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Exceptional Terahertz Transparency and Stability above Dome A, Antarctica

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ABSTRACT. We present the first direct measurements of the terahertz atmospheric transmission above Dome A, the highest point on the Antarctic plateau at an elevation of 4.1 km. The best-quartile atmospheric transmission during the Austral winter is 80% at a frequency of 661 GHz (453 μm), corresponding to a precipitable water vapor column of 0.1 mm. Daily averages as low as 0.025 mm were observed. The Antarctic atmosphere is very stable, and excellent observing conditions generally persist for many days at a time. The exceptional conditions over the high Antarctic plateau open new far-infrared spectral windows to ground-based observation. These windows contain important spectral-line diagnostics of star formation and the interstellar medium which would otherwise only be accessible to airborne or space telescopes.

Online material: color figures

1. INTRODUCTION

The two most critical considerations when selecting a site for ground-based astronomical telescopes operating at terahertz frequencies (submillimeter wavelengths) are the atmospheric transparency and stability, which are largely governed by the amount of and variation in the atmospheric water vapor. This has driven submillimeter-wave telescopes to the highest, driest, and coldest sites where the water vapor column is reduced substantially. The extreme conditions on the Antarctic plateau should therefore be especially favorable for a new generation of automated submillimeter-wave and terahertz observing facilities.

Atmospheric constituents, such as water vapor, oxygen, and ozone absorb far-infrared light efficiently, forcing submillimeter-wave astronomical observatories to the highest, driest sites where the adverse impact of atmospheric absorption is minimized. The first large submillimeter-wave telescopes were deployed to the 4 km high summit of Mauna Kea in Hawaii, and more recently, the 5 km high Chajnantor plain of the Atacama desert in northern Chile and the geographic South Pole at 2.8 km elevation. The midlatitude observatory sites typically show a best-quartile precipitable water vapor (PWV) column of 0.4 mm to 1.0 mm in winter. However, the dry, calm, and extremely cold conditions prevalent on the Antarctic plateau allow the lower elevation South Pole site to surpass Mauna Kea and rival that of the Chajnantor plain in atmospheric transparency (Chamberlin 2004). Furthermore, the stability of the transmission over the South Pole far surpasses that of either of the two midlatitude sites (Peterson et al. 2003). Thus, prospects for submillimeter-wave astronomy from higher points on the plateau are expected to be better still. While limited summertime submillimeter measurements from 3.2 km high Dome C are consistent with these expectations (Calisse et al. 2004), the 4.1 km high summit of the plateau, Dome A, is expected to be the coldest, driest, and calmest place in Antarctica (Lawrence 2004); ideal for an astronomical observatory.

2. OBSERVATIONS

In order to determine the characteristics of sites on the high Antarctic plateau, data must be obtained during the Austral winter, when temperatures and submillimeter opacities are lowest (Chamberlin et al. 1997), and where the differences in conditions between sites are most significant. Obtaining these data represented a formidable technical and logistical challenge, since the Dome A site is uninhabited and was only first visited in 2005 by a Chinese traverse. Without existing infrastructure,

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such as electrical power or communications, a remote autonomous observatory was required: the PLATeau Observatory (PLATO) (Yang et al. 2009), which builds on the heritage of the Automated Astrophysical Site Testing International Observatory (AASTINO), deployed to Dome C in 2003 (Lawrence et al. 2005). Comprised of two modules separately containing power generators and scientific instruments, PLATO provides heat, electrical power, Iridium satellite communications, and computer control for a series of site-testing and astronomical instruments. PLATO was designed and constructed at the University of New South Wales and successfully deployed to Dome A in 2008 January on a second Chinese traverse led by the Polar Research Institute of China and the Chinese Academy of Sciences. The submillimeter site-testing component of PLATO is called Pre-HEAT, a reference to the High Elevation Antarctic Terahertz (Walker et al. 2005) telescope for which Pre-HEAT is a technological prototype. As one of the key scientific instruments of the PANDA project for the International Polar Year, Pre-HEAT is a complete submillimeter observatory: a 0.20 m off-axis paraboloid mirror feeds a Schottky diode heterodyne receiver tuned to 661 GHz (453 μm) coupled to a fast Fourier transform digital spectrometer (Kulesa et al. 2008). Pre-HEAT measures the submillimeter sky opacity and performs astronomical observations of the $J = 6 - 5$ rotational transition of the ^{13}CO molecule toward star-forming interstellar clouds in the plane of our Milky Way Galaxy.

PLATO, and hence its instruments including Pre-HEAT, operated for a total of 204 days in the 2008 season, from January 18 to August 9. The submillimeter-wave sky opacity was measured using the skydip technique in which the antenna temperature difference between the sky and a calibrated reference load is measured sequentially at several elevation angles from 15° to the zenith (Dicke et al. 1946; Chamberlin et al. 1997). Over most of the season, skydip measurements of 2 minute total duration were taken every 10 minutes. However, owing to an unfortunate loss in receiver sensitivity during deployment, all skydip measurements were averaged into hourly values to reduce the instrumental noise. The reference load was occasionally heated to measure the gain of the radiometer (Ulich & Haas 1976), which varied slightly (10%) with ambient temperature during the year. Other aspects of the calibration, such as the optical throughput of the telescope system, were measured in the laboratory before deployment to Antarctica. Figure 1 shows 5 months of Pre-HEAT submillimeter opacities, demonstrating the exceptional stability and extremely favorable conditions of the site. The seasonal opacity trends echo those seen at the South Pole (Chamberlin et al. 1997): the best conditions are typically observed in late winter and early spring, and generally accompany conditions of low atmospheric pressure (550 mbar, a pressure altitude of 4700 m), calm surface winds (denoted by a strong radiative cooling gradient at the surface), and cold surface temperatures (−80°C).

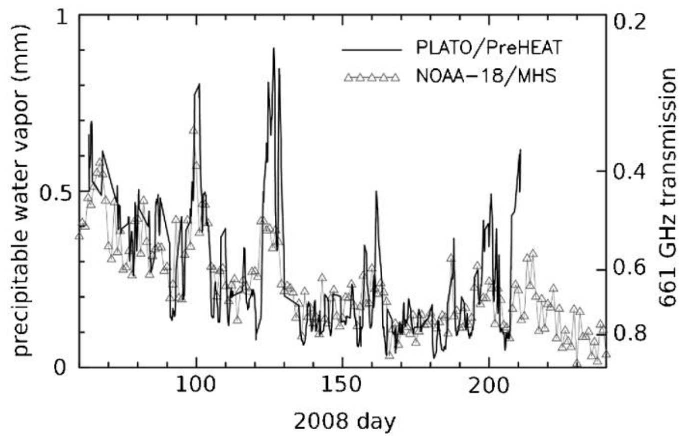

FIG. 1.—Overlay of the measured Pre-HEAT 661 GHz transmission (*solid line*) atop the 183 GHz microwave soundings (*triangles*), converted to 661 GHz equivalent, from the MHS instrument on NOAA-18 during 5 months of 2008. The left axis shows the precipitable water vapor corresponding to the observed transmissions. See the electronic edition of the *PASP* for a color version of this figure.

3. ANALYSIS AND DISCUSSION

While measurement of the submillimeter-wave transmission is directly relevant to astronomy, it is not readily compared with other sites due to the paucity of comparable 661 GHz heterodyne radiometers. However, when combined with atmospheric temperature and pressure profiles, the precipitable water vapor (PWV) column is a common figure for parameterizing terahertz atmospheric transmission. Translation of the 661 GHz opacity to estimates of the precipitable water vapor (PWV) column are made through application of the AM atmospheric model (Paine 2004) which has provided excellent fits to submillimeter Fourier transform spectrometer measurements of the sky above the Chajnantor plain in Chile (Paine et al. 2000) and the South Pole (Chamberlin et al. 2000). Comparison with the MOLIERE-5, ATM, and LLRTM atmospheric models (Urban et al. 2004; Pardo et al. 2001; Clough et al. 2005) shows less than 20% intermodel variance in the precipitable water vapor estimate at 661 GHz.

An independent, year-long assessment of the water vapor content above Dome A can be derived from 183 GHz passive radiometry from the Microwave Humidity Sounder (MHS) on NOAA-18 (Miao et al. 2001). In Figure 1, the solutions for precipitable water vapor measured by NOAA-18/MHS in 2008 are zero-point calibrated with and overlaid atop automated Pre-HEAT measurements of submillimeter opacity, which are converted to water vapor column. The match of these data sets is striking. Only during storms are significant differences noted. While the direct measurements of atmospheric transmission are already appropriate for astronomical application, blind translation to water vapor column yields a PWV *overestimate* during bad weather, since the submillimeter opacity is treated as pure absorption, ignoring the contribution of ice particle scattering.

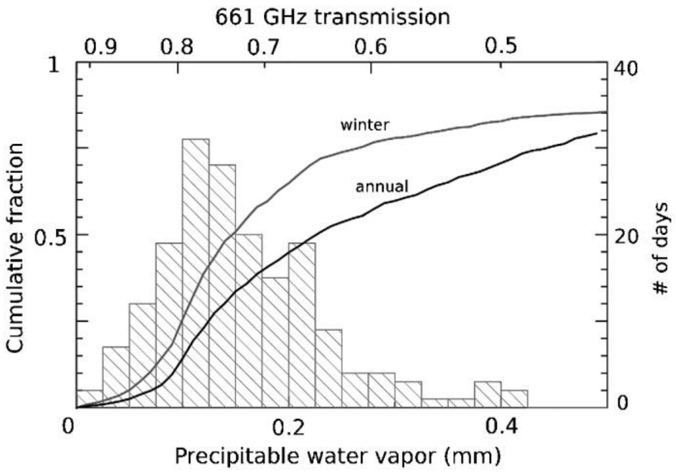

FIG. 2.—Combined cumulative and histogram plots of the derived precipitable water vapor and submillimeter transmission from the combined Pre-HEAT and MHS/NOAA-18 data for the 2008 Austral winter (days 120–300) and the full year. See the electronic edition of the *PASP* for a color version of this figure.

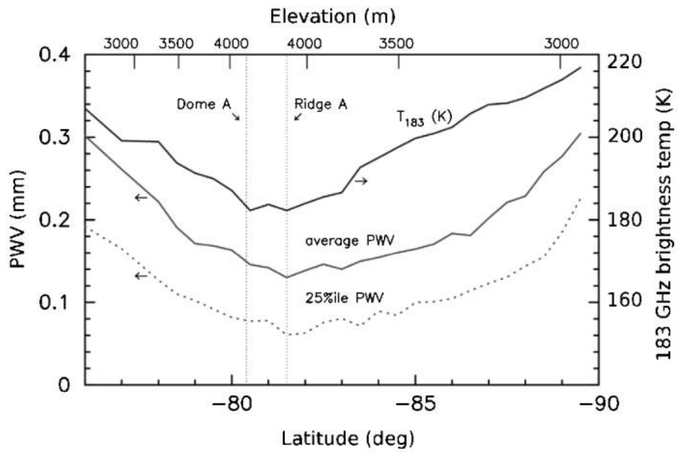

FIG. 3.—Precipitable water vapor and microwave sky brightness temperature derived from MHS/NOAA-18 data during late winter (2008, days 200 to 280) as a function of latitude through the Dome A region toward the South Pole. See the electronic edition of the *PASP* for a color version of this figure.

The 183 GHz satellite-based measurements are also subject to ice particle scattering, which precludes an accurate measure of the surface temperature. Thus, the satellite measurements tend to *underestimate* the PWV when ice clouds are present (Miao et al. 2001). By combining both measurements, one can even identify the periods during which the Pre-HEAT window was contaminated by snow or frost. Such inclement conditions constitute about 20% of the data taken in 2008.

Figure 2 shows the cumulative distribution of precipitable water vapor and 450 μm atmospheric transmission over the Austral winter and the whole year, combining the calibrated satellite measurements with the direct measurements of transmission provided by the Pre-HEAT telescope. The best quartile of winter weather yields 0.10 mm of precipitable water vapor; the best 20 days (10%) of winter weather, about 0.07 mm. Ten days averaged 0.06 mm of water vapor column or less, with the lowest daily average reaching 0.025 mm. To the authors' knowledge, these are the driest values measured anywhere from the ground; that such conditions are frequently realizable makes them even more remarkable.

Stability of the atmospheric transmission is nearly as important as its magnitude. With Pre-HEAT's relatively slow data-acquisition cadence, smoothed to hourly mean values, it is only possible to assess the long-term variation in sky transmission. The standard deviation of the midwinter (day 160–day 300) transmission is 9%, equivalent to 0.07 mm of precipitable water vapor, the dominant source of variation in terahertz transmission. During the same period of time, the MHS-derived PWV deviation at the South Pole was 0.13 mm. It is almost certain, then, that the terahertz transmission at Dome A is even more stable than at the South Pole. This is indeed a strong statement—in comparison to other sites, Peterson et al. (2003) demonstrated that the 350 μm opacity over the South Pole was 4 times more stable than on Mauna Kea, and 3 times better than at Chajnantor. Bolometric measurements from all three sites at millimeter wavelengths demonstrate that the fluctuations in the sky brightness power amplitudes are more than an order of magnitude smaller at South Pole than at either temperate site (Bussmann et al. 2005; Sayers et al. 2010). Thus, even from these early data, Dome A appears to be the most stable submillimeter site yet, because of the dry atmosphere that is indicated by the Pre-HEAT measurements.

Even better conditions may be possible from the Antarctic plateau. Figure 3 shows a plot of MHS-derived radiometric brightness temperature and precipitable water vapor along "Ridge A," which extends over 100 km south and west from Dome A. It would appear that the most southern, inland side of Ridge A lies closer to the null, or origin of the katabatic winds, and has lower atmospheric temperatures and water vapor and less cloud cover (Saunders et al. 2009). It may therefore represent an even better site for both infrared and terahertz astronomy than Dome A.

4. IMPLICATIONS FOR TERAHERTZ OBSERVATIONS

Table 1 compares Dome A and Ridge A with other established infrared and submillimeter observing sites. In calculating the terahertz transmission from the measured PWV, the following surface temperatures and pressures were assumed: Mauna Kea: 270 K and 620 mbar, the Atacama plain: 260 K and 525 mbar, South Pole: 210 K and 690 mbar, Dome C: 210 K and 645 mbar, Dome A and Ridge A: 200 K and 550 mbar. The scaling of these parameters with height is derived from averaged radiosonde measurements from each site; the Dome A and Ridge A profiles are truncated South Pole profiles. While traditional submillimeter-wave observations still benefit from the very driest Antarctic sites, it is the opening of new atmospheric windows above

TABLE 1
COMPARISON OF TERAHERTZ TRANSMISSION AT DIFFERENT OBSERVATORY SITES

Site[a]	25%ile PWV (mm)	50%ile PWV (mm)	Median winter transmission, 660 GHz	Best 25% winter transmission, 1460 GHz	Best 10% winter transmission, 1900 GHz
Dome A, 4100 m	0.10	0.14	74%	28%	4%
Ridge A, 4050 m	0.08	0.12	77%	33%	11%
Dome C, 3250 m	0.15	0.24	60%	13%	<1%
South Pole, 2850 m	0.23	0.32	52%	6%	0%
Chajnantor[b], 5050 m	0.35	0.60	47%	7%	0%
Mauna Kea[c], 4100 m	1.0	1.5	15%	0%	0%

[a] Ridge A and Dome C water vapor estimates made from MHS/NOAA-18 soundings in 2008. South Pole water vapor statistics come fromdaily radiosonde data in 2008. The Chajnantor plain (ALMA site) and Mauna Kea (CSO tipper) values are typical water vapor distributions from the literature as indicated.

[b] Delgado et al. 1999.

[c] Hogg 1992

1 THz (<300 μm) that represents the most significant impact of these results from Dome A. In the atmospheric windows from 0.8–1.5 THz (350–200 μm), the improvement in observing conditions at Dome A reduces the integration time of an observation by an order of magnitude over other sites. At shorter wavelengths, where atmospheric windows become ever narrower and more opaque, such observations may only be possible from Dome A. To illustrate this point, Figure 4 shows an atmospheric transmission model (Paine 2004) of the Dome A site, validated at 661 GHz and extrapolated to other frequencies. It demonstrates clearly the new terahertz frequency windows that open on the high Antarctic plateau. While terahertz observing conditions are possible on the Atacama plain and especially on the high (5.6 km) mountain summits that surround it, such conditions are both more frequent and stable in Antarctica.

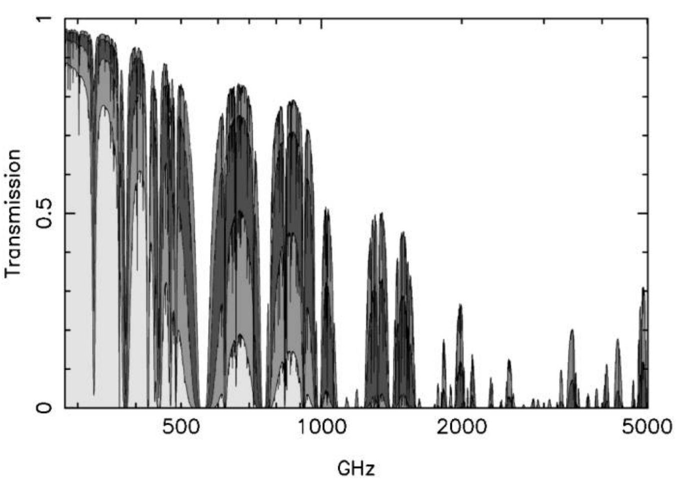

FIG. 4.—Atmospheric transmission plot from 300 to 5000 GHz, or 1000 to 60 μm, for median winter conditions on Mauna Kea: 270 K, 620 mbar and 1.5 mm PWV (*lowest curve*); the Atacama plain: 260 K, 525 mbar and 0.6 mm PWV; Dome A: 200 K, 550 mbar and 0.14 mm PWV, and the best tenth percentile conditions at Dome A: 0.07 mm PWV (*top curve*). See the electronic edition of the *PASP* for a color version of this figure.

These new spectral windows harbor important spectral diagnostics of star formation, the life cycle of the interstellar medium, and the global evolution of galaxies through cosmic time. Highly excited rotational transitions of the common CO molecule probe warm, dense regions in hot star-forming cloud cores, circumstellar disks, shock fronts, and photodissociation regions which represent the intricate interplay between clouds and the stars that are born from them. The far-infrared fine structure lines of oxygen, nitrogen, and carbon are the most luminous spectral features in the Galaxy. They probe and regulate the thermal balance, and the formation and destruction of interstellar clouds; pivotal processes which have yet to be studied in detail on a Galactic scale. For example, the luminous $2P_{3/2} -^2 P_{1/2}$ fine structure line of ionized carbon at 1.901 THz (158 μm) could be detected toward warm photodissociation regions at a sensitivity of 2×10^{-5} erg s^{-1} cm^{-2} sr^{-1} and with 1 km s^{-1} spectral resolution in less than 5 minutes in excellent winter weather with a cryogenic heterodyne receiver. Primordial species such as HeH^+ and H_2D^+, and light hydrides like NH^+, are central to interstellar chemistry, and have favorable transitions at terahertz frequencies. Near the centers of the atmospheric windows at 1.3 and 1.5 THz, line fluxes of 10^{-6} erg s^{-1} cm^{-2} sr^{-1} would be detectable in less than 30 minutes with sub-kilometer s^{-1} spectral resolution. Studies of all these species are possible from a site like Dome A. Furthermore, in distant galaxies, bright far-infrared spectral lines and dust continuum emission are redshifted to submillimeter wavelengths where the Dome A site will present the greatest sensitivity from the ground. In particular, the stable atmosphere and low sky noise on the high Antarctic plateau will be crucial in enabling deeper extragalactic measurements.

With the 2009 launch of the submillimeter-wave *Herschel Space Observatory*, the importance of complementary, ground-based terahertz observations has become acute. Small, dedicated observatories that can map bright terahertz spectral lines over large portions of the sky will place detailed *Herschel* observations in a broader, richer context. Such observatories would answer important scientific questions in their own right, and continue long after *Herschel*'s 3 yr mission has ended. Terahertz frequencies represent the last portion of the electromagnetic spectrum that has the potential of being explored from the ground. The identification of Dome A and Ridge A as ground-based sites where terahertz astronomy can be pursued productively dramatically broadens our long-term capabilities in this important wavelength regime.

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