$  ( $238.8 \times 238.8$  kpc at the absorption redshift) Sloan *gri* color image of the quasar field. The DIS/APO slit is superimposed on the image. The “+” and “-” on the slit indicate the positive and negative arcseconds where  $0''$  is defined at the target galaxy center. This field contains two absorbing galaxies labeled as G1 and G2. An additional galaxy located at the far southeast of the quasar is not part of this group and has a redshift of  $z = 0.1390 \pm 0.0007$  which is more than  $1250 \text{ km s}^{-1}$  redward of the galaxy pair. (b) The DIS/APO rotation curve of G1 and the LRIS/Keck absorption profiles aligned with the galaxy systemic velocity. The zero-point velocity is set by G1. The quasar continuum fit is indicated by the dashed line, and the solid line (red) shows the Gaussian fit to the absorption features. Below, the solid (green) line shows the sigma spectrum. (c) Same as (b) except the DIS/APO rotation curve determined from the H $\alpha$  emission line is for G2.

(A color version of this figure is available in the online journal.)



**Figure 7.** (a) A  $100'' \times 100''$  ( $205.6 \times 205.6$  kpc at the absorption redshift) Sloan *gri* color image of the quasar field. The DIS/APO slit is superimposed on the image for G1 and the ESI/Keck  $20''$  slit superimposed over G2. The "+" and "-" on the slit indicate the positive and negative arcseconds where  $0''$  is defined at the target galaxy center. This field contains two absorbing galaxies labeled as G1 and G2. (b) The DIS/APO rotation curve of G1 and the LRIS/Keck absorption profiles aligned with the galaxy systemic velocity. The zero-point velocity is set by G1. The quasar continuum fit is indicated by the dashed line, and the solid line (red) shows the Gaussian fit to the absorption features. Below, the solid (green) line shows the sigma spectrum. (c) Same as (b) except the rotation curve for G2 is obtained with ESI/Keck.

(A color version of this figure is available in the online journal.)



two galaxies. G1 is a  $2.86L_r^*$  elliptical galaxy located 32 kpc from the quasar line of sight and G2 is a  $0.23L_r^*$  emission-line galaxy located 86 kpc from the quasar line of sight. In the short exposure SDSS image, there is no evidence of galaxy–galaxy interaction.

The rotation curve of G2, presented in Figure 6(b), is derived from Ca II absorption and exhibits a maximum projected rotation velocity of  $\sim 143 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $-15 \text{ km s}^{-1}$  from the galaxy systemic velocity. The rotation curve of G2, presented in Figure 6(c), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 74 \text{ km s}^{-1}$ . Below, the Mg II  $\lambda\lambda 2796, 2803$  absorption profiles are shown with the systemic velocity of G1 is the velocity zero point. The mean absorption redshift is offset by  $+82 \text{ km s}^{-1}$  from the galaxy systemic velocity. We find that the absorption spans both sides of the systemic velocity for both galaxies.

The Mg II absorption has a broad profile with two clear kinematic components that span roughly  $596 \text{ km s}^{-1}$ . The doublet ratio suggests that this strong  $W_r(2796) = 1.43 \text{ \AA}$  system is partially saturated.

### 3.2.2. J144033G1 and J144033G2

In Figure 7(a), we show that the absorption system detected in the spectrum of the background quasar may be associated with two spiral galaxies: G1 is a  $1.72L_r^*$  galaxy located 67 kpc from the quasar line of sight and G2 is a  $0.56L_r^*$  galaxy located 25 kpc from the quasar line of sight. In the short exposure SDSS image, there is no clear evidence of galaxy–galaxy interaction.

The rotation curve of G1, presented in Figure 7(b), is derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 91 \text{ km s}^{-1}$ . The mean absorption redshift is offset by  $+91 \text{ km s}^{-1}$  from the galaxy systemic velocity.

The rotation curve of G2, presented in Figure 7(c), is also derived from H $\alpha$  and exhibits a maximum projected rotation velocity of  $\sim 112 \text{ km s}^{-1}$ . Below, the Mg II  $\lambda\lambda 2796, 2803$  absorption profiles are shown with the systemic velocity of G1 is the velocity zero point. The mean absorption redshift is offset by  $+89 \text{ km s}^{-1}$  from the galaxy systemic velocity. The absorption resides to one side of systemic velocity of both galaxies.

The Mg II absorption consists of a broad single kinematic component that spans roughly  $408 \text{ km s}^{-1}$ . The doublet ratio suggests that this  $W_r(2796) = 1.18 \text{ \AA}$  system is mostly saturated.

### 3.3. Summary I: Observational Kinematic Comparisons

We find that for the nine isolated galaxy–absorber pairs, seven galaxies have well-defined rotation curves while two galaxies display only shear. We find that in only 3/9 cases the absorption resides to one side of the galaxy systemic velocity and the absorption redshift tends to align with one side of the rotation curve. In the remaining 6/9 cases, the absorption spans both sides of the galaxy systemic velocity, although the bulk of the Mg II resides mostly to one side of the galaxy systemic velocity.

For our double galaxy–absorber pairs, we find that all four galaxies exhibit well-defined rotation curves. In one case, the absorbing gas spans both sides of both host galaxy systemic velocities. In the other case, the absorbing gas resides to one side of the systemic velocity of both absorbing galaxies.

In the next section, we explore if extended disk-like halo rotation can explain the distribution of absorption kinematics detected at a range of impact parameters from the host galaxies.

**Table 4**  
Galaxy Model Parameters and Disk Model Input Values

Galaxy Name	$D$ (kpc)	$i$ (deg)	P.A. (deg)	$v_{\max}$ ( $\text{km s}^{-1}$ )	$r_h$ (kpc)
J005244G1	$32.4 \pm 0.2$	$45^{+5}_{-3}$	$59^{+7}_{-6}$	143.9	5.91
J005244G2	$86.1 \pm 1.2$	$42^{+10}_{-10}$	$65^{+25}_{-31}$	$-73.5$	3.57
J081420G1	$51.1 \pm 0.3$	$40^{+1}_{-2}$	$68^{+3}_{-2}$	131.4	7.18
J091119G1	$72.1 \pm 0.4$	$82^{+1}_{-1}$	$6^{+0}_{-1}$	231.6	7.84
J092300G1	$11.9 \pm 0.3$	$56^{+2}_{-2}$	$25^{+3}_{-3}$	$-107.7$	5.96
J102847G1	$89.8 \pm 0.4$	$54^{+2}_{-2}$	$62^{+2}_{-1}$	161.6	6.44
J111850G1	$25.1 \pm 0.3$	$30^{+2}_{-2}$	$29^{+0}_{-2}$	$-116.2$	6.31
J114518G1	$39.4 \pm 0.8$	$34^{+2}_{-2}$	$74^{+4}_{-5}$	$-161.5$	6.90
J114803G1	$29.1 \pm 0.5$	$45^{+4}_{-3}$	$62^{+4}_{-4}$	$-67.2$	5.63
J144033G1	$67.1 \pm 0.1$	$30^{+3}_{-3}$	$89^{+6}_{-4}$	$-90.7$	4.62
J144033G2	$24.9 \pm 0.2$	$55^{+3}_{-5}$	$38^{+7}_{-8}$	$-111.8$	2.99
J161940G1	$45.7 \pm 0.7$	$12^{+12}_{-12}$	$45^{+47}_{-28}$	59.1	4.49
J225036G1	$53.9 \pm 0.7$	$70^{+1}_{-2}$	$15^{+1}_{-1}$	$-239.7$	4.96

## 4. GALAXY KINEMATICS AND HALO–DISK MODELS

We now apply the simple monolithic halo model of Steidel et al. (2002) to determine whether an extended disk-like rotating halo is able to account for all or most of the observed Mg II absorption velocity spread measured in our galaxy/absorber systems (see Steidel et al. 2002 for a detailed description of the model). Here we briefly describe the model, which treats the halo gas as a co-rotating thick disk with decreasing velocity as a function of scale height.

The line-of-sight disk–halo velocity,  $v_{\text{los}}$ , is dependent on four measurable quantities,  $D$ ,  $i$ , P.A., and  $v_{\max} \equiv$  maximum projected galaxy rotation velocity, such that

$$v_{\text{los}}(y) = \frac{-v_{\max}}{\sqrt{1 + \left(\frac{y}{p}\right)^2}} \exp\left\{-\frac{|y - y_0|}{h_v \tan i}\right\}, \text{ where} \quad (1)$$

$$y_0 = \frac{D \sin \text{P.A.}}{\cos i} \quad \text{and} \quad p = D \cos \text{P.A.},$$

where the free parameter,  $h_v$ , is the lagging halo gas velocity scale height. The line-of-sight velocity is a function of  $y$ , which is the projected line-of-sight position above the disk plane, and the parameter  $y_0$  represents the position at the projected mid-plane of the disk. The range of  $y$  is constrained by the model halo thickness,  $H_{\text{eff}}$ , such that  $y_0 - H_{\text{eff}} \tan i \leq y \leq y_0 + H_{\text{eff}} \tan i$ . The distance along the line of sight relative to the point where it intersects the projection of the disk mid-plane is then  $D_{\text{los}} = (y - y_0)/\sin i$ , thus,  $D_{\text{los}} \equiv 0$  at the disk mid-plane. There are no assumptions about the spatial density distribution of Mg II absorbing gas, except that  $H_{\text{eff}}$  is the effective gas layer thickness capable of giving rise to absorption.

Here we set  $h_v = 1000 \text{ kpc}$  in order to maximize the rotational velocity predicted by the model, which effectively removes the lagging halo velocity component (such that the exponential in Equation (1) is roughly equal to unity).

### 4.1. Dealing with Spectral Resolution

In order to compare our present low-redshift results directly to the kinematic studies of Kacprzak et al. (2010a) and Steidel et al. (2002) performed at intermediate redshift, we must account for

the difference in the spectral resolution of the two samples. Here, our LRIS spectra have a velocity resolution of  $v \simeq 155 \text{ km s}^{-1}$ , whereas the Kacprzak et al. (2010a) HIRES/Keck and UVES/Very Large Telescope (VLT) spectra have a velocity resolution of  $v \simeq 6 \text{ km s}^{-1}$ .

To compute the velocity broadening of the LRIS Mg II absorption profiles due to spectral resolution, we degraded 26 HIRES/Keck and UVES/VLT  $W_r(2796) > 0.2 \text{ \AA}$  systems from Kacprzak et al. (2010b) and Kacprzak et al. (2010c) to have identical resolution of the LRIS data (these include the systems of the kinematics studies of Kacprzak et al. 2010a and Steidel et al. 2002). We utilized the Voigt profile parameters (column densities,  $b$  parameters, and velocities) from the Voigt profile fits to the Kacprzak et al. spectra and generated synthetic LRIS spectra of the profiles. We convolved the smooth Voigt profile model with a Gaussian instrumental spread of LRIS ( $R = 3500$ ) and sampled the spectra with a pixel size of  $0.18 \text{ \AA}$ . We introduced noise using a signal-to-noise ratio (S/N) of 15 per pixel (using Gaussian deviates). An uncertainty spectrum,  $\sigma(\lambda)$ , is generated that accounts for the LRIS read noise (which affects the noise in the line cores), using a Poisson plus read-noise, model (see Churchill 1997)

$$\sigma(\lambda) = I_c^{-1} [F(\lambda)I_c + \text{RN}^2]^{1/2}, \quad (2)$$

where  $F(\lambda)$  is relative counts in the synthesized spectra at wavelength  $\lambda$  and the continuum  $I_c$  is

$$I_c = \frac{(S/N)^2}{2} \left\{ 1 + \left[ 1 + \left( \frac{2\text{RN}}{S/N} \right)^2 \right]^{1/2} \right\}, \quad (3)$$

where S/N is the signal-to-noise ratio and RN is the read noise.

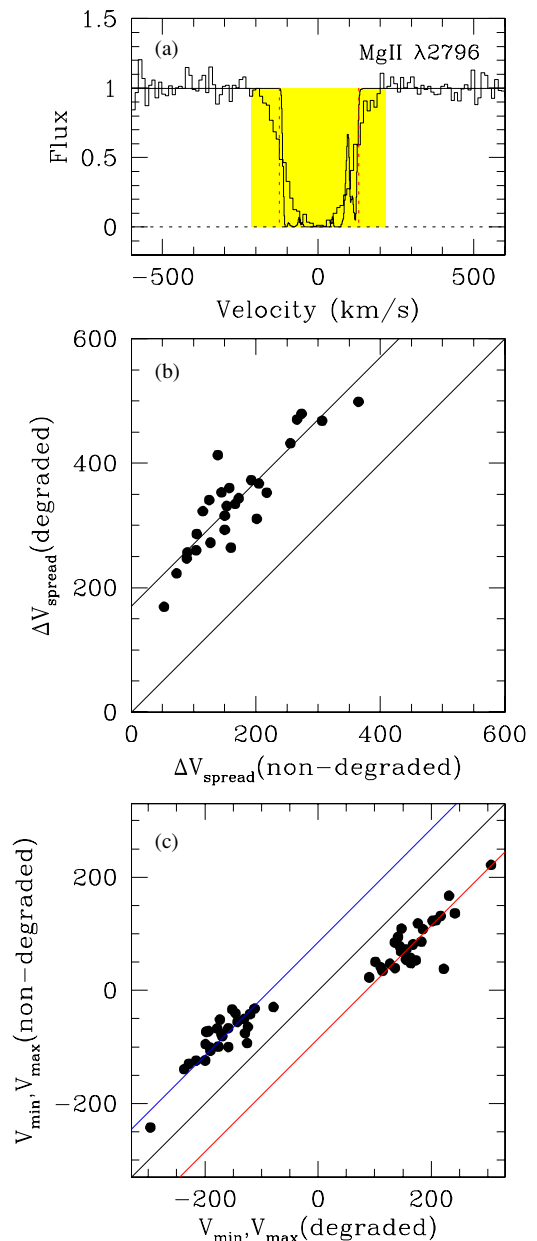
We generated synthetic LRIS spectra of both members of the Mg II doublet and then fully analyze these spectra in an identical fashion performed for the LRIS data used in this work. We thus obtained the equivalent widths, double ratios, velocity moments, and velocity spreads (and all uncertainties) for these synthetic LRIS spectra. In Figure 8(a), we show an example of the degraded spectra, noting the symmetric broadening of the absorption profile.

In Figure 8(b), we show the distribution of absorption velocity widths for the degraded and non-degraded systems. We find that, using the identical measurement standards for both the synthetic LRIS spectra and the observed LRIS spectra, the resolution, pixelization, and noise in the observed spectra introduce an average apparent velocity spread increase of  $\sim 170 \text{ km s}^{-1}$  with a scatter of  $\sim 60 \text{ km s}^{-1}$ . Furthermore, Figure 8(c) shows that the average apparent increase of velocity is symmetric for both the blue and red wings (edges) of the absorption profiles. We find an average velocity increase of  $\pm 85 \text{ km s}^{-1}$  (to the red and to the blue) relative to the Voigt profile models of the absorbers observed at HIRES and UVES resolution. There is a scatter of approximately  $25 \text{ km s}^{-1}$  for the 26 systems we examined from the Kacprzak et al. spectra.

We have now applied a resolution correction such that the LRIS Mg II absorption velocity widths are translated into observed HIRES or UVES velocity widths.

#### 4.2. Results of the Halo–Disk Models

In Figures 9(a)–(l), we show the Mg II absorption profiles for each galaxy, where the shaded regions indicate detected absorption. We have applied a resolution correction such that

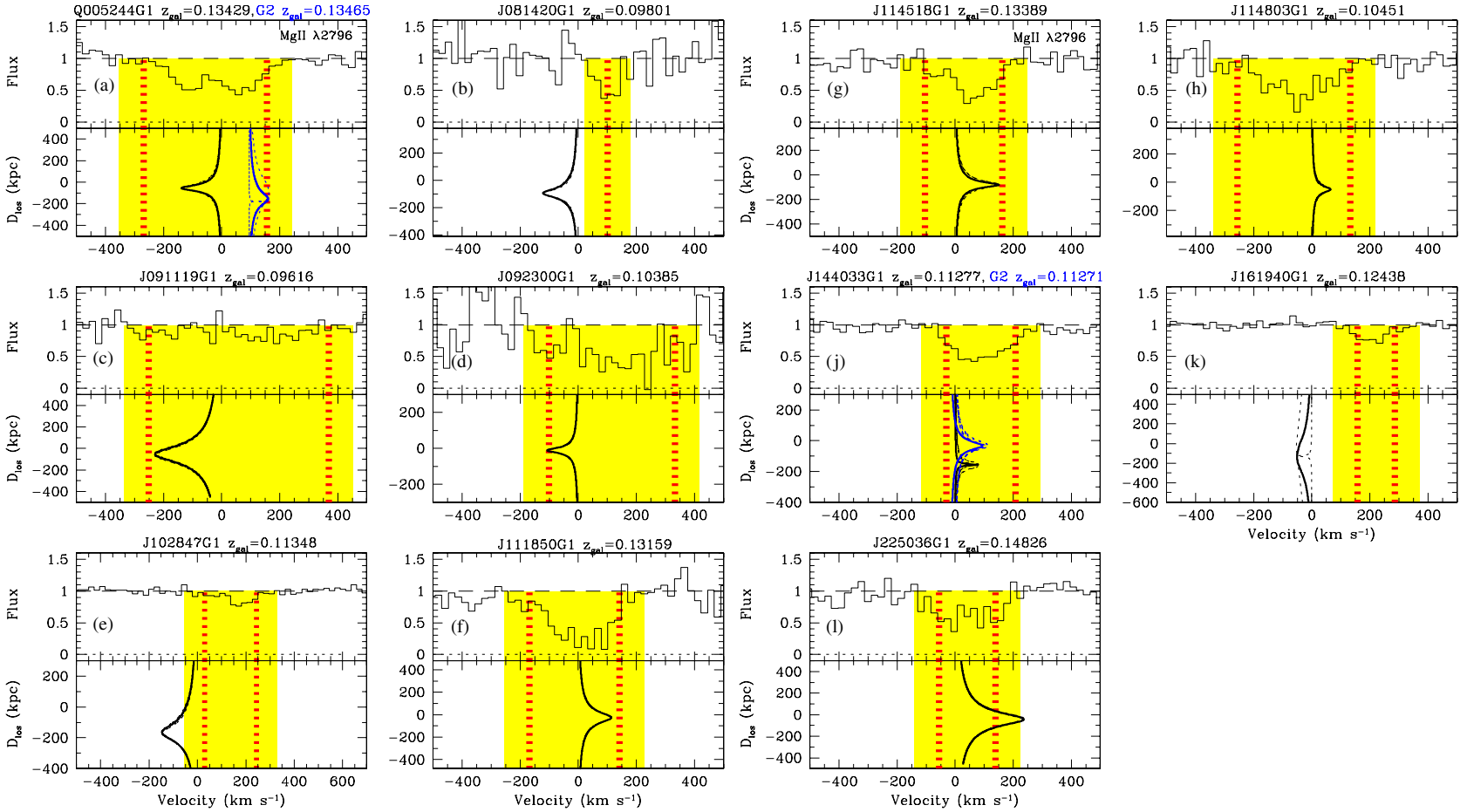


**Figure 8.** (a) The solid line shows an example of a Voigt profile fit to an HIRES/Keck Mg II  $\lambda 2796$  absorption system obtained from Kacprzak et al. (2010b). The histogram data show the high-resolution Voigt profile fit degraded to the resolution typical LRIS/Keck data. The vertical dashed (red) lines indicate the velocity width of the Mg II  $\lambda 2796$  as measured from the HIRES/Keck data and the highlighted region shows the velocity width of the degraded spectrum. (b) The velocity widths of the 26 high-resolution Mg II  $\lambda 2796$  absorption profiles obtained from Kacprzak et al. (2010b, 2010c), as measured from HIRES and UVES spectra (non-degraded), vs. the velocity widths measured from the degraded synthetic LRIS spectra (degraded). We find that the resolution, pixelization, and noise in the observed spectra introduce an average apparent velocity spread increase of  $\sim 170 \text{ km s}^{-1}$  with a scatter of  $\sim 60 \text{ km s}^{-1}$ . (c) The shift in velocity due to the degrading of the spectra from both the blue (min) and red (max) velocity edges (or wings) of the absorption profiles. We find a symmetric shift of  $85 \text{ km s}^{-1}$  with a scatter of  $25 \text{ km s}^{-1}$ .

(A color version of this figure is available in the online journal.)

the Mg II velocity widths (shaded region) are translated into “observed” HIRES or UVES velocity widths as indicated by the vertical dashed lines (red).

Below each absorption profile are the thick-disk–halo model velocities as a function of  $D_{\text{los}}$  derived for each galaxy (solid



**Figure 9.** The Mg II absorption profiles and the disk model velocities as a function of  $D_{\text{los}}$  (solid curve) are shown for each galaxy in the top and bottom panels, respectively. The solid curve is computed using Equation (1) and the values from Table 4. The dashed curves are models computed for the maximum and minimum predicted model velocities given the uncertainties of  $i$  and P.A. The Mg II absorption velocities are shaded in. The thick-disk-halo model is successful at predicting the observed Mg II absorption velocity distribution when the solid (or dashed) curves span the same velocity spread as that of the Mg II absorption gas defined by the shaded region between the vertical dashed (red) lines. The vertical dashed (red) lines are an applied  $85 \text{ km s}^{-1}$  resolution correction such that the LRIS Mg II absorption velocity widths translated into observed HIRES or UVES velocity widths. The thickness of the vertical dashed (red) lines indicates the  $\pm 25 \text{ km s}^{-1}$  uncertainty in the velocity correction.  $D_{\text{los}}$  is equal to zero when the quasar line of sight intersects the projected mid-plane of the galaxy. The panels are as follows: (a) J005244G1 and G2, (b) J081420G1, (c) J091119G1, (d) J092300G1, (e) J102847G1, (f) J111850G1, (g) J114518G1, (h) J114803G1, (i) J144033G1 and G2, (j) J161940G1, and (l) J225036G1.

(A color version of this figure is available in the online journal.)

line) using Equation (1) and parameters in Table 4. Recall that, at  $D_{\text{los}} = 0$  kpc, the model line of sight intersects the projected mid-plane of the galaxy. The dashed curves represent the range of disk–halo model velocities derived from the combination of the minimum and maximum uncertainties in the P.A. and  $i$ . In some cases, the values of the P.A. and  $i$  are well determined such that the dashed curves lie on the solid curves (see Figure 9(b)). The model also predicts the line-of-sight position,  $D_{\text{los}}$ , of the halo gas at each velocity,  $v_{\text{los}}$ .

The thick-disk–halo model is successful at predicting the observed Mg II absorption velocity distribution when the solid (or dashed) curves span the same velocity spread as that of the Mg II absorption gas defined by the shaded region between the vertical dashed (red) lines. If this is not the case, one can conclude that disk-like halo rotation is not the *only* dynamic mechanism responsible for the Mg II kinematics. In the following subsections, we discuss the halo models of the individual galaxies.

#### 4.2.1. J005244G1 & J005244G2

Galaxies G1 and G2 are potentially interacting galaxies, given their close angular proximity and redshifts. G1 is the brightest galaxy of the two and is also the closest to the quasar line of sight. In Figure 9(a), we plot the disk–halo models for G1 and G2. The G1 model has velocities that are consistent with up to  $150 \text{ km s}^{-1}$  of the Mg II blueward of its systemic velocity. There is a  $100 \text{ km s}^{-1}$  gap between the models of G1 and G2. G2 is also counter-rotating with respect to G1 as viewed from the quasar sight line. The G2 model velocities are consistent with the remaining absorption redward of its systemic velocity. Although the disk-like halo model is mostly successful at accounting for some of the absorption velocity, it does not reproduce all of the Mg II absorption velocities.

#### 4.2.2. J081420G1

Galaxy G1 is a low-inclination galaxy with the absorption lining up exactly with one side of the galaxy rotation curve. In Figure 9(b), we show the halo model velocities and the Mg II absorption profile. Note that there is only a single dashed line (red) indicating the corrected velocity width since the profile velocity width is less than the  $\pm 85 \text{ km s}^{-1}$  velocity correction. As we previously mentioned, there is a velocity correction scatter of  $\pm 25 \text{ km s}^{-1}$  and by taking this into account, the Mg II absorption line is likely a very narrow component centered on the dashed line. Regardless, we see that although the absorbing gas is aligned with the rotation curve, it is in the opposite direction expected for disk rotation, i.e., the galaxy is “counter-rotating” with respect to the Mg II absorption.

#### 4.2.3. J091119G1

Galaxy G1 is an edge-on spiral with the quasar line-of-sight probing roughly perpendicular to the galaxy major axis. The Mg II  $\lambda 2796$  spans both sides of the galaxy systemic velocity. In Figure 9(c), the halo model can account for the Mg II absorption blueward of the galaxy systemic velocity. However, the bulk of the Mg II (specifically the  $\lambda 2803$  transition) is redward of the galaxy systemic velocity and is “counter-rotating” with respect to the galaxy’s direction of rotation.

#### 4.2.4. J092300G1

Galaxy G1 is an S0-like galaxy that does not have emission lines but exhibits rotation as measured from the absorption

lines. Since the quasar line of sight probes along the minor axis of the galaxy, if halo rotation was responsible for the absorption kinematics, then one would expect the absorbing gas to have velocities more consistent with the galaxy systemic velocity. In Figure 9(d), we find that the halo model can adequately account for the total velocity spread blueward of the galaxy systemic velocity. However, the model cannot explain  $\sim 300 \text{ km s}^{-1}$  of Mg II absorption detected redward of the galaxy systemic velocity. These high velocities detected along the quasar line sight only 12 kpc away only the major axis may be signatures of outflow or infall. The galaxy does appear to have a separate optical clump/component or satellite seen below the galaxy (along the slit) which may be interacting and causing an infall of metal-enriched gas. We do not have a spectrum of this second object.

#### 4.2.5. J102847G1

The strongest component of the Mg II absorption associated with G1 aligns exactly with its redward maximum rotation. In Figure 9(e), we find that the galaxy is “counter-rotating” with respect to the strongest Mg II component. In fact, the halo model cannot explain the large velocity width of the absorption. The halo model does not well represent the kinematics observed along this quasar line of sight.

#### 4.2.6. J111850G1

The quasar line of sight probes the minor axis of G1 and the absorption spans the entire rotation velocity. In Figure 9(f), we see that disk rotation can account for the bulk of the Mg II that is redward of the galaxy systemic velocity. However, it cannot account for the absorption blueward of the galaxy systemic velocity. Thus, this gas is also “counter-rotating” with respect to the galaxy and is inconsistent with disk rotation.

#### 4.2.7. J114518G1

The quasar line of sight near G1 probes the galaxy major axis with the bulk of the Mg II residing to one side of the galaxy systemic velocity. In Figure 9(g), we find that the disk model can adequately account for the Mg II absorption that has velocities redward of the galaxy systemic velocity along the line of sight. However, the model does not account for a small fraction of the Mg II absorption blueward of the galaxy systemic velocity. Thus, the model can account for the majority of the absorption but cannot explain some of the weaker absorption  $100 \text{ km s}^{-1}$  blueward of the galaxy systemic velocity.

#### 4.2.8. J114803G1

The galaxy G1 exhibits a low-level velocity shear. Given the velocity spread of the Mg II absorption, it is impossible for the bulk of the absorbing gas to be consistent with the observed velocities of G1. In Figure 9(h), we see that the galaxy–disk–halo model is counter-rotating with respect to the bulk of the absorbing gas. There is little overlap between the predicted halo model velocities with those of the Mg II absorption. Even if the galaxy had a highly significant velocity shear, the bulk of the Mg II would not be consistent in velocity space.

#### 4.2.9. J144033G1 and J144033G2

Galaxies G1 and G2 are potentially interacting galaxies, given their close angular proximity and redshifts. G1 is the brightest galaxy of the two, however G2 is much closer to the quasar sight line and is clearly forming stars. In Figure 9(j), we plot the disk–halo models for G1 and G2. The halo models for G1 and



**Table 5**  
Environment within 0.5 Mpc of Mg II Host Galaxy(ies)

Galaxy Name	Companion ID	Companion R.A. (J2000)	Companion Decl. (J2000)	$D$ (kpc)	Mag	$z_{\text{gal}}$	$\Delta v_r$ (km s $^{-1}$ )
J081420G1	...	...	...	...	...	...	...
J102847G1	...	...	...	...	...	...	...
J111850G1	...	...	...	...	...	...	...
J114518G1	...	...	...	...	...	...	...
J114803G1	...	...	...	...	...	...	...
J225036G1	...	...	...	...	...	...	...
J005244G1	G2 <sup>a</sup>	00:52:44.02	−00:56:46.41	32	19.5	$0.13465 \pm 0.00002$	+82.2
J091119G1	G2	09:11:00.97	+03:12:33.61	428	16.5	$0.09705 \pm 0.00005$	−188.7
J144033G1	G2 <sup>a</sup>	14:40:34.56	+04:48:25.10	25	17.2	$0.11271 \pm 0.00001$	+88.8
J161940G1	G2	16:19:39.27	+25:43:33.63	383	17.2	$0.12470 \pm 0.00015$	−82.7
J092300G1	G2	09:22:58.65	+07:52:37.10	187	17.5	$0.10368 \pm 0.00015$	+149.5
	G3	09:23:05.55	+07:47:41.38	408	17.6	$0.10315 \pm 0.00016$	+293.7

**Note.** <sup>a</sup> Companion galaxies identified during our survey and discussed in the text.

G2 cover roughly the same velocity range of 100 km s $^{-1}$  and are rotating in the same direction. Although the model is mostly successful, it fails to predict the absorption at higher velocities between 100 and 200 km s $^{-1}$ .

#### 4.2.10. J161940G1

The galaxy G1 exhibits a low-level velocity shear. In Figure 9(k), we see that the galaxy disk–halo model is “counter-rotating” with respect to the dominant saturated Mg II component. There is no overlap between the predicted halo model velocities with those of the Mg II absorption. Even if the galaxy had a highly significant velocity shear, the bulk of the Mg II clouds would not be consistent in velocity space.

#### 4.2.11. J225036G1

The almost edge-on galaxy G1 has the bulk of the Mg II residing to the redward side of the galaxy systemic velocity. In Figure 9(l), we see that the disk–halo model can account for almost all of the Mg II absorbing gas velocity spread. It does not quite account for the gas blueward of the galaxy systemic velocity, however with the  $\pm 25$  km s $^{-1}$  errors on the corrected absorption line widths (red lines), we can say that the model is likely consistent with the absorption velocities. Thus, a disk-like halo model well represents the absorption kinematics.

#### 4.3. Summary II: Disk–Halo Model

In an effort to reproduce the observed Mg II absorption velocity spread, we have applied a simple disk–halo model to compute the expected absorption velocities. In only one case, J225036G2, we were able to reproduce almost the full Mg II absorption velocity spread with the thick disk model. In four cases, including the two double galaxy systems, the halo rotation model can account for a large fraction of the absorption, however, it still cannot account for all of the absorbing gas velocity spread. In six cases (55%), the model is “counter-rotating” with respect to the bulk of the Mg II absorption. This indicates that gaseous galaxy halos at  $z \sim 0.1$  are likely not co-rotating with their host galaxy.

We emphasize again that our halo model is an extreme case where all of the gas is assumed to rotate at the maximum observed galaxy rotation velocity. Under these unrealistic model parameters, the disk–halo model provides insight into the degree at which rotation kinematics can account for limited regions of the absorption velocity spread. Relaxing these conditions would

significantly diminish the level of agreement between the model and the observed Mg II velocity spread.

The inability for the models to account for all of the halo gas velocity spread and direction suggests that additional dynamical processes are giving rise to some of the Mg II absorption (such as galaxy–galaxy interactions, outflow, infall, or a combination thereof).

### 5. ENVIRONMENT, OUTFLOW, OR INFALL?

There are three likely scenarios that could help produce extended metal-enriched gaseous halos around galaxies: (1) galaxy group environments producing tidal streams and stripped gas from galaxies, (2) outflowing gas from star-forming regions and/or supernovae, and/or active galactic nuclei, and (3) infalling gas from streams, filaments, high-velocity clouds, satellites, and previously ejected gas from outflows. In this section, we attempt to determine if the Mg II halo gas detected in absorption is produced via environmental effects, outflow, or infall.

#### 5.1. Environment

In Table 5, we show additional galaxies spectroscopically identified by SDSS within  $\pm 1000$  km s $^{-1}$  of the Mg II absorption redshift and within 0.5 Mpc (projected) of the quasar sight line. Six of the quasar lines of sight do not have any near neighbors that can be further associated with the absorption. Thus, these six absorption systems appear to arise within isolated galaxy halos.

The remaining five absorption systems have multiple galaxies at a range of impact parameters along the quasar sight lines; two are galaxy pairs identified during our own spectroscopic surveys (J005244G1, G2 and J144033G1, G2). Other than these two less massive satellite galaxies identified here (G2s), there are no other galaxies associated with these absorbers within the limits defined above. For both of these absorbers, we have shown that the galaxies are within the standard Mg II halo size, and their galaxy dynamics are consistent with the absorption velocities. It is possible that, given their close proximity in both projected distance and line-of-sight velocity, they may have undergone some interactions in the past. Although, given the luminosity ratios for these galaxies pairs, both companion galaxies are more consistent with being satellite galaxies within a main galaxy halo.

The remaining 3/5 absorption systems that have multiple galaxies within  $\pm 300$  km s $^{-1}$  of the Mg II absorption redshift

tend to be at much higher impact parameters. The impact parameters range between 190 and 430 kpc: much larger than the standard halo size. Thus, for the most part, these galaxies would appear similar to isolated galaxies.

To further study the environments of these  $z = 0.1$  Mg II absorbing and non-absorbing galaxies, Barton & Cooke (2009) created an artificial redshift survey through cosmological dark matter simulations. They found that Mg II host galaxies appear to reside low-density environments while non-absorbing galaxies seem to reside denser regions and are likely to have companions. They further suggest that non-absorbing galaxies may result from stripping of the outer gas halo as galaxies fall into a denser environment. This truncation of halo sizes may decrease by as much as a factor of 10 when observed in clusters (Padilla et al. 2009). Given that we detected Mg II absorption over a large range of impact parameters and that the host galaxies appear to be in isolated, galaxy environment does not appear to be a strong factor in determining the absorption strength of the halo gas.

In our sample, environment may not play a crucial role in producing the extended metal-enriched galaxy halos. This result is supported by the data as well as mock surveys through cosmological simulations. Although, two of our systems hint that minor interactions occur and likely produce a combination of streams plus an additional source of inflowing gas toward the host galaxy.

### 5.2. Outflows

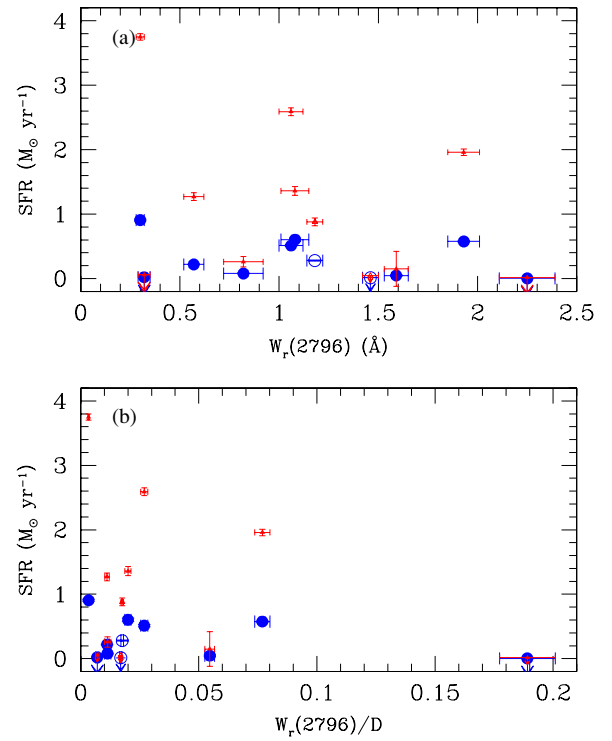
Here we explore evidence of outflows using two techniques: we first compute the host galaxy SFRs and compare them to the halo gas absorption strength. We then compute Mg II (stellar) and Na I D (stellar+ISM) line ratios in order to identify possible outflows.

#### 5.2.1. Star Formation Rates

We have computed SFRs for the host galaxies where possible. We note that the SDSS spectra are obtained using fibers that have an aperture radius of  $1''.5$ , which translates into 2.77 kpc at  $z = 0.10$ . Our galaxies have an average half-light radius, as measured from GIM2D (see Table 4), of  $\langle r_h \rangle = 5.6 \pm 1.3$  kpc, so the SDSS fibers cover only the inner regions of the galaxies. Therefore, SFRs computed here are only within the fiber. This still provides useful information since all galaxies are roughly at the same redshift and therefore probing the same physical scales, and strong winds are expected to originate within the central regions.

For the fiber SFRs we have applied Galactic extinction correction obtained from NED.<sup>5</sup> We are not able to apply Balmer decrement corrections since only two galaxies have detected H $\beta$  emission. The H $\alpha$  luminosities were measured from the SDSS spectra and H $\alpha$ -derived SFRs were computed using the formalism of Kewley et al. (2002). We also performed aperture loss corrections to the SFRs. The applied scaling factor was determined from the ratio of the  $r$ -band galaxy total counts to those within the SDSS fiber.

In Figure 10(a), we show the inner galaxy (fiber) SFRs, and corrected SFRs, as a function of the Mg II absorption strength. We find no correlation between the SFRs and the halo gas absorption strength. A similar distribution arises if one plots H $\alpha$  against  $W_r(2796)$ . Note that some galaxies have only low SFR limits yet are still associated with strong absorption. Given



**Figure 10.** (a) SDSS fiber SFR computed for the absorbing galaxies as a function of  $W_r(2796)$ . The open circles are the two galaxies J005244G1 and J144033G1 that have minor companions. The small (red) triangles are the SDSS aperture-corrected SFRs. Note there is no trend with SFR and galaxies with little star formation are associated with some of the high equivalent width systems. (b) The Mg II equivalent width normalized by impact parameter as a function of SFR. Again, we find no correlation suggest an absence of star formation driven winds.

(A color version of this figure is available in the online journal.)

that Barton & Cooke (2009) noted that red galaxies appear to be closer to the quasar line of sight than blue star-forming galaxies, we normalized out the impact parameter in Figure 10(b): we find no statistically significant trend here.

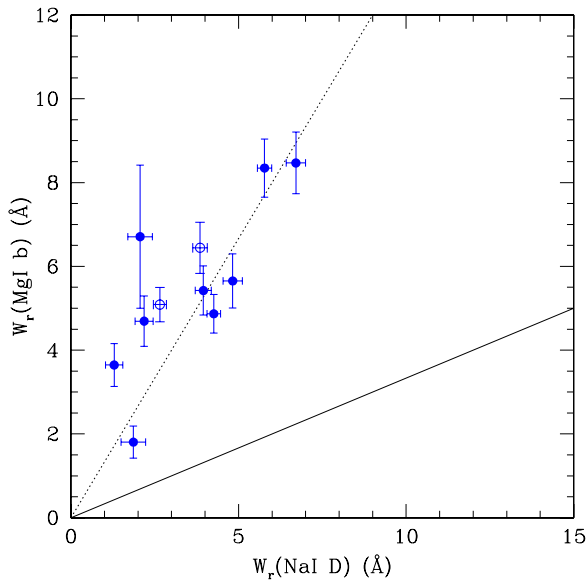
Another indicator of galaxy outflows is the star formation per unit area. Heckman (2002, 2003) demonstrated that outflows are ubiquitous in galaxies where the global SFR per unit area exceeds  $\Sigma = 0.1 M_\odot \text{ yr}^{-1} \text{ kpc}^2$  (the area is defined by the half-light radius). The interstellar medium (ISM) entrained in these winds has outflow speeds of  $\sim 100$  to  $\sim 1000 \text{ km s}^{-1}$ . Although the half-light radii of our galaxies are larger than the SDSS fibers, we can compute the surface star formation density within the SDSS fiber. For our sample, we find that the star formation per unit area of  $0.03 M_\odot \text{ yr}^{-1} \text{ kpc}^2 \leq \Sigma \leq 0.0002 M_\odot \text{ yr}^{-1} \text{ kpc}^2$ , which is well below what is expected for strong winds.

These results possibly suggest that star formation-driven winds, at least in the galaxy central regions, are not producing the observed kinematics and absorption strength of the metal-enriched halo gas. It is possible that the metal-enriched gas detected along the quasar sight lines are potential reservoirs for future star formation.

#### 5.2.2. Na I D and Mg II b Line Ratios

It has been demonstrated that Na I D and Mg II b absorption line ratios are good tracers of outflows. Both Na I D and Mg II b have similar ionization potentials (5.14 eV for Na I D, 7.65 eV for Mg II b). Although both Na I D and Mg II b appear in stellar

<sup>5</sup> <http://nedwww.ipac.caltech.edu/>



**Figure 11.** Equivalent widths of the Na I D (stellar+ISM) and Mg II b (stellar) absorption lines. The open circles are the two galaxies J005244G1 and J144033G1 that have minor companions. The lower solid line is the relation of Rupke et al. (2005a, 2005b) who found that 80% of the galaxies below this line have winds, while only a small fraction above the solid line have winds (25%). The dotted line represents the expected stellar contribution to the Na I D by scaling the equivalent width of Mg II b. Note that our galaxies reside near this relation and far from where winds are expected to dominate.

(A color version of this figure is available in the online journal.)

spectra, where the absorption strength peaks in spectra of cool K–M stars (see Jacoby et al. 1984), the Mg II b band is a highly excited transition making it purely stellar in origin. On the other hand, the Na I D resonance line can also be absorbed by the ISM and has been detected as entrained gas within galactic scale winds (e.g., Martin 2005; Rupke et al. 2005a, 2005b; Heckman et al. 2000). Thus, this line ratio can be used to successfully separate starburst outflowing galaxies from quiescent galaxies with little to no winds (e.g., Heckman et al. 2000).

We have used the Na I D and Mg II b equivalent widths computed by SDSS, as observed in galaxy spectra to study the wind properties of our galaxy sample. Again, we note that the SDSS spectral fibers have an aperture radius of  $1''.5$ , which translates into 2.77 kpc at  $z = 0.10$ , thus the fibers only cover the central regions of the galaxies. The line ratio is only computed within the fiber, however, galactic winds are expected to originate from the centers of galaxies, which is where the wind signature in the line ratio is expected. As one would include more of the galaxy light, from regions where no winds are found, we would expect the wind line ratios to be more consistent with stellar origins.

In Figure 11, we show the Na I D and Mg II b equivalent width distribution. Heckman et al. (2000) estimated the expected stellar contribution to the Na I D, by scaling the equivalent width of Mg II b, and found the relation  $W_r(\text{Na I D}) = 0.75 W_r(\text{Mg II b})$  represented by the dotted line in Figure 11. Galaxies that reside to the right of the solid line are most likely to have contributions from the ISM to the Na I D absorption. The solid line, which is expressed as  $W_r(\text{Na I D}) = 3 W_r(\text{Mg II b})$ , is the approximate location of starbursting galaxies with strong Na I D winds observed by Rupke et al. (2005a, 2005b). They found that 80% of the galaxies below this line have winds, while only a small fraction above the solid line have winds (25%).

All of our galaxies reside far from the relation where winds are expected and reside tightly near the expected stellar contribution

line, suggesting that our galaxy sample has little to no strong winds. Scatter about that line is most likely due to interstellar Na I D absorption.

Another way to detect outflows is to observe velocity offsets between galaxy nebular emission lines and absorption lines. This technique has been applied in previous studies on a range of absorption lines and has been demonstrated to detect strong winds (see Heckman et al. 2000; Rupke et al. 2005b; Weiner et al. 2009; Steidel et al. 2010; Rubin et al. 2010, etc.). Eight of our absorbing galaxies have measurable H $\alpha$  and Na I D lines. Although we have discussed above that Na I D absorption is contaminated by stellar absorption, it can still be used to trace winds from velocity offsets from the emission lines (e.g., Heckman et al. 2000; Rupke et al. 2005b). Furthermore, Heckman et al. (2000) found that galaxies with Na I D absorption residing within  $\pm 70 \text{ km s}^{-1}$  of the systematic galaxy redshift were consistent with a predominantly stellar origin. Na I D absorption blueshifted with velocities greater than  $100 \text{ km s}^{-1}$  was associated with outflows  $\sim 70\%$  of the time. They also found that galaxies with strong outflows were viewed at low inclination angles.

For the eight galaxies in our sample, we find a mean velocity intrinsic Na I D absorption offset of  $\Delta v = -71 \pm 26 \text{ km s}^{-1}$ , consistent with a predominantly stellar origin. However, all galaxies have a negative velocity offset from the H $\alpha$  emission line. This offset may suggest low-level winds, although we find no correlation between the velocity offset and the galaxy SFR, or  $\Sigma$ , as would be expected (Weiner et al. 2009).

The average galaxy inclination angle is  $46^\circ$  which is less than the average expected for a random distribution of galaxies. However, we do not find a significant correlation between the velocity offset and the galaxy inclination or absorption strength.

These results suggest that active outflows are not responsible for the dominant component of the Na I D absorption and are consistent with a stellar component plus some contribution from dynamically cold interstellar gas. The lack of strong outflows close to the galaxy suggests alternate origins of the Mg II halo gas ( $0.3 \text{ \AA} \leq W_r(2796) \leq 2.3 \text{ \AA}$ ).

## 6. DISCUSSION

Kacprzak et al. (2010a) compared Mg II absorption and galaxy rotation kinematics of 10  $W_r(2796) < 1.4 \text{ \AA}$  systems and found that, in most cases, the absorption was fully to one side of the galaxy systemic velocity and usually aligned with one arm of the rotation curve. These results are consistent with earlier studies of five galaxies by Steidel et al. (2002), one galaxy by Ellison et al. (2003), and three galaxies of Chen et al. (2005). In only 5/19 cases, the absorption velocities span both sides of the galaxy systemic velocity. Three of those have  $W_r(2796) > 1 \text{ \AA}$  and their absorption kinematics displayed possible signatures of winds or superbubbles (Bond et al. 2001; Ellison et al. 2003); two of these galaxies have SFRs and SFRs per unit area consistent with wind-dominated galaxies (Kacprzak et al. 2010a).

For our  $z \sim 0.1$  sample, we find that for only 5/13 galaxies the Mg II absorption resides to one side of the galaxy systemic velocity and aligns with one side of the rotation curve. For the remaining 8/13 galaxies, the absorption spans both sides, although the bulk of the Mg II resides mostly to one side of the galaxy systemic velocity.

In comparing the results from  $z \sim 0.5$  to our  $z \sim 0.1$  sample, we find a factor of three increase in the fraction of systems where the Mg II absorption resides on both sides of the galaxy

systemic velocity at lower redshift. These results may suggest an evolution in the halo gas kinematics as a function of redshift. Both samples span a similar range of impact parameters and Mg II equivalent width. Hints that halo gas properties may evolve with redshift have already been observed. Barton & Cooke (2009) found that gas covering fractions may decrease by a factor of 2–3 by  $z = 0.1$ . It is also important to note that the samples of Kacprzak et al. (2010a) and Steidel et al. (2002) have an average  $\langle L_B \rangle = 0.6L_B^*$  whereas our sample has a  $\langle L_B \rangle = 1.9L_B^*$ : in this study, we have probed more massive galaxies at lower redshift. This leads to the possibility that there could be an evolution as a function of host galaxy mass. This is consistent with the cosmological smoothed particle hydrodynamic simulations of Stewart et al. (2010) who predict that the halo gas covering fraction exhibits a sharp decrease when the galaxy mass exceeds a critical minimum mass to form stable shocks which results in a transition from cold mode to hot mode gas accretion. This can reduce the covering fraction, over the same redshifts observed here, by factors of 6–10. It has also been demonstrated that for massive galaxy halos of  $\gtrsim 10^{13} h^{-1} M_\odot$  at  $z \sim 0.5$ , the covering fractions decrease by a factor of 7–15 (Gauthier et al. 2010; Bowen & Chelouche 2011). A more uniform sample is required to explore the possibility of an evolution as a function of mass and/or redshift.

Since the halo gas velocities at intermediate redshift were found to align in the same sense and as velocities expected for co-rotation, it strongly suggests “disk-like” rotation of the halo gas. Both Kacprzak et al. (2010a) and Steidel et al. (2002) applied simple co-rotating disk–halo models and concluded that an extension of the disk rotation was able to explain some of the gas kinematics. However, the models were not able to account for the full absorption velocity spreads.

Here we obtain a similar conclusion, except for one case, all of the observed kinematics velocity spread of the halo gas cannot be explained with a simple rotating disk model. However, contrary to previous studies, for 55% of our sample, the halo model is “counter-rotating” with respect to the bulk of the Mg II absorption, and in two cases, there is zero overlap between the model and the absorption velocities. This suggests that at least some gaseous halos at  $z \sim 0.1$  are not co-rotating with their host galaxies and to a lesser extent than what was found at  $z \sim 0.5$ . Again this implies that other mechanisms must be invoked to account for the full velocity spreads.

In an effort to identify the origins of the Mg II absorption, Kacprzak et al. (2010a) used hydrodynamical cosmological simulations, combined with the quasar absorption line methods, to demonstrate that the majority of the Mg II absorption arises in an array of cosmological structures, such as filaments and tidal streams. They showed that metal-enriched gas was infalling toward the galaxy along these structures with velocities in the range of the rotation velocity of the simulated galaxy and consistent with the observed galaxy halo gas kinematics. In this paper, we have not gone to these efforts to explore the origins of the halo gas, however this will be part of our future work. We have instead chosen to explore the galaxy environment and also physical properties of the host galaxies that are indicative of strong outflows.

The  $z \sim 0.1$  Mg II galaxies appear to be isolated, aside from the two double galaxy systems identified in our own survey. Again, these two pairs are consistent with one dominate host galaxy and a smaller satellite galaxy. Only three host Mg II absorbing galaxies have other nearby galaxies, however they reside far from the quasar line of sight making it unlikely that

they contribute to the absorbing gas. Thus, for our sample, interactions may not play a crucial role in producing the halo gas absorption.

It is well known that highly star-forming galaxies tend to have strong outflows that are also detected in absorption (e.g., Weiner et al. 2009; Martin & Bouché 2009; Nestor et al. 2010). However, for our sample the host galaxy SFRs computed within the SDSS fiber, representing the galaxy central regions, are all less than  $1 M_\odot \text{ yr}^{-1}$ . In addition, we find no correlation between the SFRs and the  $W_r(2796)$  even when normalized by the impact parameter. Heckman (2002, 2003) demonstrated that outflows with speeds of  $\sim 100$  to  $\sim 1000 \text{ km s}^{-1}$  are ubiquitous in galaxies where the global SFR per unit area exceeds  $\Sigma = 0.1 M_\odot \text{ yr}^{-1} \text{ kpc}^2$ . For our sample we find  $\Sigma \leq 0.03 M_\odot \text{ yr}^{-1} \text{ kpc}^2$ , which is well below what is expected for strong winds.

We also find that the Na I D (stellar+ISM) and Mg I b (stellar) absorption line ratios are consistent with being predominately stellar in origin and having kinematically cool ISM. The velocity offsets between the Na I D line and the nebular H $\alpha$  emission line are on average  $-71 \pm 26 \text{ km s}^{-1}$ . Although the shift is in the negative direction, which is associated with outflows, the velocity shifts are small and consistent with little-to-no outflows (Heckman et al. 2000). In addition, the velocity offsets between Na I D and H $\alpha$  do not correlate with SFR or  $\Sigma$ .

Our sample of galaxies appear to be isolated, and undergoing some star formation, but too little to be producing strong outflows. We find it is unlikely that the Mg II gas originates from either environmental effects, such as galaxy–galaxy interactions or mergers, and/or outflowing gas; although accretion of cold gas ejected from previous star formation events is possible. We favor a scenario where the metal-enriched halo gas is infalling onto the host galaxy with velocities comparable to the dynamics of their host.

## 7. CONCLUSIONS

We have examined and compared the detailed galaxy and Mg II absorption kinematics for a sample of 13 intermediate redshift,  $\sim L_*$  galaxies along 11 quasar sight lines. The galaxy–quasar impact parameters range from  $12 \text{ kpc} \leq D \leq 90 \text{ kpc}$ . The galaxy rotation curves were obtained from DIS/APO and ESI/Keck spectra and the Mg II absorption profiles were obtained from LRIS/Keck quasar spectra. In an effort to compare the relative kinematics, we used a disk–halo model to compute the expected absorption velocities through a monolithic gaseous halo model. We further examined the host galaxy environments and also studied the intrinsic host galaxy properties, using them to quantify and identify strong outflows.

Our main results can be summarized as follows.

1. For all 13 galaxies, the velocity of the strongest Mg II absorption component lies in the range of the observed galaxy rotation curve. We find that for the nine isolated galaxy/absorber pairs, seven galaxies have well-defined rotation curves while two galaxies display only shear. In 3/9 cases, the absorption resides to one side of the galaxy systemic velocity and the absorption redshift tends to align with one side of the rotation curve. In the remaining 6/9 cases, the absorption spans both sides of the galaxy systemic velocity, although the bulk of the Mg II resides mostly to one side of the galaxy systemic velocity.

For our double galaxy/absorber pairs, we find that all four galaxies exhibit well-defined rotation curves. In one



case, the absorbing gas spans both sides of both host galaxy systemic velocities. In the other case, the absorbing gas resides to one side of the systemic velocity of both absorbing galaxies.

2. In all cases, the thick disk rotating halo models are unable to reproduce the full spread of observed Mg II absorption velocities. Contrary to previous studies at higher redshifts, for 55% of our sample the halo model is “counter-rotating” with respect to the bulk of the Mg II absorption and in two cases there is zero overlap between the model and the absorption velocities. This potentially suggests that  $z \sim 0.1$  gaseous halos are not co-rotating with their host galaxies and to a lesser extent than what was found at  $z \sim 0.5$ . In this simple scenario, even if some of the absorbing gas arises in a thick disk, there must be dynamical processes (such as infall, outflow, supernovae winds, etc.) that give rise to the remaining Mg II absorption.
3. Host galaxy SFRs are all  $\lesssim 1 M_{\odot} \text{ yr}^{-1}$  and we find no correlation between the SFRs and the  $W_r(2796)$  even when normalized by the impact parameter. Their SFRs per unit area are  $\leq 0.03 M_{\odot} \text{ yr}^{-1} \text{ kpc}^2$ , which is well below the lower limit of  $0.1 M_{\odot} \text{ yr}^{-1} \text{ kpc}^2$  expected for strong winds.
4. We find our absorbing galaxies tend to be isolated, or at least in low-density environments. This is further supported by an analysis of cosmological simulations at  $z \sim 0.1$  performed by Barton & Cooke (2009).
5. The Na I D (stellar+ISM) and Mg I b (stellar) absorption line ratios are consistent with being predominately stellar in origin and having kinematically cool ISM. The velocity offsets between the Na I D line and the nebular H $\alpha$  emission line are on average  $-71 \text{ km s}^{-1}$ . Although the shift is in the negative direction, the velocity shifts are small and are not correlated with SFR or  $\Sigma$ . These results are consistent with our Mg II absorption-selected galaxies having little-to-no outflows.

In our detailed study of 13  $z = 0.1$  absorbers, we find it unlikely that the Mg II gas originates from either outflowing gas and/or environmental effects. These results are consistent with the hydrodynamical simulations of Kacprzak et al. (2010a) where the Mg II gas is inflowing along the streams and filaments with kinematics comparable to the host galaxy. Thus, we favor a scenario of infalling gas that provides a gas reservoir for star formation at these low redshifts.

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