

First detection of [CII]158 μm at high redshift: vigorous star formation in the early universe

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Abstract. We report the detection of the ${}^2\text{P}_{3/2} \rightarrow {}^2\text{P}_{1/2}$ fine-structure line of C^+ at $157.74 \mu\text{m}$ in SDSS J114816.64+525150.3 (hereafter J1148+5251), the most distant known quasar, at $z = 6.42$, using the IRAM 30-m telescope. This is the first detection of the [CII] line at high redshift, and also the first detection in a Hyperluminous Infrared Galaxy ($L_{\text{FIR}} > 10^{13} L_{\odot}$). The [CII] line is detected at a significance level of 8σ and has a luminosity of $4.4 \times 10^9 L_{\odot}$. The $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio is 2×10^{-4} , about an order of magnitude smaller than observed in local normal galaxies and similar to the ratio observed in local Ultraluminous Infrared Galaxies. The [CII] line luminosity indicates that the host galaxy of this quasar is undergoing an intense burst of star formation with an estimated rate of $\approx 3000 M_{\odot} \text{yr}^{-1}$. The detection of C^+ in SDSS J1148+5251 suggests a significant enrichment of metals at $z \sim 6$ (age of the universe $\sim 870 \text{ Myr}$), although the data are consistent with a reduced carbon to oxygen ratio as expected from chemical evolutionary models of the early phases of galaxy formation.

Key words. galaxies: high redshift – galaxies: ISM – quasars: individual: J114816.64+525150.3 – infrared: galaxies – submillimeter – ISM: abundances

1. Introduction

The ${}^2\text{P}_{3/2} \rightarrow {}^2\text{P}_{1/2}$ fine-structure line of C^+ at $157.74 \mu\text{m}$ is often the brightest emission line in the spectrum of galaxies, accounting for as much as $\sim 0.1\text{--}1\%$ of their total luminosity (Crawford et al. 1985; Stacey et al. 1991; Wright et al. 1991). The line is emitted predominantly by gas exposed to ultraviolet radiation in photo dissociation regions (PDRs) associated with star forming activity (even in galaxies hosting AGNs), and has been extensively used to investigate the physical conditions of PDRs and to trace star formation in external galaxies (e.g. Malhotra et al. 2001; Luhman et al. 2003; Kaufman et al. 1999; Genzel & Cesarsky 2000; Boselli et al. 2002; Pierini et al. 2003).

In local galaxies, with far-infrared luminosities¹ $L_{\text{FIR}} < 10^{12} L_{\odot}$, the fractional contribution of the C^+ luminosity to the

far-infrared luminosity, which is a measure of the gas heating efficiency, is typically in the range $-3 \leq \log(L_{[\text{CII}]} / L_{\text{FIR}}) \leq -2$ (e.g., Stacey et al. 1991). For sources with far-infrared luminosities in excess of $10^{12} L_{\odot}$ or with increasing star formation activity, this ratio drops by an order of magnitude (Malhotra et al. 2001; Luhman et al. 1998, 2003; Negishi et al. 2001). Various possibilities have been proposed to explain this effect at high luminosities, specifically: 1) a high ratio of ultraviolet flux to gas density, resulting in positively charged dust grains which in turn reduce the efficiency of the gas heating by the photoelectric effect (e.g. Kaufman et al. 1999); 2) opacity effects which weaken the [CII] emission line in infrared luminous galaxies (Gerin & Phillips 2000; Luhman et al. 1998); 3) contribution to L_{FIR} from dust associated with HII regions (Luhman et al. 2003); 4) contribution to L_{FIR} from an AGN (see Malhotra et al. 2001).

The possibility of probing the interstellar medium and tracing star formation in galaxies at cosmological distances by

¹ We adopt the $L_{\text{FIR}} = L(40\text{--}500 \mu\text{m})$ definition given in Sanders & Mirabel (1996).

using the bright C^+ emission line, when redshifted into submillimeter atmospheric windows, was proposed by Petrosian et al. (1969), and further discussed by Loeb (1993), Stark (1997) and Blain et al. (2000). However, [CII] has so far only been detected in local galaxies ($z < 0.1$) from space and airborne observatories (e.g. Luhman et al. 2003), while all the searches for C^+ at higher redshifts have been unsuccessful. Deep searches for C^+ were carried out in $z > 3$ infrared luminous galaxies and quasars having massive reservoirs of molecular and neutral gas detected in CO emission lines. Specifically, C^+ was searched for in the $z = 3.13$ damped Ly α absorption system towards PC 1643+4631A (Ivison et al. 1998), the $z = 4.12$ quasar PSS 2322+1944 (Benford et al., in prep.), the $z = 4.69$ quasar BR 1202–0725 (Isaak et al. 1994; van der Werf 1999, Benford et al. in prep.), a $z = 4.92$ lensed galaxy in the cluster CL 1352+62 (Marsden et al. 2005), and the $z = 6.42$ quasar SDSS J1148+5251 (Bolatto et al. 2004, the same object discussed here).

In this letter, we report the detection of C^+ in J114816.64+525150.3 (hereafter J1148+5251) the most distant quasar known whose redshift of 6.42 puts it at the end of the epoch of re-ionization (Fan et al. 2003). Millimetric and submillimetric continuum detections indicate that the host galaxy of this quasar radiates a far-IR luminosity² of $\approx 2 \times 10^{13} L_{\odot}$, which, if ascribed to starburst activity (and not to the QSO itself), would imply star formation rates of a few times $10^3 M_{\odot} \text{ yr}^{-1}$ (Bertoldi et al. 2003a; Robson et al. 2004). A massive reservoir of molecular and neutral gas of a few $10^{10} M_{\odot}$ has been detected via CO line emission (Walter et al. 2003, 2004; Bertoldi et al. 2003b). The detection of copious amounts of dust and molecular gas indicates that the interstellar medium in J1148+5251 is significantly enriched in metals. This enrichment is also seen through the detection of prominent iron line emission in the rest-frame UV spectrum of the quasar (Maiolino et al. 2003), although the latter samples its nuclear region.

The deep observations described in this paper, improve significantly the noise-level reported by Bolatto et al. (2004) and enabled us to achieve the first detection of the C^+ emission line at cosmological distances as well as the first detection of this line in a galaxy with an infrared luminosity in excess of $10^{13} L_{\odot}$. We discuss the implications of this detection for the physical properties of the ISM and of star formation in J1148+5251³.

2. Observations and results

Observations were carried out with the IRAM 30 m telescope in two observing runs: February 2–3 and March 8–10, 2005. We used alternatively the C and D 150 receivers with filter banks covering a bandwidth of 1 GHz with 256 channels spaced by 4 MHz. The receivers were tuned to 256.1753 GHz corresponding to the frequency of the [CII] emission line (rest frequency

² Thanks to new submm data Beelen et al. (in prep.) obtained a new estimate of the far-IR luminosity, which is in the range $1.2\text{--}3.2 \times 10^{13} L_{\odot}$.

³ In this letter we assume the concordance Λ -cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\Lambda} = 0.73$ and $\Omega_m = 0.27$ (Spergel et al. 2003).

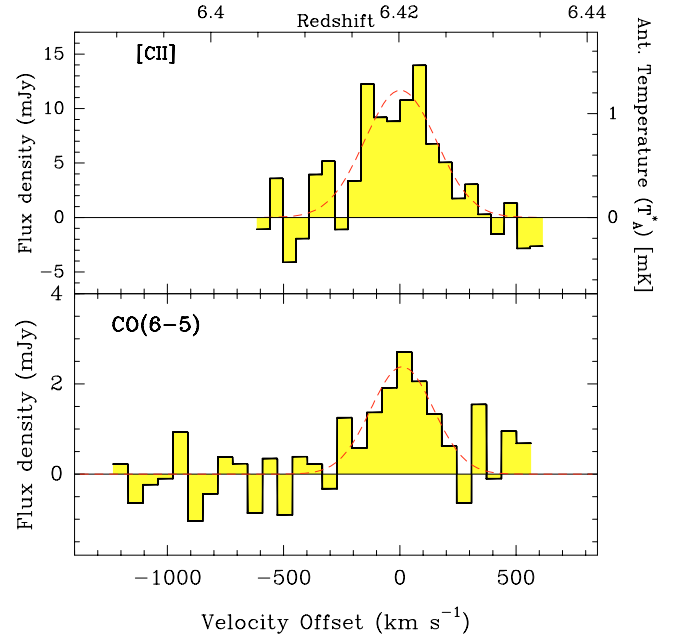


Fig. 1. Spectrum of the [CII] 157.74 μm emission line in the quasar J1148+5251 at $z = 6.42$ shown with a velocity resolution of 56 km s^{-1} (top panel) compared to the CO(6–5) emission line (bottom panel – from Bertoldi et al. 2003b). The dashed curves show the gaussian fits to the line profiles (see Table 1).

1900.539 GHz) redshifted to $z = 6.4189$, the redshift of the CO emission lines, but we also observed with the frequency offset by $\pm 100 \text{ km s}^{-1}$ to minimize, and check, the effects of possible instrumental artifacts. At this frequency the Half Power Beam Width is $9.6''$ and the 1 GHz bandwidth corresponds to 1170 km s^{-1} . The observing conditions were generally good: low opacity, with $\tau_{256 \text{ GHz}} < 0.1$ during the March run and $\tau_{256 \text{ GHz}} < 0.2$ during the February run, and system temperature $T_{\text{sys}} \sim 350 \text{ K}$. The observations were done in wobbler switching mode with a switching frequency of 0.5 Hz and a wobbler throw of $200''$. In total, the source was observed for 12.4 h. Calibration was obtained every 15 min using the standard hot/cold-load absorber measurements. Pointing was checked about every 1.5 h by means of one of the two 3 mm receivers (A100/B100) and the pointing accuracy was found to be in the range $1\text{--}3''$. The focus was checked about every 3–4 h and was found not to change significantly.

The data were processed using the CLASS software. After dropping some bad scans, only linear baselines were subtracted from individual spectra. The individual scans were realigned in frequency and co-added by weighting with $1/\text{rms}^2$. The resulting profiles were re-gridded to a velocity resolution of 56 km s^{-1} leading to an rms of about 0.3 mK (2.8 mJy)⁴. We estimate the flux density scale to be accurate to about 30%.

The final spectrum of the [CII] emission line in J1148+5251 is shown in Fig. 1. The C^+ fine-structure line is detected with a confidence 8σ . The velocity integrated flux is $0.44 \pm 0.05 \text{ K km s}^{-1}$ (in antenna temperature, $T_{\text{mb}} = 1.91 T_A$), or $4.1 \pm 0.5 \text{ Jy km s}^{-1}$, and the line center corresponds within

⁴ The conversion between antenna temperature and flux density scale at 256 GHz for the 30 m is 9.5 Jy/K .

Table 1. Properties of the [CII] line observed toward SDSS J1148+5251 compared with the CO(6–5) line observed by Bertoldi et al. (2003b).

Line	ν_{rest}	ν_{obs}	z_{line}	Peak int.	ΔV_{FWHM}	I	L
	[GHz]			[mJy]	[km s $^{-1}$]	[Jy km s $^{-1}$]	[$10^9 L_{\odot}$]
[CII] ($^2\text{P}_{3/2} - ^2\text{P}_{1/2}$)	1900.54	256.172	6.4189 ± 0.0006	11.8	350 ± 50	4.1 ± 0.5	4.4 ± 0.5
CO (6–5)	692.473	93.204	6.4189 ± 0.0006	2.45	279 ± 65	0.73 ± 0.076	0.29 ± 0.02

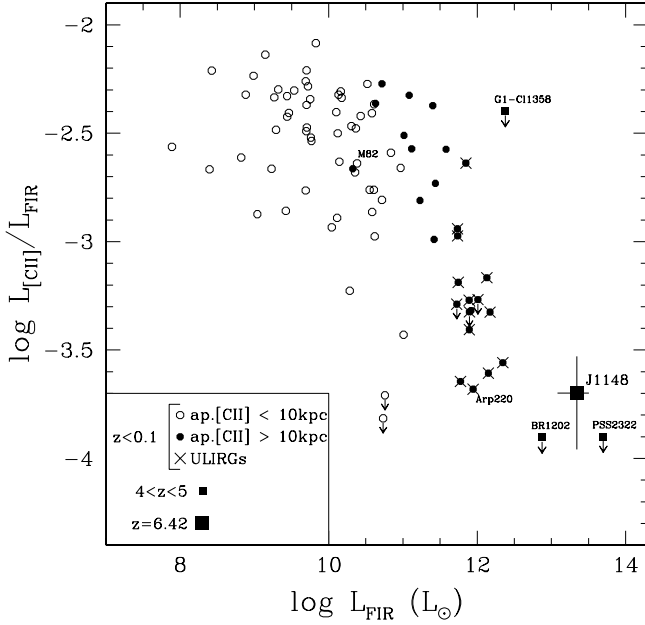


Fig. 2. The $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio versus L_{FIR} for normal and starburst local galaxies (circles), as measured by the ISO Long Wavelength Spectrometer (LWS), and for high- z sources (squares), as measured from the ground. J1148+5251 is shown with a large square. The small squares indicate the upper limits for the three other high- z sources (identified by their names) where [CII] was searched for. Empty circles indicate galaxies for which the aperture to measure [CII] (i.e. ISO–LWS) is smaller than 10 kpc, and therefore it may sample a smaller region relative to the IRAS beam used for the far-IR flux. Crosses indicate local ULIRGs ($L_{\text{IR}} > 10^{12} L_{\odot}$). For reference, well-known local galaxies (Arp 220, M 82) are also identified.

the uncertainties to the center of the CO line emission (Table 1 and Fig. 1).

Bolatto et al. (2004) used the James Clerk Maxwell Telescope to detect the C^+ line in J1148+5251, but could only place an upper limit to its line strength. To compare their limits with our result we note that the peak intensity of our line (12 mJy) is three times lower than the rms (32 mJy) in their final spectrum smoothed to a resolution of 10 MHz (or 12 km s $^{-1}$). The [CII] velocity integrated flux reported in this paper is twice larger than the 1σ limit estimated by Bolatto et al. for the intensity of any putative line in the JCMT spectrum.

3. Discussion

The emission of C^+ in J1148+5251 is an extreme example of what is seen in local infrared galaxies. The $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio in J1148+5251 is 2×10^{-4} , about an order of magnitude smaller than in local starburst galaxies. This is illustrated in Fig. 2,

where we plot the $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio in nearby star-forming galaxies as a function of their far-infrared luminosity, together with the current upper limits for high-redshift sources and the value obtained for J1148+5251. A decrease of the $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio with increasing L_{FIR} beyond $10^{11.5} L_{\odot}$ is clearly apparent in Fig. 2. The $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio for J1148+5251 is consistent with this general trend. Note also that our sensitive detection is consistent with the upper limits inferred for other high- z QSOs in Fig. 2.

The detection of strong [CII] emission suggests that the interstellar medium was already significantly enriched with metals at $z = 6.4$, i.e. when the universe was as young as 870 Myr. However, the chemical evolutionary models predict that the enrichment of carbon relative to the α elements is delayed (since carbon is mostly produced by intermediate/low mass stars), and in particular the C/O ratio should be about 1/6 in the young stages of massive elliptical galaxies, while the absolute abundance of O should be similar to the local value, at least at an age of about 1 Gyr (Pipino & Matteucci 2004). To achieve a better physical understanding of this source, and in particular to investigate whether the C-poor scenario is consistent with the data or not, we have compared all available observational data for the host galaxy of the quasar (i.e. [CII], FIR and CO transitions) with PDR models. The relevant observational data are summarized in the second column of Table 2. We used the PDR model of Kaufman et al. (1999), modified for the conditions appropriate for J1148+5251. In particular, we lowered the carbon-to-oxygen abundance as discussed above. We did not include detailed models for the evolution of dust (Morgan & Edmunds 2003), nor the possible contribution of dust from SNe (Maiolino et al. 2004), we simply scaled the the abundance of dust grains and PAHs proportionally to the carbon abundance. The model requires high densities and high UV radiation fields to reproduce the data. However, a PDR model which fits observations of typical star forming regions fails to reproduce the strength of the high- J CO transitions observed by Bertoldi et al. (2003b). It is possible to increase the gas heating in the CO-emitting region by increasing the cosmic ray ionization rate. Such a high ionization rate can mimic the higher gas heating due to an increased X-ray flux associated with the powerful QSO hosted by this system. We find a good fit to the observations with a gas density $n = 10^5 \text{ cm}^{-3}$, a FUV field $G_0 = 10^{3.8}$ times stronger than the average value in the Galactic ISM, C/O = 1/6, and a cosmic ray ionization rate ζ per H nucleus of $\sim 10^{-16} \text{ s}^{-1}$, i.e. about 10 times the Galactic value. The cosmic background radiation at $z = 6.4$ has a temperature of about 22 K, much lower than the gas temperature observed in this system, it may however slightly affect the lower CO transitions, but the latter are less relevant for our model (especially CO(1–0) which only has an upper limit). The resulting model

Table 2. PDR model results ($n = 10^5 \text{ cm}^{-3}$, $G_0 = 10^{3.8}$, $\zeta = 1.8 \times 10^{-16} \text{ s}^{-1}$).

Ratio	Observed	Model ^a	
		C/O = 1/6	C/O = local
$L_{[\text{CII}]} / L_{\text{FIR}}$	$2.0(\pm 0.9) \times 10^{-4}$	1.4×10^{-4}	3.8×10^{-4}
$L_{\text{CO}(6-5)} / L_{[\text{CII}]}$	$6.6(\pm 2.0) \times 10^{-2}$	5.7×10^{-2}	6.7×10^{-2}
$L_{\text{CO}(7-6)} / L_{\text{CO}(6-5)}$	$1.02(\pm 0.17)$	0.85	1.18
$L_{\text{CO}(3-2)} / L_{\text{CO}(6-5)}$	$0.22(\pm 0.03)$	0.27	0.17
$L_{\text{CO}(1-0)} / L_{\text{CO}(6-5)}$	$< 2.4 \times 10^{-2}$	8.3×10^{-3}	4.4×10^{-3}

Note: ^a the abundances for the models with “local” ISM fractions are specifically $\text{O}/\text{H} = 3.2 \times 10^{-4}$ and $\text{C}/\text{H} = 1.4 \times 10^{-4}$ (Savage & Sembach 1996), while for the “reduced” C/O model $\text{C}/\text{H} = 5.6 \times 10^{-5}$ and O/H has been kept to the same value as “local”.

reproduces all the observed line ratios and line-to-FIR ratios within a factor of 30%. This result shows that the C-poor scenario is consistent with the data. On the other hand it is not a proof of a low C-to-O ratio. Indeed, even using the C/O ratio typical of the local ISM the results of the model are still in fair agreement with the data, as shown in the third column of Table 2. Summarizing, PDR models with high densities and enhanced X-ray (cosmic ray) flux can reproduce the observed properties of J1148+5251, both with local ISM abundances and with a reduced C/O ratio predicted by chemical evolutionary models. Tackling the issue of the chemical abundances in detail will require the observation of additional lines.

As discussed in the introduction, the [CII] line is produced by the UV field in star forming regions and therefore can be used as an indicator of the star formation rate (SFR). Boselli et al. (2002) calibrate the luminosity of [CII] in terms of SFR, but their calibration only applies to low luminosity systems ($L_{\text{FIR}} < 10^{10.5} L_{\odot}$). We have attempted to derive the $L_{[\text{CII}]} - \text{SFR}$ relation at high luminosities ($L_{\text{FIR}} > 10^{12} L_{\odot}$). One possibility is to combine the relationship between far-IR luminosity and star formation rate derived by Kennicutt (1998) with the $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio predicted by the model (where we use the intermediate value of the $L_{[\text{CII}]} / L_{\text{FIR}}$ obtained from the two models in Table 2), yielding the relation:

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) \approx 6.5 \times 10^{-7} \left(\frac{L_{[\text{CII}]}}{L_{\odot}} \right). \quad (1)$$

From Eq. (1) and from the [CII] luminosity we infer a star formation rate in the host of J1148+5251 of $\text{SFR} \sim 3000 M_{\odot} \text{ yr}^{-1}$, consistent with the SFR estimated from L_{FIR} (Bertoldi et al. 2003a). Therefore our result demonstrates that the host galaxy of this quasar is the site of extremely powerful massive star formation, and it is probably tracing the earliest stages of the black hole–spheroid co-evolution.

The first detection of the fine-structure line of C^+ in a high redshift object shows the potential use of this emission line to investigate star formation and the physics of the interstellar medium in the early universe. Further detections and imaging of C^+ in high- z objects will continued to be made by using existing instruments and forthcoming facilities, in particular

with the Atacama Large Millimeter Array (ALMA) for which this topic is one of the primary scientific goals.

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