

The Scientific Case for Antarctic Astronomy

Michael Burton

University of New South Wales, School of Physics, PO Box 1, Kensington, NSW 2033,
Australia.

1 Introduction

The Antarctic Plateau is almost certainly the best site on the surface of the Earth for many types of astronomical observations. The extremely cold, dry and tenuous atmosphere offers observing conditions unequalled elsewhere on our planet. Undertaking astronomy from the Plateau does, however, present a considerable challenge to our logistical and technological capabilities. A clear understanding of the potential scientific gains is essential prior to planning facilities. This paper describes the scientific rationale behind moves to construct an Antarctic observatory, and discusses how to achieve it.

1.1 The Challenge of Astronomy

The study of astronomy addresses the fundamental questions of what the universe is made of, why it is this way, and what will become of it? During the past century many of the basic questions concerning the nature of visible objects in the universe have been answered. The past 50 years have witnessed the opening up of new wavelength regimes to investigation, from gamma rays to radio waves, and uncovered a plethora of new and unimagined objects, such as quasars, pulsars, and protostars shrouded in cocoons of gas and dust. Some of these objects we now believe we understand whereas others have thrown up completely new puzzles. How for instance, did galaxies form from the initially smooth and expanding primordial gas, from which we see today the relic microwave background radiation? How do stars form, how long does it take and what determines their mass? When do they form planetary systems and which might be suitable as the progenitors of life?

Figure 1: Map of Antarctica

This map shows the location of sites being considered for astronomy on the high plateau (Dome A, Dome C, South Pole and Vostok), as well as the Australian bases along the coast, Casey, Davis and Mawson, the US base at McMurdo, and the adjacent New Zealand base, Scott. The limits of the Australian Antarctic Territory (AAT) and the Ross Dependency are marked.

We address such fundamental questions using instrumentation capable of collecting and measuring the fluxes of photons and particles across the entire energy spectrum. Four principle factors affect our ability to do so:

- Technological limitations.
- Poor transmission through the atmosphere.
- Local sources of interference.
- At infrared wavelengths, thermal radiation from the telescope and atmosphere.

As detector efficiencies approach 100% with near-zero readout noise, and telescopes approach the maximum sizes permitted by engineering constraints, we are nearing the limits placed by technology on the number of photons that can be collected. The other three factors can in principle be overcome by cooling the observatory (for the infrared) and placing it in space. Although space offers the ultimate observatory location, economic considerations restrict our progress in this direction. The terrestrial problems can be minimised by siting telescopes on high, dry, cold mountain tops with stable weather patterns. Mauna Kea in Hawaii is the pre-eminent such site now in use. The conditions on the Antarctic Plateau are, however, considerably superior for many kinds of observation.

1.2 The Challenge of Antarctica

Antarctica is simultaneously the coldest, driest and highest continent on the Earth. Indigenous life is confined to the coastal perimeter; the vast, empty ice plateau provides a pristine environment to conduct scientific experiments free from many of the debilitating and contaminating influences experienced elsewhere. The great depth of ice provides a continuous record of climatic conditions over thousands of years. The clean, pure air provides a reference benchmark with which to examine human influence on the environment. The clear skies above provide an unparalleled view upon the cosmos.

Several potential observing sites are being considered. The South Pole site, where a US research base is sited, is the most accessible. Potentially the best site is the crest of Dome Argus

(Dome A), but this is relatively inaccessible at present. An interesting compromise, certainly better than South Pole and more accessible than Dome A, is Dome Circe (Dome C), where a French research station is being developed. Another high plateau site is the Russian base at Vostok.

2 The Potential of Antarctic Astronomy

The combination of cold, dry and tenuous air makes the Antarctic Plateau the premier astronomical observing site on the Earth. It reaches nearly 4,300 m altitude and is both the coldest and driest place on the Earth. Temperatures average -50°C year round, dropping below -90° at higher elevations in winter. Winds are generally light; the katabatic air flow originating on the highest parts of the Plateau does not develop its fury till it nears the coast. Records from Vostok (3,500 m) show a year-round average wind speed of only 5 m/s for instance, and less than $(\frac{2}{8})^{\text{ths}}$ cloud cover for over half the year. The air is exceedingly dry, averaging 0.3 mm of precipitable water vapour. These climatic factors enhance conditions for astronomy:

2.1 The Darkest Sky

Imaging in the near-infrared ($1\text{--}5\ \mu\text{m}$) is limited by a combination of the airglow emission from altitudes of 80–90 km and thermal emission from the atmosphere and telescope. The near-infrared lies on the Wien side of the blackbody emission curve from room temperature objects. In consequence, a small drop in temperature yields a large decline in thermal radiation. At -60°C , typical of the South Pole in winter, this translates to a reduction of over two orders of magnitude in the sky flux at $2.4\ \mu\text{m}$ compared to the level at 0°C , typical of Mauna Kea. The spectral band between 2.27 and $2.45\ \mu\text{m}$ is devoid of strong airglow emission. Thus background-limited observations in this window will experience a signal-to-noise gain of over an order of magnitude.

The reduction in the thermal background should place it close to the natural limit set by zodiacal emission (Harper, 1989). Coincidentally, the zodiacal emission is at a minimum in the near-infrared, between the scattered sunlight and thermal emission components. Thus, it

would not be possible to find as dark a site elsewhere on the Earth, nor a darker site anywhere within the inner solar system, over the electromagnetic spectrum.

2.2 The Driest Air

The Antarctic Plateau is the driest desert on the Earth, with the lowest columns of precipitable water vapour of any ground-based site. Atmospheric water vapour absorbs most of the incident radiation in the infrared and millimetre wavebands. Typical winter time values are 100–300 μm ppt H_2O on the Plateau. For comparison, an excellent night on Mauna Kea would experience 1.2 mm, and for Siding Spring Observatory typically 5–10 mm. In the sub-millimetre, wavelengths that can barely be observed on a good night from Mauna Kea will be accessible nearly all the time from Antarctica. In the mid- and far-infrared some completely new wavebands would be opened from the ground for the first time.

2.3 The Steadiest Air

In the visible and near-infrared, the degree of blurring of images due to the Earth’s atmosphere, or “seeing”, is just as significant a factor as a telescope’s diameter in determining its sensitivity, as well as limiting the angular resolution obtainable in direct imaging. Image degradation is due to differential diffraction caused almost entirely by microthermal inhomogeneity of the atmosphere. At most sites, much of the microthermal activity results from diurnal temperature variation. There may also be contributions induced by air flow over rough ground. In the Antarctic winter the diurnal temperature variation will be negligible, so a major cause of seeing is eliminated (Gillingham, 1993). Moreover, the Antarctic circulation pattern centres on the highest part of the Plateau, with a predominantly laminar flow due to settling of the cold air. Thus we expect extraordinarily stable and uniform optical conditions in the upper atmosphere above the highest part of the Plateau.

Mitigating against these positive attributes, however, is the presence of a strong surface inversion layer, which can occur during the most stable conditions, wherein the temperature can rise over 10 degrees in a few vertical metres. Stirring of this boundary layer will lead to large air temperature variations, which would degrade the seeing. Quantitative data on the effect is

now being obtained.

The potential exists for seeing conditions superior to any other ground-based site. This is particularly relevant to optical and near-infrared wavelengths, where even the most sophisticated adaptive optics packages cannot attain significantly sub-arcsecond images over a large field of view. Since the diffraction limit is much less than the best seeing obtained, there is much to gain from a telescope on the Antarctic Plateau.

2.4 The Clearest Air

At optical wavelengths, especially towards the ultraviolet, atmospheric extinction can be quite high due to particulate content from smoke and dust (both natural and man-made). The Antarctic Plateau has the lowest concentration of suspended particulates of air anywhere on the planet. With the additional advantage of altitude, it potentially offers the most stable photometric site in the world.

2.5 Minimal Interference

Increasingly, astronomical observations are being compromised by man-made interference due to artificial lighting and electronic transmissions. Ultimately these will limit both optical and radio astronomy from inhabited locations. The Antarctic Plateau is almost entirely free from such pollution, and should remain so for centuries.

2.6 Continuous Observation

An astronomical source visible from the South Pole never sets, and in principle is observable continuously. Moreover it is always at the same zenith angle. Elsewhere on the Antarctic Plateau, the majority of sources will always remain above the horizon, and the daily range in zenith angle will be small. Hence very long period monitoring is possible, providing gains to selected projects across the entire spectrum.

2.7 Geographical Considerations

For some purposes the location of Antarctica is itself a bonus. Particularly relevant is the ability to use long north–south baselines for radio interferometry between Antarctica and Australia, unattainable elsewhere in the southern hemisphere. Links to spacecraft (*e.g.*, Radioastron, VSOP) would also be particularly valuable for the same reason.

2.8 Particle Astronomy

The needs of particle astronomy, observing cosmic rays, gamma rays and neutrinos, differ from those of photon astronomy. Yet Antarctica again offers some significant advantages, as is evidenced by the extensive activity now taking place in these fields at several locations around the continent. These arise from several factors. Proximity to the magnetic poles allows neutron secondaries from cosmic rays of lower energies to be detected. Large quantities of ice are available as pure absorbers of incident particles. The geographical location is vital to the complete global coverage required to observe some phenomena effectively. And the search for ultra-high-energy gamma-ray point sources with high southern declinations can be undertaken only from Antarctica.

3 Scientific Issues

3.1 Cosmology and the Formation of Galaxies

A central question in cosmology is when the first galaxies formed from the initially homogeneous distribution of matter and radiation evidenced by the smoothness of the Cosmic Microwave Background (CMB) radiation. The collapse of matter into clusters of galaxies must be imprinted on the CMB as small-scale irregularities, as reported from the COBE satellite (Smoot *et al.*, 1992). The nature of the trigger mechanism for the collapse is widely debated but unknown and it is necessary to map the level of the anisotropy in order to constrain the many competing theories. Fluctuations in the CMB towards distant clusters of galaxies due to their peculiar velocities with respect to the smooth Hubble flow, the kinematic Sunyaev-

Zel'dovich effect, yields the density of the universe. An Antarctic telescope could provide the most sensitive instrument for both these projects because of the excellent transmission in the 1-3 mm waveband, where the CMB peaks, the long continuous observations that could be made, and the stable air.

3.2 The Birth of the First Stars in Galaxies

The formation of the first stars took place in a gas composed essentially of pure hydrogen and helium. Cooling of the collapsing clouds must have been through the inefficient mechanism of molecular hydrogen line emission, and thus the whole process would be quite different from star formation occurring today. Depending on the redshift of the proto-galactic cloud, the H_2 lines will now lie in the range 5 to 300 μm . Models suggest that the interstellar medium would be quickly enriched by elements with masses around that of oxygen, so that the next generation of star formation would be detected through emission of [O I] 63 μm , [C II] 158 μm , [Si II] 35 μm , and the H_2 lines. Eventually dust would form and re-process the radiation into far-infrared continuum. The signposts of the first star formation therefore lie in the far-infrared and sub-millimetre bands, regimes almost exclusively observable from the ground in Antarctica.

3.3 The Evolution of Galaxies

As a galaxy evolves, and a substantial fraction of the interstellar medium is locked up in stars, the veil surrounding the galaxy will clear and the starlight will shine through. For redshifts in the range $z=3$ to 10 the peak of the mean stellar spectrum can be seen in the near-infrared. The faint proto-galactic stellar light should be detectable by sensitive observations in the 2.4 μm window only possible from Antarctica.

Between 0.1 and 1% of the total luminosity of the stars is processed into a few far-infrared spectral lines. Observation of these lines would allow the build-up of metallicity to be followed, as well as the derivation of physical parameters of the medium, such as its density, temperature and radiation field. The new atmospheric windows available from Antarctica will allow such studies to be made.

3.4 The Interstellar Medium

Many fundamental processes in our interstellar medium (ISM) can be studied only at far-infrared and sub-millimetre wavelengths. These include the ground-state fine-structure lines of many common elements, such as O, C, C⁺ and Si⁺, continuum emission from the cold interstellar dust which makes up most of the dust mass in the Galaxy, and high rotational transitions of excited molecules such as CO, CS and HCO⁺. Such lines provide unique tracers of the events which stir up and regulate the ISM, shock waves and ultraviolet radiation. The interaction of star forming regions with molecular clouds gives rise to strong shocked and fluorescent emission from H₂, in the near- and mid-infrared.

3.5 The Formation of Stars and Planets in our Galaxy

The southern skies contain some of the nearest and richest star forming regions in the Galaxy, such as those in ρ Ophiuchus, Corona Australis, Chameleon and Lupus. Little is known of how a molecular cloud collapses to form stars, or of what determines the number and range of masses that form. Proto-stellar condensations emit in the millimetre and sub-millimetre continuum. The dynamics and conditions in the associated dense clumps of gas can be probed with high-rotational transitions of CS, also in the sub-millimetre. The populations of embedded star-forming clusters are revealed in the near-infrared, allowing study of the initial mass function, and particularly its form at the low mass end, extending down to the brown dwarf regime. An infrared excess due to a hot proto-planetary disk surrounding a forming star would also be detectable.

4 The Way Forward

This paper has discussed the scientific gains attainable from an astronomical observatory sited on the Antarctic Plateau. It is clear that opportunities exist across many facets of both the electromagnetic and high-energy particle spectra for new science to be undertaken. There are formidable logistical and operational requirements to be overcome, akin in many respects to a space programme, but none which present an insurmountable obstacle. The possibilities for considerably furthering our understanding of the universe are sufficiently high as to merit pursuit of the goal of establishing an astronomical observatory on the Antarctic Plateau. The opportunities for infrared and sub-millimetre astronomy are truly exceptional.

We need to devise a programme for Antarctic astronomy. The programme must recognize the challenges ahead and thus explore the technical limitations thoroughly before embarking on the building of astronomical facilities. It should complement developments occurring world-wide in astronomy, and be clearly focused to exploit those aspects of Antarctica which provide truly unique conditions for astronomy. It should follow a staged approach towards an observatory, starting with simple and limited facilities and gradually increasing the degree of sophistication and performance as our technical capabilities develop and our expectations of the site quality are proven.

An Antarctic astronomy programme should have as its long term goal the construction of a major facility at the best site available, most probably the highest parts of the Plateau, Domes A or C. Such a goal is indeed ambitious and beyond the resources of any one country. It will not take place within this century. A likely route is as follows:

- Site testing.
- Operation of testbed facilities and development of infrastructure.
- Construction of intermediate-sized facilities.
- Construction of a major observatory at the premier site available.

Thorough site testing now is absolutely essential. Much of the argument given in this document assumes superlative observing conditions, but these need to be verified.

The next stage is the development of small-scale facilities in order to gain the experience necessary to operate in the extreme environment. Concurrently, the level of infrastructure and logistical support needs to be built up. The US *Center for Astrophysical Research in Antarctica* is undertaking such an exercise at the Amundsen-Scott South Pole station. Under development are three facilities: the Cosmic Background Anisotropy Experiment (COBRA; Ruhl *et al.*, 1993), consisting of a 2-m and a 0.5-m antenna designed to measure the microwave background anisotropy on angular scales from 15 arcmin to 20° ; the Antarctic Sub-millimeter Telescope and Remote Observatory (ASTRO; Stark, 1989), a 1.7-m offset-fed parabolic antenna capable of surveying spectral lines in the sub-millimetre window; and the South Pole Infrared Explorer (SPIREX; Hereld, 1993), consisting of an infrared camera and spectrometer, mounted on a 60-cm telescope capable of exploiting the low thermal background at $2.4\ \mu\text{m}$. Australia is planning a 60-cm telescope capable of being equipped with optical, infrared and sub-millimetre instrumentation. At 5500\AA the diffraction limit will be 0.2 arcsec and thus capable of exploiting conditions of ‘super-seeing’.

The third stage is the development of a significant facility, capable of undertaking whole new areas of science. Likely interest will centre on a 2.5-m class optical/IR telescope. From $3,000\text{\AA}$ to $2.5\ \mu\text{m}$ this would be expected to achieve image performance no worse than 0.2 arcsec over a wide field, and make the most sensitive observations possible in the near-IR. It would be located on the high plateau, and possibly even flown as a payload of a balloon tethered above the surface inversion layer. Other facilities might be constructed concurrently. They include a millimetre and/or sub-millimetre antenna, a radio VLBI dish and a neutron monitor and muon telescope system.

Looking further ahead, to the development of a major international facility, the possibilities are many and exciting. An 8-m class optical/IR telescope, an optical interferometer, a 10-m class mid-IR/sub-mm telescope, a 15-m class sub-millimetre antenna, a sub-millimetre and millimetre array, and a large neutrino telescope all seem promising projects. All can be more cheaply and effectively operated from Antarctica than from space platforms or the moon. If developed to this degree, the Antarctic Plateau could become one of the world’s major astronomical observatories.

Acknowledgements

This paper is an abbreviated version of a report of the Australian Working Group for Antarctic Astronomy, entitled 'The Scientific Potential for Astronomy from the Antarctic Plateau', published in the 1994 'Proceedings of the Astronomical Society of Australia'. I am grateful to the support of my colleagues on the working group; Dave Aitken, David Allen, Michael Ashley, Russell Cannon, Brad Carter, Gary DaCosta, Mike Dopita, Marc Duldig, Phil Edwards, Peter Gillingham, Peter Hall, Harry Hyland, Peter McGregor, Jeremy Mould, Ray Norris, Elaine Sadler, Craig Smith, Jason Spyromilio and John Storey.

References

- Gillingham, P.R., 1993. *ANARE research notes*, **88**, 290, Australian Institute of Physics 10th Congress, Melbourne University, February 1992. Publications of the Antarctic Division.
- Harper, D.A., 1989. in 'Astrophysics in Antarctica', *Amer. Inst. Phys. conf. proc.* **198**, 123. Eds. D.J. Mullan, M.A. Pomerantz, T. Stanev.
- Hereld, M., 1993. in proceedings of the 'IR astronomy with arrays: the next generation' conference, UCLA, July 19-23 1993, in press. Ed. I.S. McLean.
- Ruhl, J., Dragovan, M., Novak, G., Platts, S., Crone, S. and Pernic, R., 1993. *BAAS*, **25**, 927.
- Smoot, G.F. *et al.*, 1992. *Astrophys. J. (Lett)*, **396**, L1.
- Stark, A.A., 1989. in 'Astrophysics in Antarctica', *Amer. Inst. Phys. conf. proc.* **198**, 67. Eds. D.J. Mullan, M.A. Pomerantz, T. Stanev.