Formation and Evolution of Galaxy Outskirts
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Outflows in low-mass galaxies at $z > 1$

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Abstract. Star formation histories of local dwarf galaxies, derived through resolved stellar populations, appear complex and varied. The general picture derived from hydrodynamical simulations is one of cold gas accretion and bursty star formation, followed by feedback from supernovae and winds that heat and eject the central gas reservoirs. This ejection halts star formation until the material cools and re-accretes, resulting in an episodic SFH, particularly at stellar masses below $\sim 10^9$ $M_\odot$. Such feedback has often been cited as the driving force behind the observed slowly-rising rotation curves in local dwarfs, due to an under-density of dark matter compared to theoretical models, which is one of the primary challenges to LCDM cosmology. However, these events have not yet been directly observed at high-redshift. Recently, using HST imaging and grism spectroscopy, we have uncovered an abundant population of low-mass galaxies ($M_\star < 10^9$ $M_\odot$) at $z = 1-2$ that are undergoing strong bursts of star formation, in agreement with the theoretical predictions. These Extreme Emission Line Galaxies, with high specific SFRs and shallow gravitational potential wells, are ideal places to test the theoretical prediction of strong feedback-driven outflows. Here we use deep MUSE spectroscopy to search these galaxies for signatures of outflowing material, namely kinematic offsets between absorption lines (in the restframe optical and UV), which trace cool gas, and the nebular emission lines, which define the systemic redshift of the galaxy. Although the EELGs are intrinsically very faint, stacked spectra reveal blueshifted velocity centroids for Fe II absorption, which is indicative of outflowing cold gas. This represents the first constraint on outflows in $M_\star < 10^9$ $M_\odot$ galaxies at $z = 1-2$. These outflows should regulate the star formation histories of low-mass galaxies at early cosmic times and thus play a crucial role in galaxy growth and evolution.

Keywords. galaxies: dwarf, galaxies: starburst, ISM: jets and outflows

1. Introduction

Within the standard cold dark matter (ΛCDM) framework, galaxies are predicted to live in dark matter halos that extend significantly beyond their visible boundaries. The exact interplay between the baryonic material and the dark matter is complex, but generally galaxies are not able to convert all of their baryons into stars: by combining the observed mass function of galaxies with N-body simulations of dark matter halos, Moster *et al.* (2010) parameterized the relationship between a galaxy's stellar mass and the mass of its dark matter halo. In all cases, this ratio is considerably lower than the cosmic baryon fraction, implying that star formation is an intrinsically inefficient process. The ratio of the two is a function of mass, such that both lower and higher mass galaxies have fractionally less stellar mass (star formation is most efficient in dark matter halos of mass $\sim 10^{12}$ $M_\odot$). We can thus assume that there are (at least) two separate feedback processes: star formation feedback is thought to dominate at low masses and active galactic nuclei (AGN) feedback is thought to dominate at high masses.

In particular, feedback from star formation occurs when supernovae or stellar winds inject mechanical energy into the interstellar medium (ISM) of a galaxy. Depending on

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the strength of this feedback, the gas can be ejected out of the main disk of the galaxy, suppressing subsequent star formation. One proxy for the feedback strength is the velocity of the outflowing material, typically traced by the kinematics of interstellar absorption lines. If there is a shell of gas being driven outwards, absorption lines that trace cold, low-ionization gas (such as Na I, Fe II, and Mg II) will be blueshifted with respect to the systemic redshift of the galaxy. Observations of galaxies in the local universe have shown scaling relations that exist over several orders of magnitude between the galaxy's current star formation rate (SFR) and the outflow velocity (e.g. Martin 2005). At higher redshifts, only the highest-mass galaxies can be observed, but even still they lie on the same scaling relations as at lower redshifts (e.g. Weiner *et al.* 2009).

Constraints on feedback in low mass galaxies at high-redshift are observationally difficult to make, so most of the progress on understanding star formation feedback in the early universe has been made in simulations. Sophisticated implementations of feedback from supernovae and stellar winds have allowed hydrodynamical simulations to successfully reproduce the properties of low-z galaxy population. One such simulation, FIRE (Feedback In Realistic Environments; Hopkins *et al.* 2014) predicts that star formation proceeds in an episodic fashion at low masses ($M_\star \lesssim 10^{10}$ $M_\odot$) at $z > 1$ (Muratov *et al.* 2015). This is significantly different than what is observed locally, where low-mass galaxies do not exhibit significant ongoing bursts of star formation (Lee *et al.* 2009).

In order to directly test this paradigm, then, we need to identify this population of low-mass, bursty galaxies at $z > 1$. With a strong burst of star formation comes strong nebular emission lines, such as [O III] $\lambda\lambda 4959, 5007$ and Hα, which could be strong enough to make an appreciable difference in the broad-band photometry of a low-mass galaxy. Exactly such a phenomenon was studied in van der Wel *et al.* (2011): many objects selected from broadband near-IR imaging with the Hubble Space Telescope (HST) have peculiar $I - J$ to $J - H$ colors: strong nebular [O III] emission at $z = 1.7$ produces this excess, with the Hα emission lying outside the coverage of the H-band. Slitless grism spectroscopy has subsequently confirmed the phenomenon generally at $z > 1$, revealing an abundant population of galaxies with high optical emission line equivalent widths (Maseda *et al.* 2013, 2014). With measured stellar masses of $\lesssim 10^9$ $M_\odot$, these are the ideal systems to search for signatures of star formation-driven outflows.

2. Observations and Results

We identify a sample of these Extreme Emission Line Galaxies (EELGs) in the near-IR slitless grism spectroscopy from the 3D-HST survey (Brammer *et al.* 2012), selecting those galaxies with an equivalent width of [O III] and/or Hα in excess of 250 Å. These galaxies were observed with MUSE on the ESO Very Large Telescope (PI: R. Bacon) providing $R \sim 3000$ spatially-resolved spectroscopy from $\sim 4650 - 9300$ Å. As part of the GTO program, we have observations of a $3' \times 3'$ area within the Hubble Ultra Deep Field to 6 hour depth and a $1' \times 1'$ subregion to 20 hour depth. For these EELGs we also require a MUSE detection of either [O II] $\lambda 3727$ or C III] $\lambda 1909$ to get a precise systemic redshift, leaving us with a sample of 38 galaxies (median V-band magnitude of 25.2).

A median stack of the rest-UV region of these spectra are shown in left panel of Figure 1. Clear Fe II absorption lines are visible, as well as Mg II in emission. In order to determine the amount of blueshift, we need to correct the stacked absorption line profiles for emission fill-in. To do this, we follow the procedure outlined in Zhu *et al.* (2015) where non-resonant Fe II* emission lines are used to estimate the intrinsic underlying emission profile and are iteratively combined with the observed absorption profile to

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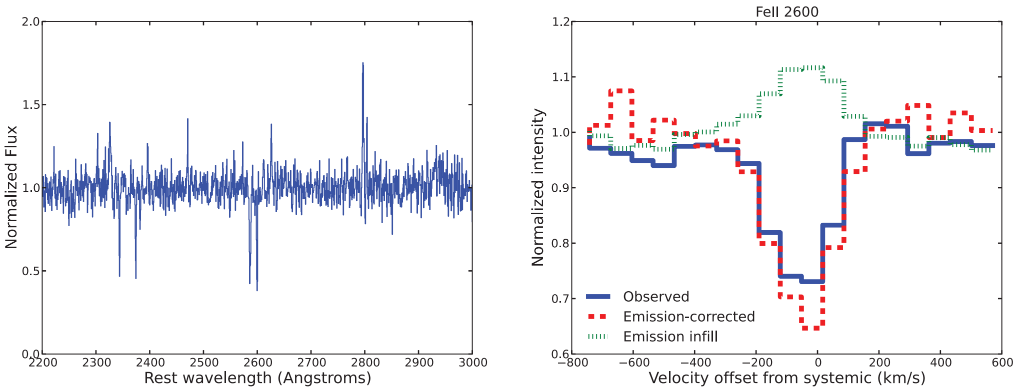

Figure 1. (Left) Median stack of the MUSE optical spectra of EELGs. The four Fe II absorption features are clearly visible in the stack even though they are not typically visible in individual objects. (Right) Decomposed line profile for one of the Fe II transitions (λ2600). Both the emission infill profile and the emission-corrected absorption profile show clear blue wings.

obtain a unified underlying (emission-corrected) absorption profile. An example of this decomposition is shown in the right panel of Figure 1.

It is clear that both the underlying emission and the intrinsic absorption profiles are blueshifted as evidenced by tails to negative velocities, indicative of the presence of outflowing material. The velocity-weighted centroid of the absorption profile is -40 km/s: for galaxies with these SFRs ($\sim 1 - 10$ $M_{\odot}$/yr), this outflow velocity is what is expected from the Martin (2005) scaling relation. Despite the fact that these galaxies have specific SFRs (SFR/$M_{\star}$) that are nearly a factor of 100 larger, implying that they are much lower mass than the Martin (2005) galaxies at the same SFR, we still see relatively low-velocity outflows. While duty cycle arguments could play a role (there is a physical time delay between the peak of star formation and the peak of the emission line strength), in general this result implies that the feedback processes operating at low-z are the same in these extreme star forming galaxies. Likewise, these outflows are not fast enough to eject the gas completely from the galaxy's dark matter halo, implying that the gas will remain to fuel future bursts of star formation.

This work is still ongoing, as we intend to reach a depth of 10 hours in the $3' \times 3'$ and 80 hours in the $1' \times 1'$ region. With deeper spectroscopy we will be able to include more objects in the stacks (since we require MUSE detections of faint emission lines), allowing us to create samples split by e.g. SFR or $M_{\star}$. The same analysis techniques can also be applied to higher mass galaxies, giving us the capability of testing the scaling relations over a larger dynamical range than previously possible.

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