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Smithsonian at the Poles

Contributions to International Polar Year Science

Igor Krupnik, Michael A. Lang,
and Scott E. Miller
Editors

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HEAT: The High Elevation Antarctic Terahertz Telescope

Christopher K. Walker and Craig A. Kulesa

ABSTRACT. The High Elevation Antarctic Terahertz Telescope (HEAT) is a proposed 0.5-m THz observatory for automated, remote operation at the summit of Dome A, the highest point on the Antarctic plateau. The altitude of Dome A combined with the extreme cold and dry conditions prevalent there make it the best location on Earth for conducting many types of astronomical observations. The HEAT will operate at wavelengths from 150 to 400 micrometers and will observe the brightest and most diagnostic spectral lines from the galaxy. It will follow PreHEAT, an NSF-funded 450-micrometer tipper and spectrometer that was deployed to Dome A in January 2008 by the Polar Research Institute of China. PreHEAT is one of several instruments designed to operate with the University of New South Wales' Plateau Observatory (PLATO). A 1.5-THz (200-micrometer) receiver channel will be installed onto PreHEAT in Austral summer 2008–2009. PreHEAT/HEAT and PLATO operate autonomously from Dome A for up to a year at a time, with commands and data being transferred to and from the experiment via satellite daily. The Plateau Observatory is the Dome A component of the multinational Astronomy at the Poles (AstroPoles) program, which has been endorsed by the Joint Committee for the International Polar Year (IPY).

INTRODUCTION

From the Milky Way to high-redshift protogalaxies, the internal evolution of galaxies is determined to a large extent by the life cycles of interstellar clouds, as shown in Figure 1. These clouds are largely comprised of atomic and molecular hydrogen and atomic helium, which are notoriously difficult to detect under normal interstellar conditions. Atomic hydrogen is detectable via the 21-cm spin-flip transition and provides the observational basis for current models of a multiphase galactic interstellar medium (ISM). Its emission is insensitive to gas density and does not always discriminate between cold ($T \sim 70$ K) atomic clouds and the warm ($T \sim 8000$ K), neutral medium that is thought to pervade the galaxy. Furthermore, neither atomic helium nor molecular hydrogen (H_2) have accessible emission line spectra in the prevailing physical conditions in cold interstellar clouds. Thus, it is important to probe the nature of the ISM 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.

Christopher Walker and Craig Kulesa, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA. Corresponding author: C. Walker (cwalker@as.arizona.edu). *Accepted 25 June 2008.*

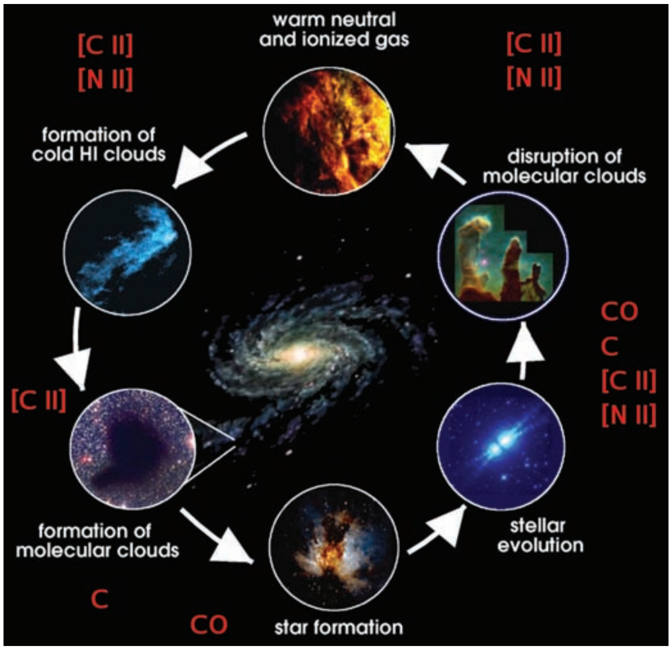

FIGURE 1. The High Elevation Antarctic Terahertz Telescope (HEAT) will observe the fine-structure lines of N^+, C^+, C, and CO that probe the entire life cycle of interstellar clouds. In particular, HEAT will witness the transformation of neutral atomic clouds into star-forming clouds, the interaction of the interstellar medium (ISM) with the young stars that are born from it, and the return of enriched stellar material to the ISM by stellar death.

Although we are now beginning to understand star formation, the formation, evolution, and destruction of molecular clouds remains shrouded in uncertainty. The need to understand the evolution of interstellar clouds in the context of star formation has become a central theme of contemporary astrophysics. Indeed, the National Research Council's most recent decadal survey has identified the study of star formation as one of the key recommendations for new initiatives in this decade.

HEAT SCIENCE GOALS

Via resolved C^+, C, CO, and N^+ THz line emission, the High Elevation Antarctic Terahertz Telescope (HEAT) uniquely probes the pivotal formative and disruptive stages in the life cycles of interstellar clouds and sheds crucial light on the formation of stars by providing new insight into the relationship between interstellar clouds and the stars that form in them, a central component of galactic evolution. A detailed study of the ISM of the Milky Way is used to construct a template to interpret global star formation in other spiral galaxies.

The minimum science mission of HEAT is to make significant contributions to achieving the three major science goals described below. Using the proposed instrument and observing methodology, the minimum mission is expected to be achievable in a single season of survey operation from Dome A.

Goal 1: Observing the Life Cycle of Interstellar Clouds

The formation of interstellar clouds is a prerequisite for star formation, yet the process has not yet been observed! The HEAT is designed with the unique combination of sensitivity and resolution needed to observe atomic clouds in the process of becoming giant molecular clouds (GMCs) and their subsequent dissolution into diffuse gas via stellar feedback.

Goal 2: Measuring the Galactic Star Formation Rate

The HEAT will probe the relation between the gas surface density on kiloparsec scales and the N^+−derived

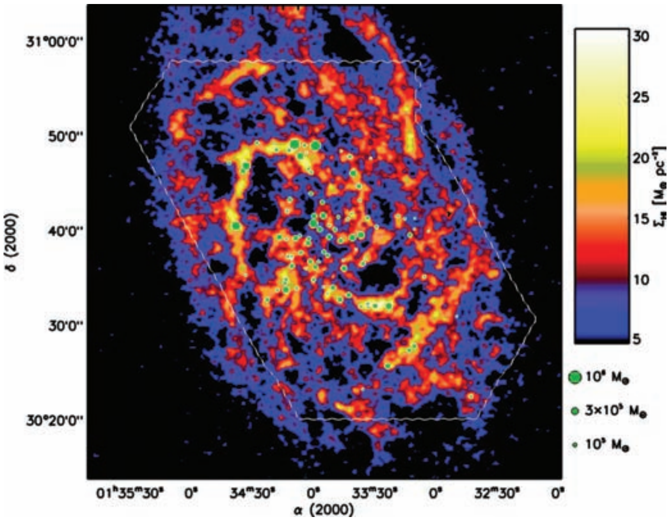

FIGURE 2. The location of GMCs in the nearby spiral galaxy M33 are overlaid upon an integrated intensity map of the HI 21-cm line (Engargiola et al., 2003). These observations show that GMCs are formed from large structure of atomic gas, foreshadowing the detailed study of GMC formation that HEAT will provide in the Milky Way.

star formation rate, so that we might be able to better understand the empirical Schmidt law used to estimate the star-forming properties of external galaxies (Schmidt, 1959; Kennicutt et al., 1998).

GOAL 3: CONSTRUCTING A MILKY WAY TEMPLATE

C^+ and N^+ will be the premier diagnostic tools for terahertz studies of external galaxies with large redshifts (e.g., with Atacama Large Millimeter Array, or ALMA). In such spatially unresolved galaxies, however, only global properties can be measured. The HEAT observations will yield detailed interstellar studies of the widely varying conditions in our own Milky Way galaxy and serve as a crucial diagnostic template or "Rosetta Stone" that can be used to translate the global properties of more distant galaxies.

PROPERTIES OF THE PROPOSED SURVEY

The HEAT's science drivers represent a definitive survey that would not only provide the clearest view of interstellar clouds and their evolution in the galaxy but would also serve as the reference map for contemporary focused studies with space, suborbital, and ground observatories. The following properties define the science requirements for the HEAT survey.

HIGH-RESOLUTION SPECTROSCOPIC IMAGING

Techniques commonly used to diagnose the molecular ISM include submillimeter continuum mapping of dust emission (Hildebrand et al., 1983) and dust extinction mapping at optical and near-infrared wavelengths (Lada et al., 1994). Large-format detector arrays in the infrared are now commonplace, and with the advent of bolometer arrays, both techniques have performed degree-scale maps of molecular material. However, these techniques have limited applicability to the study of the structure of the galactic ISM due to the complete lack of kinematic information.

The confluence of many clouds along most galactic lines of sight can only be disentangled with spectral line techniques. Fitting to a model of galactic rotation is often the only way to determine each cloud's distance and location within the galaxy. With resolution finer than 1 km/s, a cloud's kinematic location can even be distinguished from other phenomena that alter the line shape, such as turbulence, rotation, and local effects, such as protostellar outflows. These kinematic components play a vital role in the sculpting of interstellar clouds, and a survey that has the goal of understanding their evolution *must* be able to measure them. The HEAT will easily resolve the intrinsic profiles of galactic interstellar lines, with a resolution of <0.4 km/s up to 370 km/s of spectrometer bandwidth, comparable to the galactic rotational velocity.

A TERAHERTZ GALACTIC PLANE SURVEY

Molecular line surveys have been performed over the entire sky in the light of the 2.6 mm $J = 1–0$ line of ^{12}CO, and they have been used to synthesize our best understanding of the molecular content of the galaxy. Still, our understanding of the evolution of galactic molecular clouds is woefully incomplete. As already described in the HEAT Science Goals section, the dominant spectral lines of the galaxy are the fine-structure far-infrared and submillimeter lines of C, CO, C^+, and N^+. They probe and regulate all aspects of the formation and destruction of star-forming clouds. They will provide the first barometric maps of the galaxy and illuminate the properties of clouds and their life cycles in relation to their location in the galaxy. They will highlight the delicate interplay between (massive) stars and the clouds which form them, a critical component of galactic evolution. A terahertz survey will dramatically enhance the value of existing millimeter-wave CO observations by providing critical excitation constraints.

ARCMINUTE ANGULAR RESOLUTION AND FULLY SAMPLED MAPS

Good angular resolution is a critical aspect of improvement for a new galactic survey. Previous surveys of [N II] and [C II] were limited to very small regions (KAO and ISO) or had low angular resolution (COBE and BICE) (Bennett et al., 1994; Nakagawa et al., 1998). The HEAT will fully sample both species over large regions of sky to their diffraction-limited resolution of 1.7′ and 1.3′, respectively. Arcminute resolution with proper sampling is crucial to disentangling different clouds and cloud components over large distances in the galaxy. For example, the Jeans length for star formation in a GMC is approximately 0.5 pc. This length scale is resolved by HEAT to a distance of 500 pc at CO $J = 7–6$ and [C I] and 1200 pc at [C II]. Warm and cold HI clouds and GMCs can be resolved well past 10 kpc.

HIGH SENSITIVITY

The HEAT's high sensitivity is due mostly to the superlative atmospheric conditions expected above Dome A, Antarctica. The extreme cold and exceptional dryness allow ground-based observations into the otherwise forbidden terahertz windows. A plot of the expected atmospheric transmission for excellent winter observing conditions at Dome A versus the comparable opacity at the South Pole is plotted in Figure 3. The high elevation, cold atmosphere, and benign wind conditions at Dome A definitively open the terahertz windows to ground-based observatories and cannot be matched anywhere else on Earth. The implications for the sensitivity to each spectral line is discussed below.

CO J = 7–6 and [C I] J = 2–1

We aim to detect all CO and C^0 to $A_V = 1–2$, where most hydrogen has formed H_2 and CO is just forming. This extinction limit corresponds to $N(CO) \sim 5 \times 10^{15}$ cm^{-2} and $N(C) = 1.6 \times 10^{16}$ cm^{-2} for integrated intensities of 3 K k/ms in CO $J = 7–6$ and 1.8 K km/s in [C I]. These sensitivity limits are achievable (three sigma) within 1.6 and 5 minutes, respectively, of integration time at 810 GHz in median winter atmospheric conditions on Dome A with an uncooled Schottky receiver. Limits on line emission in that time would constrain the gas density, based upon the line brightness of millimeter wave transitions.

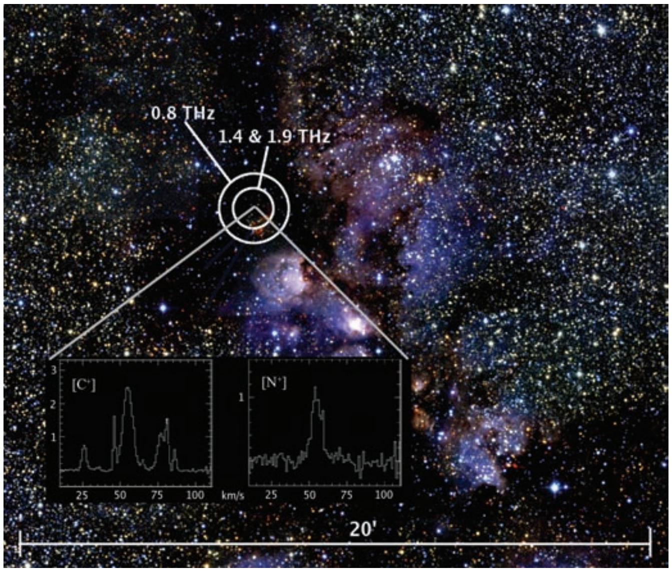

FIGURE 3. Each of HEAT's heterodyne beams is overlaid upon a 2MASS infrared image of NGC 6334. The beams will measure high-resolution spectra in the 0.81-, 1.46-, and 1.90-THz bands, respectively; a small portion (25%) of each is shown as synthetic spectra of NGC 6334.

N^+ and C^+

The fine-structure lines of ionized carbon and nitrogen represent the dominant coolants of the interstellar medium of the galaxy and star-forming galaxies. Indeed, the integrated intensity of the 158-micrometer C^+ line alone represents ~1% of the bolometric luminosity of the galaxy! As such, these lines are relatively easy to detect in the ISM. Our most demanding requirements for detection of C^+ and N^+ lie in the search for the formation of giant molecular clouds (via C^+) and the measurement of the diffuse warm ionized medium in the galaxy (via N^+). A flux limit of 2 K km/s will detect N^+ in warm HI as far away as the molecular ring, achievable in good winter weather in three minutes with velocity smoothing to 3 km/s, appropriate for hot ionized gas. Similarly, the accumulation of GMCs from many cold neutral clouds of atomic hydrogen occurs at low relative column densities of $\sim 5 \times 10^{20}$ cm^{-2}. Since essentially all carbon in such clouds is ionized, $N(C^+) \sim 10^{17}$ cm^{-2}. At the $T = 70$ K common in cold atomic clouds and $n_H = 10^3$ cm^{-3}, the expected C^+ line emission would be 2.5 K km/s, detectable with a Schottky receiver in 10 minutes in excellent winter weather on Dome A. The three sigma limit achievable with deep integrations (two hours) with HEAT would reach $n_H = 10^2$ cm^{-3}. This pressure limit would readily determine whether interstellar material causing significant infrared extinction but without CO is gravitationally bound and likely to be a forming molecular cloud or is simply a line of sight with numerous overlapping diffuse HI clouds.

LARGE-AREA MAPPING COVERAGE OF THE GALACTIC PLANE

From previous CO surveys it is known that the scale height of CO emission toward the inner galaxy is less than one degree (Dame et al., 1987, 2001). The BICE balloon experiment demonstrated that the C^+ distribution is more extended but is still confined to $|b| < 1$. Interstellar pressure, abundances, and physical conditions vary strongly as a function of galactocentric radius, so it is necessary to probe the inner galaxy, the outer galaxy and both spiral arms and interarm regions to obtain a statistically meaningful survey that encompasses the broad dynamic range of physical conditions in the galaxy. We propose therefore to probe the entire galactic plane as seen from Dome A ($0^o > l > -120^o$). An unbiased survey will be undertaken, ul-

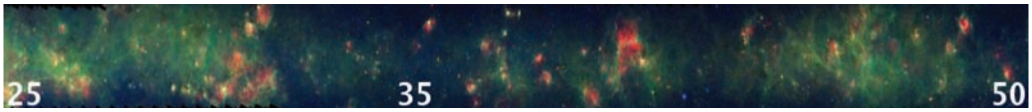

FIGURE 4. An 8.3-micrometer map of the galactic plane from the molecular ring through the Scutum-Crux spiral arm ($-20^{o} > l > -55^{o}$). The yellow rectangle highlights the region to be explored by HEAT in its first season at Dome A. A definitive chemical and kinematic survey of star-forming clouds in [C I] $J = 2$–1 and ^{12}CO $J = 7$–6 of 40 square degrees (~10 square degrees in [C II] and [N II] emission) can be performed in a single season using Schottky receivers. No other site on Earth allows routine access to both far-infrared lines.

timately covering up to 240 square degrees ($-1^{o} < b < 1^{o}$); however, 80 square degrees in two years will be targeted by the Schottky receiver system described here. Figure 4 demonstrates the sky coverage of HEAT's survey of the inner galaxy, with the first season coverage highlighted in yellow. It will probe three crucial components of the galaxy: the molecular ring, the Crux spiral arm, and the interarm region. The remaining sky coverage will be provided by a future upgraded instrument package from the Netherlands Institute for Space Research (SRON), featuring a cryocooled 4 K superconductor insulator superconductor and hot-electron bolometer system. The "inner" galaxy survey will coincide with Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE), a Spitzer Space Telescope (SST) Legacy Program (Benjamin et al., 2003). Above $l = 90^{o}$, most of the CO emission is located at higher galactic latitude, so l and b "strip mapping" will locate the target regions, generally following the outskirts of CO $J = 1$–0 distribution (Dame et al., 1987, 2001), and the best-characterized star-forming regions in the galaxy. The observing program will be designed to maximize synergies with the "Cores to Disks" SST Legacy program (Evans et al., 2003) and other SST GTO programs.

HEAT INSTRUMENTATION OVERVIEW

The HEAT will be a fully automated, state-of-the-art terahertz observatory designed to operate autonomously from Dome A in Antarctica. The combination of high altitude (4,100 m), low precipitation, and extreme cold make the far-infrared atmospheric transmission exceptionally good from this site. In Figure 5 we present a plot of the expected atmospheric transmission above Dome A as a function of wavelength (Lawrence, 2004), indicating that winter weather at Dome A approaches (to order of magnitude) the quality of that achieved by the Stratospheric Observatory for Infrared Astronomy (SOFIA). The wavelengths of several important astrophysical lines are indicated with arrows. The HEAT is designed to take advantage of these unique atmospheric conditions and observe simultaneously in [C II] (158 micrometer), [N II] (205 micrometer), and CO $J = 7$–6 and [C I] (370 micrometer).

A conceptual drawing of HEAT is shown in Figure 6. For robustness and efficiency, the telescope and instrument are integrated into a common optical support structure. The HEAT will be mounted on top of the University of New South Wales' Plateau Observatory (PLATO), which was deployed to Dome A in January 2008. The Plateau Observatory is the successor to the Automated Astrophysical Site-Testing International Observatory (AASTINO) deployed to Dome C in 2003, and it provides power and

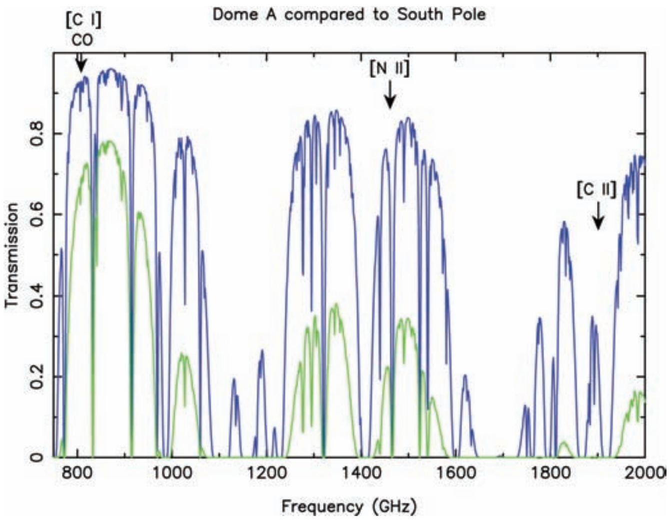

FIGURE 5. Terahertz atmospheric transmission for good (twenty-fifth percentile) winter conditions for the South Pole (bottom line) and Dome A (top line), derived from PWV measurements at the South Pole, atmospheric models from Lawrence (2004), and actual automatic weather station data collected during 2005 from Dome A. The PWV content for each model atmosphere is 210 and 50 micrometers, respectively. Arrows indicate the wavelengths of the [N II], [C II], and CO/[C I] lines.

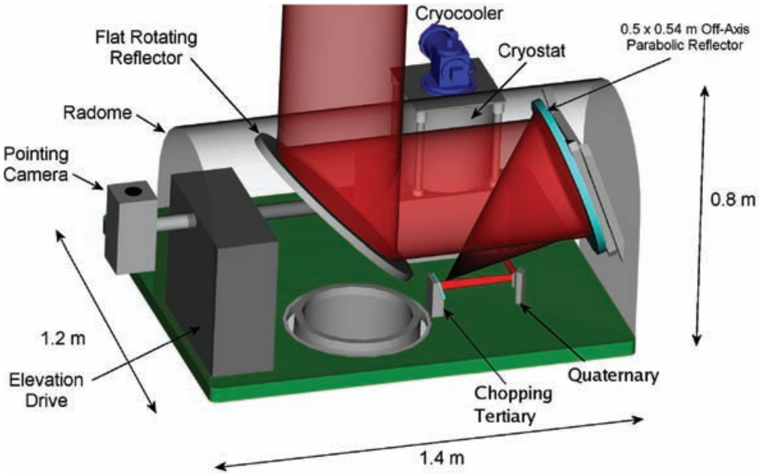

FIGURE 6. The HEAT telescope has an effective collecting area of 0.5 m. Elevation tracking is accomplished by rotating the 45° flat reflector. The entire telescope structure is warmed by waste heat from the PLATO instrument module below. The Schottky mixers used in the instrument package are efficiently cooled to 70 K using a reliable off-the-shelf closed-cycle cryocooler.

communications for the HEAT telescope and instrument. The total power budget for HEAT, including cryogenics, telescope drive system, and instrument control system, is maximally 600 W, which is readily provided by efficient, high-reliability generators within PLATO. Data transfer and control of HEAT will be done via Iridium satellite through the PLATO facilities. The combined HEAT and PLATO facility is functionally equivalent to a space-based observatory.

The HEAT will be able to calibrate observations through several means. (1) A vane with an ambient temperature absorbing load will be located at the cryostat entrance window, allowing standard chopper wheel calibration to be performed. (2) HEAT will routinely perform sky dips to compute the atmospheric optical depth in each of its three wavelength bands. (3) HEAT will regularly observe a standard list of calibration sources. (4) The PLATO currently hosts PreHEAT, a 450-micrometer tipper and spectrometer that measures atmospheric transmission. Its measurements will be coordinated with HEAT spectral line observations to provide cross calibration.

LOGISTICS: DEPLOYMENT TO DOME A

Antarctic science has reached a level of maturity where several options exist for fielding instruments on remote sites. For Dome A, these options include the following:

1. (Chinese) Traverse from Zhongshan Station to Dome A: PLATO and its complement of instruments (including PreHEAT) were deployed to Dome A by a 1300-km Chinese traverse from the coastal Zhongshan station in January 2008. The expedition was a collaborative effort with the Polar Research Institute of China, the National Astronomical Observatory of China, and the Nanjing Institute of Astronomical Optics Technology. Upgrades to PreHEAT and the installation of the full HEAT experiment could potentially be deployed in a similar manner.
2. (American) Twin Otter air support: If a Chinese traverse brings PLATO (in 2007–2008) and HEAT to Dome A (in 2009–2010), U.S. Antarctic Program Twin Otter air support would allow personnel to be flown in from the South Pole or the forthcoming AGAP field camps (such as AGO3) to facilitate the HEAT installation. Furthermore, the HEAT experiment is small enough to be deployed by Twin Otter.
3. (Australian) An Australian Antarctic Division CASA 212 cargo flight directly from Mawson/Davis to Dome A may be possible for transport of the HEAT experiment, with subsequent flights to support fuel and/or personnel for the HEAT installation.

SUMMARY

At this writing, the pathfinder for HEAT, PreHEAT, is operating autonomously from a PLATO module recently deployed to the summit of Dome A by the Polar Research Institute of China. Because of the altitude and extreme cold/dry conditions known to exist at Dome A, the atmospheric opacity above the site is expected to be the lowest on Earth, making it ideal for far-infrared/terahertz observatories. Our hope is that HEAT will follow quickly on the heels of PreHEAT and provide a powerful new window to the universe.

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