Exploring [OIII]88μm /[CII]158μm ratios at $z > 10$ with JWST and ALMA

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1 Abstract

[OIII]88μm and [CII]158μm are two far-infrared lines (FIR) often used to probe galaxy formation. Understanding their ratio as a function of star formation rate (SFR) at different redshifts can aid in our understanding of cosmic history. Galaxies residing at $z \sim 6-9$ have [OIII]/[CII] ratios $\sim$ 10x those in the local universe indicating evolution in the interstellar medium (ISM) with z [5]. However, the highly luminous and distant ($z > 10$) galaxies candidates recently detected with JWST have upper limit [OIII]/[CII] ratios on the scale of $z \sim 0$ galaxies. We propose to conduct a spectroscopic follow up with ALMA of the JWST galaxy candidate SMACS_z12b (S12b), targeting the [OIII]88μm line. This detection, even if an upper limit, will add an additional point to the [OIII]/[CII] -SFR function for $z > 10$ galaxies allowing us to better understand its deviation from the high [OIII]/[CII] ratios of $z \sim 6-9$ galaxies. Additionally, a 0.5 mJy/beam level of the detection of [OIII]88μm at a central frequency of 257 GHz will spectroscopically confirm the S12b making it one of the most distant galaxies discovered.

2 Scientific Justification

2.1 Background

Understanding how star formation changes with redshift is a crucial aspect of galaxy evolution. One probe for physical conditions in star forming regions of a galaxy is the interstellar medium (ISM). Far infrared (FIR), fine structure lines of the ISM such as [OIII]88μm and [CII]158μm are two important regulators of star formation [4]. The [OIII]88μm line comes from the HII regions around hot young stars and traces ionized gas. [CII]158μm is found on the boundary of the HII regions, traces neutral gas (see Figure 1) and is one of the brightest emission lines associated with star formation [8]. Their ratio, [OIII]/[CII] , is ideal for investigating ionization states and ionization structure of the gas within galaxies. In the last several years observations of the [OIII]/[CII] vs SFR function have shown that it changes with redshift, with $z \sim 6-9$ galaxies having much higher ratios than local galaxies [5]. It is still unknown what causes this disparity, but a number of physical explanations for high [OIII]/[CII] ratios exist in the literature including strong bursts of star formation at high z, higher electron densities and higher ionization parameters [11] [5].

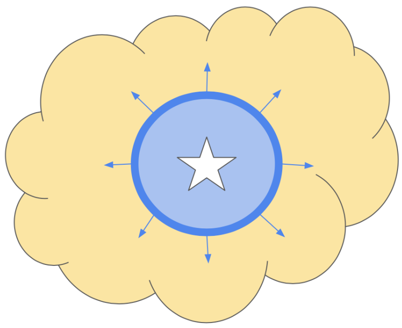

Figure 1: Visualization of the ionization front expanding away from a hot star as neutral gas gets turned to HII. Blue region signifies where [OIII]88μm emission originates while [CII]158μm emission occurs at the boundary and from the yellow neutral gas region.

Only recently have we gotten robust data on UV luminous galaxies at $z > 10$ with JWST [3] [7] [10]. Their detections have caused tensions with current galaxy models such as the UV luminosity function, which predicted less bright galaxies at such high z [6]. Such divergence from expected models motivates exploring properties associated with UV emission and active star formation, such as [OIII]/[CII] ratios. Where does the [OIII]/[CII] ratio of these $z > 10$ galaxies lie with respect to the local and $z \sim 6-9$ galaxies?

For $z > 6$ galaxies the [OIII]88μm and [CII]158μm lines are shifted to the sub-mm wavelength range which makes the Atacama Large Millimeter Array (ALMA) the ideal instrument for detecting the lines of distant galaxies due to its high velocity, spatial and angular resolution. Two UV luminous galaxy candidates, GHZ1($z \sim 10$) and GHZ2($z \sim 12$) found with JWST have already been followed up with ALMA in order to measure their [OIII]88μm lines [12][2]. The [CII]158μm luminosities for GHZ1 and GHZ2 were approximated from the [CII]158μm -SFR function which has little z dependence in the relevant SFR ranges [5]. The upper limits of the [OIII]/[CII] ratio for GHZ1/2 indicate that they fall well below the regime for $z \sim 6-9$ galaxies as seen in figure 2, even though they are estimated to contain rapid star formation [6]. Additional $z > 10$ galaxies should be added to the [OIII]/[CII] -SFR function to validate that their [OIII]/[CII] ratios lie well below what is expected for high z, star forming galaxies, and to better understand the relationship between the ISM, galaxy properties and redshift.

2.2 Source detection with JWST

We propose to do an ALMA follow up on another $z > 10$, UV luminous JWST galaxy candidate, SMACS_z12b (S12b), to measure its [OIII]88μm line. This would allow us to potentially determine the magnitude of its [OIII]/[CII] ratio and spectroscopically confirm its redshift. S12b is a target behind the lensing cluster SMACS0723 and is summarized in table 1[1]. Detected with JWST's Near Infrared Camera (NIRCam) and Imager (NIRISS), its photometric redshift, mass, stellar age and dust attenuation properties are derived in [1]. Atek et al. 2022 uses the Spectral Energy Distribution (SED) fitting codes EAZY and BEAGLE to construct SEDs of from the multi-wavelength photometry. The photometric redshift ($z \sim 12.26$) reported in table 1 comes from the BEAGLE SED as this code performs MCMC analysis and is best fitted to determine photometric redshifts [1]. S12b is a suitable candidate for ALMA follow up due to its relatively high UV luminosity, large effective radius and near-zero probability that it is a low z galaxy masquerading as a $z \sim 12$ galaxy (see figure 2).

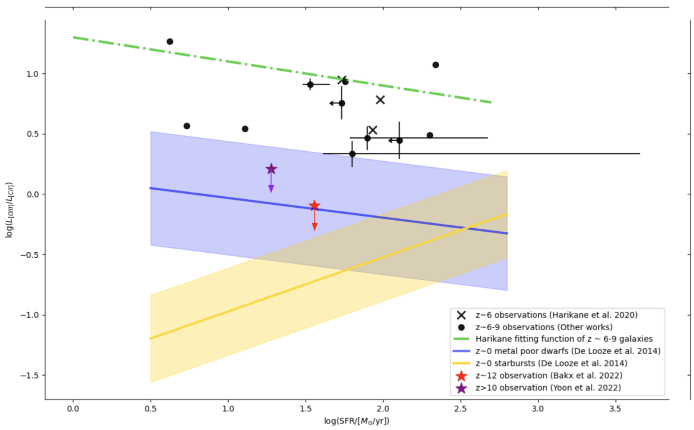

Figure 2: [OIII]88μm/[CII]158μm luminosity ratio plot as a function of star formation rate for local galaxies, $z \sim 6-9$ galaxies and the newest observations of $z > 10$ galaxies. Upper limit of GHZ1 (red star) and GHZ2 (purple star) place them in the same regime as the $z \sim 0$ galaxies [2],[12],[5].

Obtaining the [OIII]88μm measurement for S12b , along with its [CII]158μm luminosity approximated from the [CII]158μm -SFR fitting function, will add another point to figure 2. Even obtaining an upper limit detection of the [OIII]88μm line, as was the case for GHZ1/2, will give valuable information of [OIII]/[CII] ratio in relation to the $z \sim 6-9$ and $z \sim 0$ galaxies. Additionally, detecting the [OIII]88μm line for S12b will give a spectroscopic redshift and confirm it as a $z > 10$ galaxy. If spectroscopically confirmed, S12b will be an ideal follow up for NIRSpec on JWST for further high resolution measurements of its ISM properties.

Table 1: *Selected properties of S12b as derived in [1]*

ID	RA	Dec	z_{phot}	M_{UV}	r_e[kpc]
SMACS_z12b (S12b)	07:22:52.261	-73:27:55.497	$12.26^{+0.17}_{-0.16}$	-20.01 $\pm$0.17	1.99

3 Technical Justification

In order to measure [OIII]88μm ($\nu_{rest} = 3393.0062$ GHz) we request a frequency range of 255 GHz - 259 GHz with a central frequency of 257 GHz to cover the central peak of the redshift posterior distribution of S12b as seen in figure 2. This corresponds with ALMA's band 6 frequency range. During the month of August the Precipitable Water Vapor (PWV) is at its lowest for Band 6 with a greater than 75% chance that the PWV will be less than 1.7mm, an important consideration for necessary high sensitivity[1]. We also request an observation period between 19-8hr Local Sidereal Time as suggested for optimal observing conditions[1]. For cycle 10 the configuration that will be available in August 2023 is C-9 with 43 antennas, which is available for Band 6 and has a maximum baseline of 13.9 km corresponding with an angular resolution of 0.025"[1]. This resolution is sufficient for the 1.99 kpc effective radius of S12b (as reported in table 1) which corresponds with 0.54" at $z \sim 12.26$ [2] [1].

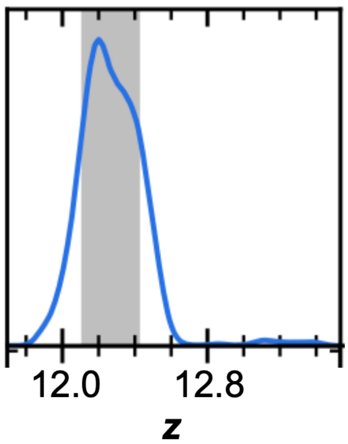

Figure 3: Posterior distribution for S12b as derived from BEAGLE SED fitting of photometric data collected from JWST [1].

In order to achieve a 5σ SNR detection at 35 km/s, a 0.5 mJy/beam sensitivity is necessary [2]. Given the resolution, the flux density estimated per beam is equal to 0.58 mJy [3]. The ALMA sensitivity calculator (ASC)[4] gives an estimate of the total on source integration time of 152 minutes given the sensitivity of 0.58 mJy. The internal calculation of the ASC uses the standard equation for sensitivity RMS given various parameters for an interferometer (effective dish area, number of antenna, channel width, integration time), including a system temperature of 109.89 K.

$$\delta S_\nu = \frac{2k_B T_{sys}}{A_{eff}\sqrt{N_a(N_a-1)t_{int}\Delta\nu}} \tag{1}$$

Equation (1) (from [9]) represents a simplified version of the full equation used in the ASC. Dual polarization will be used to get independent estimates of the source that combined to improve sensitivity. Approximately 10 minutes will be needed for bandpass calibration and 20 for phase calibration[5], for a total time request of 182 minutes. The data will be reduced using the standard ALMA pipeline and imaging will be performed using the CASA software. UV visibilities will be weighted using the Briggs' weighting scheme instead of natural weighting in order to maximize the depth of the observations [2].

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[2]https://astro.ucla.edu/ wright/CosmoCalc.html
[3]https://tinyurl.com/ydehnxpa
[4]https://almascience.eso.org/proposing/sensitivity-calculator
[5]https://almascience.nrao.edu/documents-and-tools/cycle9/alma-technical-handbook

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