A SENSITIVE SEARCH FOR [NII]$_{205\mu m}$ EMISSION IN A Z=6.4 QUASAR HOST GALAXY

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ABSTRACT

We present a sensitive search for the $^3P_2 \rightarrow ^3P_0$ ground state fine structure line at 205 microns of ionized nitrogen ([NII]$_{205\mu m}$) 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 [NII]$_{205\mu m}$ luminosity limit of $L_{[NII]} < 4.0 \times 10^8 L_{\odot}$ and a $L_{[NII]}/L_{FIR}$ 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 [CII] 158 micron line strength, we derive an upper limit for the [NII]$_{205\mu m}$/[CII] line luminosity ratio of $\sim 1/10$ in J1148+5251. Our upper limit for the [CII]/[NII]$_{205\mu m}$ ratio is similar to the value found for our Galaxy and M82 (the only extragalactic system where the [NII]$_{205\mu m}$ line has been detected to date). Given the non-detection of the [NII]$_{205\mu m}$ line we can only speculate whether or not high-z detections are within reach of currently operating observatories. However, [NII]$_{205\mu m}$ 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 (ALMA), for which the highly excited rotational transitions of CO will be shifted outside the accessible (sub–)millimeter bands.

Subject headings: galaxies: active, starburst, formation, high redshift — cosmology: observations — radio lines: galaxies

1. INTRODUCTION

Forbidden atomic fine structure transitions are important coolant lines of the interstellar medium (ISM). They provide effective cooling in cold regions where allowed atomic transitions can not 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 ([CII]) at 158 microns. Other main cooling lines are the oxygen [OI] (63 microns) and [OIII] (at 52 and 88 microns) lines, as well as the nitrogen [NII] lines at 122 and 205 microns (hereafter [NII]$_{205\mu m}$). 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 interstellar UV radiation field, photon dominated regions [PDRs], temperature, gas density and mass, e.g., Petuschowski & Bennett 1993, van der Werf 1999). As the ionization potential of carbon is 11.3 eV (hydrogen: 13.6 eV), [CII] 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 [NII]$_{205\mu m}$ 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 [CII], thus potentially providing complementary information on the origin of the [CII] emission (e.g. Oberst et al. 2006).

Given the poor atmospheric transmission at mid-/far–infrared wavelengths most of 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 [CII] 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 [NII]$_{205\mu m}$ line are scarce. The line was first detected by FIRAS aboard COBE in the Milky Way (Wright et al. 1991), where a global [CII]/[NII]$_{205\mu m}$ flux ratio of 10.4±1 was observed (first laboratory measurements were obtained by Brown et al. 1994). The [NII]$_{205\mu m}$ line was later detected in the Galactic HII 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 (us–

8 This is due to the fact that [CII] was accessible with the Infrared Space Observatory Long Wavelength Spectrometer (ISO/LWS, Clegg et al. 1996) whereas [NII]$_{205\mu m}$ was not.
Fig. 1.— The CO(6–5) line in J1148+5251 from the data that were taken in parallel to the [NII]205µm observations. Velocities are given offset to the tuned redshift of z = 6.4189. The best Gaussian fit is overplotted as a solid curve (see Sec. 3.1 for fit parameters).

Fig. 2.— Spectrum of the [NII]205µm observations towards J1148+5251 of the velocity and redshift range (lower and upper x-axis, respectively), expected for the [NII]205µm line. The line is not detected. Fluxes were typically 130 K at 3mm and ~210 K at 1mm. 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 3mm receiver and the 256 × 4 MHz filter banks for the 1mm 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 [NII]205µm observations. The conversion factors from K (T∗)−1 to Jy at our observed frequencies are 6.1 Jy K⁻¹ at 3mm and 7.6 Jy K⁻¹ at 1mm. 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 [NII]205µm observations. In this letter we express line luminosities both based on the source’s flux density (L_{CO}/[NII] in units of L_⊙), and the source’s brightness temperature (L′_{CO}/[NII] in units of K km s⁻¹ pc²). 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 Fig. 1. The line is detected and Gaussian fitting gives a redshift of z = 6.4187±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 ±10^{10} K km s⁻¹ pc², or

| Redshift | Velocity Offset [km s⁻¹] | Flux density [mJy] |
|----------|--------------------------|-------------------|
| J1148+5251 | CO(6–5)                |                  |

- System temperatures were typically 130 K at 3mm and ~210 K at 1mm.
- Data were taken with a wobbler rate of 0.5 Hz and a wobbler throw of 50° in azimuth.
- Calibration was done every 12 min with standard hot/cold load absorbers.

2. OBSERVATIONS

J1148+5251 (z = 6.4189, Bertoldi et al. 2003b) was observed with the IRAM 30m telescope in March and April 2007 in good weather conditions. We used the AB and CD receiver setups, with the AB receivers tuned to CO(6–5) (3mm band, ν_{obs} = 93.20426 GHz, ν_{rest} = 691.473 GHz) and the C/D receivers simultaneously tuned to [NII]205µm (1mm band, ν_{obs} = 196.9472 GHz, ν_{rest} = 1461.132 GHz, Brown et al. 1994). System temperature was tuned to [NII]691.473 GHz) and the C/D receivers simultaneously tuned to CO(6–5) (3mm band, ν_{obs} = 93.20426 GHz, ν_{rest} = 691.473 GHz) and the C/D receivers simultaneously tuned to [NII]205µm (1mm band, ν_{obs} = 196.9472 GHz, ν_{rest} = 1461.132 GHz, Brown et al. 1994). System temperature...
3.2. \([\text{NII}]\) observations

The \([\text{NII}]\)\textsubscript{205\,\mu m} spectrum is shown in Fig. 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 3\(\sigma\) upper limit of 0.53 mJy. The 3\(\sigma\) upper limit for the integrated flux thus is 3\times10^{-3}\,\text{Jy}\,\text{km}\,\text{s}^{-1}=0.48\,\text{Jy}\,\text{km}\,\text{s}^{-1}. This translates to a 3\(\sigma\) upper limit for the \([\text{NII}]\)\textsubscript{205\,\mu m} line luminosity of \(L'_{\text{[NII]}}<4.0\times10^8\,\text{K}\,\text{km}\,\text{s}^{-1}\,\text{pc}^2\), or \(L_{\text{[NII]}}<4.0\times10^8\,L_{\odot}\). The \(L_{\text{[NII]}}/L_{\text{FIR}}\) flux ratio is thus \(<2\times10^{-5}\) and the \(L_{\text{[NII]}}/L_{\text{CO}\,(6-5)}\) ratio is \(<0.9\).

4. SUMMARY AND DISCUSSION

4.1. Comparison to \([\text{CII}]\) 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 \([\text{NII}]\)\textsubscript{205\,\mu m} and \([\text{CII}]\) transitions have nearly identical, low critical densities (\([\text{NII}]\)\textsubscript{205\,\mu m}: 44 cm\(^{-3}\), \([\text{CII}]\): 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 \([\text{NII}]\)\textsubscript{205\,\mu m} observations are overplotted on the \([\text{CII}]\) spectrum obtained at the PdBI (Walter et al. 2009) in Fig. 3. The integrated flux of the \([\text{CII}]\) measurement is \(I_{\text{[CII]}=}3.9\pm0.3\,\text{Jy}\,\text{km}\,\text{s}^{-1}\), i.e. an order of magnitude higher than our \([\text{NII}]\)\textsubscript{205\,\mu m} upper limit. In terms of luminosities, the \([\text{CII}]\) luminosity is \(L_{\text{[CII]}=}4.69\pm0.35\times10^8\,L_{\odot}\), a factor of 12 higher than the our upper limit for \(L_{\text{[NII]}}\). Our derived upper limit for the \([\text{CII}]\)/\([\text{NII}]\)\textsubscript{205\,\mu m} flux ratio thus is comparable to the values found in the Milky Way (Wright et al. 1991) and M82 (Petricchowski et al. 1994) and sets tighter limits on the \([\text{CII}]\)/\([\text{NII}]\)\textsubscript{205\,\mu m} ratio than previous measurements at high redshifts (Table 1). Given the non–detection of the \([\text{NII}]\)\textsubscript{205\,\mu 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 \(J\sim6\) for QSOs and \(J\sim5\) 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 instru–
ments. 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 [NII] $\nu_{205\mu m}$ line in our observations, we have reached a limit that is consistent with what is found in our Galaxy and in the starburst galaxy M82. This may indicate that we are close to being able to detect atomic fine structure lines other than [CII] at high redshift — however it is not clear if detections can be obtained given currently operating facilities. In the 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 HERSCHEL).

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