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Searching primeval galaxies through gravitational telescopes

A. Monna[1] and G. Covone[1,2,3]

[1] Dipartimento di Scienze Fisiche, Università degli Studi di Napoli "Federico II", Italy
[2] INFN, Sezione di Napoli, Italy
[3] INAF, Osservatorio di Capodimonte, Italy

Abstract. Present-day instruments allow us to investigate the epoch of formation of the first structures of the Universe, the so-called *Reionization epoch*. First studies of the UV luminosity function at $z > 6$ suggest that in the high-z Universe the galaxy population is dominated by low-luminosity systems. Such sources are difficult to detect because of their intrinsic small size and faintness. Gravitational Telescopes offer a unique tool to detect such sources, thanks to the magnification induced in their fluxes. Candidate galaxies at high-z are identified through the multi-band photometric analysis called *dropout* technique, aimed at identifying the Lyman-Break at $\lambda_{\rm rest} = 1216$Å , a typical spectral feature of galaxies at $z > 6$. We present preliminary results from our project, aimed at selecting sources at $z > 6$: we selected a sample of optical and near-infrared dropouts in the field of view of two massive galaxy clusters (CLG 0152-1357 and RDCS 1252-2927). Analysis of physical properties of such sources will shed much light on the galactic and stellar sources that populated the epoch of reionization.

Key words. Galaxy: galaxy clusters – photometric redshift– Cosmology: reionization epoch – gravitational lensing

1. Introduction

The observation of first stages of galaxy evolution is finally within the reach of modern instruments, as present-day telescopes are now detecting sources at $6 \lesssim z \lesssim 10$, allowing us to investigate the epoch of formation of first galactic structures. First studies of the luminosity function (LF) at high redshift suggest that, at $z > 6$, the galaxy population of the Universe was dominated by low-luminosity and small star-forming galaxies. These are the best candidate as sources of the UV radiation that ionized the neutral inter-galactic-medium (IGM) of the Universe in the so-called *Epoch of Reionization* (EoR), spanning the redshift interval $6 \lesssim z \lesssim 30$ (e.g., Fan X. (2006)). However, such faint ($M_{1700} \sim -17$, see Bouwens et al. (2010)) and small ($r \sim 1$ kpc, see Oesch et al. (2010)) sources are difficult to observe, even on 10 m telescopes.

Two main observing strategies are currently being used to investigate galaxies at $z > 6$: blank field and "gravitational telescopes" surveys. The two techniques are complementary to constrain the LF at high redshift. Blank field surveys require long exposure times to obtain deep imaging data: they are efficient to

Send offprint requests to: A. Monna

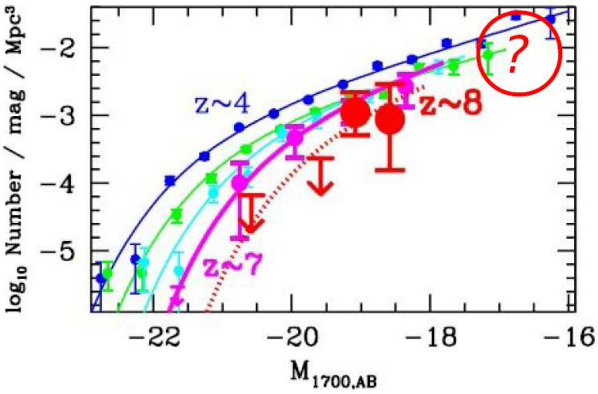

Fig. 1. The rest-frame UV luminosity function determined at $z \sim 4$ (blue), $z \sim 5$ (green), $z \sim 6$ (cyan), and $z \sim 7$ (magenta). The dotted red line is the extrapolated luminosity function at $z \sim 8$ (Bouwens et al. 2010). Through gravitational telescopes surveys we aim to investigate the faint (M~ -17) end of the LF at high z.

investigate only the bright end of the LF at $z > 6$ (see for instance Bouwens et al. (2007), Bouwens et al. (2008)).

The study of the faint end of the LF results to be more efficient through gravitational telescopes surveys (Maizy et al. 2010): due to magnification induced by massive clusters in sources behind them, faint high$-z$ galaxies, otherwise invisible at our present instruments, can be detected. Gravitational telescopes can shift the survey depth $\sim$ 1 mag deeper than blank field, even if on a small survey area[1]. Moreover this technique allows us only to explore the high-z Universe behind massive galaxy clusters.

In our observational program we aim at investigating the sources that populated the EoR, and in particular the dominant population of this epoch, i.e. low-luminosity star-forming galaxies. We searched for $z > 6$ sources, in the field of view of two massive galaxy clusters, CLG 0152-1357 and RDCS 1252-2927, taking advantage of their gravitational magnification. In a next step, these candidate primeval galaxies are to be confirmed by NIR spectroscopy.

2. The Epoch of Reionization

In the Λ-CDM scenario, the epoch of Reionization is the epoch in which the neutral IGM of the Universe was ionized by an intense UV-radiation field: the dominant contribution to this UV field was likely given by very massive, metal-free stars born in the first galaxies (Fan X. 2006).

According to the Λ-CDM model, after the Recombination epoch[2] the Universe expanded and cooled, with the contemporaneous growth of the density inhomogeneities. Because of their gravitational instability, primordial matter inhomogeneities hierarchically grew into structures that later became bounded systems. These were the nurseries of the first stars born in the Universe, massive stars composed by light elements (H, He), that were the sources of an intense field of UV radiation. The period between the Recombination epoch and the ignition of the first stars is called the *Dark Ages*. The Universe began to become optically thin as the ionization of the neutral IGM by the first stars started. We refer to the epoch in which such ionization occurs as the *Reionization epoch*: it started with the ignition of the first stars (likely at $z \sim 30$) and ended when all the IGM was ionized ($z \sim 6$, Fan

[1] Indeed due to the lensing magnification, the effective solid angle of the survey volume reduces

[2] At this epoch ($z \sim 1100$), neutrons and electrons combined in atomic form.

2006). Therefore, investigating the EoR is crucial to study the nature of the first stellar population and galactic structures, and to understand how they built up and evolved.

Source at $z > 6$ can be identified in photometric data by means a peculiar spectral feature: the strong spectral break at the rest-frame Lyman-α emission line $\lambda_{Ly-\alpha} = 1216\text{Å}$. This break is due to the absorption of radiation with $\lambda < \lambda_{Ly-\alpha}$ by the neutral IGM (*Gunn-Peterson* effect, see Gunn & Peterson, 1965). A template spectrum of such galaxies, called *Lyman Break Galaxies* (LBGs), is shown in Fig. 2: it is redshifted at $z = 8$ and is compared with optical and near-infrared filters.

3. Searching high-z sources

The first step in our observational project consists in the selection of sources candidate at $z > 6$ by means of deep photometric data of massive galaxy clusters. We combine gravitational telescope strategy and the so-called *dropout technique*, a photometric analysis aimed at identifying LBGs. This well-known method is based on the identification of the Lyman-break. Meier et al. (1976) first suggested that three band photometry could be used to detect primeval galaxies: if their redshifted Lyman limit is bracketed by two of the bands, they will appear red in one of the colors (U-B) while remaining blue in the other (B-V). Since for galaxies at $z > 6$ the Lyman break is redshifted in the near-infrared interval (see Fig. 2), the search of galaxies at the EoR needs the collection of deep optical and near-infrared images.

We collected archival space-based and ground-based data of the massive galaxy clusters CLG 0152-1357 ($z \sim 0.83$) and RDCS1252-2927 ($z \sim 1.2$). Our dataset includes: optical data from HST/ACS in the filters r_{650}, i_{775} and z_{850} and near-infrared from VLT/ISAAC in the filters J and H for CLG 0152, and optical data in the i_{775} and z_{850} and near-infrared in the filters Js and Ks for RDCS 1252. Spitzer/IRAC archival data have also been retrieved for both clusters.

We selected a sample of optical and near-infrared dropouts in our multi-band dataset, and we computed their photometric redshift by fitting their spectral energy distribution (SED) with a library of synthetic spectra. We used here the software tool *Le PHARE* (Ilbert 2010). We removed objects with photometric redshift $z_{\rm ph} < 6$ from our sample to reduce low-redshift contaminants, like early-type galaxies at $z \sim 3$ (which Balmer break is confused with the Lyman break of higher-z galaxies) or galactic L and T dwarf stars. Then we visually inspected the high-z candidates to remove spurious selections, due to (for instance) background inhomogeneities. Our final sample includes 3 candidates in the CLG 0152 field and 11 in RDCS 1252 as sources likely at redshift larger than 6 (see Fig. 3).

4. Modelling galaxy clusters

An accurate model of the mass distribution of the lensing cluster is mandatory in order to derive the magnification map and to trace the critical and the caustic lines for sources at different redshifts. The knowledge of the critical and caustic curves allows to identify regions on the image plane where high magnification occurs, that is regions where we have more chances to detect faint highly magnified sources. The knowledge of magnification maps allows to determine the intrinsic luminosity of lensed sources, giving the magnification factor for which we have to correct the observed magnified fluxes.

To determine the mass distribution of the gravitational lenses CLG 0152 and RDCS 1252, we fitted parametric mass models using the software *Lenstool* (Kneib et al. (1993), Jullo et al. (2007)). For each cluster, the mass model is composed by two main components:

i) the smooth cluster-scale halo (representing the dark matter and the intra-cluster gas) that we described with the Navarro-Frenk and White (NFW) density profile (Navarro, Frenk, & White 1997);

ii) the galaxy components: we included in the model a sample of galaxies spectroscopically confirmed as members of the cluster and modelled them with the *pseudo-isothermal elliptical mass distribution*.

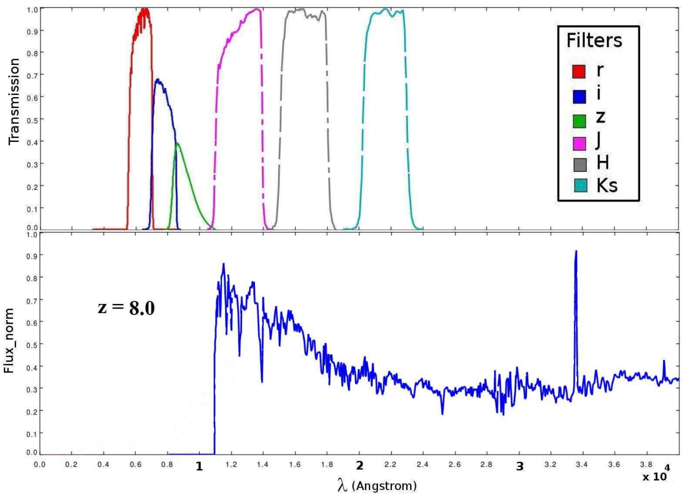

Fig. 2. Template spectral energy distribution of a Lyman Break Galaxy redshifted at $z = 8$. On the top panel they are shown the optical r_{650}, i_{775}, z_{850} filters from HST/ACS and the near-infrared J- and K-band from VLT/ISAAC. Because of the spectral break, these galaxies are not detected in all the bands: in that case the source is not detected in the optical bands and it results as a z_{850}-*dropout*

Due to the parameter degeneracies of lensing modelling, in order to obtain a robust model of the cluster mass distribution, strong constrains are needed, as position and shape of multiple images and their spectroscopic redshift. Additional constrains are given by knowledge of parameters from other studies (e.g., for ClG 0152 we used the scale radius[3] of the smooth halo estimated by X-ray observations (Huo et al. 2004)).
Therefore, position and shape of multiple images and known parameters of the mass distribution profile are used as constrains to optimize the models through a Bayesian optimization. In the field of ClG 0152 we identified 6 families of multiple images (one of them with spectroscopic redshift known, see Umetsu et al. (2005)): using them we determine a robust model of the cluster, in agreement with information from X-ray studies (Huo et al. 2004). In Fig. 4 we present our final model of ClG 1252.
In the field of RDCS 252, there are several distorted images resembling gravitational arcs, but it was not possible to identify families of multiple images, hence our model is mainly based on the weak lensing analysis carried out by Lombardi et al. (2005).

[3] See Navarro, Frenk, & White (1997)

5. Star-formation rate at $z > 6$

Once we determined the mass distribution of both the clusters, we computed the magnification maps for sources at $z > 6$, and then we corrected the photometry of our high-z candidates for the respective magnification factor. Through the SED-fitting code *Le Phare*, we computed the spectra for our candidates, that better matched their *corrected* magnitudes. In order to estimate the star-formation rate, we measured the UV continuum luminosity at the rest-frame wavelength $\lambda = 1500$ Å (L_{1500}) from these spectra, and converted it in SFR, through the calibration given by Kennicutt (1998):

$$\mathrm{SFR} = 1.05 \times 10^{-40} L_{1500}\,,$$

where the SFR is given in $M_{\odot}$/yr, and L_{1500} in erg s^{-1} Å^{-1}. We note that this correlation has been calibrated by observing nearby (i.e., $z \sim 0$) galaxies and never tested for the primeval

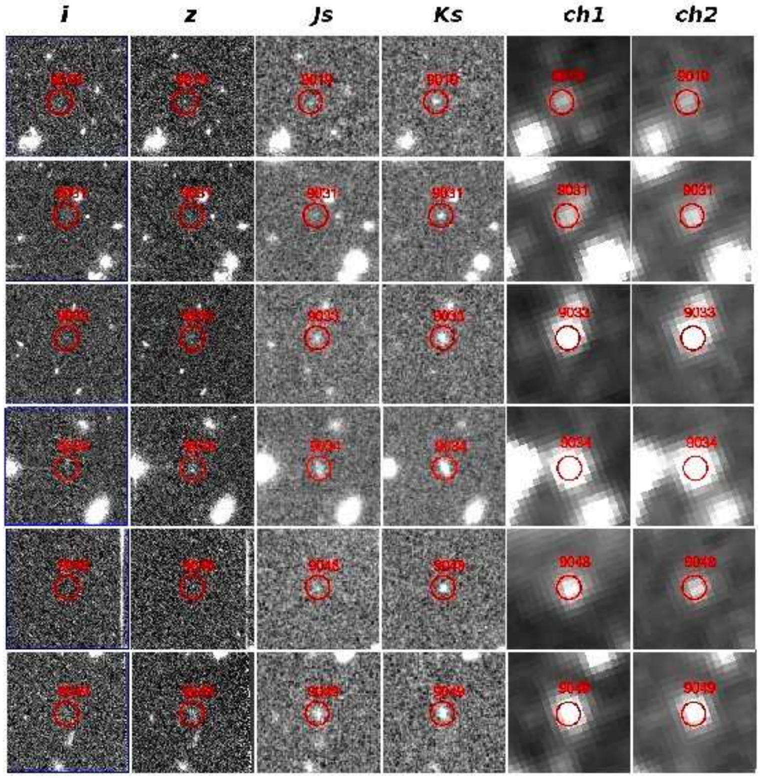

Fig. 3. Some of the optical and near-infrared dropouts in the FOV of RDCS 1252 candidates at $z > 6$. We show data from the optical i_{775} and z_{850} filters (from HST/ACS), near-infrared filters Js and Ks (from VLT/ISAAC) and mid-infrared filters (ch1 and ch2 are from Spitzer/IRAC). Each panel is $10'' \times 10''$ wide.

galaxies in the young Universe. However, as it is widely-used, it allows to compare straightforwardly our results with those in literature.

From this analysis we obtained SFR values ranging between a few to ∼ 50 $M_{\odot}$/yr, with mean value ∼ 10 $M_{\odot}$/yr. Our result is in good agreement with the ones obtained by Richard et al. (2006) from the study of $z > 6$ candidates selected in the field of three massive galaxy clusters.

6. Conclusions

We combined the gravitational lensing observing strategies with the dropout technique to search for $z > 6$ galaxies, thought to be the main sources of the UV field that ionized the neutral IGM. Through a multi-band analysis, involving optical and near infrared dataset, we selected sources candidate at $z > 6$ in the field of two massive clusters: ClG 0152 and RDCS 1252. For both the clusters we modelled the mass distribution, needed to correct our selected sources from lensing effect. Our final sample of high-z galaxies counts 3 sources in ClG 0152 field, and 11 in RDCS 1252.
We have started a preliminary statistical study of the physical properties of these sources: we determined the intrinsic UV luminosities L_{1500}, allowing first estimate of their star-formation rate. We find a mean SFR∼ 10 $M_{\odot}$/yr, in good agreement with results from other gravitational telescopes analysis (e.g., Richard et al. 2006).

Follow-up near-infrared spectroscopic analysis of these candidates is needed: first

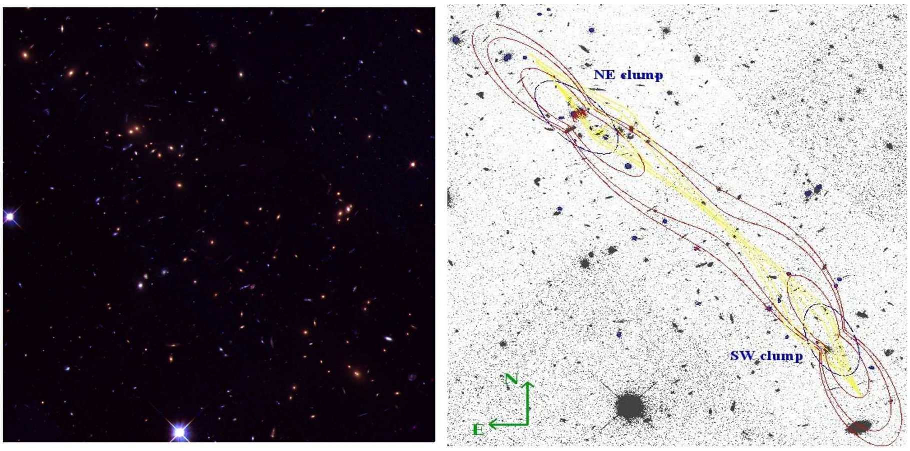

Fig. 4. Left Panel: HST/ACS color image of the sky region centered on the cluster ClG 0152-1357; **Right Panel**: HST/ACS r-band image of cluster CLG 0152. The over-plotted lines are the critical lines (red) and the caustics, for sources at redshift $z_s = 4$ (the inner lines) and at $z_s = 7$ (the outer lines), that we obtain for our best model of the mass distribution of the cluster.

of all, to confirm the estimated photometric redshift, and better constrain the selection strategy of our final high-redshift sample, and second to obtain more robust information on the stellar properties of the first galaxies from their spectra. We plan spectroscopic observations of our candidates, aimed at detecting the Lyman-α emission line, since detecting the spectral continuum of sources at $z > 6$ is still out of range of present instruments.

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