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# Opportunities for Terahertz Facilities on the High Plateau

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**Abstract.** While the summit of the Antarctic Plateau has long been expected to harbor the best ground-based sites for terahertz (THz) frequency astronomical investigations, it is only recently that direct observations of exceptional THz atmospheric transmission and stability have been obtained. These observations, in combination with recent technological advancements in astronomical instrumentation and autonomous field platforms, make the recognition and realization of terahertz observatories on the high plateau feasible and timely. Here, we will explore the context of terahertz astronomy in the era of *Herschel*, and the crucial role that observatories on the Antarctic Plateau can play. We explore the important scientific questions to which observations from this unique environment may be most productively applied. We examine the importance and complementarity of Antarctic THz astronomy in the light of contemporary facilities such as ALMA, CCAT, SOFIA and (U)LDB ballooning. Finally, building from the roots of THz facilities in Antarctica to present efforts, we broadly highlight future facilities that will exploit the unique advantages of the Polar Plateau and provide a meaningful, lasting astrophysical legacy.

**Keywords.** infrared: general, submillimeter, galaxies: ISM, ISM: clouds, stars: formation, molecular processes, instrumentation: spectrographs, instrumentation: interferometers, site testing

## 1. Introduction

Terahertz (THz) radiation, from 0.5 – 5 THz (600 – 60 micrometers wavelength), is one of the last regions of the electromagnetic spectrum which remains largely unexplored. This is partly due to the opacity of the Earth's atmosphere at these frequencies and partly due to the difficulty constructing terahertz detectors, spectrometers, and telescopes. Nestled between traditional radio astronomy at cm- and mm-waves using heterodyne receivers, and the bolometer and photoconductor detectors of infrared astronomy, the terahertz regime is a technological hybrid; a confluence that often necessarily inherits the most difficult aspects of both worlds. Thus, terahertz telescopes are often built in the style of radio telescopes but with optical figure requirements akin to infrared telescopes.

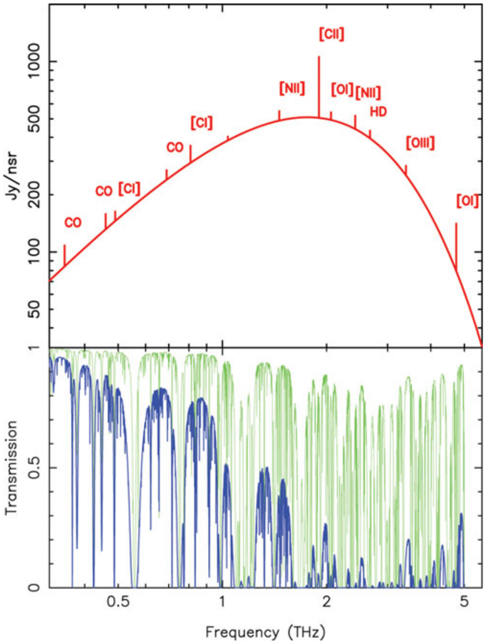

**Figure 1.** Schematic of the spectral characteristics observed toward an interstellar cloud, featuring a ∼30K continuum, an assortment of selected atomic and molecular spectral lines, underlined by exceptional atmospheric transmission observed from the ground (75 micrometers of precipitable water vapor at Dome A and Ridge A, Antarctica) (Yang *et al.* 2010) and airborne platforms such as SOFIA (8 micrometers of precipitable water vapor).

The sensitivity of terahertz telescopes hinges delicately on the water vapor content of the atmosphere above the telescope, as it does for the infrared. Heterodyne receivers are used for high resolution spectroscopy as at radio wavelengths, but the special challenges of fabricating submillimeter-scale quasioptical and waveguide structures, in addition to THz local oscillator sources, are both extreme and unique. Even the units in which terahertz astronomers speak reflect this unusual conglomeration of overlapping instrumentation – while heterodyne spectroscopists speak in units of frequency (GHz or THz), bolometer imaging cameras typically adopt wavelength units (micrometers), and the devotees of Fourier Transform Spectrometers and laboratory astrochemistry inevitably speak in wavenumbers ($\mathrm{cm}^{-1}$). New researchers in terahertz astronomy, particularly from radio or optical regimes, often find the lingual partitioning of the field practically schizophrenic.

Regardless of language, the most diagnostic and luminous spectral signatures of many common elemental species lie at terahertz frequencies. These spectral lines are signposts of star and planet formation, the evolution of matter in galaxies, the rich astrochemistry of interstellar clouds, even the prebiotic building blocks of life. Furthermore, the reprocessing of visible and ultraviolet light by dust grains in interstellar clouds makes the continuum emission of star forming regions, circumstellar (pre-planetary) disks, and entire galaxies peak at terahertz frequencies. This continuum emission is often comparable to, if not significantly larger than, starlight directly generated at visible wavelengths. The spectroscopic signatures of pivotal atoms and molecules, coupled with bright continuum emission, leads to a rich spectrum of emission and absorption lines which is uniquely diagnostic of a wide variety of astrophysical phenomena (Figure 1).

Table 1 reflects a sample of important atomic and molecular species at terahertz frequencies, along with their observability from excellent mid-latitude sites, the summit

**Table 1.** Observability of Important THz Lines

| Species | Freq (THz) | Midlatitude Ground[a] | Antarctic Ground[a] | Airborne[a] |
|---|---|---|---|---|
| C | 0.492, 0.809 | Y | Y | Y |
| CH | 0.532, 0.536 | N | Y | Y |
| $H_2O$ | 0.557, 1.113 | N | N | N |
| HCl | 0.635 | Y | Y | Y |
| $D_2H^+$ | 0.691 | Y | Y | Y |
| CO | 1.037-1.497 | N | Y | Y |
| $CH^+$ | 0.835 | M | M | Y |
| $OH^+$ | 0.909 | M | Y | Y |
| $NH_2$ | 0.953 | M | Y | Y |
| NH | 0.974 | N | M | Y |
| $NH^+$ | 1.013 | N | Y | Y |
| $H_2O^+$ | 1.115 | N | N | N |
| HF | 1.232 | N | N | Y |
| $H_2D^+$ | 1.370 | N | Y | Y |
| $N^+$ | 1.461 | N | Y | Y |
| OH | 1.835, 1.838 | N | M | Y |
| $H_2O_2$ | 1.846 | N | N | N |
| $C^+$ | 1.901 | N | M | Y |
| O | 2.060, 4.746 | N | M/N | Y |
| HD | 2.675 | N | N | Y |
| $O^{++}$ | 3.394 | N | M | Y |

*Notes:*
[a] Excellent ground-based facilities such as those on the Chilean Atacama desert host a median value of 500 μm of precipitable water vapor (PWV); the best Antarctic sites such as Ridge A and Dome A denote best quartile winter conditions of 75 micrometers precipitable water vapor (PWV). The airborne facility (SOFIA) assumes 8 micrometers at an elevation of 13 kilometers. A zenith angle of 30 degrees is assumed throughout. A "Y" label implies 25% transmission or greater, "M" implies marginal transmission of 5-25%, whereas "N" implies typical transmission of less than 5%. Atmospheric transmission computed from the *am* model (Paine & Blundell 2004).

of the Antarctic Plateau, and airborne observatories. They encompass the fine structure transitions of elemental ions and atoms, particularly those of carbon, nitrogen and oxygen; the ground state transitions of pivotal light diatomic molecules, particularly hydrides; and the low-frequency vibrational modes of heavy molecules.

## 2. The Role of the Antarctic Plateau for Terahertz Exploration

The capabilities of ground-based, airborne and space instrumentation are leading to a renaissance in terahertz astronomy. In particular, the SPIRE-FTS, PACS and HIFI instruments aboard the *Herschel* Space Observatory have expanded the reach of terahertz spectroscopy by orders of magnitude. However, the lifetime of Herschel is relatively short; breaking new scientific ground will require renewed effort in terahertz spectroscopic instrumentation. In the post-Herschel world, this field will be dominated by three major players: the Atacama Large Millimeter Array (ALMA), the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the 25-meter CCAT antenna on Cerro Chajnantor. The combination of ALMA and CCAT will provide excellent coverage of the traditional submillimeter-wave bands below 1 THz (300 μm) at high angular resolution and sensitivity, whereas SOFIA will provide access to the >1 THz universe at sub-arcminute resolution for up to 1000 hours per year (Figure 5). To maximize scientific impact, terahertz facilities on the Antarctic Plateau should complement these major facilities in a meaningful way. The exceptional atmosphere above the Ridge A and Dome A sites provides unique and important opportunities that represent expansion of capability and uniquely answer crucial astronomical questions by direct observation. Here, we present two examples that illustrate two unique classes of opportunities. The first application focuses on wide-field, large scale imaging spectroscopy of the Galaxy; the second on targeted terahertz interferometric studies of star forming regions.

### 2.1. *Large-Scale Spectroscopic Mapping of the Galaxy – the HEAT telescope at Ridge A*

The evolution of galaxies is determined to a large extent by the life cycles of interstellar clouds, as shown in Figure 2. The interstellar medium in the Galaxy is a patchy, clumpy medium that encompasses extremes of temperature and a wide range of densities (Cox 2005).

Interstellar clouds play a central role in cosmic evolution; they are simultaneously the sites of formation of all stars and planets, and the reservoirs of material that has been processed through previous generations of stars. Although they are among the coldest, least energetic objects in astronomy, they depend upon interactions with high energy photons and cosmic rays for much of their internal heating and chemical activity. They are largely comprised of molecular hydrogen and atomic helium, neither of which have accessible emission line spectra in the prevailing physical conditions in cold interstellar clouds. Thus, it is necessary to probe the nature of the cold interstellar gas via rarer trace elements. Carbon, for example, is found in ionized form ($C^+$) in neutral clouds, eventually becoming atomic (C), then molecular as carbon monoxide (CO) in dark molecular clouds. Just as there is a "carbon cycle" on the Earth, there is an equivalent life cycle of matter in the Galaxy that is traced well via carbon species. Critically, these three forms of elemental carbon are readily observable at terahertz frequencies (Table 1).

Although we are now beginning to understand star formation, the formation, evolution and destruction of molecular clouds remains shrouded in uncertainty. For example, the formation of interstellar clouds is a prerequisite for star formation, yet the process has not yet been identified observationally! Theories of cloud formation and destruction must be guided and constrained by observations of all atomic and molecular gas components and therefore should be comprised of observations spanning $C^+$, C and CO, over the full range of environments in which molecular clouds are constructed and destroyed.

After a handful of heterodyne measurements from the Kuiper Airborne Observatory (Boreiko & Betz 1991, 1995, 1997), the first landmark steps toward the dissection of Galactic interstellar material via the heterodyne measurement of the 1.9 THz line of $C^+$ were taken by the Herschel open time key program "GOT C+" (Figure 3). Analysis of diffuse clouds in a sample characterized by $C^+$ and HI emission but without CO demonstrates the presence of a significant diffuse warm, dark $H_2$ component (Langer *et al.* 2010; Velusamy *et al.* 2010; Pineda *et al.* 2010) that had been suggested by previous work (Grenier *et al.* 2005; Wolfire *et al.* 2010). The diversity of clouds that may be disentangled along even a single line of sight is nothing short of spectacular. While "GOT C+" now demonstrates what can be accomplished by combining $C^+$ emission with CO and HI maps, it is limited to 900 individual lines of sight through the Galaxy, summing to less than 0.1 square degree of sky. However fully sampled two-dimensional maps in $C^+$ and C must await dedicated survey facilities at THz frequencies.

To fill this need, the 60 centimeter aperture High Elevation Antarctic Terahertz (HEAT) telescope was installed near the summit of the Antarctic Polar Plateau, Ridge A, at 4040 meter elevation. Coupled to the UNSW-built PLATeau Observatory for Ridge A (PLATO-R), its survey operations began in January 2012 with Galaxy-wide mapping of the ${}^3P_2 - {}^3P_1$ line of atomic carbon at 809 GHz. It will be joined by the lower lying 492 GHz line of atomic carbon and the 1900 GHz line of ionized carbon in 2013. These

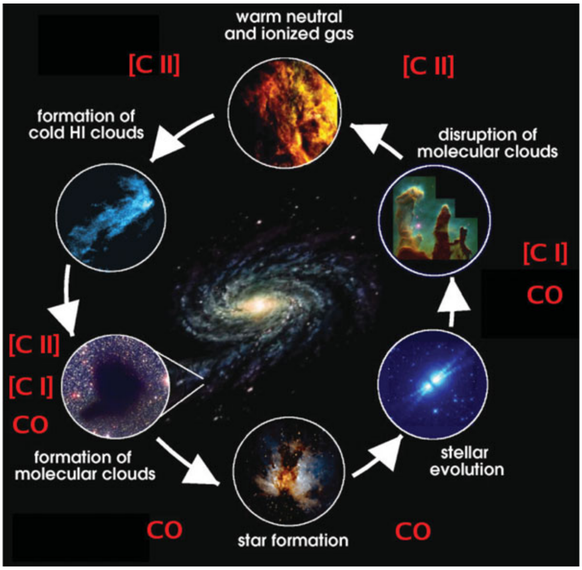

**Figure 2.** Sketch of the various stages in the life cycle of interstellar clouds.

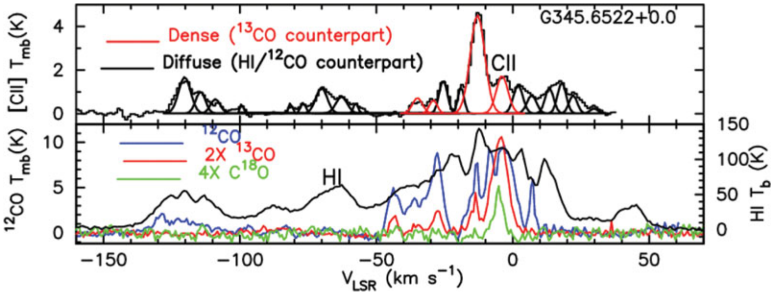

**Figure 3.** Spectra of $C^+$ obtained with Herschel/HIFI for the GOT $C^+$ program at $l = 345.65°$ and $b = 0°$ , along with the CO data from the Mopra telescope and HI surveys. Many different types of interstellar clouds can be seen in this line of sight. The Gaussian decomposition for $C^+$ is also shown in the upper panel. Caption and figure from Langer *et al.* (2010).

surveys will connect the molecular cloud component with the atomic diffuse interstellar medium, illuminating the origin of molecular clouds and the origin of turbulence in the cold ISM. The first data from HEAT have already uncovered diffuse atomic carbon emission in the Galaxy and directly measured the dark molecular gas ($H_2$ clouds without CO emission). Initial estimates show this component to be almost 40% of the molecular mass assessed by CO emission alone (Figure 4). Much more of the cold, neutral ISM is in the form of clumpy photoionization regions (PDRs) than previously suspected.

HEAT has also shown the Ridge A site to be an exceptional location from which to perform terahertz astronomy from the ground. Based on the correlation of HEAT tipping measurements at 809 GHz (370 $\mu$m) and satellite-based soundings at infrared and microwave wavelengths from January through October 2012, the number of productive "submillimeter" days in which the mean daily atmospheric opacity $\tau_{810}$ at 810 GHz (370 $\mu$m) is $\leqslant$1.5 has been 258, or almost 86% of the time. Even more impressive, the number of "terahertz" days in which the daily mean atmospheric opacity at 1.5 THz (200 $\mu$m) is $\leqslant$1.5, equivalently $\tau_{810} \leqslant 0.5$, has been 85, or 28% of the time. In comparison to data returned from the APEX radiometer on the Chajnantor plain, there are 2.45× more

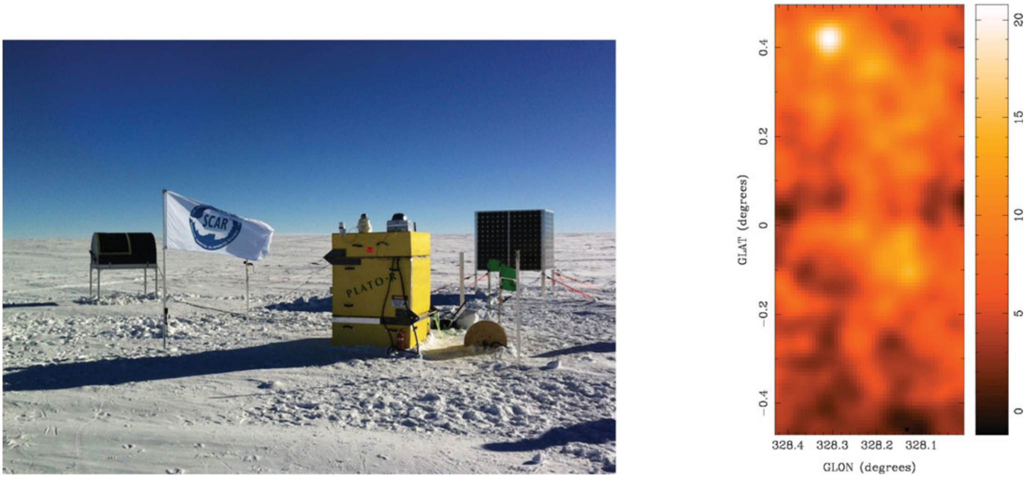

**Figure 4.** The international PLATO-R and HEAT observatory at Ridge A, Antarctica (left) and a first-light integrated intensity map of 0.6 square degrees of the Galactic Plane (right), observed in the 809 GHz fine structure line of atomic carbon. The widespread emission and filamentary structure highlights molecular gas not previously traced by CO.

**Table 2.** Exceptional THz transmission above Ridge A, Jan–Oct 2012

| Metric | Ridge A | Chajnantor | Advantage |
|---|---|---|---|
| fraction($\tau_{810} \leqslant 1.5$) | 87% | 38% | 2.3× |
| days $<\tau_{810}> \leqslant 1.5$ | 258 | 105 | 2.45× |
| fraction($\tau_{1500} \leqslant 1.5$) | 32% | 4% | 8× |
| days $<\tau_{1500}> \leqslant 1.5$ | 85 | 5 | 17× |

“fully submillimeter” days and 17× more “fully terahertz” days (Table 2) at Ridge A. Observing at 1.5 THz from Ridge A is not so different than observing at 810 GHz from South Pole, as was done at the AST/RO telescope for over a decade (Stark *et al.* 2001).

The atmospheric stability, critical to the construction of high-fidelity Galactic Plane maps, is a characteristic that is even more advantageous for Antarctic terahertz astronomy. Peterson *et al.* (2003) demonstrated that the submillimeter-wave sky noise is dominated by fluctuations in water vapor content, and is over 30 times lower at South Pole than at Mauna Kea or Chajnantor owing to the reduced water vapor content of the Antarctic atmosphere. Initial data at Ridge A in 2012, in comparison to the operation of the HEAT telescope at South Pole in 2011, suggests that the sky noise is less than half that of South Pole on average, and therefore scales somewhat more sharply than linear with total water vapor content.

### 2.2. *Beyond ALMA: Terahertz Interferometry*

The same exceptional site characteristics that make the summit of the Antarctic Plateau so well suited for large-scale mapping also render it ideal for terahertz interferometry. Indeed, the phase noise between arms of a terahertz interferometer is dominated by the time variation of water vapor along a line of sight, which is dramatically lower over the Antarctic Plateau than at the best developed mid-latitude sites. The parameter space filled by other major facilities shows opportunity for a high resolution facility at frequencies $\geqslant$1 THz (Figure 5). Such a facility could essentially only be performed from a site such as Dome A or Ridge A, based on the excellent likelihood of stable

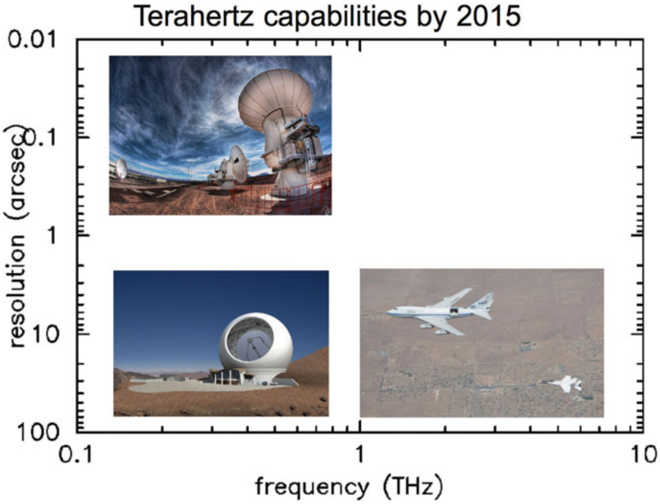

**Figure 5.** Major new facilities to be commissioned in this decade include ALMA, SOFIA and CCAT. A significant opportunity lies in terahertz interferometry, which will not be practical from airborne platforms nor productive from mid-latitude ground-based sites.

terahertz conditions for long periods of time. Furthermore, airborne and balloon-borne experiments are not conducive to the long baselines needed to achieve sub-arcsecond angular resolution at these frequencies. Not only would such a facility provide unprecedented angular resolution in the far-infrared, it would also act as an important low-cost pathfinder for future space-borne interferometers such as SPIRIT or TPF/I.

What might be the principal science drivers of an initial two or three element interferometer, providing high resolution terahertz astronomy?

The spectroscopic measurement of molecules in the dense cores of dark clouds, where high column densities ($\mathrm{N}_H > 10^{22}$ cm$^{-2}$) and high volume densities ($n_H > 10^4$ cm$^{-3}$) are prevalent, are frustrated by the freeze-out of gas phase volatiles onto dust grains. In particular, CO, the common tracer for molecular hydrogen, is observed to form ices under such circumstances (Hotzel *et al.* 2002). Thus, infrared dark clouds (IRDCs) and actively collapsing protostellar cores are difficult to measure in the gas phase, since gaseous abundances are often reduced by gas-grain interactions. However, primordial hydrogenic ions like $\mathrm{H}_3^+$ are especially important as they do not aggregate onto dust grains and therefore remain in the gas phase. While $\mathrm{H}_3^+$ does not have a radio spectrum, its deuterated forms such as $\mathrm{H}_2\mathrm{D}^+$ are sensitively probed at terahertz frequencies. Thus, they constitute crucial spectroscopic probes of the velocity field in dark, starless, and collapsing cloud cores (Bergin & Tafalla 2007) (Figure 6). Light hydrides with ground state lines at terahertz frequencies are among the best probes of residual gas in planet-forming circumstellar disks.

## 3. Conclusions and Prospects

As preceded by the development of charge-coupled devices (CCDs) for visible light in the 1980's and large format photodiode arrays in the infrared during the 1990's, terahertz instrumentation and science is poised to make significant advances in capability in the coming decade. While it is likely that the unexpected discoveries will leave the greatest legacy, the impact of anticipated discoveries is no less exciting and encompasses the broad

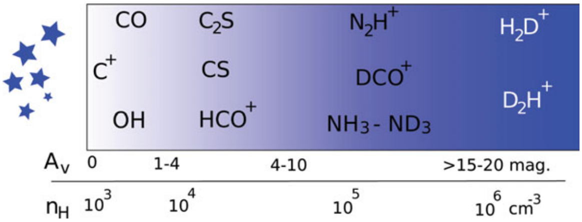

**Figure 6.** Schematic summary of the major gas phase probes of starless cores as function of depth and density into a cloud. In deep protostellar environments, only primordial molecules with terahertz spectra remain diagnostic. Adapted from Bergin & Tafalla (2007).

range of astrophysical studies, from Solar System astronomy to the formation of stars and galaxies at high redshift.

Furthermore, the opportunities provided by the Antarctic Plateau are important not only to the development of the terahertz waveband, but also as a technological testbed. Meaningful improvements to natal terahertz technologies are required in the context of development of large format focal plane arrays, wide instantaneous spectral coverage, and detector sensitivity. However, the number of terahertz observatories where new concepts in instrumentation can be tested and deployed for science is very small and needs to be developed further in the post-Herschel era. Ground based sites such as the summit of the Antarctic plateau (Ridge A and Dome A) therefore offer great promise in the terahertz atmospheric windows and represent an excellent proving-ground for promising technologies, which can then be productively applied to airborne, balloon-borne, and space-based platforms.

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