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THE SCIENCE CASE FOR A 2M-CLASS TELESCOPE AT DOME C, ANTARCTICA

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Abstract. Dome C, being one of the summits of the Antarctic plateau, is an exceptional site for astronomy. Its advantages over a temperate-latitude site for a wide range of observations are considerable, as well as becoming increasingly appreciated by the scientific community. We discuss what these advantages are, and some of the science possibilities they offer. They fall under four principal regimes: (i) diffraction-limited observations (i.e. $\lambda > 3\,\mu$m), (ii) wide-field thermal infrared observations (i.e. $\lambda > 2.2\,\mu$m), (iii) when observations are seeing-limited (i.e. from 0.4–3μm) and (iv) new windows (i.e. in the mid–IR and sub–mm). Each regime offers particular advantages over corresponding observations made from a temperate site. When more than one of these advantages applies the gains can be potent.

The science possibilities are many, ranging from solar system science, such as monitoring the global climate of Mars and Venus, to the study of the distant universe, such as ultra-deep fields to probe the assembly process of galaxies and the search for the "first light" through thermal–IR emission from gamma ray bursters. In this paper we discuss a range of science opportunities offered by each of these regimes, making use of a 2m-class telescope. Such a facility would serve as an essential next step in the development of Antarctic astronomy, and the far-reaching possibilities offered by larger telescopes and interferometers on the Antarctic plateau.

1 The Advantages of Dome C for Antarctica

1.1 Introduction

The summits of the Antarctic plateau provide a unique environment for observational astronomy. They provide the coldest, driest and most stable atmospheric conditions on the Earth, which in turn leads to the darkest skies, the best sky transparency and the sharpest imaging possible from any ground-based site. Thermal

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sky backgrounds are 20–100 times less than at temperate sites, with seeing, isoplanatic angles, coherence times and scintillation noise 2–4 times better, and aerosol levels up to 50 times lower (see Storey 2005). These in turn lead to gains in sensitivity, angular resolution, field of view and/or measurement precision, depending on the particular type of observation being undertaken. All these factors conspire to present a remarkable opportunity to conduct new science with a modest-sized facility, across the optical, infrared and sub-millimetre wavebands. An Antarctic telescope would be more sensitive than an equivalent temperate-latitude telescope, be able to measure radiation through new spectral windows, and be able to image at close to the diffraction limit across wide fields of view. A rule of thumb for performance comparisons is that, on account of the factor 20 drop in background, an Antarctic telescope, for wide-field, thermal infrared imaging, is equivalent in sensitivity to a temperate telescope with $\sqrt{20} \sim 4$ times the diameter. The detailed comparison with wavelength is, however, complex, and needs to be considered for each particular investigation under consideration.

These conditions make some grand-design investigations possible from the Earth, rather than needing a space environment (e.g. Storey et al. 2006b). They include the search for exo-earths in other solar systems, and the measurement of light from the first stars to form after the Big Bang. Such ambitious projects also require a new generation of large telescopes and interferometers. A 2m-class Antarctic telescope has been proposed as pathfinder facility towards such goals. It would both serve as a technology demonstrator, able to show that the operation of complex instrumentation through the Antarctic winter is indeed possible, as well as be able to undertake a wide range of exciting new science in its own right. The niche that such a telescope can best exploit is when deep imaging, with high spatial resolution, over wide field fields of view, is required.

In this paper we describe some of the science that could be undertaken with a 2m-sized telescope at Dome C. It is based on the concept for *PILOT* (Storey et al. 2006a), and in particular the science case presented by Burton et al. (2005), where the sensitivity, angular resolution and field of view are quantified, from the optical to the mid–IR. The initial science program is also based on using simple imaging cameras, whose field of view is determined by the largest currently available array at the relevant wavelength, sampling with a pixel scale commensurate with the seeing or diffraction limit. We outline this science below, and provide further detail on selected programs in the subsequent section.

1.2 Science Regimes for Antarctica

Telescope performance can be compared by the time, t, to reach a given sensitivity:

$$t \propto B \times \left[\frac{\theta}{\eta D}\right]^2, \qquad (1.1)$$

where B is the total background emission from sky and telescope at the wavelength of interest, θ the image size, η the atmospheric transmission and D the telescope diameter. Gains may be achieved for the first three of these quantities by locating a telescope on the Antarctic plateau instead of a temperate site.

The low temperature and low aerosol content combine to reduce the background by 20–100 times from temperate sites, so facilitating wide-field IR imaging (i.e. $\lambda > 2.27\mu$m), when thermal emission (as opposed to airglow) dominates the background. Science this facilitates includes:

- Conducting a census for nearby brown dwarfs and giant exo-solar planets,
- Conducting a census of protostellar disks in star formation regions,
- The galactic ecology – the interplay between stars and the ISM,
- Searches for AGB (i.e. post helium-burning) stars in the Magellanic Clouds,
- The star formation history of the Universe through red-shifted Hα at 2.4μm,
- The "First Light", probed through Gamma Ray Bursts redshifted to 2–5μm.

The dry conditions improve atmospheric transmission, including opening new windows in the mid–IR and THz wavebands for ground-based observation. This facilitates the study of, for instance:

- Grains and ices, and the associated interstellar chemistry,
- Molecular cloud cores, in particular the birth of massive protostars.

The improved seeing leads to a number of gains. For instance, diffraction limited observations will be obtained automatically for $\lambda > 3\mu$m. In seeing-limited regimes (i.e. in the optical and near–IR), image sizes will be smaller. The proximity of telescope to the turbulent layer that generates the seeing also leads to significant improvements in both photometric and astrometric precision. Examples of science programs these gains facilitate include:

- Full-disk planetary imaging in the Solar System to monitor global weather,
- Detection of exo-planets via transits of their parent star,
- Detection of exo-planets via microlensing of a background star,
- Asteroseismology – stellar internal structure through surface oscillations,
- Monitoring variability and motions in pulsar wind nebulae,
- Time delays in gravitational lenses, probing variability in H_0 with direction.

Some investigations require improvements in more than one of these parameters if advances are to be made. Examples, which require infrared measurements made over wide fields of view with high angular resolution, include:

- Stellar populations – near-field cosmology in the Local Group, to examine galaxy accretion history,
- Stellar tidal streams in the Local Group, probing the shapes of galaxy dark matter halos,
- IR surveys to find core collapse supernovae in starbursts, to follow the history of light element production,
- An ultra deep field at 2.4μm (K_{dark}) to follow the evolution of galaxy mass and morphology,
- The cosmic web of dark matter through precise mapping the effect of cosmic shear on galaxy orientations, and of the dark energy, through imaging arcs of high-z galaxies lensed by foreground galaxy clusters,
- Probing the "first light" in the Universe, through measurement of Gamma Ray Bursts where all the light is redshifted to 2–5μm.

The alternative to pursuing gains in B, θ or η is to increase the telescope diameter, D. This is the route being pursued through the aim of building an ELT. Antarctica provides an alternative route for conducting some of the science that an ELT could undertake. It should be noted, though, that for some key investigations increased collecting area is essential, wherever the telescope is located. Indeed, an examination of the ELT science cases (e.g. Hook et al. 2005), in comparison with that written for PILOT (Burton et al. 2005), indicates a great deal of complementarity between the programs that might be undertaken.

1.3 Wide Field Thermal Infrared Surveys

Of particular interest for a 2m-class telescope at Dome C is the ability to conduct wide-field thermal infrared surveys at 2.4, 3.8 and 4.7μm (i.e. K_{dark}, L and M bands). In the table below we show the relevant performance parameters for a KLM camera, and compare these to some surveys already conducted (i.e. 2MASS/DENIS at K, Spitzer–GLIMPSE at L & M). The figures are for one month of observing (at 25% efficiency) in each filter. If increased coverage is needed, these may be scaled by the number of months devoted to the survey $\times$ the number of array detectors that are available for the instrumentation.

At 2.4μm the survey would be nearly 5 magnitudes deeper than 2MASS/DENIS, with an angular resolution six times better. Of course, other surveys are beginning at 2.1μm. A more relevant comparison may be to the anticipated performance of UKIRT–UKIDSS (18.4 mags, $0.8''$, $63^{\circ 2} \equiv 4000^{\circ\times\circ}$) or VISTA, though these projects are still several years from completion. In the L and M bands the sensitivity cannot match that obtained from space, though it will only be about 1 magnitude inferior to GLIMPSE. However, it would provide substantially better spatial resolution, as well the option to include areas not covered by the Spitzer surveys.

	K$_{dark}$(2.4μm)	**L (3.8μm)**	**M (4.7μm)**
Achieved so far	2MASS/DENIS	GLIMPSE	GLIMPSE
S/N = 5	(2.1μm)	(3.6μm)	(4.5μm)
Point Source Sensitivity	15.1 mags[1]	15.5 mags	14.6 mags
Resolution	$2''$	$2''$	$2''$
Area	All Sky	$15^{\circ 2}$	$15^{\circ 2}$
Ant. 2m + KLM Camera	19.8 mags	14.8 mags	13.4 mags
($1K \times 1K$ @ $0.23''$ pixels)	$0.3''$	$0.4''$	$0.5''$
1 month observing (25% eff.)[2]	$7^{\circ 2}$	$7^{\circ 2}$	$7^{\circ 2}$

[1]On the Vega scale. [2]Other parameters may apply; for instance a dedicated K$_{dark}$ survey could use a $4K \times 4K$ detector, but choose $0.3''$ pixels, giving an areal coverage of $35^{\circ 2}$.

2 Sample Science Programs for a 2m-class Telescope

2.1 Global Climate Monitoring on Venus and Mars

By using the technique of selective imaging (or "lucky imaging", Baldwin et al. 2001) it is possible to obtain diffraction-limited images of a bright source from a telescope; short (10-50ms) exposures with the frames exhibiting near-diffraction-limited images extracted and coadded. For a 2m telescope this would provide $0.07''$ at 500nm and $0.3''$ at 2.4μm; i.e. ∼50–200 km resolution at closest approach for Venus and Mars. For such a technique to work it is essential to have high quality seeing in the first place, to obtain a sufficient number of diffraction-limited frames to produce a high signal to noise image. The Antarctic plateau provides the best sites on Earth for these kind of measurements.

Such imaging would benefit studies of the atmospheric circulation on Venus and Mars. For instance, on Venus the high-altitude clouds can be seen in narrow-band filters 1.7 and 2.3μm, silhouetted against the thermal radiation from the lower atmosphere. On Mars imaging at 2μm isolates the CO_2 bands, permitting the surface pressure distribution to be followed; i.e. weather systems could be followed around the planet (see Bailey et al. 2004). Monitoring over several days would allow global circulation models for the planets to be tested. Full disk imaging cannot be conducted by satellites in orbit around these planets as they are too close. Favourable opportunities occur when the planets are in the south at closest approach to Earth. For Venus this will be in daylight, but such measurements have been made regularly from temperate sites and would be further facilitated in Antarctica by the low scattering in the atmosphere.

2.2 Brown Dwarfs and Giant Exo-planets: Direct Detection

Brown dwarfs are sub-stellar mass objects who mass is too low for nuclear fusion to sustain their luminosity over the bulk of their lifetime. They are born hot, and then spend their lives cooling (see e.g. Burrows et al. 2001). As they do their spectra change, initially looking like M–dwarfs, and then passing through the L– and T–dwarf stage as first dust emission dominates, to be swamped by methane absorption. They may end up looking spectrally like planets such as Jupiter.

Giant exo-planets fall into the same class of objects as brown dwarfs, though their origins are probably quite different (formed in a disk rather than being the centre of a self-gravitating cloud). While brown dwarfs do not account for the missing mass, they are a fundamental part of the study of stars. Their mass distribution (particularly their occurrence in binary systems) has yet to be determined.

An Antarctic 2m telescope can facilitate the search for such objects primarily through the high sensitivity in the thermal IR bands (KLM). While young brown dwarfs are hot (and relatively luminous), the majority will be cool and faint, and so can only be detected relatively close to the Sun. High angular resolution across wide fields of view is required, conditions facilitated on the Antarctic plateau. With a $10'$ field of view a KLM camera, and with dichroic beam splitters to image the three bands simultaneously, it would be able to survey a degree-sized region in 1–2 weeks, to find all brown dwarfs of T–class out to a distance of ~ 20 pc, of L–class to ~ 70 pc and of M–class to ~ 200 pc.

2.3 Exo-planets: Indirect Detection by Microlensing

Gravitational microlensing occurs if the light ray from a star passes sufficiently close to a massive foreground object so that its path is bent, or lensed into multiple (but unresolved) images, so amplifying the light from the star. If the lensing star has a planetary companion this produces a short duration perturbation on the light curve, whose signal depends upon the mass of the planet and its proximity to the lensing star. Such a technique is even sensitive to the presence of earth-mass planets at AU-scale distances from their parent star, which no other planet search technique can yet approach (e.g. Beaulieu et al. 2006). A Dome C telescope could continuously monitor a field in the southern Galactic bulge for such events, eliminating the need to operate a network around the southern hemisphere (e.g. as per the PLANET consortium). The high spatial resolution both improves the photometric precision needed to find microlensing events, and facilitates resolving the crowded fields to identify the star with the planetary companion.

2.4 The Early Stages of Planetary Formation

As Sun-like stars form, an inevitable consequence appears to be that a disk of gas and dust forms around the young star, a result of angular momentum conservation plus the need to feed the growing star through accretion. These disks provide the raw material for planetary formation, which suggests that planets will commonly be found around low-mass stars. The disks have temperatures of a few hundred degrees and emit strongly in the infrared. They can be distinguished in infrared surveys of star forming regions. Those stars with disks show up with an excess in the 3–4μm band. The number of stars in a molecular cloud that have disks, and the evolution of these disks towards planetary systems, can thus be investigated through thermal infrared observations. Relatively little work has so far been done in these wavebands, however, because of the difficulty of making such measurements from temperate sites. From Antarctica, the extreme cold and the stable conditions make these measurements much easier. Indeed such science has already been demonstrated through the pioneering 60cm SPIREX telescope, which operated in these bands at the South Pole in 1998-99, resulting in a series of papers on the fraction of stars with disks in several star forming regions (e.g. see Kenyon & Gomez 2001, Maercker & Burton 2005, Lyo & Lawson 2006).

2.5 Galaxy Formation and Evolution: a K_{dark} Ultra Deep Field

Our view of the high-redshift Universe was revolutionized through the deep, high-resolution images obtained by the HST. Galaxies are spread throughout the sky, at number densities of up to one for every square arcsecond. Their star formation rates are much higher in the past than today, appearing to peak at redshifts from $z = 1$–4. Such deep fields obtained by HST are biased, however, as in the optical they sample the rest-frame UV, where only young, massive star forming regions contribute to the flux. They appear to be regions of great disturbance, with many galaxies showing unusual morphologies in comparison with those in the nearby universe. Older, redder, more typical stellar population components are missed. Deep surveys in the infrared are needed to characterise the galaxies in the high-z universe, for these will sample the rest wavelengths where the bulk of the stellar light emerges. High angular resolution over wide fields is also essential, to overcome cosmic variance and to resolve the galaxy morphologies to obtain statistically useful samples of their population distribution.

The K_{dark} 'cosmological' window at 2.4μm is attractive for such studies, where the Antarctic skies are particularly dark on account of the extreme cold and absence of airglow. In 100 hours of integration a galaxy of $K_{AB} \sim 26.5$ mags could be detected[1], over a magnitude deeper than the current deepest field (VLT/FIRES; Labbé et al. 2003), with 16× the area and 40% finer resolution. It is also over 3 magnitudes deeper than will be obtained for the ultra deep fields with UKIDSS and VISTA (albeit over an order of magnitude smaller area). This would be the deepest field available for detecting galaxy "drop-outs" at high redshift (the longer wavelength field available through Spitzer/GOODS at 3.6μm having a detection limit 2 mags brighter at L_{AB}). The Lyman break is moved to $z \sim 25$ and the Balmer break to $z \sim 4$ at 2.4μm. The former is biased to finding exotic starbursts, whereas the latter probes the evolved galaxy distribution (i.e. where most of the stars are). This is the next step to be probed back to in cosmic history.

2.6 The First Light: Gamma Ray Bursters in the Thermal Infrared

Gamma Ray Bursts (GRBs) are the most powerful explosions in the Universe. They can be readily found using satellites and can be hundreds of times more luminous than quasars for a few days, before fading. There is strong evidence that GRBs are related to the collapse of massive stars, with the rate of GRBs associated with the rate of massive star formation in galaxies. If so, GRBs provide

[1] At S/N=10 with a FWHM 0.3″ over a 10′ field using a single $4K \times 4K$ array.

a probe of the star formation rate of the high-redshift universe, back to the epoch of the first star formation, a few million years (between $z = 7$ and 20) after the Big Bang. At the highest redshifts, all the light from GRBs is shifted into the thermal infrared and longer, and so observation at these wavelengths is required to probe back to the "first light" in the universe.

While the effects of distance and redshift act to reduce the flux of a GRB at a fixed λ, time dilation acts to increase it, at a fixed time of observation from onset. Thus, in a given spectral band, there is little decrease in the intensity with redshift at a fixed time after it began. Based on fitting the spectral energy distribution to one GRB, Lamb & Reichart (2001) estimate that the flux, one day after burst, will range from 10–20μJy in the K, L and M bands for redshifts from $z = 3$ to 20 (except for K–band at $z = 20$, when the flux is shifted out of the band!). In 5 minutes of observations, an Antarctic 2m telescope would detect these objects with an SNR > 10 at K and ~ 1 at L and M. At earlier times, with the flux estimated to vary as $t^{-4/3}$, higher SNRs would be anticipated. Within the first hour of the burst they should readily be detectable. It suggests a filter sequence for an search for GRBs, from J, through HKL, to M, starting with one to two minutes at J & H. If no object is detected, then 5–10 minutes would be spent at K, rising to an hour at M. A GRB found only in M band would have $z > 30$!

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