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The SCAR Astronomy & Astrophysics from Antarctica Scientific Research Programme

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Abstract. SCAR, the Scientific Committee on Antarctic Research, is, like the IAU, a committee of ICSU, the International Council for Science. For over 30 years, SCAR has provided scientific advice to the Antarctic Treaty System and made numerous recommendations on a variety of matters. In 2010, Astronomy and Astrophysics from Antarctica was recognized as one of SCAR's five Scientific Research Programs. Broadly stated, the objectives of Astronomy & Astrophysics from Antarctica are to coordinate astronomical activities in Antarctica in a way that ensures the best possible outcomes from international investment in Antarctic astronomy, and maximizes the opportunities for productive interaction with other disciplines. There are four Working Groups, dealing with site testing, Arctic astronomy, science goals, and major new facilities. Membership of the Working Groups is open to any professional working in astronomy or a related field.

Keywords. Telescopes, Atmospheric Effects, Instrumentation, Site Testing, Antarctica.

1. Introduction

The *Astronomy & Astrophysics from Antarctica* (AAA) Scientific Research Program kicked-off in 2011. The objectives of AAA are to coordinate astronomical activities in Antarctica to ensure the best possible outcomes from international investment in Antarctic astronomy, and to maximize the opportunities for productive interaction with other disciplines. To achieve this, AAA is working to:

- Coordinate site-testing experiments to ensure that results obtained from different sites are directly comparable and well understood,
- Build a database of site-testing data that is accessible to all researchers,

- Increase the level of coordination and cooperation between astronomers, atmospheric physicists, space physicists and meteorologists,
- Extend existing Antarctic site-testing and feasibility studies to potential Arctic sites; for example, in Greenland and Canada,
- Define and prioritise current scientific goals,
- Create a roadmap for development of major astronomical facilities in Antarctica,
- Stimulate international cooperation on major new astronomical facilities in Antarctica.

In order to carry out these tasks, AAA has created four Working Groups. These Working Groups are open to all interested researchers, and are:

- A. Site testing, validation and data archiving (chair: Tony Travouillon),
- B. Arctic site testing (chair: Eric Steinbring),
- C. Science goals (chair: Michael Burton),
- D. Major new facilities (chair: Peter Tuthill).

In the following sections we describe the progress made so far.

2. Working Group A: Site Testing, Validation and Data Archiving

2.1. *Scope and Aims*

A large number of studies have been conducted, particularly over the past 15 years, into the site conditions at the various Antarctic stations. To a significant extent, however, these studies have been carried out using different instruments and indeed different techniques at the different sites. This makes inter-comparison of the sites difficult, and direct assessment of the relative merits of different sites is often unreliable. Atmospheric models and satellite data have also been used to generate predictions of site conditions and to further our understanding. Again, the different approaches used by different groups can sometimes make comparisons problematic.

The first task for Working Group A is therefore to create a database of all published papers that contain site testing data. This database will then link to the original data, where publicly available, or provide contact details for the authors where the data are not in a readily accessible form.

Secondly, Working Group A will identify gaps in our knowledge of the different sites, and recommend programs to acquire and make available the missing information.

2.2. *Current status*

Work is currently underway to identify and catalogue all published papers on Antarctic site testing. Each paper is to be tagged according to a non-exclusive set of 33 different descriptors:

1. **Methodology**
   (*a*) In situ/ground-based observations
   (*b*) Satellite observations
   (*c*) Modelling
   (*d*) Instrument design
2. **Location**
   (*a*) Arctic
   (*b*) Antarctic
   (*c*) South Pole
   (*d*) Dome A
   (*e*) Dome C
   (*f*) Dome F

(*g*) Ridge A
(*h*) McMurdo/balloon
(*i*) Greenland
(*j*) Northern Canada
(*k*) Other

3. Wavelength

(*a*) γ-ray/X-ray,
(*b*) UV
(*c*) Optical
(*d*) Infrared
(*e*) THz
(*f*) Millimetre/Sub-mm
(*g*) Particle
(*h*) Other

4. Parameter

(*a*) Meteorological data
(*b*) Atmospheric transparency
(*c*) Sky brightness and stability
(*d*) Seeing and integrated turbulence
(*e*) Free atmosphere turbulence profiles
(*f*) Boundary layer turbulence
(*g*) Precipitable water vapour
(*h*) Aerosols/ice crystals
(*i*) Ozone
(*j*) Other

It is hoped to have the bulk of the catalogue completed by June 2013.

3. Working Group B: Arctic Site Testing

3.1. *Scope and Aims*

This section defines the implementation plan of the the Arctic Site Testing Working Group (ASTWG). The ASTWG has connections to the known site-testing activities in the Arctic, and seeks to be inclusive to all. Unlike the other three Working Groups, ASTWG does not involve any specific activity in Antarctica, although there are several areas of overlapping interest. The intention here is to outline efforts already underway in the Arctic, to indicate similarities and differences with those undertaken in the Antarctic, and thereby facilitate improved communication and knowledge sharing. This can further assure the compatibility of datasets, and potentially guide cross-linked investigations or spur new activities of possible benefit for both Poles.

3.2. *Background*

The two major landmasses nearest the North Pole are Greenland (Denmark) and Ellesmere Island (Canada). Neither of these provide elevations as high as attainable on the Antarctic plateau, but they are comparably cold and dry. A geographical parallel is provided by the Greenland icecap, reaching 3,200m at Summit (72N). At high northern latitudes, the polar vortex functions in the same way as in the Antarctic, although in detail there are differences. Away from the icecaps, a strong and stable surface-based thermal inversion peaked at about 1,000m develops and remains during much of winter. Several locations rise above this. One is Barbeau Peak (82N, 2,600m) within Quttinirpaaq National Park on Ellesmere Island, but mountains nearer the coast top 1,400m to 1,900m.

Meteorological records date back decades for several major bases and research stations in the Arctic. The most northern is the military outpost at Alert (82N), on Ellesmere Island. It is provided with broadband communications via microwave repeater stations linking to Eureka (80N), where geosynchronous satellites become visible. Eureka is accessible year-round by air, and by ship in summer. This is a manned weather station, providing among many other meteorological and atmospheric observations, twice-daily balloon aerosondes. Nearby is the Polar Environment Atmospheric Research Laboratory (PEARL) on a 600m high ridge which is linked by a road. Another scientific base to the south is located at Resolute Bay (76N), which along with Eureka provides aircraft support for field logistics. On Greenland, the United States military base at Thule (76N) provides access to the Summit station (72N) via support from the National Science Foundation.

Serious interest in astronomical site testing in the High Arctic was initiated with the first conclusive evidence of excellent free-atmospheric seeing above the Antarctic glacial plateau (Lawrence *et al.* 2004). The analogy to the Greenland icecap initiated observations at Summit (Andersen & Rasmussen 2006, Andersen, Pedersen & Sorensen 2010). An independent investigation into the feasibility of observations from high and very remote mountain peaks on northwestern Ellesmere Island was also undertaken (Steinbring *et al.* 2008, Wallace *et al.* 2008), anticipating the avoidance of boundary conditions associated with the surface of an ice plateau (Hickson *et al.* 2010, Steinbring *et al.* 2010, Steinbring *et al.* 2012). A strong advantage for a high mountain site over the icecap has not yet been proved, and in the meantime a compromise afforded by the year-round logistics provided by the mid-elevation site at PEARL is also being investigated.

3.3. *Astronomical Site-Testing Observations in the Arctic*

Compared to the Antarctic, astronomical site testing in the Arctic is only in the early stages, with the first work commencing in 2006. Several university and government laboratory groups are collaborating to deploy various instruments, either of their own design or closely following standard ones. Observations are taking a path typical of mid-latitude sites. Initial meteorological and basic sky-quality measurements are now leading to more detailed studies, first with observations obtained during brief campaigns. Characterisation of the scientific potential of the sites starts by deploying small semi-autonomous telescopes, desirably followed by fully robotic versions.

3.3.1. *Instrumentation Deployment*

Several investigations of which the ASTWG is familiar have been undertaken or will be underway in the next two to three years:

- Basic meteorological and sky-clarity observations. Small autonomous weather stations and cameras were constructed by National Research Council of Canada Herzberg Institute of Astrophysics (NRC/HIA) and deployed on three mountains on northwestern Ellesmere Island. These data can be compared with manned sea-level stations, e.g. those of Environment Canada – counterpart to the US National Oceanographic and Atmospheric Organization (NOAO) – that have records dating back over 50 years.
- Sky-monitoring cameras. Data from existing atmospheric-science instrumentation at PEARL are being analysed. Of key interest are all-sky camera images taken by the University of New Brunswick beginning in 2007. Some sky surface-brightness measurements have also been taken in the optical and near-infrared using instruments from the University of Toronto.
- Sub-mm radiometer. A commercial 225 GHz tipping radiometer provided by Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan was

operated at PEARL in the winter of 2010/11, and has since winter 2011/12 been operating at Summit in Greenland (see Matsushita *et al.* paper in these Proceedings).

- Specialised optical turbulence measuring instruments. A Polaris-tracking instrument was installed on a 39m high mast at Summit by the University of Copenhagen. At Eureka, two Sound Detection and Ranging (SODAR) units surplus from TMT site testing have been operated nearby for two winters. At the same time the Arctic Turbulence Profiler (ATP), a lunar scintillometer built by University of British Columbia, and similar to an instrument at Cerro Tololo Inter-American Observatory, has been undergoing field-readiness testing on the PEARL roof. The intention is to re-deploy it at a remote Ellesmere mountain site. Balloon-borne thermosondes are also being considered for Eureka.
- Small telescopes. A Differential Image Monitoring Measurement (DIMM), a clone of the unit at the Canada-France-Hawaii Telescope, was built by University of Toronto and utilised on a portable 0.35m telescope. That, combined with Multi-Aperture Seeing Sensor (DIMM/MASS) has also been deployed in 2012, with further observations planned. This might be improved to include a variant of Single-Star Scintillation Detection and Ranging (SCIDAR).

3.3.2. *Initial Results to be Followed Up*

Preliminary Arctic results from these studies, either presented in the literature or known to the ASTWG, are encouraging:

- Remote Ellesmere Island mountain sites are accessible by helicopter in summer and above the thermal inversion in winter, providing reliable logistics and good weather (Steinbring *et al.* 2010). Skies are clear 65% of the time or better, as expected from satellite measurements. All-sky camera measurements indicate that photometric conditions occur for a significant fraction of that time, typical of the best mid-latitude sites such as Mauna Kea, Hawaii (Steinbring *et al.* 2012).
- Skies are dark, as expected in the optical based on latitude, and with indications that this follows into the near infrared consistent with atmospheric conditions. The atmosphere is extremely dry, with mean precipitable water vapour below 2mm at sea level from Eureka in winter, allowing for good 225 GHz transparency at PEARL, possibly opening useful sub-mm windows (Sivanandam *et al.* 2012, Asada *et al.* 2012).
- The boundary layer appears to be thin at PEARL, according to ATP measurements. For photometric conditions, the median boundary-layer seeing in winter below 10m is better than $0.55''$, improving to $0.45''$ at 20m. The first wintertime data taken with DIMM are consistent with those results; seeing of $0.6''$ to $1.2''$ under clear skies from the 6m high PEARL roof.
- Some Polaris-tracking seeing measurements taken at Summit in summer show seeing as good as $0.5''$ at 39m, suggesting conditions comparable to the Antarctic icecap (Andersen, Pedersen & Sorensen 2010).

3.4. *Future Steps*

Clearly, more site testing is needed to fully realise the potential of Arctic sites. Within Canada this features as a priority among small projects within the 2010 Long Range Plan for Canadian Astronomy, which recommends that the conditions at the PEARL site be characterised, as well as at least one of the remote mountain sites. If justified by the site conditions, this would lead to the development and construction of a 1 to 4m class optical/NIR telescope. That recommendation does not provide funding, although incentive could come with published results. Costs for Arctic logistics are relatively inexpensive, considering the remoteness of the locations. For example, transport from northern

Canadian cities to Eureka is only approximately $20 per kilogram by air, and considerably less via the yearly sea voyage. The AST seeks to encourage the follow-up of initial results, along with the other items highlighted below:

- Carrying on with current instrumentation. Summit station can easily support field-readied autonomous instruments such as the ASIAA radiometer. Winter campaigns at Eureka take advantage of year-round logistics and existing atmospheric research programs underway. Coordination with groups there and elsewhere is sought, e.g., other site-testing groups or those in atmospheric or space physics research such as aurora observations and orbital-debris tracking.
- Improvement in site-testing apparatus. Advancements in field-readying instrumentation for polar environments are always on-going, with some special aspects for the High Arctic, especially survivability under conditions of rime-icing and in high winds. Installation of a stand-alone 6m tall site-testing tower near the PEARL facility is planned. This can reduce the deleterious effects of heat and turbulence associated with the PEARL building itself, and so provide more reliable seeing measurements.
- Further study of the high mountain sites on Ellesmere Island. That could include re-deployment of the ATP, although this would require a reliable source of power. Both wind-power and fuel-cell generators were investigated but not fully developed during the initial feasibility study. One possibility would be a PLATO-like system, similar to the compact unit built for Ridge A.
- Initiation of scientific productivity. A 0.5m wide-field optical imaging telescope, primarily for planet-hunting via transits - is being readied for PEARL as a collaboration between the Dunlap Institute, NRC/HIA, and other Canadian government departments. It takes advantage of the already excellent infrastructure in place at Eureka, and is not strongly dependent on the local seeing conditions near PEARL. It is to act as a pathfinder to future, larger instrumentation yet to be designed. Engineering studies for a 2m class telescope comparable to those for the Antarctic Domes are to follow. The deployment of a sub-mm antenna for Very-Long Baseline Interferometry (VLBI) from Summit is being investigated.

SCAR can facilitate these advancements in a number of ways, all of which fall largely within the activities recommended under the 'Coordination' section of Working Group C (see §4.7). Some key interactions of particular value for the Arctic are as follows:

- Provide a forum for increasing awareness among the Antarctic and broader scientific community of Arctic site-testing activities, the currently known conditions, and efforts to characterise those for scientific utility.
- Encourage interaction among users of the different polar research facilities, potentially leading to improved use of sites otherwise not considered. For example, the reversed seasons of the poles may provide opportunities for more rapid deployment or field-readying of instruments. Of particular note are the year-round logistics available at Eureka.
- Providing opportunities for the international astronomical site-testing community to meet and discuss methods and results. This might be in the form of sponsoring conferences and workshops, as well as encouraging or developing other web-based formats. This can help ensure complementarity of data, sharing of engineering or scientific resources, and possibly reveal new synergies between programs at various sites.

4. Working Group C: Science Goals

4.1. *Scope and Aims*

The Science Goals Working Group (SG) is one of four groups reporting to the Scientific Committee on Antarctic Research (SCAR) Astronomy & Astrophysics from Antarctica (AAA) Scientific Research Programme. This document defines the implementation plan for the SG. The main objective is to define the kinds of astrophysical observations and experiments that are best conducted from Antarctica, to outline some of the science investigations such observations would facilitate, and to suggest ways by which these may be achieved.

4.2. *Background*

Extensive site testing activities undertaken by the international science community in Antarctica over the past two decades have established that the continent provides a unique environment that is favourable for many kinds of astronomical research programs. This is on account of the cold, dry and stable air found above the high Antarctic plateau, as well as the pure ice below. The opportunities for astronomy are found across both the photon and particle spectrum. The summits of the Antarctic plateau provide the best seeing conditions, the darkest skies and the most transparent atmosphere of any earth-based observing site. The astronomy that has been conducted from Antarctica so far includes optical, infrared, terahertz and sub-millimetre astronomy, measurements of the cosmic microwave background radiation anisotropies, solar astronomy, as well as high-energy astrophysics involving the measurement of cosmic rays, gamma rays and neutrinos. Antarctica is also a rich source for meteorites.

Many sources have been drawn upon for the material presented here, in particular the reviews of Burton (2004), Storey (2005), Storey (2009) and Burton (2010), as well as the report from the "Astrophysics from the South Pole" workshop held in Washington DC in April 2011. Several books have also been devoted entirely to astronomy in Antarctica, the proceedings of conferences held on the subject. These provide sources for further reading on the science ideas presented here, as well as on many others. The books include the proceedings of the American Institute of Physics conference on Astronomy in Antarctica in Newark, USA in 1989 (Mullan, Pomerantz & Stanev 1990), the Astronomical Society of the Pacific symposium on Astronomy in Antarctica in Chicago, USA in 1997 (Novak & Landsberg 1998), the Concordia station workshop in Capri, Italy in 2003 (Fossat & Candidi 2003) and the three European ARENA conferences, held in Roscoff, France in 2006 (Epchtein & Candidi 2007), Potsdam, Germany in 2007 (Zinnecker, Epchtein & Rauer 2008) and Frascati, Italy in 2009 (Spinoglio & Epchtein 2010).

4.3. *Site Conditions for Astronomical Observations in Antarctica*

As a result of the site testing campaigns conducted in Antarctica (e.g. see the Working Group A implementation plan) we know that the following facets of the environment on the Antarctic plateau provide exceptional conditions for many types of astronomical observation:

- The darkest infrared sky background of any ground-based location due to being the coldest place on the Earth's surface, the flux dropping by factors between 20 and 100 in the thermal infrared (from 2.2–30μm) from good temperate sites.
- The most transparent skies of any ground-based site, from 3μm to 3mm, due to the lowest precipitable water vapour columns, 3–5 times lower than at the best temperate sites.

- Clear skies, with photometric conditions occurring an exceptional 75–90% of the time at some high plateau locations.
- The high stability of the sky background, in particular when above the thin, turbulent surface boundary layer, important for accurate sky subtraction across infrared to millimetre wavelengths.
- Exceptional seeing conditions above a narrow surface boundary layer, typically twice as good as from excellent temperate sites and sometimes falling below $0.1''$ in the visual. In addition, there are larger isoplanatic angles and longer coherence times than found at good temperate latitude sites (typically 2–3 times as good).
- Long interrupted periods of darkness during winter months.
- Reduced scintillation noise, 3–4 times lower than at temperate sites.
- Aerosol levels up to 50 times lower than at temperate sites, together with minimal pollution.
- The circumpolar vortex, allowing high-altitude balloons to circulate the continent in summer with near-constant elevation.
- Vast quantities of pure, clear ice approximately 3 km deep, suitable for as both a target for high energy particles and a conduit for observing the resultant Cherenkov radiation from the particle interactions in the ice.
- No aircraft contrails in winter.
- Antarctica is the quietest continent, seismically.

4.4. *Astronomical Techniques Advantaged by Antarctica*

The site conditions outlined above provide advantages for many kinds of astronomical observations. Here we list techniques that would benefit from them, and the nature of the gain achievable over good temperate-latitude sites.

- Optical: improved image quality.
- Infrared: low sky & telescope backgrounds, together with improved sky stability, in addition to better image quality.
- Terahertz: windows opened for regular observation.
- Sub-millimetre: improved sky transmission and improved sky stability.
- Millimetre: improved sky stability.
- Time series astronomy: high duty cycle measurements, with stable conditions and long, uninterrupted periods of darkness.
- Precision photometry: low scintillation noise.
- Infrared interferometry and adaptive optics: improved values of coherence time, isoplanatic angle and Fried parameter, together with the temperature stability for delay lines.
- Cosmic rays: low energy threshold due to the proximity to geomagnetic pole.
- Neutrinos: use of vast quantities of pure ice as an absorber as well as for the deployment of detectors to observe the radiation tracks produced when high energy neutrinos interact with nuclei in the ice.
- Balloons: long duration flights in a constant environment, due to the Antarctic circumpolar vortex.
- Solar: excellent daytime seeing, low coronal sky brightness and high duty cycle for measurements during summer months.
- Paleo-astronomy: fossil signatures of externally induced atmospheric disturbances embedded within ice columns.

We highlight two specific examples further here:

- In the field of infrared astronomy Antarctica can facilitate big science with small telescopes. A telescope on the plateau, with an aperture four times smaller in diameter to a good temperate-latitude telescope, will have similar sensitivity for many applications.

- In the sub-millimetre and THz bands, Antarctica facilitates big dishes and big interferometers. The vast expanse, low winds and stable conditions of the Antarctic plateau places less restrictions on the scope that possible facilities may have than when placed at high-altitude temperate sites.

4.5. *Astronomical Science Programs Conducted in Antarctica*

Astronomy programs have been conducted in Antarctica since the IGY, 50 years ago. We briefly summarise some of these programs here. This list provides a practical guide to the scope of activities it is possible to accomplish in this field in Antarctica.

- Meteorites: most productive place to search for meteorites on account of their relative ease of identification (Nagata *et al.* 1975), including discovery of meteorites from Mars (McKay *et al.* 1996).
- Helioseismology, through extended observations of solar oscillations (e.g. Grec, Fossat & Pomerantz 1980).
- Cosmic microwave background anisotropies: determination of the flat Universe (BOOMERanG; de Bernardis *et al.* 2000), first detection of CMBR polarization (DASI; Kovac *et al.* 2002), high angular scale anisotropy (ACBAR; Kuo *et al.* 2004), Sunyaev-Zeldovich effect in galaxy clusters (SPT; Staniszewski *et al.* 2009).
- Sub-millimetre & terahertz astronomy: first detection of [CI] in the Magellanic Clouds (AST/RO; Stark *et al.* 1997), mapping of [CI] and high-J CO across the warm gas of the Central Molecular Zone (Martin *et al.* 2004), first ground-based spectrum of the THz [NII] line (Oberst *et al.* 2006), measurement of large-scale toroidal magnetic fields through dichroic polarization (Viper; Novak *et al.* 2003), determination of cosmic infrared background contributions (BLAST; Devlin *et al.* 2009), mapping of the cold dust cores across the Vela Molecular Ridge (Netterfield *et al.* 2009).
- Infrared astronomy: mapping of PAHs emission across star forming complexes (SPIREX; NGC6334 – Burton *et al.* 2000, Carina – Brooks *et al.* 2000), IR–excesses from disk around young stars (Chamaeleon I – Kenyon & Gomez 2001, 30 Doradus – Maercker & Burton 2005, NGC3536 – Maercker, Burton & Wright 2006).
- High-energy astrophysics.
  - For cosmic rays, the spiral nature of the solar magnetic field (McCracken 1962).
  - For gamma rays, search for point sources using the SPASE and SPASE–2 air shower arrays (Smith *et al.* 1989, Dickinson *et al.* 2000).
  - The detection of high energy neutrinos with AMANDA (Andrés *et al.* 2001), AMANDA–II (Ackermann *et al.* 2005) and IceCube (Ahrens *et al.* 2004 and see references under Abbasi *et al.* 2011b, Abbasi *et al.* 2011c); in the TeV to EeV energy range IceCube is now able to detect $\sim 50,000$ atmospheric neutrinos, 1 billon air showers and 100 billion atmospheric muons per year. IceCube performs searches for cosmic neutrinos at a wide energy range as well as neutrino physics, cosmic rays physics and anisotropy searches.
  - Search for the Askaryan effect (ultra-high energy neutrinos) with RICE (Kravchenko *et al.* 2008) and, from balloons, with ANITA (Gorham *et al.* 2010) and with the Askaryan Radio Array (Hanson *et al.* 2012).
  - In addition, an ice core timeline has been found to show changes in atmospheric composition possibly attributable to ionization events caused by gamma rays from historical supernovae (Motizuki *et al.* 2010).

4.6. *Science Opportunities for Antarctic Astronomy*

Several extensive science cases have been published encompassing observatory-style science that could be advantageously carried out with Antarctic telescopes, in particular across the optical to sub-millimetre wavelength domain (e.g. Burton *et al.* 1994, Burton *et al.* 2005, Lawrence *et al.* 2009a, 2009b, 2009c, Epchtein 2010). There have also been many descriptions given for specific science investigations (e.g. as found in the three ARENA conference proceedings). Identifying any particular science case as the feature for a science program is, of course, fraught with difficulty, as ideas constantly evolve as the nature of scientific enquiry does. However, we may indicate some of the programs that have received wide interest:

4.6.1. *Optical and Infrared Astronomy*

First Light in the Universe

- A near infrared search for pair-instability supernovae at redshift 6 and beyond. Here the wide-field, high sensitivity capabilities of an Antarctic telescope would provide a powerful synergy for the James Webb Space Telescope (JWST). It would probe a different region of the pair-instability supernovae parameter space, i.e. allowing detection of these theoretically predicted objects if they are either faint and common (JWST), or bright and rare (Antarctica).
- Identifying gamma-ray bursters at high redshifts. Due to their high intrinsic luminosity, gamma-ray bursts are a powerful probe of the Universe at a range of cosmological distances. By following-up in the near infrared every high energy satellite gamma-ray burst alert in the observable sky, an Antarctic telescope would be expected to find a number of objects in the redshift range z=6–10, if they exist. Wide field infrared surveys would also probe the rate of occurrence of high redshift gamma-ray burst orphan afterglows to lower number densities than possible with any other facility.
- The 1.25 to 2.5μm range is traversed by the Lyman break at redshifts 12 to 26, allowing identification of sources in the early phase of the epoch of reionization. Light signatures of the development of supermassive black holes and the formation of globular clusters are to likely to be found during this crucial period. Deep surveys of significant regions of sky will be required. If JWST is restored and flies, objects discovered in these surveys will have their spectra analysed by JWST. Otherwise the ELTs will tackle this task. Either way, the large fields of infrared Antarctic telescopes will be of tremendous value.
- The 2 to 4μm range corresponds to the rest-frame optical range for galaxies at $2 < z < 5$. An Antarctic telescope would be well suited to extend the determination of the physical parameters, largely used today in the local universe, to the high-redshift universe. The H–Lyα line is one of the main tracers of star formation at all redshifts. It lies in the K (2μm) band for $z = 2$ to 3, the peak for star bursts in the evolution of galaxies. In the L band (3–4μm) band the $z = 4$ to 5 range can be explored. These two domains are crucial to understanding of the star formation history of the universe. The low sky thermal emission and the wide field of view would also allow a wide-area 2.4μm $\mathrm{K_{dark}}$ survey to find more distant galaxies at lower limiting masses than possible with other facilities. Additionally, the combination of deep $\mathrm{K_{dark}}$ survey data with longer wavelength Spitzer "warm mission" observations, would allow the identification of significant numbers of Balmer break galaxies in the redshift range $z = 5$–7. These evolved galaxies represent the very earliest stellar populations to form in the Universe.

The Equation of State of the Universe and the Dark Universe (Dark Energy and Dark Matter)

- Dusty supernovae: with a wide field-of-view combined with a high infrared sensitivity and wide wavelength coverage an Antarctic telescope should be able to detect and obtain infrared light-curves for larger numbers of Type Ia supernovae at higher redshift than possible with any other current facility. Infrared supernova data, with reduced effects of dust extinction and reddening, also show less dispersion in SN1a peak magnitudes, and allow tighter constraints to be placed on the parameters of the expansion of the Universe.

- Weak lensing imaging at 2.4μm in Antarctica offers a unique capability to image distant galaxies with high sensitivity in this band, over wide fields with an angular resolution comparable to their size due to the excellent seeing. Obvious applications are the more precise determination of independent masses for the oldest clusters found by the South Pole Telescope – a crucial diagnostic of structure formation – or weak lensing studies at larger depths, or on smaller scales, than will be possible with, e.g., LSST or PANSTARRS, to distinguish between cosmology variants. Similarly this capability also benefits measurements of baryonic acoustic oscillations, whose constant size provides a standard cosmological ruler, to determine the angular diameter distance relationship with redshift.
- Optical weak lensing: the image quality over wide fields allows lensing studies to a depth not otherwise achievable from the ground in the riz bands. Uniquely, Antarctic telescopes can take full advantage of orthogonal transfer arrays, allowing fast-guiding over arbitrarily large fields. The aim would again be to push lensing studies to redshifts not accessible to LSST or PANSTARRS.
- The cosmic web. The high-redshift intergalactic medium could be studied over large fields of view through observations of resonant UV lines, in particular from Lyα at 121.6nm at redshifts of z ~2–3, in contrast to the pencil-beam sight lines currently provided through use of quasar absorption lines. Such observations would provide direct probes of large scale structure and the dark matter distribution in the early Universe. They are facilitated by continuous access to a dark and stable sky, with low extinction and scattering, to enable accurate spectral cancellation of the sky background emission, but does not need high spatial resolution. Such conditions are found, for instance, at the South Pole.

Stellar Populations

- Stellar populations: the combination of high sensitivity, wide field of view, and good spatial resolution would enable an Antarctic optical/infrared telescope to conduct a range of studies of stellar populations in nearby galaxies. These range from detailed studies of the Magellanic clouds in new wavelength bands, and to studies of the high surface brightness inner parts of disc galaxies out to the edge of the Local Group. Multiple epochs of observation could be conducted for the Magellanic Clouds, so allowing light curves to be determined.
- Asteroseismology: the good image quality over wide fields, the low scintillation noise, and the long-time duration observations possible, allows for precision milli-magnitude optical photometry of entire star clusters simultaneously. This means that asteroseismology can be undertaken en masse for stellar populations of uniform age and metallicity in order to probe stellar activity.

The Galaxy and Galactic Ecology

- Mid-infrared spectrophotometric surveys searching for signatures of embedded protostars, crystalline silicates, and circumstellar disks around young stellar objects and brown dwarfs.
- The site conditions on the summits of the Antarctic plateau makes possible sensitive measurements in the mid-infrared of two of the lowest energy lines of molecular hydrogen, emitted at 12 and 17μm, which could not be undertaken from temperate sites. This makes it possible to directly image the warm environment of molecular clouds, on the arcsecond

scale, over wide regions of the Galactic plane. These lines arise from the surface layers of molecular clouds, warmed by the interstellar radiation field or in clouds heated by turbulence. They comprise much of the molecular environment of the Galaxy, outside the cold, dense cores where star formation is initiated. The turbulent injection of energy and its dissipation is suspected of being the primary agent responsible for the initiation and regulation of star formation through molecular clouds, and so is a central facet affecting the Galactic ecology of the star-gas cycle. The turbulence distribution and strength could be directly probed through measurement of these H_2 lines over wide angular scales.

Exo-planets

- Exoplanets by the transit technique. The observation of known transits, selecting the brightest targets, is the only way to characterise the planetary atmospheres, through their composition (molecules, clouds, hazes) and temperature profiles, by recording the stellar spectrum at low resolution during a transit. From the difference between two spectra, one obtained with the planet in front of its host star (i.e. the primary transit) and the other of the planet + star, one can derive the transmission spectrum of the planet. Observations in the 2 to 5μm range, where the emission is dominated by common molecules such as H_2O, CH_4 and CO_2, are recommended. With a measurement of the secondary transit (planet behind its star) as well, an emission spectrum of the planetary day-side can also be obtained.
- Exoplanets by the micro-lensing technique. This technique is powerful method for providing statistical results on exoplanets in the parameter space of [mass, distance to star] that are not accessible by other methods, making possible the detection of Earth-mass planets from one to a few AUs from their host star. For the best chance of detecting the perturbation of the light curve due to a planet, continuous monitoring is necessary during the few days around the light maximum. Photometry undertaken in the 2μm K band, rather than in the visible, significantly reduces the extinction toward the Galactic Bulge, which, in addition, is rich in old star populations having their maximum flux in this band. The two Magellanic Clouds are also favourable targets for such a program.
- The inner parts of debris disks and exo-zodiacal dust clouds could be examined in a range of stellar systems using an infrared nulling interferometer. Such physical features are of considerable importance in characterising the nature of planetary systems, and more-over such warm zodiacal dust around nearby stars may hinder future space missions aimed at the direct detection and study of Earth-like planets.
- Direct detection of exo-planets. The highest spatial resolution can be obtained through infrared interferometry, also providing spatial filtering in high contrast imaging, necessary for the direct detection and characterisation of planets orbiting around other stars. Optimally, such an instrument would be placed in space, but the extreme cost of such a mission likely precludes it in the near future. Infrared interferometric observations are suited from the Antarctic plateau due to the combination of slow, low-altitude turbulence, low water vapour content and low temperature, as well as the completely temperature stable sub-ice environment for housing the delay lines.

4.6.2. *Terahertz and Sub-millimetre Astronomy*

The Formation of Molecular Clouds

Molecular clouds can be formed from large structures of atomic gas that envelope spiral arms of galaxies. Observations made in other galaxies do not show us how this occurs as they lack the resolution needed to resolve the processes at work; the structures must be studied within our own Galaxy. They must include the diagnostic emission features that trace the three main types of clouds: atomic clouds (where H is dominant), clouds with only hydrogen in molecular form (known as “dark” clouds for they have little or no CO emission), and fully molecular clouds (i.e. with CO and other molecules). The problem is a challenging one, for there are no direct emission signatures from the newly-formed hydrogen molecules that mark where molecular clouds manifest themselves – hydrogen molecules will all be in their ground state unless the gas is heated to temperatures > 100 K. The process of molecular cloud formation thus needs to be inferred from trace species, by measurement of C^+, N^+, C, H and CO lines, arising from ionized, atomic and molecular gas. Thus THz observations of the [CII] 158μm and [NII] 205μm lines, combined with sub-mm and mm observation of [CI] (371, 610μm) and CO (e.g. 652μm, 870μm, 1.3mm, 2.6mm) and existing HI (21cm) data, are needed.

The Origins of Stellar Mass

Stars arise from molecular cores, and their mass must be related to the physical environment existing in these natal cores and the size of their gas reservoirs. The pre-stellar and proto-stellar core mass functions are therefore important quantities to measure in order to determine the physical basis of the initial mass function (IMF). Core mass and luminosity, together with density and temperature profiles, can be determined through measurement of a core's spectral energy distribution. For the coldest cores this will peak in the THz and sub-mm bands; for instance a 15 K dust core will emit most strongly at ~ 1.5 THz (200μm).

The Galactic Star Formation Rate: calibrating the "Schmidt" law

Star formation in external galaxies has commonly been estimated using the "Schmidt" law, which relates the star formation rate to the gas surface density, with a threshold surface density below which star formation is suppressed. This law has been used with great success despite its simplicity as a power law relationship, being based on just empirical data, for it is not possible to resolve the individual star forming regions in other galaxies. However, it does not explain why the rate of star formation has such a correlation. THz observations, together with sub-mm and mm supporting data, will make it possible to directly examine the relationship, and so allow this question to be addressed. This is possible because they permit calibration of the law by measuring the two relevant quantities, the star formation rate and the gas column density. The N^+ line intensity is directly proportional to the flux of ionizing photons, which in turn arises mostly from short-lived massive stars, so providing a measure of the star formation rate. To find the gas surface density requires measurement of the atomic and molecular components of the gas over the same region, and is given by combining data from four species (C^+, C, CO & H). Taken together, these provide a determination of the amount of material existing along a sight line.

The ISM of the Magellanic Clouds

The LMC and SMC are the nearest galaxies to us, and provide laboratories where galactic-scale processes can be readily studied. As low-metallicity systems they are also used as templates to compare with star formation in our Galaxy and so for conjecture how star formation may occur in the early universe. The sub-mm and mm molecular lines have proved to be hard to measure in the LMC/SMC, with only the CO J=1–0 line readily mappable in reasonable integration times. The strength of the two bright THz lines, [NII] and [CII], will therefore be particularly valuable for understanding the molecular environment and the star formation occurring within the Magellanic Clouds. The N^+ line intensity can be used to provide a measure of the star formation rate across each Galaxy, and the C^+ line is the dominant cooling line of their ISMs.

Templates for Understanding High Redshift Extra-galactic Emission

As principal cooling lines in the interstellar medium, C^+ and N^+ emission will provide primary diagnostic tools for studying the most distant galaxies with ALMA, where the lines will be red-shifted into the sub-millimetre bands. However such galaxies will be spatially unresolved, with only global properties of their emission measurable. Observations in our own Galaxy which encompass a wide range of physical conditions are therefore essential in providing a template for use in interpreting the emission from galaxies in the early universe.

4.6.3. *Cosmic Microwave Background Radiation (CMBR)*

The exceedingly good stability of the sky in the millimetre-bands, together with the possibility of extended observations of a section of the celestial sphere at near constant zenith angle, have allowed several frontier investigations into the CMBR, as outlined above. While this has been largely led by investigations conducted at the South Pole, high plateau sites away from the Pole may offer an advantage in not having exactly the same zenith angle, allowing for cross-linked scans and drift removal techniques to further improve the background subtraction and removal of instrumental artefacts.

There are two areas of CMBR research with clear potential for undertaking new science from Antarctica: small-scale temperature anisotropies and the B–mode polarization power spectrum.

Small-scale Temperature Anisotropies

Clusters of distant galaxies can be readily detected through the Sunyaev-Zel'dovich (SZ) effect, measuring across the peak of the CMBR spectrum (which occurs around 1mm wavelength) at high angular resolution, as has been demonstrated through the success of the 10m South Pole Telescope (SPT). The brightness of the SZ–effect is independent of redshift, so that high-redshift clusters are equally easy to find as those nearby, providing the measurements have sufficient spatial resolution. The magnitude of the SZ-effect depends on the thermal energy of the cluster, and so of its mass, a parameter that cosmological models can predict. Combined with subsequent red-shift determinations, the mass distribution of large-scale structures can then be determined. This provides completely independent constraints on the nature of the Dark Energy that is presumed to be driving the accelerating Universe than the direct measurements of cosmological expansion inferred from observations of distant supernovae.

B–mode Polarization

Polarization measurements of the CMBR provide a means to understand dark matter, dark energy, neutrino mass and the epoch of Inflation. Density perturbations at the epoch of Recombination ($z \sim 1000$) result in "E–mode" polarization of the CMBR, as was first measured by the DASI experiment at the South Pole (Kovac *et al.* 2002). Their signal is about 1% the level of the CMBR itself. Additional signals in the CMBR can be generated by gravitational waves. Unlike the density fluctuations, these need not obey parity, and therefore can generate what are known as "B–mode" polarization, a further $10^2 - 10^3$ times weaker again then the E–mode signal. There are two likely contributors to any B–mode polarization. The first are gravity waves generated during the epoch of Inflation, occurring at, or near, the GUT (Grand Unified Theory) energy scale. They might generate signals on angular scales of 1 degree. A second, stronger means of producing B–modes is through gravitational lensing of the CMBR signal on its passage to us, which can convert some of the E–mode polarization into a B–mode signal. This is expected to peak on angular scales of a few arcminutes. The lensing signal depends on the dark energy equation of state, the spatial curvature of the Universe, and the sum of the neutrino masses, so any measurement of it provides constraints on these parameters.

4.6.4. *High Energy Astrophysics: Neutrinos and Cosmic Rays*

An intriguing questions in physics is the origin and evolution of the cosmic accelerators that produce the highest energy particles known: ultra-high energy cosmic rays

(UHECR) with energies up to $\sim 10^{20}$ eV for a single particle. These can "only" travel for $\sim$ 100 Mpc from their origin before interacting with a microwave background photon, in the process creating an UHE ("cosmogenic") neutrino. Cosmic rays at lower energies will be deflected by intergalactic magnetic fields and high energy gamma rays will get absorbed by interaction with lower energy photons. The neutrino can travel virtually unimpeded throughout the Universe, and so provides a messenger from the creation of those high energy particles in nature, if they can be detected. Detection can occur as a result of their interactions with nuclei in large volumes of a dense dielectric, and the subsequent particle cascades that are produced. The Antarctic icecap provides the most suitable such medium, as its clarity also allows the resultant Cherenkov radiation pulse to be detected and traced back along the direction of the incoming neutrino, and so towards its source. This has been exploited by the construction of the IceCube neutrino telescope, sensitive to neutrinos in the 10^{11-18} eV energy range detectable via their optical Cherenkov light. At higher energy radio frequency emission dominates, and this has driven the construction of the RICE and ANITA experiments seeking to measure the radio pulse caused by the resulting Askaryan effect. More recently the construction of the first phase of the Askaryan Radio Array has begun at the South Pole.

Astrophysical Sources of Neutrinos

A galactic or extra-galactic source of neutrinos would be manifested with IceCube as a statistically significant clustering of high energy neutrinos on the sky, a small excess on the background created by atmospheric muons and neutrinos (Abbasi *et al.* 2011a). At energies above one PeV there is essentially no background from atmospheric neutrinos. At lower energies the excess would be defined as a clustering in direction and or time. No such excess has yet been detected, though IceCube was only fully-completed in 2011.

Gamma-ray bursts (GRBs) may also be sources of cosmic rays and therefore of high-energy neutrinos. Coincidence timing over the few tens of seconds when the gamma rays are seen (by space-based telescopes) may establish the connection, as well the source if the GRBs are also optically identified. A neutrino detection would provide evidence for proton acceleration in the progenitors, and so of the processes that fuel them.

IceCube is also highly sensitive to the neutrino burst from the core collapse in a supernova explosion in our galaxy. With 99% on-time operation it is prepared to record such an event with high precision.

Cosmic Rays

A surface detector array called IceTop is integral part of IceCube making it a versatile cosmic ray laboratory. The detailed measurements of cosmic rays will allow a very precise measurement of the energy spectrum as well as the composition of cosmic rays from PeV to EeV energies. The flux of about 100 billion muons per year can be used to measure for the first time the anisotropy of cosmic rays in the Southern sky to a precision of 10^{-4} on small and large scales (Abbasi *et al.* 2011d).

Extension to Lower Energy Neutrinos

IceCube may be extended to lower energy neutrinos, in the GeV range, using a "close-packed" array of photomultiplier strings in the centre of the array. 6 such strings have been included as part of IceCube itself ("Deep Core"), which lowers the energy threshold to $\sim$ 10 GeV. A further $\sim$ 20 strings would lower the threshold to $\sim$ 1 GeV. At such energies neutrino measurements would be sensitive to indirect searches for dark matter and to precision measurements of atmospheric neutrino oscillations. The lower energy threshold also allows for a dramatically increased sensitivity in the indirect search for dark matter. Dark matter annihilation e.g. in the Sun allows IceCube to explore a large parameter space of dark matter models by looking for an excess of neutrinos from the sun at energies above 10 GeV. There are visions for much denser instrumentation which could allow the measurements of the proton decay.

Dark Matter

Dark matter might be detected directly through scintillation occurring in pure crystals where a dark matter interaction has occurred. The recoiling nuclei in a pure crystal of sodium iodide can emit photons which are detectable with photomultiplier tubes buried in the ice. An annual modulation in such a signal, the result of the Earths motion around the Sun, provides a means of extracting the dark matter signal from the background flux.

Cosmogenic Neutrinos

The interaction of the highest energy cosmic rays ($\sim 10^{20}$ eV) with a cosmic microwave background photon ($\sim 10^{3}$ eV) results in the production of a charged pion. This then decays to produce "cosmogenic" neutrinos that may continue, unimpeded, across the entire Universe. This is the Greisen-Zatsepin-Kuzmin (GZK) effect (Greisen 1966, Zatsepin & Kuzmin 1966). An image of the neutrinos from such a source would reveal a small halo surrounding the emitting source of the cosmic rays, whose size is determined by where they interact with CMBR photons. These neutrinos might be detected by the Askaryan effect, a shower of particles caused by the interaction of such a cosmogenic GZK neutrino with a nucleus and a subsequent charge anisotropy that develops in the particle cascade as the positrons annihilate. This results in a plug of charge, a few cm across, travelling faster than light in its medium, and producing a pulse of Cherenkov radiation, which then manifests itself observationally as a pulse of radio waves at a frequency of ~ 1 GHz.

The most promising location to employ the Askaryan Effect is within the Antarctic icecap. The ice is several km thick over the Antarctic plateau and relatively transparent to radio waves. By placing an array of radio antennae beneath the ice surface a neutrino detector can be constructed with an effective volume given by the surface area covered by antennae multiplied by the thickness of ice. Accurate timing of the radio pulses can then be used to reconstruct the direction of the incoming neutrinos to within $\sim 6^{\circ}$ for an instrument about 10 km across. The strength of the radio signal gives information on the energy of the neutrinos, and provides a probe of the very highest energy interactions known in nature. IceCube is likely too small to reliably detect the small fluxes of such GZK neutrinos; a collecting volume 2–3 orders of magnitude larger is required. Such a detection experiment is proposed for the Askaryan Radio Array at the South Pole.

4.6.5. *Solar Astronomy*

High plateau sites provide unique conditions for solar astronomy. The periods of excellent daytime seeing (as observed at Dome C), combined with low coronal sky brightness (due to minimal aerosols and low water vapour), IR–accessibility and high duty cycle observations (the Sun being continuously above the horizon for several months, 1,700 hours with a Fried parameter $r_0 > 12$ cm allowing adaptive optics), offer interesting prospects for permanent high angular resolution solar studies (i.e. $<< 0.1''$) and for coronal access (cf. Damé *et al.* 2010). These conditions facilitate continuous observations at high resolution of the corona-chromosphere interface, notably for direct measurements of the magnetic field in the corona and chromosphere (prominences), as well as of waves (MHD or Alfvén) passing through them (and contributing to heating?). The magnetic investigation of the Sun, from the convection zone to the corona, could be undertaken from Antarctic solar telescopes, requiring instrumentation for 2D spectro-imaging, spectro-polarimetry, magneto-seismology and for chromospheric & coronal magnetometry.

A first mid-size facility is proposed, AFSIIC (Antarctica Facility for Solar Interferometric Imaging and Coronagraphy), using 3 off-axis telescopes of 50cm diameter each (1.4m equivalent telescope), and high resolution up to $0.06''$, allowing access these objectives with the proper flux, angular resolution and coronagraphic potential. Coronal sky conditions associated to high resolution (direct access to the free atmosphere seeing at temperature gradient inversion in the afternoon) provide unique conditions opening the possibility to test future coronal space missions like ESA ASPIICS/PROBA–3. Support infrastructure and logistics have been studied and evaluated to optimise observing conditions, noticeably a 30m tower (cf. Dournaux *et al.* 2010) to place the observatory over the very thin surface turbulent layer of Dome C, 70% of the time (i.e. almost 100% of the clear accessible time).

Another non-negligible advantage to be considered is complementarity with northern hemisphere observation sites that will suffer winter (non) observing conditions while excellent summer conditions prevail on Antarctica high plateau sites.

4.7. *Coordination*

Antarctic astronomy is not a special kind of astronomy; it is all astronomy that is facilitated by the special conditions of Antarctica. The astronomy that is conducted in Antarctica should only be that astronomy which can be done better there, whether it is by improved capability, or by its cost effectiveness compared to other locations, whether they are Earth-based or in space. For instance, transportation costs to Antarctica are of order \$10 per kg of material, compared to \$15,000/kg for a payload launched on a rocket to low Earth orbit (the typical cost of space hardware is also about \$140,000/kg). Antarctica thus provides a much cheaper alternative to space, as well as the ability to recover from failures. Nevertheless, conducting astronomy in Antarctica does face special challenges, largely on account of the geo-political environment. Antarctica is not owned by anyone, it is international territory. It functions as an international science reserve, and activities conducted there are thus facilitated by international collaboration and co-operation, more so than from anywhere else. There is a special need for bodies like SCAR and the IAU (International Astronomical Union) to play a role in nurturing such activities and bringing together prospective partners to make the science happen.

SCAR can facilitate such interactions in a number of ways, which we highlight below:

- Providing a forum for the international community to meet, and in them showcasing the opportunities provided by Antarctica for astronomy.
- Bringing prospective partners together through awareness of the different, and complementary skills and capabilities they possess, so that these can all be used to tackle a particular project.
- Provide a forum to facilitate moving beyond national priorities, to setting objectives for international facilities, while taking account of disparate national capabilities and interests.
- Sponsoring conferences, workshops and meetings, to highlight the opportunities, and making the international science community aware of them. While SCAR cannot determine the new science that should be done in Antarctica, it can publicise the scientific techniques that Antarctica facilitates, so that individual scientists become aware of new opportunities to pursue ideas they have.
- In particular, by promoting such linkages with the IAU, SCAR may educate the astronomical science community about opportunities they may otherwise be unaware of. The IAU host a tri-annual General Assembly (similar to the bi-annual SCAR meeting), and SCAR could usefully have a presence at that Assembly. There is an IAU Working Group for Antarctic astronomy through which networks can be developed. In this vein, the IAU allocated this Symposium (IAU Symposium 288, "Astrophysics from Antarctica") for the General Assembly held in Beijing in China in August 2012. This was the first IAU Symposium to ever be held on the theme of astronomy in Antarctica.

- Through its websites, SCAR can provide information summarising the state of knowledge and practice in Antarctic astronomy. This would primarily be through giving direct linkages to other sites where that information is being actively generated.

5. Working Group D: Major New Facilities

5.1. *Scope and Aims*

This section is intended to capture the essence of discussions of this Working Group at the Taronga Zoo meeting (July 2011). Suggestions were wide-ranging and some do not lend themselves to easy categorisation. Organisation of this section attempts to group things according to four major themes.

5.2. *The International High Plateau Station*

Although national polar programs have many advantages in terms of leveraging resources from government and industry bodies, it was noted that the exclusive population of national bases also generates significant disadvantages and complications. They are often set up in an environment where political motives are competitive rather than collegial. When they become the vehicle for national prestige, the ethos of rapid and fluid international collaboration which is the lifeblood of the most successful modern scientific endeavours becomes difficult to support. This motivated the idea of some form of international station which would have some form of relatively open-door policy to national membership from a wide range of countries. This follows the trend of international astronomical observatories such as the Gemini partnership or the European Southern Observatory. Much of the same logic applies, with immediate and profound advantages gained by sharing infrastructure and creating a crucible for cross-fertilisation with scientists from many nations working together. This is surely a recipe for the construction and maintenance of healthy international collaborations.

Such an International High Plateau Station would have strong resonance with the spirit of the Antarctic Treaty itself. Perhaps most importantly of all, it would provide a vehicle for smaller countries (such as Indonesia or Denmark) with Antarctic aspirations to share the otherwise prohibitive costs of running an entire program alone. The democratisation of access to the Antarctic would surely yield long term benefits with a far wider national demographic to draw upon for new ideas in the exploration of the scientific potential of working there. It is not clear if such a station would be sited completely separately from existing infrastructure, or whether there could be a case for leveraging from existing supply and communications lines. Such an initiative already has a precedent in the ARENA program, albeit operating with a European rather than an International theatre. A further advantage of such an organisational structure is the security of commitment provided by international treaty level co-operative agreements: surely a lesson from space missions and major observatories we would do well to emulate.

5.3. *What are the major enabling technologies needed for the next steps?*

In no particular order of importance, enabling technologies required for new generation initiatives to take form on the ice were discussed.

- PLATO already forms an excellent model for providing much of the requirements for science from the High Plateau.
- Ground Layer Adaptive Optics (Inexpensive and likely to become far more common at mid-latitude observatories in coming years).
- Stable tower designs (and foundations that do not sink or differentially shift).

- Mitigating the effects of high relative humidity (but low absolute humidity).
- High bandwidth communications back to home institutions.
- Versatile devices and computing platforms which are robust and operate with low power demands (e.g. efficient Cryo-coolers).

5.4. *Are there simple strategies to adopt to help facilitate better collaborative links?*

- Again, PLATO sets an excellent precedent here in providing a "standard platform".
- Do we need a data standard/format/definitions for site testing data metrics?
- Push for portable science verification instruments which can be shared between sites.
- Is it possible to define standard hardware interfaces?

5.5. *Example science domains for major new initiatives*

For the present, this is an incomplete listing intended as a starting point for fleshing out of areas for growth of scientific capacity.

- High energy/particle astrophysics (already mature)
- CMB astronomy (already mature)
- Balloon-borne platforms (mature)
- Meteor sample programmes (mature)
- THz astronomy
  - Single dish
  - Interferometry
- IR astronomy
  - Wide-field imaging
  - Continuous cadence observing for variable/transitory phenomena
- Visible light adaptive optics (AO)
  - Hubble will likely be de-orbited someday and the demand for visible-light wide-field, high angular resolution imaging will suddenly be thrust upon ground based observatories. It is doubtful if any of the available flavours of AO at mid-latitude observatories will deliver sufficiently in this regard.
- Solar astronomy
  - Continuous cadence observing
- Optical interferometry
  - Several architectures possible: astrometric/nulling/imaging/closure phase.
  - Each has quite distinct science reach and distinct advantage from the Antarctic.

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† See www.astronomy.scar.org

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