The Astrophysical Journal, 896:170 (20pp), 2020 June 20
https://doi.org/10.3847/1538-4357/ab91a5
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The Semiforbidden CIII $\lambda 1909$ Emission in the Rest-ultraviolet Spectra of Green Pea Galaxies

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Received 2019 October 21; revised 2020 May 7; accepted 2020 May 7; published 2020 June 25

Abstract

We used the Space Telescope Imaging Spectrograph on the Hubble Space Telescope (HST) to observe the semiforbidden CIII $\lambda\lambda 1907$, 1909 doublet emission in green pea galaxies at $0.13 \leq z \leq 0.3$. We detect CIII emission in 7/10 galaxies with CIII equivalent widths (EWs) that range from 2 to 10 Å, confirming that CIII emission is almost ubiquitous in low-mass, low-metallicity ($12+\log(O/H) < 8.4$) galaxies that are characterized by strong optical [O III] $\lambda 5007$ emission. The composite UV spectrum shows evidence for the He II $\lambda 1640$ emission line and interstellar absorption features (e.g., C IV $\lambda\lambda 1548, 1550$, Al III $\lambda 1854, 1862$). We do not detect the O III $\lambda\lambda 1661, 1666$ emission with $>3\sigma$ significance. The observed C III emission line strengths are consistent with the predictions from photoionization models that incorporate the effects of binary stellar evolution with young stellar ages $\leq 3-5$ Myr and high ionization parameters ($\log U > -2$). The hard ionizing radiation from young massive stars and high nebular temperatures at low metallicities can account for the observed high EWs of C III $\lambda 1909$ and [O III] $\lambda 5007$ emission lines. Some of the star-forming galaxies at high redshift and local blue compact dwarf galaxies show offsets from the EW(C III) versus EW([O III]) model grids, indicating an additional contribution to the continuum emission from composite stellar populations or different C/O abundances, nebular temperatures, and electron densities than assumed in the photoionization models. The green pea galaxies do not show a significant correlation between the Ly$\alpha$ and C III emission, and the observed scatter is likely due to the variations in the optical depth of Ly$\alpha$ to the neutral gas. Green pea galaxies are likely to be density-bounded, and we examined the dependence of CIII emission on the Lyman continuum optical depth. The potential LyC leaker galaxies in our sample have high C III EWs that can only be produced by starburst ages as young as $< 3$ Myr and harder ionizing spectra than the nonleakers. Among the galaxies with similar metallicities and ionization parameters, the C III EW appears to be stronger for those with higher optical depth to LyC, as expected from the photoionization models. There are various factors that affect the C III emission line strengths, and further investigation of a larger sample of C III emitters is necessary to calibrate the dependence of C III emission on the escape of LyC radiation and enable application of the C III diagnostics to galaxies in the reionization epoch.

Unified Astronomy Thesaurus concepts: Starburst galaxies (1570); High-redshift galaxies (734); Emission line galaxies (459); H II regions (694); Spectroscopy (1558)

1. Introduction

The semiforbidden [C III] $\lambda 1907 +$ C III $\lambda 1909$ doublet (hereafter C III $\lambda 1909$ or C III)) is one of the strongest nebular emission line features observed in the rest-frame ultraviolet (rest-UV) spectrum of low-metallicity, $12+\log(O/H) < 8.4$ ($Z < 0.5 Z_\odot$) star-forming galaxies (SFGs) both locally (Garnett et al. 1995; Rigby et al. 2015; Berg et al. 2016, 2019; Senchyna et al. 2017, 2019) and at high redshifts (Fosbury et al. 2003; Erb et al. 2010; Bayliss et al. 2014; Stark et al. 2014, 2015a, 2017; de Barros et al. 2016; Vanzella et al. 2016; Amorín et al. 2017; Laporte et al. 2017; Maseda et al. 2017; Berg et al. 2018; Hutchison et al. 2019; Le Fèvre et al. 2019). The C III emission line is frequently observed in gravitationally lensed SFGs at $z > 2-6$ as the strongest line after Ly$\alpha$ $\lambda 1216$ emission. Since the Ly$\alpha$ emission at $z > 6$ is expected to be severely quenched by the increasingly neutral intergalactic medium (IGM), C III is emerging as an alternative redshift indicator for galaxies in the reionization era (Stark et al. 2015a, 2017; Ding et al. 2017). At $z > 6$, the rest-UV spectrum of galaxies is redshifted to the near-infrared (NIR) wavelengths and is accessible to the spectrographs on upcoming facilities (such as the James Webb Space Telescope (JWST) and the $>20$ m class Extremely Large Telescopes), which will address the key goal of identifying the sources of reionization. In recent years, there has been considerable effort to develop spectral diagnostics involving the C III emission line and other UV spectral features (e.g., C IV $\lambda\lambda 1548, 1550$, He II $\lambda 1640$, and O III $\lambda\lambda 1661, 1666$ (hereafter O III $\lambda 1663$ or O III)) that can be used to understand the nature of the reionizers, their hard ionizing continua, and the physical conditions in their ISM (Feltre et al. 2016; Gutkin et al. 2016; Jaskot & Ravindranath 2016, hereafter JR16; Byler et al. 2018; Nakajima et al. 2018b). The C III emission observed at high redshifts is mostly from strongly lensed low-metallicity ($<0.5 Z_\odot$, low-mass ($<10^{10} M_\odot$) galaxies with high specific star formation rates (SSFRs $\geq 2$ Gyr$^{-1}$), and their C III equivalent widths (EWs) show a broad range: EW(C III) $\sim 3-25$ Å (Fosbury et al. 2003; Erb et al. 2010; Bayliss et al. 2014; Stark et al. 2014; de Barros et al. 2016; Vanzella et al. 2016; Berg et al. 2018). The composite rest-UV spectra of Lyman-break galaxies at $z \sim 3$ (Shapley et al. 2003) and SFGs at $z = 1-2.5$ (Steidel et al. 2016; Amorín et al. 2017) also reveal the C III $\lambda 1909$ and O III $\lambda 1663$ nebular lines at subsolar metallicities.

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In the local universe \((z \sim 0)\), the UV spectra of SFGs obtained with the Faint Object Spectrograph and Goddard High Resolution Spectrograph on the Hubble Space Telescope (HST) revealed C\textsc{iii} \(\lambda 1909\) and O\textsc{iii} \(\lambda 5007\) in metal-poor blue compact dwarfs (BCDs) and Wolf–Rayet (WR) galaxies (Garnett et al. 1995; Leitherer et al. 2011). These UV lines, although measured only in a small sample of low-metallicity galaxies, were used to determine C/O ratios and infer the elemental carbon abundances (Garnett et al. 1995). Based on the compilation of all available C\textsc{iii} EW measurements for SFGs at low and high redshifts, Rigby et al. (2015) found that low-metallicity galaxies tend to have a stronger C\textsc{iii} emission, and C\textsc{iii} EW values seen for the local universe. Most of these SFGs have EW(C\textsc{iii}) \(\geq 5\) \(\AA\) is only found in galaxies with \(Z < 0.5 Z_\odot\). Only three galaxies in their compilation of 46 local SFGs showed EW(C\textsc{iii}) \(\geq 14\) \(\AA\), comparable to the strongest C\textsc{iii} emitters at \(z > 2\), and all three are WR galaxies with high H\textsc{o} EWs. More recently, UV spectroscopy of BCDs (Berg et al. 2016, 2019), He II emitters (Senchyna et al. 2017), and extremely metal-poor galaxies (Senchyna et al. 2019) with the HST/Cosmic Origins Spectrograph (COS) has increased the number of C\textsc{iii} emission line measurements in the local universe. Most of these SFGs have EW(C\textsc{iii}) in the range of values seen for the \(z \sim 2\) galaxies, and only a few of them with very low metallicities reach high EWs of \(\sim 12–14\) \(\AA\). The distribution of EW(C\textsc{iii}) as a function of metallicity from these new studies also confirms that C\textsc{iii} emission EWs >\(5\) \(\AA\) occur at low metallicities, with a clear transition occurring at \(12+ \log(\text{O/H}) < 8.4\) or \(Z < 0.5 Z_\odot\) (Senchyna et al. 2017, 2019).

The physical properties of the C\textsc{iii} emitters at \(z \sim 3\) inferred from the UV–optical spectra reveal that the interstellar medium (ISM) conditions in these low-metallicity SFGs are different from the high-metallicity SFGs, as evidenced by the presence of extreme optical emission lines with high EWs. Most of the C\textsc{iii} emitters for which optical spectra are available show high EWs (\(\sim 1000\) \(\AA\)) for the [O\textsc{iii}] \(\lambda 5007\) (hereafter [O\textsc{iii}] \(\lambda 5007\) or [O\textsc{iii}] emission line (Stark et al. 2014; Vanzella et al. 2016; Maseda et al. 2017) and would be identified as extreme emission line galaxies (EELGs; van der Wel et al. 2011) based on the contribution of the [O\textsc{iii}] emission to their broadband colors. The SFGs at \(z > 2\) with strong UV–optical emission lines in their spectra commonly show high ionization parameters (log \(U > -2\)), blue UV continuum slopes (\(\beta > -2\)), low dust content, and evidence for strong outflows (Steidel et al. 2014; Maseda et al. 2014; Shapley et al. 2015). The best-fit photoionization models based on the photometric spectral energy distributions (SEDs) suggest low metallicities and large EW([O\textsc{iii}] +H\beta) (>\(700\) \(\AA\)) for the C\textsc{iii} emitters at \(z > 6\) (Stark et al. 2015a, 2017). The contribution of strong nebular [O\textsc{iii}] \(\lambda 5007 + H\beta\) to the Spitzer IRAC [3.6]–[4.5] colors is being increasingly used to identify \(z \sim 6.6–9.0\) galaxies (Smit et al. 2014, 2015; Roberts-Borsani et al. 2016; Stark 2016), and their follow-up spectroscopy has revealed some of the strongest C\textsc{iii} emitters with EW(C\textsc{iii}) >\(20\) \(\AA\) (Stark et al. 2017; Hutchison et al. 2019). Many of these high-redshift sources are also Ly\(\alpha\) emitters (LAEs), and the EWs of the C\textsc{iii} and Ly\(\alpha\) emission lines are found to be correlated (Shapley et al. 2003; Stark et al. 2014, 2015a; Rigby et al. 2015). The LAEs are also actively star-forming with high SSFRs, low dust content, and strong [O\textsc{iii}] \(\lambda 5007\) emission, and their [O\textsc{iii}] \(\lambda 5007/[\text{O}\textsc{ii}] \lambda 3727\) ratios (hereafter \(O_{32}\)) imply high ionization parameters (Nakajima & Ouchi 2014; Nakajima et al. 2016).

Although low metallicities and young stellar ages are favorable for C\textsc{iii}, the strength of the emission is determined by many other factors that are not yet fully understood. The C\textsc{iii} is a collisionally excited emission line, and high nebular temperatures and densities are expected to enhance the emission due to the increased collisional rates. Photoionization codes are increasingly being used to try and understand the role of age, ionization parameter, metallicity, and dust on the emergent C\textsc{iii} nebular line flux (JR16; Nakajima et al. 2018b). The models are able to reproduce the observed EW(C\textsc{iii}) values, including the very high values >\(10–15\) \(\AA\), but require extreme values of ionization parameter (log \(U > -2\)) and very young stellar populations with ages <\(3\) Myr at \(Z < 0.5 Z_\odot\). Only models that incorporate the effects of binary stellar evolution (Eldridge & Stanway 2009; Eldridge et al. 2017) are able to produce the hard ionizing continuum required to produce the strong C\textsc{iii} emission with EW(C\textsc{iii}) >\(10\) \(\AA\) over long timescales (>\(3\) Myr) as compared to the single-star models (JR16). The stellar population models including massive star binaries are also known to consistently account for the observed nebular emission line ratios in the rest-UV and optical spectra of \(z \sim 2.4\) galaxies (Steidel et al. 2016). Photoionization models predict that high optical depths, high C/O ratios, and the presence of shocks can enhance the C\textsc{iii} emission for a given age, metallicity, and log \(U\) (JR16). In recent years, UV spectral diagnostics involving C\textsc{iii}, CIV, and He II have been identified (Feltre et al. 2016; Gutkin et al. 2016) that have the ability to distinguish between an ionizing continuum powered by SFGs versus active galactic nuclei (AGNs). However, observations of low-metallicity galaxies that span the range of physical properties that determine the C\textsc{iii} strengths are limited, offering few constraints to disentangle the effect of various model parameters on the emergent nebular line fluxes.

The green pea galaxies (GPs) are among the closest low-redshift analogs to the low-mass, low-metallicity SFGs in the reionization era. The GPs at \(z = 0.1–0.3\) were originally identified in the Sloan Digital Sky Survey (SDSS) DR7 data through a \(gri\) color selection based on the unusually strong [O\textsc{iii}] \(\lambda 5007\) emission (EW([O\textsc{iii}] >\(300\) \(\AA\)) in the \(r\) band (Cardamone et al. 2009). Their optical emission line spectra imply high star formation rates (SFRs >\(10–60\) \(M_\odot\) \(\text{yr}^{-1}\)), high SSFRs (\(10^{-7}–10^{-3}\) \(\text{yr}^{-1}\)), low metallicities (\(Z < 0.5 Z_\odot\)), low extinction (\(E(B-V) < 0.25\)), and the presence of hard ionizing spectra produced by very hot stars (Cardamone et al. 2009; Izotov et al. 2011; Amorín et al. 2012). The GPs have high electron temperatures (>\(15,000\) K) derived from the optical nebular lines, and the high \(O_{32}\) ratios suggest that they have high ionization parameters (Kewley & Dopita 2002; Jaskot & Oey 2013). The strong Balmer lines and detection of the He II \(\lambda 4686\) line indicate very young ages of <\(3–5\) Myr for the dominant stellar population (Jaskot & Oey 2013). Although the UV–optical spectra of GPs are dominated by the recently formed young stars, modeling their star formation history shows that they host an older population (>\(1\) Gyr), which contributes most of the stellar mass (Amorín et al. 2012). The GPs have high EW([O\textsc{iii}] >\(500–1000\) \(\AA\)), similar to the C\textsc{iii} emitters at \(z \sim 2\), and their \(O_{32}\) ratios, ionization parameters, metallicities, and SSFRs are more extreme than the normal, low-\(z\) SFGs but comparable to LAEs at \(z > 2\) (Nakajima &
Ouchi (2014). The GPs have low stellar masses ($M \sim 10^8–10^{10} M_\odot$), are UV-luminous ($L_{UV} \sim 3 \times 10^{10} L_\odot$), and have compact sizes ($\lesssim 5$ kpc). In the HST images, some of the GPs appear as clumpy galaxies, with one or a few bright super star clusters that dominate the morphology, giving them a close resemblance to SFGs at $z > 2$ (Henry et al. 2015; Izotov et al. 2018a).

The GPs are extremely valuable for exploring the nebular line diagnostics because they are at low redshifts, $z < 0.3$, and all of the rest-UV–optical spectra are accessible to determine their physical properties, ISM conditions, and escape fractions in much more detail than can be done for the high-redshift galaxies. The rest-UV spectra of GPs taken with the HST/COS covering the rest wavelengths 950–1450 Å show strong Ly$\alpha$ emission with a variety of profile shapes and escape fractions, $f_{esc}(\text{Ly}\alpha) = 0\%–98\%$ (Jaskot & Oey 2014; Henry et al. 2015; Izotov et al. 2018b). Their Ly$\alpha$ profiles are most often double-peaked, and the separation between the peaks is an indicator of the column density of neutral hydrogen and possible leakage of ionizing radiation (Verhamme et al. 2015, 2017). Direct measurements of the Lyman continuum (LyC) escape are only available for a handful of galaxies at low redshifts, and GPs have been the most promising candidates with high observed escape fractions, $f_{esc}(\text{LyC}) = 3\%–72\%$ (Izotov et al. 2016a, 2016b, 2018a, 2018b). Recently, Schaerer et al. (2018) reported the detection of intense C$\text{[III]} \lambda1909$ emission with EW(C$\text{[III]}$) = 11.7 $\pm$ 2.9 Å in GP J1154+2443, a galaxy that has $f_{esc}(\text{Ly}\alpha) = 98\%$ and is a confirmed LyC emitter with $f_{esc}(\text{LyC}) = 46\%$. In JR16, we presented various diagnostics involving the C$\text{[III]}$ emission line and offered specific predictions for the dependence of EW(C$\text{[III]}$) on the optical depth in GPs. Galaxies that have weaker EW(C$\text{[III]}$) than predicted for their O$_{32}$ ratio are likely to be density-bounded or optically thin systems with a high fraction of LyC escape.

Thus, EW (C$\text{[III]}$) can be an indicator of the optical depth if the ionization parameter, age, and metallicity can be constrained using other emission lines in the spectra. According to the JR16 models with $Z \sim 0.003$ and age $< 10$ Myr, for the GPs with O$_{32}$ ratios $\sim 1–10$, the C$\text{[III]}$ EWs are $\lesssim 1–4$ Å at low optical depths, and EW (C$\text{[III]}$) $> 6$ Å would require extremely young stellar ages, $\lesssim 2$ Myr. The photoionization models predict C$\text{[III]}$ EWs for most of the GPs to be in the range of 2–10 Å, depending on the age of the starburst. Further, the models predict C IV $\lambda1549$ emission in GPs to be $\lesssim 50\%$ of the C$\text{[III]}$ emission and He II $\lambda1640 < 10\%$ of C$\text{[III]}$, although the latter may be affected by contributions from other sources, such as a significant WR population or shocks.

In this paper, we present new rest-UV spectroscopy of a sample of 10 GPs and compare it with the JR16 photoionization model predictions to understand the conditions that give rise to the C$\text{[III]}$ nebular emission and its dependence on metallicity ($Z$) and ionization parameters ($U$). Since optical emission line ratios from SDSS spectra offer independent constraints on the metallicity ($Z$) and ionization parameter ($U$), and the Ly$\alpha$ lines offer information about the optical depth, these galaxies are excellent candidates to test the model predictions for C$\text{[III]}$ emission. The details of the observations and analysis are presented in Section 2. The results of the correlations between C$\text{[III]}$ emission and other UV–optical lines are presented in Section 3, followed by a comparison with photoionization models in Section 4. We discuss the results from GPs in the context of low-metallicity galaxies at high redshifts and implications for galaxies in the reionization era in Section 5. Throughout this paper, we assume $12+\log(O/H) = 8.69$ for solar metallicity (Asplund et al. 2009).

### 2. HST/STIS Observations and Data Analysis

The HST observations for the sample of GPs were obtained with the Space Telescope Imaging Spectrograph (STIS) through the program GO-14134 (PI: Ravindranath), which was awarded 18 orbits. All of the galaxies in our sample have archival HST/COS spectra covering the wavelengths that include the Ly$\alpha$ emission. The STIS observations were designed to use the HST UV spectra to measure the C$\text{[III]}$ 1909 Å line fluxes and EWs, investigate the correlations between C$\text{[III]}$ and Ly$\alpha$ emission, and examine the behavior of C$\text{[III]}$ emission relative to the rest-optical emission line diagnostics derived from the SDSS spectra.

#### 2.1. The Sample and Observations

We selected all GPs that had existing archival HST/COS spectra covering the wavelengths that include the Ly$\alpha$ emission from two previous HST-GO programs that observed GPs. The sample consists of 10 GPs (Table 1) at redshifts $z = 0.1–0.3$ with low metallicities ($< 0.4$ Z$_\odot$; Izotov et al. 2011), of which four are classified as “extreme” GPs based on their high optical emission line ratios, with [O$\text{[II]}$] $\lambda\lambda4959, 5007$/[O$\text{[II]}$] $\lambda\lambda727 > 9$ (Jaskot & Oey 2013). For eight of the objects, HST/COS G130M and G160M spectra are available in the

| Name          | R.A. (J2000) | Decl. (J2000) | Redshift | g (AB mag) | NUV (AB mag) | Exposure Time (s) | $\lambda_{rest}$ frame (Å) |
|---------------|--------------|---------------|-----------|------------|--------------|-------------------|-----------------------------|
| J00321−075923 | 03:03:21.41  | −07:59:23.2   | 0.165     | 19.4       | 19.6         | 4924              | 1345–2733                  |
| J081552+215623| 08:15:52.00  | +21:56:23.6   | 0.141     | 20.1       | 20.1         | 7499              | 1374–2790                  |
| J091113+183108| 09:11:13.34  | +18:31:08.1   | 0.262     | 19.5       | 19.8         | 4896              | 1242–2522                  |
| J105330+523752| 10:53:30.82  | +52:37:52.8   | 0.253     | 18.8       | 19.2         | 2300              | 1251–2541                  |
| J113300+651341| 11:33:03.79  | +65:13:41.3   | 0.241     | 19.1       | 19.7         | 5282              | 1263–2565                  |
| J113722+352426| 11:37:22.14  | +35:24:26.6   | 0.194     | 18.9       | 19.3         | 2163              | 1313–2666                  |
| J121903+152608| 12:19:03.98  | +15:26:08.5   | 0.196     | 19.5       | 19.3         | 1909              | 1311–2662                  |
| J124423+021540| 12:44:23.37  | +02:15:40.4   | 0.239     | 19.2       | 19.9         | 4974              | 1265–2569                  |
| J124834+123402| 12:48:34.63  | +12:34:02.9   | 0.263     | 19.9       | 19.9         | 4698              | 1241–2520                  |
| J145735+223201| 14:57:35.13  | +22:32:01.7   | 0.149     | 19.4       | 19.9         | 4926              | 1364–2771                  |

Note. The coordinates, redshifts, and g magnitudes are from SDSS DR7, and the NUV magnitudes are taken from GALEX. The last two columns provide the total exposure times for the HST/STIS observations and the rest-UV wavelength coverage in the G230L grating for each galaxy based on its redshift.
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archive covering the rest wavelengths $\lambda \sim 950$–1450 Å from GO-12928 (PI: Henry), and two of the remaining galaxies have COS G160M spectra from GO-13293 (PI: Jaskot). The COS G160M spectra from both of these programs provide Lyα emission line detections with a signal-to-noise ratio $(S/N) > 10$. The sample of GPs represents a range of physical properties with EW (Lyα) $\sim 0$–170 Å, nebular oxygen abundances with $7.8 < 12 + \log (O/H) < 8.3$ (0.15–0.40 Z$_\odot$), and stellar masses $(<3 \times 10^7 M_\odot)$. The GPs have high UV surface brightnesses ($<20$ mag arcsec$^{-2}$) in the Galaxy Evolution Explorer (GALEX) near-UV (NUV) images and compact sizes ($\sim 1''$) that correspond to physical sizes of 2.5–3.5 kpc for their redshifts.

The HST/STIS observations were carried out using the G230L grating that covers the wavelength range 1700–3200 Å at a spectral resolution of $R \sim 300$–600 across these wavelengths. The average dispersion with the G230L grating is 1.58 Å per pixel, resulting in a spectral resolution of $\sim 3$ for the spectrum. The STIS is equipped with the NUV-MAMA detector, with a pixel scale of 0.025 pixel$^{-1}$ (or 0.05 per 2 pixel resolution element). The GPs are barely resolved in the SDSS images, with sizes of $\sim 1''$. We used the 52$''$ × 0.5 slit to optimize between slit loss and spectral resolution, resulting in $R \sim 500$ over most of the wavelength range. The target acquisition images were taken using short exposures ($\sim 100$ s) on the STIS CCD detector. The exposure times for the STIS NUV spectra were estimated based on the GALEX NUV flux for the continuum and using the predicted C III] $\lambda\lambda 909$ and O III] $\lambda 1663$ emission line fluxes from CLOUDY photoionization models (Ferland et al. 2013). The total exposure times varied from 2500 to 7500 s based on the target brightness and predicted emission line fluxes.

2.2. Analysis

We retrieved STIS spectra from the MAST archive that are pipeline-processed and calibrated using CALSTIS. The pipeline produces flux-calibrated, rectified two-dimensional spectroscopic images and one-dimensional spectra of flux versus wavelength for each target. The default aperture used for spectral extraction in the pipeline is 11 pixels (0.2''75) along the cross-dispersion axis. However, some of the GPs are clearly more extended in the spatial direction based on the two-dimensional spectroscopic image and the acquisition images. We reprocessed the raw data files using updated reference files and performed the spectral extraction using optimized extraction boxes. The standard extraction height of 11 pixels was used for the more compact GPs, and the spectra of the more extended sources were extracted using 21 pixels in the spatial direction. The extracted one-dimensional spectra were smoothed by 2 pixels in the wavelength direction to a final spectral resolution of 3.2 Å per pixel$^{-1}$. In the cases where there were multiple exposures from two or more orbits, the one-dimensional spectra from multi-orbit visits were combined using scombine in pyRAF. The final combined spectra have $S/N \geq 4$ pixel$^{-1}$ in the continuum at $\sim 1900$–2000 Å for all GPs.

The HST/STIS spectra covering rest-UV wavelengths from 1400 to 2200 Å for the sample are presented in Figures 1 and 2. The C III] emission line is detected with greater than 3σ significance in seven of the 10 GPs. We measured the fluxes and EWs of the C III] emission line using the splot task within the speced package in PyRAF. We used the HST/COS acquisition images to measure the extent of the UV continuum and correct for the slit losses due to the 0.5'' × 0.5''25 aperture used for HST/STIS spectral extraction for the GPs. In most cases, the UV continuum is compact and the extraction box includes 75%–80% of the flux, except for two galaxies that have multiple UV-bright knots, and only 62% of the flux is within the extraction box. There is a possibility that the nebular emission may be more extended than the continuum. We used the HST/ACS images taken in the narrowband ramp filter tuned to [O III] $\lambda 5007$ from HST-GO-13293 (PI: Jaskot) to measure the slit losses for four galaxies (J0303–0759, J0815+2156, J1219+1526, and J1457+2232) in our sample. The extent of the nebular emission and measured slit losses was found to be comparable to that measured from the UV continuum in all cases. The EW(C III]) measurements were performed by using direct integration of the area under the line, as well as the Gaussian profile fitting method. The measurements from the two methods are in close agreement, and the average of the two is used for further analysis. The continuum flux ($F_c$) is assumed to be flat in the vicinity of the C III]] line. The noise in the continuum spectrum on either side of the emission line contributes to the uncertainty in the measured EWs. We include this in the errors by using repeated measurements with different continuum levels to determine the rms uncertainty arising from the continuum noise.

We do not detect any measurable C III] emission in three GPs, J0911+1831, J1053+5237, and J1137+3524, and we provide upper limits on their C III] fluxes in Table 2. These GPs with no C III] emission line in their rest-UV spectrum have dominant interstellar (and possibly stellar) absorption features, in particular, Si IV $\lambda\lambda 1393, 1402$ and C IV $\lambda 1548, 1550$. We detect strong C IV $\lambda 1458, 1500$ absorption lines with EW(C IV) = −10.53 ± 0.3, −4.55 ± 0.02, and −14.8 ± 1.91 Å in J0911+1831, J1053+5237, and J1137+3524, respectively. In the case of J0911+1831 and J1053+5237, the spectra also show Si IV $\lambda 1393, 1402$ absorption. The GP 1137+3524 has a lower redshift ($z = 0.194$), and only a broad C IV absorption is detected. Because it falls in the low-S/N blue end of the spectrum, Si IV absorption cannot be identified for this galaxy.

We do not detect the O III] $\lambda 1663$ doublet in any of the GPs, although it is one of the most prominent nebular lines seen in the rest-UV spectra of low-metallicity galaxies. We provide 3σ upper limits for the O III] $\lambda 1663$ doublet in Table 2. The photoionization models from JR16 show a tight correlation between the [O III] $\lambda 4363$ optical line emission and the O III] $\lambda 1663$ emission, and this allows us to predict the expected O III] fluxes. We estimate a value for the ionization parameter $(U)$ using the $O_{32}$ versus C III] EW diagram from JR16. Then, keeping $U$ fixed, we interpolate the predicted O III] $\lambda 1663$ ratios as a function of metallicity $(Z)$, given the GP’s calculated metallicities. The uncertainty in $Z$ dominates over the uncertainty in our $U$ estimate, and the errors provided in Table 2 show the uncertainty in the predictions given the GP’s metallicity uncertainties. The predicted O III] $\lambda 1663$ fluxes are below or close to the detection limits in most cases. In the LyC leaker GP, J1154+2443, Schaefer et al. (2018) detected O III] $\lambda 1663$ with EW = 5.8 ± 2.9 Å, which is $\sim$0.5 EW(C III]). However, that galaxy has a much lower metallicity than our sample with $12 + \log(O/H) \sim 7.65$, closer to the metallicities of BCDs (Berg et al. 2016, 2019) that also show significant O III] $\lambda 1663$ detections. There are five galaxies in our sample with $Z \lesssim 0.2 Z_{\odot}$, but even in such low-metallicity galaxies, the O III]
$\lambda 1663$ can be weak with a median EW < 2.4 Å (Senchyna et al. 2017).

We measured the fluxes and EWs of the Ly$\alpha$ emission from their HST/COS far-UV (FUV) spectra and the [O III] $\lambda$4363, [O III] $\lambda$5007, and H$\alpha$ emission lines from the SDSS spectra for all of the GPs. The line fluxes were corrected for Milky Way extinction using the Fitzpatrick (1999) extinction law and the Schlafly & Finkbeiner (2011) dust map. The fluxes were corrected for internal reddening using the Balmer decrement derived from the observed H$\alpha$/H$\beta$ ratio and the Cardelli et al. (1989) reddening law, taking into account the variation of $R_V$ in the presence of intense UV radiation as outlined in Izotov et al. (2017). All of the GPs exhibit very low internal reddening with $E(B-V) = 0.03$–0.2. The extinction-corrected fluxes for rest-UV and rest-optical emission lines are provided in Table 2, and the EWs are presented in Table 3.

2.3. The Composite Rest-UV Spectrum

The stacked composite rest-UV spectrum of the GPs was created after applying a Doppler correction to bring each individual spectrum to the rest-frame wavelengths using the redshifts inferred from the [O III] $\lambda$5007 emission line in the SDSS spectrum. Each GP spectrum was scaled to match the flux density between 2000 and 2100 Å, which is redward of the C III] doublet, a continuum region that has high S/N, and free of absorption lines. The stacking was done using the scombine task in the PyRAF/Spec2d package by averaging at each dispersion point after applying a 3σ clipping factor. The composite spectrum created from all 10 GPs is shown in Figure 3. The composite spectrum reveals weak spectral features, particularly the broad emission feature at the location of the He II $\lambda$1640 line. Only three GPs in the sample show a weak He II emission feature in their individual spectra, with
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EW(He II) = 0.77 ± 0.05 Å for J0815+2156, 2.32 ± 0.02 Å for J1244+0215, and 1.02 ± 0.03 Å for J1457+2232. The EW(He II) as measured in the composite spectrum is ~20% of the C III] emission flux. As noted in JR16, the photoionization models for GPs predict much weaker nebular He II λ1640, <10% of C III]. However, it is known that the models tend to underpredict the He II emission strengths, as also evidenced by the observed higher optical He II λ4686/ Hβ line ratios for GPs. Additional sources, such as WR stars, shocks, or high-mass X-ray binaries, have been invoked to explain the higher-than-predicted He II strengths (Shirazi & Brinchmann 2012; Jaskot & Oey 2013). The composite spectrum also reveals stellar photospheric and interstellar absorption features, including Si II λ1526, C IV λ1548, 1550, and Al III λ1854, 1862. The C IV absorption does not show the characteristic P Cygni profile shape in the composite spectrum because the stacking is performed using a small sample of 10 galaxies, of which only three have the strong C IV absorption feature and with widely different profile shapes.

In Figure 3, the normalized composite spectrum is shown separately for the GPs with C III] detections and nondetections. The interstellar absorption features are more prominent in the composite spectra of galaxies with C III] nondetections compared to the stack of the entire sample. The C IV

Figure 2. Same as Figure 1 but for the galaxies J121903+152608, J124423+021540, J124834+123402, and J145735+223201.

Table 2

| Name                  | $F_{\lambda}$(C III] 1909) | $F_{\lambda}$(O III] 1666) | $I_{\lambda}$(C III] 1909) | $I_{\lambda}$(O III] 1666) | $I_{\lambda}$(O III] 5007) | O III] λ1666 - [O III] λ4363 | $I_{\lambda}$(O III] 1666) |
|-----------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| J030321−075923        | 0.849 ± 0.09                | 0.714                       | 1.918 ± 0.21                | 1.428                       | 52.88                       | 1.709 ± 0.098                | 1.767 ± 0.015               |
| J081552+215623        | 1.617 ± 0.01                | 0.460                       | 3.210 ± 0.01                | 0.853                       | 42.45                       | 1.456 ± 0.014                | 1.083 ± 0.012               |
| J091113+183108        | 0.446 †                      | 0.605                       | 2.318 †                     | 2.991                       | 27.84                       | 0.926 ± 0.025                | 0.300 ± 0.011               |
| J105330+523752        | 0.987 †                      | 2.505                       | 2.262 †                     | 5.579                       | 43.77                       | 0.849 ± 0.025                | 0.350 ± 0.012               |
| J113303+651341        | 0.368 ± 0.08                | 0.556                       | 0.865 ± 0.18                | 1.278                       | 16.32                       | 1.185 ± 0.046                | 0.330 ± 0.018               |
| J113722+352426        | 0.856                       | 1.479                       | 1.666                       | 2.791                       | 65.06                       | 0.898 ± 0.025                | 0.610 ± 0.018               |
| J121903+152608        | 1.992 ± 0.01                | 1.141                       | 3.069 ± 0.02                | 1.708                       | 61.37                       | 1.768 ± 0.062                | 2.211 ± 0.034               |
| J124423+021540        | 0.656 ± 0.06                | 0.742                       | 1.794 ± 0.18                | 1.971                       | 76.83                       | 1.013 ± 0.064                | 0.917 ± 0.049               |
| J124834+123402        | 0.998 ± 0.09                | 0.727                       | 2.439 ± 0.25                | 1.748                       | 33.13                       | 1.055 ± 0.032                | 0.444 ± 0.012               |
| J145735+223201        | 2.080 ± 0.02                | 0.622                       | 5.846 ± 0.06                | 1.605                       | 95.61                       | 1.400 ± 0.007                | 2.345 ± 0.019               |

Note. Observed emission line fluxes (columns (2) and (3)) and fluxes corrected for internal reddening and Milky Way extinction (columns (4)–(6)) in units of 10^{-15} erg s^{-1} cm^{-2}. The 3σ upper limits are indicated by the † symbol. The O III] λ1666 fluxes are all upper limits (†) from HST/STIS spectra, and the expected fluxes (column (8)) are based on the O III] λ1666/O III] λ4363 ratio (column (7)) from CLOUDY models. The [O III] λ4363 and [O III] λ5007 fluxes are from the SDSS spectra.
The O III λ1661, 1666 lines are not detected at >1σ significance in the stacked spectrum. The O III λ1666 lines are not detected even in the stack created using only the C III detections. The very broad wing of the C IV wind features and interstellar absorption features are stronger when the C III emission is weak. The C IV wind features and interstellar absorption features are stronger when the C III emission is weak.

Table 3

| Name          | Lyα λ1216 (Å) | C III λ1909 (Å) | [O III] λ4363 (Å) | [O III] λ5007 (Å) | Hα λ6563 (Å) |
|---------------|---------------|-----------------|-------------------|-------------------|--------------|
| J030321−075923 | 6 ± 1         | 3.72 ± 0.24     | 11.4 ± 0.5        | 826 ± 10          | 697 ± 12     |
| J081552+215623 | 68 ± 4        | 8.27 ± 0.53     | 18.5 ± 1.5        | 1365 ± 29         | 898 ± 16     |
| J091113+183108 | 52 ± 4        | 0.49±             | 2.3 ± 0.5         | 274 ± 3           | 422 ± 7      |
| J105330+523752 | 8 ± 1         | 0.66±             | 2.3 ± 0.3         | 350 ± 3           | 401 ± 4      |
| J113303+651341 | 35 ± 2        | 1.66 ± 0.44     | 5.0 ± 0.6         | 394 ± 5           | 305 ± 6      |
| J113722+352426 | 28 ± 2        | 0.59±             | 4.3 ± 0.3         | 582 ± 4           | 575 ± 6      |
| J121903+152608 | 174 ± 9       | 5.66 ± 0.48     | 21.5 ± 0.7        | 1488 ± 16         | 1266 ± 21    |
| J124423+021540 | 34 ± 2        | 2.87 ± 0.44     | 8.0 ± 0.4         | 985 ± 10          | 841 ± 11     |
| J124834+125402 | 96 ± 6        | 4.14 ± 0.98     | 7.4 ± 0.7         | 842 ± 12          | 743 ± 19     |
| J145735+223201 | –4 ± 1        | 9.35 ± 0.76     | 19.3 ± 0.7        | 1433 ± 14         | 1000 ± 14    |

Note. The Lyα EWs are based on HST/COS measurements (Jaskot & Oey 2014; Henry et al. 2015), the C III λ1909 EWs are measured from HST/STIS, and the EWs of the optical emission lines are measured from SDSS spectra. The 1σ upper limits are indicated by the ± symbol.

The O III and C IV absorption strengths are very likely to also be strong C III emitters. We detect C III emission in 7/10 GPs in our sample, and the measured EWs are provided in Table 3, along with upper limits for the three nondetections. The rest-frame EWs for the GPs span values from as low as 1.67 Å to as high as 9.35 Å, comparable to the strengths of C III emission seen in C III emitters at high redshifts (z ∼ 2–6). When detected, the EW(C III) is >3 Å in most cases and consistent with the predictions for C III emission lines in GPs from the photoionization models of JR16. Based on the GPs’ metallicities, derived using the direct abundance method, and their observed [O III] λ5007, [O II] λ3727, and [Ne III] λ3869 line strengths, these models predict C III EWs in the range of 2–10 Å, which is in close agreement with what we observe in the HST STIS spectrum. None of the GPs in our sample have the very high (>15 Å) EWs seen in high-redshift (z ∼ 3–6) galaxies (de Barros et al. 2016; Ding et al. 2017; Stark et al. 2017). However, GPs with lower metallicities than this sample, such as J1154+2443 from Schaerer et al. (2018), do show high EW(C III).

3. Semiforbidden C III] Emission in GPs

The C III] nebular emission line is clearly the most prominent spectral feature in the HST/STIS rest-UV 1400–2200 Å spectra of the GPs. We detect C III] emission in 7/10 GPs in our sample, and the measured EWs are provided in Table 3, along with upper limits for the three nondetections. The rest-frame C III] EWs for the GPs span values from as low as 1.67 Å to as high as 9.35 Å, comparable to the strengths of C III] emission seen in C III] emitters at high redshifts (z ∼ 2–6). When detected, the EW(C III]) is >3 Å in most cases and consistent with the predictions for C III] emission lines in GPs from the photoionization models of JR16. Based on the GPs’ metallicities, derived using the direct abundance method, and their observed [O III] λ5007, [O II] λ3727, and [Ne III] λ3869 line strengths, these models predict C III] EWs in the range of 2–10 Å, which is in close agreement with what we observe in the HST STIS spectrum. None of the GPs in our sample have the very high (>15 Å) EWs seen in high-redshift (z ∼ 3–6) galaxies (de Barros et al. 2016; Ding et al. 2017; Stark et al. 2017). However, GPs with lower metallicities than this sample, such as J1154+2443 from Schaerer et al. (2018), do show high EW(C III])

3.1. Frequency of C III] Emitters

By definition, GPs are a class of strong [O III] λ5007 emitters with EW([O III]) > 300 Å. The frequency of C III] emitters (~70%) we find among the GPs suggests that EELGs selected by the presence of strong high ionization lines (e.g., [O III] λ5007) are very likely to also be strong C III] emitters. It is interesting, therefore, to see how this fraction compares to SFGs selected using different criteria. In the sample of He II emitters in the local universe, C III] doublet emission is detected in 7/10 galaxies, with EW(C III]) ∼ 3–14.8 Å (Senchyna et al. 2017). The He II emitters
span a wider range in metallicities (7.81 < 12+log(O/H) < 8.48), particularly toward lower metallicities than our GP sample. Local BCD galaxies with low metallicities (7.2 < 12+log(O/H) < 8.2) have a higher fraction of strong C III emitters (Berg et al. 2016, 2019), with EW(C III) reaching as high as >15 Å at the lowest metallicities.

At higher redshifts, C III emitters have been identified in surveys of SFGs that employ a broader range of selection criteria (e.g., UV luminosity or color selection). Using MUSE observations, Maseda et al. (2017) found 17 C III emitters, which represents only ~3% of their photometric sample of SFGs in the range 1.5 < z < 4 in the Hubble Deep Field South and Ultra Deep Field. The C III EWs of these galaxies are in the range of 2–10 Å, similar to the GPs in most cases. However, a larger fraction (five out of 17) among these high-redshift SFGs are strong C III emitters with EW(C III) > 10 Å, and three of them have EW(C III) > 11.7 Å, which is the highest value observed for the GPs (Schaerer et al. 2018). Among the UV-selected star-forming population at 2 < z < 3.8 in the VUDS survey (Le Fèvre et al. 2019), 24% of the SFGs have EW(C III) > 3 Å, and of these, 4% have >10 Å. While the number of known high-redshift C III emitters at z > 6 is small, in almost all cases, they have high EWs for C III, and their broadband colors suggest the presence of strong optical emission lines with EW(O III) > 500 Å (Stark et al. 2014, 2017). In summary, the frequency of C III emitters among GPs and other low-metallicity galaxies with strong optical emission lines is higher compared to populations of SFGs selected based on UV luminosity or colors, which likely span a wider range of metallicities.

3.2. C III] and Lyα Emission

Previous studies have highlighted the empirical relation between the C III] and Lyα emission line EWs (Shapley et al. 2003; Stark et al. 2014, 2015a; Rigby et al. 2015; Nakajima et al. 2018a). Both C III] and Lyα emission lines are produced in the ionized gas and are powered by the ionizing radiation from young, massive stars. The Lyα is a resonant line and sensitive to neutral gas, while C III] emission escapes freely. The relation between C III] and Lyα EWs is important in the context of the potential use of C III] emission as a redshift indicator and a tracer of the ionizing populations during the reionization epoch. At z > 6, the Lyα photons are resonantly scattered by the neutral hydrogen in the IGM, making the detection of Lyα emission difficult (Konno et al. 2014; Tilvi et al. 2014; Mason et al. 2018). The C III] emission from actively SFGs at these redshifts, however, is often strong and easily observable (Stark et al. 2015a, 2017; Ding et al. 2017; Hutchison et al. 2019), making it a useful diagnostic emission line at high redshifts.

In Figure 4 (left), we present the observed relation between EW(C III]) and EW(Lyα) for the GPs, along with other samples at low and high redshift from the literature. The GPs mostly lie with the high-redshift z = 2–6 galaxies, with an EW(C III]) that spans the range ~2–10 Å and EW(Lyα) ~ 0–175 Å. The Pearson correlation coefficient suggests a strong linear relationship between EW(C III]) and EW(Lyα) for SFGs in Figure 4, with r P = 0.61, and a low probability (p = 7.80 × 10−8) that the two quantities are uncorrelated. However, there is no strong correlation that is evident within the GP sample alone. By definition, the GP selection isolates strong emission line galaxies, and the scatter in Lyα EW among the GPs is likely driven by the variations in Lyα optical depth due to the neutral gas. The SFGs that are non-GPs are not necessarily extreme emission line objects, and their weak Lyα emission may indicate that the flux in the emission lines is intrinsically low. One of the two deviant points in Figure 4 is J1457 +2232, which has the highest EW(C III]) among the GP sample, but the measured EW(Lyα) is weak or absent. Jaskot & Oey (2014) proposed that the dominant broad absorption feature of the Lyα profile in this galaxy implies the presence of a high column density of neutral gas along the line of sight, and the weak Lyα emission probably escapes via scattering, perhaps in a bipolar outflow. On the other hand, J1219+1526 has the highest EW(Lyα) = 174 ± 9 Å among the GP sample and rest-frame EW(C III]) = 5.66 ± 0.48 Å, which is lower than expected from the empirical EW(C III])–EW(Lyα) relation. There are various factors that can impact the C III] line strengths, and they are discussed in detail in Section 3.5.
Figure 5. (Left) Relation between EW(C III) and EW([O III]) and (right) relation between EW(C III) and EW(Hα) for the GPs and other C III emitters from the literature. The dashed line shows the linear regression fit to the data with slope = 0.007 ± 0.001 and rms scatter = 3.65 for EW(C III) vs. EW([O III]) and slope = 0.009 ± 0.002 and rms scatter = 2.56 for EW(C III) vs. EW(Hα). The points shown are high-z galaxies (2 < z < 7) from Stark et al. (2014, 2015a; blue), BX 415 from Erb et al. (2010; magenta), GP sample from this work (green), [O III] emitters at z ~ 3 from Vanzella et al. (2016) and de Barros et al. (2016; gold), C III emitters at 1.5 < z < 4 from Maseda et al. (2017; purple), He II emitters from Senchyna et al. (2017; turquoise circles), and dwarf galaxies from Berg et al. (2016; turquoise triangles).”

Among the non-GPs, the noticeably deviant points from the empirical correlation between EW(C III) and EW(λ Ly) are the highest-redshift galaxies: EGS-zs8-1 at z = 7.73 with high EW(C III) = 22 ± 2 Å and weak EW(λ Ly) = 21 ± 4 Å (Stark et al. 2017) and z7-GND-42912 at z = 7.50 with EW(C III) = 16.23 ± 2.32 Å and EW(λ Ly) = 33.2 ± 3.2 Å (Hutchison et al. 2019). Both galaxies exhibit very red [3.6]–[4.5] color in the Spitzer IR bands, which results from the large rest-frame EW of the [O II] + H β in the 4.5 μm band, a selection criterion that is comparable to the GP selection at low redshift. For EGS-zs8-1, Stark et al. (2017) found that the velocity offset of the Ly α emission line, ΔVλLy = 340–520 km s⁻¹, implies that the Ly α profile is modulated by the presence of dense neutral gas close to the systemic redshift of the galaxy. The high column density of neutral gas is responsible for the observed low EW(λ Ly). The case of the GP J1457+2232 is similar, as the Ly α profile shows a large velocity separation of ~750 km s⁻¹ between the emission peaks, which suggests a high column density along the line of sight. The galaxies EGS-zs8-1, z7-GND-42912, and J1457+2232 have higher EW(C III) than expected for their EW(λ Ly) from the EW(C III)–EW(λ Ly) empirical relation. Such galaxies illustrate the utility of the C III] emission line as an alternate diagnostic for the spectroscopic redshifts and ISM conditions when Ly α is absorbed by the neutral gas in the ISM and IGM.

3.3. C III] and Rest-optical Emission Lines

The SDSS spectra of GPs provide a suite of rest-frame optical emission lines, which are useful to derive electron temperatures (T_e) and estimate the gas-phase metallicities or nebular oxygen abundances (12+log(O/H)). The nebular abundances used in our analysis are based on the direct method using T_e ([O III]) calculated from the [O III] line fluxes from SDSS spectra. In Figure 4 (right), we present EW(C III]) versus metallicity for the GPs, along with various samples of C III] emitters at low and high redshifts from the literature (Stark et al. 2014; Rigby et al. 2015; Berg et al. 2016, 2019; Vanzella et al. 2016; Maseda et al. 2017; Senchyna et al. 2017, 2019; Nakajima et al. 2018a). Previous studies have highlighted the significant trend of increasing EW(C III]) with decreasing metallicity, reaching values ≥5 Å only at 12+log(O/H) < 8.4 or 0.5 Z_⊙ (Rigby et al. 2015; Maseda et al. 2017; Senchyna et al. 2017; Nakajima et al. 2018b). Using photoionization models, it has been shown that low metallicities create ISM conditions that are necessary to produce significant C III] emission (JR16; Feltre et al. 2016; Gutkin et al. 2016; Byler et al. 2018; Nakajima et al. 2018b). At low metallicities, stars have higher effective temperatures with weaker stellar winds, and their harder ionizing SED boosts the supply of C+ ionizing photons. Also, since the ionized nebulae predominantly cool via the forbidden emission of metal lines, the low-metallicity nebulae tend to have higher T_e favoring high collisional excitation rates and stronger C III] emission. At a fixed C/O ratio or carbon abundance, the photoionization models require a metallicity threshold of Z ~ 0.006 for the C III] to be strong with EWs in excess of 3 Å. The GPs have metallicities Z/Z_⊙ ≤ 0.4 (or Z ≤ 0.006), and their EW(C III]) shows a large spread at a given metallicity, indicating that the C III] emission is also influenced by other factors, such as ionization parameter, age of the stellar population, and C/O ratio (JR16, Nakajima et al. 2018b).

High nebular temperatures, high ionization parameters, and hard ionizing radiation from metal-poor, young stellar populations with ages <5 Myr enhance the C III] λ1909 emission. The same physical conditions that produce strong C III] emission also favor the emission of strong forbidden lines from collisionally excited species in the optical wavelengths. The relation between EW(C III]) and the EW of [O III] λ5007 (hereafter EW([O III])) provides insight into the frequency of C III] emission among the [O III] emitters and how the relative emission line fluxes inform us about the ISM properties. In Figure 5, we show the empirical relation between EW(C III]) and EW([O III]) for the GPs, along with other SFGs for which measurements are available in the literature. The sample presented in Figure 5 is inhomogeneous, in the sense that some of the measurements correspond to individual compact star-forming regions, while the others are integrated measures over the entire galaxies. Also, the apertures used for measuring the rest-UV and rest-optical fluxes are not matched in all cases.
However, it is clear that there is a strong trend between the C III] and [O III] EWs. The EW(C III])–EW([O III]) relation is almost linear, since both C III] and [O III] are collisionally excited lines that are favored by higher nebular temperatures and ionization parameters. The Spearman rank correlation statistic between EW(C III]) and EW([O III]) indicates a strong correlation with $r_{sp} = 0.65$ ($p = 3.02 \times 10^{-6}$), and the Pearson correlation statistic suggests a strong linear correlation with $r_p = 0.62$ ($p = 1.41 \times 10^{-5}$). As seen from the photoionization models [JR16; their Figure 8], the relation between the two EWs exhibits a large spread that reflects the range in ionization parameter, nebular temperature, and dependence on metallicity. Extreme values of EW([O III]) > 2000 Å and EW(C III]) > 10 Å require both high ionization parameters ($\log U > -2$) and young stellar populations with ages less than 3 Myr. The energy requirements for the excitation of these two emission lines are different, although similar physical conditions tend to favor them. Both emission lines require an ionizing spectrum that has high-energy photons, since the ionization energy for C $^{+2}$ is 24.4 eV and that for O $^{+2}$ is 35.1 eV. However, because of the temperature dependence of the collisional excitation rates, the C III] emission exhibits a greater sensitivity to metallicity. This may also explain the offset of the GPs in our sample from the other low-redshift samples. The BCDs (Berg et al. 2016) and HeII emitters (Senchyna et al. 2017) mostly have lower metallicities with $12 + \log(O/H) < 8.0$ for the strong C III] emitters. The location of the low-metallicity GP J1154+2443 (Schaerer et al. 2018), which lies along with the BCDs and HeII emitters in Figure 5, also seems to suggest that the offset for the GPs in this work may be due to their relatively higher metallicities.

The EW(C III]) also shows a trend with EW(Hα) as expected, because the nebular emission lines both depend on the amount of ionizing radiation. The Spearman rank correlation statistic between EW(C III]) and EW(Hα) indicates a strong correlation with $r_{sp} = 0.72$ ($p = 2.85 \times 10^{-5}$), and the Pearson correlation statistic suggests a strong linear correlation with $r_p = 0.71$ ($p = 4.75 \times 10^{-5}$). The EW(C III]) versus EW(Hα) relation is tighter than the EW(C III]) versus EW(λLyα) relation (Figure 4), which is significantly modified by radiative transfer effects, as the Lyα is resonantly scattered.

Even the GPs that show large deviations in the EW(C III]) vs. EW(λLyα) relation follow a tight correlation with EW(Hα). Since Hα is a well-calibrated SFR indicator (Kennicutt 1998), it is encouraging to consider the possibility of using the C III] emission as a diagnostic for the ionizing flux and SFR at high-z. The C III] emission depends on the ionization parameter and ionizing flux, as does the Hα emission, but the dependence of C III] on metallicity and density makes it a weaker diagnostic for SFR. However, when Hα emission is redshifted beyond the NIR wavelengths at $z > 7$, the C III] emission may serve as a useful diagnostic for estimating the production rate of ionizing photons (Chevallard et al. 2018; Schaerer et al. 2018).

### 3.4. Estimate of the C/O Ratios

The elemental carbon abundance is one of the parameters that influences the C III] emission. Previous studies have used the C III] λ1909 and O III] λ1663 emission line doublets to derive the C/O ratios in SFGs (Garnett et al. 1995; Erb et al. 2010; Berg et al. 2016, 2019). Since we do not detect the O III] λ1663 doublet, we use the dust-corrected C III] and optical O III] doublets to derive the C/O ratios. Following the equation in Izotov & Thuan (1999),

$$\frac{C}{O}^{2+} \approx 0.093 \exp \left( \frac{4.656}{T_e} \right) \frac{I(C \text{ III}] \lambda 1906 + \lambda 1909)}{I([O \text{ III}] \lambda 4959 + \lambda 5007)}$$

where $T_e = 10^4$ K

$$\frac{C}{O} = \text{ICF} \left( \frac{C}{O} \right) \frac{C^{2+}}{O^{2+}}$$

The correction factor ICF(C/O) was derived from the CLOUDY photoionization models for $\log U = -2$ and $-3$. The measured C/O ratios are presented in Table 4, and the range of observed values is consistent with the C/O ratio $= 0.20$ assumed in the JR16 models. We also used the C III] fluxes along with the O III] λ1663 upper limits from the HST/STIS spectra to compute the lower limits on the observed C/O using the equations from Erb et al. (2010). Taking advantage of the tight correlation between O III] λ1663 and [O III] λ4363 emission (JR16), we also used the observed O III] λ4363 fluxes to get the predicted O III] λ1663 fluxes.

\[ \text{Table 4} \]

Elemental Abundances and ISM Properties of GPs

| Name       | O_32 | 12+log(O/H) | log(C/O) | log(C/O)^2 | log(C/O)^3 | f_{esc}(Lyα) | V_{esc}(Lyα) (km s^{-1}) |
|------------|------|-------------|----------|------------|------------|-------------|--------------------------|
| J030321−075923 | 7.1 ± 0.5 | 7.91 | −1.247 (−1.002) | −1.014 (−0.769) | −1.105 (−0.859) | 0.05 | 460 |
| J081552+215623 | 10.1 ± 0.7 | 8.02 | −0.960 (−0.618) | −0.580 (−0.338) | −0.683 (−0.441) | 0.28 | 260 |
| J091131+183108 | 1.9 ± 0.2 | 8.15 | ... | ... | ... | 0.17 | 370 |
| J105330+523752 | 2.5 ± 0.2 | 8.31 | ... | ... | ... | 0.08 | 410 |
| J113300+651341 | 3.8 ± 0.4 | 8.03 | −0.994 (−0.751) | −1.329 (−1.087) | −0.742 (−0.499) | 0.31 | 330 |
| J113722+352426 | 2.9 ± 0.2 | 8.29 | ... | ... | ... | 0.11 | 550 |
| J121903+152608 | 10.5 ± 0.7 | 7.88 | −1.134 (−0.888) | −0.882 (−0.636) | −0.994 (−0.748) | 0.58 | 270 |
| J124423+021540 | 3.7 ± 0.2 | 8.24 | −1.109 (−0.869) | −1.237 (−0.997) | −0.901 (−0.661) | 0.06 | 530 |
| J124834+123402 | 3.5 ± 0.3 | 8.22 | −0.665 (−0.423) | −1.041 (−0.799) | −0.442 (−0.199) | 0.42 | ... |
| J145735+223201 | 7.2 ± 0.5 | 8.05 | −0.950 (−0.707) | −0.592 (−0.349) | −0.756 (−0.513) | 0.01 | 750 |

Note: The O_32 and nebular oxygen abundances are based on the SDSS optical spectra. The log(C/O) is computed using the C III] λ1909 line fluxes from HST/STIS and [O III] λ5007 line fluxes from SDSS spectra. The log(C/O)^2 values are computed from the observed C III] λ1909 line fluxes and upper limits for O III] λ1663 line fluxes using ICF from CLOUDY models for ionization parameter $\log U = -2$. The C/O abundances derived for the ICF corresponding to $\log U = -3$ are included in parentheses. The expected C/O abundances, log(C/O), are computed using the observed C III] λ1909 fluxes and the O III] λ1663 fluxes predicted based on the observed [O III] λ4363 emission line in the SDSS spectrum. The $f_{esc}(Ly\alpha)$ are calculated from the HST/COS spectra as detailed in Jaskot et al. (2017), and the velocity separations between the two peaks of the Lyα emission line are from Jaskot & Oey (2014) and Henry et al. (2015).
from the photoionization models. The C/O ratios derived based on the predicted O III fluxes and observed C III emission are also presented in Table 4. The C/O ratios measured using the observed [O III] and predicted O III fluxes are consistent and range from log(C/O) ~ −0.6 to −1.1, similar to the range of C/O ratios found in high-redshift galaxies (Erb et al. 2010; Stark et al. 2014; Amorín et al. 2017) and local BCDs (Berg et al. 2016).

### 3.5. ISM Conditions and C III Detectability

In this section, we examine how the ionization parameter and optical depth of the ISM affect the detectability of C III emission. In Figure 6, we show the relation between EW(C III)] and the O32 = [O III] λ5007/[O II] λ3727 ratio (upper left) and EW(C III)] vs. the velocity separation between the red and blue peaks of the Lyα emission profile (lower left). The EW(C III)] vs. O32 ratio includes BCDs (Berg et al. 2016; turquoise triangles) and He II emitters (Senchyna et al. 2017; turquoise circles) at z ~ 0. The Lyα velocity profile measurements are from Jaskot & Oey (2014) and Henry et al. (2015). We also show the escape fraction of Lyα emission as a function of the velocity separation (upper right) and EW(C III)] (lower right). Larger velocity separation implies a larger optical depth and lower Lyα escape fractions. The GPs from this work are shown as green stars, and J1154+2443 (Schaerer et al. 2018) is shown as green circle.

![Figure 6](https://example.com/image6)

**Figure 6.** Relation between EW(C III)] and the O32 = [O III] λ5007/[O II] λ3727 ratio (upper left) and EW(C III)] vs. the velocity separation between the red and blue peaks of the Lyα emission profile (lower left). The EW(C III)] vs. O32 ratio includes BCDs (Berg et al. 2016; turquoise triangles) and He II emitters (Senchyna et al. 2017; turquoise circles) at z ~ 0. The Lyα velocity profile measurements are from Jaskot & Oey (2014) and Henry et al. (2015). We also show the escape fraction of Lyα emission as a function of the velocity separation (upper right) and EW(C III)] (lower right). Larger velocity separation implies a larger optical depth and lower Lyα escape fractions. The GPs from this work are shown as green stars, and J1154+2443 (Schaerer et al. 2018) is shown as green circle.

from the SDSS based on their high O32 ≥ 5 are mostly found to be LAEs, with few exceptions (Jaskot et al. 2017; McKinney et al. 2019). In a sample of 11 GPs with O32 ≥ 5 targeted with HST/COS FUV spectroscopy to look for escaping ionizing radiation, all of them showed evidence for LyC leakage with escape fractions (fesc) in the range 2%–72% (Izotov et al. 2016a, 2016b, 2018a, 2018b). In general, the fesc(LyC) is found to be higher for GPs with higher O32, although the relation between the two quantities shows considerable scatter (Izotov et al. 2016b, 2018b). High O32 has been proposed to be a diagnostic for density-bounded H II regions, which are potential LyC leaker candidates (Guseva et al. 2004; Jaskot & Oey 2013; Nakajima & Ouchi 2014; Izotov et al. 2018b). It is, therefore, interesting that EW(C III)] also shows a positive trend with O32; hence, LyC leakers should be strong C III emitters because the high ionization parameter would favor C III emission. However, the observed strength of the C III] emission can be reduced due to other factors, such as the decrease in absorbed ionizing flux at low optical depth, the transition of C+2 to C+3 for log U > −2, and a low elemental carbon abundance. The EW(C III)] versus O32 diagram shows a linear relation for the GPs when C III] emission is detected, with C III] strength
increasing as the $O_{32}$ ratio increases, and $EW(C\text{III}) \geq 3$ Å for $O_{32} \geq 5$. For similar $O_{32}$ values, even the He II emitters that overlap with GPs in their metallicities have significantly higher $EW(C\text{III})$, which may be due to contributions from additional ionizing sources (such as shocks or X-ray binaries).

The velocity separation between the peaks of the double-peaked Ly$\alpha$ emission profile shows a tight relation with the escape fraction of Ly$\alpha$ and Ly C emission (Henry et al. 2015; Verhamme et al. 2015, 2017; Izotov et al. 2018b). According to the radiative transfer models from Verhamme et al. (2015), the velocity separation is strongly correlated with the neutral hydrogen column density. At low column densities, the Ly$\alpha$ photons experience less scattering in the surrounding neutral medium and are observed closer to the systemic velocity. The galaxies that have small separations ($<300$ km s$^{-1}$) have low column densities ($N_{H_1} \leq 10^{18}$ cm$^{-2}$), while those with larger separations ($\geq 600$ km s$^{-1}$) have higher column densities ($N_{H_1} \geq 10^{20}$ cm$^{-2}$). We used the velocity separations of the Ly$\alpha$ profile peaks measured from the HST/COS spectra for the GP galaxies in our sample to examine the ISM conditions that allow the detectability of the LyC escape. As shown in Figure 6, GPs with small velocity separations have highest escape fractions for Ly$\alpha$ emission and are also potential LyC leakers. Since the $EW(C\text{III})$ correlates with $EW(Ly\alpha)$ for SFGs, we examine how the $EW(C\text{III})$ relates to velocity separation. There is no obvious correlation overall between $EW(C\text{III})$ and the peak velocity separation of Ly$\alpha$ profiles for the GP sample.

Among the sample of GPs in this work, J0815+2156 and J1219+1526 have small velocity separation and high $EW(C\text{III})$. The narrow Ly$\alpha$ profiles of J0815+2156 and J1219+1526 indicate that the Ly$\alpha$ radiation escapes more easily with less resonant scattering. Both of these GPs are suggested to be possible LyC leakage candidates by Jastok & Oey (2014). Henry et al. (2015) also noted that J1133+6513 and J1219+1526 are good candidates for LyC leakers based on the narrow velocity separations (see Table 3). The galaxy J1219+1526 has a high Ly$\alpha$ escape fraction ($f_{esc} = 58\%$), large $EW(Ly\alpha) = 174 \pm 9$ Å, and $EW(C\text{III}) = 5.7 \pm 0.48$ Å, while J0815+2156 also has strong Ly$\alpha$ emission ($f_{esc} = 28\%$) with $EW(Ly\alpha) = 68 \pm 4$ Å and $EW(C\text{III}) = 8.27 \pm 0.53$ Å. The galaxy J1133+6513 has low EWs, $EW(Ly\alpha) = 35 \pm 2$ Å and $EW(C\text{III}) = 1.67 \pm 0.44$ Å, even though the velocity separation of the Ly$\alpha$ emission peaks is small ($330$ km s$^{-1}$) and $f_{esc} = 31\%$. Henry et al. (2015) argued that the low EWs for Ly$\alpha$ and H$\alpha$ emission of this GP are consistent with higher LyC leakage, because the lack of any prominent interstellar (IS) absorption lines supports that the system is optically thin along the line of sight. The small observed EW(CIII) is also consistent with the high escape fraction of ionizing radiation in optically thin, density-bounded systems. However, the low C III] values can also be accommodated by models with high optical depth but older ages for the stellar population (JR16). The galaxy J1133+6513 has a relatively high escape fraction, and the low EW($H\alpha$) suggests a low intrinsic $EW(Ly\alpha)$ before scattering, which may reflect an older age for the current starburst or a continuous star formation history.

The galaxies J0303−0759 and J1457+2232 have low EW($L_{\text{Ly}\alpha}$) and the lowest Ly$\alpha$ escape fractions ($f_{esc} \leq 5\%$ for Ly$\alpha$) among the GP sample but high observed EW($C\text{III}$). Their neutral column densities are likely high based on the large velocity separations, 460 and 750 km s$^{-1}$ for J0303−0759 and J1457+2232, respectively. While the velocity separation for GP 0303−0759 is very similar to the range of velocities seen for the LyC leakers (Izotov et al. 2016b, 2018b), the escape fraction for Ly$\alpha$ is low, $\sim 5\%$, and it is likely that $f_{esc}(Ly\alpha)$ should be larger than observed for both of these GPs. Jastok & Oey (2014) used the C II $\lambda 1334$ and Si II $\lambda 1260$ IS absorption lines to infer the optical depth and geometry of these systems. Both galaxies show strong IS absorption lines that confirm their high neutral column densities consistent with the observed weak Ly$\alpha$ emission. Both J0303−0759 and J1457+2232 are good local analogs that emphasize the utility of the strong C III] $\lambda 1909$ emission in optically thick systems. The galaxies J0815+2156, J1219+1526, and J1457+2232 have comparable $O_{32}$ (indicating high log $U$), low $12+log(O/H)$, and large optical emission line EWs and exhibit the highest EW($C\text{III}$) among the GPs in our sample, while their Ly$\alpha$ emission suggests low optical depths in J0815+2156 and J1219+1526 and a high optical depth in J1457+2232.

4. Comparing the C III] Emission to Photoionization Model Predictions

In JR16, we used CLOUDY photoionization models (Ferland et al. 2013) to explore the C III] EWs and line ratios as a function of starburst age, metallicity, and ionization parameter. The models also considered a range of $C/O$ ratios, dust content, gas densities, nebular geometries, and optical depths. One of the main conclusions was that only the binary population and spectral synthesis (BPASS; Eldridge & Stanway 2009; Eldridge et al. 2017) models that incorporate the effects of binary star interactions are able to reproduce the highest CIII] EWs ($\geq 15$–$20$ Å) found in high-redshift galaxies and sustain high EW(CIII]) values ($>5$ Å) over longer timescales beyond 3 Myr. The GPs offer a valuable test for the predictions from the photoionization models because the optical SDSS spectra are available for all galaxies in the sample and include many diagnostic optical emission lines that offer strong constraints on the metallicity and ionization parameter. This allows one to explore the C III] EWs as a function of age for the metallicities and ionization parameters determined from the optical emission lines.

4.1. Dependence on Metallicity and Ionization Parameter

In Figure 7, we show the predicted EW(CIII]) as a function of metallicity for the instantaneous burst models with different burst ages (Figure 15 from JR16), along with the measured EWs for the GPs. The EW(CIII]) measurements from the literature for high-$z$ (Erb et al. 2010; Stark et al. 2014; de Barros et al. 2016; Vanzella et al. 2016; Maseda et al. 2017; Le Fèvre et al. 2019) and low-$z$ (Rigby et al. 2015; Berg et al. 2016; Sanchyn et al. 2017) galaxies are also shown. The BPASS models are able to fully reproduce the range of C III] EWs observed for GPs, and for high C III] EWs $>5$ Å, the models require very young burst ages ($<3$ Myr) and high ionization parameters (log $U \geq -2$) even at low metallicities. The older burst ages are not able to reproduce the high C III]) EWs $>5$ Å even for high ionization parameter values (log $U \sim -1$) at the observed metallicities of the GPs. The BPASS models with the youngest ages, $\sim 1$–$3$ Myr, are also required to accommodate the high EW(CIII]) values observed.
for the He II emitters and BCDs with lower metallicities (<1/3 Z⊙) and most of the C III] emitters at z > 2. The lower EW(C III]) values can be accommodated by the models with log U ∼ −2. Although the GPs in our sample only span a narrow range of metallicities, it is evident that their observed EWs follow the expected trend of EW(C III]) with metallicity from the CLOUDY models. In addition to metallicity and ionization parameter, the C/O ratio also affects the observed EW(C III]). The models presented in Figure 7 assume a fixed C/O = 0.2, which is consistent with the C/O values inferred for our GP sample (Section 3.4).

In Figure 8, the observed EWs of the collisionally excited emission lines C III] λ1909 and [O III] λ5007 presented in Figure 5 are compared to the predictions from the photoionization models (Figure 8 of JR16). Among the z > 1 galaxies for which the EWs have been measured, the 1.8 < z < 2.5 galaxies from Maseda et al. (2017) have metallicities that overlap with the GPs and comparable EW(C III]) and EW(O III]). The one exception is the galaxy UDF 10-164 from Maseda et al. (2017), with high C III] EW = 14.80 ± 3.10 Å but lower [O III] EW = 1170 ± 292 Å compared to the predicted value of >2000 Å expected from the models for its metallicity (Z ≥ 0.004). In Figure 8, this galaxy lies with the galaxies that have much lower metallicities (Z ≤ 0.003).

The observed EWs for low- and high-redshift non-GPs are clearly offset from the photoionization model grids in the EW(C III]) versus EW([O III]) diagram. As noted in JR16, the EW([O III]) is the likely source of the discrepancy because the models do not include the redder continuum emission from an older population. So, the predicted [O III] EWs are higher than what is observed, while the EW(C III]) remains almost unaffected. However, this effect alone may not account for all of the offsets seen for the measured EWs, in particular, for the galaxies that have higher EW(C III]) than predicted by the models and are only accommodated by models with the youngest ages (∼1–2 Myr) and highest ionization parameters. The He II emitters from

Figure 7. Predicted C III] EW as a function of metallicity from Jaskot & Ravindranath (2016). Each panel shows a different instantaneous burst age. The models assume log nH = 2 and C/O ratio = 0.2, consistent with the values for low-metallicity emission line galaxies, and a low dust-to-metal ratio = 0.1. The fiducial model considers optically thick, filled spherical geometry and does not include the effect of shocks. The green stars are the GPs from this work, filled black circles are the low-redshift galaxies (Rigby et al. 2015; Berg et al. 2016; Senchyna et al. 2017), and open black circles are the high-redshift samples (Erb et al. 2010; Stark et al. 2014; Vanzella et al. 2016; Maseda et al. 2017; Le Fèvre et al. 2019). Maseda et al. (2017) reported two values for the metallicity of every galaxy based on the mapping of the R23 ratio to gas-phase metallicity, and they are shown connected by dotted lines in each panel.
Senchyna et al. (2017) have metallicities similar to the GPs but possibly have additional sources of nebular heating, such as shocks or WR stars, that can explain their higher EW(C III)\[249\]A. The dwarf galaxies from Berg et al. (2016) have very low nebular oxygen abundances, with 12\[249\]log(O/H)\[249\]<8.0, ranging from \[249\]\[252\]1/5 to \[249\]\[252\]1/20 Z_\odot, which are lower than the average metallicities of the GP sample in this study. In Figures 5 and 8, these dwarf galaxies have consistently higher EW(C III)) and low EW([O III]) than the models. On the SDSS images, the dwarf galaxies show bright star-forming regions and diffuse continuum from the underlying galaxy, which may partly explain the observed EW([O III]) being lower than the model predictions compared to the GPs. In addition, the dwarf galaxies show a range in C/O ratios ranging from 0.15 to 0.50, while the photoionization models use C/O = 0.20. The low-metallicity GP, J1154+2443, shows a similar offset as the BCD galaxies, which suggests that the physical conditions in the ionized gas may be different from the input model parameters. Berg et al. (2016) inferred electron temperatures that are higher (\[249\]\[252\]15,200–19,600 K) for the BCDs compared to the GPs (\[249\]\[252\]14,100–15,500 K; Jaskot & Oey 2013). For three of the dwarf galaxies, the ionization parameters derived from the UV spectra are \[249\]\[252\]2.15 \[249\]\[252\]log(U) \[249\]\[252\]< \[249\]\[252\]1.5, consistent with the high ionization parameters required by the models to reproduce the higher EW(C III)).

4.2. Dependence on Optical Depth

The high LyC escape fractions observed for GPs may indicate that these galaxies are density-bounded systems (Guseva et al. 2004; Jaskot & Oey 2013; Nakajima & Ouchi 2014; Izotov et al. 2018b). Galaxies with highly...
concentrated star formation, as in the compact GPs, have a high surface density of star formation, and the feedback from such systems can be very effective in clearing out pathways that allow the escape of LyC and Ly\(\alpha\) (Heckman et al. 2011; Verhamme et al. 2017). The high LyC escape fractions also have implications for the observed emission line ratios. The density-bounded nebulae are optically thin, and compared to the radiation-bounded nebulae, they have lower column densities of surrounding gas in the outer layers where the low-ionization lines originate (Pellegrini et al. 2012; Jaskot & Oey 2013; Zackrisson et al. 2013). In JR16, we found that predicted C III\] EWs from the photoionization models are lower for density-bounded nebulae and suggested that the C III\] could be a possible diagnostic for optical depth. The transition from radiation-bounded to density-bounded nebulae is equivalent to truncating the nebular gas at different outer radii within the Stromgren sphere. To characterize the effect of varying optical depth in the models, we followed Stasinska et al. (2015) and used the \(f_{H\beta}\) parameter, which is the ratio of the total H\(\beta\) produced inside the nebular radius to the total integrated H\(\beta\) in a radiation-bounded Stromgren sphere. In this parameterization, \(f_{H\beta} = 1\) for optically thick radiation-bounded nebulae, and \(f_{H\beta} < 1\) for optically thin density-bounded nebulae. The photoionization models show that the C III\] flux declines with decreasing \(f_{H\beta}\), and the effect is strongest for the models with the highest ionization parameters. For high values of \(U\), the C III\] originates at larger radii because the higher-ionization C IV emission dominates in the inner regions of the nebulae closer to the ionizing source.

In Figure 9, the model grids for C III\] EWs versus O32 are shown as a function of ionization parameter \(U\) (dashed orange lines), optical depth \(f_{H\beta}\) (solid blue lines), and instantaneous burst age (grid thickness). The green stars show the observed values for the GPs on model grids (JR16) corresponding to their metallicity. For a given value of O32, the optically thin systems tend to have smaller EW(C III\]) due to escape of ionizing photons, making the combination of these two parameters a diagnostic for potential LyC leakers. The CLOUDY models are generated for an assumed C/O = 0.2. However, a higher C/O ratio or younger ages can also lead to high values of observed EW(C III\]).

**Figure 9.** Predicted C III\] EWs vs. O32 ratio as a function of ionization parameter \(U\) (dashed orange lines), optical depth \(f_{H\beta}\) (solid blue lines), and instantaneous burst age (grid thickness). The green stars show the observed values for the GPs on model grids (JR16) corresponding to their metallicity.
the JR16 models predict that galaxies with low EW(C III)] for a
given O32 tend to be optically thin, with high escape fractions
for LyC. Both age and metallicity also affect the scaling of
C III] EWs with optical depth. In each panel, we show the
location of the GPs on the diagnostic grids corresponding to
the metallicities derived from the optical spectra. The model grids
in Figure 9 are based on an instantaneous burst scenario and
assume a C/O ratio = 0.2.

The GPs J0815+2156 and J1219+1526 have similar O32
ratios of \( \sim 10 \) and are likely optically thin based on the velocity
separation measured for the Ly\( \alpha \) profiles. Both galaxies also
have high C III] EWs, as expected given their high ionization
parameters and low metallicities. These GPs, similar to J1154+
+2443 from Schaerer et al. (2018), are high EW(C III)]
galaxies that have high \( f_{\text{esc}}(\text{Ly}\alpha) > 25\% \) and are expected to
be optically thin to the LyC. The strong C III] emission in all of
these GPs is primarily driven by the very young ages, low
metallicity, and high ionization parameter that may be a
common property among the LyC leakers, and the effect of
optical depth \( (f_{\text{esc}}) \) may be relatively small. Some of the LyC
leaker candidates have such high C III] EWs that they can only
be reproduced with starburst ages of 1–2 Myr, suggesting that
the LyC leakers are very young or have harder ionizing spectra
than the nonleakers.

The galaxies J0303–0759 and J1457+2232 also have low
metallicities and comparably high O32 values of \( \sim 7.2 \) but their
Ly\( \alpha \) profiles suggest that they are optically thick with
\( f_{\text{esc}}(\text{Ly}\alpha) \sim 0 \). Both J0303–0759 and J1457+2232 have high
EW(C III)] > 3 Å. Interestingly, the C III] EWs of J0815+2156
and J1219+1526 are slightly lower than that of the optically
thick galaxy J1457+2232, in spite of their high O32 values. It is
plausible that there is a slight suppression of the C III] EW due
to the lower optical depth to Ly\( \alpha \) in J0815+2156 and J1219+
+1526, although the dominant factors that influence the C III]
strength appear to be the age and ionization parameter. On the
other hand, J0303–0759 has lower EW(C III)] than the other
three GPs, although it has low metallicity \( (Z \leq 0.003) \) and high
O32 = 7.1. The EWs of the optical nebular lines [O III] \( \lambda 5007 \)
and H\( \alpha \) are also relatively low for this galaxy, which suggests
a lower intrinsic ionizing flux and possibly an older burst age
for the stellar population. For the remaining GPs in our sample,
with low C III] EW and low O32 < 5, the combined effects of
an older average starburst age and higher metallicities influence
the EW(C III)] and do not offer sufficient constraints on the
optical depth. Since EW(C III)] depends on various factors, the
model grids presented in Figure 9 only serve as a diagnostic for
the effect of optical depth for C III] emitters with comparable
ages, ionization parameters, and metallicities. The analysis of a
larger sample is required to isolate the influence of LyC escape
on the strength of the C III] emission.

5. Discussion

5.1. Interpreting C III] Emission in Low-metallicity SFGs

The semiforbidden C III] nebular line is one of the most
prominent emission features in the rest-UV spectra of
low-metallicity SFGs. The C III] emission appears to be ubiquitous
in \( z > 2–6 \) low-metallicity galaxies selected by various criteria,
including the \( z > 2 \) Lyman-break galaxies (Shapley et al. 2003;
Steidel et al. 2016), LAEs at \( z \sim 3 \) (Erb et al. 2010; de Barros
et al. 2016; Vanzella et al. 2016), gravitationally lensed low-
mass galaxies at \( z > 6 \) (Stark et al. 2015a, 2017), and UV
luminosity-selected SFGs at \( 1.5 \lesssim z \lesssim 4 \) (Maseda et al. 2017;
Le Fèvre et al. 2019). As discussed in the previous sections, the
interpretation of the C III] emission depends on various
parameters, including metallicity, shape of the ionizing spectrum,
starburst age, LyC optical depth, and dust extinction. The high fraction of C III] emitters among the local GPs (8/11,
including J1154+2443) and the IRAC color-selected galaxies
at high redshifts show that low-metallicity galaxies that are
selected by their strong [O III] emission line are likely to also
show C III] emission. The higher effective temperatures of low-
metallicity ionized nebulae favor the collisionally excited
[O III] and C III] emission lines. In the presence of hard ionizing
radiation with high ionization parameters \( (\log U \gtrsim -2) \)
powered by very young \( (\sim 1 \text{ Myr}) \) metal-poor massive stars (Figure 7) or a weak AGN (Le Fèvre et al. 2019), the C III]
emission can be very strong, with EW(C III)] > 20 Å. In the
inner regions of such highly ionized nebulae, C III] emission
can be lowered by the transition to triply ionized carbon
resulting in C IV emission. At metallicities \( Z < 1/5 Z_\odot \), the
C IV emission line has been observed in local star-forming
dwarf galaxies (Berg et al. 2016; Sencyna et al. 2017). Strong
C IV emission frequently detected in \( z > 6 \) galaxies suggests
that such hard ionizing SEDs may be common for SFGs in the
reionization epoch (Stark et al. 2015b; Mainali et al. 2017;
Schmidt et al. 2017).

The burst ages and star formation history can affect the
observed emission line EWs. As shown in JR16, for an
instantaneous burst, the high C III] EWs \( \sim 5 \text{ Å} \) at young ages
\( < 3 \text{ Myr} \) are primarily driven by the ionization parameter
and metallicity. The same is true for EW(C III)] > 10 Å and a
continuous star formation history. In both star formation
scenarios, for a given metallicity and ionization parameter, the
EW(C III)] initially declines quickly with age due to the
decrease in the production rate of high-energy photons. However,
in the case of continuous star formation, an equilibrium is reached between the birth and death of massive stars beyond \( \sim 20 \text{ Myr} \), such that the C III] nebular emission
remains approximately constant with age and only the increasing
donorionizing UV continuum at 1909 Å from the stellar population
lowers the EW(C III)]. The EWs of the optical lines are lowered
by the continuum from the current star formation, in addition to
the contribution to the optical continuum from the underlying
older stellar population. Therefore, when comparing the C III]
EWs against EW([O III]) or EW(H\( \alpha \)), the contribution to the
continuum from the older stellar component has to be considered,
although the photoionization models used here do not include
multiple stellar populations (Figures 5 and 8). For the C III]
emitters at \( z = 2 \), Stark et al. (2014) proposed photoionization
models with two-component stellar populations, one young \( < 3 \text{ Myr} \) and one older, to provide a better fit to their SEDs.
Multicomponent star formation histories with a recent burst
\( < 10 \text{ Myr} \) that powers the nebular emission and an older few
hundred Myr stellar population that contributes to the UV–optical
continuum have been proposed to consistently explain the
observed UV spectra and IRAC (rest-optical) colors of \( z = 6–7 \)
galaxies (Stark et al. 2015a). The GPs and EELGs at lower
redshifts also show evidence for multiple stellar populations.
Amorín et al. (2012) found that the star formation history of GPs
indicates the presence of an evolved stellar component with an age
between 10^7 yr and several Gyr. For example, in the case of J1133+
+6513 with EW(C III)] = 1.67 Å and EW([O III]) = 394 Å,
which is in common with our sample, they noted that the presence
of the broad Mg I λ5167, 5173 absorption feature confirms the presence of old stars. The high EWs of the nebular lines, however, are powered by the ionizing continuum from the young stellar component, which may only be <20% of the total mass. The high SFR (>4–60 M_\odot yr^{-1}) and short mass doubling time of \( \lesssim 1 \) Gyr imply that the GPs are currently experiencing a powerful starburst phase that dominates their UV–optical continuum. Izotov et al. (2011) found that the GPs and similar luminous compact SFGs have \( M_{\text{Ly}\alpha}/M_{\text{total}} \sim 0.03–0.05 \), on average, for a galaxy with a total stellar mass of \( M_{\text{total}} = 10^9 M_\odot \). Although there is a higher fraction of young stars in the lower-mass galaxies, the range in the fraction of young stars for a given galaxy mass can be large based on their star formation histories. Among the GPs in this work, four (J0303–0759, J0815+2156, J1219+1526, and J1457+2232) have O_{32}>5 and low-metallicity Z \( \lesssim 0.003 \), and their large optical emission line EWs are consistent with a very young starburst (<3 Myr). The lower CIII and optical line EWs of the other GPs may result from older burst ages, lower ionization parameters, or high metallicities, and the effect of each individual parameter cannot be entirely disentangled using the present data.

The same physical conditions that produce strong intrinsic LyC and Ly\( \alpha \) emission also favor strong C III emission at low metallicities. However, while LyC and Ly\( \alpha \) are absorbed or scattered by neutral gas, C III can escape unimpeded. Therefore, C III is a potentially useful probe for systems where LyC and Ly\( \alpha \) are suppressed due to a surrounding neutral ISM or IGM. For instance, J1457+2232 and J0303–0759 in our GP sample are optically thick, with low escape fractions for Ly\( \alpha \) and possibly to LyC, and have high EW(CIII)). Many GPs have lower optical depths, allowing the escape of the ionizing continuum, and the LyC leakage can lower the observed EW(CIII)). At fixed age, metallicity, and ionization parameter, a lower EW(CIII)) can be interpreted as arising from a star-forming region that is optically thin to the LyC. As discussed in Section 4.2, the trends seen for the EW(CIII)) with optical depth for a subset of the current GP sample appear to be consistent with this interpretation and should be revisited using a larger sample of CIII emitters.

The overall carbon abundances and dust content in the ionized nebular regions are also expected to influence the C III EWs. Since carbon acts as a coolant in ionized regions, the lower carbon abundance in the low-metallicity galaxies results in higher nebular temperatures and increases the C III collisional excitation rates. As shown in JR16, the C III emission does not scale linearly with the C/O ratio, but the higher nebular temperatures at low C/O ratios can partially compensate for the lower carbon abundance and result in strong C III emission. The LyC-emitting GP J1154+2443 with a high EW(CIII)) = 11.7 ± 2.9 Å has low C/O \( \sim 0.13 \) (Schaefer et al. 2018) compared to most GPs in our sample. The enhanced C III emission in this low-metallicity galaxy with 12+log(O/H) \( \sim 7.6 \) is consistent with the JR16 models that predict the strongest C III) emission at Z < 0.002 because of the higher electron temperature, even if there are fewer carbon atoms. The dust content in ionized nebulae also affects the emergent C III) EWs through its dependence on the dust extinction and the role of photoelectric heating versus cooling via the forbidden lines. The photoelectric heating can enhance the C III) emission, but as the dust content increases, the extinction begins to be dominant and lowers the EW(CIII)). However, low-metallicity SFGs are relatively dust-poor systems. The GPs in our sample have very low nebular extinction, with \( E(B - V) = 0.03–0.2 \), as inferred from the Balmer decrement.

5.2. Constraints on the Ionizing Sources and Inputs to the Photoionization Models

Although a large number of C III] observations have become available in recent years, the nature of the ionizing sources that provide the high ionization parameters to account for the C III] emission strengths is not fully understood. The C III] emission requires high-energy photons (>24.4 eV) that can be provided by young, massive stars in low-metallicity SFGs or by AGNs (Feltre et al. 2016; Gutkin et al. 2016; Nakajima et al. 2018b). In the case of SFGs, the effects of binary stellar evolution have to be incorporated to successfully reproduce the high C III] EWs measured in SFGs consistent with their ages (JR16; Nakajima et al. 2018b). The X-ray observations of GPs reported by Svoboda et al. (2019) show that some GPs have X-ray luminosities that are a factor of 6 higher than expected for SFGs, which may be attributed to a hidden AGN, ultraluminous X-ray sources, or a higher fraction of high-mass X-ray binaries. However, the optical emission line ratios of GPs are compatible with SFGs in the BPT diagram (Baldwin et al. 1981) and inconsistent with an AGN contribution, although some extreme GPs can lie close to the maximum line for starburst (Jaskot & Oey 2013). While the emission lines from GPs in our sample can be accommodated by models with ages \( \gtrsim 3 \) Myr and the ionization parameter \( log U \gtrsim -2 \), some of the strong C III] emitters in the literature require extremely young ages (\( \sim 1 \) Myr) and very high ionization parameters (\( log U \sim -1 \)). The role of other exotic ionizing sources, such as very massive stars with masses >100 M_\odot (Smith et al. 2016), and the contribution from low-luminosity AGNs (Nakajima et al. 2018b; Le Fèvre et al. 2019) cannot be ruled out for the most extreme C III] emitters.

The C III] emission line in combination with other UV and optical emission lines forms an important diagnostic that helps to reveal the ionizing sources that are responsible for the nebular emission (Feltre et al. 2016; Byler et al. 2018). In addition to photoionization, the contribution of shocks can enhance the flux of C III] emission and low-ionization optical emission lines. Among the six GPs in Jaskot & Oey (2013), five of them showed He II λ4686 emission that may be produced by WR stars or shocks. The radiative shocks originating from supernova explosions can generate He II emission even without the WR stars and are most efficient in the dense, low-metallicity systems that are characteristic of GPs (Guseva et al. 2000; Thuan & Izotov 2005). In order to understand the ionizing spectrum and optical depth effects, the contribution from shocks should be subtracted. Although GPs are young enough to host large numbers of ionizing O stars or WR stars, supernovae and stellar winds from an ongoing or previous burst of star formation can reshape their ISM. In JR16, we showed that the presence of shock always contributes to an increase in the observed C III] flux and proposed a diagnostic involving C III]/He II versus C IV/ He II to distinguish nebular emission from purely photoionized and shock-ionized gas. However, we only detect weak He II λ1640 in the composite STIS spectrum from this study. Future spectroscopic observations of GPs with higher spectral resolution and high S/N to measure various shock diagnostics in the UV–optical wavelength range will be required to calibrate the shock diagnostics.
The UV spectra of GPs can constrain the input ISM parameters used in the photoionization models, such as C/O ratios and electron densities. The sample of ~eight GPs with detectable C III emission (including J1154+2443 from Schaefer et al. 2018) shows that the C/O ratios range from ~0.08 to 0.35 and are similar to the other C III emitters locally (Garnett et al. 1995; Berg et al. 2016, 2019; Senchyna et al. 2017) and at z > 2 (Shapley et al. 2003; Erb et al. 2010; Stark et al. 2014; Amorín et al. 2017). The variation of C III emission over the same range of C/O ratios has been explored in JR16 and found to have a significant effect on the EW(C III). The electron densities, $n_e \sim 100$ cm$^{-3}$, used in the photoionization models (JR16) are similar to that seen in typical H II regions. However, various measurements of electron densities from the [C III] $\lambda 1906 +$ C III $\lambda 1908$ doublet give $n_e$ values that are about 2 orders of magnitude higher than derived using optical diagnostics (e.g., [O II] or [S II] doublets) for galaxies at low and high redshifts (Baily et al. 2014, Berg et al. 2018; James et al. 2014, 2018). A possible reason for the different $n_e$ values is that the density-sensitive doublets in the optical are tracing the low-density regions compared to the C III doublet, which originates in higher-density regions closer to the ionizing source (Berg et al. 2018; James et al. 2018). The existing HST/STIS observations of GPs do not resolve the C III doublet lines, and high-resolution UV spectra of GPs would be required to constrain the electron densities used for the model predictions of C III emission.

5.3. C III] Emission Diagnostics to Explore the Galaxies in the Reionization Epoch

One of the key goals of the JWST and upcoming large 20 m class ground-based telescopes is to reveal the physical properties of the galaxies responsible for the reionization of the universe and quantify their contribution of ionizing photons. The relative contributions of SFGs and AGNs to the total ionizing budget for reionizing the universe are still debated (Madau & Haardt 2015; Finkelstein 2016; Hassan et al. 2018; Matsukawa et al. 2018). The UV luminosity function from deep surveys suggests that SFGs are the primary agents for reionization (Finkelstein 2016), but recent faint AGN surveys suggest that AGNs may have also contributed to the transition (Madau & Haardt 2015). The spectroscopic capabilities of the JWST instruments will play a critical role in identifying AGNs and starbursts in the reionization epoch. While the commonly employed optical nebular diagnostics of the BPT diagram (Baldwin et al. 1981) will be redshifted to the mid-IR wavelengths at z > 8, the bulk of the JWST spectroscopic data at NIR wavelengths obtained using NIRSpec and slitless spectroscopy with NIRISS and NIRCam will provide access to the rest-UV emission lines (e.g., Ly$\alpha$, C IV, O III], He II, and C III]). For the gravitationally lensed galaxies at z > 8, the NIRSpec IFU, NIRISS, and NIRCam grism modes will provide spatially resolved emission line maps over physical scales of a few tens to hundreds of pc.

The SFGs in the reionization epoch are compact, have high SSFRs and low metallicities similar to the GPs, and are likely to show strong C III] and nebular UV emission lines. The young ages of the starbursts and low metallicities of the ISM would favor high C III] EWs (Figures 5 and 8), making C III] one of the most easily detected emission features in the NIR spectra of z > 6 galaxies. Since the observability of Ly$\alpha$ emission drops at z > 6 due to the increased IGM absorption, the C III] emission could be used as an alternate probe of the ionizing flux and SFR based on the empirical relation between C III] and H$\alpha$ emission lines (Figure 5). The C III] emission line in combination with other nebular lines, such as N V $\lambda$1240, C IV $\lambda$1548, 1550, He II $\lambda$1640, O III] $\lambda$1661, 1666, and Si III] 1883, 1892 Å, can be used to reveal the nature of the ionizing sources and derive the nebular abundances (Feltre et al. 2016; Gutkin et al. 2016; JR16; Nakajima et al. 2018b). The C IV/ C III] ratio that uses UV emission lines that originate from different ionization states of carbon can constrain the ionization parameter, similar to the O$_{32}$ optical emission line ratio. The C III] and Si III] doublet lines can both be used for deriving the electron densities (JR16; Gutkin et al. 2016; Byler et al. 2018), while the commonly used C III]/O III] can be used to determine the elemental carbon abundances (Garnett et al. 1995; Berg et al. 2016, 2018). Feltre et al. (2016) used photoionization models to show that the AGNs and SFGs separate out well in the C IV/C III] versus C IV/He II and C III]/He II versus C IV/He II diagnostic diagrams. The He II line serves as a key diagnostic for hard ionizing radiation with high-energy photons (>54.4 eV), since the enhanced He II emission would lower the C III]/He II ratio. The models that include shock contribution can produce emission line ratios that overlap with the AGNs in the C III]/He II versus C IV/He II diagnostic diagram, but the pure photoionization models occupy an entirely different part of the diagram (JR16). As seen from the composite spectrum of C III] emitters among GPs, the He II emission line can be strong enough (Section 2.3) to be observable in the low-metallicity, high-redshift galaxies with JWST.

The semiforbidden C III] nebular emission doublet serves as an important diagnostic spectral line to infer the physical properties of reionizers. However, extensive calibration by applying the UV diagnostics to low-redshift galaxies is necessary for them to be used effectively to interpret sources in the reionization epoch. Currently, the number of galaxies in the low-metallicity regime with the required wavelength coverage to test the diagnostics based on rest-UV emission line ratios at z > 2 is very sparse. Only in recent years have the rest-UV spectroscopic data become available for local analogs of the high-z galaxies, which include GPs, BCDs, and EELGs at lower redshifts. In this work, we have explored the conditions that favor the C III] emission and examined diagnostics involving the C III] and optical emission lines for the GPs. We have shown that the GPs with high O$_{32}$ also have high EW(C III]) because the high ionization parameters favor C III] emission, but there is also a weak dependence on the optical depth to LyC (Figure 9). The C III] emission tends to be weaker for optically thin density-bounded nebulae compared to radiation-bounded nebulae for similar values of the ionization parameter. If these trends are calibrated for a sample of confirmed LyC-leaking GPs, the dependence of the C III] EW on the optical depths can be used to quantify the LyC escape from SFGs in the reionization epoch. Future work will require deep UV spectroscopy to detect the weaker UV spectral lines for a larger sample of GPs and other local analogs that extend these analyses to lower metallicities and a wide range of Ly$\alpha$ emission profiles. Detailed calibrations of the rest-UV nebular diagnostics in combination with the commonly used optical emission line diagnostics is a crucial step to be able to characterize and interpret the spectroscopic observations of the sources of reionization obtained with JWST.
6. Summary

We have analyzed the HST/STIS NUV spectra for a sample of 10 GPs at redshifts 0.1 \( \leq z \leq 0.3 \) to explore the semiforbidden C\( \text{III} \) \( \lambda \)1909 nebular emission line in low-metallicity SFGs with \( 7.8 \leq 12 + \log(O/H) \leq 8.4 \). We selected galaxies that have archival HST/COS FUV spectroscopic observations that include the Ly\( \alpha \) emission. The UV spectra were used along with the optical spectra from SDSS to constrain the metallicity and ionization parameter, examine the correlations between the UV and optical nebular lines, and compare the C\( \text{III} \) emission properties with predictions from the photoionization models. We summarize the results as follows.

(1) The C\( \text{III} \) emission is detected in 7/10 GPs, confirming that C\( \text{III} \) emission is almost ubiquitous in low-metallicity galaxies. The composite spectrum of the C\( \text{III} \) emitters shows an emission feature at the location of He\( \text{II} \) \( \lambda \)1640. The composite spectrum of the C\( \text{III} \) nonemitters shows strong interstellar absorption lines, particularly CIV absorption with a broad blueshifted profile wing, likely from the presence of strong outflows.

(2) The observed C\( \text{III} \) EWs of GPs are in the range 2–10 \( \AA \), consistent with the predictions from the photoionization models of JR16 that used constraints on model inputs (such as metallicity and ionization parameter) from the optical SDSS spectra. The GPs have C\( \text{III} \) EWs that overlap with the range of values seen in \( z \geq 2 \) SFGs but do not reach the high EW(C\( \text{III} \)) values (\( >15 \AA \)) seen in some \( z \geq 2 \) SFGs, local He\( \text{II} \) emitters, and BCDs that have very low metallicities with \( 12 + \log(O/H) \leq 7.5 \). At very low metalicities, the lack of metals that act as coolants can considerably enhance the C\( \text{III} \) emission even when the abundance of carbon atoms is low.

(3) Although the ensemble of SFGs appears to follow the empirical relation between EW(C\( \text{III} \)) and EW(Ly\( \alpha \)), the GPs do not seem to closely follow this relation. The GPs are strong emission line galaxies by definition, and the observed trend in the EW(C\( \text{III} \)) vs EW(Ly\( \alpha \)) diagram is primarily driven by the variation in the Ly\( \alpha \) optical depth. For non-GPs, weak Ly\( \alpha \) emission may indicate that the emission lines are intrinsically weak due to a weak ionizing spectrum. In our sample, J1457+2232 has the strongest C\( \text{III} \) emission with EW(C\( \text{III} \)) = 9.35 \( \pm \) 0.76 \( \AA \), but it is offset from the EW(C\( \text{III} \)) versus EW(Ly\( \alpha \)) relation. This galaxy has a broad absorption in the Ly\( \alpha \) profile at the systemic velocity and profile peaks with large velocity separation, \( \Delta v = 750 \text{ km s}^{-1} \), indicating a high neutral gas column along the line of sight. At high redshift, EGS-zs8-1 at \( z = 7.73 \) (Stark et al. 2017) is a galaxy in the reionization epoch with substantial neutral gas present at the Ly\( \alpha \) line center leading to a low EW(Ly\( \alpha \)) = 21 \( \pm \) 4 \( \AA \), but it has high EW(C\( \text{III} \)) = 22 \( \pm \) 2 \( \AA \). Such examples highlight the utility of the C\( \text{III} \) emission as a key nebular diagnostic when Ly\( \alpha \) is attenuated by the ISM or IGM.

(4) The C\( \text{III} \) emission does not show any obvious relation between velocity separation of the Ly\( \alpha \) profiles and escape fraction of the Ly\( \alpha \). For a given flux of hard ionizing radiation powered by young massive stars of fixed low metallicity, a narrow velocity separation for the Ly\( \alpha \) profile implies low neutral hydrogen column densities and a high Ly\( \alpha \) escape fraction. In such optically thin systems, the intrinsic and observed EW(Ly\( \alpha \)) and EW(C\( \text{III} \)) will be high for a high ionizing flux. However, such systems are likely to have higher LyC leakage, which may lower the observed EW(C\( \text{III} \)). In the case of optically thick systems, the Ly\( \alpha \) profile has broad velocity separation, and Ly\( \alpha \) emission may be weak with low EW(Ly\( \alpha \)) or even absent. The C\( \text{III} \) EW remains unaffected compared to the optically thin case.

(5) The C\( \text{III} \) emission in GPs correlates with the [O\( \text{III} \)] \( \lambda \)5007 and H\( \alpha \) optical emission lines, which are also powered by the ionization by massive stars with young ages. The presence of strong C\( \text{III} \) and [O\( \text{III} \)] emission confirms the presence of the hard ionizing radiation required to produce the high-ionization nebular lines. The C\( \text{III} \) EW in GPs also correlates strongly with the O\( \text{32} \) ratio, which is a proxy for the ionization parameter.

(6) The observed EW(C\( \text{III} \)) and EW([O\( \text{III} \)]) values for the GPs lie within the predictions from the model grids. However, most of the non-GPs have higher EW(C\( \text{III} \)) for a given EW([O\( \text{III} \)]). Unlike most of the GPs and other EELGs that have very strong nebular lines with EW([O\( \text{III} \)] \( \gtrsim \) 800 \( \AA \)) that dominate their spectrum, most of the SFGs selected using different criteria have a significant older stellar population that contributes to the continuum, which may explain the offset from the models. Other factors that can influence the C\( \text{III} \) and [O\( \text{III} \)] EWs include the C/O ratios, nebular temperatures, and electron densities, which are different compared to the GPs.

(7) We compared the properties of the C\( \text{III} \) emission for the GPs to the predictions from the JR16 photoionization models that use BPASS input SEDs and a grid of model parameters (e.g., metallicities, ages, log\( U \), and optical depth). The observed ranges of EW(C\( \text{III} \)) are consistent with the model predictions and require young stellar ages (\( \lesssim \)3–5 Myr), high ionization parameters (log\( U \) \( \gtrsim \) −2), and low metallicities (\( Z \leq 0.006 \)).

(8) The GPs are very likely to be LyC emitters, and the leakage of LyC radiation from the nebular region can reduce the C\( \text{III} \) emission. The JR16 models predict that for density-boundary regions with similar metallicities, ages, and O\( \text{32} \) ratios, the EW(C\( \text{III} \)) will be lower when the optical depth to LyC is lower. At very young stellar ages (<3 Myr), high ionization parameters (log\( U \) > −2), and low metallicities (\( Z < 0.15 Z_\odot \)), the EW(C\( \text{III} \)) values are high (\( >3 \) \( \AA \)), mainly due to the high ionizing flux and nebular temperatures, and the effect of optical depth is not the dominant factor. Four of the GPs in our sample with high O\( \text{32} \) > 5 are found to have EW(C\( \text{III} \)) > 3 \( \AA \). Two of the most promising candidates for LyC escape from our sample are J0815+2156 and J1219+1526, and, much like the LyC-leaking GP, J1154+2443 (Schaerer et al. 2018), they have high C\( \text{III} \) EWs consistent with extremely young ages and high\( U \). These could be common properties of LyC-leaking GPs. Interestingly, J0815+2156 and J1219+1526 are candidate LyC emitters based on their Ly\( \alpha \) profiles and have lower EW(C\( \text{III} \)) than J1457+2232, which has lower O\( \text{32} \) and comparable metallicity but is likely optically thick to the LyC.

In this work, we have focused on the semiforbidden C\( \text{III} \) and trends involving C\( \text{III} \) EWs and other UV–optical lines. Since C\( \text{III} \) is one of the strongest and most abundant nebular emission lines that will be used to reveal the nature of ionizing sources at the reionization epoch, it is important to calibrate line ratios involving C\( \text{III} \) and other UV lines for a large sample of galaxies with a broad range of nebular properties. Such calibrations based on low-redshift samples where both the UV and the commonly used optical diagnostics can be combined will be crucial to interpret the spectra of \( z > 7 \).
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARAA, 47, 481
Amorín, R., Fontana, A., Pérez-Montero, E., et al. 2017, NatAs, 1, 52
Universities for Research in Astronomy Science Institute, which is operated by the Association of telescopes.

The Astrophysical Journal, 2015, ApJ, 809, 19
Henry, A., Scarlata, C., Martin, C. L., & Erb, D. K. 2015, ApJ, 809, 19
Hassan, S., Davé, R., & Mitra, S. 2018, MNRAS, 473, 227

Heckman, T. M., Borthakur, S., Overzier, R., et al. 2011, ApJ, 730, 5
Henry, A., Scarlata, C., Martin, C. L., & Erb, D. K. 2015, ApJ, 809, 19
Hutchison, T. A., Papovich, C., Finkelstein, S. L., et al. 2019, ApJ, 879, 70
Izotov, Y. I., Guseva, N. G., & Thuan, T. X. 2000, ApJ, 531, 776
Guseva, N. G., Papaderos, P., Izotov, Y. I., Noeske, K. G., & Fricke, K. J. 2004, A&A, 421, 519
Gutkin, J., Charlot, S., & Bruzual, G. 2016, MNRAS, 462, 1757
Hassan, S., Davé, R., & Mitra, S. 2018, MNRAS, 473, 227

Heckman, T. M., Borthakur, S., Overzier, R., et al. 2011, ApJ, 730, 5
Henry, A., Scarlata, C., Martin, C. L., & Erb, D. K. 2015, ApJ, 809, 19
Hutchison, T. A., Papovich, C., Finkelstein, S. L., et al. 2019, ApJ, 879, 70
Izotov, Y. I., Guseva, N. G., & Thuan, T. X. 2011, ApJ, 728, 161
Izotov, Y. I., Orlitová, I., Schauer, D., et al. 2016a, Nat, 529, 178

Izotov, Y. I., Schauer, D., Guseva, N. G., et al. 2017, MNRAS, 467, 4118
Izotov, Y. I., Schauer, D., Thuan, T. X., et al. 2016b, MNRAS, 461, 3683
Izotov, Y. I., Schauer, D., Worseck, G., et al. 2018a, MNRAS, 474, 4514
Izotov, Y. I., & Thuan, T. X. 1999, ApJ, 511, 630
Izotov, Y. I., Worseck, G., Schauer, D., et al. 2018b, MNRAS, 478, 4851
James, B. L., Auger, M., Pettini, M., et al. 2018, MNRAS, 476, 1726
James, B. L., Pettini, M., & Christensen, L. 2014, MNRAS, 440, 1794
Jaskot, A. E., & Oey, M. S. 2013, ApJ, 766, 91
Jaskot, A. E., & Oey, M. S. 2014, ApJ, 791, 19
Jaskot, A. E., Oey, M.S., Scarlata, C., & Dowd, T. 2017, ApJL, 851, L9
Jaskot, A. E., & Ravindranath, S. 2016, ApJ, 833, 136
Kenneicutt, R. C. 1998, ARAA, 36, 189
Kewley, L. J., & Dopita, M. A. 2002, ApJS, 142, 35
Konno, A., Ouchi, M., Ono, Y., et al. 2014, ApJ, 797, 16
Laporte, N., Nakajima, K., Ellis, R. S., et al. 2017, ApJ, 851, 40
Le Fèvre, O., Lemaux, B. C., Nakajima, K., et al. 2019, A&A, 625, 51
Leitherer, C., Tremonti, C. A., Heckman, T. M., & Calzetti, D. 2011, AI, 141, 37
Madau, P., & Haardt, F. 2015, ApJ, 813, 8
Mainini, R., Kollmeier, J. A., Stark, D. P., et al. 2017, ApJ, 836, 14
Maseda, M. V., Brinchmann, J., Franz, M., et al. 2017, A&A, 608, 4
Maseda, M. V., van der Wel, A., & Rix, H.-W. 2014, ApJ, 791, 17
Mason, C. A., Treu, T., Djikstra, M., et al. 2018, ApJ, 856, 2
Matsunaga, Y., Strauss, M. A., Kashikawa, N., et al. 2018, ApJ, 869, 150
McKinney, J. H., Jaskot, A. E., Oey, M. S., et al. 2019, ApJ, 874, 52
Nakajima, K., Ellis, R. S., Iwata, I. et al. 2016, ApJ, 831, 9
Nakajima, K., Fletcher, T., Ellis, R. S., Robertson, B., & Iwata, I. 2018a, MNRAS, 477, 2098
Nakajima, K., & Ouchi, M. 2014, MNRAS, 442, 900
Nakajima, K., Schauer, D., Le Fèvre, O., et al. 2018b, A&A, 612, 94
Pellegrini, E. W., Oey, M. S., Winkler, P. F., et al. 2012, ApJ, 755, 40
Rich, J. R., Bayliss, M. B., Gladders, M. D., et al. 2015, ApJ, 814, 6
Roberts-Borsani, G. W., Bouwens, R. J., Oesch, P. A., et al. 2016, ApJ, 823, 143
Schauer, D., Izotov, Y. I., Nakajima, K., et al. 2018, A&A, 616, L14
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shapley, A. E., Reddy, N. A., & Kriek, M. 2015, ApJ, 801, 88
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
Shirazi, M., & Brinchmann, J. 2012, MNRAS, 421, 1043
Smit, R., Bouwens, R. J., Franx, M., et al. 2015, ApJ, 801, 122
Smit, R., Bouwens, R. J., Labbé, I., et al. 2014, ApJ, 784, 58
Smith, L., Crowther, P. A., Calzetti, D., & Sidoli, F. 2016, ApJ, 823, 38
Stark, D. P. 2016, ARAA, 54, 761
Stark, D. P., Ellis, R. S., Charlot, S., et al. 2017, MNRAS, 464, 469
Stark, D. P., Richard, J., Charlot, S., et al. 2015a, MNRAS, 450, 1846
Stark, D. P., Richard, J., Stiana, B., et al. 2014, MNRAS, 445, 3200
Stark, D. P., Walth, G., Charlot, S., et al. 2015b, MNRAS, 454, 1393
Stasinska, G., Izotov, Y., Morisset, C., & Guseva, N. 2015, A&A, 576, A83
Steidel, C. C., Rudie, G. C., & Stom, A. L. 2014, ApJ, 795, 165
Steidel, C. C., Stom, A. L., Pettini, M., et al. 2016, ApJ, 826, 159
Svoboda, J., Douna, V., Orlová, I., & Ehle, M. 2019, ApJ, 880, 444
Thuan, T. X., & Izotov, Y. I. 2005, ApJS, 161, 240
Tilvi, V., Papovich, C., Finkelstein, S. L., et al. 2014, ApJ, 794, 5
van der Wel, A.,Straughn, A. N., Rix, H.-W., et al. 2011, ApJ, 742, 111
Vanzella, E., de Barros, S., Cupani, G., et al. 2016, ApJ, 821, 27
Verhamme, A., Orlitová, I., Schauer, D., et al. 2017, A&A, 597, 13
Verhamme, A., Orlová, I., Schauer, D., & Hayes, M. 2015, A&A, 578, 7
Zackrisson, E., Inoue, A. K., & Jensen, H. 2013, MNRAS, 777, 39