On the radial profile of gas-phase Fe/$\alpha$ ratio around distant galaxies

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ABSTRACT

This paper presents a study of the chemical compositions in cool gas around a sample of 27 intermediate-redshift galaxies. The sample comprises 13 massive quiescent galaxies at $z = 0.40 - 0.73$ probed by QSO sightlines at projected distances $d = 3 - 400$ kpc, and 14 star-forming galaxies at $z = 0.10 - 1.24$ probed by QSO sightlines at $d = 8 - 163$ kpc. The main goal of this study is to examine the radial profiles of the gas-phase Fe/$\alpha$ ratio in galaxy halos based on the observed Fe II to Mg II column density ratios. Because Mg$^+$ and Fe$^+$ share similar ionization potentials, the relative ionization correction is small in moderately ionized gas and the observed ionic abundance ratio $N$(Fe II)/$N$(Mg II) places a lower limit to the underlying (Fe/Mg) elemental abundance ratio. For quiescent galaxies, a median and dispersion of $\log \langle N$(Fe II)/$N$(Mg II) $\rangle_{\text{med}} = -0.06 \pm 0.15$ is found at $d < \sim 60$ kpc, which declines to $\log \langle N$(Fe II)/$N$(Mg II) $\rangle_{\text{med}} < -0.3$ at $d > \sim 100$ kpc. On the other hand, star-forming galaxies exhibit $\log \langle N$(Fe II)/$N$(Mg II) $\rangle = -0.25 \pm 0.21$ at $d < \sim 60$ kpc and $\log \langle N$(Fe II)/$N$(Mg II) $\rangle = -0.9 \pm 0.4$ at larger distances. Including possible differential dust depletion or ionization correction would only increase the inferred (Fe/Mg) ratio. The observed $N$(Fe II)/$N$(Mg II) implies super-solar Fe/$\alpha$ ratios in the inner halo of quiescent galaxies. An enhanced Fe abundance indicates a substantial contribution by Type Ia supernovae in the chemical enrichment, which is at least comparable to what is observed in the solar neighborhood or in intracluster media but differs from young star-forming regions. In the outer halos of quiescent galaxies and in halos around star-forming galaxy, however, the observed $N$(Fe II)/$N$(Mg II) is consistent with an $\alpha$-element enhanced enrichment pattern, suggesting a core-collapse supernovae dominated enrichment history.

Key words: galaxies:haloes – galaxies:elliptical and lenticular, cD – quasars:absorption lines – galaxies: abundances

1 INTRODUCTION

The presence of chemically-enriched gas out to large projected distances $d \sim 100$ kpc from galaxies is commonly attributed to super-galactic winds in starburst galaxies (e.g., Murray et al. 2011; Booth et al. 2013, Borthakur et al. 2013). However, the presence of chemically-enriched cool gas around quiescent galaxies both in the local universe and at high redshifts (e.g., Young et al. 2011; Gauthier & Chen 2011; Zhu et al. 2014; Huang et al. 2016) is difficult to reconcile on the basis of a simple outflow model. Because of a lack of intense star formation for $\lesssim 1$ Gyrs in these quiescent galaxies, additional mechanisms beyond super-galactic winds are clearly needed to explain the presence of chemically enriched gas around galaxies. While tidal interactions and ram pressure force can work to remove interstellar gas of satellite galaxies and fill the halo around the primary galaxy (e.g., Wang 1993; Agertz et al. 2009; Gauthier 2013), without a continuing feedback mechanism the gas is expected to cool and trigger new generations of star formation in the center of the galaxy (e.g., Conroy et al. 2015).

In a recent study, Zahedy et al. (2016) investigated the cool gas content around three lensing galaxies at redshift
dependence in Fe/\alpha systems is locally enriched by SNe Ia, then a radial profile describing the stellar light distribution of the galaxy resembles the same S´ersic profile. SNe in early-type galaxies appear to follow the same S´ersic profile. It has been found that the radial distribution of the rate of Type Ia SNe-dominated feedback in quiescent galaxies. It has been found that the radial distribution of the rate of Type Ia SNe-dominated feedback in quiescent galaxies. This expanded sample allows us to examine the radial profiles of the gas-phase Fe/\alpha ratio in galaxy halos based on the observed N(FeII)/N(MgII).

This paper is organized as follows. Section 2 presents the QSO-galaxy pair sample, as well as the QSO spectroscopic data and corresponding data reduction. The absorption-line measurements are presented in Section 3, and the observed absorption-line properties as a function of projected distance from passive and star-forming galaxies are presented in Section 4. Finally, a discussion of the implications is presented in Section 5. Throughout this paper, a \Lambda cosmology of \Omega_M = 0.3 and \Omega_\Lambda \approx 0.7, with a Hubble constant of \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is adopted.

2 OBSERVATIONAL DATA

A sample of 27 intermediate-redshift galaxies is assembled for investigating the radial profiles of the gas-phase Fe/\alpha ratio in galaxy halos. This galaxy sample comprises 13 passive galaxies at \( z = 0.40 - 0.73 \) and 14 star-forming galaxies at \( z = 0.10 - 1.24 \) from a combination of a literature search and our own observations. These galaxies are probed by background QSO sightlines over a range of projected distances, from \( d \approx 3 \text{ kpc} \) to \( d \approx 400 \text{ kpc} \) for the subsample of passive galaxies and from \( d \approx 8 \text{ kpc} \) to \( d \approx 160 \text{ kpc} \) for the subsample of star-forming galaxies. Here we describe the assembly of the galaxy sample, and associated echelle spectroscopy of the background QSOs.

2.1 Absorbing Galaxy Sample

We first performed a literature search of intermediate-redshift galaxies that are associated with known MgII absorbers and have high-resolution echelle absorption spectra. This allows us to identify the background QSOs available in the public data archives. Our search resulted in 16 MgII absorbing galaxies at redshifts \( 0.10 \leq z \leq 0.95 \) in 10 QSO fields: PKS0122−0021, PKS0349−1438, PKS0439−433, PKS0454−2203, Q1148+387, Q1241+176, PKS1354+1933, PKS1424−1150, 3C336, and Q2206−199. A number of studies have previously investigated the photometric and spectroscopic properties of these absorbing galaxies (e.g., Steidel et al. 1997, 2002; Chen et al. 1998, 2001, 2005, 2008; Kacprzak et al. 2010, 2011), based on high-resolution Hubble Space Telescope (HST) imaging and deep ground-based spectroscopic observations. We utilized these studies to classify the selected galaxies into two subsamples: star-forming and passive galaxies. Star-forming galaxies are classified based on an emission-line dominated spectrum or a disk-dominated light profile (disk-to-bulge light ratios > 3, e.g., Chen et al. 1998) when the galaxy spectrum is not available. Passive galaxies are classified based on an absorption-line dominated spectrum and a bulge-dominated light profile (disk-to-bulge light ratios of < 3). Following these criteria, 13 galaxies are classified as star-forming galaxies, whereas 3 galaxies are classified as passive galaxies. In addition to these previously known MgII-absorbing galaxies, we included a
newly identified $z_{gal} = 1.248$ star-forming galaxy at $d = 17$ kpc from the QSO SDSSJ1430+0141, where an ultra-strong Mg II absorber of rest-frame absorption equivalent width $W_{(2796)} \approx 2.8$ Å had been identified at the same redshift (e.g., Zych et al. 2009).

To increase the number of passive galaxies in our sample, we included Luminous Red Galaxies (LRGs) at $z \approx 0.5$ with associated Mg II absorption features from Gauthier & Chen (2011). We further supplemented this passive galaxy subsample with new, unpublished Mg II-absorbing LRGs from our own survey. Together with two massive lensing galaxies with associated Mg II absorption from Zahedy et al. (2016), this process resulted in 10 additional passive galaxies with associated Mg II absorption from Zahedy et al. (2011). We further supplemented this passive galaxy sample with two massive lensing galaxies with associated Mg II absorption from Zahedy et al. (2016), where an ultra-strong Mg II absorber of rest-frame absorption equivalent width $W_{(2796)} \approx 2.8$ Å had been identified at the same redshift (e.g., Zych et al. 2009).

### Table 1. Summary of galaxy and absorption properties

| QSO | RA (2000) | Dec (2000) | Epoch | Ref. | L_2/L_1 | d (kpc) | $W_{(2796)}$ (Å) | $N_{	ext{MgII}}$ (FeII) | $N_{	ext{MgII}}$ (SiII) | $N_{	ext{MgII}}$ (SiII) | $N_{	ext{MgII}}$ (SiII) | $N_{	ext{MgII}}$ (SiII) |
|-----|-----------|------------|-------|------|---------|--------|------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| PKS 0222-0021 | 00:25:27.67 | -00:05:31.44 | 0.385 | M15 | 1.8 | 0.34 | 12.74 | 11.92 | 15.2 ± 2.5 |
| PKS 0328-125 | 03:28:36 | -00:05:54.26 | 0.941 | M15 | 1.8 | 0.12 | 12.00 | 10.89 | 15.0 ± 1.1 |
| PKS 0410-1438 | 04:15:27.00 | -14:28:58.82 | 0.67 | C98 | 0.6 | 0.21 | 11.07 | 10.58 | 15.1 ± 1.0 |
| PKS 0419-439 | 04:11:17.42 | -43:13:40.11 | 0.49 | C98 | 0.4 | 0.10 | 13.49 | 11.18 | 15.2 ± 0.7 |
| PKS 0454-2203 | 04:56:08.92 | -21:59:27.00 | 0.85 | K10 | 1.4 | 108 | 13.74 | 11.08 | 15.2 ± 0.6 |
| Q1414+367 | 14:11:56.25 | +38:25:56.54 | 0.55 | S10 | 0.2 | 23 | 14.35 | >11.80 | 15.2 ± 0.3 |
| Q1452+0487 | 14:52:19.51 | +04:19:53.15 | 0.55 | S10 | 0.2 | 55 | 14.73 | >11.28 | 15.2 ± 0.2 |
| Q1424-1150 | 14:24:39.81 | -12:33:09.30 | 0.48 | M15 | 0.6 | 0.60 | 11.07 | 10.25 | 15.2 ± 0.1 |
| Q1430+0491 | 14:30:40.71 | +04:40:49.80 | 1.21 | Z98 | 0.8 | 27 | 13.73 | >11.08 | 15.2 ± 0.0 |
| 3C336 | 16:24:38.19 | +23:45:25.02 | 0.70 | S97 | 1.2 | 30 | 13.52 | >11.70 | 15.2 ± 0.0 |
| Q2006--199 | 22:08:55.15 | -19:45:52.94 | 0.48 | S10 | 2.1 | 87 | 14.47 | >11.50 | 15.2 ± 0.0 |

| Notes |
|------|
| The quoted uncertainty in $log(N$(FeII)/$N$(SiII)) (Column 12) for each system is the dispersion from the weighted mean, which represents the scatter in $N$(FeII)/$N$(SiII) among individual components of the corresponding absorber. |
| The error is estimated by propagating the statistical errors for log $N$(FeII)/$N$(SiII) and $N$(SiII), and the uncertainty in the adopted (Mg/S) ratio from Asplund et al. 2009; see Table 2. |

#### 2.2 QSO Absorption Spectroscopy

High-resolution echelle spectra of the QSOs PKS 0349–1438, PKS 1421–1150, SDSS J1430+0149, 3C366, and Q2206–199 were obtained using the Ultraviolet and Visual Echelle Spectrograph (UVES; D’Odorico et al. 2000) on the VLT-UT2 telescope under multiple observing programs (PIDs 076A-0860(A), 075A-0841(A), 079A-0656(A), 081A-0478(A), 69A-0371(A), and 65O-0158(A), respectively). We retrieved the reduced and order-combined individual exposures from the ESO Advanced Data Products Archive. Following data retrieval, we performed vacuum and heliocentric corrections to the QSO spectra, co-added different exposures, and performed continuum fitting to the data. The resulting spectra typically have a high signal-to-noise ratio of $S/N > 15$ per resolution element of 7 – 8 km s$^{-1}$ in full-width-at-half-maximum (FWHM).
between October 2007 and April 2015. A 1″ slit and 2×2 binning were employed for the observations of PKS 0122–0021, PKS 0349–1438, PKS 0454–2203, SDSSJ1144–0714, SDSSJ1422+0414, SDSSJ1506+0419, SDSSJ2116–0624, and SDSSJ2324–0951. A 0.7″ slit and 2×2 binning were employed for the observations of SDSSJ1146+0207, and a 0.7″ slit and 3×3 binning were employed for the observations of SDSSJ1025+0349. MgII delivers spectral resolutions of FWHM ~ 12 km s\(^{-1}\) and 8 km s\(^{-1}\) for the 1.0″ and 0.7″ slits, respectively. The spectra were reduced using a custom data reduction pipeline previously described in Chen et al. (2014) and Zahedy et al. (2016). The final combined spectra are characterized by S/N > 10 per resolution element at λ > 3500 Å. Finally, details of the data reduction for the echelle spectroscopy of the two lensed QSO systems HE0047–1756 (MIKE) and HE1104–1805 (UVES and Keck HIRES) have previously been described in Zahedy et al. (2016). A journal of the echelle spectroscopic observations of the QSO sightlines in our study is shown in Table 2.

3 ABSORPTION LINE ANALYSIS

The high-resolution echelle spectra of the QSOs described in §2 enable accurate constraints on both the integrated rest-frame MgII absorption equivalent width \(W_c(2796)\) and the ionic column densities of Fe\(^{+}\), Mg\(^{2+}\), and Mg\(^{+}\) for each galaxy in our sample. In particular, a component-by-component analysis allows us to examine how the relative abundance ratios between any two ions vary within individual galaxy halos and across the full sample (e.g., Zahedy et al. 2016). We employ a custom software, previously developed by and described in Zahedy et al. (2016), to perform a Voigt profile fitting analysis for constraining the MgII, MgI, and FeII column densities of individual absorbing components. We perform a simultaneous fit to prominent absorption transitions, including the MgII λλ 2796, 2803 doublet, MgI λ 2852, and a series of FeII transitions. For all galaxies, FeII λ 2600 and FeII λ 2586 transitions are included in the Voigt profile analysis. For galaxies at \(z > 0.5\), additional FeII λ 2382, FeII λ 2374, and FeII λ 2344 transitions are included.

For individual MgII absorbing components with no corresponding FeII or MgI absorption, we measure a 2–σ upper limit in the absorption equivalent width of the strongest transitions using the error spectrum. The upper limits are evaluated over a spectral window twice the FWHM of the corresponding MgII component. The measured 2–σ equivalent width limits are then converted to 2–σ upper limits of the component column densities under an optically-thin assumption. For saturated MgII absorbing components, we place 2–σ lower limits of the component column densities based on a grid search of the \(x^2\) values from the Voigt profile fitting results.

In five cases, we cannot measure the MgII absorption strength directly either due to missing echelle spectra in the public archives or a lack of spectral coverage for the relevant transitions. Three of these systems are identified along QSO sightlines Q1241+176 and Q1148+387. The observed \(W_c(2796)\) and total FeII, MgII, and MgI column density measurements for these systems have been published in Churchill et al. (2000) and Churchill & Vogt (2001). We adopt these values for our subsequent analysis. In addition, the galaxy at \(z = 0.101\) in the field of PKS 0439–433 does not have MgII absorption spectra available. The MgII absorber associated with the galaxy at \(z = 1.24\) in the field of SDSSJ 1430+0549 is heavily saturated, and no useful constraint for the MgII absorption column density is available. Finally, two lensing galaxies have been published in Zahedy et al. (2016). Excluding these galaxies leads to 20 galaxies for which we can perform our own Voigt profile analysis. The results of the component-by-component Voigt profile analysis of MgII, MgI, and FeII absorption for these 20 galaxies are presented in Figure 1.

For the galaxy at \(z = 0.101\) and \(d = 8\) kpc from PKS 0439–433, a damped Lyman \(\alpha\) (DLA) absorption feature is found in the QSO spectrum. Measurement of the total FeII column density, \(N_{\text{FeII}}\), is based on far-ultraviolet transitions observed using the Cosmic Origins Spectrograph (COS; Green et al. 2012) on board HST. We adopt \(\log N_{\text{FeII}} = 14.92 \pm 0.03\) from Som et al. (2015). Furthermore, because no MgII column density measurement is available for this galaxy, we infer the total MgII column density, \(N_{\text{MgII}}\), from the reported total column density of another \(\alpha\)-element ion \(S^+\). For this DLA, Som et al. (2015) measured \(\log N_{\text{tot}}(\text{SII}) = 15.03 \pm 0.03\). We assume a solar elemental abundance pattern of \(\log (\text{Mg}/\text{S})_{\odot} = 0.5\) dex (Asplund et al. 2009) for this system, motivated by the observed near-solar metallicity of the DLA (e.g., Chen et al. 2005; Som et al. 2015). To investigate the ionization correction between the elemental ratio \((\text{Mg}/\text{S})\) and the observed ionic ratio \(N_{\text{FeII}}/N_{\text{MgII}}\), we perform photoionization calculations using CLOUDY (Ferland et al. 2013; v.13.03) for a \(T = 10^4\) K cloud with neutral hydrogen column density and metallicity reported for this system (\(\log N(\text{HI}) = 19.63; [\text{S}\text/H] = 0.1\)). We assume a plane-parallel geometry for the gas cloud, which is illuminated on both sides with an updated Haardt & Madau (2001) ionizing radiation field (HM05 in CLOUDY) at \(z = 0.1\). Using the photoionization model and applying \(N_{\text{FeII}}/N_{\text{MgII}}\) of the absorbing gas for constraining the mean ionization parameter, we find that the ionization correction is negligible.
Figure 1. Summary of the component-by-component Voigt profile analysis of Mg II, Mg I, and Fe II absorption for 20 galaxies that have not been published previously. For each galaxy, the observed absorption files of the Mg II doublet, Mg I $\lambda$2852, and Fe II $\lambda$2600 are presented from top to bottom panels. In each panel, the absorption spectra and corresponding 1-$\sigma$ error array are shown in black and cyan, respectively. The best-fit Voigt profile is shown in red. Contaminating features have been dotted out for clarity. The centroid of each absorbing component is marked by a blue tick mark at the top of each panel. Zero velocity corresponds to the systemic redshift of the absorbing galaxy. Galaxy projected distance is indicated at the top of each four-panel block. Finally, the red outlining box encloses passive galaxies and blue includes star-forming galaxies.
Figures 2. Rest-frame Mg II absorption equivalent width $W_r(2796)$ versus galaxy projected distance $d$ for the galaxy sample in this study. Circles represent passive galaxies, while stars represent star-forming galaxies. The color of each data point represents the total Fe II column density, log $N_{\text{tot}}$(Fe II) of the absorption system associated with each galaxy. Greyed out data points mark absorption systems with no constraints on the mean Fe II/Mg II ratio (see Figure 4 below) due to saturation (three galaxies) and poor signal-to-noise ratio (one galaxy). We note that the Mg II doublet falls outside the observable window for galaxies and poor signal-to-noise ratio (one galaxy). We note that the Mg II doublet falls outside the observable window for PKS 0439−433 and thus is not plotted here (see also § 3 for a detailed discussion on this system).

\[
\frac{\text{Fe II}}{\text{Mg II}} = 15.51 \pm 0.06, \text{ where the error is estimated by propagating the statistical error for log} N_{\text{tot}} \text{and the uncertainty in the adopted (Mg/S) ratio from Asplund et al. 2009.}
\]

For the galaxy at $z = 1.2418$ and $d = 17$ kpc from SDSS J1430+0149, the Mg II absorption line is heavily saturated. We infer $N_{\text{tot}}$(Mg II) from the absorption strength of the weaker and non-saturated Si II $\lambda$ 1808 transition also recorded in the public UVES spectra. A Voigt profile analysis returns a best-fit integrated log $N_{\text{tot}}$(Si II) = 15.75 ± 0.05, which is consistent with the published value in Zych et al. (2009). We adopt a solar elemental abundance ratio of log $(\text{Mg/Fe}) = 0.1$ dex for this system, which is consistent with what has been observed for a number of $z > 1$ DLAs (e.g., Dessauges-Zavadsky et al. 2006). The ionization correction between (Mg/Si) and ionic ratio $N_{\text{tot}}$(Mg II)/$N_{\text{tot}}$(Si II) is estimated using a CLOUDY photoionization model for a plane-parallel cloud with 0.1 solar metallicity and log $N$(H II) = 19.5, which is illuminated on both sides with the HM05 radiation field at $z = 1.24$. Using the model output and the observed $N_{\text{tot}}$(Mg I)/$N_{\text{tot}}$(Si II) ratio, we estimate $N_{\text{tot}}$(Mg II)/$N_{\text{tot}}$(Si II) = 0.44 × $N$(Mg)/$N$(Si) for this system and infer log $N_{\text{tot}}$(Mg II) = 15.48 ± 0.07, where the error is estimated by propagating the statistical error for log $N_{\text{tot}}$(Si II) and the uncertainty in the adopted (Mg/Si) ratio from Asplund et al. 2009.

The results of the absorption-line analysis are summarized in Columns 8 through 11 of Table 1, which present $W_r(2796)$ and the total column densities of Fe II, Mg II, and Mg I absorption, log $N_{\text{tot}}$(Fe II), log $N_{\text{tot}}$(Mg II), and log $N_{\text{tot}}$(Mg I), summed over all individual components.

Figure 3. Observed Fe II to Mg II column density ratios versus Fe II column density for individual components associated with passive (circles in the top panel) and star-forming (star symbols in the bottom panel) galaxies in this study. Error bars associated with each data point show the measurement uncertainties. The color of each data point represents the projected distance $d$ of the absorbing galaxy. Saturated components associated with galaxies with poor constraints on the mean Fe II/Mg II ratio (see Figure 4 below) are greyed out. Both lensing galaxies in the passive subsample exhibit strong Mg II absorption at $d < 10$ kpc. The absorbers are resolved into 8−15 components and show pre-dominantly Fe-rich gas (Zahedy et al. 2016). Components associated with these lensing galaxies are shown in pale red to be separated from non-lensing galaxies at $d > 10$ kpc in the top panel. In both panels, when a Mg II absorbing component has no corresponding Fe II absorption detected, it is shown as downward and left-pointing arrows with the data point indicating the 2-$\sigma$ upper limit on $N$(Fe II). In addition, when Mg II components are saturated, the inferred 2-$\sigma$ lower limit on $N$(Mg II) directly translates to a 2-$\sigma$ upper limit on $N$(Fe II)/$N$(Mg II). The dotted horizontal line indicates the solar (Fe/Mg) abundance pattern from Asplund et al. (2009), log $(\text{Fe/Mg}) = −0.10$, to guide visual comparisons.

Upper limits of the total column densities indicate non-detections, whereas lower limits indicate saturated absorption. The typical uncertainty in the total integrated column densities is smaller than 0.05 dex for all absorption systems.

The general absorption properties of the galaxy sample are summarized by the radial profile of Mg II absorption in Figure 2, which displays the observed $W_r(2796)$ versus...
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Projected distance \( d \) for all galaxies in the sample where \( W_r(2796) \) measurements are available. The data points are color-coded according to \( N_{\text{tot}}(\text{Fe II}) \) associated with each galaxy. Absorption systems with poor constraints on the \( N(\text{Fe II})/N(\text{Mg II}) \) ratio due to either saturation or low signal-to-noise ratios are shown in grey (see below). With the exception of two passive galaxies at \( d > 100 \) kpc which exhibit saturated Mg II absorption features, the Mg II absorbing gas around the galaxies in our sample follow a similar declining trend of \( W_r(2796) \) with increasing \( d \) as presented in Chen et al. (2010) and Nielsen et al. (2013). In addition, the observed \( N(\text{Fe II}) \) also appears to decline with increasing \( d \).

To examine the relative Fe to Mg abundance pattern, we present in Figure 3 the Fe II to Mg II column density ratio, \( N(\text{Fe II})/N(\text{Mg II}) \), versus Fe II column density, \( N(\text{Fe II}) \), for individual absorbing components associated with passive (circles in the top panel) and star-forming (star symbols in the bottom panel) galaxies. The data points are color-coded by the projected distances of the absorbing galaxies, and components associated with the two lensing galaxies (both passive) at \( d < 10 \) kpc are shown in red to be separated from absorbing components found at \( d > 10 \) kpc from non-lensing galaxies. When Fe II absorption is not detected or when Mg II components are saturated, a 2-σ limit is placed on \( N(\text{Fe II})/N(\text{Mg II}) \). For heavily saturated Mg II components, no sensitive constraints can be obtained. These components are shown in grey.

Two interesting features are seen in Figure 3. First, passive galaxies (including both lensing and non-lensing galaxies) display a large fraction (>50%) of Fe II-rich gas at \( d < 100 \) kpc (data points with colors red through green) with \( \log N(\text{Fe II})/N(\text{Mg II}) > -0.1 \) dex. At larger distances, \( d > 100 \) kpc, only five components associated with two passive galaxies show predominantly Fe II-rich content and the remaining 33 components are consistent with Mg II-rich gas with \( \log N(\text{Fe II})/N(\text{Mg II}) \lesssim -0.1 \) dex (data points with colors blue through magenta). Secondly, the majority of absorbing components associated with star-forming galaxies are consistent with an Mg II-rich content with \( \log N(\text{Fe II})/N(\text{Mg II}) \lesssim -0.1 \) dex over the full projected distance range probed by the sample. Only three out of 43 non-saturated components display \( \log N(\text{Fe II})/N(\text{Mg II}) > -0.1 \) dex.

\section{The radial profile of \( N(\text{Fe II})/N(\text{Mg II}) \) in galaxy halos}

Figure 3 suggests that \( N(\text{Fe II})/N(\text{Mg II}) \) in galaxy halos depends on both the projected distance and star formation history of the absorbing galaxy. To better quantify how the observed \( N(\text{Fe II})/N(\text{Mg II}) \) ratio depends on galaxy properties, we compute a \( N(\text{Mg II}) \)-weighted mean Fe II to Mg II column density ratio for each absorption system according to the following equation,

\[
\log \left( \frac{N(\text{Fe II})}{N(\text{Mg II})} \right) = \log \sum_i w_i \frac{N_i(\text{Fe II})}{N_i(\text{Mg II})} = \log N_{\text{tot}}(\text{Fe II}) - \log N_{\text{tot}}(\text{Mg II}), \tag{1}
\]

where \( w_i = N_i(\text{Mg II})/N_{\text{tot}}(\text{Mg II}) \) for component \( i \), and \( \log N_{\text{tot}}(\text{Fe II}) \) and \( \log N_{\text{tot}}(\text{Mg II}) \) are the total column densities of Fe II and Mg II, respectively, summed over all individual absorbing components in a given system. The mean \( N(\text{Fe II})/N(\text{Mg II}) \) ratio for each absorption system is presented in Column 11 of Table 1. The quoted uncertainty in \( \log (N(\text{Fe II})/N(\text{Mg II})) \) for each system is the dispersion from the weighted mean, which represents the scatter in Fe II to Mg II column density ratio among individual components of the corresponding absorber.

Figure 4 displays \( N(\text{Fe II})/N(\text{Mg II}) \) versus \( d \) for passive (red circles) and star-forming (blue stars) galaxies. Three galaxies exhibit heavily saturated Mg II absorbers: (1) the passive galaxy at \( z = 0.5437 \) and at \( d = 74 \) kpc from SDSSJ1146+0207; (2) the passive galaxy at \( z = 0.465 \) and at \( d = 166 \) kpc from SDSSJ1025+0349; and (3) the star-forming galaxy at \( z = 0.892 \) and at \( d = 23 \) kpc from 3C336. No meaningful constraints for \( N(\text{Fe II})/N(\text{Mg II}) \) can be obtained for these absorbers. In addition, the star-forming galaxy at \( z = 0.3404 \) and at \( d = 85 \) kpc from PKS 1424–1150 exhibit only a weak Mg II absorber and Fe II absorption is not detected. The available absorption spectra do not place a sensitive constraint for \( N(\text{Fe II})/N(\text{Mg II}) \). All four galaxies are greyed out in Figure 4 for clarity. Considering only galaxies for which measurements of (or

\[ \text{Figure 4. Mean Fe II to Mg II column density ratio, } (N(\text{Fe II})/N(\text{Mg II})), \text{ from Equation (1) versus galaxy projected distance, } d, \text{ for absorbers associated with passive galaxies (red circles) and for those associated with star-forming galaxies (blue stars). Error bars for each data point represent the dispersion among individual component Fe II to Mg II ratios of the corresponding absorber. As shown in Figure 3, only 2-σ upper limits can be placed on } N(\text{Fe II})/N(\text{Mg II}), \text{ if Fe II absorption is not detected or if Mg II components are saturated. These upper limits are propagated into the estimates of } N(\text{Fe II})/N(\text{Mg II}), \text{ for both passive and star-forming galaxies and are indicated as downward arrows. Four galaxies do not have sensitive constraints for } (N(\text{Fe II})/N(\text{Mg II})), \text{ either due to heavily saturated Mg II absorbers or absence of a strong limit on the Fe II absorption. These data points are greyed out for clarity. Following Figure 3, the dotted horizontal line indicates the solar (Fe/Mg) abundance pattern, for visual comparisons. Two interesting features are evident: (1) passive galaxies exhibit on average higher \( (N(\text{Fe II})/N(\text{Mg II})) \) than star-forming galaxies; and (2) \( (N(\text{Fe II})/N(\text{Mg II})) \) appears to show a mild declining trend toward larger } d \text{ for both passive and star-forming subsamples.} \]
strong constraints for \( \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle \) are available, it is clear that passive galaxies exhibit on average higher \( \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle \) than star-forming galaxies. In addition, \( \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle \) appears to show a mild declining trend toward larger \( d \) for both passive and star-forming subsamples.

To further examine the dependence of \( N(\text{Fe}II)/N(\text{Mg}II) \) on galaxy projected distance \( d \), we divide each of the passive and star-forming subsamples into low- and high-\( d \) subsamples. The adopted bin size in \( d \) is determined so that there are roughly equal number of galaxies (five to seven galaxies) in each subsample. We then compute the median value \( \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} \) in each bin as well as the dispersion of each subsample around the median value. Saturated absorption systems are excluded from this exercise, because no constraints on \( N(\text{Fe}II)/N(\text{Mg}II) \) can be derived either due to heavily saturated MgII absorption or insufficient limits on \( N(\text{Fe}II)/N(\text{Mg}II) \) (see Column 12 of Table 1). In addition, for passive galaxies at \( d \geq 100 \) kpc two of the seven galaxies have only a relatively strong upper limit at \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle \approx -0.3 \). For this subsample, we infer a 85% upper limit for the underlying distribution of \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} < -0.3 \). The results are presented in Figure 5 for passive galaxies (red circles) and star-forming galaxies (blue stars).

Figure 5 shows that \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} \) declines with increasing \( d \), from \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} = -0.06 \pm 0.15 \) at \( d < 60 \) kpc to \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} < -0.3 \) at \( d > 100 \) kpc. For star-forming galaxies, a similar declining trend is found with increasing \( d \), from \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} = -0.25 \pm 0.21 \) at \( d < 44 \) kpc to \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} = -0.91 \pm 0.44 \) at \( d > 70 \) kpc. Furthermore, while \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} \) is about 0.21 dex higher in the inner halos (\( d \leq 60 \) kpc) of passive galaxies than those around star-forming ones, both galaxy populations display a comparable \( \log \langle N(\text{Fe}II)/N(\text{Mg}II) \rangle_{\text{med}} \) in the outer halos.

5 DISCUSSION

A primary goal of our study is to determine the extent SNe Ia-dominated feedback in gas around galaxies. The analysis presented in §§ 3 & 4 indicate that passive galaxies display on average a higher \( N(\text{Fe}II)/N(\text{Mg}II) \) in their halos than star-forming galaxies. In addition, there also appears to be a modest decline in the relative ionic ratio with increasing projected distance. To infer the underlying elemental abundance ratio between Fe and Mg from the observed relative abundances of Fe\(^{+}\) and Mg\(^{2+}\), it is necessary to first address the differential ionization fraction between the two ions. Furthermore, it is also necessary to quantify possible systematic biases due to differential dust depletion. Here we discuss both of these effects and the implications of our findings.

5.1 Differential ionization fraction

To determine the ionization state of the gas, measurements of \( N(\text{H}I) \) and relative abundance ratios between multiple ions are often necessary. While the observed relative ionic ratios constrain the ionization parameters, knowledge of \( N(\text{H}I) \) determines whether the gas is optically-thin or optically-thick to the background radiation field. However, \( N(\text{H}I) \) is not known for all but one galaxy in our sample. As illustrated in Zahedy et al. (2016), useful empirical constraints on the relative Fe/$\alpha$ abundances can be obtained in the absence of \( N(\text{H}I) \). This is achieved by performing a series of photoionization calculations that explore a wide range of ionization conditions. Then, constraints on the ionization state of the gas are obtained based on comparisons of the predicted and observed column density ratios between Mg\(^{2+}\) and Mg\(^{+}\) ions.

In Figure 6 we present the observed MgI to MgII column density ratio, \( N(\text{Mg}I)/N(\text{Mg}II) \), versus MgII column density, \( N(\text{Mg}II) \), for individual absorbing components associated with passive (circle symbols) and star-forming (star symbols) galaxies. The data points are color-coded by the projected distances of the absorbing galaxies. Grey data points represent 2-$\sigma$ upper limit of \( N(\text{Mg}I)/N(\text{Mg}II) \), due to either non-detection of MgI or saturated MgII absorption. Figure 6 shows that the majority ($> 90\%$) of absorbing components with \( \log N(\text{Mg}II) \lesssim 13.8 \) occur in a range of \( \log N(\text{Mg}I)/N(\text{Mg}II) \) values of $-2.2 \lesssim \log N(\text{Mg}I)/N(\text{Mg}II) \lesssim -1.4 \). On the other hand, for high column density absorbing components, \( \log N(\text{Mg}II) \gtrsim 14 \), the ratios are lower with a typical \( \log N(\text{Mg}I)/N(\text{Mg}II) \sim -2.5 \), albeit with larger uncertainties. The range of \( N(\text{Mg}I)/N(\text{Mg}II) \) in Figure 6 is consistent with what has been found for randomly selected MgII absorbers by Churchill et al. (2003).

In Zahedy et al. (2016), we performed a series of photoionization calculations for a photoionized gas of tempera-
ture $T = 10^4$ K and a range of gas densities, metallicities, and $N$(HI). A plane-parallel geometry was assumed for the gas, which was illuminated on both sides with the updated Haardt & Madau (2001) ionizing background radiation field (HM05 in Cloudy v.13.03; Ferland et al. 2013) at $z = 0.5$. For each model, the expected relative abundance ratio between Mg$^+$ and Mg$^2+$ ions and the ionization fraction ratio between Fe$^+$ and Mg$^+$ were calculated for a gas that follows the solar abundance pattern. For absorption components with log $N$(Mg II) $\gtrsim 13.8$ in the present study, comparing the observed $N$(MgI)/$N$(Mg II) and predictions from Zahedy et al. (2016) leads to constraints on the gas density $n \approx 2 \times 10^{-3}$ cm$^{-3}$. Over the range of allowed gas densities, we find that the ionization fraction of Fe$^+$ ($f_{\text{Fe}^+}$) remains roughly equal to that of Mg$^+$ ($f_{\text{Mg}^+}$) in the optically-thick regime and lower than Mg$^+$ in optically-thin gas. As a result, $f_{\text{Fe}^+}/f_{\text{Mg}^+} < 1$ and $N$(Fe II)/$N$(Mg II), which is equal to $(f_{\text{Fe}^+}/f_{\text{Mg}^+}) \times N$(Fe)/$N$(Mg), marks a lower limit to the underlying $N$(Fe)/$N$(Mg).

For strong Mg II components of log $N$(Mg II) $\gtrsim 14$, however, the observed low $N$(MgI)/$N$(Mg II) ratios require a low density gas of $n_{\text{HI}} \approx 10^{-3}$ cm$^{-3}$ for the same HM05 ionizing radiation intensity. The inferred low gas density together with a large $N$(MgII) implies a cloud size of $> 10$ kpc if the gas has a solar metallicity or $> 100$ kpc if the gas metallicity is 0.1 solar. The unphysically large cloud sizes inferred for the strongest Mg II absorbing components raise questions for the accuracy of the photoionization models.

Because the observed ionic ratios in photoionization models is dictated by the ionization parameter, which is the number of ionizing photons per atom, a natural explanation for the inferred low gas density is that the ionizing radiation intensity has been underestimated. To increase the ionizing radiation intensity from the standard HM05, we experiment with adding a local ionizing radiation field due to the absorbing galaxy. We first generate a synthetic galaxy spectrum using Starburst99 (Leitherer et al. 1999) and assuming a star formation rate of $1 M_\odot$ yr$^{-1}$, an age of $10^7$ yr, and an ionizing photon escape fraction of 2%. Then, we normalize the flux to match an $L_\odot$ galaxy at $z = 0.5$. For a gas cloud located at 15 kpc from the galaxy, we find that the ionizing radiation from the galaxy provides a 20-fold increase to the number density of hydrogen-ionizing photons. With an increased ionizing radiation intensity, the inferred underlying gas density increases accordingly. We find that with this revised radiation field the observed low $N$(MgI)/$N$(Mg II) for strong Mg II components of log $N$(Mg II) $\gtrsim 14$ can be reproduced for a gas density of $n_{\text{HI}} \approx 0.01$ cm$^{-3}$. At this gas density, we find that log $f_{\text{Fe}^+}/f_{\text{Mg}^+} \approx -0.4$ and confirm that the observed $N$(Fe II)/$N$(Mg II) represents a lower limit to the underlying $N$(Fe)/$N$(Mg).

An alternative explanation for the observed low $N$(MgI)/$N$(Mg II) in strong Mg II absorbing components is the presence of additional heating sources that may increase the ionization of the gas in a warmer temperature regime. To explore this alternative scenario, we repeat the photoionization calculations for a higher temperature of $T = 3 \times 10^4$ K, assuming the original HM05 radiation field. The adopted higher temperature is motivated by the observed Doppler parameters of individual Mg II, Mg I and Fe II absorption components. A median value of $b \sim 5$ km s$^{-1}$ is found for each of the three transitions, placing an upper limit on the allowed gas temperature at $T \lesssim 3 \times 10^4$ K.

The resulting model predictions show that the observed log $N$(MgI)/$N$(Mg II) $\sim -2.5$ in most log $N$(Mg II) $\gtrsim 14$ absorbing components can also be reproduced for a warm ($T = 3 \times 10^4$ K) optically-thick gas of log $N$(HI) $\lesssim 19$ and 0.1 solar metallicity under a standard HM05 radiation field over a wide range of gas densities. For gas with lower-$N$(HI), a still higher gas temperature is required, which then becomes incompatible with the observed $b$ value. Imposing a maximum cloud size of $l \sim 10$ kpc based on observations of Galactic high-velocity clouds (e.g., Putman et al. 2012) constrains the gas density to be $n_{\text{HI}} \gtrsim 4 \times 10^{-3}$ cm$^{-3}$ for a gas with 0.1 solar metallicity. Over the range of allowed $n_{\text{HI}}$, log $f_{\text{Fe}^+}/f_{\text{Mg}^+} \approx -0.3$, indicating that the observed $N$(Fe II)/$N$(Mg II) marks a lower limit to the underlying $N$(Fe)/$N$(Mg).

In summary, the exercise described in this section demonstrates that for both weak and strong Mg II absorption systems identified in this study, the observed $N$(Fe II)/$N$(Mg II) ratio represents a lower limit to the underlying elemental (Fe/Mg) ratio of the gas for both optically-thin and thick gases. Comparing the observed $N$(Fe II)/$N$(Mg II) to the solar (Fe/Mg) abundance ratio from Asplund et al. (2009; dotted line in Figures 3 – 5), our analysis shows that $> 60\%$ of passive galaxies exhibit an enhanced Fe/o elemental abundance ratio at $d < 60$ kpc that exceeds what is observed in the solar neighborhood. At the same time, the majority of passive galaxies at $d < 100$ kpc and all star-forming galaxies at $d < 150$ kpc exhibit chemical compositions consistent with $\alpha$-element enhancement.
5.2 Differential dust depletion

It is known from observations of the Milky Way ISM that Fe is more readily incorporated into dust grains than Mg, showing in excess of 0.5 dex more depletion than Mg in cool ($T \sim 500$ K) ISM gas (e.g., Savage & Sembach 1996). Including such differential dust depletion, the inferred $N$(Fe)/$N$(Mg) after accounting for possible differential ionization fraction correction may still represent a lower limit to the underlying elemental abundance ratio. At the same time, dust grains are expected to be easily destroyed in warmer environment (e.g., Draine & Salpeter 1979). Indeed, the observed differential depletion between Fe and Mg reduces to $\approx 0.35$ dex in warm ($T \approx 6000$ K) ISM gas (e.g., Savage & Sembach 1996). For Mg II absorbing gas of $T \sim 10^4$ K, it is expected that dust destruction is still more effective (e.g., McKee et al. 1987) and that differential dust depletion is at its minimum. X-ray observations of the hot ISM gas in 19 local early-type galaxies from Humphrey & Buote (2006) have yielded a median Fe to Mg ratio of $\log (\text{Fe}/\text{Mg}) = -0.01 \pm 0.18$ at $d \lesssim 10 - 60$ kpc from these galaxies. This median value is consistent with what we found for singly ionized Fe and Mg at $d < 60$ kpc from $z \sim 0.5$ passive galaxies, supporting the expectation that dust depletion is not significant in the cool ($T \sim 10^4$ K) halo clouds revealed by Mg II absorption transitions.

However, it is possible that the observed low $N$(Fe II)/$N$(Mg II) ratio around star-forming galaxies is due to a larger amount of differential dust depletion around these galaxies, particularly for the Mg II absorbers detected at $d < 50$ kpc. These absorbers are all relatively strong with $W_r(2796) \gtrsim 0.6$ Å, and it has been shown that $\approx 30 - 40\%$ of these strong Mg II absorbers contain neutral gas of $N$(H I) $\gtrsim 2 \times 10^{20}$ cm$^{-2}$ (e.g., Rao et al. 2006). Therefore, a large fraction of these absorbers are likely to arise in DLA gas. For DLAs at $z \sim 0.5 - 3$, Fe is found to be more depleted than Mg by $\approx 0.2$ dex (e.g., Vladilo et al. 2011; De Cia et al. 2016). If dust is present in these strong Mg II absorbers around $z \sim 0.5$ star-forming galaxies, then adopting the mean differential dust depletion between Fe and Mg observed for DLAs would imply a median underlying (Fe/Mg) abundance correction of $\log (\text{Fe}/\text{Mg}) = -0.05$ at $d < 50$ kpc, comparable to both the solar value and what is observed at $d < 60$ kpc from passive galaxies. For weaker Mg II absorbers at $d > 50$ kpc, the dust content is expected to be significantly less and little correction for differential dust depletion is expected.

The differential dust depletion between Fe and Mg can be inferred directly for the absorption systems around two star-forming galaxies in the $d < 50$ kpc subsample, providing a comparison to the underlying (Fe/Mg) ratio implied from the subsample median. For the star-forming galaxy at $z = 0.101$ and $d = 8$ kpc from PKS 0439−433, the roughly solar metallicity known for the DLA gas associated with this galaxy (Chen et al. 2005; Som et al. 2015) allows us to estimate the dust depletion factors for Fe and Mg based on a known correlation between dust depletion and gas-phase metallicity. The differential dust depletion between Fe and Mg is expected to vary between $+0.5$ and $+0.8$ dex for a solar-metallicity gas, based on observations of Galactic absorbers (e.g., De Cia et al. 2016). If dust is present in this DLA, this range of differential dust depletion would imply an underlying (Fe/Mg) abundance ratio of $\log (\text{Fe}/\text{Mg}) = -0.1$ to $+0.2$ for the gas. Similarly for the ultra-strong Mg II absorber associated with the $z = 1.24$ galaxy at $d = 17$ kpc from SDSS J1430+0149, although the metallicity is not known, the relative abundance ratio of Cr to Zn is estimated to be $[\text{Cr}/\text{Zn}] = -0.51 \pm 0.06$ (Zych et al. 2009), indicating a modest level of dust depletion comparable to what is seen in the Galactic Halo (e.g., Savage & Sembach 1996). The expected differential depletion between Fe and Mg in such an environment is $\approx +0.2$ dex, which would imply an underlying (Fe/Mg) ratio of $\log (\text{Fe}/\text{Mg}) = -0.05$ for this Mg II absorber. In both of these cases, applying the estimated dust depletion correction individually for each galaxy results in an implied underlying (Fe/Mg) abundance ratio that is comparable to solar value, consistent with what is found by applying the mean dust depletion correction for DLAs on the median value for the inner-$d$ bin. This exercise lends strong support for the finding that solar-level (Fe/Mg) gas may not be uncommon at $d < 50$ kpc from intermediate-redshift, star-forming galaxies.

5.3 Implications on the origin of chemically enriched gas in galaxy halos

As previously mentioned in § 1, iron is produced in both core collapse and Type Ia SNe, whereas magnesium is produced primarily in massive stars and core-collapse SNe. Specifically, a Type Ia supernova is expected to produce $\sim 0.7 M_\odot$ of Fe while releasing no more than 0.02 $M_\odot$ of magnesium at the same time (e.g., Iwamoto et al. 1999). Different types of SNe originate in different progenitor stars of different stellar ages. The elemental (Fe/Mg) ratio therefore provides a measure of the relative contributions from different massive stars to the chemical enrichment history of a galaxy (e.g., de Plaa et al. 2007; Zahedy et al. 2016). Consequently, the inferred lower limit of the underlying (Fe/Mg) elemental abundance ratio from the observed $N$(Mg II)/$N$(Mg II) provides a useful “clock” for timing the age of the stellar population. In addition, the spatial profiles of $N$(Mg II)/$N$(Mg II) offers important constraints for the extent of SNe Ia-dominated chemical enrichment in galactic halos.

For quiescent galaxies in this study, the observed $N$(Fe II)/$N$(Mg II) at $d < 60$ kpc is high with a median and dispersion of $\log (N$(Fe II)/$N$(Mg II))$_{\text{med}} = -0.06 \pm 0.15$. The large column density ratio implies a lower limit to the underlying (Fe/Mg) ratio of the gas at $[\text{Fe}/\text{Mg}] \equiv \log (\text{Fe}/\text{Mg}) - \log (\text{Fe}/\text{Mg})_{\odot} < 0$. The implied fractional contribution from SNe Ia to the chemical enrichment of the gas is $f_{\text{Fe}} \gtrsim 17\%$ based on the expected nucleosynthetic yields for Type Ia and core-collapse SNe from Iwamoto et al. (1999). This minimum value is comparable to what has been estimated for solar-abundance gas in the Milky Way (e.g., Tsuru et al. 1995). With such a significant contribution from SNe Ia, it can also be expected that cool gas at $d < 60$ kpc from passive galaxies has been enriched to a relatively high metallicity, reflecting the role of multiple generations of massive stars and SNe Ia in its chemical enrichment history. Indeed, this expectation is at least consistent with what has been found in the hot ISM of local elliptical galaxies, where near-solar mean metallicities are commonly observed at a similar range of $d$ (e.g., Humphrey & Buote 2006; Loewen-
The radial profile of gas-phase Fe/α ratio around distant galaxies

The radial profile in these galaxies is consistent within measurement errors with being flat at [Fe/α] ∼ 0 level at d ≤ 40 kpc, comparable to what can be inferred from our observations at d ≤ 60 kpc from z ∼ 0.5 passive galaxies.

Our analysis also provides a quantitative constraint on the Fe/α ratio at d ≥ 100 kpc from passive galaxies, where the gas is typically too diffuse to be detected in emission even in the local universe. We find that at d = 100 kpc the absorbing gas generally shows lower N(Fe II)/N(Mg II) ratios than typically seen at d ≤ 60 kpc. Specifically for passive galaxies, the N(Fe II)/N(Mg II) ratios at d ≥ 100 kpc can be characterized by a 85% upper limit to the underlying distribution of log(N(Fe II)/N(Mg II))med < −0.3. In at least three out of seven cases (≈ 40%), the absorbing gas displays log(N(Fe II)/N(Mg II))med ≪ −0.6. Allowing a modest differential ionization fraction between Fe⁺ and Mg++ of up to log f_Fe++/f_Mg++ ≈ −0.3 dex (assuming an optically thick gas, see § 5.2), the implied underlying (Fe/Mg) relative abundance ratio is [Fe/Mg] ≈ −0.2 for a log N(Fe II)/N(Mg II) = −0.6 gas. This range of [Fe/Mg] ratios is comparable to that of high-redshift DLAs, where the mean [Fe/α] has been found to be −0.26 ± 0.12 at z ≥ 3 (e.g., Rafelski et al. 2012). For [Fe/Mg] ≲ −0.2, the expected maximum fractional contribution from SNe Ia to the chemical enrichment is fIa ≲ 5%, based on supernova nucleosynthetic yields from Iwamoto et al. (1999). Our analysis therefore indicates that SNe Ia-driven chemical enrichment is relatively localized in inner halos at d ≤ 60 kpc and that the chemical enrichment of the cool gas at d ≥ 100 kpc from z = 0.5 passive galaxies is consistent with an early enrichment driven by core-collapse SNe.

For star-forming galaxies, interpretations of our observations are more uncertain. As previously noted in § 5.2, if differential dust depletion is important, then the absorbing gas at d ≤ 50 kpc from these star-forming galaxies may also have a near solar-level (Fe/Mg) ratio. Such a high level Fe/Mg ratio may not be surprising for a mature disk galaxy at low- to intermediate-redshifts. However, it is interesting to find that a strong Mg II absorber of W₅(2796) = 2.86 at d = 17 kpc from a star-forming galaxy at z = 1.24 could potentially have a solar Fe/Mg ratio after differential dust depletion corrections. The implication is that the galaxy contains a relatively evolved stellar population, while maintaining an active level of star formation when the universe was ≈ 5 Gyr old. Follow-up studies of the stellar populations and star formation history in this galaxy are necessary for a better understanding of the observed high Fe/Mg ratio in the absorber.

At d > 70 kpc from star-forming galaxies, the observed Fe II to Mg II column density ratios are generally low with a median and dispersion of log(N(Fe II)/N(Mg II))med = −0.91 ± 0.44. For a median N(Mg I)/N(Mg II) ratio of log N(Mg I)/N(Mg II) = −1.9, the expected differential ionization fraction between Fe⁺ and Mg++ is log f_Fe++/f_Mg++ ≈ −0.6 dex for an optically-thin gas (and negligible for an optically-thick gas). Applying this ionization correction leads to an implied underlying (Fe/Mg) relative abundance ratio of [Fe/Mg] ≲ −0.2 at d = 70 − 160 kpc. Similar to what is seen at d > 100 kpc from passive galaxies, cool gas at d > 70 kpc from star-forming galaxies also shows an α-element enhanced abundance pattern driven by core-collapse SNe.

In summary, our analysis suggests that Fe/α in galactic halos declines with increasing projected distance from both passive and star-forming galaxies. At d ≤ 60 kpc, a significant contribution from SNe Ia (fIa ≳ 15%) is necessary to explain the observed Fe/Mg ratios, whereas at d > 70 kpc, contributions from SNe Ia are limited to fIa ≲ 5% in both star-forming and quiescent halos. Together, our analysis shows that SNe Ia-driven chemical enrichment is relatively localized in inner halos at d ≤ 60 kpc. Alternatively, inflowing gas from the IGM could also “dilute” an Fe-rich gas and produce a declining Fe/α radial profile in the halo, because accreted IGM gas is expected to show an α-enhanced abundance pattern which reflects the early enrichment history (e.g., Rauch et al. 1997). However, such dilution effect is likely minimal if the metallicity of an α-enhanced inflowing gas is significantly lower than the Fe-rich gas.

It is clear that there is a significant scatter in the empirical measurements of N(Fe II)/N(Mg II), while the inferred fIa depends sensitively on the input Fe/α elemental abundance ratio. We anticipate that future observations combining metallicity and relative abundance measurements in stars/ISM and in halo gas for a large sample of galaxies will provide the precision necessary to distinguish between different scenarios.

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