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

Daniel P. Marrone, Raymond Blundell, Edward Tong, Scott N. Paine, Denis Loudkov
Harvard-Smithsonian Center for Astrophysics
Email: dmarrone@cfa.harvard.edu

Jonathan H. Kawamura
Jet Propulsion Laboratory,
California Institute of Technology

Daniel Lühr, Claudio Barrientos
Universidad de Chile

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, and the 1.37 THz ground-state transition of H$_2$D$^+$, 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 [5]–[8]. Here we discuss the first measurements

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.
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, $^{12}$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 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 ($^{12}$CO $J = 7 \rightarrow 6, J = 9 \rightarrow 8,$ and $J = 11 \rightarrow 10, ^{13}$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 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 $^{12}$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$^\circ$ beam, 5.4 GHz maximum spectral resolution), found that the [N II] lines at 1.46 and 2.46 THz (205 and 122 $\mu$m) were the brightest lines in the Galaxy after the 1.90 THz (157 $\mu$m) line of [C II] [12]–[14]. These two lines can be used together as a density probe for gas up to $\sim 10^5$ 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 $^{13}$CO $J = 8 \rightarrow 7$ (0.881 THz) overplotted as a rough velocity reference. The spectral rms is shown in the lower left.

center, $\tau_{O_2} \approx 130$ 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 $\sim 0.35$ at the [N II] frequency, compared to $\sim 0.16$ at Sairecabur$^1$. 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 5), 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 $^{13}$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 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 [C II]/[N II]$_{1.46\,THz} = 50$. 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 [N II]$_{1.46\,THz}$/[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 ($n > 10^3$ 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 $\mu$m, including the 93 $\mu$m shown in Figure 11 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.
ACKNOWLEDGMENT

The authors thank the many current and former members of the Receiver Lab who have worked on bringing the RLT into existence and contributed to its operations in Chile, in particular, Hugh Gibson and Cosmo Papa. Site evaluation and RLT development could not have taken place without the ever present support of Irwin Shapiro, former director of the Center for Astrophysics. The project also owes a great deal to the many years of assistance provided by Jorge May and Leo Bronfman at Universidad de Chile. We also thank Imran Mehti, John Ward, and their LO team for providing us with an oscillator for 1.5 THz observations. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration. DPM acknowledges support from an NSF Graduate Research Fellowship.

REFERENCES

[1] S. Matsuhashi, H. Matsujo, J. R. Pardo, and S. J. E. Radford, “FTS Measurements of Submillimeter-Wave AtmosphericOpacity at Pampa la Bola II: Supra-Terahertz Windows and Model Fitting,” Pub. of the Astronomical Society of Japan, vol. 51, pp. 603–9, Oct. 1999.

[2] S. Paine, R. Blundell, D. C. Papa, J. W. Barrett, and S. J. E. Radford, “A Fourier Transform Spectrometer for Measurement of Atmospheric Transmission at Submillimeter Wavelengths,” Pub. of the Astronomical Society of the Pacific, vol. 112, pp. 108–118, Jan. 2000.

[3] J. R. Pardo, E. Serabyn, and J. Cernicharo, “Submillimeter atmospheric transmission measurements on Mauna Kea during extremely dry El Nino conditions: implications for broadband opacity contributions,” Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 68, pp. 419–433, Feb. 2001.

[4] J. Kawamura, T. R. Hunter, C.-Y. E. Tong, R. Blundell, D. C. Papa, F. Patt, W. Peters, T. L. Wilson, C. Henkel, G. Gol’tsan, and E. Gerchunzen, “Ground-based terahertz CO spectroscopy towards Orion,” Astronomy & Astrophysics, vol. 394, pp. 271–274, 2002.

[5] D. P. Marrone, J. Battat, F. Bensch, R. Blundell, M. Diaz, H. Gibson, T. Hunter, D. Meledin, S. Paine, D. C. Papa, R. Blundell, M. Smith, and E. Tong, “A Map of OMC-1 in CO J = 9–8,” The Astrophysical Journal, vol. 612, pp. 940–945, Sept. 2004.

[6] R. Blundell, J. W. Barrett, H. Gibson, C. Gottlieb, T. R. Hunter, R. Kimberk, S. Leiker, D. Marrone, D. Meledin, S. N. Paine, R. J. Plante, P. Riddle, M. J. Smith, T. K. Sridharan, C. E. Tong, R. W. Wilson, M. A. Diaz, L. Bronfman, J. May, A. Otarola, and S. J. Radford, “Prospects for Terahertz Radio Astronomy from Northern Chile,” in 13th International Symposium on Space Terahertz Technology, ed. C. E. Tong & R. Blundell, 2002, pp. 159–166.

[7] D. P. Marrone, R. Blundell, H. Gibson, S. Paine, D. C. Papa, and C.-Y. E. Tong, “Characterization and Status of a Terahertz Telescope,” in 15th International Symposium on Space Terahertz Technology, ed. G. Narayanan, 2004, pp. 426–432.

[8] D. Marrone et al., “A Ground-based Terahertz Observatory,” 2005, in preparation.

[9] J. Ward, F. Maiwald, G. Chattopadhyay, E. Schlecht, A. Maestrini, F. Gill, and I. Mehti, “1400–1900 GHz Local Oscillators for the Herschel Space Observatory,” in 14th International Symposium on Space Terahertz Technology, 2003, pp. 94–101.

[10] C.-Y. E. Tong, D. N. Loudovk, S. N. Paine, D. P. Marrone, and R. Blundell, “Vector Measurement of the Beam Pattern of a 1.5 THz Superconducting HEB Receiver,” in Sixteenth International Symposium on Space Terahertz Technology, 2005.

[11] D. J. Fixsen, E. S. Cheng, D. A. Cottingham, R. E. Eplee, T. Hewagama, R. B. Isaacman, K. A. Jensen, J. C. Mather, D. L. Massa, S. S. Meyer, P. D. Norrdling, S. M. Read, L. P. Rosen, R. A. Shafer, A. R. Trencholme, R. Weiss, C. L. Bennett, N. W. Bogess, D. T. Wilkinson, and E. L. Wright, “Calibration of the COBE FIRAS instrument,” The Astrophysical Journal, vol. 420, pp. 457–473, Jan. 1994.

[12] E. L. Wright, J. C. Mathcr, C. L. Bennett, E. S. Cheng, R. A. Shafer, D. J. Fixsen, R. E. Eplee, R. B. Isaacman, S. M. Read, N. W. Bogess, S. Gulkis, M. G. Hauser, M. Janssen, T. Kelsall, P. M. Lubin, S. S. Meyer, S. H. Moseley, T. L. Murdock, R. F. Silverberg, G. F. Smoot, R. Weiss, and D. T. Wilkinson, “Preliminary spectral observations of the Galaxy with a 7 deg beam by the Cosmic Background Explorer (COBE),” The Astrophysical Journal, vol. 381, pp. 200–209, Nov. 1991.

[13] C. L. Bennett, D. J. Fixsen, G. Hinshaw, J. C. Mather, S. H. Moseley, E. L. Wright, R. E. Eplee, T. Gales, T. Hewagama, R. B. Isaacman, R. A. Shafer, and K. Turpie, “Morphology of the interstellar cooling lines detected by COBE,” The Astrophysical Journal, vol. 454, pp. 587–598, Oct. 1994.

[14] D. J. Fixsen, C. L. Bennett, and J. C. Mather, “COBE Far Infrared Absolute Spectrophotometer Observations of Galactic Lines,” The Astrophysical Journal, vol. 526, pp. 207–214, Nov. 1999.

[15] P. E. Clegg, P. A. R. Ade, C. Armand, J.-P. Baluteau, M. J. Barlow, M. A. Buckley, J.-C. Berges, M. Burgdorf, E. Cau, C. Ceccarelli, R. Cerulli, S. E. Church, F. Cotin, P. Cox, P. Cruvellier, J. L. Culhane, G. R. Davis, A. di Giorgio, B. R. Diplock, D. L. Drummond, R. J. Emery, J. D. Ewart, J. Fischer, I. Furniss, W. M. Glencross, M. A. Greenhouse, M. J. Griffin, C. Gry, A. S. Harwood, A. S. Hazell, M. Joubert, K. J. King, T. Lim, R. Liseau, J. A. Long, D. Lorenzetti, S. Molinari, A. G. Murray, D. A. Naylor, B. Nisini, K. Norman, A. Omont, R. Orfei, T. J. Patrick, D. Peugniott, D. Pouliquen, M. C. Price, Nguyen-Q-Rieu, A. J. Rogers, F. D. Robinson, M. Saisse, P. Saraceno, G. Serra, S. D. Sidher, A. F. Smith, H. A. Smith, L. Spinoglio, B. M. Swinyard, D. Texier, W. A. Snowdon, N. R. Trams, S. V. Unger, and G. J. White, “The ISO Long-Wavelength Spectrometer.” Astronomy & Astrophysics, vol. 315, pp. L38–L42, Nov. 1996.

[16] S. W. J. Colman, M. R. Haas, E. F. Erickson, R. H. Rubin, J. P. Simpson, and R. W. Russell, “Detection of the N II 122 and 205 micron lines - Densities in G333.6-0.2,” The Astrophysical Journal, vol. 413, pp. 237–241, Aug. 1993.

[17] S. J. Petuchowski, C. L. Bennett, M. R. Haas, E. F. Erickson, S. D. Lord, H. R. Rubin, S. W. J. Colman, and D. J. Holenbach, “The N (II) 205 micron line in M82: The warm ionized medium,” The Astrophysical Journal, vol. 427, pp. L17–L20, May 1994.

[18] S. N. Paine, “The um Atmospheric Model,” Submillimeter Array Project, Tech. Rep. 152, 2004, http://sma-www.cfa.harvard.edu/private/memos/152-03.pdf.

[19] R. T. Boreiko, A. L. Betz, and J. Zmuidzinas, “Heterodyne spectroscopy of the 158 micron C II line in M42,” The Astrophysical Journal, vol. 325, pp. L47–L51, Feb. 1988.