New Ground Based Facilities for THz Astronomy

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Abstract— **Contemporary ground based facilities for terahertz astronomy are discussed including details on telescopes, instrumentation, and science. Our discussion includes the present and developing facilities in Antarctica and at high sites in the northern Atacama desert in Chile, and projects planned for these sites within the near term horizon.**

I. INTRODUCTION

Over the past decade remarkable leaps forward have been made in receiver technologies for THz astronomical applications. With the imminent launch of the Hershel Space Telescope and the SOFIA airborne observatory, these new technologies will bring forth exciting new science. To date however, these new technologies have been employed nearly entirely on ground-based facilities located at the best developed submillimeter sites – those in Antarctica, and those on the Chajnantor region of northern Chile.

II. ANTARCTIC FACILITES

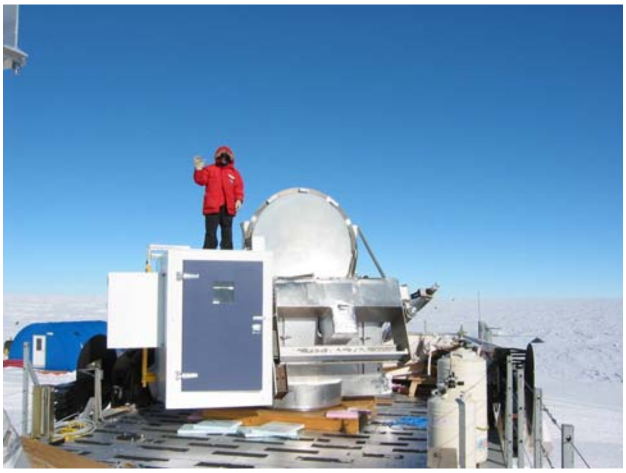
The Antarctic Plateau is extremely cold, very high, and very dry. Developed sites on the Plateau include South Pole, Dome A and Dome C. South Pole is a proven excellent site for THz astronomy, while it is suspected that the Dome C and in particular the Dome A sites are better still, due to their higher elevation and expected lower water vapour burden.

B. South Pole: AST/RO

The first ground-based telescope optimized for THz astronomy was the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) installed at South Pole in the Austral summer season of 1994/95 ([1], Fig. 1). The 1.7 m telescope is an off-axis Gregorian, mounted on an altitude azimuth structure on the roof of the AST/RO receiver room. A Nasmyth focus is available on the azimuth mount, while a Coude focus in the receiver room permits co-mounting of several receivers. The telescope has excellent surface accuracy (~9 μm rms) enabling efficient observations at THz frequencies. During its eleven year lifetime (the telescope was de-comissioned in late in 2005) a wide variety of heterodyne receivers were used at the facility from 230 GHz through 850 GHz, including a dual (810/492 GHz) band, and a four-beam (810 GHz) receiver [2]. A crowning achievement for the facility are large (~ 10 square degree) scale maps of the Galaxy in the CO(7-6), CO(4-3), and 492 GHz [CI] lines (e.g. [3]).

During its last seasons, two 1.4 THz receivers were installed on AST/RO: the Terahertz Receiver with NbN HEB Device (TREND), and the South Pole Imaging Fabry-Perot Interferometer, SPIFI. TREND is a sensitive (T_{rec} ~ 800 K) heterodyne receiver utilizing a hot electron bolometer mixer [4], while SPIFI is a 25 pixel direct detection spectrometer [5]. Here we focus on the SPIFI reveiver and results.

Fig. 1. SPIFI mounted on the AST/RO telescope.



SPIFI is an imaging Fabry-Perot interferometer utilizing a 25 pixel array of bolometers held at 60 mK as detective devices. SPIFI's is designed to operate at in the 200, 350 and 450 μm telluric windows and can achieve resolving powers, R up to R $\equiv \lambda/\Delta\lambda$ ~ 10,000 for high resolution spectroscopy in these bands. SPIFI was successfully used on the 15 m JCMT telescope from 1999-2003 in the 350 μm telluric window [e.g. 6], and subsequently deployed for work in the 200 μm window on the AST/RO telescope at South Pole. At 200 μm (1.5 THz) SPIFI's best pixels have a noise-equivalent-power (NEP) ~ 2.5×10^{-15} W/Hz$^{1/2}$ equivalent to T_{rec}(DSB) ~ 150 K. During the Austral winter of 2005 SPIFI detected and mapped the 205.178 μm $^3P_1 - {}^3P_0$ ground state fine-structure line of N^+ from the Carinae Nebula [7,8]. This was the first reported detection of this important cooling line from a ground based observatory (but see RLT section below).

The Carina region was mapped in its 121.898 μm $^3P_2 - {}^3P_1$ line of N^+ using the LWS on the Infrared Space Observatory (ISO) [9]. The ratio between the the 205 μm and 122 μm lines is density sensitive (Fig. 2), and the line ratio is used to determine the density of the ionized gas enveloping the dense Carina I and II HII regions is ~ 33 cm^{-3}.

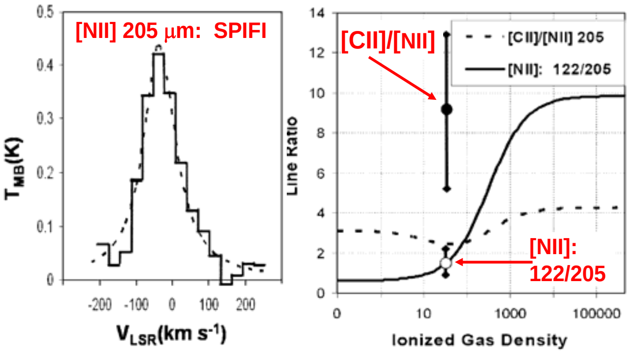


Fig. 2 (left) [NII] 205 μm line detected from the Carinae Nebula. (right) [CII]/[NII] 205 μm and [NII 122/205 μm line ratios as a function of ionized gas density. The filled dot is the observed [CII]/[NII] 205 μm ratio (with large systematic error bar), and the open dot is the observed [NII] 122/205 μm line ratio.

In addition to being a major cooling line and probe of HII region density, the 205 μm [NII] line intensity is very important for interpreting observations of the 158 μm [CII] line. The [CII] line is also an important coolant for HII regions, but is the dominant coolant for major phases of the neutral ISM: the cold neutral medium (atomic clouds), the warm neutral medium, and the photodissociated surfaces of molecular clouds (PDRs). Although the [CII] line is a ubiquitous coolant, its origins are uncertain. Estimates of the fraction of the Galactic [CII] emission from the ionized medium range from 10 to 50%. Fortunately, the 205 μm [NII] line intensity provides a means for unraveling the various components. Since N^+ requires 14.53 eV to form, the 205 μm line only arises from HII regions. Furthermore, the critical density for thermalization of the 205 μm [NII] line emitting level is nearly identical to that of the 158 μm [CII] line emitting level, so that the line ratio from ionized gas is only a function of the assumed N^+/C^+ abundance ratio (Fig. 2). Comparison of the SPIFI [NII] line to the ISO [CII] line observations indicates that only 27% of the of the observed [CII] line emission comes from the ionized gas. These results support and underpin prior studies that suggest most of the observed [CII] line emision from Galactic and extra-galactic sources arises from the warm, dense PDRs on the surfaces of molecular clouds -- an important constraint on the models for the interstellar medium in galaxies.

B. *The South Pole Telescope*

The AST/RO telescope (among others) paved the way for the next generation, large aperture telescope at South Pole the South Pole Telescoe (SPT) (10). The SPT is funded by the NSF Office of Polar Programs and is at present dedicated to large scale surveys of the Cosmic Microwave Background Radiation (CMBR) anisotropies and polarization. In the future, it is likely that it will be used for THz science. Construction began at the site in November 2004, and the telescope achieved first light on February 16, 2007. With its 10 m aperture, it is the largest astronomical facility on the Antartic continent. The SPT is a collaboration between the University of Chicago, UC Berkeley, Case Western Reserve University, the University of Illinois, and the Smithsonian Astrophysical Observatory. It is primarily funded by the NSF Office of Polar Programs.

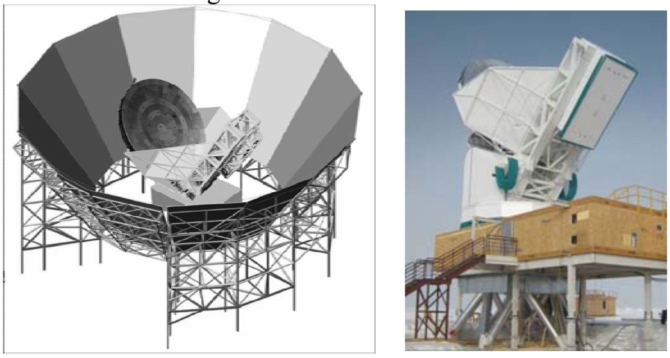


Fig. 3 (left) Layout for SPT including ground shields. (right) Photograph of SPT taken during Austral summer 2007-2008 (J.E. Carlstrom personal communication).

The telescope design is an off-axis Gregorian on an altitude-azimuth mount (Fig. 3). The secondary/camera system is contained within a single cryostat, so that the secondary and aperture stop can be held at 10 K, minimizing the thermal background. The combined surface accuracy of the system is better than 20 μm rms. The optical system is enveloped by both an inner movable ground shield and fixed outer ground shield (not yet installed). The pointing goal is 1”, and the telescope scans up to 4°/second. The off-axis design, cold secondary/stop, and ground shields minimize stray thermal emission on the detectors, thereby maximizing system sensitivity. Together with the fast scan rate, these features also minimize systematics.

At 2 mm wavelength, the telescope optics can support a $1(°)^2$ field of view. This field is to be populated with a 966 pixel array divided into 6-161 pixel wedge-shaped sub-arrays in 5 colors. The detectors are TES “spiderweb” bolometers (made at UC Berkeley) in a bath temperature of 300 mK. At present (April 2008) there are about 600 detectors working in three bands (90, 150, and 200 GHz), most of them at, or near the background limit.

The SPT will deliver exciting new results in exploring the anisotropy and polarization of the CMBR. Its promise is enabled by its large aperture, excellent sensitivity, and the exceptionally stable South Pole site. The first key project is a 4000 square degree anisotropy survey of the CMBR which will pick out the Sunyaev-Zel’dovich Effect (SZE) signals from galaxy clusters. Together with follow-up redshift surveys, these SZE surveys will measure the number density evolution of massive galaxy clusters. Since the growth of massive clusters is constrained by the underlying cosmology, the SPT/SZE surveys promise to constrain fundamental cosmological pararmeters including the dark energy equation of state. The system has already detected the SZE effect from known clusters and is at present beginning the survey in $10(°)^2$ patches.

In 2010 it is anticipated that the SPT will begin deep surveys of CMBR polarization. Measuring the extremely small polarization signals are quite a challenge, but the rewards are great: polarization signals can indicate the presence of primordial gravity waves during the inflationary epoch, and they also relate to fundamental parameters such as neutrino mass and the dark energy equation of state.

C. HEAT

South Pole is an excellent site for THz astronomy, but there are at least two sites, Dome A and Dome C that are at significantly higher elevations on the ice sheet, and promise lower water vapour columns, opening windows into the far-IR bands (1-10 THz). Here we focus on the High Elevation Antarctic Terahertz (HEAT) Telescope that is beginning to explore the Dome A site [11].

Dome A is the highest point on the ice sheet at an elevation 4093 m. Very recently (2008, January) an expedition led by the Polar Research Institute of China (PRIC) successfully installed a fully robotic observatory, the PLATeau Observatory (PLATO) on Dome A. PLATO was constructed by a team from the University of New South Wales. The primary goal is to use its 7 robotic telescopes to fully characterize this site at several astrophysically interesting windows. One of these robotic telescopes is Pre-HEAT – a 20 cm tipping telescope equipped with a Schotty diode receiver and FFT spectrometer (Fig. 4). Its purpose is to measure the sky transmission (and obtain astrophysical spectra) at the 661 GHz frequency of the ^{13}CO(6-5) line. It has been operating successfully since 2008 January, and is currently mapping the Galactic Plane in this transition.

Fig. 4 Pre-HEAT telescope as tested in Sydney, before shipment to Antarctica

Following successful demonstration of the site's utility for THZ spectroscopy, HEAT will be deployed. HEAT is envisioned as a 50 cm aperture telescope, equipped with Schottky receivers at 0.81, 1.46 (from JPL) and 1.9 THz. There is also a cryogenic hot electron bolometer instrument package for HEAT that is being investigated by the group at SRON for possible future deployment. HEAT is a collaborative project between the University of Arizona, PRIC, Purple Mountain Observatory (China), the University of Exeter, SRON, and the University of New South Wales.

The scientific goals for HEAT are to map the $^3P_2$-$^3P_1$ [CI] and CO(7-6) transitions at 0.81 THz over much of the 4th Galactic quadrant (Fig. 5), covering the Scutum-Crux arm through the Carinae and Vela regions. These lines are important coolants for the neutral ISM, and probes of gas density and temperature. HEAT will also map selected regions within these zones in the $^3P_1$-$^3P_0$ [NII] (1.46 THz) and $^2P_{3/2}$-$^2P_{1/2}$ [CII] (1.9 THz) lines complementing planned Herschel and Stratospheric Terahertz Observatory (STO) surveys. These lines are important coolants for the diffused ionized gas, and the [CII] line is both the dominant coolant for the photodissociated surfaces of molecular clouds and the warm and cool phases of the atomic media. The line ensemble (together with lower J CO and [CI] lines) well traces the physical conditions of the most important phases of the interstellar medium constraining modes of star formation with the Milky Way galaxy.

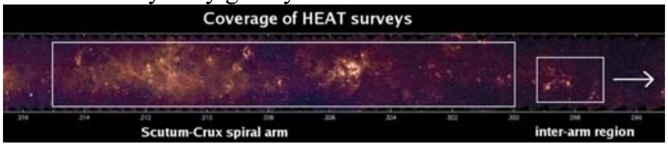


Fig. 5 Planned coverage of HEAT Galactic plane surveys.

III. CHILEAN FACILITIES

The Atacama Desert is a nearly 1000 km north-south strip of high desert in northern Chile. It is arguably the "driest place on Earth", and at its southern extreme, it is already the site of two leading ESO observatories (La Silla and Paranal). The northern end of the desert is significantly higher and drier, and is an excellent location for ground based THz astronomy. This Chajnantor region is the site for the Atacama Large Millimeter Array (ALMA) of 50 to 64 – 12 m antennas, which will eventually have receiver bands from 30 to 850 GHz. ALMA is located at an elevation of 5000 m – 750 meters higher than the summit of Mauna Kea – and there is significantly lower water vapor burden at the ALMA site at most times. ALMA is scheduled for completion in 2012. Below we discuss two telescopes sited very near ALMA that are currently operating in the THz, or near THz bands: the Atacama Pathfinder Experiment (APEX), and the NANTEN2 telescope. We also discuss the 25 m CCAT telescope envisioned for the nearby summit of Cerro Chajnantor, and begin our discussion with the pioneering Receiver Lab Telescope (RLT) located near the summit of Cerro Sairecabur located 35 km to the northwest of the ALMA site.

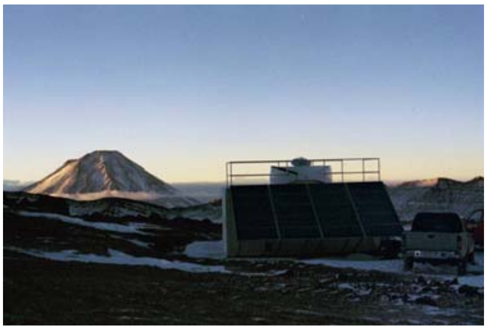


Fig. 6 RLT at the Sairecabur site (photo credit: D. Marrone).

Receiver Lab Telescope (RLT)

The RLT is an 80 cm telescope located at 5525 m elevation near the summit of Cerro Sairecabur [12]. The site is accessible by truck, and available for year round observing

(Fig. 6) The high frequency telluric transmission is monitored continuously by a Fourier transform spectrometer [13], and is is significantly better than that at the ALMA site – typically 40% better as measured in optical depth. This opens up ground based observations to a wide variety of spectral lines in the THz bands (Fig. 7). At the frequency of the astrophysically important [NII] line (1.46 THz), the zenith transmission is better than 10% about 35% of the time.

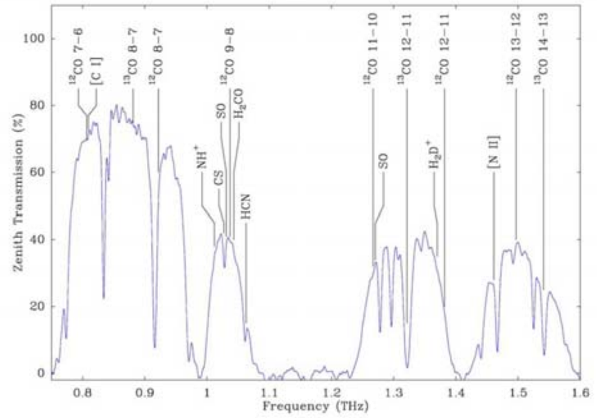


Fig. 7. Spectral lines transmitted in the THZ bands at the Sairecabur site.

The RLT employs heterodyne hot electron bolometer mixers kept at 4 K in liquid helium cryostats, and achieved first light at THz frequencies in 2002 [14]. Initial observations were limited to 0.85 and 1.03 GHz due to the availability of solid state local oscillators, but in 2005 the higher frequency oscillators became available, and the group began observations at 1.3 and 1.5 THz.

The first THz science obtained with the RLT was a 35 point map of the Orion A HII region/photodissociation region interface in the CO(9-8) (1.037 THz) line obtained in 2002 December [14]. This was the first CO(9-8) map of Orion, and only the second velocity resolved observation of any THz line from an astronomical source using a ground based telescope. Their CO(9-8) line observations reveal the physical conditions in the PDR as well as the velocity structure in the molecular outflow from the embedded young stellar object, IRc2.

The group fielded 1.3 and 1.5 THz receivers in December 2004, and presented maps of the Orion/BN-KL outflow and the NGC 2024 PDR in the CO(11-10) (1.26 THz) line as well as first detections of the CO(13-12) (1.5 THz) line at the 2005 Space Terahertz Conference [15] (Fig. 8). The CO(13-12) observations were the first ground based observations in the 1.5 THz window.

Most recently, the group has focused on detection of the [NII] line from Galactic HII regions. As mentioned above, this line is an important coolant and density probe for low density HII regions, and a discriminant for the fraction of the [CII] line emission that arises in low density HII regions. The RLT has obtained reported tentative detections of this line from about 6 HII regions, including G333.6, and G0.6. For both of these sources, the [CII]/[NII] 205 μm line intensity ratio is ~ 20, which means that only a small fraction (< 20%) of the observed [CII] line emission arises from the ionized gas in these sources (see Fig. 2). They also have reported upper limits on the line intensity from the Orion HII region that are very small when compared with the observed [CII] line: $I_{[CII]}/I_{[NII]} > 50$. This is very likely due to the harder radiation field in this source. Since θ^1 Ori C is an O6V star, one would expect to find most of the nitrogen in the form N^{++}.

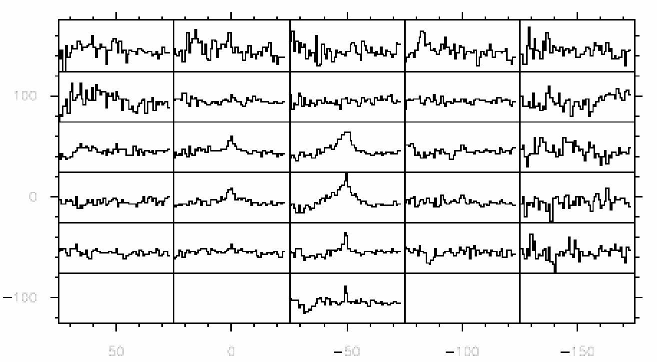


Fig. 8. CO(11-10) Map of BN/KL region in Orion. Each panel is 50" apart and N is up. Horizontal axis in each panel spans -80 to 100 km/s. Data are not calibrated on vertical scale [15]

A. APEX – CONDOR

Located on the Chajnantor plain at 5107 m, not far from the ALMA site is the Atacama Pathfinder Experiment (APEX) telescope [16] (Fig. 9). APEX is an ALMA prototype antenna that was manufactured by VERTEX Antennentechnik, GmbH, Germany, then modified to have two Nasmyth receiver cabins for single dish work. The APEX project was initiated in 2001 as a collaboration between the Max-Planck-Institut für Radioastronomie, the Onsala Space Observatory, and the European Southern Observatory (ESO). APEX operations are undertaken by ESO. Construction began in spring of 2003, with first light in the summer of 2005.

APEX is a 12 m Cassegrain telescope with a surface accuracy better than 18 μm rms. The telescope aperture, site and surface accuracy have ensured that it is one of the premier facilities for short-submillimeter, and even THz observations. A series of papers on first light science with APEX appeared in Astronomy and Astrophysics Volume 454 in 2006, including the first THz observations with the telescope, undertaken with the CONDOR receiver [17].

CONDOR (CO N+ Deuterium Observations Receiver) is a 1.25 – 1.5 THz receiver that employs a HEB mixer yielding a 0.8 GHz IF bandwidth that is spectrally analyzed with APEX's fast Fourier transfer spectrometer. CONDOR was the first receiver to employ a HEB mixer in a closed cycle refrigerator. They successfully used a pulse tube cooler that was vibrationally isolated from the mixer with flexible cold leads. Elimination of expensive cryogens is an important operational consideration while observing at Chajnantor. The receiver achieves a noise temperature ~ T_{rec}(DSB) ~ 1600 over much of the tuning band from 1 to 1.5 THz, and Allen variance minimum times are excellent, about 35 seconds for total power mode, and over 100 seconds for spectroscopy.

Fig. 9 APEX telescope.

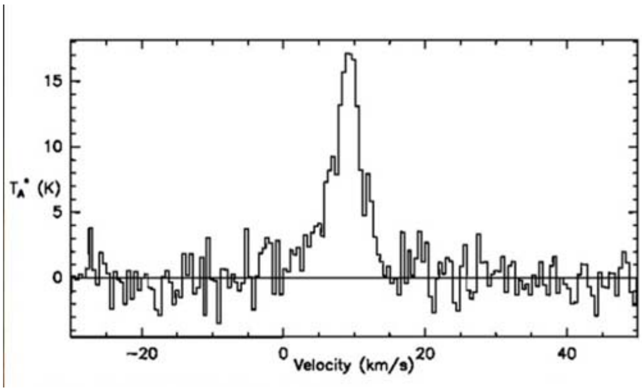


Fig. 10 CO(13-12) spectrum of Orion FIR4 [17]

CONDOR was first installed on APEX in November 2005 and obtained first light on a science target on November 20. The first science was detection and mapping of the CO(13-12) 1.5 THz line from the southern source on the Orion ridge, Orion FIR4, also known as Orion S6 [17] (Fig 10). At this time the line-of-sight transmission at the source elevation (57°) was 19% at 1.5 THz – excellent for the APEX site. The observed CO(13-12) line is narrower than the mid-J CO line suggesting that the high J level excitement is from gas heating in PDRs rather than shocks in outflows. The CO(13-12) line emission was also mapped around the IRc2 outflow [18] and from the PDR in NGC 2024 [19].

CONDOR is designed to detect the [NII] line as well. A line search was initiated in Orion at the Bar interface region, but the line was not detected to good significance (~ 10^{-14} W/m^2) despite good line-of-sight transmission (~ 18%). As for the RLT [NII] studies the weak [NII] there because most N is in N^{++} due to the hardness of the θ^1 Ori C radiation field.

CONDOR is now retired from APEX, and a second generation facility receiver is coming on line: the Single-Pixel Heterodyne Facility Instrument (SHFI). SHFI covers the frequency bands from 0.211 – 1.390 THz with 6 receiver channels. The highest frequency 1.250-1.390 THz band employs a HEB mixer [20].

Fig. 11 NANTEN2 Telescope at the site.

B. NANTEN2/KOSMA

The NANTEN2 observatory consists of a 4 m telescope located at 4850 m altitude on Pampa la Bola in the Atacama desert (Fig 11). The observatory is a collaboration between research institutes in Japan (Nagoya and Osaka University), South Korea (Seoul National University), Germany (KOSMA, Universität zu Köln, Argelander-Institut Universität Bonn), Switzerland (ETH Zürich), Australia (University of New South Wales), and Chile (Universidad de Chile). The observatory began operations in 2006, May.

The telescope has very good surface quality (< 20 μm rms) enabling observations in the short submillimeter windows. The primary goals are to survey the southern skies and nearby galaxies in various molecular and atomic lines in the spectral regime between 110 and 880 GHz with a primary scientific emphasis on starformation. At the highest frequencies, the observatory is equiped with a 2×8 pixel receiver the Submm Array Receiver (SMART) that operates simultaneously at 461 and 807 or 492 and 809 GHz [21]. In this way, both the CO(4-3) and CO(7-6) or the [CI] (492) and (809) GHz lines can be observed at the same time with perfect spatial registration and excellent relative calibration between the two sets of complementary spectral probes. The SIS mixers are cooled to 4 K within the cryostat using a closed cycle refrigerator, and achieve receiver temperatures of ~ 250 and 750 K (DSB) respectively at 460 and 810 GHz. There is a K-mirror configuration in the fore-optics so that the array orientation can be rotated to match the source morphology.

The first science results from the NANTEN2/SMART collaboration include mapping of N149W region of the Large Magellanic Cloud in the [CI] $^3P_2$-$^3P_1$, CO(7-6), and ^{13}CO(4-3) lines (Fig 12). The [CI] and ^{13}CO(4-3) detections are the first from the LMC. They find the C to CO abundance ratio is close to unity, much higher than that found in massive star-forming regions in the Milky Way. They model the observed submm line intensities together with 158 μm [CII] line (from the Kuiper Airborne Observatory) in a clumpy PDR context and find the UV field strength is ~ 220 times the local interstellar radiation field, and the average cloud densities are quite high, ~ 10^5 cm^{-3} [22]

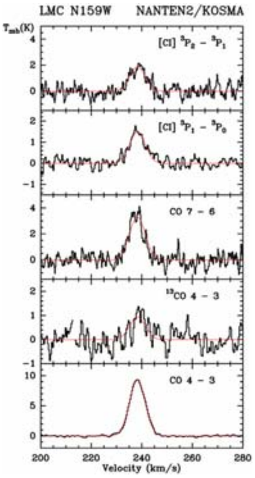


Fig.12. Lines observed from the N149W region of the LMC with SMART on NANTEN2. From top to bottom: [CI] $^3P_2$-$^3P_1$, [CI] $^3P_1$-$^3P_0$, CO(7-6), ^{13}CO(4-3), and CO(4-3).

C. *Cornell Caltech Atacama Telescope (CCAT)*

The Cornell Caltech Atacama Telescope (CCAT) is proposed 25 m telescope with excellent surface accuracy (~ 9 μm rms) located at an excellent site (at 5600 meters, near the summit of the Cerro Chajnantor). With an actively controlled surface, CCAT promises to work with very high efficiency at 850 GHz, and good efficiencies in the THz windows as well. It is expected that CCAT will have cameras and spectrometers operating from the very short submm (1.5 THz, or 200 μm) windows through the 2.2 mm window. The telescope optical design (Richie-Chretien) provides for a 20' diffraction limited field of view at wavelengths as short at 200 μm, so that large scale surveys with very large format arrays are enabled. CCAT is a collaborative project between Cornell University, the California Institute of Technology and the Jet Propulsion Laboratory, the University of Colorado, the Universities of Waterloo and British Columbia, the UK Astronomy Technology Centre on behalf of the UK community, and the Universities of Cologne and Bonn. Partnership fund raising efforts are underway, and it is hoped that construction can begin in 2009, with completion in the 2013 timeframe.

The primary science drivers for CCAT focus on origins, and include (1) exploring the early Universe through high spatial resolution, multiwavelength surveys of the CMBR, in particular using the SZE to understand the growth of galaxy clusters and its relation to dark energy and dark matter (2) exploring galaxy formation and evolution through large area surveys of distant galaxies in the submillimeter bands (3) studies of star and planet formation through multiwavelength surveys and imaging of nearby young stellar objects, protostellar, and debris disks (4) explorations of the solar system including surveys of trans-Neptunian objects to constrain theories of solar system formation.

Fig. 13. View of the proposed site for CCAT from the summit of Cero Chajnantor. Visible is the 350 μm tipper.

The CCAT site near the peak of Chajnantor (Fig. 13) was primarily chosen for its excellent water vapor characteristics. Based on balloon-borne radiosonde surveys, it was expected that a site a few hundred meters higher than the ALMA site would have significantly between water vapor statisitics [23]. This expectation was confirmed through a 350 tipping radiometer comparison between the proposed site and the CBI (5050 m elevation) site near ALMA. Identical ratiometers have been taking data since May of 2006. The news is good. The water vapor burden over the CCAT site is only 70% that over CBI so that, for example, 0.7 mm precipitable water vapor or less occurs 65% of the time for CCAT, and only 40% of the time over CBI (Fig. 14).

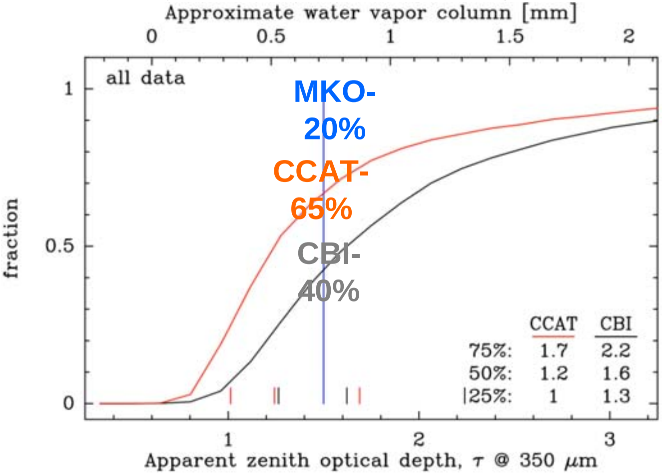


Fig. 14. Fraction of time with precipitable water vapor less than a given value obtained for the CCAT site as compared with the lower elevation CBI site. CCAT should have a water column less than 0.7 mm 65% o the time, while CBI reaches that value only 40% of the time and Mauna Kea only 20% of the time.

The CCAT telescope needs to be enclosed within a dome to achieve its high surface accuracy in the face of the winds near Chajnantor. A concept that minimizes dome size is the "Calotte" style dome (Fig. 15)

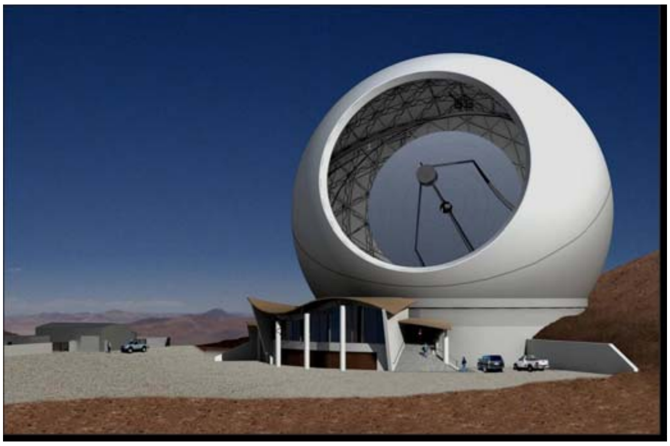


Fig. 15. Artist conception of the CCAT telescope with its Calotte style dome and the observers facilities at the Chajnantor site..

Baseline first light instrumentation includes two direct detection cameras to enable our planned large scale surveys: the Short-Wavelength Camera (SWCam), and the Long-Wavelength Camera (LWCam) [24]. Remarkably, in the short submillimeter (350 and 450 μm) windows, the excellent site, large aperture, excellent surface quality, and the use of broad-band direct detection enable CCAT to achieve point source sensitivities per beam that are comparable with those of the ALMA array (Fig. 16). Therefore, CCAT can map the sky far faster than ALMA at 350 and 450 μm, and deliver a large catalogue of interesting sources for detailed follow-up with ALMA. There is excellent synergy between CCAT and ALMA: CCAT is a finder-scope for the ALMA array.

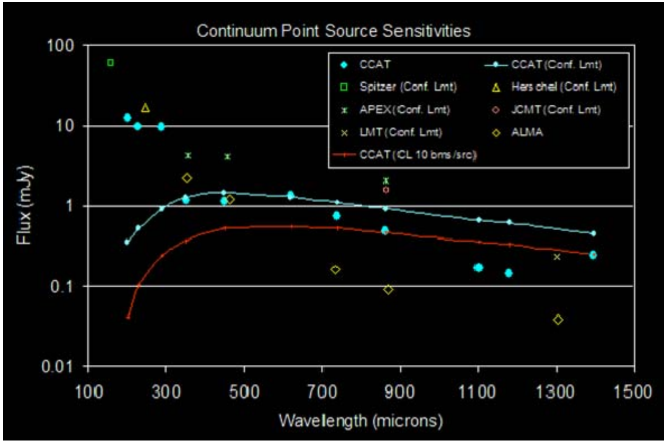


Fig. 16. Expected point source sensitivity for CCAT cameras compared with other facilities. Estimates are 5σ in 3600 seconds, and account for the mean precipitable water vapor column at each site. Confusion limits (30 beams/source) are included in all estimates. The top (cyan) line indicates the confusion limit for CCAT with 30 beams per source, while the bottom (red) plot indicates the more generous limit of 10 beams per source.

The SWCam covers frequencies from 0.5 to 1.5 THz. It is envisioned to have a 5’×5’ field of view populated with about 32,000 pixels to provide diffraction limited, Nyquist sampled operation at 350 μm. Detectors are baselined as SCUBA 2-like TES bolometers held at 90 mK in an ADR. The array size at present is cost limited based on current technology. However, there is growth potential to a 400,000 pixel array which would Nyquist sample the entire 20’×20’ field of view of the telescope. The SWCam covers the 200, 350, 450, and 620 μm telluric windows by rotating a filter wheel. It is conceivable that the development of the SWCam would be delayed for next generation technologies if the SCUBA 2 camera with its twin 5120 pixel arrays operating at 450 and 850 μm can be successfully transferred from the JCMT to CCAT.

The LWCam covers frequencies from 150 to 405 GHz, including the trans-millimeter wavelength windows at 0.74, 0.87, 1.1, 1.4, and 2.0 mm. LWCam detectors are envisioned as slot dipole antenna coupled kinetic inductor detector arrays such as those being developed at Caltech/JPL [25,26] and elsewhere. We plan an array that can be configured to have 1024 to 16,384 pixels depending on wavelength, covering either a 10’×10’, or 20’×20’ field of view.

CCAT will also include spectrometers. Likely first light spectrometers include modest resolving power direct detection spectrometers such as the long slit grating spectrometer ZEUS [27] or the waveguide grating spectrometer Z-Spec [28] that are now in use on the CSO. There will also be heterodyne receivers arrays, like those being developed at several institutions. The direct detection receivers will have a distinct advantage for detection broad lines from distant galaxies, while good velocity resolution is achieved with the heterodyne systems.

The primary science goal for CCAT is to explore the birth and evolution of galaxies in the early Universe. CCAT will survey tens of square degrees finding several hundred thousand star forming galaxies at redshifts between 1 and 5 and find a smaller number of sources out to redshifts of 10 (if they exist!). A few hundred of these submillimeter bright galaxies (SMGs) have been discovered to date through painstaking surveys such as those undertaken with SCUBA on the JCMT. CCAT will find these galaxies at the rates several hundred per hour! The primary discovery bands are at 350 and 450 μm. However shorter, and longer wavelength observations will be important to derive source submillimeter spectral energy distributions, hence their photometric redshifts and total far-IR luminosities. These statisitical redshifts will enable much of the expected science: the star and galaxy formation history of the Universe, and evolution of large scale structures. However, accurate redshifts refine these studies, enable splitting the sample into small redshift bins, and permit detailed studies of individual systems. It is possible to obtain redshifts for a sizeable fraction (10%?) of the survey by detecting the bright 158 μm [CII] line with a suitably designed far-IR/submm spectrometer such as a multi-beam version of ZEUS or Z-Spec. Calculations show that the [CII] line can be detected from systems only twice as luminous as the Milky Way out to redshifts of 2, and 10 times the Milky Way luminosity to z > 5. The [CII] line to far-IR continuum ratio in of itself constrains the strength of the ambient far-UV radiation field in starforming galaxies (Fig. 17). This yields the source beam filling factor, hence size of the starburst. For example the hyperluminous galaxy MIPS J142824.0 +352619 at z ~ 1.325 was detected in the [CII] line using ZEUS on the CSO [30]. The relative bright line emission observed there constrains the far-UV fields to be less than ~ 2000 times the local interstellar radiation field, so that the starburst must be distributed over kpc scales in this system. So, unlike ULIRG and starburst galaxies in the local Universe, at least some galaxies at z ~ 1 are undergoing global bursts of starformation.

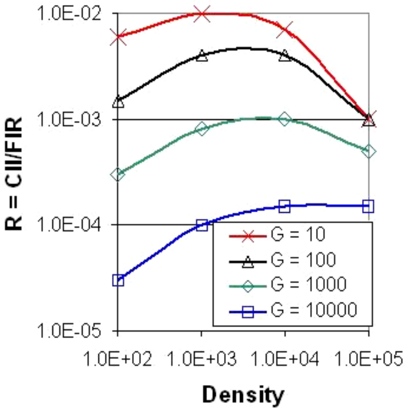


Fig. 17. The ratio, R of the [CII] line to far-IR continuum luminosity as a function of the strength of the far-UV radiation field, G, and molecular cloud density (adapted from [30]. For densities typical of starforming galaxies (100 < n < 10,000) R is mostly a function of G only.

CONCLUSIONS

There are many exciting new facilities and instruments now operating or on the near horizon for THz astronomy from the ground. Most of these facilities are in Antarctica, or in the northern Atacama desert in Chile. The superb sensitivities being delivered by these facilities and receivers are enabling exciting new science, whose promise will only grow as telescopes and receivers continue to improve.

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