Physical Properties of Strongly Lensed, Low-mass, High-redshift Galaxies Observed with X-shooter

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One of the science drivers for the second generation VLT instrument X-shooter is the exploration of emission-line galaxies at high redshifts. By targeting gravitationally lensed galaxies, we have demonstrated that, with the full spectral coverage and high overall sensitivity at medium spectral resolution for X-shooter, we can explore the physics of galaxies at redshifts between one and four, using the same methods as employed for local galaxies. In particular, we have determined abundances via direct temperature-sensitive methods, and have shown that galaxies at high redshifts also follow a relation between the physical properties of stellar mass, abundance and star formation rate, as seen in the local Universe.

During the past decade, our knowledge of galaxies in the high-redshift Universe has increased tremendously, thanks to the advent of large-aperture telescopes and deep-field surveys. Galaxies selected from Lyman-break dropout techniques have allowed us to efficiently find galaxies up to redshifts of $z \sim 10$. Broadband selection and subsequent fitting of the photometry with template models have enabled us to explore the general characteristics of the galaxies. However, a detailed understanding of their physical properties still requires suitable spectroscopic measurements.

The majority of galaxies at $z > 2$ are faint, and spectroscopic observations are time consuming, considering that the magnitudes of typical Lyman-break galaxies are fainter than $R \sim 24$. Follow-up spectroscopy of individual galaxies at $z > 2$ is limited to the most massive galaxies in a few selected redshift ranges, where strong optical emission lines are redshifted into convenient wavelength ranges that are not absorbed by the Earth's atmosphere.

Measurements of strong emission lines and their line flux ratios are essential to derive the global chemical abundance of galaxies (e.g., Kewley & Ellison, 2008), which is a key ingredient in our understanding of galaxy evolution. Measurements of oxygen abundances of low-redshift galaxies in the Sloan Digital Sky Survey (SDSS) have shown that a relation exists between galaxy mass and metallicity (Tremonti et al., 2004). Further observations have indicated that this relation evolves in such a way that at progressively higher redshifts the abundances are lower for a given stellar mass. While this relation is well-recognised, the still unknown factor is the evolution of low-mass, high-redshift galaxies, because individual galaxies are too faint for conventional follow-up spectroscopy. To date, only a few individual high-redshift galaxies have been targeted for detailed medium to high resolution spectroscopy, generally using tens of hours of telescope time per target.

Before the advent of the E-ELT, the only available method that could increase our knowledge about the physical properties of low-mass, high-redshift galaxies is to take advantage of strong gravitational lensing, which can boost the total flux of a distant galaxy by a factor of 10–100, thereby allowing us to study galaxies that are 2–5 magnitudes fainter than would otherwise be possible. Furthermore, the stretching of some lensed galaxies along tangential giant arcs provides a much higher spatial resolution, thus enabling more detailed analyses to be performed of structures with sizes of around 100 pc in galaxies at $z > 2$.

Currently, a couple of Hubble Space Telescope (HST) multi-cycle programmes are devoted to imaging massive galaxy clusters in multiple filters: the CLASH survey (Postman et al., 2012), and the deeper Frontier Fields cluster survey. These studies are vital for achieving multiple science goals. In the cluster fields, HST images have revealed dozens of spectacular arcs and arclets from multiple background sources. For many of these systems, where several redshifts of lensed galaxies have been spectroscopically confirmed, the mass distribution of the clusters has been modelled and reconstructed very accurately. Given a lens model, it is possible to estimate the factor by which any background source galaxy is magnified. This is a crucial quantity when studying the intrinsic properties of the background sources.

Here we provide a summary of our X-shooter programme for lensed low-mass galaxies, focussing on the study of the detailed physical properties of individual high-redshift galaxies.

The X-shooter survey

The X-shooter instrument has a great advantage in the field of studying strongly lensed galaxies. Firstly, we have no previous information on the redshift of the sources, and, since X-shooter covers the entire wavelength range from 300–2500 nm, any spectral feature, be it the emission or absorption lines that appear in the spectrum, will allow us to constrain the redshift. Secondly, the large wavelength coverage enables us to measure several strong emission lines, which all fall in the near-infrared (NIR) part of the spectrum for galaxies at $z > 1.4$. Thirdly, using the same instrument with no difference in the slit position and instrument setup implies that there are no differential slit losses, apart from the effect of seeing changes, which can safely be ignored in the NIR range. This in turn implies that we can accurately determine emission-line ratios, which are necessary for deriving physical quantities.

The experience from X-shooter science verification (SV) data of lensed galaxies at previously unknown redshifts (Pettini et al., 2010; Christensen et al., 2010; Grillo & Christensen, 2011) demonstrated the strength of X-shooter in deriving physical characteristics of high-redshift galaxies with only a modest investment of telescope time. This advantage is allied to the possibility of deriving accurate lens models that can reproduce the observed geometrical configurations of the background lensed sources.

Subsequent to the SV demonstration, we proceeded with a larger programme using guaranteed time observations (GTO) in the period from 2010–12. The GTO observations were primarily aimed at determining source redshifts for intrinsically faint galaxies magnified by massive galaxy clusters, some of which are part of the CLASH survey. In total we targeted 13 galaxies using one hour of integration time per target. Figure 1 illustrates the lensed galaxies as observed with HST.

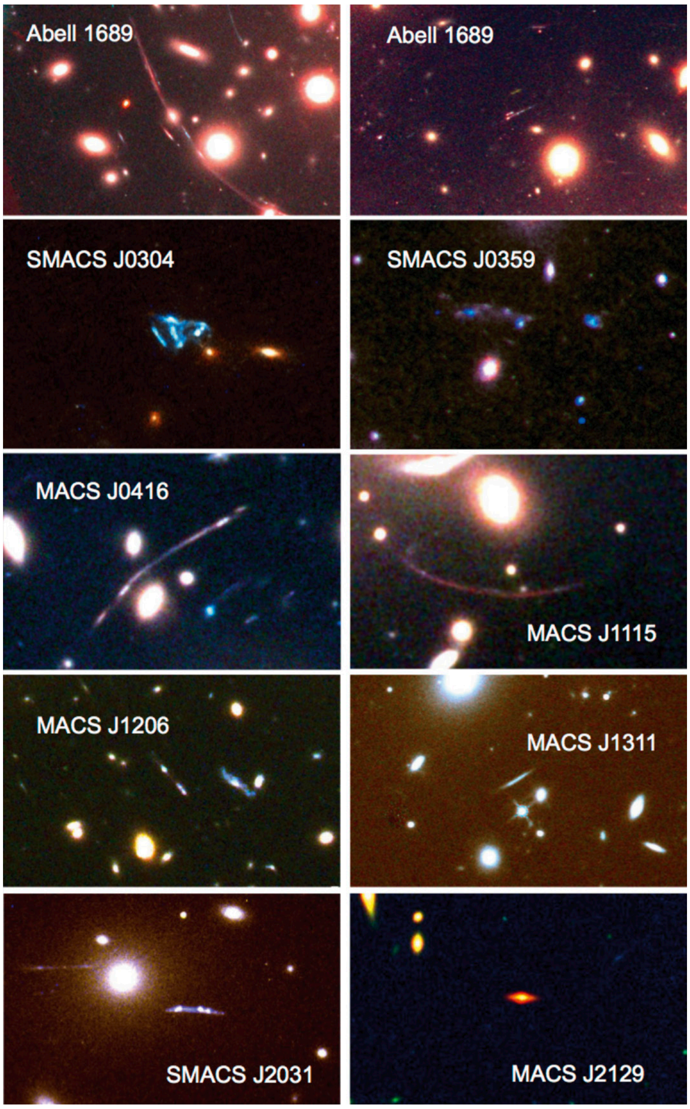


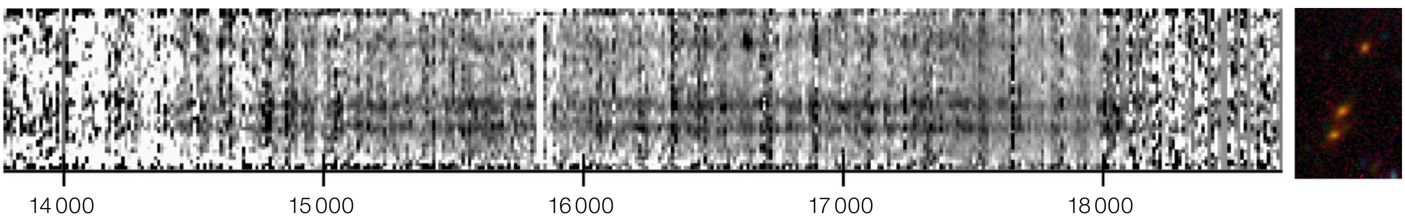
Figure 1. 20 × 15 arcsecond HST snapshots of the lensed arcs and multiple images in the selected galaxy clusters. The colour-composite images are based on the F606W, F814W, F125W and F160W bands. With our spectroscopic observations we targeted the regions with highest surface brightness, which give the highest chance of detecting bright emission lines.

Physical characteristics of the galaxies

From the spectra of the lensed galaxies, we have measured the redshifts of 12 of the galaxies to be in the range $0.6 < z < 5$. While the continuum emission of the galaxies, which have apparent magnitudes between 21 and 24 mag, is only detected at low signal-to-noise levels per pixel for the faintest galaxies; binning the spectra to a lower resolution of $R \sim 50–100$ allows us to confidently fit spectral template models and derive stellar ages and masses. Figure 2 shows the *H*-band 2D spectra of several lensed galaxies. The technique is similar to that used to determine the physical properties of galaxies by fitting their spectral energy distributions from multiband photometric measurements to template models. Targets are selected for their high surface brightness and for being good candidate-lensed objects. For these reasons, some of them have spectral characteristics of star-forming galaxies, while others display much older and more massive stellar populations.

Since the high-redshift galaxies are unresolved in ground-based images, we are typically limited to studying their integrated properties with X-shooter. Although some of the lensed sources are extended along the slit, we only derive integrated quantities. Star formation rates (SFRs) are inferred from the emission-line (typically Hα and [O II] λλ3727,3730) luminosities. All the quantities are corrected for lens magnification factors and slit losses. The latter are obtained by measuring, for each target, the fraction of the light falling into the slit relative to the total amount of flux in the broadband HST images. Including these corrections, we measure stellar

Figure 2. X-shooter 2D spectra in the NIR (between 1400 and 1800 nm) of three red galaxies that have been magnified by a factor of three by a foreground massive galaxy cluster. The galaxy *H*-band magnitudes range between 22 and 23. For the galaxy at the top, the detection of an emission line at 1663 nm, identified as [O III] λ5007, has been used to estimate a redshift value of 2.32. For the two lower galaxies, the continuum emission is consistent with a template of a passive galaxy at an approximate redshift of 2.



masses spanning four decades from 10^7 to 10^{11} $M_\odot$, relative luminosities between 0.004 and 9 L^*, where L^* corresponds to a characteristic galaxy luminosity at a given redshift, and SFRs from 1–50 $M_\odot$/yr. The range of these quantities is compatible with that of large-scale flux-limited surveys, but, on average, the lensed galaxies probe the low stellar mass end of the distribution.

Since the spectra cover the restframe optical wavelengths of the high-redshift galaxies, we can use conventional strong line abundance diagnostics, such as R_{23} (Pilyugin & Thuan, 2005) to measure their global oxygen abundances. This diagnostic uses ratios of oxygen and hydrogen Hβ emission lines. Unlike the SFRs and stellar masses, the abundance measurements do not depend on the lensing magnification factors, since the abundances are derived from line ratios. The inferred oxygen abundances, 7.6 < 12+log(O/H) < 8.7, corresponding to the range from 10 % to 100 % solar metallicity, are on average smaller than those derived for other high-redshift galaxy flux-limited samples. This finding is in agreement with the trend of how metallicity traces the stellar mass.

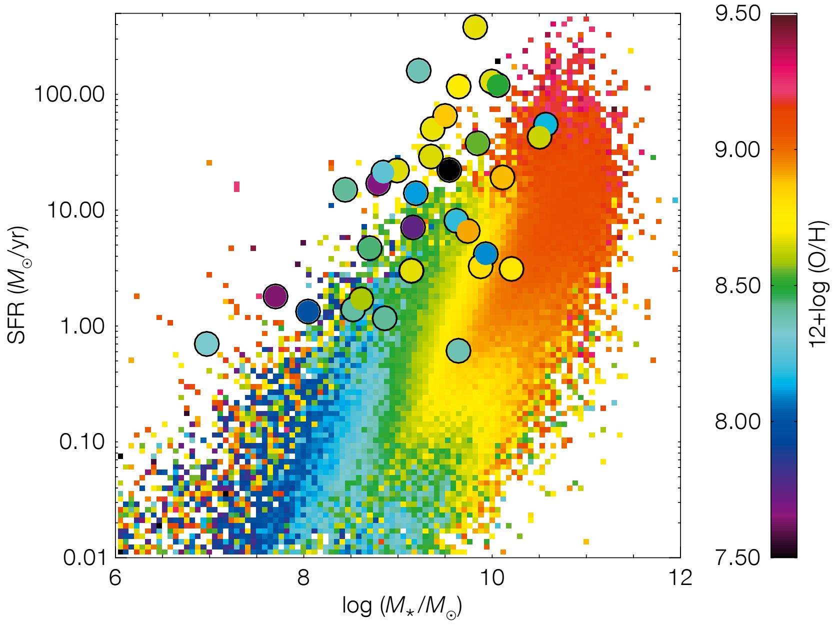


Figure 3. Correlations between integrated galaxy stellar masses and star formation rates. The colour scale represents the oxygen abundances, where the smooth distribution is the average metallicity at a given bin in stellar mass and SFR for ~ 400 000 SDSS galaxies. The three parameters form a tight plane, termed the fundamental relation for star-forming galaxies. The large circles are gravitationally lensed galaxies at $1 < z < 4$ (Richard et al., 2011; Wuyts et al., 2012; Christensen et al., 2012a), and they generally lie above the M–SFR relation of lower-redshift galaxies. Typical uncertainties are 0.2 dex for the stellar mass and 0.1 dex for the abundance. For reference, the solar oxygen abundance, 12+log(O/H) = 8.69, is shown in yellow.

Fundamental relation for star-forming galaxies

Figure 3 shows the relation between the SFRs, stellar masses and oxygen abundances for lensed galaxies at $1 < z < 4$. The galaxies fall on a simple relation between SFR and M^* known as the "main sequence for star-forming galaxies" (Noeske et al., 2007). Higher redshift galaxies have progressively higher SFRs.

The scatter in the SFR-mass plot is large, but recent analyses have revealed that taking into account the oxygen abundance as a third parameter, a tight sequence, termed "the fundamental metallicity relation" for star-forming galaxies, has been found (Mannucci et al., 2011). As that study is based mainly on low-redshift galaxies, plus a few high-mass high-redshift galaxies, by including lensed galaxies we show that the low-mass high-redshift galaxies also appear to follow the same kind of fundamental relation, albeit with a larger scatter than seen at low redshift (Christensen et al., 2012a).

Direct abundance measurements of high-redshift galaxies

For faint high-redshift galaxies, spectroscopic studies to derive the physical properties are mainly limited to what can be gained from the strong optical emission lines. The abundance determination depends critically on the temperature in the H II regions. All the strong line abundance diagnostics have been calibrated empirically relative to the direct methods using observations of local H II regions in the Milky Way and in nearby galaxies. To measure the temperatures and abundances with direct methods, detection of auroral lines such as [O III] λ4363, [N II] λ5755 or [O II] λλ7320,7330 is required. These auroral lines are however very faint compared to the strong emission lines from the same atomic species. The [O II] λλ7320,7330 doublet flux is known to contain large random errors, and the line strength of the [O III] λ4363 line flux increases with decreasing metallicity. Since at high redshifts the galaxies that are typically studied are the most luminous and massive ones, and thus also the most metal-rich, the temperature-sensitive lines are increasingly difficult to detect. Rather than exploring individual galaxies, multiple galaxy spectra are usually stacked in order to detect the faint lines and provide average quantities for a population of galaxies.

Again, the lensing magnification effect allows us to probe deeper into the physical conditions of individual low-mass galaxies, since intrinsically fainter emission lines are boosted by the high magnification factor. Among the sample of galaxies observed with X-shooter, three systems at $2 < z < 3.5$ show temperature-sensitive lines (Christensen et al., 2012b). In a similar way to the conventional use of the [O III] λ4363/[O III] λ5007 line ratio, the O III] λ1666/[O III] λ5007 ratio is also sensitive to the electron temperature. We detect the ultraviolet oxygen lines in two of the objects and use direct methods to calculate their abundances. Finally, we can establish whether using the strong line diagnostics is a valid approach, also at the highest redshifts where such a comparison is currently feasible with ground-based observations. Figure 4 shows the differences between the oxygen abundance derived from direct methods and the strong line methods for the sample observed with X-shooter. The panel also includes all the other $z > 2$ galaxies where direct abundances have been measured, and illustrates that, within the considerable uncertainties, the R_{23} calibration gives results consistent with the direct methods.

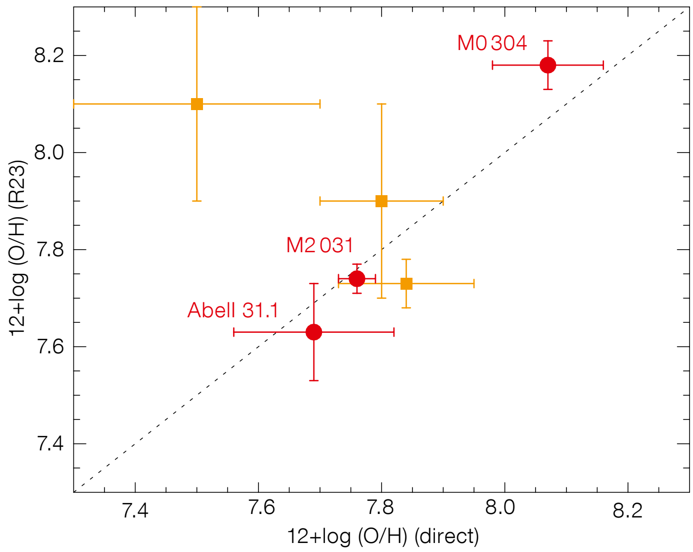


Figure 4. The oxygen abundances of six galaxies at $z \geq 2$ measured via the direct method versus those derived from the R_{23} strong line diagnostic. The dotted line is the one-to-one relation. The three lensed galaxies observed in this programme are the annotated red circles, while the yellow squares are two lensed and one unlensed galaxies from the literature.

Next steps

Not only do our observations target the background sources, they also allow us to characterise the mass properties of the main lens galaxies for two systems (Pettini et al., 2010; Grillo & Christensen, 2010) revealing high stellar velocity dispersions between 300 and 500 km/s and dark matter fractions in excess of those typically seen in individual field galaxies. Upcoming X-shooter observations of selected lens galaxies will show if those are indeed the most massive early-type galaxies at intermediate redshifts.

The success of X-shooter observations in finding source redshifts can be extended to lens systems selected by other methods. The Herschel observatory has recently discovered a population of highly luminous submillimetre galaxies, which have been magnified by foreground galaxies at intermediate redshifts. Recent X-shooter observations (March 2013; Christensen et al., in prep.) for 12 systems have revealed the lens galaxies to be very massive, with redshifts at $0.3 < z < 0.8$, but the background sources have much fainter emission lines than seen in the HST sources. Preliminary results show two possible counterparts at $z \sim 2.9$ to the submillimetre galaxies consistent with the average redshift of the population of known submillimetre galaxies. One galaxy has a strong Lyα emission line. The remaining galaxies may be too faint, extremely dusty, or without Lyα emission. The redshift could also be so high that even strong optical emission lines are redshifted out of the NIR region.

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Part of the COMBO-17 extragalactic survey area is shown in this image taken with the MPG/ESO 2.2-metre and Wide Field Imager. The COMBO-17 survey (Classifying Objects by Medium-Band Observations in 17 Filters) was a project dedicated to deep imaging of several small patches of the sky through 17 different filters across the visible spectral range. This image was taken with only three of the 17 filters from the project: *B*, *V* and *R*, but data through an additional near-infrared filter was also used. Further details can be found in the Picture of the Week for 9 January 2012.