Deciphering Chemical Abundance in the First Galaxies

One of the most mysterious objects is the first generation of stars and galaxies, which may have formed 13.6 billion years ago. These primordial objects, which illuminated the early universe, are believed to contain only hydrogen and helium, with trace amounts of lithium. Since light requires time to travel, telescopes act as our time machine, allowing us to observe the universe's most distant reaches and, consequently, the earliest objects in cosmic history. The James Webb Space Telescope (JWST), a groundbreaking telescope that costs over ten billion US dollars to build, was designed specifically to study these first stars and galaxies. I have been a JWSTaholic, with three first-author papers published on distant galaxies using JWST observations. As a junior fellow of the Society of Fellows at Harvard, I plan to analyze imaging and spectroscopic data from JWST to search for, study, and characterize the physical properties of these ancient galaxies and star clusters. My research will focus particularly on the chemical abundances, including the oxygen-to-hydrogen and carbon-to-oxygen ratios, within these early galaxies and down to the scale of individual star clusters.

1. Metal-free objects: The quest for the first galaxies and star clusters

When and how did the first generation of stars, star clusters, and galaxies form? Did they truly lack elements heavier than helium (dubbed "metals") [1, 2]? To address these questions, the search for the first stars has intensified, with significant advancements following the launch of JWST. For instance, an extremely low-metallicity galaxy ($Z < 0.001Z_{\odot}$) was recently discovered at a redshift of $z = 6.6$, approximately 800 million years after the Big Bang (about 13 billion years ago) [3]. As a junior fellow of the Society of Fellows at Harvard, I plan to search for galaxies and star clusters with extremely low metallicity, employing two approaches: grism spectroscopy and medium-band photometry.

Strong hydrogen but weak oxygen features: grism spectroscopy

Near Infrared Camera (NIRCam) Wide Field Slitless Spectroscopy simultaneously captures all galaxy spectra within a field of view, minimizing selection biases and providing a more comprehensive sample using grism. Specifically, JWST Cycle 2 GO 2883 (PI Sun): MAGNIF, observed four lensed clusters, in which I am involved and have access to the reduced data. MAGNIF is expected to produce 20 times more spectra than the typical Micro-Shutter Assembly. In the study of high redshift (early universe), astronomers usually define metallicity as the oxygen abundance relative to hydrogen abundance (O/H). Since the first stars are expected to be metal-free, I will select galaxies based on a ratio between two emission lines: Hα/[O III] λ5008, the brightest hydrogen and oxygen emission lines in the rest-frame optical. Galaxies with high Hα/[O III] λ5008 are potential candidates for being extremely metal-poor. Depending on the detected emission lines, I will estimate their physical properties, including star-formation rates, ionizing photon production efficiency, and the "direct" metallicity if electron temperature-sensitive and electron density-sensitive lines are detected, where I have experience with and have published two papers using these methods [4, 5]. I will propose follow-up JWST integral-field unit (IFU) spectroscopic observations to further study these first galaxies candidates in greater spatial detail.

Deeper sensitivity and better resolution: medium-band photometry

Although grism spectroscopy efficiently collects spectra of all galaxies within a field of view, it has limitations, particularly in disentangling clumps within a galaxy and detecting faint helium lines : HeII λ1640, which is considered a promising tracer of the first stars [6]. NIRCam's medium-band filters onboard JWST offer a valuable alternative, providing the capability to detect potential HeII λ1640 signatures without requiring spectrum [7]. Additionally, medium-band imaging data offers breathtaking resolution, , allowing us to focus on star clusters or halos, which may provide clearer signatures of the first stars, as opposed to entire galaxies that might be quickly contaminated by supernovae [8]. Therefore, I plan to use publicly available JWST medium-band imaging data to look for this HeII λ1640 signature,as well as to identify galaxies or star clusters with high Hα/[O III] λ5008 ratios. My expertise in spectral energy distribution (SED) fitting will be crucial for analyzing the photometry and deriving physical properties [9–11]. I also intend to submit a JWST Cycle 4 proposal for a medium-band imaging survey on five galaxy clusters, which host small-scale, strongly-lensed star clusters recently studied with JWST [11–14] This survey will allow for more precise measurements of redshifts (distances) and stellar masses.

These two observational techniques, grism spectroscopy and medium-band photometry, are complementary and together offer a robust approach to finding the first stars. Grism spectroscopy captures spectra of multiple galaxies in a field of view simultaneously, while medium-band photometry excels in resolving individual star clusters and detecting faint HeII λ1640. By combining these methods, we can leverage their respective strengths to enhance our understanding of the earliest stellar populations in the universe.

2. Carbon footprints of first galaxies and first star clusters

Carbon footprints have been extensively studied as an indicator of global warming. In the context of astrophysics, carbon is one of the most abundant metals and has been detected in the spectra of galaxies when the universe was only 350 million years old [15]. Studying carbon pieces how massive and intermediate-mass stars evolve and release their heavy elements into the interstellar medium (ISM) [e.g., 16–19]. However, prior to the advent of the JWST, our understanding of carbon abundance in the early universe was limited. Now, JWST has opened a new window for spectroscopic studies of carbon abundances in high-redshift galaxies ($z > 6$) [e.g., 15, 20–25]. Despite the numerous observations made by JWST, with over 400 galaxies at $z > 6$ observed spectroscopically, only a few have had their carbon-to-oxygen ratio (C/O) measured [26].

A statistical study of C/O in the early universe

I plan to conduct a comprehensive and statistical study of C/O in galaxies at $z > 6$, using publicly available JWST spectroscopic data, supplemented by the grism spectroscopic data from the MAGNIF project. This approach will allow me to investigate the potential evolution of the C/O ratio in relation to oxygen abundance (O/H) over time. Simultaneously, I will explore whether strong-line diagnostics can be established for future high-redshift spectroscopic surveys, enabling the estimation of C/O without relying on temperature-sensitive lines. Additionally, I will search for galaxies exhibiting a high C/O ratio but low O/H, potentially identifying the signatures of the first stars, as found in D'Eugenio et al. [15].

C/O in star clusters

While upcoming studies on the chemical abundances of high-redshift galaxies will provide crucial insights, most of these studies analyze galaxies as a whole. However, metal enrichment within a galaxy is not homogeneous on a galaxy scale. Additionally, any indication of a high C/O ratio combined with low metallicity is more likely to be detected in individual star clusters or star-forming regions, as other regions might introduce contamination that is difficult to disentangle. Therefore, in addition to examining the carbon abundance across galaxies, I plan to focus on individual star clusters in the early universe using NIRSpec IFU spectroscopy. I will follow a similar analytical process but will extract spatial information to estimate abundances pixel-by-pixel. Although the sample size will likely be smaller than in the previous study, this approach will allow me to assess whether chemical abundances are generally homogeneous within any given galaxy. In parallel, I plan to submit a JWST Cycle 4 proposal this year to request high-resolution IFU spectroscopy on a galaxy observed just 460 million years after the Big Bang. I have already authored three papers on this galaxy, including ongoing work on its C/O ratio. Upon successful approval of this program, I will write a detailed paper on C/O ratios in two distinct star clusters at $z > 10$.

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