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Probing Individual Star Forming Regions Within Strongly Lensed Galaxies at z > 1

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Abstract. Star formation occurs on physical scales corresponding to individual star forming regions, typically of order ∼100 parsecs in size, but current observational facilities cannot resolve these scales within field galaxies beyond the local universe. However, the magnification from strong gravitational lensing allows us to measure the properties of these discrete star forming regions within galaxies in the distant universe. New results from multi-wavelength spectroscopic studies of a sample of extremely bright, highly magnified lensed galaxies are revealing the complexity of star formation on sub-galaxy scales during the era of peak star formation in the universe. We find a wide range of properties in the rest-frame UV spectra of individual galaxies, as well as in spectra that originate from different star forming regions within the same galaxy. Large variations in the strengths and velocity structure of Lyman-alpha and strong P Cygni lines such as C IV, and MgII provide new insights into the astrophysical relationships between extremely massive stars, the elemental abundances and physical properties of the nebular gas those stars ionize, and the galactic-scale outflows they power.

Keywords. gravitational lensing: strong — high-redshift galaxies — galaxies: star formation

1. Introduction

The rest-frame ultraviolet spectra of galaxies contain a wealth of information about the population of massive stars, the properties of the nebular gas those stars ionize, and the galactic-scale outflows they power. We can therefore use rest-UV spectra to constrain the famous "galactic feedback" that drives metals into the intergalactic medium and to better understand the role of this feedback in shutting down future star formation. A key science goal for 20–30 m telescopes is to understand this feedback process, but until the next generation of telescopes are built, there are only two ways to obtain rest-UV diagnostics for typical star-forming galaxies at redshifts above z ∼1.5. The first is to stack low-quality spectra of many galaxies (e.g., Shapley *et al.* 2003). This results in a good sampling of the average properties of star forming galaxies, but removes the possibility of understanding the variations in the observable properties and how changes in one or more observables affects some or all of the others. The second way is to target galaxies that have been highly amplified by gravitational lensing. In previously published good signal-to-noise (S/N) rest-frame UV spectra for four such bright gravitationally lensed galaxies there are numerous strong features that trace the properties of massive stars and outflowing gas (Pettini *et al.* 2002, Finkelstein *et al.* 2009, Quider *et al.* 2009, 2010). All four of these galaxies have remarkably similar P Cygni profiles, yet each has very different outflow properties – we do not yet know what is a "normal" outflow at z > 1.

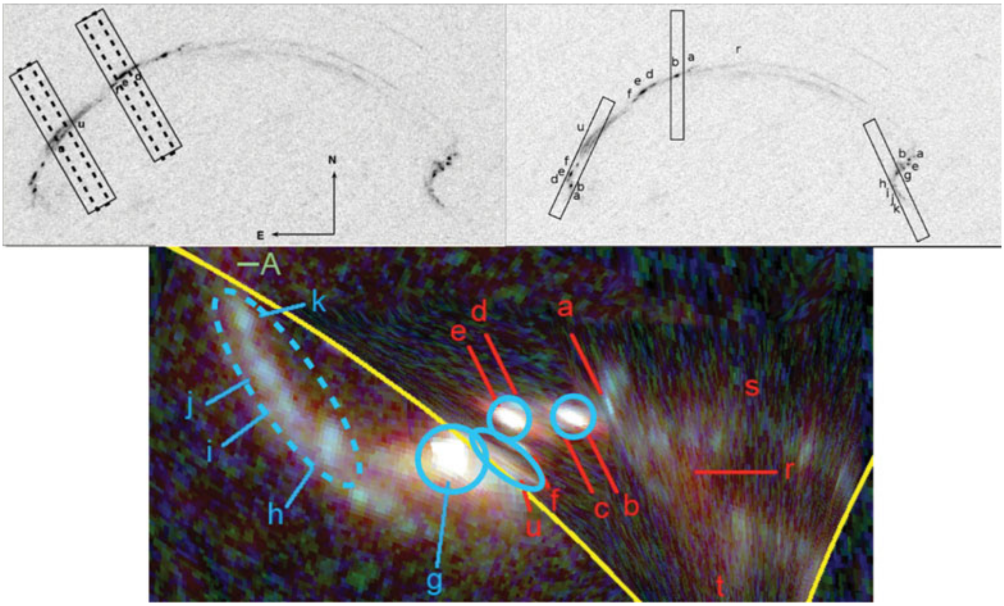

Figure 1. Slit positions for MagE observations of RCS2 J0327-1326. The top grayscale images show individual emission regions/knots in the arc labeled with lowercase letters. Solid and dashed lines indicate the positions of the MagE slit along the arc. Slits indicated by solid and dashed lines on the top left depict the slit positions for observations taken at two different slit widths, where the wider-slit was used for observations during times of worse seeing. The bottom panel shows a reconstruction of the giant arc in the source plane from Sharon *et al.* (2012), with the same emission knots – each with a physical size of $\lesssim$100 pc – are labeled with lowercase letters. The solid cyan ellipsoids indicate the four knots for which we have good S/N spectra.

At the heart of the problem is the fact that the fundamental physical scale of star formation and stellar outflows is not the scale of a single galaxy, but rather the scale of individual star forming regions within galaxies. However, strong gravitational lensing provides uniquely powerful views of distant galaxies, and in the most extreme high-magnification cases we are able to spatially resolute structures on $\lesssim$100 pc scales within galaxies at z > 1. In this proceeding we present a few highlights of the first results from an ongoing effort to obtain good S/N rest-frame UV spectra of individual star forming regions within distant galaxies. Here we will focus on two source in particular – RCS2 J0327-1326 and SGAS J1050+0017.

2. RCS2 J0327-1326

RCS2 J0327-1326 is a spectacular strongly lensed galaxy at $z = 1.704$ that forms a giant arc extending ~38" along the sky (Wuyts *et al.* 2010, Sharon *et al.* 2012). This galaxy has been well-studied at NIR wavelengths, which samples the rest-frame optical (Rigby *et al.* 2011, Whitaker *et al.* 2014, Wuyts *et al.* 2014). We have also been conducting a follow-up campaign to acquire good S/N moderate resolution optical spectra of this arc with the MagE spectrograph on the Magellan-II (Clay) telescope. Due to the high magnification it is possible to place standard spectroscopic slits at different positions that map to distinct star forming regions with sizes $\lesssim$100 pc in the source galaxy (Figure 1).

Spectra of each of four star forming knots within RCS2 J0327-1326 exhibit strong differences in the strength and structure of many prominent rest-UV features. In particular, the C IV and Mg II P Cygni lines, which result from outflowing gas, show large variations

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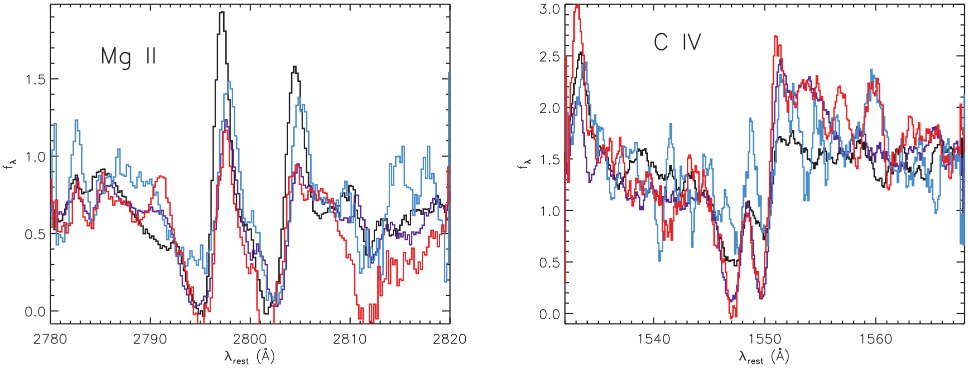

Figure 2. The Mg II 2796,2803 (left) and C IV 1548,1551 (right) P Cygni lines as observed in four different $\lesssim$100 pc scale star forming regions within RCS2 J0327-1326. Both panels are consistent in their use of four different colors to indicate the four distinct star forming regions.

between the different knots (Figure 2). It is also notable that there is no positive correlation between the strength of the C IV and Mg II lines, indicating that these two lines are generated by different mechanisms and/or in different physical locations. These data also informed the observed lack of correlation between Ly-α and Mg II P Cygni emission in a sample of strongly lensed galaxies (Rigby *et al.* 2014), which further supports a physical picture in which Mg II emission traces stellar wind driven outflows, possibly providing a diagnostic measure of the radiative transfer mechanisms in those outflows.

3. SGAS J1050+0017

This bright lensed galaxy at $z = 3.625$ was published by Bayliss *et al.* (2014), in which the authors analyzed optical through NIR (rest-frame UV through optical) spectra of the source, as well as imaging data spanning 0.4 through 4.5 microns. This multi-wavelength analysis had difficultly explaining the properties of the integrated spectra of the giant arc, including very strong and narrow P Cygni features, as well as differences between the ionization parameter measurements. Here we show a new analysis of the Gemini/GMOS-North spectra of this arc in which we isolate and individually extract the emission from two distinct ~100-200 pc star forming knots along the arc (see Figures 1 & 2 in Bayliss *et al.* 2014). The spectra clear exhibit differences between the two distinct knots, with the second knot, plotted in red, having a much weaker C IV feature, as well as weaker He II emission (Figure 3). These spectra provide direct evidence that the conditions of the ionizing radiation field and the population of massive stars vary significantly across different regions at $z = 3.625$.

4. Conclusions

Looking at individual star forming regions within the most highly magnified giant arcs we see significant variations along different lines of sight, including variable strength and profile shape of structure of P Cygni wind lines, with no evidence for correlation between C IV and Mg II P Cygni features, and indications of significant differences in the ionizing radiation field. These results reinforce the argument that the astrophysics of the interstellar medium (ISM) in distant star forming galaxies is a complex business.

Bright lensed galaxies extending out to z ~ 5 have recently become common place (e.g., Bayliss *et al.* 2010, Koester *et al.* 2010, Bayliss *et al.* 2011b, Gladders *et al.* in prep), and

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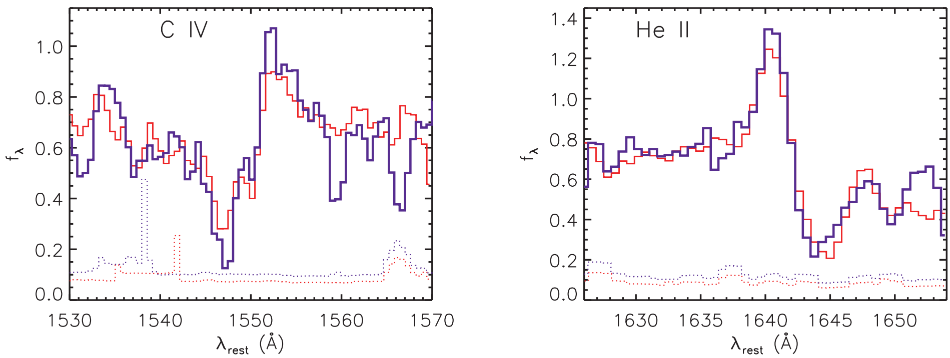

Figure 3. The C IV 1548,1551 (left) P Cygni lines and He II 1640 (right) emission line as seen in distinct star forming regions (indicated by different colors) within SGAS J1050+0017.

these lensed galaxies typically reside at z $\sim$ 2, and therefore sample the epoch of peak star formation in the universe (Bayliss *et al.* 2011a, Bayliss 2012). The highest magnification systems drawn from these large samples provide a new opportunity to leave single-object analysis behind and study the UV spectra of individual star forming regions within many z $>$ 1 galaxies. Such observations would allow us to characterize the relationship between local signatures of the winds of massive stars and their interaction with their surrounding ISM. These data will, in turn, reveal important new information about the astrophysics of the radiative transfer in the ISM in regions of prolific star formation.

Acknowledgements

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