

Observations in the 1.3 and 1.5 THz Atmospheric Windows with the Receiver Lab Telescope

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Abstract—The Receiver Lab Telescope (RLT) is a ground-based terahertz telescope; it is currently the only instrument producing astronomical data between 1 and 2 THz. The capabilities of the RLT have been expanding since observations began in late 2002. Initial observations were limited to the 850 GHz and 1.03 THz windows due to the availability of solid state local oscillators. In the last year we have begun observations with new local oscillators for the 1.3 and 1.5 THz atmospheric windows. These oscillators provide access to the $J = 11 \rightarrow 10$ and $J = 13 \rightarrow 12$ lines of ^{12}CO at 1.267 and 1.497 THz, as well as the [N II] line at 1.461 THz. We report on our first measurements of these high CO transitions, which represent the highest-frequency detections ever made from the ground. We also present initial observations of [N II] and discuss the implications of this non-detection for the standard estimates of the strength of this line.

I. INTRODUCTION

Atmospheric absorption prevents astronomical observations from the ground at frequencies between 1 and 10 THz (300–30 μm), with the dominant contributor to the opacity being tropospheric water vapor. However, towards the ends of this frequency interval it is possible to find atmospheric windows at very dry locations. In particular, atmospheric transmission measurements between 1 and 3.5 THz show that a few strong windows open up under extremely dry conditions [1], [2]. An example of the atmospheric transmission at a very dry site under the best conditions is shown in Figure 1.

The Receiver Lab Telescope (RLT) is a ground-based terahertz telescope, located 40 km north of the ALMA site in northern Chile. The site, at an elevation of 5525 meters, shows some of the best terahertz weather in the world, with transmission as high as 50% observed in three supra-terahertz windows in the last year. The RLT is equipped with phonon-cooled HEB waveguide mixers for observations in four atmospheric windows between 800 GHz and 1.6 THz. Within these windows we have access to numerous atomic, molecular, and ionic lines, including seven transitions of ^{12}CO and ^{13}CO , the 809 GHz transition of [C I], and the 1.46 THz transition of [N II]. These bright lines are relevant to many topics in astronomy including star formation, the interstellar medium, and starburst/luminous infrared galaxies. Other, weaker lines that are unique to terahertz astronomy are also extremely interesting, in particular the 1.01 THz transitions of NH^+ , an undetected molecular ion in the formation chain of ammonia,

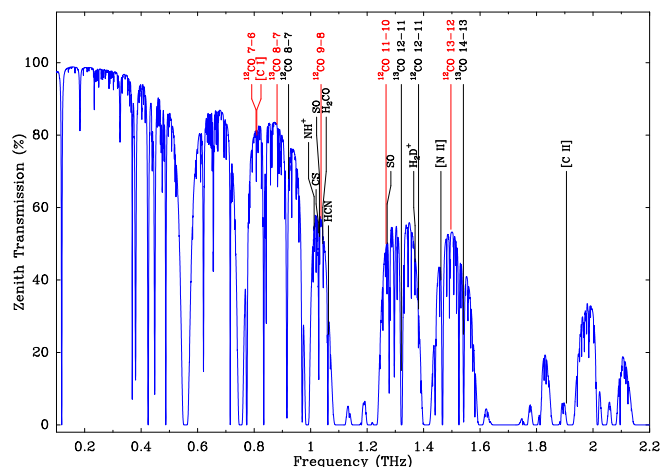


Fig. 1. Atmospheric transmission on Cerro Sairecabur on 24 January 2005 based on data from the Receiver Lab Fourier Transform Spectrometer (FTS) [2]. The FTS measures the sky emission spectrum from 300 GHz to 3.5 THz at 3 GHz resolution; this spectrum is then fit to an atmospheric model, which can be used to examine the transmission at full resolution. The model indicates that at the time of the measurement the precipitable water vapor (PWV) was only 93 μm . Several astronomically interesting lines are plotted for reference, including those detected by the RLT (in red). The few percent transmission at the 1.9 THz frequency of the [C II] line is unusual for this site, but suggests that even drier sites may provide access to this important line from the ground.

and the 1.37 THz ground-state transition of H_2D^+ , a tracer of the molecule responsible for chemistry inside cold molecular cores. Astronomical interest in these and other lines has driven the development of several instruments for ground-based terahertz astronomy, as is discussed further in Section IV. Due to the atmospheric limitations at nearly all telescope sites, most of the lines in the RLT bands have not been observed from the ground (excepting, rarely, the 1.037 THz CO $J = 9 \rightarrow 8$ line [3]–[5]), and received little attention from the Kuiper Airborne Observatory (KAO) before it was decommissioned in 1995. Until the launch of Herschel in 2007–2008, or possibly the installation of the first heterodyne instruments on the Stratospheric Observatory For Infrared Astronomy (SOFIA, 2006–2007), these lines will only be observable from ground-based telescopes like the RLT or APEX.

The RLT and its first observations in the 1.03 THz window have been described in previous editions of these proceedings and elsewhere [5]–[8]. Here we discuss the first measurements

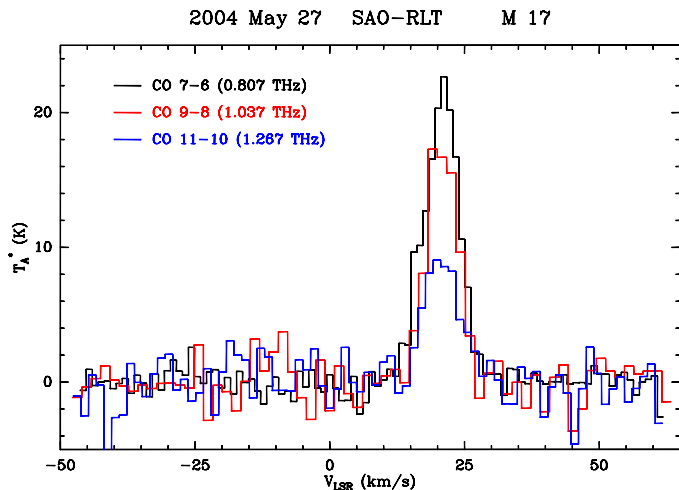


Fig. 2. CO emission detected in M17 from the RLT on 2004 May 27. At the time of this measurement, the $^{12}\text{CO } J = 11 \rightarrow 10$ line was the highest frequency line ever detected from the ground.

made in the 1.3 and 1.5 THz windows, the highest-frequency astronomical detections made from the ground at radio frequencies, along with our first attempt at measuring the [N II] line at 1.46 THz.

II. OBSERVATIONS AT 1.3 AND 1.5 THZ

In its first 18 months of operation the RLT was confined to observations in the 850 GHz and 1.03 THz windows. For much of this time we possessed a local oscillator (LO) source for the 1.3 THz window, but were prevented from using it by the RF bandwidth of the waveguide-coupled hot-electron bolometer mixer installed at the telescope. In May 2004 we installed a mixer with slightly larger RF bandwidth, sacrificing some performance in the low frequency windows to enable operation at 1.3 THz. On May 27 we obtained the first detection of an astronomical line in the 1.3 THz window, $^{12}\text{CO } J = 11 \rightarrow 10$ at 1.267 THz. This line, along with two lower transitions observed in the same source on the same night, is shown in Figure 2. All three lines have the same velocity extent, as is expected for optically thick transitions, while the $J = 11 \rightarrow 10$ emission is weaker than the lower lines suggesting that the gas temperature is not high enough to thermalize the 365 K $J = 11$ rotational state.

Since this first observation, the RLT has routinely observed the CO $J = 11 \rightarrow 10$ line in other sources. The atmospheric conditions on Sairecabur allow regular observations of many high-frequency lines ($^{12}\text{CO } J = 7 \rightarrow 6$, $J = 9 \rightarrow 8$, and $J = 11 \rightarrow 10$, $^{13}\text{CO } J = 8 \rightarrow 7$, and [C I]) that are difficult or impossible to detect at other observatories. These lines allow us to characterize the large-scale gas conditions in very warm sources where the lower energy transitions available from other telescopes are insensitive to the temperature.

RLT observations moved to even higher frequency in December 2004 with the arrival of an LO and receiver for 1.5 THz. The LO is on loan from the Jet Propulsion Laboratory and was constructed as a prototype for the HIFI instrument of the Herschel satellite [9]. The receiver was built and tested

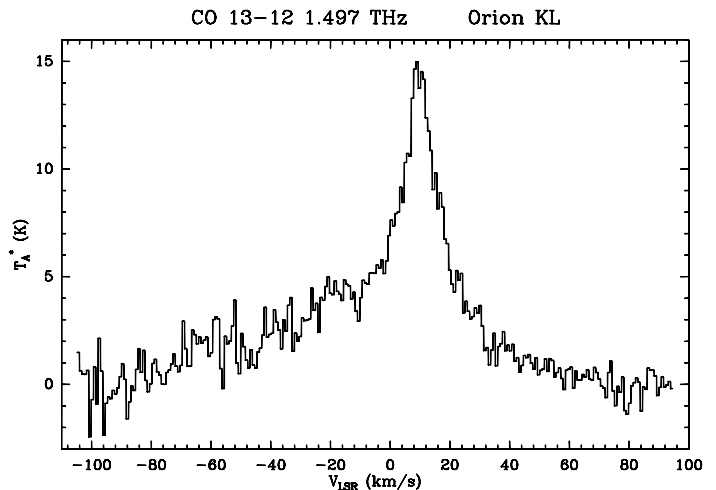


Fig. 3. $^{12}\text{CO } J = 13 \rightarrow 12$ (1.497 THz) emission from Orion-KL, as measured with the RLT on 2004 December 17. The flux scale is somewhat uncertain because the telescope efficiency has not yet been measured at this frequency, but the amplitude matches higher frequency observations made with the KAO. This now stands as the highest frequency line detected from the ground.

in the Receiver Lab and some of the testing is described elsewhere in these proceedings [10]. As of this writing, only two marginal nights have been available for observations at 1.5 THz with this receiver. Most of this time was reserved for the [N II] line, but several minutes were spent observing $^{12}\text{CO } J = 13 \rightarrow 12$ at 1.497 THz to confirm that the receiver was functioning properly. A detection of this line in Orion-KL, using only 4 minutes on-source integration time, is shown in Figure 3. This detection represents the highest frequency line measured from the ground and the only line observed in the 1.5 THz atmospheric window.

III. OBSERVATIONS OF [N II]

The 1.4611 THz [N II] line is one of the most important targets of ground-based terahertz astronomy. The FIRAS instrument [11] on the COBE satellite, which mapped the entire sky at low-angular and spectral resolution (7° beam, 5.4 GHz maximum spectral resolution), found that the [N II] lines at 1.46 and 2.46 THz (205 and 122 μm) were the brightest lines in the Galaxy after the 1.90 THz (157 μm) line of [C II] [12]–[14]. These two lines can be used together as a density probe for gas up to $\sim 10^3 \text{ cm}^{-3}$, typical of the diffuse warm ionized medium [15]. The higher-frequency [N II] line has been studied in this galaxy and others at angular resolution comparable to that of the RLT (but much lower velocity-resolution) using the Long-Wavelength Spectrometer on the Infrared Space Observatory satellite [16]. This instrument was not sensitive to the 1.46 THz line and it is therefore poorly studied: there are only two published detections, both from the KAO [17], [18].

Ground-based telescopes at exceptional locations like the South Pole and the Atacama sites have access to this line in the 1.5 THz window, although the transmission is somewhat degraded by a nearby strong O_2 line at 1.4668 THz (at the line

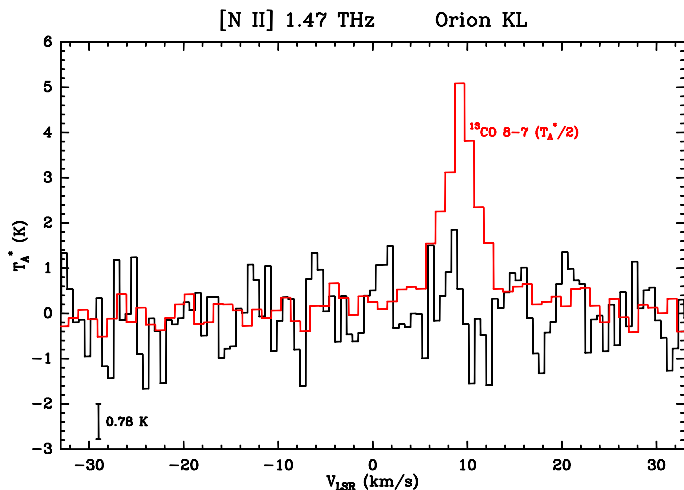


Fig. 4. [N II] in Orion-KL, with $^{13}\text{CO } J = 8 \rightarrow 7$ (0.881 THz) overplotted as a rough velocity reference. The spectral rms is shown in the lower left.

center, $\tau_{\text{O}_2} \simeq 130$ for the South Pole and Sairecabur). The effect is worse at lower altitude where pressure-broadening increases the O_2 line width; at the South Pole it contributes an opacity of ~ 0.35 at the [N II] frequency, compared to ~ 0.16 at Sairecabur¹. With our new 1.5 THz LO the RLT now has access to [N II], and observations of this line are now our key science goal.

As mentioned above, the 1.5 THz receiver arrived at the RLT in December 2004 shortly before the end of the observing year. The two nights available were somewhat below average for observations in this window, with transmission of 11-13% and 15-16%, respectively, at 1.461 THz. Orion-KL was well placed in the sky for our observations and contains an extended region of ionized gas, the edges of which contain strongly excited CO (see Figure 3), so we used this as our main source. We also briefly attempted NGC 2024 IRS5 and G270.3+0.8, using much less integration time and did not detect [N II] emission. The resulting spectrum at the [N II] frequency is shown in Figure 4, with $^{13}\text{CO } J = 8 \rightarrow 7$ overplotted to indicate the velocity extent of another optically thin line in this source (although the CO emission traces slightly different gas). No detection is apparent. The observations of Orion-KL totaled 78 minutes on source and the rms on the spectrum is around 0.8 K, although the telescope efficiency has not been measured at this frequency and could be different from our (conservatively low) assumption. Higher efficiencies would place even more stringent limits on the line strength.

The lack of a detection of this line comes as something of a surprise to us; many groups have proposed ambitious studies of [N II] and it is expected to be quite bright. Of course, because there is little data on its strength on angular scales smaller than the large COBE beam one must make many assumptions to arrive at a predicted strength. The simplest argument (and one that is frequently used) is to take the [C II] line strength measured from the KAO and divide by ten, the

¹Based on calculations performed with the *am* atmospheric model [19], available at <http://cfarx6.cfa.harvard.edu/am>

average of [C II]/[N II] as observed by COBE [12]. In the case of Orion-KL the velocity-resolved [C II] observations of [20] suggest a brightness temperature of around 5 K, easily measured with our sensitivity. Our non-detection suggests that this common argument is too simplistic. In fact, the average over the whole sky is not representative of the [N II] and [C II] emission in a given smaller region because the two lines trace different gas. The [N II] line can be expected to be present over much of the sky at a low level, while the [C II] emission has a diffuse component but is most often found on the surfaces of molecular clouds, which fill a much smaller fraction of the sky. When averaged over the whole sky at low resolution, this difference in filling factor suppresses the [C II]/[N II] ratio, making this argument unreliable. A better estimate of the emission in a small patch of sky can be made from KAO observations of a somewhat analogous source, G333.6-0.2 [17]. Both [C II] and [N II] were detected in this source, with a line ratio of $[\text{C II}]_{1.46\text{THz}}/[\text{N II}]_{1.46\text{THz}} = 50$. Given this ratio, we may expect something closer to 1 K in Orion-KL, which is entirely consistent with our observations.

RLT observations have been suspended since January for the summer wet season known locally as “Bolivian Winter”. Operations resume in late April or early May with a new list of target sources. In particular, we are using ISO observations of the 2.46 THz line of [N II] to select our sources. Although COBE observations suggest that the Galactic average $[\text{N II}]_{1.46}/[\text{N II}]_{2.46}$ line ratio is approximately unity [14], in the individual sources we observe it is likely to be lower. In the high-density limit ($n > 10^3 \text{ cm}^{-3}$) this ratio is around 0.1, and most gas in discrete sources will be at or above this density threshold. The ISO observations are not velocity resolved in most sources so the measured line fluxes cannot be directly inverted to obtain a peak line strength, but many sources with [N II] emission stronger than that observed in Orion have been obtained in the appropriate hour angle range.

IV. PROSPECTS FOR THz ASTRONOMY FROM THE GROUND

For the next two or more years, terahertz astronomy will only be possible from the ground. The Receiver Lab Telescope has now demonstrated observations of astronomical line radiation in all three of the atmospheric windows between 1.0 and 1.6 THz. From our site and nearby sites in northern Chile, the 1.5 THz window is likely to be the highest frequency window that will be regularly usable for astronomy. Observations of the transmission on very dry nights (multiple instances of PWV below $200 \mu\text{m}$, including the $93 \mu\text{m}$ shown in Figure 1, have been observed in the last year) suggest that from an even drier site one may be able to move to higher frequencies, including observations of the [C II] line at 1.9 THz. Proposed observations from Antarctic Dome A, for which measurements of submillimeter opacity are not yet available, may be able to make this step to higher frequencies if PWV predictions for this site are accurate.

Ground-based measurements will continue to have an important place in terahertz astronomy even in the era of SOFIA

and Herschel. First, telescopes on the ground can be much larger than is possible from airplanes or from space at similar cost. In the next year the 12-meter APEX telescope will begin observations above 1 THz with multiple receivers. Planning for an even larger telescope, the 25-meter Caltech-Cornell Atacama Telescope (CCAT), are underway. CCAT would achieve angular resolution around $2''$ at 1.5 THz, better than is now available from any single-aperture radio telescope, and almost an order of magnitude better than will be obtained from SOFIA or Herschel. Moreover, Herschel will lack receiver coverage between 1.25 and 1.41 THz, a gap that lines up well with the 1.3 THz atmospheric window. Sensitive observations from the ground, particularly with the angular resolution available from these larger telescopes, will access important science that Herschel will miss.

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