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A SENSITIVE SEARCH FOR [N II]$_{205\,\mu m}$ EMISSION IN A $z = 6.4$ QUASAR HOST GALAXY

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ABSTRACT

We present a sensitive search for the $^3P_1 \rightarrow {}^3P_0$ ground-state fine structure line at 205 μm of ionized nitrogen ([N II]$_{205\,\mu m}$) in one of the highest-redshift quasars (J1148+5251 at $z = 6.42$) using the IRAM 30 m telescope. The line is not detected at a (3σ) depth of 0.47 Jy km s^{-1}, corresponding to a [N II]$_{205\,\mu m}$ luminosity limit of $L_{[\rm N\,II]} < 4.0 \times 10^8\, L_\odot$ and a $L_{[\rm N\,II]}/L_{\rm FIR}$ ratio of $< 2 \times 10^{-5}$. In parallel, we have observed the CO ($J = 6$–5) line in J1148+5251, which is detected at a flux level consistent with earlier interferometric observations. Using our earlier measurements of the [C II] 158 μm line strength, we derive an upper limit for the [N II]$_{205\,\mu m}$/[C II] line luminosity ratio of ∼1/10 in J1148+5251. Our upper limit for the [C II]/[N II]$_{205\,\mu m}$ ratio is similar to the value found for our Galaxy and M 82 (the only extragalactic system where the [N II]$_{205\,\mu m}$ line has been detected to date). Given the non-detection of the [N II]$_{205\,\mu m}$ line we can only speculate whether or not high-z detections are within reach of currently operating observatories. However, [N II]$_{205\,\mu m}$ and other fine-structure lines will play a critical role in characterizing the interstellar medium at the highest redshifts ($z > 7$) using the Atacama Large Millimeter/submillimeter Array, for which the highly excited rotational transitions of CO will be shifted outside the accessible (sub-)millimeter bands.

Key words: cosmology: observations – galaxies: active – galaxies: formation – galaxies: high-redshift – galaxies: starburst – radio lines: galaxies

1. INTRODUCTION

Forbidden atomic fine-structure transitions are important cooling lines of the interstellar medium (ISM). They provide effective cooling in cold regions where allowed atomic transitions cannot be excited, thus providing critical diagnostic tools to study the star-forming ISM. Perhaps the most important cooling line is the forbidden $^2P_{3/2} \rightarrow {}^2P_{1/2}$ fine-structure line of ionized carbon ([C II]) at 158 μm. Other main cooling lines are the oxygen [O I] (63 μm) and [O III] (at 52 and 88 μm) lines, as well as the nitrogen [N II] lines at 122 and 205 μm (hereafter [N II]$_{205\,\mu m}$). Observations of a combination of these lines have proven to provide key diagnostics regarding the physical properties of the atomic interstellar medium in galaxies (e.g., probes for the interstellar UV radiation field, photon-dominated regions [PDRs], temperature, gas density and mass, e.g., Petuchowski & Bennett 1993, van der Werf 1999). As the ionization potential of carbon is 11.3 eV (hydrogen: 13.6 eV), [C II] is a tracer for both the neutral atomic and ionized medium, predominantly of PDRs. The ionization potentials for oxygen and nitrogen, on the other hand, are 13.6 eV and 14.53 eV, respectively, implying that their forbidden ionized fine-structure lines trace the ionized medium only. The [N II]$_{205\,\mu m}$ line, which is the focus of this study, is of particular interest as it has a critical density that is very close to that of [C II], thus potentially providing complementary information on the origin of the [C II] emission (e.g., Oberst et al. 2006).

Given the poor atmospheric transmission at mid-/far-infrared wavelengths most of these lines in the local universe can only be studied using airborne or space-based observatories. At sufficiently high redshift, however, some of the lines are shifted to the (sub-)millimeter bands that can be observed from the ground. Especially at redshifts approaching the epoch of reionization ($z > 7$) these lines provide the only tools by which to study the properties of the star-forming ISM using (sub-)millimeter facilities, as the excited rotational lines of the standard tracer, CO, will be shifted outside the observable (sub-) millimeter bands (Walter & Carilli 2008).

Whereas the [C II] line has now been abundantly detected in the local universe (e.g., Stacey et al. 1991; Malhotra et al. 1997; Luhman et al. 1998; Madden et al. 1997), measurements of the [N II]$_{205\,\mu m}$ line are scarce.[8] The line was first detected by FIRAS aboard *COBE* in the Milky Way (Wright et al. 1991), where a global [C II]/[N II]$_{205\,\mu m}$ flux ratio of 10.4 ± 1 was observed (first laboratory measurements were obtained by Brown et al. 1994). The [N II]$_{205\,\mu m}$ line was later detected in the Galactic H II region G333.6–0.2 (Colgan et al. 1993) and subsequently in the Carina Nebula (Oberst et al. 2006); the first detection from the ground (using SPIFI on AST/RO). Again a flux ratio around 10 (9.2 ± 3.0) relative to the [C II] line was found. The [N II]$_{205\,\mu m}$ line was detected in only one extragalactic system, M 82, using the Kuiper Airborne Observatory, with a [C II]/[N II]$_{205\,\mu m}$ flux ratio of 20.0 ± 3.4 (Petuchowski et al. 1994). At high redshift, the ratio may be susceptible to N/C abundance variations (e.g., Matteucci & Padovani 1993). Given the potential importance of the [N II]$_{205\,\mu m}$ line in studies of the ISM in the very early universe, multiple attempts were performed to detect this line at high redshift (4C41.17 and PC2047+0123: Ivison & Harrison

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[8] This is due to the fact that [C II] was accessible with the Infrared Space Observatory Long Wavelength Spectrometer (ISO/LWS, Clegg et al. 1996) whereas [N II]$_{205\,\mu m}$ was not.

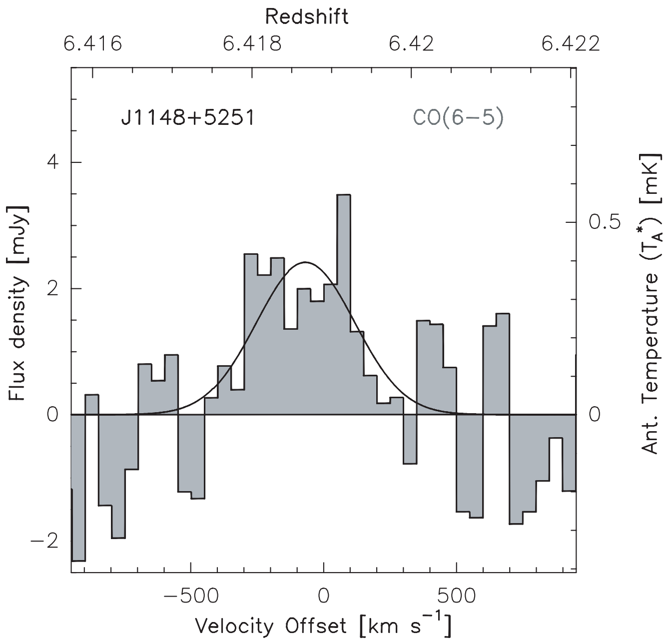

Figure 1. CO(6–5) line in J1148+5251 from the data that were taken in parallel to the [N II]$_{205\,\mu m}$ observations. Velocities are given offset to the tuned redshift of $z = 6.4189$. The best Gaussian fit is overplotted as a solid curve (see Section 3.1 for fit parameters).

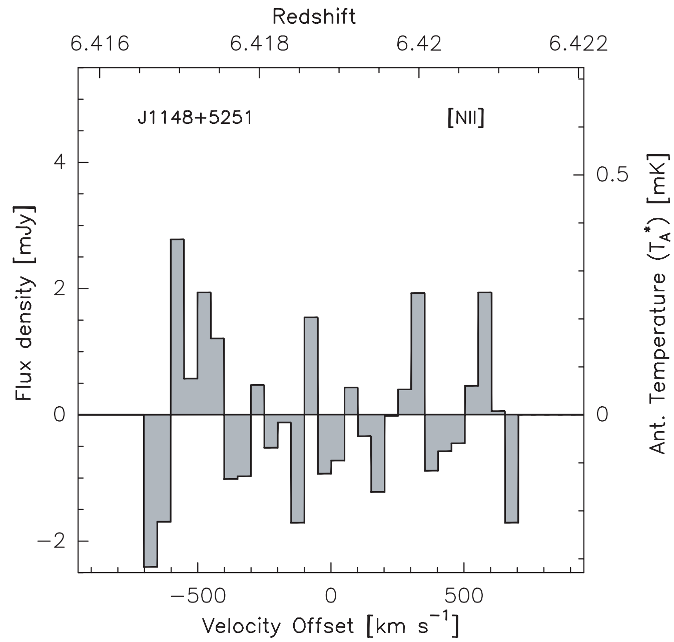

Figure 2. Spectrum of the [N II]$_{205\,\mu m}$ observations towards J1148+5251 of the velocity and redshift range (lower and upper x-axes, respectively), expected for the [N II]$_{205\,\mu m}$ line. The line is not detected.

1996; the Cloverleaf: Benford 1999; APM 08279: Krips et al. 2007; see Table 1 for a summary).

Here we present a sensitive search for [N II]$_{205\,\mu m}$ emission in one of the highest-redshift quasars, SDSS J114816.64+525150.3 (hereafter: J1148+5251) at $z = 6.42$. It has a far-infrared (FIR) luminosity of $2.2 \times 10^{13}\,L_{\odot}$ (Bertoldi et al. 2003a; Beelen et al. 2006) and hosts a large reservoir of molecular gas ($2 \times 10^{10}\,M_{\odot}$), the prerequisite for star formation, which has been detected through redshifted rotational transition lines of CO (Walter et al. 2003; Bertoldi et al. 2003b; Walter et al. 2004). Besides BR 1202−0725 (Iono et al. 2006), it is the only system detected in [C II] at $z > 0$ to date (Maiolino et al. 2005; Walter et al. 2009) and is thus an obvious target to search for emission from [N II]$_{205\,\mu m}$. We use a concordance, flat ΛCDM cosmology in this Letter, with $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$ (Spergel et al. 2007), and a resulting luminosity distance of 63.8 Gpc at $z = 6.42$ (Wright 2006).

2. OBSERVATIONS

J1148+5251 ($z = 6.4189$, Bertoldi et al. 2003b) was observed with the IRAM 30 m telescope in 2007 March and April in good weather conditions. We used the AB and CD receiver setups, with the AB receivers tuned to CO(6–5) (3 mm band, $\nu_{obs} = 93.20426$ GHz, $\nu_{rest} = 691.473$ GHz) and the C/D receivers simultaneously tuned to [N II]$_{205\,\mu m}$ (1 mm band, $\nu_{obs} = 196.9472$ GHz, $\nu_{rest} = 1461.132$ GHz, Brown et al. 1994). System temperatures were typically 130 K at 3 mm and ∼210 K at 1 mm. Data were taken with a wobbler rate of 0.5 Hz and a wobbler throw of 50″ in azimuth. The pointing was checked frequently and was found to be stable within 3″ during all runs. Calibration was done every 12 min with standard hot/cold load absorbers, and we estimate fluxes to be accurate to within ∼10–15% in both bands. We used the 512 × 1 MHz filter banks for the 3 mm receiver and the 256 × 4 MHz filter banks for the 1 mm receivers. As part of the data reduction, we dropped all scans with distorted baselines, subtracted linear baselines from the remaining spectra, and then rebinned to a velocity resolution of 50 km s^{-1}. The remaining useable "on-source" time is 11.0 hr for the CO(6–5) and 8.1 hr for the [N II]$_{205\,\mu m}$ observations. The conversion factors from K (T_A^* scale) to Jy at our observed frequencies are 6.1 Jy K^{-1} at 3 mm and 7.6 Jy K^{-1} at 1 mm. We reached an rms noise of 0.2 mK (1.2 mJy) for CO(6–5) and of 0.17 mK (1.3 mJy) for the [N II]$_{205\,\mu m}$ observations. In this letter, we express line luminosities both based on the source's flux density ($L_{CO/[N\,II]}$ in units of $L_{\odot}$) and the source's brightness temperature ($L'_{CO/[N\,II]}$ in units of K km s^{-1} pc^2). The reader is referred to the review by Solomon & Vanden Bout (2005, their Equations (1) and (3)) for a derivation of these quantities.

3. RESULTS

3.1. CO(6–5) Observations

The CO(6–5) spectrum is shown in Figure 1. The line is detected and Gaussian fitting gives a redshift of $z = 6.4187 \pm 0.0002$, a peak flux density of 2.42 mJy (0.4 mK), a line width of 430 ± 100 km s^{-1}, leading to a flux integral of 1.12 ± 0.3 Jy km s^{-1}. Our peak flux is in good agreement with the measurement by Bertoldi et al. (2003b) using the Plateau de Bure interferometer (PdBI); however our line-width is larger (430 km s^{-1} vs. 279 km s^{-1}), leading to a flux integral that is 50% higher than the one quoted by Bertoldi et al. We attribute the difference to the lower signal-to-noise ratio of our observations. Adopting our measurements, we derive a CO(6–5) line luminosity of $L'_{CO} = 4.2 \pm 1.0 \times 10^{10}$ K km s^{-1} pc^2, or $L_{CO(6-5)} = 4.4 \pm 1.0 \times 10^8\,L_{\odot}$.

3.2. [N II] Observations

The [N II]$_{205\,\mu m}$ spectrum is shown in Figure 2. No line emission is detected at the sensitivity of our observations (1.3 mJy in a 50 km s^{-1} channel). If we assume a linewidth of 300 km s^{-1} this results in a 1σ rms of 0.53 mJy. The 3σ upper

Table 1
High-Redshift [N II] Limits from the Literature

Source	S([N II]$_{205\,\mu m}$)[a] Jy km s^{-1}	$L_{[N\,II]205}$ $10^8\ L_\odot$	L_{FIR} $10^{12}\ L_\odot$	$L_{[N\,II]205}/L_{FIR}$	Reference
Cloverleaf	<26.7	<4.6[b]	5.6[b]	<8.2 10^{-5}	Benford (1999)
APM08279	<5.1	<4.6[c]	4.6[c]	<1.0 10^{-4}	Krips et al. (2007)
4C41.17	<120	<447	15	<3.0 10^{-3}	Ivison & Harrison (1996)
J1148+5251	<0.48	<4.0	22	<2.0 10^{-5}	this study

Notes.
[a] 3σ upper limits for the following line-widths: Cloverleaf: 416 km s^{-1} (Barvainis et al. 1997; Weiß et al. 2003, 2005), APM 08279: 480 km s^{-1} (Downes et al. 1999), 4C41.17: 1000 km s^{-1} (de Breuck et al. 2005).
[b] Corrected for a lensing magnification factor of $\mu = 11$ (Venturini & Solomon 2003).
[c] Assuming L_{FIR} of the "cold" dust component (Weiß et al. 2007a), corrected for a lensing magnification of $\mu = 4.2$ (Riechers et al. 2009).

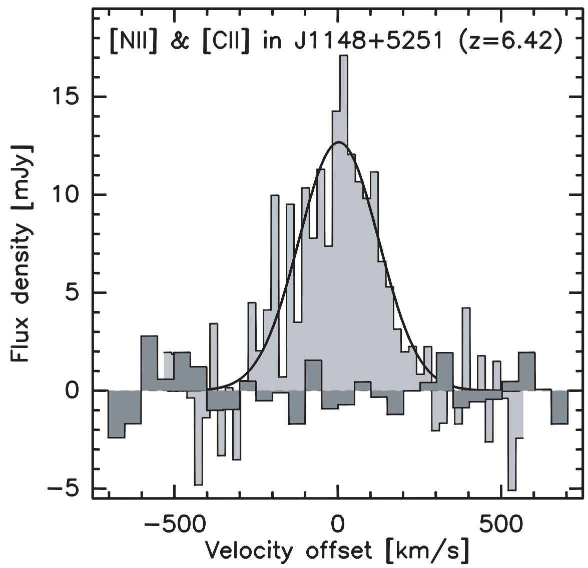

Figure 3. Comparison of the [N II]$_{205\,\mu m}$ nondetection towards J1148+5251 and the [C II] emission (continuum subtracted) in the same source (Walter et al. 2009).

limit for the integrated flux thus is 3×0.53 mJy $\times$ 300 km s^{-1} = 0.48 Jy km s^{-1}. This translates to a 3σ upper limit for the [N II]$_{205\,\mu m}$ line luminosity of $L'_{[N\,II]} < 4.0 \times 10^9$ K km s^{-1} pc^2, or $L_{[N\,II]} < 4.0 \times 10^8\ L_\odot$. The $L_{[N\,II]}/L_{FIR}$ flux ratio is thus $< 2 \times 10^{-5}$ and the $L_{[N\,II]}/L_{CO(6-5)}$ ratio is < 0.9.

4. SUMMARY AND DISCUSSION

4.1. Comparison to [C II] and Implications

The ionization potential of carbon of 11.3 eV is below that of hydrogen (13.6 eV), whereas the one for nitrogen is above that value (14.53 eV). The [N II]$_{205\,\mu m}$ and [C II] transitions have nearly identical, low critical densities ([N II]$_{205\,\mu m}$: 44 cm^{-3}, [C II]: 46 cm^{-3}, assuming an electron temperature of 8000 K, e.g. Oberst et al. 2006), i.e. their line ratio is given by the N^+/C^+ abundance ratio in the ionized medium. As pointed out by Oberst et al. (2006), this ratio is insensitive to the hardness of the radiation field as the energy levels of the next ionization states (N^{++} and C^{++}) are also similar (29.6 and 24.4 eV, respectively).

Our [N II]$_{205\,\mu m}$ observations are overplotted on the [C II] spectrum obtained at the PdBI (Walter et al. 2009) in Figure 3. The integrated flux of the [C II] measurement is $I_{[C\,II]}$ = 3.9 ± 0.3 Jy km s^{-1}, i.e. an order of magnitude higher than our [N II]$_{205\,\mu m}$ upper limit. In terms of luminosities, the [C II]

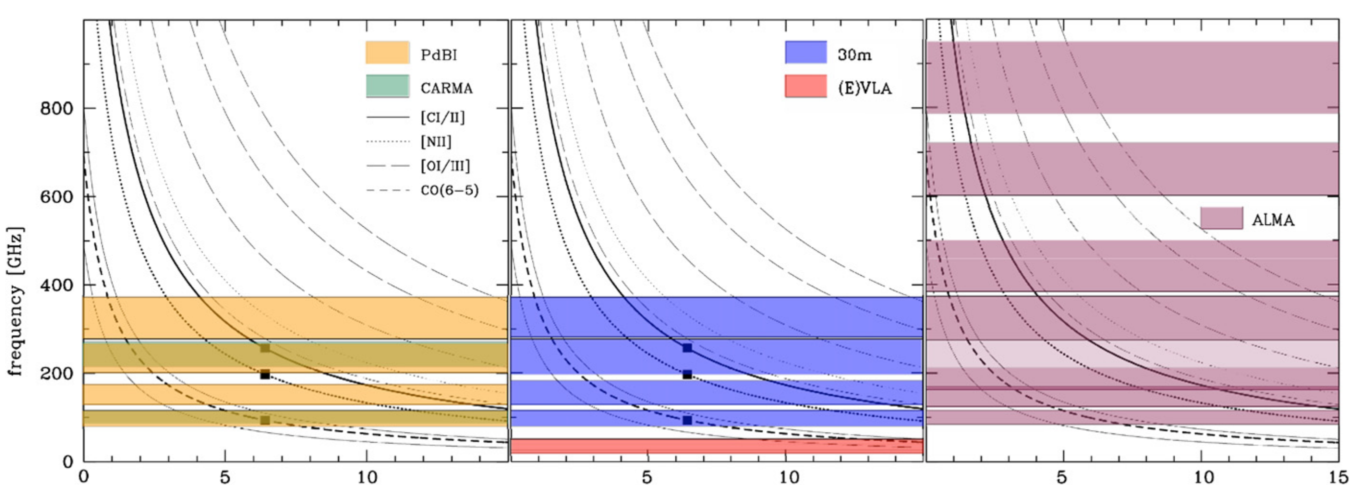

Figure 4. Frequency coverage of redshifted fine structure lines for some current (and future) key telescopes as a function of redshift. The following lines are plotted (in order of increasing frequency, given in GHz]): CIν492.2, CO(6–5)ν691.5, CIν809.3, [N II]ν1461.1 (=[N II]$_{205\,\mu m}$), [C II]ν1900.5, [O I]ν2060, [N II]ν2460, [O III]ν3393, [O I]ν4745, [O III]ν5786). The left panel shows the coverage for the PdBI and CARMA, the middle panel the respective coverages for the EVLA and the IRAM 30 m telescope and the right panel for ALMA (bands 2–9; band 5 is not fully funded and thus appears in lighter color). The three black points in the left and middle panels highlight the positions of the transitions in J1148+5251 discussed in this Letter (CO(6–5), [N II]$_{205\,\mu m}$ and [C II]).

luminosity is $L_{[\mathrm{C\,II}]} = 4.69 \pm 0.35 \times 10^9\,L_\odot$, a factor of 12 higher than the our upper limit for $L_{[\mathrm{N\,II}]}$. Our derived upper limit for the [C II]/[N II]$_{205\,\mu\mathrm{m}}$ flux ratio thus is comparable to the values found in the Milky Way (Wright et al. 1991) and M 82 (Petuchowski et al. 1994) and sets tighter limits on the [C II]/[N II]$_{205\,\mu\mathrm{m}}$ ratio than previous measurements at high redshifts (Table 1). Given the nondetection of the [N II]$_{205\,\mu\mathrm{m}}$ line in J1148+5251 and in other sources at high redshift we can only speculate whether or not high-z detections are within reach of currently operating observatories.

4.2. *Outlook*

Probing back into the epoch of reionization ($z > 7$), forbidden atomic fine-structure lines will likely be the only means by which to directly constrain the star-forming interstellar medium using (sub-)millimeter interferometers. This is due to the fact that only very high rotational transitions of CO can be observed at these redshifts using (sub-)millimeter facilities. However, strong emission from the highest ($J > 6$) CO levels requires very highly excited gas (either due to high kinetic temperatures, high densities, or both) that is typically not present in large quantities in normal star-forming environments (e.g., Daddi et al. 2008). Therefore high-J CO lines are faint and difficult to detect in such systems. Recent studies of the CO excitation in high-redshift galaxies have shown that the CO excitation ladder ("CO SEDs") peak at around $J \sim 6$ for QSOs and $J \sim 5$ for submillimeter galaxies (Weiß et al. 2005; 2007a, 2007b; Riechers et al. 2006).

Figure 4 shows which atomic fine-structure lines can be observed in a given frequency band of some (present and future) telescopes as a function of redshift. The CO(6–5) transition (which lies close to the peak of the highly excited QSOs) is also shown for comparison. It is obvious from this figure that, at $z > 7$, the atomic fine structure lines will be critical probes to constrain the properties of the interstellar medium using (sub-) millimeter instruments. Redshifted mm-wavelength molecular line observations have so far only probed the molecular medium of the target sources. Fine-structure lines of various species, and in particular their luminosity ratios, will also yield information on the neutral and ionized gas that is more dilute.

Even though we have not detected the [N II]$_{205\,\mu\mathrm{m}}$ line in our observations, we have reached a limit that is consistent with what is found in our Galaxy and in the starburst galaxy M 82. This may indicate that we are close to being able to detect atomic fine-structure lines other than [C II] at high redshift; however, it is not clear if detections can be obtained given currently operating facilities. In the Atacama Large Millimeter/submillimeter Array (ALMA) era, these lines will provide the fundamental tools needed to constrain the physical properties of the star-forming ISM in the earliest epoch of galaxy formation. These observations will then complement fine-structure line measurements in the nearby universe using future airborne and space missions (e.g., SAFIRE on SOFIA and, e.g., PACS onboard the *Herschel Space Observatory*).

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