Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
Proceedings IAU Symposium No. 255, 2008
L.K. Hunt, S. Madden & R. Schneider, eds.

doi:10.1017/S1743921308024654

LSD and AMAZE: the mass-metallicity relation at z > 3

F. Mannucci[1] and R. Maiolino[2]†

[1]INAF - IRA, Largo E. Fermi 5, I-50125, Firenze, Italy
email: filippo@arcetri.astro.it

[2]INAF - OAR, Roma

Abstract. We present the first results on galaxy metallicity evolution at $z > 3$ from two projects, LSD (Lyman-break galaxies Stellar populations and Dynamics) and AMAZE (Assessing the Mass Abundance redshift Evolution). These projects use deep near-infrared spectroscopic observations of a sample of ∼40 LBGs to estimate the gas-phase metallicity from the emission lines. We derive the mass-metallicity relation at $z > 3$ and compare it with the same relation at lower redshift. Strong evolution from $z = 0$ and $z = 2$ to $z = 3$ is observed, and this finding puts strong constraints on the models of galaxy evolution. These preliminary results show that the effective oxygen yields do not increase with stellar mass, implying that the simple outflow model does not apply at $z > 3$.

Keywords. galaxies: abundances, galaxies: formation, galaxies: high-redshift, galaxies: starburst

1. Introduction

Metallicity is one of the most important property of galaxies, and its study is able to shed light on the detailed properties of galaxy formation. It is an integrated property, not related to the present level of star formation the galaxy, but rather to the whole past history of the galaxy. In particular, metallicity is sensitive to the fraction of baryonic mass already converted into stars, i.e., to the evolutive stage of the galaxy. Also, metallicity is affected by the presence of inflows and outflows, i.e., by feedback processes and the interplay between the forming galaxy and the intergalactic medium.

It is well known that local galaxies follow a well-defined mass-metallicity relation, where galaxies with larger stellar mass have higher metallicities (Tremonti *et al.* 2004, Lee *et al.* 2006). The origin of the relation is uncertain because several effects can be, and probably are, active. It is well known that in the local universe starburst galaxies eject a significant fraction of metal-enriched gas into the intergalactic medium because of the energetic feedback from exploding SNe, both core-collapse and, possibly, type Ia (Mannucci *et al.* 2006). Outflows are expected to be more important in low-mass galaxies, where the gravitational potential is lower and a smaller fraction of gas is retained. As a consequence, higher mass galaxies are expected to be more metal rich (see, for example, Edmunds 1990, Garnett 2002). A second possibility is related to the well known effect of “downsizing” (e.g., Cowie *et al.* 1996), i.e., lower-mass galaxies form their stars later and on longer time scales. At a given time, lower mass galaxies have formed a smaller fraction of their stars, therefore are expected to show lower metallicities. Other possibilities exist, for example some properties of star formation, as the initial mass function (IMF), could change systematically with galaxy mass (Köppen *et al.* 2007).

† on behalf of the LSD and AMAZE collaborations

All these effects have a deep impact on galaxy formation, and the knowledge of their relative contributions is of crucial importance. Different models have been built to reproduce the shape of the mass-metallicity relation in the local universe, and different assumptions produce divergent predictions at high redshifts (z > 2). To explore this issue several groups have observed the mass-metallicity relation in the distant universe, around z = 0.7 (Savaglio *et al.* 2005) and z = 2.2 (Erb *et al.* 2006). They have found a clear evolution with cosmic time, with metallicity for a given stellar mass decreasing with increasing redshift.

For several reasons, it is very interesting to explore even higher redshifts. The redshift range at z∼3–4 is particularly interesting: it is before the peak of the cosmic star formation density (see, for example, Mannucci *et al.* 2007), only a small fraction (15%, Pozzetti *et al.* 2007) of the total stellar mass has already been created, the number of mergers among the galaxies is much larger than at later times (Conselice *et al.* 2007). As a consequence, the prediction of the different models tend to diverge above z = 3, and it is important to sample this redshift range observationally. The observations are really challenging because of the faintness of the targets and the precision required to obtain a reliable metallicity. Nevertheless, the new integral-field unit (IFU) instruments on 8-m class telescopes are sensitive enough to allow for the project.

2. LSD and AMAZE

Metallicity at z∼3 can be obtained by measuring the fluxes of the main optical emission lines ([OII], Hβ, [OIII], Hα), whose ratios have been calibrated against metallicity in the local universe (Nagao *et al.* 2006, Kewley & Ellison 2008). Of course, this method can be applied only to line-emitting galaxies, i. e., to low-extinction, star-forming galaxies, whose line can be seen even at high-redshifts. In contrast, the gas metallicity of more quiescent and/or dust extincted galaxies, like EROs (Mannucci *et al.* 2002), DRGs (Franx *et al.* 2003), and SMGs (Chapman *et al.* 2005), cannot be easily measured at high redshifts †.

For the **AMAZE** project we observed 30 galaxies at z∼3.3 from various sources (see Maiolino *et al.* 2008 for details). We only selected galaxies having a good SPITZER/IRAC photometry (3.6–8 μm), an important piece of information to derive a reliable stellar mass. These galaxies were observed, in seeing-limited mode, with the integral-field unit (IFU) spectrometer SINFONI on ESO/VLT, with integration times between 3 and 6 hours. When computing line ratios, it is important that all the lines are extracted from exactly the same aperture, to avoid differential slit losses that could spoil the line ratio. In this, the use of an IFU is of great help. We observed the H and K bands simultaneously with spectral resolution R∼1500, providing a full coverage of all the most important lines. This paper is based on about 1/3 of the full data sample, while the remaining fraction is still under analysis.

For **LSD**, we extracted 10 galaxies from the UV-selected Lyman Break Galaxies (LBG) sample by Steidel *et al.* 2004. The aim of this project is not only to measure metallicities, but also to obtain spatially-resolved spectra to measure dynamics and spectral gradients. For this reason we used adaptive optics to obtain diffraction-limited images and spectra in the near-IR. The target galaxies were chosen to be within 30" of bright foreground stars, needed to drive the adaptive-optics system. As the presence of a nearby bright star is the only request, this sample, albeit small, is expected to be representative of the full population of the LBGs. For LSD we used SINFONI with the same resolution of

† Stellar metallicities, measured by absorption lines, can also be measured if enough observing time is provided, and will be the subject of a future work.

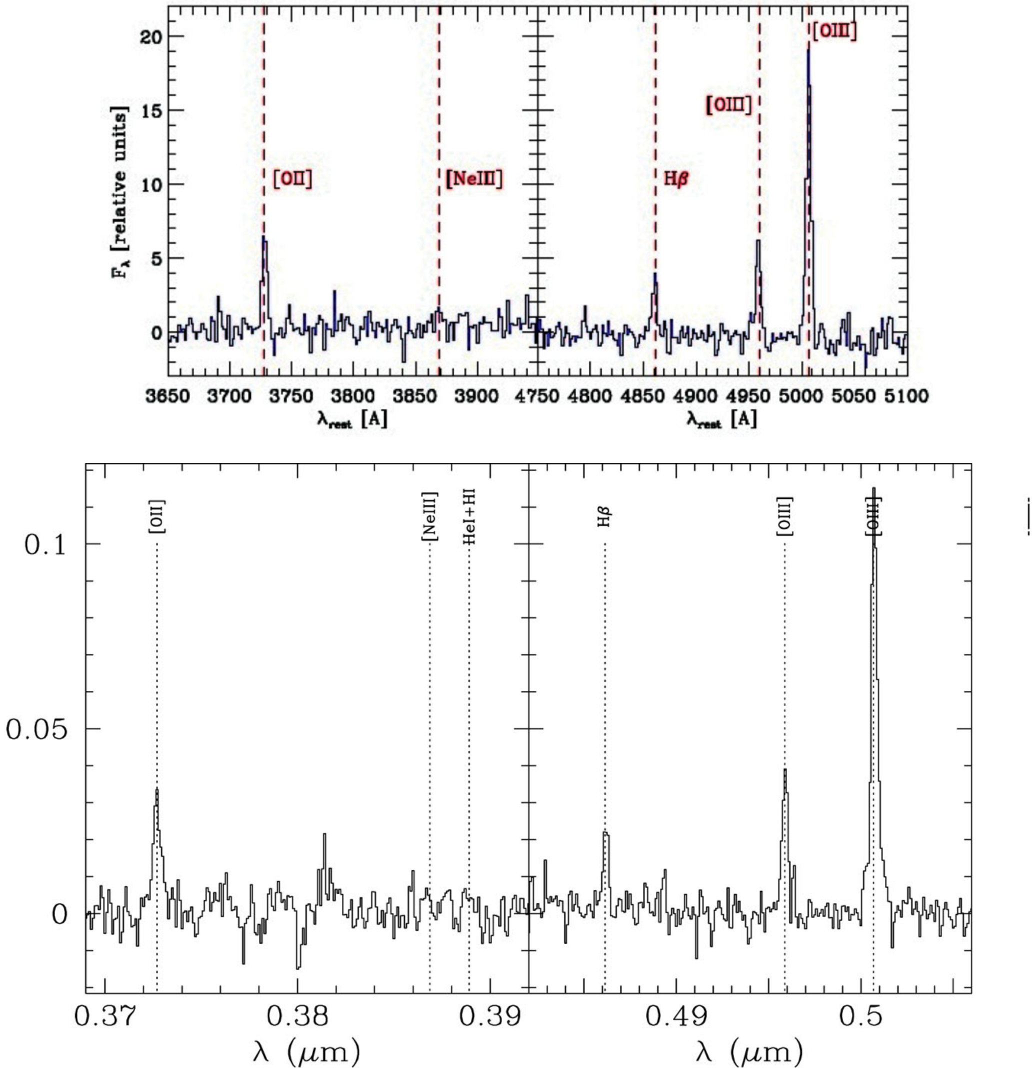

Figure 1. Composite spectra from AMAZE (top) and LSD (bottom).

AMAZE and similar integration times. About half of the LSD galaxies have been already analyzed. The typical spatial resolution is about 0.2”.

Fig. 1 shows the composite spectra of AMAZE (top) and LSD (bottom). For both AMAZE and LSD, the main optical lines are detected in most of the galaxies. A few targets also show the [NeIII]3869 line, an important piece of information to derive a robust measurement of metallicity (Nagao *et al.* 2006).

3. The Mass-metallicity relation and the effective yields

Stellar masses are derived by fitting the spectral-energy distributions (SEDs) with spectrophotometric models of galaxy evolutions, as detailed in Pozzetti *et al.* (2007) and Grazian *et al.* (2007). These fits also provide estimates of the age and dust extinction of the dominant stellar population. The presence, for most of the objects, of good IRAC

https://doi.org/10.1017/S1743921308024654 Published online by Cambridge University Press

photometry, allows the determination of reliable stellar masses as the SED is sampled up to the rest-frame J band.

Metallicities are derived by a simultaneous fit of all the available line ratios, as explained in Maiolino *et al.* (2008). In practice, the derived value is determined by the R23 indicator or, similarly, by the [OIII]5007/Hβ ratio, while the [OIII]5007/[OII]3727 ratio is used to discriminate between the two possible branches of these ratios. The [NeIII]3869/[OII]3727 line ratio is also very important, when both lines are detected. The uncertainties on metallicity are due to both the spread of the calibration and to the observational error on the line ratio, and on average amount to 0.2–0.3 dex.

Fig. 2 shows the resulting mass-metallicity relation, compared to the same relation as measured at lower redshift. A quantitative interpretation of this result will be given when the whole data sample will be analyzed. Nevertheless, a strong metallicity evolution can be seen, i.e., galaxies at z$\sim$3.1 have metallicities $\sim$6 times lower than galaxies of similar stellar mass in the local universe.

The presence, at z $>$ 3, of galaxies with relatively high stellar masses (log(M/M$\odot$) = 9-11) and low metallicity put strong constraints on the process dominating galaxy formation. Several published models (e.g., de Rossi *et al.* 2007, Kobayashi *et al.* 2007) cannot account for such a strong evolution, and the physical reason for this can be traced to be due to some inappropriate assumption, for example about feedback processes or

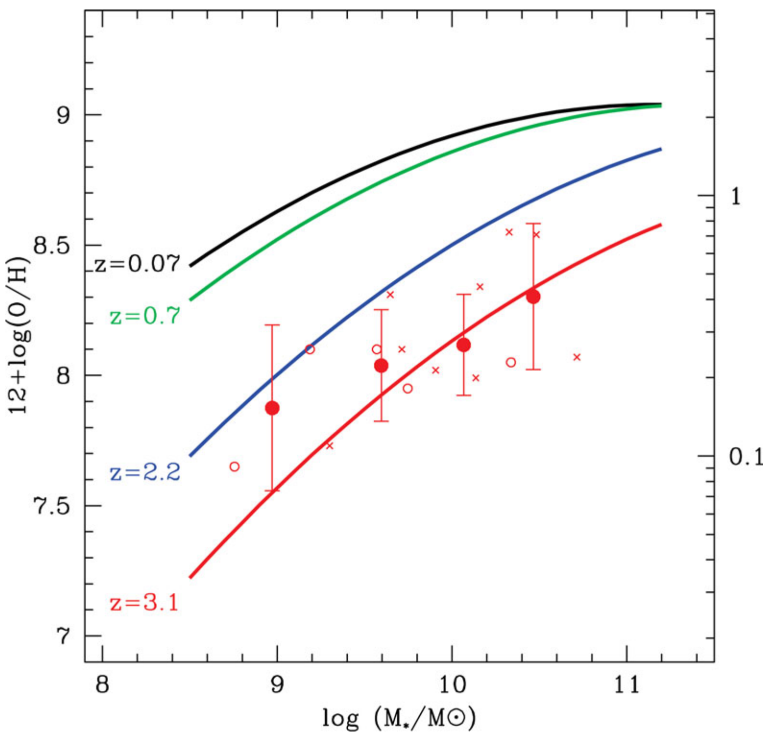

Figure 2. Evolution of the mass-metallicity relation from z = 0.07 (Kewley & Ellison 2008), to z = 0.7 (Savaglio *et al.* 2005), z = 2.2 (Erb *et al.* 2006) and z = 3.1 (AMAZE+LSD). All data have been calibrated to the same scale in order to make all the different results directly comparable. Crosses show the AMAZE galaxies, empty dots the LSD galaxies. Solid dots with error bars show the average metallicity of the galaxies in each stellar-mass bin, with the associated dispersion. The lines show quadratic fits to the data. The line corresponding to z = 3.1 shows the fit in Maiolino *et al.* (2008).

https://doi.org/10.1017/S1743921308024654 Published online by Cambridge University Press

merging history. When taken at face value, some other models (e.g., Brooks *et al.* 2007, Tornatore *et al.* 2007) provide a better match with the observations, but a meaningful comparison can only be obtained by taking into account all the selection effects and observational biases.

Important hints on the physical processes shaping the mass-metallicity relation can be understood by considering the effective yields, i.e., the amount of metals produced and retained in the galaxy per unit mass of formed stars. If outflows are the main effect in shaping the mass-metallicity relation, then the effective yields are expected to increase with stellar mass because all the galaxies have converted, on average, the same fraction of baryonic mass into stars, but lower mass galaxies have lost a larger fraction of metals into the intergalactic medium. This is what is observed in the local universe by Tremonti *et al.* (2004) (but not by Lee *et al.* 2006). For LSD and AMAZE, preliminary results show that the effective yields tend to decrease, rather than increase, with stellar mass, as in Erb *et al.* (2006). Such a decrease is partly due to selection effects (see Mannucci *et al.* in preparation, for a full explanation), but the observed trend seems to be larger than what can be attributed to the effects of biases. The presence of higher yields at lower stellar mass imply that outflows decreasing with galaxy mass are not the main driver of the mass-metallicity relation at $z > 3$, and different possibilities, related to the efficiency of star formation (e.g., Brooks *et al.* 2007) or different outflow schemes (Erb *et al.* 2006) must be considered.

References

Brooks, A. M., *et al.*, 2007, *ApJ*, 655, L17
Chapman, S. C., *et al.*, 2005, *ApJ*, 662, 772
Conselice, S. C., *et al.*, 2007, *MNRAS*, 386, 909
Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G., 1996, *AJ*, 112, 839
de Rossi, M. E., Tissera, P. B., & Scannapieco, C., 2007, *MNRAS*, 374, 323
Edmunds D., 1990, *MNRAS*, 246, 678
Erb D., 2006, *ApJ*, 644, 813
Franx, M., *et al.*, 2003, *ApJ*, 587, 79
Garnett D., 2002, *ApJ*, 581, 1019
Grazian, A., *et al.*, 2007, *A&A*, 465, 393
Kewley, L. & Ellison, S. L. 2008, *ApJ*, 681, 1183
Kobayashi, C., Springel, V., & White, S. D. M. 2007, *MNRAS*, 376, 1465
Köppen, J., Weidner, C., & Kroupa, P. 2007, MNRAS, 375, 673
Lee, H., *et al.*, 2006, *ApJ*, 647, 970
Maiolino, R., *et al.*, 2008, *A&A*, 329, 57
Mannucci, F., *et al.* 2002, *MNRAS*, 329, 57
Mannucci, F., *et al.*, 2006, *MNRAS*, 360, 773
Mannucci, F., *et al.*, 2007, *A&A*, 461, 423
Nagao, F., *et al.*, 2006, *A&A*, 459, 85
Pozzetti, F., *et al.*, 2007, *A&A*, 474, 443
Savaglio, S., *et al.*, 2005, *ApJ*, 635, 260
Steidel, C., *et al.*, 2004, *ApJ*, 604, 534
Tornatore, L. *et al.*, 2007 *MNRAS*, 382, 945
Tremonti, C. A., *et al.*, 2004, *ApJ*, 613, 898

https://doi.org/10.1017/S1743921308024654 Published online by Cambridge University Press