[CII] Emission in z ~ 6 Strongly Lensed, Star-Forming Galaxies

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Abstract

The far-infrared fine-structure line [C II] at 1900.5 GHz is known to be one of the brightest cooling lines in local galaxies, and therefore it has been suggested to be an efficient tracer for star-formation in very high-redshift galaxies. However, recent results for galaxies at $z > 6$ have yielded numerous non-detections in star-forming galaxies, except for quasars and sub-millimeter galaxies. We report the results of ALMA observations of two lensed, star-forming galaxies at $z = 6.029$ and $z = 6.703$. The galaxy A383-5.1 (star formation rate [SFR] of $3.2\,M_\odot\,yr^{-1}$ and magnification of $\mu = 11.4$) shows a line detection with $L_{[CII]} = 8.3 \times 10^6\,L_\odot$, making it the so far lowest $L_{[CII]}$ ever detected at $z > 6$. For MS0451-H (SFR $= 0.4\,M_\odot\,yr^{-1}$ and $\mu = 100 \pm 20$) we provide an upper limit of $L_{[CII]} < 3 \times 10^5\,L_\odot$, which is 1 dex below the local SFR-$L_{[CII]}$ relations. The results are consistent with predictions for low-metallicity galaxies at $z > 6$, however, other effects could also play a role in terms of decreasing $L_{[CII]}$. The detection of A383-5.1 is encouraging and suggests that detections are possible, but much fainter than initially predicted.

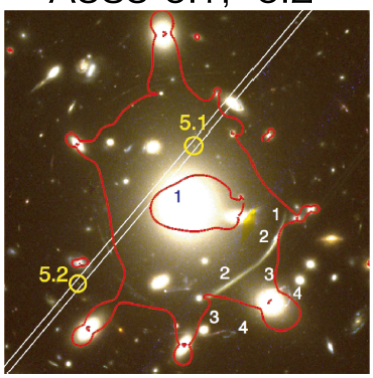
- A383-5.1 (z=6.029, SFR=3.2 M_{sun}/yr, nu=11.4), MS0451-H (z=6.703, SFR=0.4 M_{sun}/yr, nu=100+/-20) のALMA観測を報告
- A383-5.1からは[CII]158um輝線を検出（$L_{[CII]}$=8.3x10^6 L_{sun}）
- MS0451-Hからは[CII]は検出されず、$L_{[CII]}$<3x10^5 L_{sun}
- これらの[CII]光度は、近傍のSFR-$L_{[CII]}$関係よりも有意に低い
- この低い[CII]光度は z>6 の低金属量な銀河への予想と無矛盾だが、金属量以外の効果も[CII]光度の減少に寄与しているかもしれない。

Introduction

- Photo-zで高赤方偏移（i.e., z>6）だとされている銀河は数多くあるが、星形成に重要なガス（inter stellar medium; ISM）の物理的性質を知るには分光観測は不可欠である。
- ガスの物理的性質を探る手法として、CO輝線と[CII]158um輝線観測がある
  - CO輝線: H_2に次いで二番目に多い分子で、分子ガス質量の推定等に使われる
  - [CII]輝線: 近傍の星形成銀河で最も明るいFIR輝線の１つ。近傍ではSFRとの相関が示唆されている
- 地上望遠鏡の性能向上により、遠方銀河の[CII]輝線探しが可能になった
  - 1-4 L*くらいの明るい 5<z<6 LBGsでは[CII]輝線が検出され、近傍のSFR vs $L_{[CII]}$関係と無矛盾（Capak+15, Willott+15b）
  - LAEsでは、非常に明るいはずのHimikoを含め[CII]は非検出
- この論文では、重力レンズで増光された２個のsub-L* 銀河 (z>6) のALMA[CII]観測を報告する

Observation

A383-5.1, -5.2

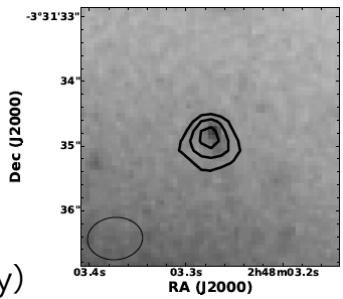


Richard+11

- ターゲット
  - A383-5.1(Richard+11, Stark+15)
  - z=6.029, SFR=3.2 M_{sun}/yr, nu=11.4
  - MS0451-H (Kneib+ in prep)
  - z=6.703, SFR=0.4 M_{sun}/yr, nu=100+/-20
- ALMA Cycle 2, Band 6で観測
  - Resolution: それぞれ 0.86" x 0.67", 1.6" x 0.9"
  - [CII] line付近のノイズレベルは、RMS=0.125, 0.163 mJy beam^{-1}。
- CASA (McMullin+07) でreduction, calibration, imaging

Results

- A383-5.1
  - [CII]輝線を検出。Speak=0.96 +/- 0.19 mJy (5.1 sigma)
  - $z_{[CII]}$=6.0274+/-0.0002
  - z_{Lya}=6.029+/-0.002, $z_{CIII]}$=6.0265+/-0.00013と無矛盾
  - FWHM=100+/-23 km s^{-1}
  - $L_{[CII]}$=8.3 x 10^6 L_{sun}
  - Dust continuumは非検出（5sigma upper limit = 55 uJy)
  - L_{FIR} < 0.5 x 10^{10} L_{sun} (modified black body, T=35 K, beta=1.6)
- MS0451-H
  - [CII]輝線は非検出（5sigma upper limit = 0.026 Jy km s^{-1})
  - $L_{[CII]}$<3.0 x 10^5 L_{sun} (FWHM=100 km s^{-1}を仮定)
  - Dust continuumも非検出 (upper limit = 55 uJy)
  - L_{FIR} < 0.07 x 10^{10} L_{sun}



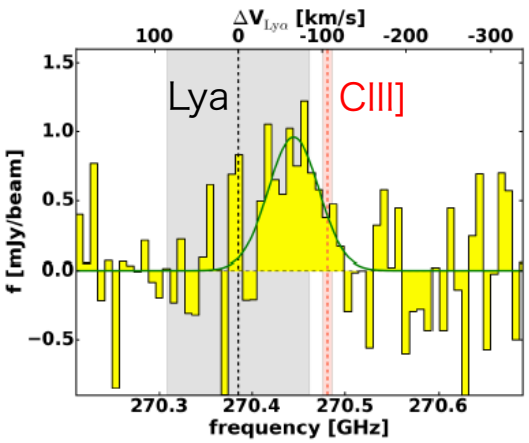


Figure 1. *Top*: HST WFC3 F140W image overlaid with the contours of the integrated spectral line. The contours show 3, 4, 5σ. The apparent gradient of NIR emission increasing from the lower part of the image is caused by the bright emission from the central galaxy of the A383 cluster. *Bottom*: ALMA spectra extracted at the position of A383-5.1 and centered at the frequency of the redshifted [C II] line. The green solid curve shows the best-fit Gaussian. The vertical dashed line and grey area shows the corresponding redshift and uncertainty determined from the Lyα line, and the red dashed line and area corresponds to the redshift measured from C III] (Stark et al. 2015). The top-axis shows the velocity relative the Lyα redshift.

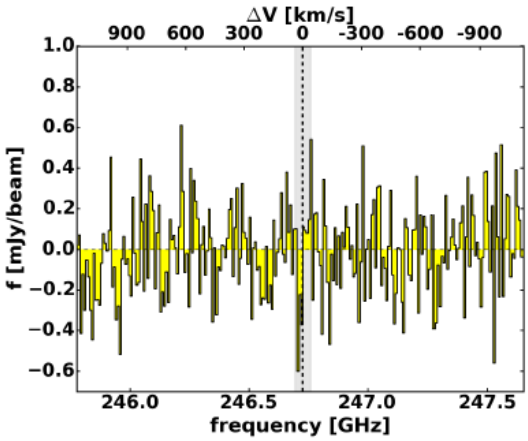


Figure 2. The ALMA band-6 spectrum extracted at the position of the MS0451-H arc. The vertical line and grey area shows indicate the corresponding redshift and uncertainty determined from the Lyα line. The top-axis shows the velocity relative the Lyα redshift.

Name	$z_{Ly\alpha}$	$z_{[CII]}$	μ	$L_{[CII]}$ [$L_\odot$]	$SFR_{[CII]}$ [$M_\odot\,yr^{-1}$]	L_{FIR} [$L_\odot$]	SFR_{FIR} [$M_\odot\,yr^{-1}$]
A383-5.1	6.029 ± 0.002	6.028	11.4	8.3×10^6	0.64	$< 0.5 \times 10^{10}$	< 0.5
MS0451-H	6.703 ± 0.001	...	100	$< 3.0 \times 10^5$ [a]	< 0.04	$< 0.07 \times 10^{10}$	< 0.07

[a] assuming a line width of 100 km s^{-1} as measured for A383-5.1

Discussion

- SFR vs $L_{[CII]}$上で、今回の２天体は近傍の関係より$L_{[CII]}$が4倍以上も低い(重力レンズのおかげ)
- IRで明るいstarburst銀河やAGNでは[CII]放射の効率が下がるとされているが、今回の天体はstarburstでもAGNでもない
- 説明1: 金属量
  - 金属量が低いほど[CII]が出ないという理論研究 (Rollig+06)
  - Vallini+15のz=6.6のsimulationの結果によると、低金属量（Z=0.05-0.2 Z_{sun}）だと近傍の関係より下にくる
  - ちなみに A383-5.2の金属量はZ=0.047 Z_{sun}
- 説明2: ハードなradiation field
  - C+を電離してしまう
  - 実際A383-5.2はionization parameter高い（logU=-1.79; Stark+15）
- 説明3: selection bias, systematics等
  - LAEではSFRを過大評価しているのかもしれない
  - Lya emissionは星形成以外にもinflowガスのshock ionizationでも起こる

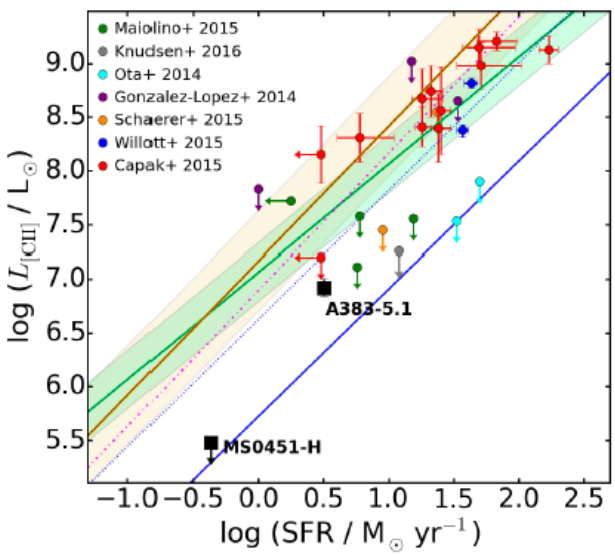


Figure 3. We plot the detection of A383-5.1 and the sensitive upper limit for MS0451-H after correcting for magnification, both black squares. We also include the recent $z \sim 6$ results from Ota et al. (2014); González-López et al. (2014); Willott et al. (2015b); Maiolino et al. (2015); Capak et al. (2015); Schaerer et al. (2015); Knudsen et al. (2016, in preparation). The $L_{[CII]}$ - SFR relation, where the green region shows the relation for local star-forming galaxies and the orange region shows that for low-metallicity dwarf galaxies (De Looze et al. 2014). The blue solid and dotted line shows the resulting relation from the low-metallicity simulations from Vallini et al. (2015) (solid: $Z = 0.05Z_\odot$, dotted: $Z = 0.2Z_\odot$) and the magenta dash-dot-line the results for massive $z \sim 2$ galaxies from Olsen et al. (2015).

Summary

- A383-5.1, MS0451-HのALMA観測を報告
- A383-5.1からは[CII]158um輝線を検出（$L_{[CII]}=8.3\times10^6\ L_{sun}$）
- MS0451-Hからは[CII]は検出されず、$L_{[CII]}<3\times10^5\ L_{sun}$
- これらの[CII]光度は近傍のSFR-$L_{[CII]}$関係よりも有意に低く、低金属量やハードなradiation fieldの影響が考えられる
- 高赤方偏移宇宙 (z>6) における[CII]観測は、近傍の関係で予想されるよりも難しいが、A383-5.1の検出により不可能でないことが示された