Journal and Proceedings of the Royal Society of New South Wales, vol. 145, nos. 443 & 444, pp. 2-18.
ISSN 0035-9173/12/010002-17

The Evolving Science Case for a large Optical – Infrared Telescope in Antarctica

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Abstract

The summits of the Antarctic plateau provide superlative conditions for optical and infrared astronomy on account of the dry, cold and stable atmosphere. A telescope on one would be more sensitive, and provide better imaging quality, than if placed anywhere else on the Earth. Building such a telescope is, of course, challenging, and so requires a strong scientific motivation. This article describes the evolution of the science case proposed for an Antarctic optical / infrared telescope, outlining the key arguments made in five separate studies from 1994 to 2010. These science cases, while designed to exploit the advantages that Antarctica provides, also needed to be cognisant of developments in astronomy elsewhere. This has seen a remarkable transformation in capability over this period, with new technologies and new telescopes, on the ground and in space. We discuss here how the science focus and the capabilities envisaged for prospective Antarctic telescopes has also changed along with these international developments. There remain frontier science programs where a 2m class Antarctic optical and infrared telescope offers significant gains over any other facility elsewhere, either current or planned.

Keywords: Antarctica, astronomy, telescopes, optical, infrared.

Introduction

The high Antarctic plateau provides a superlative environment for the measurement of the faint light from distant stars and galaxies. This is on account of the extremely dry, cold and stable air. This permits more sensitive observations to be made, across a wider wavelength range, and with sharper imaging precision, for telescope in Antarctica than if placed in any other location on the surface of the Earth. Constructing a telescope to take advantage of these conditions, however, is a formidable challenge on account of the extreme environment and the logistical difficulties that working on that continent poses. No optical telescope larger than 60cm has yet been operated on the Antarctic plateau through winter months. This was the SPIREX telescope, which ran at the South Pole from 1994 to 1999. This telescope actually worked in the infrared (IR) as it is in this regime that the gains from Antarctic operation are most readily apparent. On account of the extreme cold a telescope on the Antarctic plateau has a similar sensitivity in the IR to a temperate-latitude telescope with a mirror roughly four times larger in diameter for certain types of observation, while also offering the capability to more readily view wide fields with high image clarity. The possibilities for undertaking frontier investigations are thus enticing. For the past two decades exploratory investigations have taken place, first at the South Pole, and then at three sites on the summits of the Antarctic plateau (Domes A, C and F). This effort has been aimed at realising this opportunity by overcoming the technical and logistical challenges that confront the telescope builder. Concurrently with this activity on the continent, off it the science case for building an Antarctic telescope has also been developed, to provide the rationale for why such an endeavour should be undertaken. As astronomical infrastructure has grown elsewhere, both on the ground and in space, and as our understanding of what the right science questions to ask has been refined, following discoveries new telescopes have made, so too has the science case for an Antarctic telescope matured.

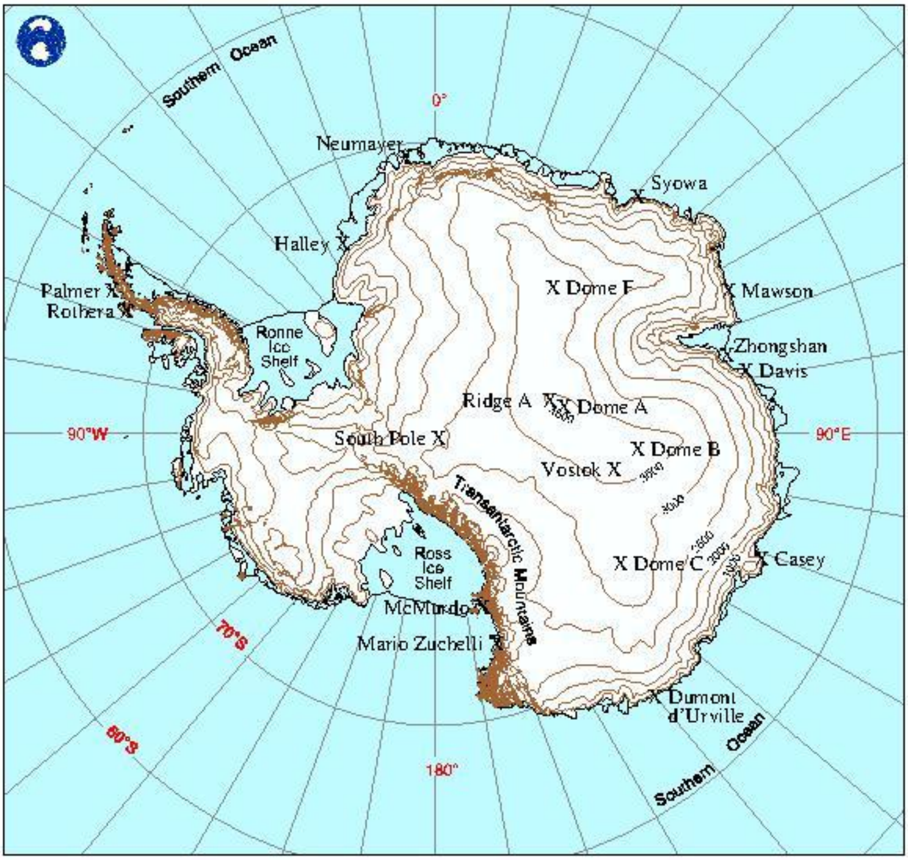

Figure 1. Topographic map of Antarctica, with the location of principal research stations indicated. The high Antarctic plateau runs along the ridge from Dome F to Dome C, through Domes A, B and Vostok. Ridge A lies 400 km SW of Dome A. The South Pole lies on the flank of the Antarctic plateau. Coastal stations supporting high plateau operations are also marked: McMurdo (USA), Mario Zuchelli (Italy), Dumont d'Urville (France), Zhongshan (China) and Syowa (Japan). In addition, the locations of major coastal stations at Casey, Davis & Mawson (Australia), Halley & Rothera (UK), Palmer (USA) and Neumayer (Germany) are shown. Map adapted from a figure supplied by the Australian Antarctic Division, with acknowledgment.

This article discusses this evolving science case, behind the quest to develop optical and infrared astronomy on the continent. A map showing the locations of the principal research stations in Antarctica, including those referred to in this article, is shown in Figure 1.

First words

The first suggestion that the Antarctic plateau might be a suitable place to pursue astronomical observation appears to have come from Admiral Robert Peary, who had led the first successful expedition to the North Pole in 1909 (see Indermuehle, Burton & Maddison 2005). He realised that the long Antarctic winter night (with ~4 months of continuous darkness at the South Pole) would offer new opportunities for astronomical investigation. However, perhaps not unsurprisingly given the heroic endeavours then underway in attempting to even reach the South Pole, he was unable to convince the Director of Yerkes Observatory in the USA, Edwin Frost, to pursue such a course of exploration[1]. The idea did not die though, and eight decades later in 1994, the then Director of Yerkes Observatory, Doyal Harper, was to become the first Director of CARA, the Center for Astrophysical Research in Antarctica. This was the year when the USA began its first major investment in the discipline with the opening of the 'Dark Sector' astronomical observatory at the South Pole. That investment had followed from a decade of modest astronomical experiment at the Amundsen-Scott South Pole Station led by Martin Pomerantz of the Bartol Institute. Pomerantz was to report on these activities at the Astronomical Society of Australia annual scientific meeting in Hobart in 1986 where he said 'one can foresee a burgeoning program of optical, infrared and microwave astronomy being carried out at the South Pole Station during the years ahead' (Pomerantz (1986)). Now, over two decades later, these words are prescient, though the field has developed in ways that Pomerantz could not then have conceived. The South Pole has indeed become a site where frontier measurements in the study of the microwave background radiation from the Big Bang have been made. However, for optical and infrared astronomy this promise has so far been muted. Furtherance of these fields has shifted to the development of sites on the summits of the Antarctic plateau, some that had never even been visited by humans in Pomerantz's day.

Three climatic factors are behind today's activities to develop astronomy on the high plateau – the extremely cold, dry and stable air found there, as first quantitatively discussed by, respectively, Harper (1989), Townes & Melnick (1990) and Gillingham (1993). Harper predicted that the cold air, dropping below -60°C at the South Pole in winter, would make the infrared sky the darkest on the Earth, with sky fluxes up to two orders of magnitude lower than at the best temperate sites, in turn dramatically improving the sensitivity when observations are limited by this sky background. Townes & Melnick analysed measurements which showed that the Antarctic air would hold just a few hundred microns of precipitable water vapour (several times lower than at the best mountain sites). Water vapour in the atmosphere blocks electromagnetic radiation from space from reaching a telescope on the ground across large portions of the infrared and millimetre wavebands, apart from through a few "windows". The much reduced water vapour above Antarctic led them to predict that new windows would be opened for observation of the spectrum.

[1] From correspondence between Peary & Frost in 1912 held at Yerkes Observatory.

Gillingham realised that the strong, but narrow surface inversion layer above the plateau, whereby the temperature could rise by 10-20°C in just a few metres, would present conditions of extraordinary imaging clarity if a telescope could be raised above it, a prediction he called 'super-seeing'.

The subsequent two decades have seen all these predictions verified and their gains further quantified, not only at the South Pole but also on the summits of Dome C and A, where the air is even drier and the depth of the surface inversion layer considerably less. Automated site testing observatories have been built (e.g. Storey, Ashley & Burton (1996), Lawrence, et al. (2005), Lawrence et al. (2009)), the infrared sky brightness at South Pole measured (Ashley et al. (1996)), exceptional seeing conditions found at Dome C (Lawrence et al. (2004)) and high sky transmission found at Dome A in the sub-millimetre and terahertz bands (Yang et al. (2010)). The site testing results, the results of efforts by many scientists, are summarised in the recent review on Astronomy in Antarctica by the author (Burton (2010)). They can be quantitatively summarised through the sensitivity equation for imaging observations made by a telescope, namely that the integration time to reach a given sensitivity level is proportional to the

$$[\text{Sky} + \text{Telescope Background}] \times \left\{ \frac{\text{Image Size}}{\begin{matrix}\text{Sky} \\ \text{Transmission}\end{matrix} \bullet \begin{matrix}\text{Telescope} \\ \text{Diameter}\end{matrix}} \right\}^2$$

In Antarctica the background flux is between 10 and 100 times lower than at good temperate site in the infrared, the median visual seeing above the boundary layer 2-3 times better and the sky transmission is improved right across the infrared and millimetre bands. Indeed, some windows are only opened at all from the ground at the very highest places on the Antarctic plateau. On substituting appropriate gains into the formula above it can be seen that, for equivalent sized telescopes and instrumentation, some kinds of astronomical observation can readily be undertaken in Antarctica two orders of magnitude more quickly than if conducted from a temperate site.

Science cases for Antarctic astronomy

Concurrent with the site testing of the Antarctic plateau has been the writing of science cases for telescopes in Antarctica. While it is easy to say that an Antarctic telescope would be more sensitive than an equivalent telescope placed on a temperate site, building and operating it is, of course, more difficult as well as being more costly. A science case needs to be cognisant of the relevant issues here if it is to contribute to the furtherance of a telescope project. The field itself is also constantly developing, not just with the building of more advanced facilities elsewhere but also in regard to what is considered to be the most exciting and interesting science to pursue. The science case for a new facility thus needs to constantly evolve if it is to remain relevant. Below we discuss the evolution of the science case for Antarctic astronomy as new opportunities presented themselves for the field's development. Five such cases will be précised. The first four of these (Burton et al. (1994), Burton, Storey & Ashley (2001), Burton et al. (2005) and Lawrence et al. (2009a, b, c)) were all published by the Astronomical Society of Australia. The fifth (Epchtein et al. (2010)) grew from these efforts and was prepared by the European ARENA consortium, but with significant Australian input.

The first Science Case of 1994

The first of these science cases (Burton et al. (1994)) was written as Antarctic astronomy began as a field of study in Australia. The 90's had been labelled as the 'decade of the infrared' by the US decadal astronomy plan. At this time infrared (IR) arrays had only recently been introduced to astronomy, providing true imaging quality in the waveband for the first time. New science was thus relatively easy to do. It was simply a matter of having an IR camera and a telescope to place it on. The 4m-sized telescope still reigned around the world, with the construction of the 8m class telescopes just beginning. In space, only the Hubble Space Telescope had infrared capability, and that only extended to a wavelength 2.5μm; Hubble is primarily an optical facility. The science case prepared, written by 20 Australian astronomers, considered a wide-ranging program of science objectives for Antarctic telescopes, placed under five principal themes:

- *Cosmology and the formation of galaxies*: i.e. fluctuations in the cosmic microwave background radiation.
- *The birth of the first stars in galaxies*: i.e. measurement of the cooling lines emitted by the interstellar gas in the IR to millimetre wavebands.
- *The evolution of galaxies*: i.e. measurement of the light from evolving stellar populations which could be probed at 2.4μm, a wavelength where an Antarctic telescope could make exceedingly sensitive measurements on account of the cold. The window here was termed "K_{Dark}" to contrast it with the "K" band window centred at 2.2μm typically used at temperate sites. It was also called the "Cosmological window" in reference to the potential it had in application for such studies.
- *The interstellar medium*: i.e. spectroscopic measurement of the many spectral features emitted by molecules and dust grains across the IR spectral bands.
- *The formation of stars and planets in our Galaxy*: i.e. measurement of the IR continuum emission that occurs from deeply embedded objects, or from disks around forming stars, or from relatively cool brown dwarfs ('failed stars').

The first of these themes became the principal focus for science at the South Pole over the past two decades. Its pursuit requires sensitive measurement of the tiny fluctuations inherent in the cosmic microwave background radiation. The high transmission of the Antarctic atmosphere at millimetre wavelengths, and the extreme stability of its emission, has enabled a series of increasingly sensitive experiments to be undertaken there, led by US scientists, culminating in the installation of the 10m South Pole Telescope (Carlstrom et al. (2011)).

The other science themes envisaged in this first science case focussed on the opportunities for IR astronomy. Given the youthful state of this field at the time, the investigations proposed were in fact little more than a list of the obvious observations that one might make given an IR facility, since these could all be guaranteed to yield new science. The emphasis on the study was more on how the capability to undertake this science might be built up in Antarctica, rather than on undertaking it. The paper envisaged a 4-step process towards constructing Antarctic telescopes:

- Site testing, to quantify the properties of the Antarctic environment that affect astronomy.
- Prototype facilities, to verify that astronomical observations could be

undertaken in Antarctica and that predicted sensitivities could be achieved, while at the same time building experience in Antarctic operation and developing the necessary infrastructure.

- The construction of intermediate scale facilities, capable of undertaking the programs envisaged in the science case. In particular, a 2.5m diameter optical / IR telescope, capable of imaging with 0.2" resolution over wide fields of view, was proposed as the first such facility to be built.
- The construction of major facilities at the best possible sites; i.e. 8m+ optical / infrared telescopes at the highest location on the Antarctic plateau (Dome A, which at that time had not even been visited by humans). Such a project would be beyond the resources of any one country, and international collaboration was envisaged as an essential element if it was to become a reality.

For step 2 of the above, a prototype telescope was operated at the South Pole from 1994-99 (the 60cm SPIREX – the South Pole InfraRed Explorer – see Hereld (1994), Fowler et al. (1998), showing that it was indeed possible to conduct IR astronomy during the Antarctic winter. Two principal kinds of investigation were undertaken with it (see Rathborne & Burton (2005) for a full summary of the science programs done with SPIREX); the study of the galactic ecology using IR spectral features emitted by the gas and dust of the interstellar medium, and the search for disks associated with the formation of stars through the excess flux they would emit at IR wavelengths. These reflected the last two themes listed above in the science case. Figures 2 and 3 show images obtained with SPIREX, illustrating these two science themes.

Figure 2. SPIREX, the South Pole Infrared Explorer, the first infrared telescope in Antarctica, as depicted on a stamp produced for the International Polar Year of 2007. The background (top) is an infrared image at 3.3μm obtained with SPIREX, showing organic molecules (polycyclic aromatic hydrocarbons) in the star forming region NGC 6334 of the southern Galactic plane (from Burton et al. *2000), and (bottom right), the Australian AASTINO autonomous site testing observatory in front of the twin towers of Concordia station at Dome C.*
***Image**: Australia Post.*

However one serendipitous project also took place, observation of the impacts of comet Shoemaker-Levy 9 with Jupiter, which took place over a 1 week period in 1994 (Severson 2000); SPIREX was the only telescope in the world where every impact could potentially be seen since Jupiter was continuously visible from the South Pole at the time. Subsequently, the prospects for time domain astronomy – i.e. of making high duty cycle, long-time duration observations – has become one of the most interesting possibilities for future Antarctic telescopes.

A study for an airborne intermediate-scale facility also was undertaken – POST, the Polar Stratospheric Telescope, whereby a 4m-class telescope would be placed into the stratosphere on a tethered aerostat (Dopita et al. 1996). A similar range of science investigations as outlined above was considered, with the focus being the exploitation of the thermal IR regime from 2 to 8μm.

The 2001 Science Case – the Douglas Mawson Telescope (DMT)

The 2001 science case (Burton, Storey & Ashley 2001) accompanied a proposal to the Australian Government Major National Research Facility (MNRF) scheme to construct a 2m telescope in Antarctica, to be called the Douglas Mawson Telescope. The name had, of course, been inspired from the pioneering science venture of the great Australian Antarctic explorer. With the 50th anniversary of Australia's first Antarctic station, Mawson Station, coming in 2004, the event was proposed as a suitable occasion to begin the construction of the DMT.

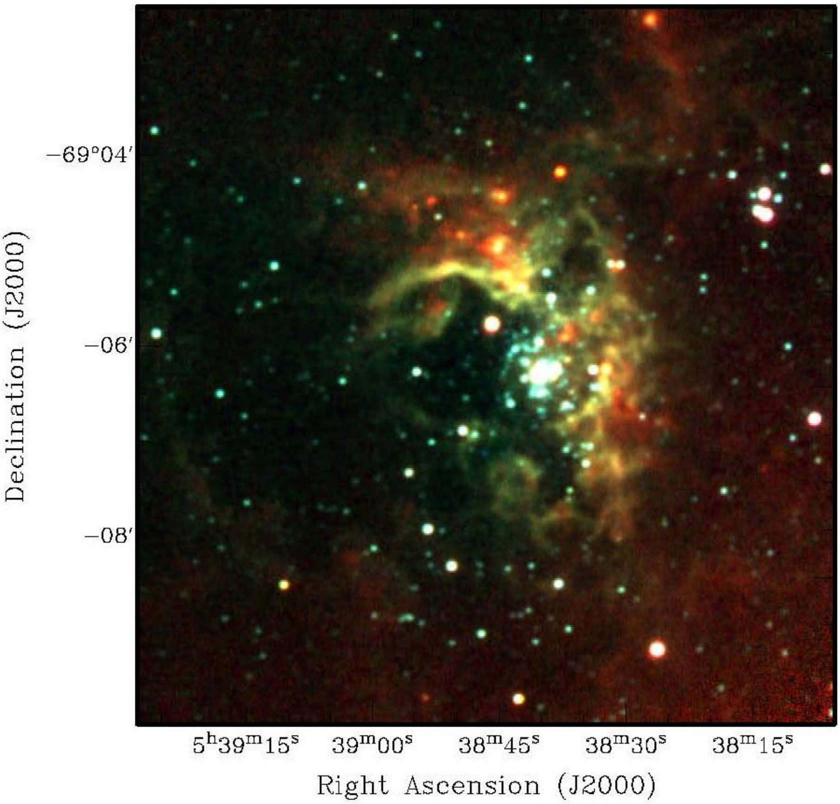

Figure 3. Infrared image of the 30 Doradus star forming region in our neighbouring Galaxy, the Large Magellanic Cloud, as taken by the SPIREX telescope from the South Pole. The red colour shows emission at 3.5µm, with the blue and green showing 1.6µm and 2.2µm band emission imaged by the 2MASS all-sky survey telescope (see Maercker & Burton 2006). When the SPIREX image was obtained it was the deepest ever taken at 3.5µm, despite the modest 60cm diameter of the telescope. ***Image****: Michael Burton.*

to have started, as a field of science, on Mawson's Australasian Antarctic Expedition of 1911-14, with the discovery of the Adelie Land Meteorite on December 5 1912. This was the first meteorite to be discovered in Antarctica and the find was subsequently written up as a scientific paper (Bayly & Stillwell (1923)). While it took nearly 50 years for the next Antarctic meteorite to be found, Antarctica has subsequently provided the majority of all meteorites discovered around the globe, on account of its special geography. The flowing ice sheets over the plateau bring meteorites from all over the continent to 'blue-ice' fields, where the wind ablates the snow, so dropping them. They can then be readily recognised and so collected.

By the time of the 2001 science case a new high plateau station was also under construction, the French-Italian Concordia station at Dome C, where the prospects of 'super-seeing' being attained were high on account of the presumed narrow boundary layer and minimal winds that must exist at that site. Three particular focus areas then presented themselves for a 2m-class telescope:

- *Wide-field, thermal infrared imaging.* For this application, an Antarctic 2m telescope would be as sensitive as the new generation of 8m class telescopes at temperate sites, but with the opportunity of wider fields of view, as well as simpler requirements on instrument design.
- *Continuous observation at 2.4μm [K_{Dark}]*, the wavelength where the background is lowest, then measured to ~100 times less than at temperate-latitude sites. At this wavelength interstellar extinction is also low, allowing one to see through to the centre of the Galaxy.
- *Mid–IR interferometric imaging*, exploiting both the lower sky background and improved sky stability over temperate-latitude sites.

The 2001 science case discussed several illustrative programs that could exploit such advantages, including:

- Near–IR imaging of the environment of embedded star-forming complexes in molecular, neutral and ionized species (e.g. through measuring molecular hydrogen (H2), polyaromatic hydrocarbons (PAH) and hydrogen Br-α spectral line emission).
- Thermal–IR imaging of the embedded stellar population of star forming regions, determining complete population statistics and in particular identifying the youngest members through the incidence of disks around them.
- Near–IR surveys for proto-galaxies and the early stages of star formation in galaxies.
- Micro-lensing studies towards the Galactic centre at 2.4μm, in particular to identify the incidence of secondary lensing caused by planetary systems.
- Mid–IR interferometric imaging of nearby star systems to search directly for proto-planetary disks, zodiacal dust clouds and Jovian-size planets around them.

Notably different from the 1994 paper, the science case had evolved towards emphasising several specific projects of interest, although the telescope was still envisaged as a general purpose facility. Interferometry, while a part of the science case, was not intended for the DMT itself, rather that it would provide a future development direction once a single telescope was operational, by expanding upon it to a suite of 2m-class telescopes. Such an Antarctic interferometer was also discussed in terms of the roadmap towards two proposed space interferometers, the TPF (Terrestrial Planet Finder) and Darwin satellites. These were then under consideration by NASA and ESA (but subsequently abandoned due to cost). A single dish successor telescope to the DMT was also envisaged – the 6.5m ALTA (A Large Telescope in Antarctica) – whose IR sensitivity and image quality would be significantly better than the then-new 8m class telescopes. Unfortunately, news that the DMT proposal had not been funded under the MNRF program was received during a workshop involving the prospective French and Italian collaborators held at the Australian Antarctic Division in Hobart in July 2001. That marked the end of the quest to build the DMT.

The 2005 Science Case – PILOT Pathfinder for an International Large Optical Telescope

In 2004 a Centre of Excellence scheme, administered through the Australian Research Council, was announced by the Government, and this provided the incentive for the next major push for an Antarctic telescope. It was to be called PILOT, the 'Pathfinder for an International Large Optical Telescope', and was proposed as a 2m diameter optical/IR telescope for building at Concordia station at Dome C. The accompanying science case was published in PASA in 2005 (Burton et al. (2005)) and now involved 27 authors. The paper included a detailed performance evaluation for the telescope, calculating sensitivities, imaging quality and survey speeds for a wide range of potential programs from visible to mid-infrared wavelengths, and comparing the Antarctic gains over facilities planned elsewhere for like measurements.

The science case was a comprehensive document, envisaging an observatory mode of operation for the telescope, so catering for the scientific interests of a diverse community. Topics ranged from Solar System studies to searching for the light from the first stars in the Universe. By now, 8m class optical/IR telescopes were common, and the development of the successor to the Hubble Space Telescope well underway (then known as the NGST – the Next Generation Space Telescope). NGST was to be an IR mission. IR missions in space had by now also included MSX and Spitzer, with their significantly better continuum sensitivities in the thermal IR than would be achievable in Antarctica (albeit with lower spatial resolution). The PILOT science case had to be cognisant of the current or planned capabilities of all these facilities, and so it emphasised the wide-field imaging ability in comparison to the deep, narrow-field studies that other facilities might undertake better. The PILOT proposal emphasised four particular science programs, each exploiting a different Antarctic advantage. These were:

- *Probing the early stages of planetary formation*. This required thermal infrared measurements (3-5μm) to search the 'excess' emission produced by a proto-planetary disk surrounding a forming star. Surveys would be undertaken to quantify the incidence and evolution of such disks in star-forming molecular clouds. The cold, stable conditions meant that such measurements would be superior when made from Antarctica than from temperate sites.
- *Revealing the internal structure of stars*, by measuring their surface oscillations, a process akin to the way the Earth resonates when a seismic wave is generated. Such oscillations can be detected by precise and continuous measurement of the photometric fluxes emitted by stars. By following the many modes of oscillations that occur, this allows the internal structure of stars to be probed. The southerly location and the stable atmosphere, in particular the low scintillation noise due to the superb visual seeing (from above the surface boundary layer), made Dome C an excellent site for such measurements.
- *The formation history of galaxies*. This required the direct measurement of the

stellar populations inside other galaxies, rather than of simply global properties (such as of their luminosity, mass and galaxy type) that were commonly obtained in studies of these objects. This, in turn, requires high sensitivity and imaging quality across a wide spectral bandpass, i.e. the determination of spectral colours of stellar groups between the visual and infrared bands, such as [V–K] (the flux difference $F_{0.5\mu m} - F_{2.4\mu m}$). High imaging quality and sensitive infrared measurements are necessary for such observations, as again possible from the Dome C site. By using a tip-tilt secondary mirror, near diffraction limited image quality could be obtained over wide fields of view on account of the seeing quality.

- *The star formation history of the early universe.* This could be probed by following the emission from hydrogen recombination lines with cosmic time. These lines are emitted from the ionized nebulae that surround luminous, massive stars. The Hα (i.e. n=3-2) line, emitted at 656nm, is particularly useful for this purpose as it is red-shifted into the infrared wavebands for galaxies emitting in the first few billion years of the Universe. At a redshift z of ~3 (i.e. about 3-4 billion years after the Big Bang) this light will be observable at a wavelength of 2.4μm, in the K_{Dark} waveband where Antarctic measurements are particularly sensitive due to the extreme cold. Combined with high imaging quality over a wide field of view, the PILOT telescope would be able to measure the star formation rate as a function of epoch and so study its evolution over cosmic time.

The Centre of Excellence proposal also failed to be selected despite strong institutional support within Australia as well as the USA and Europe. On the positive side, this failure to be funded stimulated the European scientists on the proposal to seek support from the European Union. This led to the formation of ARENA – Antarctic Research, a European Network for Astrophysics – funded under the EU Framework Program 6. Over the next few years ARENA developed its own science case for an Antarctic telescope, which we will return to below.

The 2009 Science Case – PILOT Mark II

The next opportunity to pursue support for an Antarctic telescope in Australia came in 2006 through the NCRIS scheme – National Collaborative Research Infrastructure Strategy. Funding emerged for a preliminary design study, which resulted in a comprehensive study of the key engineering issues associated with the construction and operation of an optical telescope in Antarctica [2]. In particular, careful consideration was given to how to overcome the icing problem caused by the super-saturated air within the stable boundary layer, without also degrading the superb free-air seeing. The science case was also developed further, led now by Jon Lawrence. It considered what a 2.4m-sized telescope in Antarctica could now achieve, but the name remained as PILOT (see Figure 4).

The case appeared in three papers published in PASA in 2009 (Lawrence et al. (2009a, b, c)). The number of scientists contributing to it had grown to 43. The first of these papers described the telescope and its capabilities, including the prospective instrument suite, and discussed how observing operations might be conducted. It also overviewed the science case, which had been categorised into

[2] Saunders et al. 2008 describes the telescope in more detail. The website at www.aao.gov.au/pilot provides many further documents relating to this design study.

seven themes[3]. The second and third papers discussed these science programs in detail; Paper 2 dealt with the distant universe, Paper 3 on the nearby universe, with the dividing line between these cosmic regimes drawn at the edge of our local group of galaxies. By now the 8m class telescopes were a mature technology and interest was high in the next generation of optical facilities – the so-called extremely large telescopes (ELTs) – and the capabilities they would bring. Furthermore, the NGST had matured into the 6.5m JWST – James Webb Space Telescope – and construction was underway. Another, more modest thermal IR survey satellite was about to be launched (WISE – the 40cm diameter Wide-field Infrared Survey Explorer). SOFIA (Stratospheric Observatory For Infrared Astronomy), NASA's 2.5m telescope carried by a 747 aircraft, was nearing readiness. When flying in the stratosphere the atmospheric transmission experienced would be superior to even Antarctica. The area of unique parameter available for a 2m class telescope in Antarctica thus had diminished further, despite the advantages over temperate-latitude sites. However, there were still clear areas where it would be competitive with any other facility. Indeed, the limitations of the next generation facilities, which were also becoming apparent as their designs matured, presented new opportunities for future Antarctic telescopes as well.

Four specific science projects from the PILOT science case were highlighted in the presentations made to the NCRIS review panels, and these we outline below. They centred around the use of the three instruments proposed:

(i) a wide-field, seeing limited optical imager,
(ii) a wide-field, near-infrared imager (i.e. from 2-5μm) and
(iii) a wide-field, mid-infrared spectroscopic line imager (i.e. from 8-30μm).

A fourth instrument, a 'lucky imaging' camera, was also considered for commissioning the telescope. The rationale behind this instrument suite was to maximise the scientific possibilities given the competition elsewhere. The optical cameras utilised the exceptional seeing whereas the near-IR camera exploited the low background and image quality over wide fields. In the mid-infrared it would not be possible to compete with space-based instrumentation for broad band measurements, due to the vastly lower thermal background experienced by a cryogenic telescope in space. However, the space telescopes would not have spectroscopic imaging capability, so keeping that as a niche for an Antarctic instrument.

(iv) The first of the four science focus areas was to map the cosmic web of galaxies, whose structure results from the dark matter and/or dark energy which dominates the composition of the Universe. It requires the measurement of the ellipticities of a very large sample of weakly gravitationally-lensed galaxies. Their statistically-averaged orientations can then be used to probe the evolution of the galaxy power spectrum with red-shift and hence to derive the equation of state of the Universe. The key to doing this with an Antarctic telescope is the imaging quality possible from the high plateau. Over wide fields of view the seeing attainable, of 0.2–0.3", is well matched to the typical angular size of distant galaxies. The time required to determine the orientation of a Galaxy in this limit depends on the 6th power of

[3] These were: (i) first light in the universe, (ii) the assembly of structure, (iii) dark matter and dark energy, (iv) stellar properties and populations, (v) star and planet formation, (vi) exo-planet science and (vii) solar system and space science.

the angular resolution, so providing a significant advantage for Antarctica over telescopes on temperate sites, where the seeing is 2–3 times worse.

(v) The second project was to search for the earliest evolved galaxies, i.e. with stellar populations resembling those found in galaxies at the current epoch, where the integrated light is dominated by normal (i.e. solar-like) stars. In the optical band, imaging of distant galaxies means viewing rest-frame UV wavelengths, whose light is dominated by a few, extremely rare but very massive stars, so providing a biased view of the galaxy. This project required observation in the infrared rather than the optical, as this is where the red-shifted light of normal stars would dominate a distant galaxy's light output. It also required a wide field of view, with high angular resolution, to overcome cosmic variance and to identify galaxy types from their morphology. A PILOT 'deep field' was proposed for the wavelength of 2.4μm [K_{Dark}], where the Antarctic sky is darkest and the gains over corresponding measurements from temperate sites the greatest. Such a survey would go ~2 (photometric) magnitudes deeper than any other survey contemplated for this wavelength. Moreover, 2.4μm is also the longest wavelength where truly wide-field, sensitive imaging can be obtained (the thermal background at longer wavelengths leads to much reduced sensitivity), so is the waveband of choice for probing furthest back in cosmic time in such surveys.

(vi) The third of the key projects ('first light in the Universe') was to search for gamma ray bursts (GRBs) emitted at high redshifts (i.e. z~6–10; the first few hundred million years after the Big Bang). Such GRBs, if they exist, must be probes of the 'first light' in the universe, being produced by the supernova explosions marking the death of the very first stars (which, being extremely massive, must also have very short lifetimes, of order 1 million years or less). Such distant GRBs can only be seen at thermal infrared wavelengths as their light is red-shifted out of shorter wavelength bands; i.e. at 3μm and beyond. In this project PILOT would be used to follow up satellite detections of GRBs, to search for those only emitting in the thermal IR. The increased sensitivity here compared to temperate telescopes makes Antarctica a compelling place for undertaking such an experiment. Cosmological time dilation, which results in such a burst appearing in the IR ~1 hour after the gamma rays themselves are detected, also ameliorates the technical challenge; the telescope only needs to be ready to respond when a GRB is announced, not actually observing. Of course, such distant GRBs might not actually exist in the universe; we do not yet know when the first stars formed and are only presuming what their form might have been. However, the potential for fundamental discovery made this an enticing experiment to conduct.

(vii) The fourth of the PILOT headline projects was to unveil the molecular medium of our Galaxy, by conducting a spectroscopic imaging survey of two of the lowest excitation lines from the hydrogen molecule. These are emitted in the thermal infrared (at 12μm and 17μm, respectively). Despite being the dominant molecule in space, molecular hydrogen cannot generally be seen directly unless it is warmed to temperatures of a few hundred degrees.

> Even these lowest levels are barely be excited in the typical environment of molecular clouds in space, and their emission occurs in parts of spectrum difficult to observe in from temperate latitudes, on account of poor transmission and high sky background[4]. The thermal infrared has not been accessible for large scale spectroscopic mapping surveys before. PILOT would have been able to image the molecular medium of our Galaxy through the infrared molecular hydrogen lines with a spatial resolution of ~2", nearly two orders of magnitude better than the best large-scale maps of the southern galactic plane obtained at millimetre wavelengths of the carbon monoxide (CO) molecule (the next most abundant molecule in space, but a factor ~10^{-4} less common). The Antarctic advantage for such a survey lies in the improved atmospheric transmission, due to the low water vapour, the cold temperature and the stability of the sky emission, which makes the corresponding measurements much more sensitive there than if made elsewhere.

However PILOT Mark 2 also failed to be supported by the review panel, with the recommendation being that the project required further international collaboration. While the NCRIS scheme had allowed the concept to be developed further than before through funding the preliminary design study, in the end the final evaluation process ranked the development of one of the planned extremely large telescopes – the GMT (Giant Magellan Telescope) – as a higher priority for investment. PILOT thus failed to proceed to the full design stage.

The 2010 Science Case – the Polar Large Telescope (PLT) and ARENA

The final science case described in this saga comes from that developed by the European ARENA consortium. This network of European institutions (together with the University of New South Wales) had been brought together through their involvement in the first PILOT proposal to the ARC Centre of Excellence scheme. European Union FP6 funding allowed ARENA to hold a series of workshops over the period 2007-10, ultimately recommending that a telescope based on the PILOT design – PLT (for Polar Large Telescope) – be built at Dome C (Epchtein et al. (2010)). The principal change from PILOT was not to include the optical performance as part of the design driver because that imposed significant cost penalties on an IR-optimised telescope. Wide-field, seeing limited, continuum and spectroscopic operations in the infrared were considered essential. PLT also increased the focus on time monitoring projects compared to the PILOT science case.

The PLT science case (Burton et al. (2010)) had three key program areas: (i) first light in the universe, (ii) exo-planet science and (iii) galactic ecology. These paralleled much of the PILOT science case. Deep infrared imaging surveys were given particular emphasis, such as the K_{Dark} galaxy deep field. Exo-planet science also received a greater focus than for PILOT, through both transit and micro-lensing techniques. Rather than undertake surveys to search for exo-planets, however, these programs were regarded as

[4] There is also a line at 28μm, coming from the very lowest excited level of H_2, but this is not detectable, even from Antarctica, because the atmosphere is opaque at this wavelength.

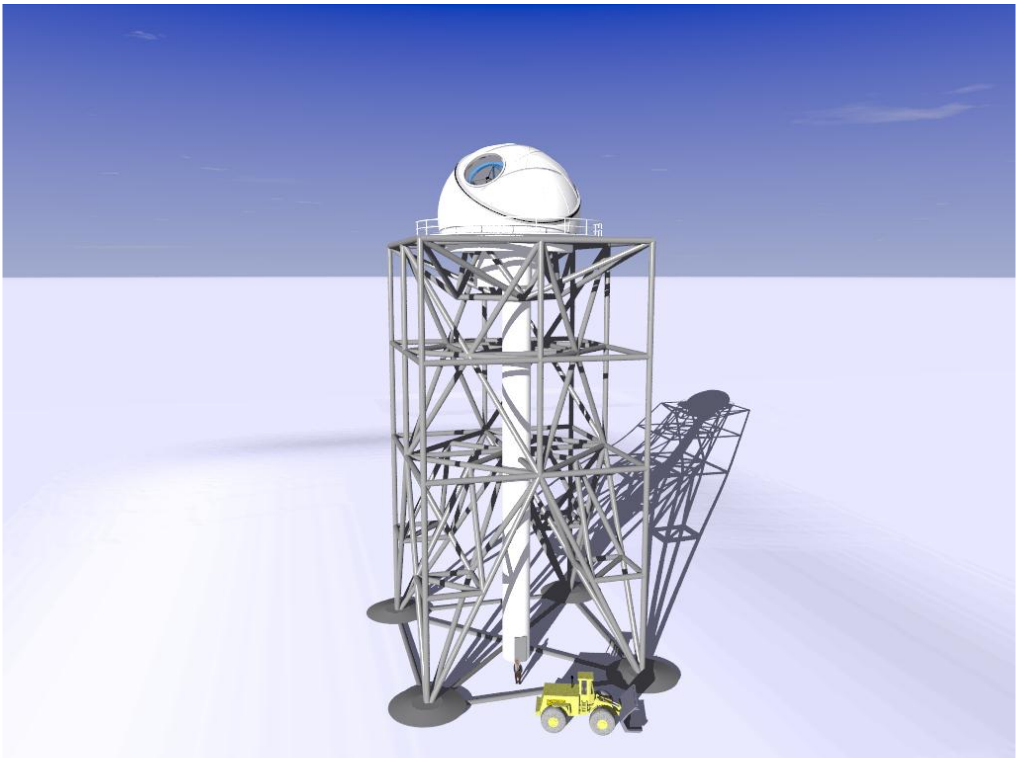

Figure 4. Design for the 2.4m PILOT telescope at Dome C, the Pathfinder for an International Large Optical Telescope (see Saunders et al. *2008). The telescope has a callote-style dome in which the temperature and humidity can be controlled and is placed on a ~30m high tower to raise it above the turbulent boundary layer which generates most of the astronomical seeing. Image Andrew McGrath (AAO).*

alert-mode projects, following up on detections made elsewhere in order to determine physical characteristics of exo-planet systems. The ability to undertake high cadence measurements from Dome C while the ARENA proposal for PLT passed through its initial reviews it too failed to be funded for full design by the European Union.

Summary and conclusions

An intermediate sized optical / infrared telescope has yet to be funded for construction in Antarctica despite its scientific potential. The reasons go beyond the science it could do, of course, and involve the politics of funding as well as human sociology. Beginning a truly new venture in the face of established competition is simply hard. Antarctica is a challenging place, and many people still find it hard to imagine that frontline facilities can be built there, despite the success of instruments like the 10m South Pole Telescope.

Nevertheless, despite the travails of DMT–PILOT–PLT there remain two current projects aimed at building a 2m-sized telescope in Antarctica. One is led from Japan and the telescope would go to the Japanese station at Dome Fuji. The other is led from China and would go the new Chinese Kunlun station, now under construction at Dome A. This latter project has advanced the furthest yet. It is under consideration for full funding in the Chinese Government's 12th 5-year plan. Called KDUST – the Kunlun Dark Universe Survey Telescope – it would be a 2.5m diameter IR-optimised telescope . As the name suggests, the science focus is on wide-field infrared surveys of distant galaxies in order to constrain the equation of state for the Universe (Zhao et al. 2011). A number of prototyping astronomical experiments are being currently being developed for Dome A, including a set of three 0.5m optical/IR telescopes known as AST3 (Yuan et al. 2010). A 5m THz frequency telescope (DATE5) is also under consideration for funding at Dome A as part of this same effort.

The PILOT science case has also been re-visited by Mould (2011), who considered further the cosmological applications of a deep, wide-field survey in the infrared K–band (2-2.4μm). It would be able to probe the so-called dark-ages (i.e. the era before stars appear in the first few hundred million years after the Big Bang, in the redshift range from z=6 to as far as z=25), searching for any objects which might contribute to the ionization of the atomic gas then pervading the universe (as produced in the recombination event that also resulted in the cosmic microwave background as the universe became transparent to radiation). In other words, the survey could search for signatures from the formation of the first massive stars. With a dedicated survey lasting over perhaps 5 years a steradian could be imaged; i.e. about 10% of the sky if the focal plane could be filled with IR arrays, a more ambitious instrument than had been envisaged for PILOT. Only the proposed WFIRST (Wide-Field Infrared Survey Telescope) satellite could provide any competition to the quality of data such a survey could yield. Mould's paper also noted that such a survey could be undertaken by the KDUST telescope as well as by PILOT.

Regardless of when and where in Antarctica an optical / infrared telescope may be built, the work of the past decade has clarified the science it should do and the capabilities it should have. Sensitive, wide-field surveys with high-angular resolution in the infrared, in particular in the K_{Dark} window at 2.4μm, are a clear focus. In the mid-infrared the emphasis is on spectroscopic line imaging surveys rather than in the continuum. The time domain, capitalising on the opportunity for high-cadence measurements, in stable conditions with high photometric precision, also providing a clear Antarctic advantage.

Telescopes in Antarctica do not need to be built for a single purpose. Some experiments require the depths of the Antarctic winter, others can be undertaken quite easily in daylight. Consideration should be given to such multi-mode operation, with projects which can be conducted in the summer daylight, in the twilight periods around the equinoxes and in the full Antarctic winter. Different instruments with different design constraints can be built appropriately. The challenge, of course, gets progressively harder as the winter sets in. Summer experiments can be readily set up and operated with people present. Winter experiments may require robotic operation, akin to space-based telescopes, with minimal access possible.

Antarctica does provide the best sites on the surface of our planet for the ultimate Earth-based telescope in the optical and infrared. The route to such a behemoth lies through an intermediate-sized facility – the 2m-class telescope discussed here – where the operational modes can be proven and the engineering challenges identified and solved.

Along the way it will also be able to undertake some excellent science.

Acknowledgements

Many people have contributed to the ideas summarised in this work. Particular thanks are due to Michael Ashley, Jon Lawrence, Jeremy Mould and John Storey who commented on the manuscript, in addition to their pivotal contributions to the development of the field of astronomy in Antarctica.

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(Manuscript received 20 January 2012; accepted 27 April 2012.)

This paper is based on a presentation given at a workshop on the KDUST telescope at the Institute for High Energy Physics (IHEP), Beijing, China, 7-9 November, 2011.

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