ALMA Observation of 158 μm [CII] Line and Dust Continuum of a $z = 7$ Normally Star-Forming Galaxy in the Epoch of Reionization

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High-z star-forming galaxies in the epoch of reionization (EoR) have been usually detected via their Lyα lines or UV continua. However, as UV light traces only ionized gas/stars, we have seen merely a portion of star formation in galaxies. Another aspect yet unexplored is dust-obscured star formation, and rest frame far-infrared (FIR) lines and continuum can probe it as they reflect fuel for star formation and light from stars once absorbed and re-emitted by dust, respectively. FIR lights from EoR galaxies are redshifted to (sub)millimeter and observable from the ground by Atacama Large Millimeter/submillimeter Array (ALMA). Among many FIR lines, 158 μm [CII] is the strongest line of an interstellar medium and suited for probing faint distant galaxies.

We conducted ALMA observations of the [CII] line and FIR continuum of a normally star-forming galaxy in EoR, a z=6.96 Lyα emitter (LAE) IOK-1 [1]. We found it undetected in both [CII] and continuum to $\sigma_{\rm line} = 240\,\mu$Jy beam^{-1} (40 km s^{-1} channel) and $\sigma_{\rm cont} = 21\,\mu$Jy beam^{-1}. Comparison of UV–FIR spectral energy distribution (SED) of IOK-1, including our ALMA limit, to those of several types of galaxies suggests that IOK-1 is similar to local dwarf/irregular galaxies in SED shape rather than highly dusty/obscured galaxies (Figure 1). Moreover, our 3σ FIR continuum limit implies intrinsic dust mass $M_{\rm dust} < 6.4 \times 10^7\,M_\odot$, FIR luminosity $L_{\rm FIR} < 3.7 \times 10^{10}\,L_\odot$ (42.5–122.5 μm), total IR luminosity $L_{\rm IR} < 5.7 \times 10^{10}\,L_\odot$ (8–1000 μm) and dust-obscured star formation rate (SFR) $< 10\,M_\odot$ yr^{-1}, if we assume that IOK-1 has a dust temperature and emissivity index typical of local dwarf galaxies. This SFR is 2.4 times lower than one estimated from the UV continuum, suggesting that < 29 % of the star formation is obscured by dust. Meanwhile, 3σ [CII] flux limit converts to luminosity $L_{\rm [CII]} < 3.4 \times 10^7\,L_\odot$. Locations of IOK-1 and previously observed LAEs on the $L_{\rm [CII]}$ vs. SFR and $L_{\rm [CII]}/L_{\rm FIR}$ vs. $L_{\rm FIR}$ diagrams imply that LAEs in EoR have significantly lower gas and dust enrichment than AGN-powered systems and starbursts at similar/lower redshifts as well as local star-forming galaxies (Figure 2).

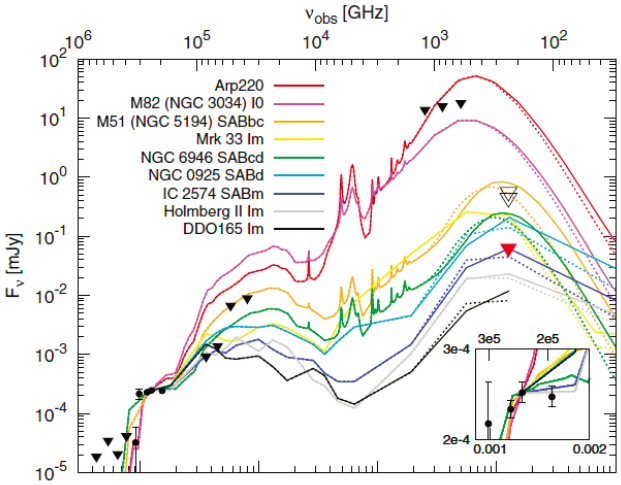

Figure 1: SED of IOK-1 (Data points. Triangles are 3σ upper limits). Our ALMA 3σ upper limit on 1.26 mm continuum is the red triangle while those from previous studies the open triangles. For comparison, various local galaxy SEDs including (not including) cosmic microwave background effects on FIR continua are shown by color coded dotted (solid) lines.

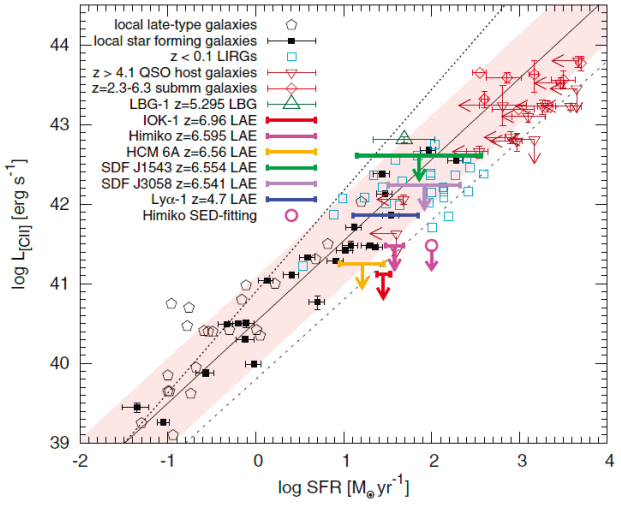

Figure 2: $L_{\rm [CII]}$ versus SFR for different types of objects compiled by us [1]. The arrows indicate upper limits. The dotted line is the correlation for local late-type galaxies. The solid line with shaded region is the correlation for local star-forming galaxies with 2σ scatter. The dashed line is the correlation for $L_{\rm FIR} > 10^{12}\,L_\odot$ sources.

Reference

[1] Ota, K., et al.: 2014, *ApJ*, **792**, 34.