Unveiling Cosmic Dawn

the synergetic role of space and ground-based telescopes

Cuby, Jean-Gabriel; Oesch, Pascal; Cooray, Asantha; Rhodes, Jason; Bremer, Malcom; Bowler, Rebecca; Capak, P.; Caputi, Karina; Castellano, Marco; Conselice, Christopher; Cuillandre, Jean-Charles; Dayal, Pratika; Davidzon, Iary; Dunlop, James; Finkelstein, Steven; Fontana, Adriano; Kashlinsky, Alexander; Koopmans, Leon; Kuijken, Konrad; Le Brun, Vincent; Le Fèvre, Olivier; Mortlock, Daniel; Pello, Roser; Pentericci, Laura; Sahlén, Martin; Schneider, Raffaella; Serjeant, Stephen; Warren, Stephen

Published in:
Bulletin of the American Astronomical Society

Publication date:
2019

Document version
Publisher's PDF, also known as Version of record

Astro2020 Science White Paper

Unveiling Cosmic Dawn: the synergetic role of space and ground-based telescopes

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☒Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract

JWST, Euclid and WFIRST will revolutionize our understanding of the formation of the first galaxies and super massive black holes and their role in reionizing the Universe during the first half billion years. While deep observations with JWST will identify the common, but extremely faint galaxies at $z > 7$, the unprecedented wide field coverage of Euclid/WFIRST will find thousands of the brightest galaxies and quasars, which pinpoint the first ionized bubbles over degree scales. Massive spectroscopic follow-up campaigns with existing and under-construction facilities are required in order to place these galaxies within their underlying large-scale structure, which will make it possible to perform cross-correlation analyses with CMB and 21-cm maps tracing the gas between galaxies. These follow-up campaigns will require near-infrared and mm spectroscopic facilities on both hemispheres. A properly coordinated large follow-up campaign is recommended.

Introduction

According to our current model, the Universe started as a singularity and then rapidly expanded, filled with hot plasma, dark matter and energy in equilibrium. About 400,000 years later (corresponding to a redshift $z{\sim}1100$; see Figure 1) the mean density of the expanding Universe became low enough that light (electromagnetic radiation) and matter decoupled and matter condensed into a neutral state. Light we see from this epoch forms the cosmic microwave background (CMB), which carries the imprint of the matter density fluctuations that existed at that time. In this scenario, condensations rapidly formed inside the growing potential wells governed by dark matter, creating the first galaxies within what we call dark matter halos [1]. These first galaxies are believed to have lit up the Universe with radiation leading to its second and last major phase transition from a neutral to an ionized state between approximately 600 and 850 million years after the Big Bang (so-called reionization [2]).

The detailed history and topology of this phase transition and the nature of the reionization sources however remain highly uncertain [2] and need to be constrained by further observations. The complex interplay between gravitational physics dominated by dark matter and the baryonic physics of black hole and star-formation, which leads to the formation of the first galaxies and quasars and to their large diversity today, is similarly still a major puzzle. A study of the first objects before reionization was complete and of the size distribution of the first re-ionized bubbles is essential to reconstruct the history of reionization above redshift $\gtrsim 7$ and for discriminating between competing models for galaxy assembly and reionization.

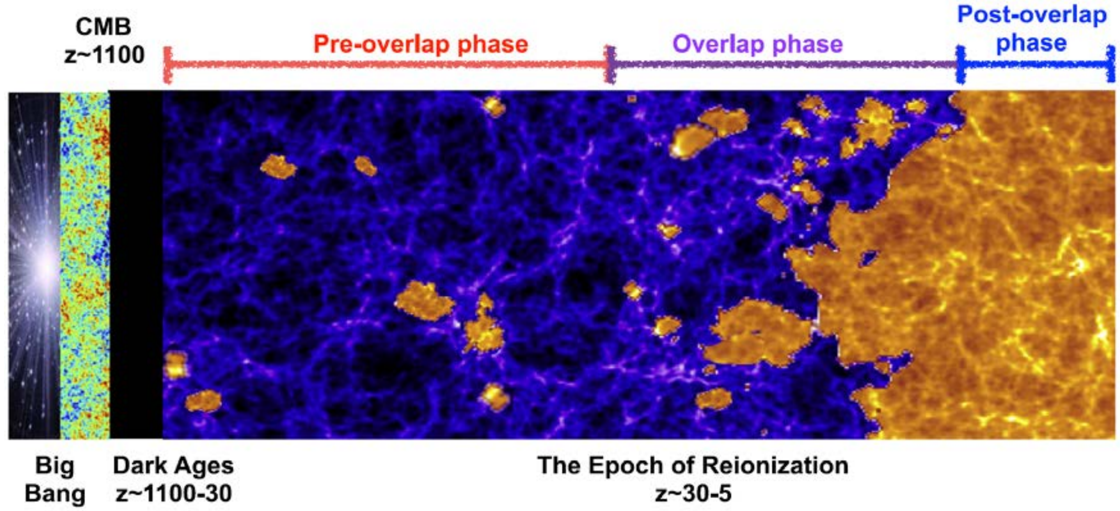

Figure 1. A timeline of the first billion years of the Universe. The dark ages ended with the formation of the first stars (at z $\lesssim$ 30). These first stars started producing the first photons that could reionize hydrogen into electrons and protons, starting the ''Epoch of cosmic Reionization'' which had three main stages: the ''pre-overlap phase'' where each source produced an ionized region around itself, the ''overlap phase'' when nearby ionized regions started overlapping and the ''post-overlap phase'' when the IGM was effectively completely ionized (z $\lesssim$ 7).
Source (image and caption): Dayal & Ferrara [2]. Reionization simulation credit: A. Hutter.

Probes and signatures of reionization and of the first objects

The three main probes of re-ionization are i) the CMB through the imprint of Thomson scattering on polarization anisotropies ii) the 21-cm HI line and iii) the galaxies and quasars that emerged and evolved from the dark ages. In the latter case, the sources can be detected individually or through their imprint on the power spectrum of the integrated background emission (so-called Cosmic Infrared Background – CIB). Objects above redshift 7 can be observed with existing facilities in the UV and far IR rest frames corresponding to the near IR and mm domains. The status and prospects for these three probes are:

i. WMAP and Planck have measured the sky average reionization optical depth, and future CMB experiments (S4) will be able to constrain the signal on degree scales and to detect patchy reionization [3].

ii. LOFAR is measuring upper limits for the strength of the 21-cm emission signal from reionization [4], and the EDGES experiment may have detected early signs of star formation through 21-cm absorption on the CMB at a redshift of $\sim$17 [5]. The Square Kilometer Array (SKA) and several other facilities (MWA, LEDA, GMRT, PAPER, HERA, NenuFAR) will measure the neutral hydrogen power spectrum over arcminute scales across the epoch of reionization.

iii. From HST and ground-based near-IR observations five $z > 7$ quasars [6] [7] [8] [9] [10] and a few hundreds of galaxies at redshifts > 7 have been detected up to redshifts $\sim$11 [11]. From these observations, a first glimpse of the physical properties of early galaxies and quasars and of the reionization history is emerging. The near infrared (IR) space missions of the next decade (JWST, Euclid and WFIRST) will enable a leap forward in the number of high-redshift objects. Euclid, WFIRST and SPHEREx will also measure the CIB power spectrum over different scales and bandpasses.

Reionization is believed to be a very inhomogeneous process that starts in the most over-dense regions that host massive early galaxies. The wide area surveys of Euclid and WFIRST will probe for the first time the relevant scales of order 10 deg^2 necessary to determine the topology of the ionized bubbles and of their underlying source populations. For each probe, the facilities of the next decade will enable detailed and complementary measurements that can be cross-correlated. For instance, one expects catalogues of individual sources and CIB maps to anti-correlate with 21-cm maps since galaxies and quasars reside in bubbles of ionized gas. The combination of these different probes will be crucial in building a detailed picture of the reionization process, including sources, propagation, feedback on galaxy formation and topology (inside-out versus outside-in).

The observed properties of galaxies and quasars also encode signatures of reionization on their own, through e.g. the evolution of the Lyα luminosity function (LF) and its co-evolution with the galaxy LF [12] [13], or the measurement of the Lyα damping wing as measured on $z > 7$ quasars [14].

Beyond their interest as probes of reionization, early sources inform our understanding of galaxy and super massive black hole formation and evolution. From high resolution imaging and spectroscopy in the rest-frame UV (e.g. Lyα and CIII] lines, UV slope) and rest-frame far IR (e.g. [OIII] 88 μm and [CII] 158 μm lines, far IR continuum), one can infer physical, chemical and morpho-kinematic properties of the sources. Examples of physical quantities that can be measured from these (possibly spatially resolved) spectral signatures are radiation field, star formation rate, stellar mass, metallicity, dust content, morphology and kinematics of the feedback- and accretion-dominated regions. Examples of studies of z > 7 galaxies in the UV rest frame and far IR rest frame can be found in [15] [16] [17] [18].

To perform these studies with a statistical power at different scales and as a function of redshift and luminosity, it is essential to assemble samples of thousands of objects. Only with such large samples will we be able to answer a key scientific objective for upcoming facilities such as JWST, Euclid and WFIRST to address the question "What Objects First Lit Up The Universe, and When?".

The synergy between ground and space based facilities for high-redshift science in the 2020-2030 period

These large samples of z > 7 galaxies and quasars will come from the planned near infrared missions of the next decade, JWST, Euclid and WFIRST, in combination with wide field optical surveys from space (Euclid) and from the ground (e.g. LSST). The unique aspect of Euclid and WFIRST is the wide area they probe, which is required to map out the large scale structure and find the highest density peaks of the underlying dark matter distribution, which are expected to be the formation sites of the first massive galaxies. Only a few bright and gravitationally amplified [19] sources with strong Lyα emission will be detected directly in (slitless) spectroscopy. The selection of the bulk of the high-redshift sources will rely on the photometric signature of the flux suppression shortward of the Lyα line due to IGM and Gunn-Peterson absorption.

Follow-up observations will be necessary to infer the detailed physical properties of the sources and to map out their underlying large-scale structure. Although follow-up observations can encompass a large variety of situations, a simplified wedding cake strategy with different areas and depths illustrates the needs:

i. Deep and pointed observations of quasars and of the brightest galaxies for detailed investigations of their physical properties and of the neutral fraction of the surrounding gas. Facilities and instrumental capabilities required for such observations are JWST (IR imaging and spectroscopy up to 20 microns), ALMA (mm wave imaging and spectroscopy), and medium-resolution near infrared spectroscopy from the ground with integral field capability when available.
ii. Deep observations over hundreds of arcmin^2 scales to map the environment of bright sources and resolve CIB galaxy populations [20]. The required facilities and instrumental capabilities are JWST and multi-object near infrared spectroscopy (MOS-IR) from the ground, with (multi-) integral field capability when available
iii. Wide-area surveys over 10 deg^2 scales to map out the large scale distribution of galaxies. The required capabilities are wide-field multi-object near infrared spectroscopy (WFMOS-IR), with (multi-)integral field capability when available.

While ALMA has the required sensitivity to follow-up the highest redshift sources, its intrinsic narrow field of view limits its capabilities as a source finder. Other (sub-)mm projects such as LMT may play important roles as source finders in the future, but their capabilities remain to be assessed. For near IR spectroscopic observations from the ground, the 8-10 meter telescopes will be initially solicited, before the Extremely Large Telescopes (ELT, TMT, GMT) become available. There is a large variety of near-IR instruments well suited for these follow-up observations, such as PFS at Subaru and MOONS at the VLT in the category of WFMOS-IR instruments. Other facilities and instruments that may be available towards the end of the decade are MOSAIC at the ELT, IRMS/IRMOS at TMT, MANIFEST-IR at GMT, or possibly MSE.

The high-redshift sources selected by Euclid and WFIRST will be distributed in the northern and southern hemispheres. It is therefore important that ground-based telescopes in both hemispheres be available for the follow-up campaigns.

The need for a large coordinated campaign for ground-based follow-up observations of Euclid and WFIRST sources

Euclid will assemble samples of more than 100 $z > 7$ quasars brighter than $J_{AB} \sim 23$ [21] from its wide survey covering 15,000 deg^2, and thousands of $z > 7$ galaxies brighter than $J_{AB} \sim 26$ [22] from its deep survey covering 40 deg^2. WFIRST will identify even larger samples of high-redshift objects by going deeper.

Barnett et al. (2019) estimate that measuring the Lyα damping wing from a high-z QSO requires a SNR $\gtrsim 4$ per Å on an 8 m telescope, corresponding to a magnitude $J_{AB} = 21.3$ in 10 hr. A straw-man spectroscopic follow-up campaign of the 50 brightest $7 < z < 9$ Euclid QSOs with $J_{AB} < 22$ would therefore require of the order of 100 nights on an 8-10 m telescope for measurement of the Lyα damping wing [21].

For galaxies, the typical integration time on an 8-10 m telescope to detect Lyα at 5σ between the OH sky lines on a redshift 8 $H_{AB} = 25.7$ galaxy with a rest frame equivalent width (EW) of 10 Å is of the order of 10 hrs. The number of $7 < z < 9$ Euclid galaxies with $H_{AB} < 25.7$ is expected to be of the order of 10,000. Assuming 5hrs of integration time per night, a straw-man spectroscopic follow-up campaign of the 5,000 galaxy sample accessible from the Northern hemisphere would require a prohibitive 4,000 nights with MOSFIRE at Keck, or a more reasonable 30 nights with PFS at the Subaru telescope. Dedicated high-z galaxy follow-up campaigns would not exploit the multiplex of the instruments and will therefore need to be combined with lower redshift galaxy observations (ex. 300 z > 7 galaxies in average per PFS field compared to a multiplex of 2,400 or 3 z > 7 galaxies in average per MOSFIRE field compared to a multiplex of 46).

This high demand for follow-up campaigns will be spread over a typical time frame of 5 years for each of the Euclid and WFIRST samples (or less in case of timely and coordinated overlap between the two surveys). For the first Euclid data releases expected before 2026, the ELTs will not be available and the demand will amount to tens of nights per year on the 8 m class telescopes. Conversely, ELTs may become available for the last Euclid releases and the initial WFIRST data releases.

Science recommendation: While the wide-field imaging surveys will find very large numbers of galaxies at redshifts above 7, massive spectroscopic follow-up campaigns are required and should be prioritized. The potentially important load on ground-based facilities – obviously subject to peer reviews by time allocation committees – should be shared between European and US facilities. On the European side, ESO / international facilities (VLT, ALMA) and shared national facilities (e.g. LBT, NOEMA) will be sought. On the US side, access to facilities such as Keck, Gemini and Subaru telescopes in the infrared, and LMT and ALMA in mm-wave will be essential. At later stages the European ELT, TMT and GMT are also expected to play crucial roles through their capabilities with first-light instruments. We urge the US agencies to participate in international efforts to make sure sufficient observing resources are available from US national telescopes and private telescopes based in the US.

Technical recommendation: To map out the large scale structure and to study the physical properties of the first galaxies in the large fields probed by Euclid/WFIRST, both very wide field, multi-object spectrographs (e.g. PFS) and large aperture, high resolution facilities for detailed studies of sources over smaller fields of view (e.g. Gemini, Keck, TMT, GMT) are required.

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