Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
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Low Metallicity Galaxies at $z \sim 0.7$: Keys to the Origins of Metallicity Scaling Laws

David J. Rosario[1], Carlos Hoyos[2], David Koo[1] and Andrew Phillips[1]

[1]Dept. of Astronomy and Astrophysics, University of California – Santa Cruz,
Santa Cruz, California, USA, 95064
email: rosario@ucolick.org, koo@ucolick.org, phillips@ucolick.org

[2]Departmento de Fisica Teórica, Universidad Autónoma de Madrid, Carretera de Colmenar
Viejo kn 15.600 28049, Madrid, Spain
email: charly.hoyos@uam.es

Abstract. We present a study of remarkably luminous and unique dwarf galaxies at redshifts of $0.5 < z < 0.7$, selected from the DEEP2 Galaxy Redshift survey by the presence of the temperature sensitive [OIII]λ4363 emission line. Measurements of this important auroral line, as well as other strong oxygen lines, allow us to estimate the integrated oxygen abundances of these galaxies accurately without being subject to the degeneracy inherent in the standard R_{23} system used by most studies. [O/H] estimates range between 1/5–1/10 of the solar value. Not surprisingly, these systems are exceedingly rare and hence represent a population that is not typically present in local surveys such as SDSS, or smaller volume deep surveys such as GOODS.

Our low-metallicity galaxies exhibit many unprecedented characteristics. With B-band luminosities close to L_*, thse dwarfs lie significantly away from the luminosity-metallicity relationships of both local and intermediate redshift star-forming galaxies. Using stellar masses determined from optical and NIR photometry, we show that they also deviate strongly from corresponding mass-metallicity relationships. Their specific star formation rates are high, implying a significant burst of recent star formation. A campaign of high resolution spectroscopic follow-up shows that our galaxies have dynamical properties similar to local HII and compact emission line galaxies, but mass-to-light ratios that are much higher than average star-forming dwarfs.

The low metallicities, high specific star formation rates, and small halo masses of our galaxies mark them as lower redshift analogs of Lyman-Break galaxies, which, at $z \sim 2$ are evolving onto the metallicity sequence that we observe in the galaxy population of today. In this sense, these systems offer fundamental insights into the physical processes and regulatory mechanisms that drive galaxy evolution in that epoch of major star formation and stellar mass assembly.

Keywords. surveys, galaxies: abundances, galaxies: kinematics, galaxies: starburst

1. Introduction

The evolution of metal abundances in galaxies is inextricably linked to a host of physical processes and properties which determine their baryonic distribution, such as star formation regulation, stellar mass functions, ISM mixing, outflows and gaseous infall, supernova enrichment, stellar winds, and grain formation and depletion. A broad brush panorama of the complex interplay of these different forces is empirically manifested in the form of the Stellar Mass-Metallicity Relationship (MZR), apparent in both gaseous and stellar abundances. Work with local galaxy samples (e.g., Tremonti *et al.* 2004, Lee *et al.* 2006) show that the expected metallicity of a galaxy increases with increasing stellar content, over 5 orders of magnitude in stellar mass with roughly constant scatter. Various models exist to explain the form of this trend, though current observational constraints are unable to easily distinguish between them. A number of authors in these proceedings

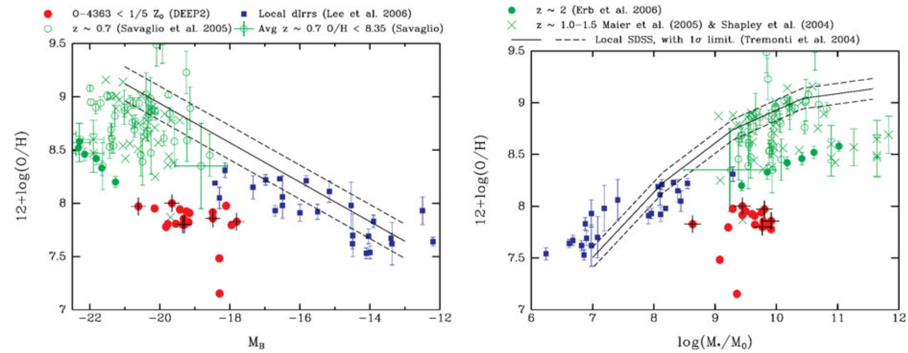

Figure 1. Luminosity-Metallicity Relation (LZR – left) and Mass-Metallicity Relation (MZR – right) for the 4363-selected DEEP2 galaxies (red points), compared to other local, intermediate and high-redshift samples. The solid and dashed black lines are the mean trend and 1σ scatter for SDSS galaxies from Tremonti *et al.* (2004). The green error bars are the mean for $z \sim 0.7$ galaxies of Savaglio *et al.* (2005) in the same luminosity and mass range of our sample.

explore the theoretical ramifications of various classes of models, such as those dominated by stellar feedback, or those with mass dependent star-formation efficiencies.

In this contribution, we discuss a new sample of intermediate redshift dwarf galaxies which have remarkably low metallicities for their measured luminosities and stellar content. More details of this study can be found in Hoyos *et al.* (2005) and Hoyos *et al.* (2008).

2. The Sample: Dataset, Selection and Measurements

The DEEP2 Redshift Survey is currently the deepest and most complete large-volume extragalactic spectroscopic survey at $z \sim 1$. The survey dataset consists of Keck/DEIMOS slit spectra of galaxies brigher than $R_{AB} = 24.1$ in four widely separated fields, over a wavelength range of approximately 6500–9000 Å. Compared to previous galaxy redshift surveys of similar depth, DEEP2 is quite efficient, yielding redshifts accurate to better than 2σ in roughly 70% of the slits. Details of the DEEP2 survey can be found in Coil *et al.* (2004) (photometry), Davis *et al.* (2003) (survey design) and Davis *et al.* (2005) (mask-making strategy and first results).

Low-metallicity galaxies were selected by searching for the [OIII]λ4363 auroral emission line in the DEEP2 spectral dataset, through a combination of automated line-fitting and visual inspection of candidates. This yielded a final sample of 25 galaxies with bonafide [OIII]λ4363 detections between the redshifts $0.55 < z < 0.7$. This choice of redshift range ensures that the [OIII]$\lambda\lambda 4959, 5007$ doublet and Hβ are also in the spectrum. Gaussian fits were made to the emission lines of the [OIII] triplet, Hβ, and where possible, the [OII]$\lambda\lambda 3726, 3729$ doublet, from which line fluxes were estimated after applying a standardized flux calibration determined for DEIMOS spectra. For galaxies in the lower redshift range of our sample, the [OII] line lies beyond the blue end of the spectra, so its strength was estimated from Hβ using the strong correlation between the equivalent widths (EWs) of the two lines found for the other sample galaxies.

3. Metallicities, Luminosities and Stellar Masses

The ratio [OIII]$\lambda\lambda 4363/5007$ is a sensitive indicator of the electron temperature in the [OIII]-emitting gas. Through the use of photoionization models of HII regions, the

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temperature of the [OII]-emitting zone can then be evaluated, enabling an unbiased estimate of the light-weighted oxygen abundance of the gas in the star-forming region. Following the procedure of Pérez-Montero & Díaz (2003) and using calibrations from Pagel *et al.* (1992), we estimate oxygen abundances for our galaxies in the range of $7.4 < 12 + [O/H] < 8.3$, with typical uncertainties around 0.1 dex, comparable to that of local BCDs.

Accurate stellar masses are the key to understanding the inter-relationship between stellar processes and metal enrichment in our galaxies and, consequently, must be determined as accurately as possible. We combine optical BRI and NIR K_s-band photometry in two independent ways to estimate the stellar masses of our sample. Our principal method is as follows: after correcting the rest-frame colors for the substantial emission line and nebular continuum contamination (0.16 mag in $U - B$ and 0.2 mag in $B - V$), we fit the BRI (and, where possible, K_s) colors of our galaxies with low-metallicity two-burst BC03 models (Bruzual & Charlot 2003), optimizing the relative fractions of the two SSP components, as well as the age of the older component. The age of the youngest burst was fixed at 2 Myr, consistent with the average EW of Hβ in the spectra of the 4363-selected sample. The resultant stellar masses have statistical uncertainties of about 0.2 dex.

These were compared to masses derived from the prescription of Lin *et al.* (2007), which are based on $BRIK_s$ SED fits to the main set of DEEP2 galaxies. Using this approach gives masses that are very comparable to the more detailed method described above. In the rest of this proceedings, including in all figures, we will adopt the stellar masses determined by the two-burst BC03 fits.

Restframe B-band luminosities of our galaxies were determined using k-corrections calculated from SED fits to the overall DEEP2 galaxy sample, following the method of Willmer *et al.* (2006).

In addition to oxygen abundances, luminosities and stellar masses, we derive star-formation rates (SFRs) from the Hβ flux, along the lines of Kennicutt *et al.* (1994). Our galaxies have intermediate to high Specific SFRs (i.e., the SFR per unit stellar mass – a measure of recent to past star-formation). Roughly half have among the highest SSFRs of all DEEP2 star-forming systems. Clearly, our galaxies are going through a burst of substantial current star-formation, which supports the choice of a two-burst framework in the estimation of their stellar masses.

4. Metallicity Scaling Relations

In Fig. 1, we plot the Luminosity-Metallicity and Mass-Metallicity relations (LZR and MZR) for our sample, compared to local SDSS galaxies (Tremonti *et al.* 2004) and local dIrrs (Lee *et al.* 2006), as well as normal star-forming galaxies at intermediate redshifts (Shapley *et al.* 2004, Savaglio *et al.* 2005, Maier *et al.* 2005) and high redshifts (Erb *et al.* 2006). Remarkably, our objects deviate strongly from both local scaling laws and those at comparable redshifts, by as much as 0.8 dex.

The abundances for all the comparison samples in Fig. 1 are derived from strong line methods, such as R_{23} and the N/O calibration. In particular, the use of the R_{23} assumes in all cases that the galaxies lie along a high metallicity branch, which places a lower limit on the abundances that can be derived by this method. Clearly, the galaxies in our sample have luminosities and stellar masses comparable to some normal star-forming systems, but with much lower metallicities. The unchecked use of R_{23} can alter the form and scatter of metallicity scaling relations, as well as result in incorrect abundances for a fraction of star-forming systems. Care must be taken when applying this method to

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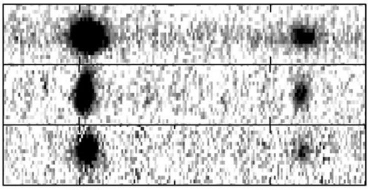

Figure 2. Sections of DEEP2 two-dimensional spectra of three 4363-selected galaxies, showing the Hγ and [OIII]λ4363 lines.

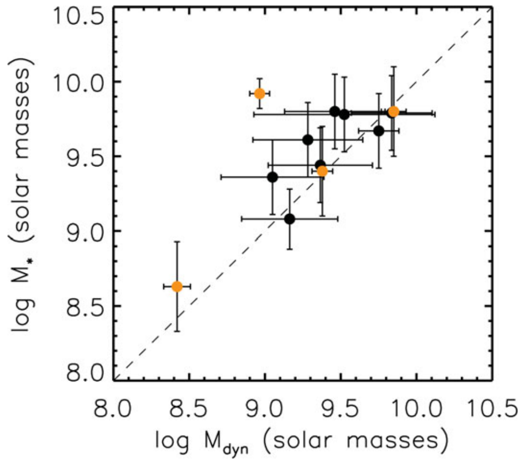

Figure 3. Dynamical vs. Stellar Masses for 4363-selected galaxies with Keck/HIRES spectra. Four galaxies with resolved HST/ACS images in AEGIS are plotted as yellow points. For the black points, M_{dyn} is estimated assuming $R_{em} = 2$ kpc, with a 0.3 dex uncertainty in the radius reflected in the errors. The dashed line has a slope of unity.

derive abundances in large-volume extragalactic spectral datasets or those with complex selection functions.

The locations of our sample galaxies in the LZR and MZR imply that they are analogs of normal star-forming systems at $z \gtrsim 2$, such as Lyman-Break Galaxies (LBGs). They promise to serve as testbeds for the physical conditions and processes which evolve such systems to the galaxy population of today.

5. Dynamical Masses and Mass-to-Light Ratios

The emission line properties of the 4363-selected sample are very similar to local HII galaxies, as well as Compact Narrow-Emission Line Galaxies (CNELGs) found at intermediate redshifts (Koo *et al.* 1995). To compare their dynamical properties as well, we embarked on a program on Keck/HIRES spectroscopy to get resolved line widths and line profiles for most of our sample objects. Despite the optical faintness of these galaxies, their high emission line EWs ensured clean line measurements in all cases. From our measured line widths σ (in km/s), we estimate a dynamical mass using the following relation (from Guzmán *et al.* 2003): $M_{dyn}/M_{\odot} = 1.1 \times 10^6 \ R_{em} \ \sigma^2$. Here, R_{em} is the half-light radius of the line emitting distribution of the galaxy, in kpc. Since we lack resolved imaging for most of our sample, we assume $R_{em} \sim 2$ kpc (but see below).

In Fig. 3, we plot the stellar mass of the galaxies with HIRES spectra against their dynamical masses. Quite unexpectedly, they are roughly the same, within the degree of uncertainty of the stellar and dynamical masses (about 0.2 dex). Implied total mass-to-light ratios (M/L) are around unity, very low compared to normal dwarf galaxies with similar kinematic properties, which typically have M/L $\sim 10 - 100$ or more. This result is fairly insensitive to the method of dynamical mass estimates or the half-light radius of the galaxy, which may account for factors of a few in dynamical mass.

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We sought to test our assumptions about the size of these systems using the four galaxies from our sample that have HST/ACS V- and I-band imaging as part of the All-Wavelength Extended Groth Strip International Survey (AEGIS – Davis *et al.* 2007). The measured size of the star-forming region in these galaxies range from $0.5 - 3$ kpc. They data points for these four galaxies (yellow points in Fig. 3) scatter nicely about the mean trend for the sample as a whole, which leads us to believe that the size of the line-emitting region (which is also the size of the star-forming region) is not a key source of systematic error in this analysis.

6. Interpretation and Conclusions

To summarize, the 4363-selected galaxies from DEEP2 have significantly lower abundances than average galaxies of the same brightness or stellar mass. In addition, they have mass-to-light ratios typical of baryonically dominated systems, unlike most isolated dwarfs. What mechanism may explain this combination of properties? Possibilities include top-heavy IMFs, the infall of primordial gas onto an older galaxy, or dwarf AGN. A more likely explanation is that these objects are mergers of dwarf systems, one or both of which are rich in low metallicity gas. We speculate that, given the importance of low-mass mergers in the early universe, observational studies of the metallicity evolution of high redshift galaxies may be subject to biased or inaccurate abundance determinations. Studies of the relative frequency, environments and clustering properties of our sample are underway and we hope to shed more light on these fascinating galaxies in the near future.

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