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Antarctic Astronomy: from Infrared to Millimeter Wave

M.G. Burton

Joint Australian Centre for Astrophysical Research in Antarctica (JACARA), School of Physics, University of New South Wales, Sydney, NSW 2052, Australia.

Abstract. The dry, cold, tenuous and stable air above the Antarctic plateau provides superb conditions for the conduct of many classes of astronomical observations. We review the rationale for undertaking photon astronomy from Antarctica, and the disciplines where telescopes are now operating at the Amundsen–Scott South Pole Station.

1. Introduction

The Antarctic plateau provides unique conditions on the Earth for the conduct of observational astronomy. Simply stated, the air is thin, dry and cold and the weather stable, attributes all offering gains to the observational astronomer. These conditions are quite different to those experienced at Antarctic coastal locations, which are frequently subject to violent storms.

The plateau is over 3,000m in elevation, rising up to 4,300m at Dome Argus. An average year-round temperature of -50°C , falling to -90°C at times, vastly reduces the thermal background in the near-IR. The precipitable water vapour content of the air is typically around $250\mu\text{m}$ and can fall below $100\mu\text{m}$, opening up new windows in the infrared and sub-millimeter regimes to ground-based observation. The lack of a diurnal temperature cycle and the low wind speeds on the highest parts of the Antarctic plateau provide conditions of extraordinarily stability, benefiting a wide range of observational programs.

Taken together these conditions provide for an unsurpassed observing environment for Earth-based astronomers across wide ranges of the electromagnetic spectrum. The new science it can engender will be significant. In particular, it will allow us to pursue “formation studies” through new observations in the infrared to millimeter spectral range. This includes the study of events such as the formation of galaxies, the birth of the first stars in them and their subsequent evolution, the life cycle of the interstellar medium and the formation of individual stars and planets in our Galaxy. There are three primary reasons why this is so: the continuum emission from these events peaks in the IR, the dominant cooling lines occur across this spectral range, and the cosmic microwave background peaks in the millimeter.

In the remainder of this paper we discuss the unique parameters of the South Pole site as determined by a suite of experiments over the past few years,

the results from the first telescopes designed to exploit them, and some of the lessons they have provided. We end with a short discussion on future plans for the Antarctic plateau. For a description of the high-energy astrophysics experiments underway the reader is directed to accompanying papers in this volume. A more detailed discussion of possible scientific projects that could be undertaken can be found in the report of the Australian Working Group for Antarctic Astronomy (Burton et al. 1994).

2. Results from Site Testing

From the extensive site testing program undertaken at the South Pole we have determined the following characteristics about the location, with regard to astronomical observations:

- Mean winter temperature -60°C .
- Mean winter windspeed 8 m s^{-1} at bottom of inversion layer and 4 m s^{-1} at top of it.
- Mean visual seeing on-ice $\sim 1.9''$.
- Mean visual seeing at top of inversion layer ($\sim 220\text{ m}$) $0.37'' \pm 0.07''$ (Marks et al. 1996, 1998).
- Fried parameter, r_0 , $\sim 5.5\text{ cm}$ at 5500\AA and $\sim 36\text{ cm}$ at $2.4\mu\text{m}$ (Marks et al. 1998). The corresponding isoplanatic angle (for adaptive optics correction to $0.3''$) at 5500\AA is $1\text{--}2'$, very much greater than at temperate sites.
- Sky background in K-dark window ($2.27\text{--}2.45\mu\text{m}$) as low as $\sim 100\mu\text{Jy arcsec}^{-2}$ (20–100 times less than at temperate sites) (Ashley et al. 1996, Nguyen et al. 1996).
- Sky background in L-band ($3\text{--}3.8\mu\text{m}$) $\sim 100\text{ mJy arcsec}^{-2}$ (~ 20 times less than at temperate sites) (Ashley et al. 1996).
- Summer time sky background at $11.5\mu\text{m}$ $\sim 35\text{ Jy arcsec}^{-2}$ (10 times less than at temperate sites), with an anticipated level of $\sim 1\text{ Jy arcsec}^{-2}$ in winter (Smith & Harper, 1997).
- Sky noise at $11.5\mu\text{m}$ restricted to frequencies below 0.2 Hz compared to 2 Hz at temperate sites (Smith & Harper, 1997).
- Vastly improved atmospheric transmission in the sub-millimeter over temperate sites, with less than $250\mu\text{m}$ ppt H_2O for half the time in winter (Chamberlin et al. 1997), compared to best values of $\sim 1\text{ mm}$ elsewhere.
- Zenith opacity at 492 GHz ($610\mu\text{m}$) below 0.7 for half the time during winter and spring, and remaining below 1 for weeks at a time (Chamberlin et al. 1997).
- Zenith opacity in the millimeter, at 225 GHz (1.3 mm), less than 0.05 for over half the time, with sky noise more than 20 times smaller than good temperate sites in the winter (Chamberlin & Bally, 1994, 1995).

3. Overview of the Scientific Potential

3.1. Near-IR astronomy

The most sensitive observations that can be made will be those in the 2.3-2.5 μm “K-dark” window. In K-dark airglow emission is virtually absent, and the thermal emission is dramatically reduced in Antarctica. The measured sky values are only an order of magnitude higher than the level of the zodiacal emission, the fundamental limit for all inner Solar System observatories. This itself is at a minimum near these wavelengths.

Of particular scientific interest will be exploiting the K-dark window for deep surveys, *e.g.*, for faint stars, embedded star-forming clusters and for proto-galaxies. For instance, for redshifts in the range $z=3-10$, where galaxy formation occurs, the peak of the mean stellar spectrum is shifted into the near-IR. However, while the absolute gains are less in the 3-4 μm L-band window than in K-dark, the opportunities offered by Antarctica are actually greater at the longer wavelength. This is a result of the combination of the reduced background, the wider bandpasses that can be employed than at temperate sites and the improved stability of the atmosphere. Only limited work has been done in L-band to date. Complete population censuses of star forming regions will be possible, the 3-4 μm band making discrimination of embedded objects with disks from background reddened stars much easier than at 2 μm (see Strom et al. 1989).

3.2. Mid-IR Astronomy

By virtue of its location, the South Pole spends six months of the year in continuous daylight. At 10 and 20 μm this represents perfectly workable conditions. By the nature of the available logistical support, it is far easier to operate through the summer months than in the winter.

The IRAS infrared survey has proved to be a fundamental starting point for many fields of astronomy, and over a decade after the satellite’s launch publication of results from it are still forthcoming. Its major drawback, though, was the large beamsize (0.5' \times 1.5'), leading to source confusion in any crowded fields. This has considerably limited its utility for studying the Galactic plane. The IRAS survey detected objects to an upper limit of 250 mJy at 12 μm . With the large format mid-IR arrays now becoming available, a 2-m class South Pole telescope would provide both the spatial resolution and sensitivity to complete a mid-IR survey of the southern Galactic plane; in one minute of integration the sensitivity would be 5 times better than IRAS even for daytime observations at 11 μm .

3.3. Millimeter and Sub-Millimeter Astronomy

The gains for millimeter and sub-millimeter astronomy stem from the tremendous improvement in the atmospheric transmission above the plateau. Many windows in the sub-mm band are opened up that have only been accessible to date from airborne and spaced-based platforms. Equally significant is the stability of the atmosphere. The windows are open virtually continuously and the sky emission in them stable, allowing accurate background subtraction and flux

calibration. Interferometry at sub-millimeter wavelengths on a regular basis will only be possible from Antarctica. The scientific possibilities are tremendous.

There is negligible extinction at these wavelengths allowing us to peer within the deepest and coldest clouds, near the peak of their black-body continuum emission. The fundamental rotational transitions of molecules such as CO, CS, and HCO⁺ and the light hydrides (*e.g.*, CaH, NaH) occur here. Several transitions can be measured per molecule allowing their excitation state to be determined. Neutral carbon, which has recently been shown to be surprisingly abundant in molecular clouds, has its cooling lines at 370+610 μ m. While the dominant cooling lines of the molecular clouds surrounding active star forming regions will still be unaccessible (*e.g.*, [OI] 63+146 μ m, [CII] 158 μ m) in the Galaxy, at modest redshifts they will be brought into view. This opens up the exciting possibility of observing the onset of star formation in proto-galaxies.

Of at least equal significance are the possibilities offered in Antarctica for studying the cosmic microwave background radiation (CMBR), the relic radiation from the hot Big Bang. It is the exceptional atmospheric stability that makes possible measurements of the background fluctuations ($\Delta T/T \sim 10^{-5}$). Following the detection by the COBE satellite efforts are now devoted to measuring the fluctuations at higher angular scales. Fluctuations arising from the Sunyaev-Zel'dovich (SZ) effect, the up-scattering of the background spectrum by both the hot gas surrounding galaxy clusters and the peculiar velocity of the cluster, should be observable on spatial scales of around 3 arcminutes. This would permit direct determinations of the peculiar velocity of the galaxies from the Hubble flow, independent of their distance, and eventually may even yield rotation curves of individual galaxies. Thus strict constraints will be placed on the matter density of the Universe.

4. Results from the South Pole Observatory (2,900 m)

Two principle astronomical activities are underway at the Amundsen-Scott South Pole Station, operated by the NSF, those of CARA and of AMANDA. Australia, France, Germany, Sweden and the UK also participate in them. We outline here some of the results from the CARA telescopes.

4.1. AST/RO

The 'Antarctic Sub-mm Telescope / Remote Observatory' is a 1.7-m diameter sub-mm telescope commissioned in 1995. It has been conducting a survey for the 492 GHz (610 μ m) [CI] line, a strong emission tracer from the interfaces of molecular clouds but only observable infrequently from other good observing sites. Carbon emission has been found to be widespread and at least as extensive as regions of CO emission in the Galactic plane. It has also been found in all high-latitude clouds searched (Ingalls et al. 1997) and in two star forming regions in the LMC (Stark et al. 1997), including a detection at the 0.02 K level in 30 Doradus, by far the weakest [CI] line ever measured.

4.2. COBRA

The 'Cosmic Background Anisotropy Experiment' was established to take advantage of the high transparency and stability of the sky at the Pole to detect

and measure anisotropies in the CMBR on degree scales. Using the 0.75-m Python telescope, a 123 square degree region of sky has been surveyed at 43 and 90 GHz, yielding a fluctuation of $\delta T = 63_{-5}^{+7} \mu\text{K}$ at an angular scale $l_e = 139_{-34}^{+99}$ (Ruhl et al. 1995, Platt et al. 1997). This is significantly greater than measured by the COBE satellite at 20° angular scales. The 2-m Viper telescope will extend the frequency range and angular scale of the Python results.

4.3. SPIREX

The ‘South Pole Infrared Explorer’ is a 60-cm near-IR telescope installed in 1994. SPIREX has achieved exceedingly dark backgrounds at $2.4 \mu\text{m}$, as low as $22.5 \text{ mags/arcsec}^2$ in one hour of integration. It enjoyed a nearly uninterrupted view of the collisions of Comet Shoemaker-Levy with Jupiter. Only 4 of 20 events were obscured by clouds. Technical problems with the telescope have, however, prevented SPIREX from achieving its full potential, but it has provided an invaluable learning experience on how to operate in the extreme conditions.

4.4. Site Testing

A major part of the effort at the South Pole has involved a comprehensive site testing program, whose principle results were summarized in §2. This work involved a close collaboration between CARA and the Australian JACARA.

5. Dome C (Circe, Concorde or Charlie; 3,200 m)

A French-Italian collaboration started construction of a station on this site in 1995. The first winter-over is scheduled for 2,001. Daytime measurements of the micro-turbulence in the atmosphere were conducted in 1996 and of the summer-time water vapour content ($\sim 500 \mu\text{m ppt}$) in 1997 (Valenziano, this volume). The AASTO (see Storey, this volume) is scheduled to spend the 1999 or 2000 winter fully quantifying the site properties. The particular advantage of Dome C over the Pole is that it is on top of an ice dome rather than being on the flank of one. Thus the katabatic wind is absent, eliminating much of the wind blown snow. It is also thought that the top of the inversion layer will be much closer to ice level, with winds gradients within it minimal, both reducing the seeing and greatly facilitating methods employed to remove the boundary layer contribution from it. Determining the height and characteristics of this layer at Dome C is a priority for the site testing program.

6. Future Plans

Detailed discussion on major facilities that might be constructed on the Antarctic plateau remains premature while site characterization has yet to be completed. Plans for second generation telescopes, intermediate scale facilities that will exploit particular niches yet present relatively simple engineering challenges, are however well advanced. Most developed are the plans for DASI (‘Degree Angular Scale Interferometer’), a 13-element interferometer for measuring CMBR fluctuations on angular scales $l=160-700$ (Carlstrom, 1996). A 10-m sub-mm telescope has been proposed (Walker et al. 1996), which would both extend the

program started by AST/RO to wavelengths from $200\mu\text{m}$ to 6 mm , and undertake CMBR measurements. ‘SPIRIT’ is an Australian proposal for a 2-m class telescope for near- and mid-IR astronomy.

6.1. SPIRIT

The ‘South Pole Infrared Imaging Telescope’ is envisaged as a 2-m class infrared optimised telescope capable of yielding near-diffraction limited images at $2.4\mu\text{m}$. It will be a wide-field telescope, instrumented with large format focal plane arrays, and operate primarily from $2\text{--}4\mu\text{m}$ and $10\text{--}12\mu\text{m}$. It will use a tip-tilt mirror, which will recover most of the diffraction limit given that $r_0 \sim 36\text{ cm}$ at $2.4\mu\text{m}$. With a $0.25''$ pixel scale and $4'$ field of view, scientific projects would emphasise deep surveys. The first programs would involve surveys of star forming regions at $3.8\mu\text{m}$ and $11.8\mu\text{m}$, to make a complete census of the embedded population of several such regions. This would not only yield exciting new science, but would also provide a testbed for more ambitious telescopes in the future.

7. Conclusions

Antarctica offers unprecedented opportunities for the advancement of the science of astronomy. Several issues do remain to be answered from the site-testing programs underway, however, before we can properly assess all the gains that are possible. In particular, we must determine at what height a telescope must be placed above the ice to benefit from superb seeing. It is clear, however, that at wavelengths beyond $10\mu\text{m}$ the plateau is the pre-eminent observatory location on the Earth, and the prospects for the near-IR are excellent.

To construct the observatory we desire presents a formidable challenge. Tremendous technological, logistical and political hurdles have to be overcome. However, as the CARA observatory at the South Pole now demonstrates, Antarctic astronomy is now a practical reality and the obstacles in front of it can be surmounted. The current CARA telescopes are small instruments, but have brought back new first scientific results. They have proved that, with sufficient determination, constructing a major international observatory on the Antarctic plateau is a realistic dream to have.

8. Further Information

The JACARA web page, at URL <http://www.phys.unsw.edu.au/~mgb/jacara.html>, provides further information on Antarctic astronomy.

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