Star Clusters: From the Milky Way to the Early Universe
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Unveiling forming star clusters in the young Universe

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Abstract. The identification of young massive star clusters (YMCs) at high redshift is becoming a real fact. We present recent results from Hubble deep imaging and VLT/ MUSE - X-Shooter observations boosted by strong gravitational lensing. We report on two parsec-scale star-forming systems at $z = 6.145$ and 2.37 (>10 Gyrs of look back time) currently representing the best candidate high-z YMCs. All of this also implies that the search for globular cluster precursors has already begun.

Keywords. star clusters, photometry, spectroscopy, galaxies: high-redshift

1. Introduction

The observational investigation of star-formation at high redshift ($z > 3$, to the first two Gyrs) at very small physical scales – at the level of star-forming complexes including young massive star clusters (YMCs) – is a new challenge in observational cosmology (e.g., Vanzella *et al.* 2017b). Thanks to strong gravitational lensing, the possibility to catch and study globular clusters precursors (GCP) is becoming a real fact, both in a statistical way (e.g., Pozzetti *et al.* 2019) and by inferring the physical properties of individual objects (e.g., Vanzella *et al.* 2017a,b, 2019a,b - hereafter EV17a,b , EV19a,b; see also Bouwens *et al.* 2017). The luminosity function of GCPs has also been addressed for the first time and their possible contribution to the ionising backgrounds is still under debate (e.g., Boylan-Kolchin 2018). While still at the beginning, the open issues of GC formation (e.g., Bastian & Lardo 2018; Renzini *et al.* 2015; Calura *et al.* 2019) and of what sources caused reionization (e.g., Dayal & Ferrara 2018) can be addressed with the

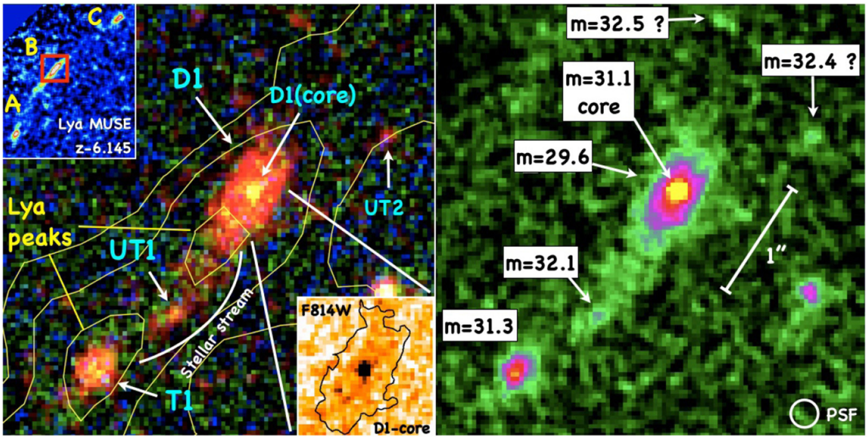

Figure 1. Color composite (left) and WFC3/F105W image (right) of tiny sources at z = 6.145 behind the HFF J0416. The region corresponds to the red square in the top-left inset which shows the extended 45″ Lyα arc of the three multiple images (A,B,C from MUSE). The de-lensed HST/F105W magnitudes are shown (right). The size of D1(core) is smaller than 13 pc and is consistent with being a YMC caught in its formation phase (adapted from EV19a).

same observational approach, at least from the high-z perspective. This might be the consequence of the fact that some of the extremely faint sources possibly dominating the ionising background seem to match the ultraviolet appearance of YMCs. In turn, these are likely to also include GCPs, whose specific properties (stellar mass, luminosity, densities) might shed light on the different formation scenarios (Bastian & Lardo 2018; Renzini *et al.* 2015; Zick *et al.* 2018).

2. High-precision lensing models, anticipating the EELT

Strong lensing has been used in the past 20 years to explore the distant universe. A first glance at an unprecedented low-mass domain at high-z has been offered by galaxy clusters acting as cosmic telescopes. Only recently the lens modeling techniques based on strong lensing constraints have reached full maturity, leading to the construction of magnification maps of unprecedented precision and accuracy and allowing to push the detection limits of sources up to $z \sim 10$. One of the reasons of the recent dramatic improvement of the lens models is the acquisition of deep photometric and spectroscopic data in the framework of several treasury and large programs of the HST (e.g., CLASH, the Frontier Fields and RELICS) and of the VLT. A particular merit goes to the recently installed VLT/MUSE integral field spectrograph (Bacon *et al.* 2010). When gravitational lenses are targeted, thanks to MUSE blind spectroscopy hundreds of highly magnified sources at $z < 6.7$ can be captured in a single shot, allowing to measure their redshifts and to confirm their association to multiple image systems. These are the fundamental ingredients to build a robust model of the mass distribution of the lens.

2.1. *Entering in the realm of Globular Cluster Precursors*

Figure 1 shows a plausible strongly lensed young star cluster at z = 6.145 with an effective radius smaller than 13 pc and stellar mass of a few 10^6 $M_\odot$, embedded in a star forming complex / dwarf galaxy with a stellar mass of a few 10^7 $M_\odot$. The inferred star formation rate surface density Σ_{SFR} of the candidate cluster exceeds 500–1000 $M_\odot$ yr^{-1} kpc^{-2}, in line with what is observed in local young massive star clusters (as discussed in EV19a). While such a lensed source is a plausible star cluster, it is still not

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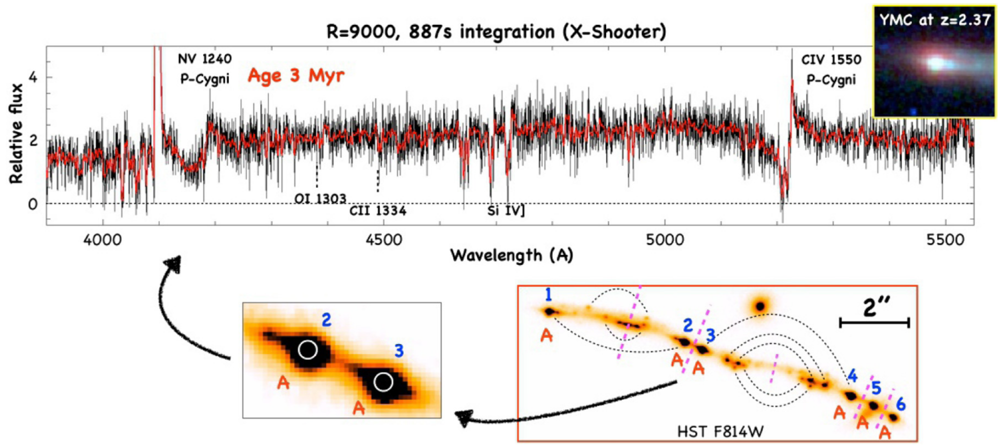

Figure 2. A portion of the VLT/X-Shooter spectrum of the star cluster hosted in the z = 2.37 Sunburst arc is shown (top, red: smoothed version). The top-right inset and the images in the lower panels show the HST F814W images of the strongly lensed knot "A" (the star cluster). "A" is marginally resolved down to $R_{eff} < 20$ pc. Six multiple images of "A" are shown in the bottom-right panel, with indicated the expected positions of the critical lines (dotted lines).

possible to securely determine if it is also a gravitationally-bound system. The identification of gravitationally-bound clusters needs the estimation of the dynamical age, that at first order implies a good knowledge of the size, stellar mass and age of the object (Gieles *et al.* 2011), all quantities that are affected by severe uncertainties when performing such analysis at high-z. The future EELT and JWST will routinely identify star cluster at cosmological distances, especially thanks to the high spatial resolution achievable with EELT (see EV19a) and the full coverage of the rest-frame optical wavelengths achievable with JWST at $z > 4$ (useful to determine ages and stellar masses). However, in exceptionally highly magnified cases ($> \times 20{-}50$) and at moderate redshift ($2 < z < 4$, but still within 3 Gyrs after the Big-Bang), the enhanced S/N and spatial resolution provided by large magnification, including the spectral coverage to the optical rest-frame, are such that the dynamical age can be inferred with reasonable accuracy already now. In this way a gravitationally-bound YMCs at z = 2.37 has been recently identified, hosted by a super-lensed system dubbed Sunburst arc. Figure 2 shows a sub-region including the magnified object and a preliminary VLT/X-Shooter 887s integration, in which the signatures of massive stars are evident (like NV 1240 and CIV 1550, see also Chisholm *et al.* 2019). Additional basic properties of the object are: a stellar mass in the range of 10^{6-7} $M_\odot$, an effective radius lower than 25 pc and an age of 2.9 Myr (Chisholm *et al.* 2019; EV19b). Remarkably, escaping ionizing radiation from such star cluster has also been observed with dedicated HST imaging (Rivera-Thorsen *et al.* 2019), making such system the first observed star cluster at cosmological distance hosting young and massive stars, whose ionizing photons escape into the IGM. This is an important piece of information for the understanding of possible analogs of the cosmic *reionizers* at $z > 6$, where the cluster formation efficiency – the fraction of star formation occurring in star clusters – could be particularly high (Reina-Campos *et al.* 2019). The very magnified objects like Sunburst are also instructive when compared to the non-lensed sources, and allow us to understand what biases enter in the determination of physical quantities. An example is shown in Figure 3, where without lensing amplification such a super-lensed object would have appeared as a single "blob", in which the internal components are not recognizable in the HST imaging. Figure 3 also reports on the dramatic effect of both spatial resolution and S/N dimming (as the lensing vanishes) have when estimating, e.g., the Σ_{SFR}

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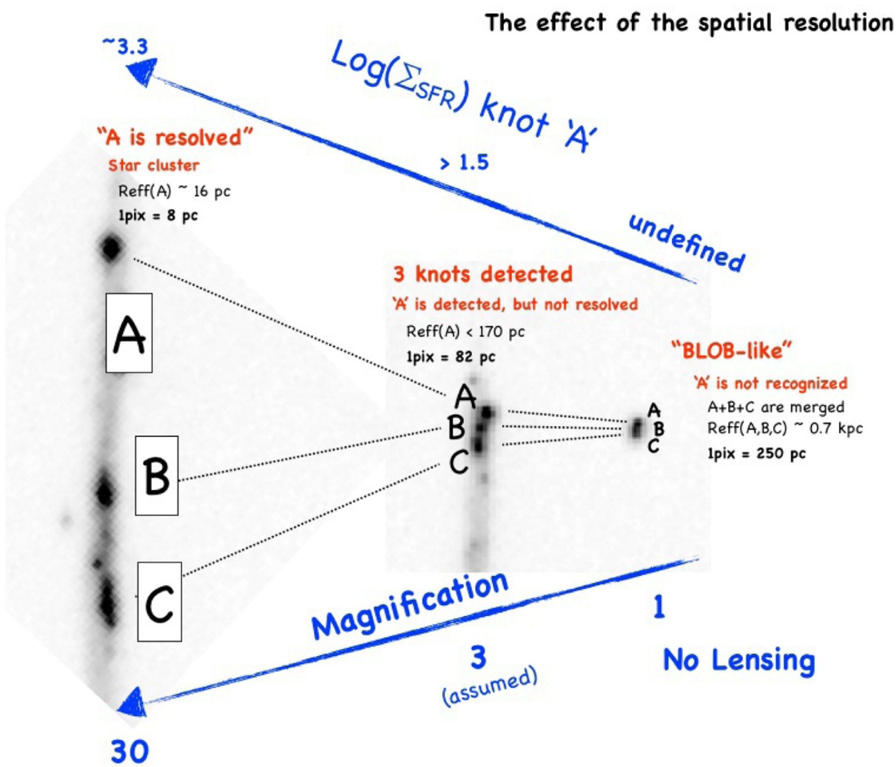

Figure 3. The observed three knots "A", "B" and "C" are well resolved at large lensing amplification $\mu = 30$ (left side of the figure, see EV19b). In the middle the same with $\mu = 3$ is shown (assumed in this exercise) and the rightmost panel shows how the system would appear without lensing, $\mu = 1$. In the last case the three knots are not well recognized, rather they are identifiable as a single "blob". In particular the estimated Σ_{SFR} for knot "A" (the star cluster) is significantly altered when the spatial resolution degrades from $\mu = 30$ to 1.

of component A. Without lensing the Σ_{SFR} of object A is undefined. Conversely, the strong lensing amplification allows us to spatially resolve and properly infer Σ_{SFR}. Such evident limitation in some cases due to poor spatial resolution significantly hampers the investigation of star clusters at high redshift, that currently relies on rare very magnified objects. The situation will change dramatically when EELT will be operational and will open for such studies for non-lensed (or moderately lensed with $\mu \sim 3$) fields.

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