CONFIRMATION OF SMALL DYNAMICAL AND STELLAR MASSES FOR EXTREME EMISSION LINE GALAXIES AT $z \sim 2$

Michael V. Maseda$^1$, Arjen van der Wel$^1$, Elisabete da Cunha$^1$, Hans-Walter Rix$^1$, Camilla Pacifici$^2$, Ivelina Momcheva$^3$, Gabriel B. Brammer$^4$, Marin Franx$^5$, Pieter van Dokkum$^3$, Eric F. Bell$^6$, Mattia Fumagalli$^5$, Norman A. Grogin$^4$, Dale D. Kocevski$^7$, Anton M. Koekemoer$^8$, Britt F. Lundgren$^8$, Danilo Marchesini$^9$, Erica J. Nelson$^3$, Shannong G. Patel$^8$, Rosalind E. Skelton$^{10}$, Amber N. Straughn$^{11}$, Jonathan R. Trump$^{12}$, Benjamin J. Weiner$^3$, Katherine E. Whitaker$^3$, and Stijn Wuyts$^{13}$

$^1$Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; maseda@mpia.de
$^2$Yonsei University Observatory, Yonsei University, Seoul 120-749, Korea
$^3$Department of Astronomy, Yale University, New Haven, CT 06520, USA
$^4$Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
$^5$Leiden Observatory, Leiden University, Leiden, The Netherlands
$^6$Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA
$^7$Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA
$^8$Department of Astronomy, University of Wisconsin, 475 N Charter Street, Madison, WI 53706, USA
$^9$Physics and Astronomy Department, Tufts University, Robinson Hall, Room 257, Medford, MA 02155, USA
$^{10}$South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa
$^{11}$Astrophysics Science Division, Goddard Space Flight Center, Code 665, Greenbelt, MD 20771, USA
$^{12}$University of California Observatories/Lick Observatory and Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
$^{13}$Steward Observatory, 933 N. Cherry St., University of Arizona, Tucson, AZ 85721, USA
$^{14}$Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany

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ABSTRACT

Spectroscopic observations from the Large Binocular Telescope and the Very Large Telescope reveal kinematically narrow lines ($\sim 50$ km s$^{-1}$) for a sample of 14 extreme emission line galaxies at redshifts $1.4 < z < 2.3$. These measurements imply that the total dynamical masses of these systems are low ($\lesssim 3 \times 10^9 M_\odot$). Their large [O III] $\lambda 5007$ equivalent widths ($500$–$1100$ Å) and faint blue continuum emission imply young ages of $10$–$100$ Myr and stellar masses of $10^8$–$10^9 M_\odot$, confirming the presence of a violent starburst. The dynamical masses represent the first such determinations for low-mass galaxies at $z > 1$. The stellar mass formed in this vigorous starburst phase represents a large fraction of the total (dynamical) mass, without a significantly massive underlying population of older stars. The occurrence of such intense events in shallow potentials strongly suggests that supernova-driven winds must be of critical importance in the subsequent evolution of these systems.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: starburst

1. INTRODUCTION

The $z > 1$ universe contains a remarkably large number of galaxies with extremely luminous emission line emissions in comparison to their faint blue continua (van der Wel et al. 2011). These extreme emission line galaxies (EELGs) can have [O III] and/or H$\alpha$ equivalent widths (EWs) in excess of $500$ Å (Atek et al. 2011; van der Wel et al. 2011; Shim et al. 2011; Brammer et al. 2012a). Such observations suggest that young starbursts dominate the energy output of these otherwise faint galaxies, potentially serving as the principle mode of mass build-up in low-mass galaxies. While similar objects exist at $z < 1$ (Cardamone et al. 2009; Izotov et al. 2011), they have a much lower comoving number density thereby implying that their abundance is a strong function of time.

Without further information, the dwarf interpretation of these galaxies is merely plausible. More massive populations of older stars could easily be outshone by the young starbursts: an old stellar population can have mass-to-light ratios up to 50 times larger than those of the bursts in the near-IR (NIR), so the main uncertainty in the interpretation of the observations hinges on the determination of the total masses of these systems. Additionally, the presence of strong emission lines can hinder attempts to determine the stellar mass content, as standard spectral energy distribution (SED)-fitting codes do not contain emission line contributions. Hence we do not yet understand the role of this mode of star formation in the broader context of galaxy formation. When these bursts occur in truly low-mass galaxies ($\sim 10^8 M_\odot$), the EELGs may represent the main formation mode of present-day dwarf galaxies, as argued by van der Wel et al. (2011). Alternatively, if these bursts are embedded in more massive systems ($\gtrsim 10^9 M_\odot$), we may be witnessing the early formation stage of Milky Way type galaxies.

Accurate mass estimates are key in addressing this issue, particularly dynamical masses. For this purpose we now present NIR spectroscopy of 14 EELGs at redshifts $1.4 < z < 2.3$ with [O III] $\lambda 5007$ EWs $> 500$ Å from the Large Binocular Telescope (LBT) and the Very Large Telescope (VLT). These are the first dynamical mass measurements of such low-mass, high-redshift galaxies, and we also derive accurate stellar mass estimates through stringent modeling of the continuum and emission line measurements from CANDELS multi-wavelength photometry (Grogin et al. 2011; Koekemoer et al. 2011) and low-resolution grism spectroscopy from the 3D-HST survey (Brammer et al. 2012b).

We adopt a flat $\Lambda$CDM cosmology with $\Omega_m = 0.3$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ throughout.
2. CANDIDATE SELECTION AND OBSERVATIONS

We select a sample of 17 objects with rest-frame EWs > 500 Å in [O iii] λ5007: five are from the photometrically selected sample of van der Wel et al. (2011) in the GOODS-S and UKIDSS Ultra-Deep Survey (UDS) fields, and the 12 remaining objects were selected based on their 3D-HST grism spectra in the COSMOS, GOODS-S, and UDS fields. One object, COSMOS-10320, although fulfilling the criteria, exhibits broad and asymmetric [O iii] (and also Hα) of 240 ± 10 km s⁻¹. As this object is an obvious outlier (with a potential active galactic nucleus contribution), we exclude it from the subsequent analysis and focus on the remaining 16 objects. Although the targets are very faint in the continuum (with a potential active galactic nucleus contribution), we estimate the dynamical masses according to

\[ M_{\text{dyn}} = \frac{G r_{\text{eff}}^2 \sigma^2}{c^2}. \]  

(1)

Here, we have adopted the half-light radius \( r_{\text{eff}} \) as the virial radius. We take \( r_{\text{eff}} \) as the half-light radius from van der Wel

\[ \text{http://www.eso.org/sci/software/pipelines/xshooter/xsh-pipe-recipes.html} \]

\[ \text{http://www.ucolick.org/~xavier/IDL/} \]
et al. (2012), who provide size measurements from the F125W and F160W Hubble Space Telescope (HST)/Wide Field Camera 3 (WFC3) CANDELS imaging. We choose the filter that does not contain the [O ii] emission line to ensure that the size is measured from the continuum light as much as possible. In cases where Hα is in F160W and [O ii] is in F125W, we use the F160W size as [O ii] is brighter and therefore may affect the broadband flux more. For objects in which the only line is [O ii] in F125W, van der Wel et al. (2011) note that the sizes measured in both bands are still consistent. The typical r_{\text{eff}} is 1 kpc, which is larger than the HWHM of the point-spread function, so these sources are indeed resolved. As noted in Weiner et al. (2006), kinematic estimates using line widths yields a variety of results: Rix et al. (1997) calculate C = 2.8 for inclined rotating disks, while Barton & van Zee (2001) calculate C = 2.1 for blue compact dwarfs; Erb et al. (2006) use a simple geometric correction to obtain C = 3.4. Here we adopt C = 3, with a conservative uncertainty of 33%, as in Rix et al. (1997). Note that this value of C would be the same if we assume that these systems are spherical. We find that the 14 EELGs have log(M_{\text{dyn}}/M_\odot) ranging from 8.7 to 9.7, with a median of 9.1 and an average uncertainty of 0.3.

There are several potential systematic effects that may affect these estimates. First, for these systems the measured half-light radius is not necessarily equal to the virial radius. Indeed, some have irregular morphologies that are not well fit by single-component profiles. Second, these systems likely have an irregular dynamical structure and may not be virialized.

3.2. Stellar Mass Measurements

With confirmed redshifts, measured EWs of multiple lines, and multi-wavelength photometry, we are now in a position to estimate the stellar masses and improve upon the photometry-only method of van der Wel et al. (2011). We take 0.3–2.2 μm photometry for the two objects in the GOODS-S field from Guo et al. (2013) and the six objects in the UDS field from Galametz et al. (2013). Visual inspection of the IRAC Ch. 1/2 images reveal that eight out of 14 objects have bright neighboring objects that contaminate the flux measurements. For consistency we perform our analysis without IRAC flux measurements for any of the objects, but we note that for those with uncontaminated IRAC fluxes, our modeling results (see below) do not change significantly. That is, the available IRAC fluxes do not reveal an underlying, older population of stars.

Table 1

| ID          | R.A. (deg) | Decl. (deg) | Instrument | zspec | EW([OIII]5007) (Å) | σ([OIII]5007) (km s^{-1}) | M_{dyn} (M_\odot) | M_{\text{MAGPHYS}} (M_\odot) |
|-------------|------------|-------------|------------|--------|------------------|-------------------------|------------------|-----------------------------|
| COSMOS-15144 | 150.156769 | 2.360800    | LUCI1      | 1.412  | 1130 ± 247       | 43.3 ± 8.9              | 9.11 ± 0.34      | 8.10^{+0.29}_{-0.26}       |
| COSMOS-13848 | 150.176987 | 2.345390    | LUCI1      | 1.444  | 888 ± 351        | 46.7 ± 14.4             | 9.22 ± 0.40      | 8.58^{+0.14}_{-0.22}       |
| COSMOS-12807 | 150.159546 | 2.333301    | LUCI1      | 1.583  | 628 ± 152        | 38.2 ± 10.0             | 8.88 ± 0.37      | 7.95^{+0.18}_{-0.24}       |
| UDS-7444     | 34.473888  | −5.234233   | X-Shooter  | 1.621  | 713 ± 42         | 71.1 ± 5.7              | 9.66 ± 0.33      | 8.78^{+0.07}_{-0.16}       |
| COSMOS-16207 | 150.183090 | 2.372948    | LUCI1      | 1.649  | 536 ± 20         | 47.7 ± 9.5              | 9.40 ± 0.34      | 8.43^{+0.17}_{-0.12}       |
| UDS-7760     | 34.428570  | −5.255318   | X-Shooter  | 1.664  | 731 ± 86         | 48.2 ± 5.9              | 9.04 ± 0.31      | 7.98^{+0.11}_{-0.09}       |
| UDS-3646     | 34.426483  | −5.255770   | X-Shooter  | 1.687  | 701 ± 95         | 54.7 ± 6.1              | 9.47 ± 0.33      | 8.51^{+0.12}_{-0.13}       |
| GOODS-S-17892| 53.071293  | −27.759146  | LUCI1      | 1.687  | 693 ± 47         | 52.3 ± 5.7              | 9.05 ± 0.30      | 8.95^{+0.10}_{-0.11}       |
| GOODS-S-26816| 53.071293  | −27.705800  | X-Shooter  | 1.738  | 861 ± 66         | 54.4 ± 4.5^a          | 8.86 ± 0.31      | 8.53^{+0.09}_{-0.11}       |
| UDS-11484    | 34.431400  | −5.212120   | LUCI1      | 2.185  | 723 ± 95         | 54.2 ± 9.4              | 9.35 ± 0.34      | 8.97^{+0.03}_{-0.01}       |
| COSMOS-11212 | 150.124237 | 2.313672    | LUCI1      | 2.199  | 598 ± 189        | 40.3 ± 8.9              | 8.78 ± 0.36      | 8.77^{+0.23}_{-0.26}       |
| COSMOS-8991  | 150.095352 | 2.287247    | LUCI1      | 2.220  | 714 ± 85         | 30.9 ± 9.0              | 8.65 ± 0.40      | 9.05^{+0.21}_{-0.27}       |
| UDS-14655    | 34.391373  | −5.195310   | LUCI1      | 2.297  | 503 ± 34         | 61.0 ± 10.8             | 9.67 ± 0.33      | 9.37^{+0.11}_{-0.31}       |
| UDS-4501     | 34.390755  | −5.250803   | LUCI1      | 2.298  | 803 ± 162        | 57.8 ± 9.7              | 9.07 ± 0.33      | 8.32^{+0.09}_{-0.19}       |

Notes. All IDs refer to the CANDELS catalog for that particular field (COSMOS, UDS, or GOODS-S), all EWs are quoted in the rest frame, and all masses are log quantities.

a Hα width.

http://www.iap.fr/magphys/magphys/MAGPHYS.html

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using the Starburst99 models (Leitherer et al. 1999). In Figure 3 we compare our stellar mass estimates with those estimated using the photometric method. Our values are 1.1 larger in the median, with a scatter of 0.20 dex. The MAGPHYS modeling results reinforce the notion that these galaxies are dominated, in terms of stellar mass, by a very young stellar population. While the MAGPHYS modeling uses much more information, the crucial elements in both mass estimates are the blue continuum and the strong emission lines, which strongly constrain any modeling approach.

Figure 4 compares the MAGPHYS stellar mass estimates with the dynamical estimates. log(M\(_{\text{dyn}}\)/M\(_*\)) = 0.57 (27% of the total mass is in stars) ±0.21 (random) ±0.34 (systematic) for the sample where the 0.34 dex systematic uncertainty is from the dynamical mass (see Section 2). The 0.21 dex random uncertainty contains the contributions from the measurement uncertainties and the limited sample size. The three points closest to the M\(_{\text{dyn}}\) = M\(_*\) line illustrate the challenges to any modeling approach. Two of them are the only z ∼ 2.2 galaxies from the COSMOS sample, where the four-band CANDELS photometry does not sample any continuum redward of [OIII] (one of which is also severely contaminated by an OH sky line, making our line dispersion estimate more of a lower limit), and the third is an object with two distinct components in the WFC3 imaging, where the assumptions contained in the dynamical mass estimate may not accurately reflect the true conditions in the system.

The low dynamical masses confirm the low-mass nature of these systems directly and exclude the presence of large amounts of unseen stars, gas, dust, or dark matter that exceed the observed amount of stellar matter by more than a factor of five. Our implied maximal gas fractions do not exceed those for more massive galaxies at similar redshifts, which range from ∼30%–80% (Daddi et al. 2010; Tacconi et al. 2013). As seen in Figure 4, our galaxies have similar M\(_{\text{dyn}}\)/M\(_*\) ratios to the star-forming sample of Erb et al. (2006), albeit with EWs (and hence specific star formation rates) that are a factor of four higher.

4. CONCLUDING REMARKS

In this Letter, we show kinematic line widths in the range 30–70 km s\(^{-1}\) for a sample of 14 EELGs (with EW > 500 Å) at redshifts 1.4 < z < 2.3. This constitutes the first direct mass measurements for such galaxies at these epochs, with total masses ∼10\(^{9.1}\) M\(_\odot\). SED modeling results in stellar masses ∼10\(^{8.5}\) M\(_\odot\), ruling out the presence of an evolved, massive stellar population. Therefore, we conclude that these nascent galaxies are undergoing intense starbursts, and the stars produced in the single burst contribute substantially to their total mass budget. This confirms that the abundant population of EELGs at z > 1 demonstrate a common starburst phase among low-mass galaxies at these epochs, the intensity of which has only recently been reproduced by hydrodynamical simulations (Shen et al. 2013). While the contribution of such strong starbursts to the growth in stellar mass over cosmic time depends on their duty cycle, which is so far unconstrained observationally, their ubiquitous nature at these redshifts (van der Wel et al. 2011) points toward the brief starburst phase as important in the mass build-up of most (if not all) dwarf galaxies.

Given the intensity of the starbursts and the shallow potential wells in which they occur, supernova-driven winds likely dominate the star formation history and subsequent evolution of these systems (Larson 1974). The starbursts may affect the central dark matter distribution (e.g., Navarro et al. 1996; Read & Gilmore 2005; Pontzen & Governato 2012; Zolotov et al. 2012) and produce cored profiles that are commonly observed in present-day, low-mass galaxies. For a review see de Blok (2010), and Walker & Peñarrubia (2011) and Amorisco & Evans (2012) for recent advances. Our current data set does not allow us to make stronger conclusions about the presence of feedback and winds via asymmetric or separate broad/narrow components in individual galaxies. However, with future spectroscopic studies of these objects, we will be able to search for such signals in stacked spectra.

In the present-day universe, such extreme starbursts are very rare (e.g., Cardamone et al. 2009), but at early epochs (z > 4–6) such events may well be the rule rather than the exception. It is becoming increasingly clear that strong emission lines affect the search for and interpretation of high-z galaxies. Strong emission line galaxies at moderate redshifts (z ∼ 2) can masquerade...
as drop-out selected $z > 10$ candidates (see discussion in, e.g., Coe et al. 2013; Bouwens et al. 2013; Ellis et al. 2013; Brammer et al. 2013). Furthermore, for true high-redshift galaxies these strong emission lines are likely omnipresent (Smit et al. 2013) and affect the broadband SED, so they should therefore be included in the modeling as described here in Section 3.2 (also see Curtis-Lake et al. 2013; Schaerer et al. 2013). However, the results presented here are encouraging. We suggest that if strong emission lines are evident, then it is likely that the total stellar mass does not greatly exceed the mass of the young stellar population traced by the blue continuum.

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Facilities: LBT, VLT:Melipal, HST

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