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ASTRONOMY FROM THE HIGH ANTARCTIC PLATEAU†

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ABSTRACT

The Antarctic high plateau offers exceptional conditions for infrared and terahertz astronomy, as well as for programs requiring long, uninterrupted periods for measurements made with high cadence and photometric precision (i.e. time domain astronomy). In this review we summarise the special conditions of the Antarctic plateau which facilitate these observing regimes. We also outline some high profile science programs in each that could be conducted most effectively from the Antarctic high plateau, involving the first light in the Universe, the life cycle of our Galaxy, and the equation of state for the Universe. Three high plateau sites are under particular consideration for furthering such scientific programs–Dome A, Dome F and Ridge A. We summarise the activity underway at each site, which includes the building of new stations and the construction of facilities for optical, infrared and terahertz astronomy, as well as the plans for their future development.

Key words: Antarctica: Infrared: Terahertz: Time Domain: Site Testing

1. INTRODUCTION

The high Antarctic plateau provides exceptional conditions for a wide range of astronomical observations. Here the atmosphere is the driest, coldest and most stable on the Earth. This results in lower background sky fluxes, improved atmospheric transmission and long periods of exceptional clarity and photometric stability, in comparison with the best temperate-latitude sites. Of course, Antarctica also presents more challenging conditions and limited access, for both experiment and experimenter. There need to be clear reasons why a particular project should be conducted in Antarctica to justify the extra demands it places on both resources and people. Conditions in space are also better for astronomy, however deployment to Antarctica remains far cheaper ($\sim$ \$10/kg *vs.* $\sim$ \$1,000/kg), and experiments can be developed and deployed there more rapidly, as well as upgraded on an annual basis. Nevertheless, operation in Antarctica is akin to that in space in many aspects, with reliable, autonomous instrumentation and inherent in-built redundancies essential for achieving mission success.

For traditional photon astronomy, from the optical to the millimetre wavebands, the principal advantages of the high Antarctic plateau over temperate sites are that (see Burton (2010); Storey (2013)):

- The sky is 20–50 times darker at infrared wavelengths, due to the extreme cold. These gains are greatest at 2.4 μm ("K_{dark}"), where airglow is low and thermal emission minimal for temperatures of $-60°$C and below.
- The water vapour content is $\sim$ 10 times lower, opening windows across the infrared to terahertz bands. Its level is stable, further facilitating background subtraction (see Fig. 1).
- The aerosol content is $\sim$ 50 times lower, improving transparency and stability in the infrared.
- The free-atmosphere seeing is $\sim$ 2 times better, above an atmospheric boundary layer that is only 10–20 m high.
- The scintillation noise is $\sim$ 2.5 times less, improving the limiting photometric accuracy attainable for precision experiments.
- The sky is continuously dark for months, making possible high cadence measurements over extended time periods.

These conditions make three regimes particular attractive for front-line investigations:

- Deep, wide-field imaging in the infrared, especially at 2.4 μm.
- Spectroscopic imaging at terahertz frequencies,

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Figure 1. Precipitable water vapour (PWV, in mm) during the first half of 2014, as measured at Ridge A, Antarctica (blue) compared to the Chajnantor plateau in Chile, site of the ALMA telescope (green, as measured by the APEX telescope radiometer). While the Chajnantor site regularly drops below 1 mm of PWV, at Ridge A it is nearly always below 250 μm, and drops below 100 μm ppt PWV at times. This opens the THz windows (> 0.5 THz) for near continuous observation. Note also the great stability in the PWV level at Ridge A. Credit: Craig Kulesa.

from 0.5 – 2 THz.

- High cadence, long duration surveys in the infrared searching for transient or time variable sources.

2. SCIENCE DRIVERS FOR ANTARCTICA

We outline here illustrative science experiments for each of these regimes. These projects can most efficiently be conducted from the high Antarctic plateau, exploiting the advantages for conducting infrared, terahertz and time domain astronomy, respectively.

2.1. The ZETA Project (z=20 from Antarctica)

Searching for the light from the first stars.

The first stars were born from gas clouds at the end of the Dark Ages of the Universe — the epoch a few hundred million years after the Big Bang when stars first lit up the Universe (e.g. Wilson et al. (2008)). The intense UV radiation from these stars heated up and ionised the clouds of hydrogen gas from which they formed, resulting in hydrogen recombination radiation. The very brightest emission line this produces, Ly α, occurs in the UV at 91 nm. Redshifted by a factor of about $z = 20$ to today, this radiation should now be detectable at $\sim 2\,\mu$m; i.e. in the infrared portion of the spectrum.

To search for this radiation requires deep, wide-field, high spatial resolution surveys in the infrared. This is best conducted where the background sky signal at these wavelengths is lowest, so as to achieve the highest sensitivities, and where the atmosphere is stable (minimum micro-turbulence) to provide for the sharpest imaging. Such conditions are found from the highest places of the Antarctic plateau, due to the combination of the extreme cold, the stable climate and the low boundary layer. Moderate-sized telescopes readily provide for wide-field of views, when combined with $\sim 0.2''$ seeing, the typical angular scale of the most distant galaxies. Such a project could be undertaken with a 2.5 m class IR telescope, using a focal plane equipped with IR arrays optimised to measure emission in the 2.4 μm $K_{\rm dark}$ window.

2.2. The Galactic Carbon Trail

Dark gas and the life cycle of our Galaxy.

The stars and the gas are phases of matter in a continuous cycle of materials that drives our Galaxy's evolution. Gas clouds collapse under gravity to form stars, and the enriched chemical products of nucleosynthesis inside these stars are returned to the interstellar gas, to be incorporated into another generation of stars. Parts of this life cycle have so far remained hidden, in particular the condensation of clouds of molecular gas out of an atomic substrate. The hydrogen molecules in these new clouds are invisible, too cold to emit radiation; i.e. the gas is "dark" in its primary component. The transformations of the gas between phases may be witnessed through following the emission from lines of the element carbon, which are readily excited in the prevailing conditions of interstellar space (e.g. Wolfire et al. (2010)).

Such measurements require wide-field, spectral line imaging of the neutral and ionised lines of carbon ([CI] and [CII]), as well as of nitrogen ([NII]), which are all emitted in the terahertz wavebands from gas clouds in the Galaxy. In turn, this needs the driest locations on the Earth, with the very lowest levels of water vapour through the atmosphere and hence consistently good transparency in the THz windows, for the radiation to be detectable from the Earth's surface. This program could be conducted using a 5 m class THz frequency telescope, with multi-beam receivers able to measure the fine structure 0.5 and 0.8 THz [CI] and 1.5 THz [NII] lines from the molecular and atomic components of the ISM. It may even be possible to detect the 1.9 THz [CII] line from the very highest places on the Antarctic plateau at times.

2.3. Supernovae and the Expansion of the Universe

The Equation of State for the Universe.

The demonstration that the Universe is flat was an observation first made from Antarctica, using a high-altitude, long duration balloon (de Bernardis et al., 2000). Then showing that the vacuum energy density was responsible for the flatness, and also results in acceleration of the Universe, required measurements of supernovae (SN) at optical wavelengths (Perlmutter et al., 1999; Riess et al., 1998). However, these SN type Ia standard candles are more accurate when measured in the near–IR than in the optical (Barone-Nugent et al., 2012). Improved measurements of the distance scale

Table 1
FUNDAMENTAL PARAMETERS FOR THE KUNLUN STATION ASTRONOMICAL OBSERVATORY AT DOME A

Parameter	Value
Altitude	4,087 m
Average Temperature	-52° C
Wind Speed	$2-5$ m/s
Precipitable Water Vapour (PWV)	0.14 mm
Boundary Layer	13.9 m
Sky Brightness (V–band)	20.5 mag/arcsec^2
Dark Time per Year	2,670 hours

All parameters quoted from the literature (Zhou et al., 2010b; Yang et al., 2010; Bonner et al., 2010).

using such SN may distinguish the Einstein vacuum energy from other possible equations of state. This requires the accumulation of hundreds of accurate SNIa measurements. These can be found using wide-field optical surveys such as that being undertaken by SkyMapper (Schmidt, 2012). However, these surveys are ill-equipped for the necessary infrared follow-up. Wide-field, high cadence measurements in the IR are needed to complement them. In undertaking such measurements, independent detections of IR transients would also be possible. SNIa peak at K = 17.5 mags at a distance 200 Mpc, so $\sim$ 200/yr should be detectable with a small (e.g. 0.5 m class) IR telescope (Dilday et al., 2010; Mould, 2013).

Detection of SN in starburst galaxies has also proven challenging due to the need for accurate subtraction of the bright nuclei in the host galaxy to yield any underlying transient SN signals. Precision photometry is thus also necessary, in addition to high sensitivity at IR wavelengths, to measure transient signals that are extinguished in the optical by dust. All these facets are facilitated for measurements made from the Antarctic plateau. However, the signals from SN buried in the cores of such galaxies are also masked by intrinsic variations in the light curves attributable to activity within these same cores (i.e. Active Galactic Nuclei — AGN). It will also be necessary to conduct a parallel survey in the optical to define the AGN activity, and so remove this component from any time varying signal. Regular monitoring is required to search for such buried SN, with cadences of about 1 week.

All these requirements benefit greatly by the qualities provided by the Antarctic high plateau when using small telescopes: high IR sensitivity, precision photometry, wide-field and high cadences. At 2.4 μm sensitivities are typically $\sim$ 2 mags. better than equivalent measurements made from a temperate site due to the reduced sky background. This is the longest wavelength at which truly deep observations can be conducted from the ground as the sky thermal emission dominates at longer wavelengths. The Antarctic plateau can open a new regime for the time exploration of variability of cosmic sources in the infrared.

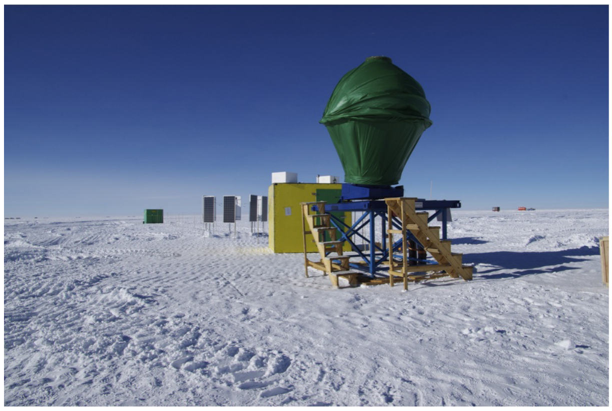

Figure 2. The first AST3 50 cm optical telescope installed at China's Kunlun station at Dome A, the highest place on the Antarctic plateau. AST3 is designed for time domain astronomy, exploiting the long winter night and stable photometric conditions for continuous monitoring. Behind it, the yellow and green buildings are the instrument and engine modules of the Australian-built PLATO automated laboratory. Credit: Chinese Center for Antarctic Astronomy.

3. CURRENT ACTIVITIES

In this section we summarise activities under way at three high plateau stations, located at Dome A, Dome F and Ridge A, respectively.

3.1. Kunlun Station at Dome A

Dome A, which has an altitude of 4,087 m and a lowest recorded temperature of -83°C, exhibits excellent astronomical site conditions (see Table 1). These have been demonstrated through a number of site testing campaigns involving international collaboration that began under the Chinese PANDA program during the International Polar Year (IPY) and have continued subsequently.

Several telescopes have now been used to conduct optical observations from Dome A. The first was CSTAR, an array of 4×14.5 cm small telescopes with a wide field of view ($4.5^\circ \times 4.5^\circ$) that was for stellar photometry in the g, r, i bands and in white light (Yuan et al., 2008; Zhou et al., 2010a). A star catalogue from CSTAR measurements was published by Zhou et al. (2010b). Results for 157 newly detected photometrically variable sources were then published by Wang et al. (2011).

Following the success of CSTAR, a moderate-sized telescope array, AST3 (3×0.5 m Antarctic Survey Telescopes; see Fig. 2), were prepared for Dome A (Cui et al., 2008; Shang et al., 2012) with the aim of conducting a survey for supernovae (SN) and transient sources. Furthermore, a 2.5 m optical/infrared telescope (KDUST – the Kunlun Dark Universe Survey Telescope) has been proposed by the Chinese Center for Antarctic Astronomy (CCAA) for Dome A to in order to explore the dark universe (e.g., Yuan et al. (2013); Zhu et al. (2014)).

Tipping radiometer measurements of the transparency of the atmosphere at 0.66 THz reveal that Dome A is an exceptionally dry site (made with the Pre-HEAT instrument; see Yang et al. (2010)), with an average precipitable water vapour (PWV) of ~ 0.14 mm. The combination of high altitude, low water vapour content and stable atmosphere makes Dome A one of the best sites for submillimetre observations on the Earth. Building on the radiometer measurements, a FIR/THz Fourier Transform Spectrometer (FTS) was installed in order to measure the atmospheric transmission over a wide band in the THz regime, 0.75–15 THz. The results, combined with the 0.66 THz radiometer measurements by Pre-HEAT, strongly suggest that Dome A is a unique site for ground-based THz observations, especially in the $200 - 350\,\mu$m window. Encouraged by these results, the Dome A Terahertz Explorer (DATE5) telescope has been proposed for Dome A. The main reflector aperture is 5 m in diameter with a field of view of 5 arcmin or larger. A surface accuracy of $10\,\mu$m was defined for use with dual-band superconducting spectroscopic arrays operating at $0.78 \sim 0.95$ THz and $1.25 \sim 1.55$ THz (Yang et al., 2013).

DATE5 and KDUST, along with their supporting facilities, form the core part of the mega-science facility for the Chinese Antarctic Kunlun Observatory at Dome A. Feasibility studies for DATE5 are now underway paying particular attention to overcoming the extreme environmental conditions presented by low temperature and low pressure, ice accumulation, as well as the limited support and unattended operation imposed by the remoteness of the Dome A site.

3.2. Fuji Station at Dome F

Dome Fuji (or Dome F; see Fig. 3) is the second highest peak (at 3810 m altitude) on the Antarctic plateau and is 1000 km away from the coastal station of Syowa of the National Institute of Polar Research, Japan. Dome F Station was established in 1995 for paleo environmental studies based on extraction of deep ice cores. Although it is expected to be one of the best astronomical sites on the Antarctic plateau, site studies at Dome F are at an early stage. The first such study was conducted in 2004, when a radiometer at 220 GHz and a SODAR (SOnic Detection And Ranging) were deployed to measure the opacity of the atmosphere and the turbulence in its upper layer. Astronomers joined for the first time in the 2006 expedition in order to undertake the site survey. As the overwinter station had by then been buried under snow after the completion of the ice core drilling program, the astronomy group installed the PLATO–F autonomous laboratory, in collaboration with the University of New South Wales (UNSW), in order to supply power to a SNODAR and various meteorological instruments.

Okita et al. (2013) investigated the astronomical seeing in the free atmosphere above Dome F with a Differential Image Motion Monitor (DIMM) at visible wavelengths (472 nm) at the snow surface and on a stage placed at 11 m height during the austral summers of 2009/2010 and 2012/2013. The seeing often had a local minimum of $\sim 0.3''$ at 18 h local time. Some periods of excellent seeing, $\sim 0.2''$ or smaller, were also observed, sometimes extending for several hours around local mid-

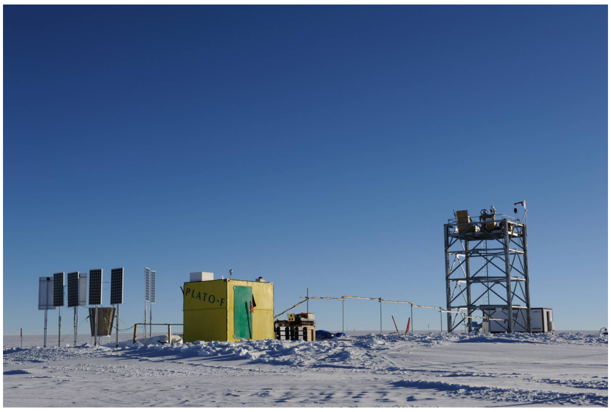

Figure 3. Site study facilities at Japan's Fuji station at Dome F as of 2013. The yellow box is the PLATO–F instrument module. The 9 m-height tower, on which 20 cm and 40 cm telescopes are located, is at the right. Credit: National Institute Polar Research, Japan.

night. The median seeing was $0.52''$. The largest seeing would be caused by periods when the telescope was within the turbulent boundary layer. The diurnal variation seen in the daytime seeing at Dome F was similar to that reported for Dome C, and the height of the surface boundary layer is consistent with previous simulations for Dome F.

Okita et al. (2014) studied the atmospheric turbulence from the snow surface to 400 m above surface boundary layer to investigate the characteristic seeing phenomena at Dome Fuji as a function of the height above the surface, based on the observational results from the SODAR, SNODAR and meteorological instruments. Two DIMMs were used to measure the seeing at 2 m and 11 m above the snow surface. Platinum thermometers placed at several heights on the 16 m meteorological mast were used to measure the vertical temperature profile. Okita et al. found the median height of the surface boundary layer in fine weather in the Antarctic autumn and winter to be 15.3 m (i.e. the 50^{th} percentile). The median absolute deviation (MAD) was 2.7 m. The height of the surface boundary layer remained low and stable for several days. The atmospheric convection is driven by solar insolation during daytime in the Antarctic summer. The local seeing minimum, which results from a balance between solar insolation and radiative cooling at dusk in the Antarctic summer, was determined. The free atmosphere seeing was found to be $\sim 0.23''$ in the visible above the convection layer.

3.3. HEAT at Ridge A

Ridge A is located 400 km from Dome A, and at 4,050 m elevation is marginally lower. From analysis of satellite data Saunders et al. (2009) predicted that Ridge A would have the lowest precipitable water vapour, and hence best THz transmission, of any site on the surface of the Earth. This led to building of the HEAT (High Elevation Antarctic Terahertz) telescope by Craig Kulesa at the University of Arizona to take advantage of this unique opportunity for THz imaging from the ground.

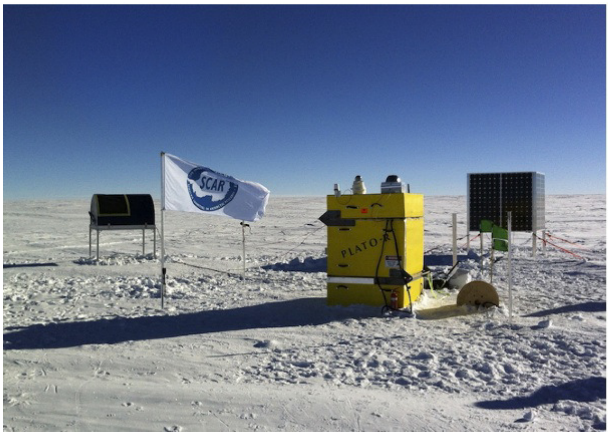

Figure 4. The HEAT (High Elevation Antarctic Terahertz) telescope at the Ridge A observatory, inside its protective enclosure (the black object to left of the SCAR flag). The yellow box is the PLATO–R instrument module, and behind it lies the solar cell cube, providing power in the summer. The PLATO engine model, providing power during winter, is out of view. HEAT is installed from a field camp via a deep-field deployment, with minimal human presence and infrastructure. From Ridge A the THz windows are open for much of the Antarctic winter, where HEAT is undertaking a spectroscopic imaging survey of the Galactic Plane in the carbon and ionized nitrogen lines. Credit: Craig Kulesa.

It has led to the implementation of new mode of undertaking leading-edge science in Antarctica via deep-field deployment to remote field stations. The telescope and associated control systems are first field-readied and tested at the South Pole. This also allows time for essential altitude acclimatisation before deployment. The latter is via Twin Otter aircraft, to Ridge A. 3–4 flights are required to transport all equipment and personnel. The latter (typically 4 people) spend a week at the site, living in tents installing the telescope and associated instrumentation, before returning. All communication is then via the Iridium satellite network.

HEAT is a 62 cm fixed telescope with adjustable tilt-mirror which directs the beam into the cryostat, placed within a (transparent) gore-tex screen to protect it from snow. It observes through the technique of drift-scanning, using the Earth's rotation and adjusting the angle of the mirror to build up an image of the source as it passes through the beam. The telescope is controlled using the Australian built PLATO autonomous laboratory (PLATO–R; see Ashley et al. (2012); see Fig. 4), which is analogous to a spacecraft bus and through which HEAT derives power and communications. PLATO is divided into a power module and an instrument module, connected through an umbilical cord to deliver power to the instrument and telescope. The system operates in a remote environment without human contact for a year at a time, requiring high reliability and redundancy of design. In summer a cube of solar panels provides up to 1 kW of power, with two small diesel generators providing power during the winter night. Two iridium modems provide contact with the facility, and allow the uplinking of commands and the downloading of science data as well as instrument telemetry. PLATO–R has maintained continuous power to HEAT through three successive winters, 2012–2014, while 950 km from the nearest person. A servicing mission each January is used for maintenance, upgrades and re-fuelling.

The cryostat is maintained at 50 K by a closed cycle cooler, drawing just 150 W of power. It contains two schottky diode detectors and heterodyne receivers operating at 0.8 THz ([CI]) and 1.5 THz ([NII]) across a 1 GHz bandpass and delivering ~ 1 km/s spectral resolution. The diffraction limited beam size is $2'$ at 0.8 THz.

HEAT has primarily been used to begin a carbon imaging survey of the southern Galactic plane, tracing the interface region between molecular clouds and the surrounding cold neutral medium. 8 square degrees have so far been mapped (Kulesa et al., 2015). In the first results, Burton et al. (2014) report the discovery of a cold, quiescent giant molecular cloud, about 80 pc long by 5 pc across, which appears to be condensing out of the surrounding substrate. They hypothesise that this represents the early stages of the formation of a giant molecular cloud, before star formation has begun in it. Molecular cloud formation is an essential step in the Galactic ecology and the cycle of material between stars and gas. If this hypothesis is confirmed it represents the first time that this process has been observed.

4. CONCLUSIONs

The Antarctic plateau offers exceptional conditions for observational astronomy. Development of the very highest places on the plateau is now under way. Modest-sized telescopes are running at Dome A, Dome F and Ridge A, testifying to the great potential of these sites. Building and operating an observatory in Antarctica is, however, challenging. A philosophy akin to a space observatory is necessary, with modular deployment, minimal maintenance, remote operations, and redundancy of design critical for success. These challenges need collaboration to solve problems and to bring in needed resources and expertise. Antarctica is set aside in the Antarctic Treaty as a reserve for the conduct of science. Developing facilities to tackle big problems in astronomy is an opportunity for furthering international collaboration and relations. Both SCAR (the Scientific Committee for Antarctic Research) and the IAU (International Astronomical Union), as members of the ICSU (International Council Scientific Unions), can play pivotal roles in bringing togethers the world's scientists and giving them a forum to exchange ideas and work towards common goals. An international astronomical observatory for the Antarctic high plateau might serve as a focus for formulating such plans and strategy.

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