ON THE LACK OF CORRELATION BETWEEN \( \text{Mg} \ II \) 2796, 2803 Å AND \( \text{Ly}\alpha \) EMISSION IN LENSED STAR-FORMING GALAXIES

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ABSTRACT

We examine the \( \text{Mg} II \) 2796, 2803 Å, \( \text{Ly}\alpha \), and nebular line emission in five bright star-forming galaxies at 1.66 < \( z \) < 1.91 that have been gravitationally lensed by foreground galaxy clusters. All five galaxies show prominent \( \text{Mg} II \) emission and absorption in a P Cygni profile. We find no correlation between the equivalent widths of \( \text{Mg} II \) and \( \text{Ly}\alpha \) emission. The \( \text{Mg} II \) emission has a broader range of velocities than do the nebular emission line profiles; the \( \text{Mg} II \) emission is redshifted with respect to systemic by 100–200 km s\(^{-1}\). When present, \( \text{Ly}\alpha \) is even more redshifted. The reddest components of \( \text{Mg} II \) and \( \text{Ly}\alpha \) emission have tails to 500–600 km s\(^{-1}\), implying a strong outflow. The lack of correlation in the \( \text{Mg} II \) and \( \text{Ly}\alpha \) equivalent widths, the differing velocity profiles, and the high ratios of \( \text{Mg} II \) to nebular line fluxes together suggest that the bulk of \( \text{Mg} II \) emission does not ultimately arise as nebular line emission, but may instead be reprocessed stellar continuum emission.

Key words: galaxies: star formation – gravitational lensing: strong – ISM: jets and outflows – techniques: spectroscopic

1. INTRODUCTION

It has recently become evident that the spectra of distant galaxies frequently show \( \text{Mg} II \) 2796, 2803 in the classic P Cygni profile of redshifted emission and blueshifted absorption. Such emission is notably absent in \( z = 0 \) analogs.

Weiner et al. (2009) reported the first detection of \( \text{Mg} II \) emission in distant galaxies, finding \( \text{Mg} II \) emission with a P Cygni profile in the stacked spectra of \( z = 1.4 \) galaxies. They attributed this emission to a small fraction (50 out of 1400) of the sample, “most probably from narrow-line active galactic nuclei (AGNs),” in part because of a high-velocity tail in the emission line profile. Rubin et al. (2010) repeated this analysis on a lower-redshift (0.7 < \( z \) < 1.5) sample of galaxies, and found \( \text{Mg} II \) emission in the stack of 468 galaxies, as well as in some individual galaxy spectra. They suggested that this \( \text{Mg} II \) emission arises not from nuclear accretion, but from resonant scattering in an expanding wind, analogous to the resonant scattering of \( \text{Ly}\alpha \).

Rubin et al. (2011) found \( \text{Mg} II \) emission that extended spatially across at least 7 kpc in a \( z = 0.69 \) galaxy, which also showed prominent Fe \( \text{II}^* \) fine structure emission. The authors noted that the Fe \( \text{II}^* \) and \( \text{Mg} II \) kinematics did not resemble those of nebular emission lines. They argued that the \( \text{Mg} II \) resonant emission and the Fe \( \text{II}^* \) fine structure emission most likely arise via photon scattering in an outflowing wind. Giavalisco et al. (2011) found \( \text{Mg} II \) and Fe \( \text{II}^* \) emission in a stack of 33 galaxies at \( z = 1.6 \), and in a stack of 92 galaxies at 1.65 < \( z \) < 2.5. They note that at matched spectral resolution, non-AGN \( z = 0 \) galaxies show no such \( \text{Mg} II \) and Fe \( \text{II}^* \) emission (Kinney et al. 1993), except for the Wolf–Rayet galaxy TOL 1924-416. None of the galaxies in the Giavalisco et al. (2011) stacks are detected in 4 Ms of \( \text{Chandra} \) X-ray integration, which argues against the significant presence of X-ray-luminous AGNs.

Erb et al. (2012) showed how common \( \text{Mg} II \) and Fe \( \text{II}^* \) emission are in 1 < \( z \) < 2 galaxies. \( \text{Mg} II \) emission is seen in one-third of their sample: 33 of 93 galaxies. Fe \( \text{II}^* \) emission appears even more ubiquitous, appearing in all the stacks of subsamples.

Prochaska et al. (2011) simulate \( \text{Mg} II \) P Cygni profiles like those observed in these distant galaxies, using a Monte Carlo radiative transfer model that assumes a cool, outflowing wind.

Thus, while the first detections of \( \text{Mg} II \) emission lines in galaxies were thought to be a rare curiosity with a suspected AGN origin, such emission is now recognized as common in distant star-forming galaxies, though notably absent in \( z = 0 \) analogs.

In this paper, we examine \( \text{Mg} II \) emission and absorption from five star-forming galaxies at 1.66 < \( z \) < 1.91 that have been gravitationally lensed by foreground galaxy clusters. While our sample size is much smaller than field samples, lensing magnification has enabled us to obtain much higher-quality spectra of individual galaxies. We compare the \( \text{Mg} II \) emission to the strengths and profiles of other emission lines, to better understand where this \( \text{Mg} II \) emission arises, and what its physical origins are.

2. SAMPLE AND OBSERVATIONS

The data analyzed in this paper are part of a larger study of the rest-ultraviolet spectral properties of bright lensed galaxies, which we are conducting with the MagE spectrograph (Marshall et al. 2008) on the Clay Magellan II telescope. The galaxies discussed in this paper are the five from our larger sample that have redshifts such that both the \( \text{Ly}\alpha \) and \( \text{Mg} II \) 2796, 2803 features have spectral coverage. Four of the five galaxies discussed here are drawn from the SDSS Giant Arcs Sample (SGAS), a set of bright gravitationally lensed galaxies.
redshifts. The spectrum for Knot E has the star-forming knots, labeled E, U, B, G, following the nomenclature of Sharon et al. (2012). The other galaxy, RCS0327 (Wuyts et al. 2010), comes from the Second Red Sequence Cluster Survey (Gilbank et al. 2011). Table 1 gives total integration times and dates of the observations. Further details of observations, data reduction, and full spectra will be published in future papers.

For RCS0327, we obtained MagE spectra for four distinct star-forming knots, labeled E, U, B, G, following the nomenclature of Sharon et al. (2012). The spectrum for Knot E has the highest signal-to-noise ratio.

3. RESULTS

3.1. Systemic Redshift

For three galaxies, we measured systemic redshifts by fitting the C [\text{iii}] 1907, 1909 Å doublet with two Gaussians. The fit was constrained such that both lines shared a common linewidth. The redshift was allowed to vary, with the ratio of the central wavelengths held fixed.

S1441 lacks detected C [\text{iii}] or other systemic lines; we therefore arbitrarily choose a systemic redshift of $z = 1.666$, which puts the reddest Mg [\text{ii}] 2796 Å absorption at zero velocity. RCS0327 has a complex velocity structure because it is undergoing a major merger (Wuyts et al. 2014). For Knot E of RCS0327 the C [\text{iii}] emission is blended with Fe [\text{ii}] 2600 absorption from an intervening system at $z = 0.98295$; we therefore instead use Si [\text{ii}] $^{*}$ 1264, Si [\text{ii}] $^{*}$ 1309, Si [\text{ii}] $^{*}$ 1533, and Si [\text{iii}] 1882, finding a weighted-average emission line redshift of 1.7034 ± 0.00014 for Knot E. (This redshift is consistent within uncertainties with the section of the C [\text{iii}] profile that is not contaminated by intervening Fe [\text{ii}] absorption.) Table 2 lists the measured systemic redshifts.

3.2. Comparison of Ly\textsubscript{\alpha} and Mg \textsubscript{ii} Emission Strength

Erb et al. (2012) reasoned that Mg [\text{ii}] emission in $z \sim 1$–2 galaxies should be similar to Ly\textsubscript{\alpha} emission, since both emission lines show P Cygni profiles, and since their emission strengths are generally correlated with UV color. However, since they lacked spectral coverage of Ly\textsubscript{\alpha}, they could not directly compare Mg [\text{ii}] and Ly\textsubscript{\alpha} emission profiles or equivalent widths.

In Figure 1, we compare the equivalent widths of Mg [\text{ii}] emission and Ly\textsubscript{\alpha} emission in our sample. The sample has reasonable dynamic range: the equivalent widths of Mg [\text{ii}] vary by a factor of six, and Ly\textsubscript{\alpha} by a factor of eight. No correlation is observed.

3.3. Ubiquity of Mg \textsubscript{ii} Emission

While the five galaxies in this paper were merely selected from our larger sample as spectral coverage of Mg [\text{ii}] and Ly\textsubscript{\alpha}, in fact, all five show detected Mg [\text{ii}] emission and absorption in a P Cygni profile. Mg [\text{ii}] spectra are plotted in Figure 2. In Section 4 we explain why the ubiquity of Mg [\text{ii}] emission in our sample is likely a selection effect.

| Source                  | Systemic Redshift $z_s$ | Emission Lines used for $z_s$ |
|------------------------|------------------------|-------------------------------|
| S0004                  | 1.6811 ± 0.0001        | C [\text{iii}] 1907/1909      |
| S0108                  | 1.91021 ± 0.00003      | C [\text{iii}] 1907/1909      |
| R0327 Knot E           | 1.7034 ± 0.00014       | Si [\text{ii}] $^{*}$ 1264, 1309, 1533, Si [\text{iii}] 1882 |
| S0957                  | 1.82042 ± 0.00004      | C [\text{iii}] 1907/1909      |

Table 2

Systemic Redshifts

| Source          | Systemic Redshift $z_s$ | Ly $\alpha$ EW (Å) |
|-----------------|------------------------|--------------------|
| S0004           | 0.00003                | 0.0001             |
| S0108           | 0.00003                | 0.0001             |
| S0957           | 0.00014                | 0.0001             |
| S1441           | 0.00014                | 0.0001             |

Notes. Source names, total integration times, and UT dates of observation. Full source names follow the convention of SGAS JHHMMSS.s±DDMMSS (Koester et al. 2010); abbreviated names (HHMM) are used subsequently.

Figure 1. Rest-frame equivalent width of Ly\textsubscript{\alpha} emission, as a function of the rest-frame equivalent widths of Mg [\text{ii}] 2796 Å emission (error bars plotted as solid lines), and Mg [\text{ii}] 2803 Å emission (error bars plotted with dotted lines). Values for each of four star-forming knots of RCS0327 are plotted in gray. The other galaxies are plotted in black. There is no apparent correlation between the equivalent widths of Mg [\text{ii}] and Ly\textsubscript{\alpha}.
Figure 2. Velocity plots of spectral features in the MagE spectra of five lensed galaxies. Each column plots the spectrum of a different galaxy, labeled at the top, as well as its 1σ uncertainty spectrum. The x-axis is velocity in km s\(^{-1}\); zero velocity should be the systemic redshift. The y-axis is flux density in \(1 \times 10^{-29}\) erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\). Each row plots a different emission line, labeled at left and right. For RCS0327, only the spectrum of Knot E is shown.

Table 3

| Source | Mg II 2796 | Mg II 2803 | Lyα | C iii 1907 | C iii 1909 | C ii 2326 | Fe ii 2396 | O ii 2470 |
|--------|------------|------------|-----|------------|------------|------------|------------|----------|
| S0004  | -0.45 ± 0.1| -0.81 ± 0.17| -3.3 ± 0.4| -0.2 ± 0.1| -0.25 ± 0.1| > -0.26| > -0.26| > 0.26 |
| S0108  | -0.9 ± 0.6| -0.87 ± 0.25| -8.9 ± 0.6| -1.2 ± 0.1| -0.7 ± 0.1| -0.5 ± 0.1| -0.55 ± 0.15| > -0.3 |
| R0327 Knot E | -1.3 ± 0.16| -1.00 ± 0.17| > -1.2| -0.8 ± 0.1| -1.2 ± 0.1| -0.6 ± 0.15| -0.8 ± 0.15| -1.0 ± 0.1 |
| Knot B | -1.1 ± 0.5| -0.8 ± 0.3| > -2.5| -1.6 ± 0.4| -1.4 ± 0.35| > -0.7| > -0.8| -1.1 ± 0.35 |
| Knot G | -1.6 ± 0.6| -1.4 ± 0.6| > -3.8| > -1.1| > -1.05| > -0.96| -0.8 ± 0.4| > -0.75 |
| Knot U | -2.8 ± 0.3| -2.55 ± 0.2| > -1.1| -1.5 ± 0.1| -0.9 ± 0.1| -1.1 ± 0.4| -1.1 ± 0.2| -0.9 ± 0.1 |
| S0957 | -2.8 ± 0.9| -1.81 ± 0.77| -8.1 ± 1.2| -2.0 ± 0.3| -1.2 ± 0.3| > -0.87| > -0.71| > -0.85 |
| S1441 | -0.95 ± 0.4| > -0.8| > -3.4| > -0.62| > -0.62| > -1.0| > -1.2| > -0.92 |

Notes. Measured rest-frame equivalent width, in Å, of the following emission lines: Mg ii 2796, Mg ii 2803, Lyα, C iii] 1907, C iii] 1909, C ii] 2326, Fe ii] 2396, [O ii] 2470. For lines with P Cygni profiles, equivalent widths are of the emission component only. Two σ upper limits are quoted for non-detections.

3.4. Velocity Structure of the Emission

We now examine the velocity structure of the Mg ii emission, compared to other prominent spectral features. Figure 2 presents velocity plots for these five lensed galaxies. Though RCS0327 has spectra measured for four knots, in Figure 2 we examine only the spectrum of Knot E, since it has the highest signal-to-noise ratio. (Detailed analysis of knot-to-knot variations in the Mg ii profile within RCS0327 is reserved for a future paper.) Zero velocity corresponds to the systemic redshift of each galaxy, as determined in Section 3.1.

In each galaxy, the Mg ii emission is broader than the C iii] lines, and the peak is redshifted with respect to systemic by 100–200 km s\(^{-1}\). When Lyα is detected, it is even more
redshifted than Mg II, with peak intensity at 200–250 km s\(^{-1}\) from systemic. The red “shoulder” of Mg II 2796 Å emission will be absorbed by the 2803 Å transition. Thus, the 2803 Å line is the one to examine for redshifted emission. The Mg II profiles of S0108 and RCS0327 Knot E show a “shoulder” of emission extending \(\sim 500 \text{ km s}^{-1}\) redward of systemic. The Ly\(\alpha\) emission in S0108 and S0957 also show redshifted shoulders to even higher velocities (\(>600 \text{ km s}^{-1}\)). Such extreme velocities imply a strong outflow. This result can be stated more generally: all the strong, high signal-to-noise Mg II and Ly\(\alpha\) emission lines in our sample show high-velocity red “shoulders.”

4. DISCUSSION AND CONCLUSIONS

Mg II emission is present in all five of the gravitationally lensed galaxies in our sample. This may seem surprising, given that Erb et al. (2012) find such emission in only one-third of their sample. An explanation may lie in the fact that Mg II emission is stronger in the Erb et al. stacked subsamples with lower stellar mass and bluer color; the reasons for this remain unclear. The lensed galaxies in our sample are quite blue. While we are still developing the lensing models required to infer intrinsic stellar mass for this sample, galaxies selected in a similar way have stronger in the Erb et al. stacked subsamples with lower stellar mass and bluer color; the reasons for this remain unclear. The lensed galaxies in our sample are quite blue. While we are still developing the lensing models required to infer intrinsic stellar mass for this sample, galaxies selected in a similar way have stronger Mg II emission. Lensed arc samples should be biased toward galaxies with high surface brightness features, in other words high specific star formation rates. Given the Erb et al. (2012) results, it is not surprising that the highly magnified, high surface brightness star-forming regions captured within the MagE slit should show Mg II emission.

In RCS0327, the MagE spectra capture four different star-forming knots, but in the other four galaxies, the MagE spectra capture only one bright knot of emission per galaxy. Past work shows that such knots typically extend only a few 100 pc (Wuyts et al. 2014; Sharon et al. 2012; Jones et al. 2012). In a future paper, we will examine the spatial variation of Mg II emission within RCS0327.

The lack of a correlation between the equivalent widths of Mg II and Ly\(\alpha\) emission is striking, and can be interpreted in several ways. Since Ly\(\alpha\) is a bluer transition with a higher absorption cross-section than Mg II, it can be expected to be more heavily obscured by dust. Galaxy-to-galaxy variations in extinction might erase an intrinsic correlation between Mg II and Ly\(\alpha\) emission, if present. A similar decoupling between UV continuum and Ly\(\alpha\) emission was proposed by Giavalisco et al. (1996). An alternate explanation for the lack of correlation would be that Ly\(\alpha\) and Mg II emission do not share common origins. As a hydrogen recombination line, Ly\(\alpha\) originates in H II regions, and is then resonantly scattered. The origin of Mg II emission in distant galaxies is not well established; the two models proposed in the literature are intrinsic production of line emission in nebular regions with subsequent scattering, and intrinsic production of continuum photons that are resonantly scattered. Plasma models of H II regions (Cloudy; Ferland et al. 2013) predict weak nebular Mg II emission (Erb et al. 2012, their Figure 16); the dominant emission mechanism is the excitation of Mg\(^{+}\) by electron impact (G. Ferland 2014, private communication). Thus, the flux of any nebular component of Mg II emission should be tied to the electron temperature and luminosity of the H II regions and the Ly\(\alpha\) flux, and not tied to the amount of Mg II absorption. A future study could test for a correlation between the extinction-corrected H\(\alpha\) luminosity, which traces star formation rate, and the luminosity of Mg II emission.

Nebular Mg II emission is observed in the local universe, in the Orion H II region complex, as reviewed by Dufour (1987). Torres-Peimbert et al. (1980) detected Mg II emission at low resolution with the International Ultraviolet Explorer (IUE) for a part of Orion; the flux of the emission was comparable to but less than C III] 1909. In high-resolution spectra of six regions of Orion, Boeshaar et al. (1982) find that the Mg II emission ranges from 0.04 to 1.35 times the strength of [O II] 2470 Å, and 0.25 to 25 times the strength of the C III] 1907,1909 Å doublet. By comparison, in our five galaxies, Mg II emission is much stronger than both [O II] 2470 and C III] 1907. These high line flux ratios argue against an intrinsically nebular origin for the bulk of the Mg II emission.

Mg II emission could also arise through the scattering of continuum photons that have the wavelength of the Mg II doublet, and are resonantly scattered through a velocity gradient until they emerge as Mg II emission. If the ultimate origin of Mg II emission is from continuum photons, then the equivalent width of Mg II emission should have no connection to that of Ly\(\alpha\), but instead be tied to the Mg II absorbing column density and the characteristics of the outflowing wind. This could be examined in future work, for example by testing for a correlation between Mg II emission and the intrinsic Ly\(\alpha\) emission inferred from the observed fluxes of Ly\(\alpha\) and two Balmer lines.

The galaxies in our sample show a complex velocity structure in the emission components, with Mg II redshifted with respect to the nebular and Fe III lines, and Ly\(\alpha\) (when present) even more redshifted, with a tail to more than 600 km s\(^{-1}\) from systemic. These observations can provide new insights into the wind structure of \(z \sim 2\) star-forming galaxies, through future multi-ion wind modeling. For now, it is enough to say that the Mg II emission does not have the velocity structure of either the nebular emission or the Ly\(\alpha\) emission. This suggests that the bulk of Mg II emission is emitted from physically different regions of the galaxy than is the nebular or Ly\(\alpha\) emission.

To conclude, the rest-ultraviolet spectra of five lensed galaxies presented here reveal that Mg II emission is not a simple proxy for Ly\(\alpha\) emission; its equivalent width is uncorrelated with that of Ly\(\alpha\), and its velocity structure is different as well. Mg II emission, since it is bright and common in \(z \sim 2\) galaxies, may prove to be a powerful diagnostic of winds driven by star formation in distant galaxies, once more work is done to understand its physical origin and radiative transfer.

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\(^9\) Several authors (Rubin et al. 2011; Prochaska et al. 2011; Erb et al. 2012) have erroneously cited Kinney et al. (1993) as claiming that Mg II can be produced in H II regions. Kinney et al. in fact claimed no such detection, but rather adopted a list of emission lines seen in H II regions by IUE, as reviewed by Dufour (1987). The correct citations should be Torres-Peimbert et al. (1980) and Boeshaar et al. (1982), as reviewed by Dufour (1987). We note this to correct the citation stream.
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