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ABSTRACT

Lyman-alpha emitters (LAEs) are low-mass, high specific star formation rate galaxies that are thought to be predominantly responsible for the reionisation of the Universe. In spite of their importance, it is extremely difficult to characterise in detail all but the brightest, most massive of these galaxies; this is unsatisfactory, since the faint LAE population is expected to contribute significantly to the reionisation. Here we present a study of a new sample of 20 strongly lensed Ly-α emitting galaxies at $z \sim 2.3$, where we take advantage of the lensing magnification (typically a factor of about 20) to characterise some of the physical properties of low star-formation rate LAEs for the first time.

Key words: gravitational lensing – galaxies: structure

1 INTRODUCTION

Lyman-alpha emitting galaxies (LAEs) represent a population of star-forming systems with very large Lyα equivalent widths and some of the highest specific star-formation rates (sSFR) in the Universe, and these low-mass galaxies are thought to be predominantly responsible for the reionisation of the Universe. However, it is extremely difficult to characterise these galaxies in detail because they are intrinsically very faint. Typical LAE galaxies have strong star-formation, high-ionisations, and are typically low metallicity; these properties, combined with a (mostly) low dust content, allow for the escape of a large fraction of Lyα photons. At redshift $2 < z < 3$, well-studied LAEs are typically at the bright end of this parameter space, being L$*$ galaxies with M$*$ $\sim$ 109 M$_\odot$ and typical SFRs of about 30 to 100 M$_\odot$/yr (e.g. Erb et al. 2016), and investigations of lower-SFR objects have generally been limited to quantifying the properties of strong optical lines (e.g. Trainor et al. 2015). For example, Hagen et al. (2016) have recently shown that low-SFR LAEs (M$*$ as low as 107 M$_\odot$ and SFR $\sim$ 1 to 100 M$_\odot$/yr, consistent with local-Universe *green pea* LAEs, e.g., Henry et al. 2015) have optical strong line (H$_\alpha$ and [O iii]) properties consistent with optically-selected star-forming galaxies of the same masses at z $\sim$ 2, but they are unable to directly determine the properties of these galaxies that may affect the UV escape fraction, including the gas metallicity, density, and kinematics, without additional very large investments in telescope time. Strong gravitational lensing can be used to overcome this limitation, but the difficulty is that most strongly lensed galaxies at z $\sim$ 2 are not LAEs, and at present the properties of only three lensed LAEs have been investigated in detail (Christensen et al. 2012; Vanzella et al. 2016). Fortunately, new HST V -band observations of LAE galaxies selected from the BOSS survey have revealed a sample of strongly lensed systems at $\langle z \rangle \sim 2.5$ for which the magnification effect could reveal the detailed structure of these LAEs at scales around 100 pcs. Our subsequent lens modelling shows that the typical lensing magnification of these objects is $\mu \sim 20$ and, after accounting for this magnification, these objects are compact galaxies with SFRs of $\sim$ 12 M$_\odot$/yr (i.e., a factor of 3 to 8 lower than previous detailed studies).

2 DATA

The dataset analysed was released as part of the third Sloan Digital Sky Survey (SDSS-III) and consists of publicly available data. A sample of 21 lensed Lyman-alpha emitting galaxies were discovered between November 2015 and December 2016 during the BOSS survey. Their redshifts span from z $\sim$ 2 to 3 while the lensing objects are mostly massive early-type galaxies, at redshift around 0.55. Out of the 21 lens candidates SDSSJ0054+2944, SDSSJ1116+0915 and SDSSJ1516+4954 turned out not to be lenses, while SDSSJ2245+0040 is not included in our final sample because of the uncertain nature of the deflector, which appears to be a spiral galaxy.

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3 LENS MODELLING

The lens modelling of each system was performed using the Bayesian pixelated technique developed by Vegetti & Koopmans (2009). The mass density distribution of the lens is parametrised with an elliptical power-law profile (plus external shear) with a total of eight free parameters,

$$\kappa\,(x, y) = \frac{k_0 \left(2 - \frac{\gamma}{2}\right) q^{\gamma - 3/2}}{2\left(q^2\left(x^2 + r_c^2\right) + y^2\right)^{(\gamma-1)/2}}\,, \tag{1}$$

the dimensionless surface mass density and the Einstein radius are related to each other as

$$R_{\rm ein} = \left(\frac{\kappa_0 \left(2 - \frac{\gamma}{2}\right) q^{(\gamma-2)/2}}{3 - \gamma}\right)^{1/(\gamma-1)}\,. \tag{2}$$

The surface brightness distribution of the lens is parametrised using elliptical Sersic profiles and it is simultaneously modelled with the lens mass distribution. The surface brightness distribution of the un-lensed background source is instead reconstructed using a magnification-adaptive Delaunay tessellation and is characterised by a form and level of regularisation, $\mathbf{R_s}$ and λ_s (see Vegetti & Koopmans 2009; Vegetti et al. 2014, for a more detailed description). In particular, the modelling procedure is performed in two steps: first we mask out the emission from the lens galaxy and, given the lensed surface brightness distribution $\boldsymbol{d}$, we optimise for the lens mass parameters $\boldsymbol{\eta} = \{\kappa_0, \theta, q, x, y, \gamma, \Gamma, \Gamma_\theta\}$ and source regularisation level by maximising the following posterior probability density

$$P(\lambda_{\rm s}, \boldsymbol{\eta} \,|\, \boldsymbol{d}, \mathbf{R}_{\rm s}) = \frac{P(\boldsymbol{d} \,|\, \lambda_{\rm s}, \boldsymbol{\eta}, \mathbf{R}_{\rm s}) P(\lambda_{\rm s}, \boldsymbol{\eta})}{P(\boldsymbol{d} \,|\, \mathbf{R}_{\rm s})}\,. \tag{3}$$

At each step of this optimisation the corresponding most probable source $\boldsymbol{s}$ is obtained by maximising the following probability density distribution

$$P\,(\boldsymbol{s} \,|\, \boldsymbol{d}, \lambda_{\rm s}\boldsymbol{\eta}, \mathbf{R}_{\rm s}) = \frac{P(\boldsymbol{d} \,|\, \boldsymbol{s}, \boldsymbol{\eta})\, P(\boldsymbol{s} \,|\, \lambda_{\rm s}, \mathbf{R}_{\rm s})}{P(\boldsymbol{d} \,|\, \lambda_{\rm s}, \boldsymbol{\eta}, \mathbf{R}_{\rm s})}\,. \tag{4}$$

Then, we use this as a fix starting point to parametrise the surface brightness of the lens galaxy as a sum of two or more elliptical Sersic profiles and optimize for the best parameters. In the third and last step we optimise simultaneously for the mass and the light distribution of the deflector found in the previous steps.

In this work we use an opposite strategy which develops in two steps.

We attempt for the first time a different modelling procedure. In previous works the emission from the lens galaxy was fitted for and subsequently subtracted from the original data, not to be considered further in the following modelling. In this work we use an opposite strategy in two steps. We first mask out the emission from the lens galaxy to proceed with the modelling of the lensed images to find the best preliminary lens model. We then use this as a fix starting model while we parametrise the surface brightness of the lens galaxy as a sum of elliptical Sersic profiles. In the third and last step we optimise simultaneously for the mass and the light distribution of the deflector.

The lens modelling of each system was performed using the Bayesian pixelated technique developed by Vegetti & Koopmans (2009) (see also Vegetti et al. 2014) and we refer to this paper for a more detailed discussion. Briefly, the mass density distribution of the lens is parametrised with an elliptical power-law profile (plus external shear) with a total of eight free parameters. The surface brightness distribution of the lens is parametrised using elliptical Sersic profiles and unlike in Vegetti & Koopmans (2009) it is simultaneously modelled with the lens mass distribution. The surface brightness distribution on the unlensed background source is instead reconstructed using a Delaunay tessellation which is adaptive with the magnification.

4 RESULTS

As can be seen in figure **??**, some of our models present quite a few residuals in correspondence of the lens galaxy. This is due to the attempt we are making to fit a pixelated emission with an analytical profile and in some cases the lens brightness profile is not well approximated by a Sersic profile. For these systems the lens brightness distribution is fitted with a B-spline profile and subtracted from the data. The obtained images are modelled again to prove that the bad fitting of the Sersic is not compromising the goodness of our lens model.

Furthermore our prior on the source regularisation changes according to the specific system. In some cases a correlation between the pixels is needed in the regin outside the mask to achieve a better modelling: the regularisation matrix is therefore no longer diagonal.

5 CCC

6 DISCUSSION

REFERENCES

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Table 1. Add caption here.

Name (SDSS)	$z_{\rm lens}$	$z_{\rm src}$	$R_{\rm ein}$

Table 2. Add caption here. This table should contain the best parameters for the sersic models

Name (SDSS)	$n_{\rm Ser}$