# The Scientific Potential for Astronomy from the Antarctic Plateau

A Report prepared by the Australian Working Group for Antarctic Astronomy

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## EXECUTIVE SUMMARY

Our knowledge of the universe comes from recording the photon and particle fluxes incident on the Earth from space. We thus require sensitive measurement across the entire energy spectrum, using large telescopes with efficient instrumentation located on superb sites. Technological advances and engineering constraints are nearing the point where we are recording as many photons arriving at a site as is possible. Major advances in the future will come from improving the quality of the site. The ultimate site is, of course, beyond the Earth's atmosphere, such as on the Moon, but economic limitations prevent our exploiting this avenue to the degree that the scientific community desires. Here we describe an alternative, which offers many of the advantages of space for a fraction of the cost: the Antarctic Plateau. Its advantages are manifold:

- The extreme cold reduces the thermal background in the near-infrared.
- The low atmospheric water vapour content, by far the driest on the Earth, significantly improves transmission throughout the infrared and millimetre regimes.
- The tenuous air reduces absorption at all wavelengths.
- The steadiest air offers superior seeing to any other ground-based location.
- It has the clearest air, with the minimum of man-made and natural interference, both particulate and electromagnetic, on the Earth.
- The geographical location contributes in several ways: the high latitude allows continuous monitoring of sources; long north–south baselines for VLBI exist, and complete global coverage of some phenomena is possible; the proximity to the South Magnetic Pole extends to lower energy the cosmic ray secondaries that reach the surface; huge quantities of ice are available as pure absorbers of incident particles such as neutrinos.

There are scientific gains to be made across virtually all areas of observational astronomy: in the near-ultraviolet from improved transmission; in the optical from improved seeing; in the near-infrared from reduced background and improved seeing; in the mid-infrared from reduced background and improved transmission; in the far-infrared from improved transmission; in the sub-millimetre and millimetre bands by improved transmission and from the ability to perform interferometry; in cm-band radio from location as a VLBI site; for cosmic rays from a greater range of particle energies; for neutrino and gamma-ray detection by using the ice as an absorber.

There are formidable logistical and engineering obstacles to developing an observatory on the Antarctic Plateau. The scientific case for Antarctic astronomy rests on the merit of programs that could be carried on exclusively on the Plateau. This document analyses and presents these programs.

After consideration of the scientific issues, we conclude that the case for the development of Antarctic astronomy is overwhelming. We propose, therefore, that a program be drawn up to this end. Its ultimate goal will be to construct a major observatory at the premier site on the Antarctic Plateau, most likely the summit of Dome Argus in the Australian Antarctic Territory. We recognise that such a goal is truly ambitious, and that concerted international collaboration will be required to achieve it. There are several stages that must be successfully completed to reach this goal, including:

- Site testing, to quantify our ability to conduct astronomical observations from the Plateau.
- Development of prototype facilities and infrastructure support. A likely project would be the construction of a 60-cm telescope, equipped with optical, infrared and sub-millimetre instrumentation.
- Construction of intermediate-sized facilities, capable of achieving significant new science in their own right, but also paving the way to a major facility. Among possible options, we suggest that the development of a 2·5-m class telescope, capable of delivering 0·2 arcsec performance across the optical and near-infrared wavebands, is particularly germane.
- The development of a major international facility at the premier site available, built to the limits of engineering and technological capability, and operable remotely.

With its acknowledged expertise in the fields of astronomy and of Antarctic science and exploration, we believe that Australia is well positioned to play a major role in the development of what may be one of the major international initiatives of the next century.
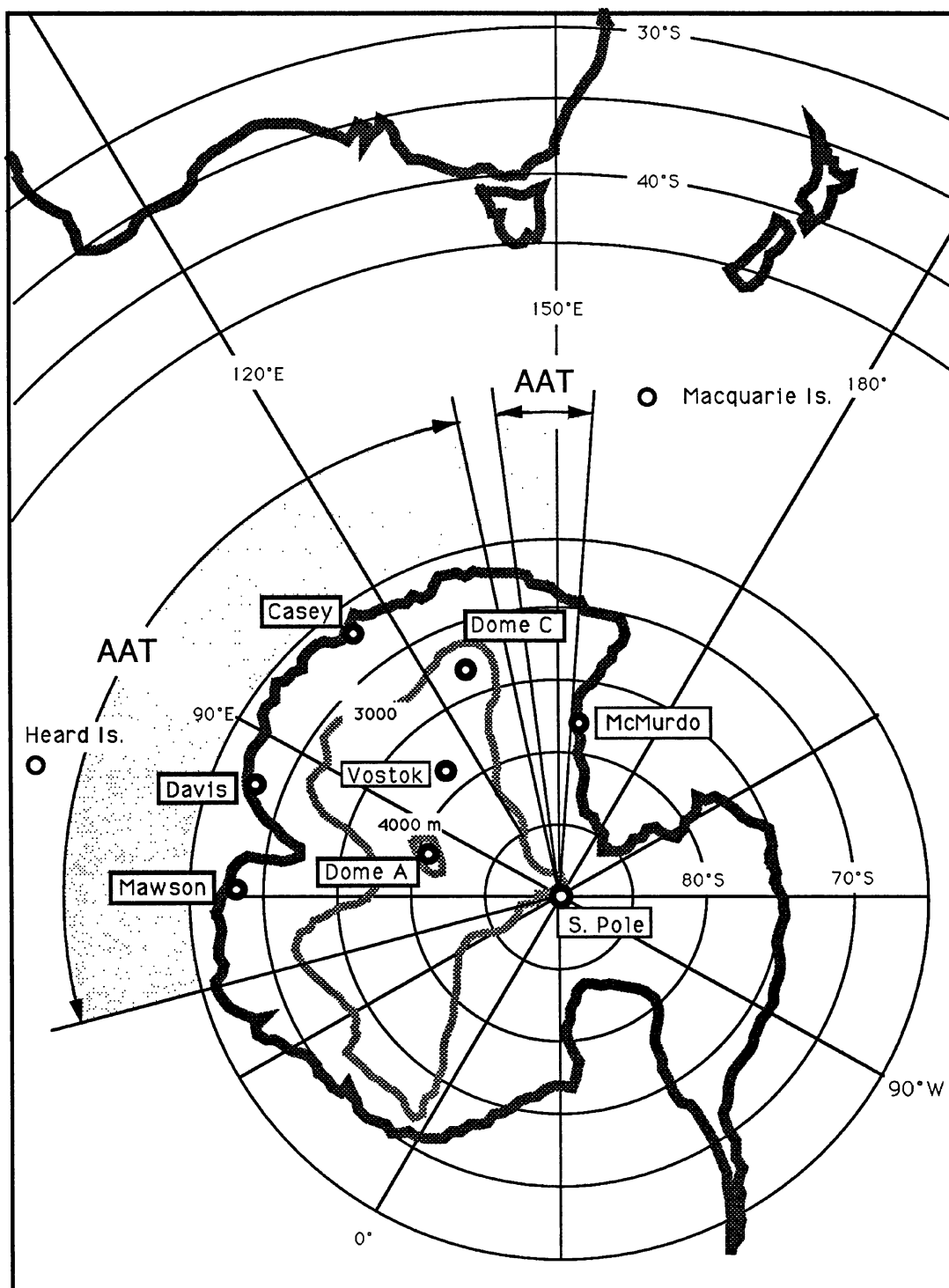
**Figure 1**—Map of Antarctica and the Australian Antarctic Territory. This sketch map shows the location of sites being considered for astronomy on the high plateau (Dome A, Dome C, South Pole and Vostok), as well as the Australian bases along the coast—Casey, Davis and Mawson—and the US base at McMurdo.

## Contents

## 1. INTRODUCTION

The Antarctic Plateau is almost certainly the best observing site on the surface of the Earth for many types of observations at optical, infrared, millimetre and radio wavelengths. The extremely cold, dry and tenuous atmosphere offers observing conditions unequalled elsewhere on the planet. Undertaking astronomical observations from the Plateau does, however, present a considerable challenge to our logistical and technological capabilities. In view of this, a clear understanding of the potential scientific gains is essential prior to the planning of facilities. This report addresses this question by discussing the scientific potential of the Antarctic Plateau as a site for an astronomical observatory. It begins by describing the conditions that make Antarctica unique for astronomy and how their implementation could lead to significant advances. Then follows the heart of this report, where consideration is given to specific wavebands and the particular kinds of investigation that can be expected to benefit most. Finally, an overview is presented of the way these goals might be achieved.

### 1.1 The Challenge of Astronomy

Fundamental questions in astronomy are addressed through the use of instrumentation capable of collecting and measuring the fluxes of photons and particles across the entire electromagnetic spectrum. Four principal factors limit our ability to do this:

- technological limitations
- poor transmission through the atmosphere
- local sources of interference
- at infrared wavelengths, thermal radiation from the telescope and atmosphere.

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

### 1.2 The Challenge of Antarctica

Antarctica is simultaneously the coldest, driest and highest continent on the Earth. Indigenous life is confined to the coastal perimeter; the vast, empty ice plateau provides a pristine environment in which

to conduct scientific experiments free from many of the debilitating and contaminating influences experienced elsewhere. The great depth of ice provides a continuous record of climatic conditions over thousands of years. The clean, pure air provides a reference benchmark with which to examine human influence on the environment. The clear skies above provide an unparalleled view upon the cosmos.

Several potential observing sites have been considered, and in this document we express no preference for any. The South Pole site, where a US research base is located, is the most accessible. Potentially the best astronomical site is the crest of Dome Argus (Dome A), but this is relatively inaccessible at present. These two sites are sometimes referred to specifically in the following document. An interesting compromise, certainly better than South Pole and more accessible than Dome A is Dome Circe (Dome C), where a French research station is being developed. Another high plateau site is the Russian base at Vostok.

The Commonwealth of Australia administers 42% of the Antarctic continent as the *Australian Antarctic Territory*. Domes A and C and Vostok all lie within the Australian Antarctic Territory. The Government has recognised the importance of the region to the scientific community, encapsulating this regard in its objectives for the management of Antarctica.

## 1.3 The Potential of Antarctic Astronomy

The combination of cold, dry and tenuous air makes the Antarctic Plateau the premier astronomical observing site on the Earth. It reaches nearly 4300 m altitude (the equivalent pressure altitude in the middle of winter exceeds 5000 m), and is both the coldest and driest place on the Earth. Temperatures average $-50°C$ year round, dropping below $-90°C$ at higher elevations in winter. Winds are generally light; the katabatic airflow originating on the highest parts of the Plateau does not develop its fury till it nears the coast. Records from Vostok (3500 m) show a year-round average wind speed of only $5 \, m \, s^{-1}$ for instance, and skies with less than 2/8 cloud cover for over half the year. The air is exceedingly dry, averaging $0 \cdot 3$ mm of precipitable water vapour. This section discusses how these climatic factors enhance conditions for astronomy.

### 1.3.1 The darkest sky

Imaging in the near-infrared (1–5 $\mu m$) is limited by a combination of the airglow emission from OH radicals at altitudes of 80–90 km and thermal emission from the atmosphere and telescope. The near-infrared lies on the Wien side of the black-body emission curve from room-temperature objects. In consequence, a small drop in temperature yields a large decline in thermal radiation. At $-60°C$, typical of the South Pole in winter, this translates to a reduction of over

over two orders of magnitude in the sky flux at $2 \cdot 4 \, \mu m$ compared to the level at $0°C$, typical of Mauna Kea. The spectral band between $2 \cdot 27$ and $2 \cdot 45 \, \mu m$ is devoid of strong airglow emission (quantitative measurement is needed to determine how weak the airglow really is). Thus, for background-limited observations in this window, a signal/noise gain of over an order of magnitude can be expected. This direct comparison can, however, be somewhat misleading, and a more complete discussion between the relative capabilities is given in the near-infrared science case (§ 3.1.2).

The reduction in thermal background in the $2 \cdot 27$–$2 \cdot 45 \, \mu m$ window at the South Pole should reduce the background to close to the natural limit set by zodiacal emission (Harper 1989). At higher and colder sites the limit may be reached. Coincidentally, the zodiacal emission is at a minimum in the near-infrared, between the scattered sunlight and thermal emission components. If the zodiacal limit is reached, it would not be possible to find as dark a site elsewhere on the Earth, nor a darker site anywhere within the inner solar system.

### 1.3.2 The driest air

The Antarctic Plateau is the driest desert on the Earth, with the lowest columns of precipitable water vapour of any ground-based site. Atmospheric water vapour absorbs most of the incident radiation in the infrared and millimetre wavebands. Observations at the South Pole indicate average values of 700 $\mu m$ ppt $H_2O$ in the summer and 300 $\mu m$ in the winter (Smythe and Jackson 1977), and at the higher altitude of Vostok 400 $\mu m$ in summer and 200 $\mu m$ in winter (Burova *et al.* 1986; Sholomitskii 1993). Values as low as 100 $\mu m$ have been recorded. Even lower values can be expected above the highest part, Dome A, perhaps as low as 50 $\mu m$ at times, comparable to columns obtainable from the Kuiper Airborne Observatory flying at 14,000 m. For comparison, an excellent night on Mauna Kea would experience $1 \cdot 2$ mm, and Siding Spring Observatory typically 5–10 mm. In the sub-millimetre, wavelengths that can barely be observed on a good night from Mauna Kea will be accessible nearly all the time from Antarctica. In the mid- and far-infrared some completely new wavebands would be opened from the ground for the first time. An Antarctic Plateau observatory has the potential of opening up for study parts of the spectrum where we have barely scratched the surface of the available opportunities.

### 1.3.3 The steadiest air

In the visible and near-infrared, the degree of blurring of images due to the Earth's atmosphere, or 'seeing', is just as significant a factor as a telescope's diameter in determining its sensitivity, as well as limiting the angular resolution obtainable

in direct imaging. Image degradation is due to differential diffraction caused almost entirely by microthermal inhomogeneity of the atmosphere. At most sites, much of the microthermal activity results from diurnal temperature variation. There may also be contributions induced by air flow over rough ground. In the Antarctic winter the diurnal temperature variation will be negligible, so a major cause of seeing is eliminated (Gillingham 1993). Moreover, the Antarctic circulation pattern centres on the highest part of the Plateau, with a predominantly laminar flow due to settling of the cold air. Thus we expect extraordinarily stable and uniform optical conditions in the upper atmosphere above the highest part of the Plateau. The tenuous atmosphere, with an equivalent pressure altitude of 5000 m, will also contribute to good seeing.

Mitigating against these positive attributes, however, is the presence of a strong surface inversion layer, which can occur during the most stable conditions, wherein the temperature can rise over 10 degrees in a few vertical metres. Stirring of this boundary layer will lead to large air temperature variations, which would degrade the seeing. Quantitative data on the seeing conditions, and in particular where the dominant contributions to it occur, are currently lacking. Such measurements are an essential prerequisite to the formulation of plans to exploit the achievable gains. The potential thus exists for seeing conditions superior to those of any other ground-based site. This is particularly relevant to optical and near-infrared wavelengths, where even the most sophisticated adaptive optics packages cannot attain significantly sub-arcsecond images over a large field of view. At these wavelengths the diffraction limit of current telescopes is much less than the best seeing obtained, so workers in this area stand to gain enormously from having a telescope on the Antarctic Plateau.

### 1.3.4 The clearest air

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

### 1.3.5 Minimal interference

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

### 1.3.6 Continuous observation

An astronomical source visible from the South Pole never sets, and in principle is observable continuously. Moreover it is always at the same zenith angle. Elsewhere on the Antarctic Plateau, the majority of sources will always remain above the horizon, and the daily range in zenith angle will be small. Hence very long period monitoring is possible, providing gains to selected projects across the entire spectrum. Currently the longest uninterrupted observations from the South Pole are of the Sun, up to 150 hours (Harvey 1991), and at night of $\gamma^2$ Velorum (Taylor 1988), up to 36 hours.

### 1.3.7 Geographical considerations

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

Another facet of the geographical location is access to the Magellanic Clouds during the southern winter. These important galaxies merit continuous observation because of the range of time-dependent phenomena that they harbour, but through the southern winter they lie too low in the sky for successful observations from Australia, a fact that became particularly apparent when Supernova 1987A erupted.

### 1.3.8 Particle astronomy

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

## 2. SCIENTIFIC ISSUES

In this section we overview some of the broad areas of astronomy where an Antarctic observatory could contribute significantly to our knowledge. An in-depth analysis of specific projects is deferred to the next section.

## 2.1 Cosmology and the Formation of Galaxies

A central question in cosmology is when the first galaxies formed from the initially homogeneous distribution of matter and radiation evidenced by the smoothness of the cosmic microwave background (CMB) radiation. The collapse of matter into clusters of galaxies must be imprinted on the CMB as small-scale irregularities, as reported from the COBE satellite (Smoot *et al.* 1992). The nature of the trigger mechanism for the collapse is widely debated but unknown, and it is necessary to map the level of the anisotropy in order to constrain the many competing theories. Fluctuations in the CMB towards distant clusters of galaxies due to their peculiar velocities with respect to the smooth Hubble flow, the kinematic Sunyaev–Zel'dovich effect, yield the density of the universe. An Antarctic telescope could provide the most sensitive instrument for both these projects because of the excellent transmission in the 1–3 mm waveband, where the CMB peaks, the long continuous observations that could be made, and the stable air.

## 2.2 The Birth of the First Stars in Galaxies

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

## 2.3 The Evolution of Galaxies

As a galaxy evolves, and a substantial fraction of the interstellar medium is locked up in stars, the veil surrounding the galaxy will clear and the starlight will shine through. For redshifts in the range $z = 3$ to 10, the peak of the mean stellar spectrum can be seen in the near-infrared. The faint proto-galactic stellar light should be detectable by sensitive observations in the 2·4 $\mu$m window only possible from Antarctica.

Between 0·1 and 1% of the total luminosity of the stars is processed into a few far-infrared spectral lines. Observation of these lines would allow the build-up of metallicity to be followed, as well as the derivation of physical parameters of the medium, such as its density, temperature and radiation field. The new atmospheric windows available from Antarctica will allow such studies to be made.

## 2.4 The Interstellar Medium

Many fundamental processes in our interstellar medium (ISM) can be studied only at far-infrared and sub-millimetre wavelengths. These include the ground-state fine-structure lines of many common elements, such as O, C, $C^+$ and $Si^+$, continuum emission from the cold interstellar dust which makes up most of the dust mass in the Galaxy, and high rotational transitions of excited molecules such as CO, CS and $HCO^+$. Such lines provide unique tracers of the events which stir up and regulate the ISM, shock waves and ultraviolet radiation. The interaction of star-forming regions with molecular clouds gives rise to strong shocked and fluorescent emission from $H_2$, in the near- and mid-infrared.

## 2.5 The Formation of Stars and Planets in Our Galaxy

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

## 3. THE SCIENTIFIC CASE FOR ANTARCTIC ASTRONOMY

From general considerations of the important problems in contemporary astrophysics it is clear that an Antarctic Plateau observatory has much to offer. We now turn to a detailed study of exactly where the gains can best be made. Observational astronomy is conducted in wavelength bands, rather than by subject area. We divide our discussion likewise.

In developing this case we have had to be guided not only by our best estimates of observing conditions, but also by assumptions about the size of telescope that could become available. We have built the

case around a 2·5-m telescope, which we believe to be achievable on a reasonable timescale. The long-term view, however, sees Antarctica equipped with telescopes as large as those in use at other observatories. We thus make occasional reference to an 8-m telescope, merely to illustrate what the future might hold. Remarks pertaining to a 60-cm telescope relate to opportunities from a possible prototype facility.

### 3.1 The Near- and Mid-infrared Wavebands

#### 3.1.1 Infrared astronomy

In its review of the future of astronomy, the Bahcall report (Bahcall 1991), commissioned for the US National Academy of Sciences, described the 1990s as the 'decade of the infrared'. The highest-priority facility for ground-based astronomy was rated an infrared-optimised 8-m telescope to be sited on Mauna Kea, Hawaii. The highest priority for space research was the Space Infrared Telescope Facility, SIRTF. In reaching these conclusions the Bahcall report recognised the extreme promise that the infrared waveband has shown with the recent dramatic developments in detector technology, as well as the remarkable science that has emerged from infrared observations over the last two decades.

We discuss in this section the gains offered by Antarctica for near- and mid-infrared astronomy; in the following section we address far-infrared astronomy.

#### 3.1.2 Near-infrared astronomy

The major contributor to the potential of the Antarctic Plateau for near-infrared observing is the low temperature, particularly at night. The black-body function that moderates emission from a telescope as well as from the atmosphere has an exponential component to the short-wavelength side of its peak. As the temperature is lowered the reduction of the black-body function is dramatic. Were the thermal emission alone the dominant factor, the gain we should expect from siting a telescope on the Antarctic Plateau would exceed a factor of 200. However, there is also atmospheric emission from elevations of order 90 km, which is likely to differ much less between the pole and mid-latitude sites. At wavelengths where airglow lines are intense, the gains afforded by Antarctic observing are much reduced. We have used a simple model to predict the sensitivity that might be attained by a telescope on the Antarctic Plateau. Table 1 lists the results of that model. Some of the input figures are little more than guesses until site testing has been performed, so all values in the table should be treated with caution. In particular, it is assumed that there are no airglow lines in the waveband 2·27 to 2·45 $\mu$m (here called $K^+$), a supposition that awaits confirmation. Figures are

**Table 1.** Gains over the Anglo-Australian Telescope in the near- and mid-infrared

Gains, in stellar magnitudes, are over the performance of a 4-m telescope with 1·5 arcsec seeing, representative of the Anglo-Australian Telescope, for broad-band photometry through each filter. Assumed temperatures are 5°C (Australia), 0°C (Mauna Kea) and −50°C (Antarctica), with clear sky emissivities of 5%, 1·5% and 0·5%, respectively. The resolution quoted is the assumed seeing in the near–IR bands, and the diffraction limit at N band. The observing time required to reach a given signal/noise ratio scales as the square of the difference in sensitivity. As an example, 2·0 magnitudes in this table corresponds to a factor of 40 in the required time

| Waveband | J | H | K′ | K⁺ | L′ | N |
|---|---|---|---|---|---|---|
| Wavelength ($\mu$m) | 1·25 | 1·65 | 2·11 | 2·36 | 3·80 | 11 |
| *2·5 m Antarctic telescope, winter* | | | | | | |
| seeing 0·5 arcsec | 0·7 | 0·6 | 0·7 | 3·2 | >1·3 | 2·3 (1·0″) |
| seeing 0·2 arcsec | 1·5 | 1·3 | 1·2 | 3·7 | >1·5 | |
| *8·0 m Australian telescope, winter* | | | | | | |
| seeing 1·0 arcsec | 1·2 | 1·2 | 1·2 | 1·2 | 1·2 | 1·0 (0·3″) |
| *8·0 m Mauna Kea telescope* | | | | | | |
| seeing 0·5 arcsec | 2·0 | 2·0 | 2·2 | 2·0 | 2·2 | 2·9 (0·3″) |
| *8·0 m Antarctic telescope* | | | | | | |
| seeing 0·2 arcsec | 3·0 | 2·9 | 3·0 | 5·52 | >3·7 | 4·8 (0·3″) |

also given for an 8-m telescope under Antarctic conditions.

We have assumed sufficient sampling of the image for the signal/noise ratio to be determined by the image size. The recent and planned developments of infrared arrays suggest that this will soon be perfectly feasible while maintaining an adequate field of view. On the other hand, Table 1 ignores a difficulty in the 3–4 $\mu$m window that afflicts all telescopes outside Antarctica. The thermal background flux rate is so high that arrays of any significant size are unable to read out the data sufficiently quickly. Unless there is a change in this technology, telescopes sited outside Antarctica will need to use a narrow-band filter instead of L′, so that the comparative gains for Antarctic telescopes would be underestimates, by as much as 2 or 3 magnitudes according to the technology available.

For many purposes the exact wavelength used in the K window is of little concern. This is the case for continuum sources such as galaxies. Observations in the $K^+$ band from Antarctica thus should be compared to those in a shorter filter (probably K′) from alternative sites. Such comparison indicates that a 2·5-m telescope in Antarctica would be about 0·4 magnitudes more sensitive than an 8-m telescope on Mauna Kea, given the same seeing.

Adaptive optics may allow comparable seeing to be attained at other sites, though never over so large a field of view as is naturally available in Antarctica. However, the conditions in Antarctica favour adaptive optics and could yield even greater gains for suitably large telescopes.

It may also be that for some deep survey work, the ability to flat-field sky images becomes the limiting factor. In the extreme, under such circumstances the gains are directly proportional to the reduction in sky background, 5·8 magnitudes at K and 3·3 magnitudes at L′.

The figures in Table 1 refer to broad-band photometry. The gains are somewhat different for spectroscopy. For example, the airglow lines that limit performance in broad-band imaging are spectrally very narrow. At high spectral resolution, therefore, they obscure a very small portion of the spectrum, and for many purposes can be ignored. Then an Antarctic telescope could yield improvements at all wavelengths in the K band roughly comparable to those listed for $K^+$. This is also the case for low-resolution spectroscopy if use is made of a novel technique recently demonstrated at the University of Hawaii to mask out the airglow lines (Tokunaga, personal communication).

The low temperature allows an Antarctic telescope to observe fainter objects in the 2-$\mu$m window than at shorter wavelengths, a remarkable reversal of the situation at other sites. It also allows, for the first time, very competitive observations in the 3–4 $\mu$m region.

Some of the important programs that could be addressed are listed below. One topic from each category is enlarged on in the subsequent text; those topics are identified by asterisks.

***High angular resolution over the full field of the telescope.*** Here the wide field of a 2·5-m telescope offers additional advantages over a larger instrument, provided that the full field is covered by abutted detectors.

- Initial mass function in star-forming regions throughout the Galaxy.
- Surveys of dark clouds, both for young stars and to map extinction.
- Search for brown dwarfs.*
- Search for cool white dwarfs.
- Search for cool high-proper-motion stars.
- Photometry in crowded regions (e.g. clusters, dwarf galaxies, Galactic bulge).
- Imaging polarimetry of star-forming regions, revealing their geometry and mapping the strength and direction of magnetic fields.
- Morphology of diagnostic lines in emission nebulae.
- Morphology of the 3·28 $\mu$m emission feature around exciting sources.
- Identification and classification of extended radio sources in the Galactic plane.
- Details of shock structures in molecular clouds and supernova remnants.
- Distance scale from Cepheid variables and M supergiants.
- Starburst regions in galaxies.

- Old stellar populations in interacting and other unusual galaxies.
- Morphology of disk galaxies viewed edge-on.
- Stellar populations in high-redshift galaxies (Butcher–Oemler effect).
- Gravitationally lensed arcs.
- Deep galaxy surveys for cosmological studies and to explore galaxy evolution.

High angular resolution on axis. For these projects a site with superb seeing is particularly valuable.
- Planetary atmospheres.*
- Dynamics of inner satellites and rings of planets.
- Disks and jets associated with star formation.
- Proper motion studies in star-forming regions.
- Binarity and multiplicity in stars, especially pre-main-sequence stars.
- Identification of compact X-ray, radio and other sources.
- Active galactic nuclei: structure and variability.
- Study of galaxies causing gravitational lenses.
- Morphology and polarimetry of high-redshift radio galaxies.
- Clustering around quasars and luminous radio galaxies.
- Galaxies responsible for damped Lyman-$\alpha$ systems.

***Low-resolution spectroscopy.*** Low-resolution spectroscopy of compact objects would benefit from the good seeing expected in Antarctica. In addition, the enhanced sensitivity in the K window would be particularly valuable, especially if the airglow lines were masked out. The following programs would use this window.

- Surface characteristics through spectroscopy of small solar system bodies.
- Classification of very-low-luminosity stars (both lower-main-sequence stars and cold white dwarfs).
- Luminosity classes for the stars in the outer parts of galaxies, cooling flows, etc..
- $^{12}C/^{13}C$ isotope ratios in late-type stars in our and other galaxies.
- Line studies in emission-line regions, including the lines at 2·058 $\mu$m of He I, 2·122 $\mu$m of $H_2$ and 2·166 $\mu$m of H I.
- High-excitation planetary nebulae, through the emission in the [Si VI] 1·96 $\mu$m and [Si VII] 2·48 $\mu$m lines.
- Study of the emission lines around 3·3 $\mu$m (attributed to complex organic molecules) found in a variety of environments, combined with quantitative analysis of the diffuse interstellar bands, notably that at 3·4 $\mu$m due to C–H bonds, along many sight lines.*
- Formation of molecules and other emission lines in novae and various types of supernovae.
- Emission lines in quasars and high-redshift galaxies, including H$\alpha$ at $z \sim 2·5$ and other lines at higher redshift.

*Moderate- and high-resolution spectroscopy.*
The limit to even high-resolution spectroscopy in the near-infrared will soon be set by the thermal radiation from the telescope. An Antarctic telescope will then win, particularly in the 2-$\mu$m window. This is a relatively new field, and has potential to touch almost every facet of astronomy. Areas readily identifiable include:

- Chemical composition of planetary atmospheres as a function of altitude.
- Abundance analyses in stars.
- Improved spectral classifications for late-type stars (giants and dwarfs).
- Kinematics of late-type components in binaries, e.g. in cataclysmic variables.
- Dynamics of shock regions for comparison with models.
- Physical conditions derived from infrared lines in emission nebulae.
- Dynamical evolution of photodissociation regions.
- Kinematics of infrared lines in emission nebulae.
- Velocity dispersion and population census in the Galactic centre.
- Line profiles, and hence velocity structure, in supernovae.
- Stellar population changes with radius in galaxies.
- Search for hidden Seyfert nuclei in galaxies.*

### 3.1.3 Selected case studies

Here we enlarge upon the highlighted areas in the four categories above.

*The search for brown dwarfs.* One of the likely contributions to the missing mass of the Galaxy is from extremely-low-mass stars. The mass/light ratio is very high for such objects at visible wavelengths, so that large total masses can be concealed if only optical data are available. The initial mass function (IMF) in the low-mass range has a differential gradient variously estimated at around $-1\cdot3$ to $-2\cdot3$ and thus predicts vast numbers of low-mass stars. Indeed, the mass at which the IMF turns over is the fundamental measure of the role and significance of the lowest-mass stars, including in particular the brown dwarfs. Only through surveys can these numbers be determined, and because of the expected temperatures of brown dwarfs the surveys are best performed at wavelengths of 2–4 $\mu$m. Irrespective of whether or not brown dwarfs form a significant proportion of the missing mass, this is an important question to address.

An Antarctic telescope of 2·5 m aperture offers not only a low background, and hence unusually deep sensitivity, but also a large field of view. There is no reason, in principle, why a field of view of about 30 arcmin diameter cannot be covered with abutted arrays. This would make an extremely potent survey instrument for many projects, including a search for brown dwarfs.

Brown dwarfs may exist down to masses of order $0\cdot01M_\odot$, and a census of such bodies would absolutely tie down their contribution to the missing mass. There are two ways to locate them—from their very cool colours or high proper motions. Both techniques would likely be attempted.

Models (Nelson *et al.* 1986) predict about $0\cdot1$ stars per cubic parsec per magnitude over the range of absolute K magnitude from 15 to 20. Colour surveys would probably use $K^+$ and $L'$, and in a one-hour exposure should sample stars of at least $0\cdot05M_\odot$ to a distance of some tens of parsecs in each field. Thus we expect several stars per square degree, allowing the detection of significant numbers in one season's observing.

Proper-motion surveys are potentially more rewarding, though they would require a protracted time span. Surveys to $K^+ \sim 23$ would be possible in one-hour observations, which would test the IMF down to at least $0\cdot03M_\odot$ within 100 pc. Again a manageable survey should lead to a statistically useful result in a modest allocation of telescope time. It would also yield a limit on the number of cool white dwarfs and would probably lead to the discovery of many new asteroids.

*The atmosphere of Venus.* About a decade ago Australian astronomers discovered that useful observations of the Venusian atmosphere can be made from Earth at near-infrared wavelengths up to $2\cdot5$ $\mu$m (Allen and Crawford 1984). Ground-based observations are obviously much cheaper and more versatile than those made from spacecraft, though the observations must be made of the dark side of the planet, which restricts them to periods of a few weeks every nineteen months, around inferior conjunction. Subsequent studies have revealed that three different elevations of the atmosphere can be observed. The highest is around 90 km altitude, where an airglow line of $O_2$ is emitted and monitors the activity of air rising on the sunlit hemisphere that circulates to the night side before descending. At 40–50 km altitude the super-rotation can be monitored *via* a broken cloud layer that is backlit by thermal radiation from below. It has recently been shown that the lowest scale height, around 5–10 km, is also accessible at wavelengths around 1 $\mu$m. Many outstanding questions about the dynamics and chemical composition of the Venusian atmosphere can be answered from observations of these three features, while other potentially useful emission or absorption lines are yet to be exploited. A better understanding of the Venusian atmosphere should ultimately assist models of the terrestrial atmosphere, which is rendered more complex by the high abundance of water vapour.

Very little exploration has yet been undertaken of the Venusian atmosphere at mid-infrared wavelengths. It is known that there are temperature anomalies in the opaque upper clouds at wavelengths between 3 and 20 $\mu$m. These require further study.

The features of the Venusian atmosphere vary on a timescale that is difficult to track from a single site on Earth. Changes from one day to the next are profound, but over the useful duration of a single day's observation, especially at sites with large diurnal temperature ranges and hence deteriorating daylight seeing, they are too small to be tracked precisely. Continuous observations with high spatial resolution are required to address these issues and to make major advances in understanding the circulation patterns. Frequent coverage is required to explore the suggested existence of anomalous pockets of water vapour and of occasional volcanic outpourings of sulphur compounds.

Observations from Antarctica would permit continuous measurement for long spells. The observations would be made during the summer, roughly every three years. The known low particulate content of the air greatly reduces scattering and would allow much more precise daylight observations closer to (and possibly right through) inferior conjunction itself.

*Diffuse interstellar bands.* One of the outstanding challenges of optical astronomy is to identify the carriers of the diffuse interstellar absorption bands. Dozens of bands, both broad and narrow, are known in the spectra of obscured stars, and from their relative intensities it is apparent that several different chemical species are involved. Interesting progress has been made by examining extended emission nebulae (principally the 'Red Rectangle' nebula around HD 44179), and there are suggestions that fullerenes may be responsible for some features.

All organic species have fundamental frequencies at infrared wavelengths, particularly in the 3–4 $\mu$m atmospheric window. Both emission and absorption bands are seen there, mostly associated with the C–H bond in organic molecules. Other significant features in the 8–13 $\mu$m window have been extensively studied. Australians have been strong players in this field. Tentative attributions have been made to polycyclic aromatic hydrocarbons (PAHs).

The level of complexity of organic molecules in space remains an intriguing problem because of the likelihood that much of the present biomass on Earth was initially seeded by cometary impacts bringing with them the organic material they captured from the pre-solar nebula. Not only is Australia already observationally strong in this field, but there is vital laboratory backing through the facility at ADFA to determine the infrared absorption spectra of organic materials under interstellar conditions.

Considerable progress can be made from studies of the emission and absorption bands in the various atmospheric windows. There is a pressing need to increase the sample of environments and sight lines by a large factor, and to improve the database on comets. In this way we may separate the variables and identify families of features. Much of this work requires low-resolution spectroscopy in the 3–4 $\mu$m window, at which an Antarctic telescope would excel.

*Hidden Seyfert nuclei.* Unification schemes for active galaxies have become fashionable but require thorough testing. In particular, it is believed that Seyfert 1 nuclei with broad permitted emission lines may lie concealed in the cores of other varieties of active galaxy, including radio galaxies, type 2 Seyferts and high-luminosity starburst galaxies found by IRAS. In all cases the concealing medium would be clouds of dust-laden gas in the inner galaxy, possibly in the form of a torus so that the information we receive at optical wavelengths depends on our sight line to the nucleus. Australians have been active in exploring this proposal, using radio observations with both the Australia Telescope and the Parkes–Tidbinbilla interferometer. There is, however, a need to complement the radio work using a technique applicable to radio-quiet galaxies as well as radio-loud.

Infrared spectroscopy offers such a technique, for the obscuring dust becomes transparent in most cases, revealing a compact infrared core. If type 1 Seyfert nuclei are generally present, they will be manifested by broad pedestals on the Paschen and Brackett lines of ionised hydrogen. Such pedestals have been seen in a small number of cases but only the brightest examples have been explored. A spectroscopic resolution no worse than a few hundred km s$^{-1}$ is required to ensure clean separation of broad and narrow components to the lines, while high signal/noise is vital to isolating the broad pedestals from the galaxy continuum. High angular resolution is also essential to maximise the contrast against the stellar contribution. An Antarctic telescope offers the opportunity to extend this work beyond the handful of galaxies presently studied to hundreds of specimens, allowing a statistically useful survey.

As well, there are a number of emission lines in the infrared that sample a range of excitation conditions. In particular, the $1 \cdot 96$ $\mu$m line of [Si VI] monitors the far-ultraviolet flux from the nucleus. At low redshift this line occurs in a region of strong telluric $CO_2$ absorptions, and high spectral resolution is highly desirable to isolate it cleanly. Again high spatial resolution will prove valuable in establishing the distribution of the line and hence

the geometry of the source of excitation and the gas it illuminates. Other lines known to be strong in active galaxies are of those [Fe II], H and $H_2$, each of which samples different excitation zones, and for which spatially resolved spectroscopy will be extremely valuable.

### 3.1.4 Mid-infrared astronomy

*N-band (8–13 μm) observations.* In the mid-infrared, the reduction in thermal background between a mid-latitude site at ∼0°C and the Antarctic Plateau is about a factor of 5. Reduced background further allows broader-band operation for the same well depth. For many cases the bandpass could be increased by the background factor, up to 5 times, further increasing the signal/noise ratio. Because it is relatively easy to attain the diffraction limit in the mid-infrared, telescope aperture is also of prime importance. We assume 3% telescope emissivity, achieved as aimed for by the Gemini 8-m telescopes, to obtain the gains listed in Table 1 with respect to the Anglo-Australian Telescope for broad-band operation in the 10–12 μm part of the N band, the cleanest portion of the mid-infrared.

An Antarctic 2·5-m telescope would therefore provide significant gains over current Australian facilities, but will not be as sensitive for N-band operation as the new generation of 8-m telescopes under construction. For broad-band imaging its performance would be equivalent to that of a 6-m instrument on a good mid-latitude site

For spectroscopy an Antarctic telescope would not gain the extra factor from increasing the bandpass, and the relevant figures in Table 1 should be reduced by 0·9 magnitudes. There are good prospects, however, of constructing an 8-m class sub-millimetre antenna with surface accuracy capable of good mid-IR performance within a decade (CARA 1993). This facility would outperform any other telescope in this wavelength regime.

Additional gains arise from improved atmospheric transmission. The 8–13 μm window will be cleaner and wider than on Mauna Kea. The high-excitation [Ne VI] line at 7·65 μm should be accessible, for instance. Spectrophotometry of higher quality than present should be possible because of reduced telluric features. This will allow searches for substructures expected from PAH models of the unidentified infrared lines at 7·7, 8·6 and 11·3 μm.

*16–35 μm observations.* At longer mid-infrared wavelengths, from 16 to 35 μm, the atmospheric transmission above the Plateau is significantly higher than at Mauna Kea, as shown in Figure 2, which is based on measurements of the precipitable water vapour at Vostok and the South Pole.

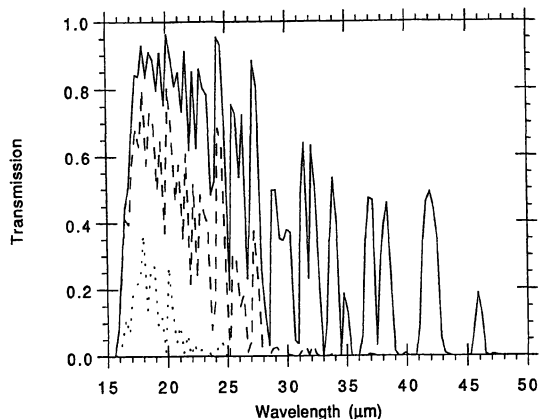Here are found the longest accessible atmospheric windows for photometry before 200 μm. Many



**Figure 2**—Atmospheric transmission in the mid-infrared from 15 to 50 μm, representative of typical observing conditions overhead for the Antarctic Plateau (solid curve), Mauna Kea (dashed curve) and Siding Spring Observatory (dotted curve). The altitudes and ppt $H_2O$ content for the model (ATRAN; Lord 1993) were taken as 4500 m and 250 μm, 4500 m and 2 mm, and 1160 m and 11 mm, respectively. The curves have been smoothed to a spectral resolution of $R = 50$.

spectral lines are also accessible, as indicated by Table 2. Spectropolarimetry at 20 μm should be relatively easy, allowing studies, for instance, of dust chemistry through comparison of the silicate absorption features at 9·7 and 20 μm, and of magnetic field directions in H II regions and molecular clouds through dichroic alignment of the grains in the fields. Many PAH-features known from laboratory studies between 17 and 45 μm remain unexplored in the ISM. PAHs are the most abundant free organic molecules in the gas phase (e.g. Leger *et al.* 1992), accounting for a considerable fraction of cosmic carbon, and presenting a geometrical surface area comparable to that of dust grains. As such, they are expected to play a dominant role in interstellar chemistry, but their role remains poorly understood to date.

One important target is the ground-state ortho transition of $H_2$ at 17·0 μm. It has been detected from Mauna Kea in just one source, BN/KL in Orion, and only in excellent conditions. The transition provides the only optically thin probe of the bulk of the gas in warm (100–300 K) photodissociation regions, the environment of much of the molecular gas in the Galaxy. Its weakness, combined with the formidable observational difficulties, have restricted its use to date, despite its potential as a probe of physical conditions (e.g. Burton *et al.* 1992). The line will be readily detectable from Antarctica, where the transmission is ∼70% and should be quite constant, in contrast to Mauna Kea. The transmission at Siding Spring is never better than about 25%.

**Table 2.  Selected atomic and ionic ground-state fine-structure lines in the mid-infrared**

Ground-state fine-structure lines from 6–50 $\mu$m with excitation potentials up to 50 eV, for elements up to the iron group. Selected excited transitions (e.g. $[Ni^+]^*$) and higher-excitation species are also given, as well as the ground-state transitions of $H_2$. Transitions already detected in the ISM are indicated by an asterisk. The excitation range is from the excitation potential to the ionisation potential. The energy level is for the upper state. The transmission is for the rest velocity, but often can be considerably improved by appropriate use of the Earth's orbital motion

| Species | Transition | Wavelength ($\mu$m) | Excitation range (eV) | Energy level (K) | Transmission for 0.25 mm ppt $H_2O$ (%) |
|---|---|---|---|---|---|
| $Si^{6+}$ | $^3P_0 \rightarrow {}^3P_1$ | 6·52* | 205–247 | 8010 | 0 |
| $Ni^+$ | $^2D_{3/2} \rightarrow {}^2D_{5/2}$ | 6·64 | 7·6–18·2 | 2170 | 0 |
| $Ar^+$ | $^2P_{1/2} \rightarrow {}^2P_{3/2}$ | 6·99* | 15·8–27·6 | 2060 | 31 |
| $Na^{++}$ | $^2P_{1/2} \rightarrow {}^2P_{3/2}$ | 7·33 | 47·3–71·6 | 1960 | 65 |
| $Ni^{++}$ | $^3F_3 \rightarrow {}^3F_4$ | 7·35 | 18·2–35·2 | 2000 | 54 |
| $Ni^0$ | $^3F_3 \rightarrow {}^3F_4$ | 7·51 | 0·0–7·6 | 1920 | 87 |
| $Ar^{4+}$ | $^3P_2 \rightarrow {}^3P_1$ | 7·90* | 59·8–75·0 | 2920 | 56 |
| $Ar^{++}$ | $^3P_1 \rightarrow {}^3P_2$ | 8·99* | 27·6–40·7 | 1600 | 98 |
| $S^{+++}$ | $^2P_{3/2} \rightarrow {}^2P_{1/2}$ | 10·5* | 34·8–47·3 | 1370 | 99 |
| $Co^+$ | $^3F_3 \rightarrow {}^3F_4$ | 10·5* | 7·9–17·1 | 1370 | 99 |
| $[Ni^+]^*$ | $^4F_{7/2} \rightarrow {}^4F_{9/2}$ | 10·7* | 7·6–18·2 | 13400 | 99 |
| $Ni^{++}$ | $^3F_2 \rightarrow {}^3F_3$ | 11·0 | 18·2–35·2 | 3270 | 98 |
| $Ni^0$ | $^3F_2 \rightarrow {}^3F_3$ | 11·3 | 0·0–7·6 | 3190 | 99 |
| $Cl^0$ | $^2P_{1/2} \rightarrow {}^2P_{3/2}$ | 11·3 | 0·0–13·0 | 1270 | 99 |
| $Cl^{+++}$ | $^3P_2 \rightarrow {}^3P_1$ | 11·8 | 39·6–53·5 | 1930 | 99 |
| $Co^{++}$ | $^4F_{7/2} \rightarrow {}^4F_{9/2}$ | 11·9 | 17·1–33·5 | 1210 | 99 |
| $[Ni^0]^*$ | $^3D_1 \rightarrow {}^3D_2$ | 12·0 | 0·0–7·6 | 2470 | 99 |
| $Co^0$ | $^4F_{7/2} \rightarrow {}^4F_{9/2}$ | 12·3 | 0·0–7·9 | 1170 | 98 |
| $[Ni^+]^*$ | $^4F_{5/2} \rightarrow {}^4F_{7/2}$ | 12·7 | 7·6–18·2 | 14600 | 97 |
| $Ne^+$ | $^2P_{1/2} \rightarrow {}^2P_{3/2}$ | 12·8* | 21·6–41·0 | 1120 | 96 |
| $Mg^{4+}$ | $^3P_1 \rightarrow {}^3P_0$ | 13·5* | 109–141 | 3620 | 8 |
| $Ne^{4+}$ | $^3P_2 \rightarrow {}^3P_1$ | 14·3* | 97·1–126 | 1600 | 11 |
| $Cl^+$ | $^3P_1 \rightarrow {}^3P_2$ | 14·4 | 13·0–23·8 | 1000 | 0 |
| $[Co^+]^*$ | $^5F_4 \rightarrow {}^5F_5$ | 14·7 | 7·9–17·0 | 5800 | 0 |
| $[Ni^0]^*$ | $^3D_2 \rightarrow {}^3D_3$ | 14·8 | 0·0–7·6 | 1270 | 0 |
| $K^{+++}$ | $^3P_0 \rightarrow {}^3P_1$ | 15·4 | 45·7–60·9 | 3340 | 0 |
| $Co^+$ | $^3F_2 \rightarrow {}^3F_3$ | 15·5 | 7·9–17·1 | 2300 | 0 |
| $Ne^{++}$ | $^3P_1 \rightarrow {}^3P_2$ | 15·6* | 41·0–63·5 | 925 | 0 |
| $Co^{++}$ | $^4F_{5/2} \rightarrow {}^4F_{7/2}$ | 16·4 | 17·1–33·5 | 2090 | 38 |
| $Co^0$ | $^4F_{5/2} \rightarrow {}^4F_{7/2}$ | 16·9 | 0·0–7·9 | 2020 | 28 |
| $H_2$ | $v = 0$–0 S(1) | 17·0* | 0·0–4·5 | 1015 | 71 |
| $P^{++}$ | $^2P_{3/2} \rightarrow {}^2P_{1/2}$ | 17·9 | 19·7–30·2 | 805 | 96 |

The potential for mid-infrared astronomy is given further impetus by recent advances in detector technology. Recently 128×128 Si:Sb impurity-band conductor arrays have become available (e.g. Herter 1994), operating out to 45 $\mu$m. From 16–35 $\mu$m no other ground-based site will be able to make effective use of this new technology, presenting the Antarctic Plateau with a unique opportunity.

### 3.2 The Far-infrared and Sub-millimetre Wavebands

#### 3.2.1 Astronomical applications

The far-infrared and sub-millimetre region of the spectrum (50 $\mu$m to 1 mm) represents one of the last frontiers for ground-based astronomy. Its importance stems from the following factors:

- The wavelength is sufficiently long that extinction by interstellar dust is generally small, yielding an unobstructed view of star-forming regions, galactic structure, and galactic nuclei.
- The peak of the Planck function for temperatures typical of cool dust falls in this range. Consequently

many H II regions and galaxies radiate the majority of their energy in the far-infrared. We cannot model the energy balance or evolution of such galaxies without a proper understanding of this radiation.

- The principal atomic (e.g. O, C, $C^+$) and molecular (e.g. CO, CS, $HCO^+$, HCN) cooling lines for molecular clouds fall in this region. An understanding of these lines is essential to models of cloud collapse and star formation.
- The light hydrides (e.g. CaH, NaH, MgH, AlH) have their fundamental rotational transitions here. These species, which are often unobservable at other wavelengths, play an important role in interstellar chemistry.

Thus the far-infrared and sub-millimetre spectrum of a typical interstellar cloud is roughly that of a blackbody at a temperature of ~30–100 K, overlaid with a vast array of lines from atomic, ionic and molecular species. Far-infrared lines have now been

**Table 2.** *Continued*

| Species | Transition | Wavelength ($\mu$m) | Excitation range (eV) | Energy level (K) | Transmission for 0·25 mm ppt $H_2O$ (%) |
|---|---|---|---|---|---|
| $[Fe^+]^*$ | $^4F_{7/2} \rightarrow {}^4F_{9/2}$ | 17·9* | 7·9–16·2 | 3500 | 96 |
| $[Ni^{++}]^*$ | $^4F_{3/2} \rightarrow {}^4F_{5/2}$ | 18·2 | 7·6–18·2 | 15300 | 95 |
| $S^{++}$ | $^3P_2 \rightarrow {}^3P_1$ | 18·7* | 23·3–34·8 | 1200 | 97 |
| $[Co^+]^*$ | $^5F_3 \rightarrow {}^5F_4$ | 18·8 | 7·9–17·0 | 6560 | 97 |
| $Cl^{+++}$ | $^3P_1 \rightarrow {}^3P_0$ | 20·4 | 39·6–53·5 | 706 | 97 |
| $Fe^{4+}$ | $^5D_4 \rightarrow {}^5D_3$ | 20·8 | 54·8–75·0 | 1850 | 94 |
| $Ar^{++}$ | $^3P_0 \rightarrow {}^3P_1$ | 21·8* | 27·6–40·7 | 2260 | 63 |
| $Fe^{++}$ | $^5D_3 \rightarrow {}^5D_4$ | 22·9* | 16·2–30·7 | 628 | 57 |
| $Fe^0$ | $^5D_3 \rightarrow {}^5D_4$ | 24·0 | 0·0–7·9 | 598 | 65 |
| $Co^{++}$ | $^4F_{3/2} \rightarrow {}^4F_{5/2}$ | 24·1 | 17·1–33·5 | 2686 | 68 |
| $[Fe^+]^*$ | $^4F_{5/2} \rightarrow {}^4F_{7/2}$ | 24·5 | 7·9–16·2 | 4080 | 96 |
| $F^0$ | $^2P_{1/2} \rightarrow {}^2P_{3/2}$ | 24·8 | 0·0–17·4 | 581 | 94 |
| $Co^0$ | $^4F_{3/2} \rightarrow {}^4F_{5/2}$ | 24·9 | 0·0–7·9 | 2600 | 87 |
| $S^0$ | $^3P_1 \rightarrow {}^3P_2$ | 25·2* | 0·0–10·4 | 570 | 3 |
| $[Co^+]^*$ | $^5F_2 \rightarrow {}^5F_3$ | 25·7 | 7·9–17·0 | 7120 | 93 |
| $O^{+++}$ | $^2P_{3/2} \rightarrow {}^2P_{1/2}$ | 25·9* | 54·9–77·4 | 556 | 48 |
| $Fe^{4+}$ | $^5D_3 \rightarrow {}^5D_2$ | 25·9 | 54·8–75·0 | 1160 | 48 |
| $Fe^+$ | $^6D_{7/2} \rightarrow {}^6D_{9/2}$ | 26·0* | 7·9–16·2 | 554 | 3 |
| $Ti^{+++}$ | $^2D_{5/2} \rightarrow {}^2D_{3/2}$ | 26·0 | 27·5–43·3 | 553 | 3 |
| $H_2$ | $v = 0$–0 S(0) | 28·2 | 0·0–4·5 | 510 | 0 |
| $F^+$ | $^3P_1 \rightarrow {}^3P_2$ | 29·3 | 17·4–35·0 | 490 | 10 |
| $P^+$ | $^3P_2 \rightarrow {}^3P_1$ | 32·9 | 10·5–19·7 | 677 | 0 |
| $Fe^{++}$ | $^5D_2 \rightarrow {}^5D_3$ | 33·0 | 16·2–30·7 | 1060 | 0 |
| $Cl^+$ | $^3P_0 \rightarrow {}^3P_1$ | 33·4 | 13·0–23·8 | 1430 | 15 |
| $S^{++}$ | $^3P_1 \rightarrow {}^3P_0$ | 33·5* | 23·3–34·8 | 430 | 0 |
| $Fe^0$ | $^5D_2 \rightarrow {}^5D_3$ | 34·7* | 0·0–7·9 | 1010 | 6 |
| $Si^+$ | $^2P_{3/2} \rightarrow {}^2P_{1/2}$ | 34·8* | 0·0–8·2 | 413 | 23 |
| $Fe^+$ | $^6D_{5/2} \rightarrow {}^6D_{7/2}$ | 35·5* | 7·9–16·2 | 960 | 0 |
| $[Fe^+]^*$ | $^4F_{3/2} \rightarrow {}^4F_{5/2}$ | 35·8 | 7·9–16·2 | 4490 | 0 |
| $Ne^{++}$ | $^3P_0 \rightarrow {}^3P_1$ | 36·0* | 41·0–63·5 | 1330 | 0 |
| $Fe^{4+}$ | $^5D_2 \rightarrow {}^5D_1$ | 36·5 | 54·8–75·0 | 600 | 33 |
| $[Co^+]^*$ | $^5F_1 \rightarrow {}^5F_2$ | 39·3 | 7·9–17·0 | 7500 | 0 |
| $V^{++}$ | $^4F_{9/2} \rightarrow {}^4F_{7/2}$ | 41 | 14·7–29·3 | 839 | 0 |
| $Ti^{++}$ | $^3F_4 \rightarrow {}^3F_3$ | 42·0 | 13·6–27·5 | 607 | 50 |
| $V^0$ | $^4F_{9/2} \rightarrow {}^4F_{7/2}$ | 43·6 | 0·0–6·7 | 796 | 0 |
| $Cr^{++}$ | $^5D_4 \rightarrow {}^5D_3$ | 45·6 | 16·5–31·0 | 827 | 9 |
| $Ti^0$ | $^3F_4 \rightarrow {}^3F_3$ | 46·1 | 0·0–6·8 | 557 | 2 |

detected in more than 30 galaxies (e.g. Stacey 1993) and have become essential tools in studies of the metallicity of galaxies, for probing the diffuse atomic and ionised interstellar medium, and for measuring the densities and stellar masses of star-forming regions.

### 3.2.2 Prospects for far-infrared astronomy

Figure 3 compares the transmission between the Antarctic Plateau, Mauna Kea and Siding Spring in the far-infrared, between 50 and 250 $\mu$m. As is evident, it is only possible to observe at all from the Plateau!

In Tables 3 and 4 (adapted and extended from Townes and Melnick 1990), are listed selected ground-state fine-structure and molecular lines between 50 and 250 $\mu$m, some of which have been detected from the Kuiper Airborne Observatory (KAO), together with the calculated atmospheric transmission at 0·1 mm precipitable water vapour, the driest conditions recorded at Vostok. It can be seen that
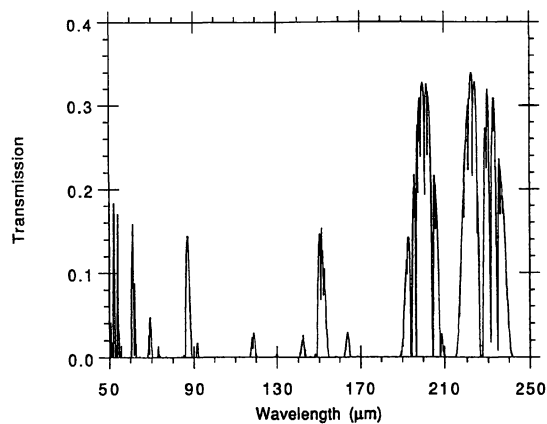


**Figure 3**—Atmospheric transmission in the far-infrared from 50 to 250 $\mu$m, for typical observing conditions overhead on the Antarctic Plateau. The spectral resolution is $R = 500$. The transmission in this band from both Mauna Kea and Siding Spring Observatories is zero.

**Table 3. Selected atomic and ionic ground-state fine-structure lines in the mid-infrared**

The excitation range is between the excitation potential and the ionisation potential. The energy level is for the upper state. Lines that have been detected, mostly with the KAO, are indicated by an asterisk. The transmission is given for the rest velocity, but usually can be considerably improved by appropriate use of our orbital Doppler motion towards a source. The $C^0$ fine-structure lines are included for completeness

| Species | Transition | Wavelength ($\mu$m) | Excitation range (eV) | Energy level (K) | Transmission for 0.1 mm ppt $H_2O$ (%) |
|---|---|---|---|---|---|
| $Sc^{++}$ | $^2D_{5/2} \rightarrow {}^2D_{3/2}$ | 50.6 | 12.8–24.8 | 284 | 0 |
| $Fe^+$ | $^6D_{3/2} \rightarrow {}^6D_{5/2}$ | 51.3 | 7.9–16.2 | 1241 | 45 |
| $Fe^{++}$ | $^5D_1 \rightarrow {}^5D_2$ | 51.7 | 16.2–13.7 | 1341 | 0 |
| $O^{++}$ | $^3P_2 \rightarrow {}^3P_1$ | 51.8* | 35.1–54.9 | 441 | 40 |
| $V^{++}$ | $^4F_{7/2} \rightarrow {}^4F_{5/2}$ | 52 | 29.3–46.7 | 490 | 80 |
| $V^0$ | $^4F_{7/2} \rightarrow {}^4F_{5/2}$ | 53.8 | 0.0–6.7 | 465 | 60 |
| $Fe^0$ | $^5D_1 \rightarrow {}^5D_2$ | 54.3 | 0.0–7.9 | 1278 | 75 |
| $Ti^{++}$ | $^3F_3 \rightarrow {}^3F_2$ | 54.4 | 13.6–27.5 | 264 | 45 |
| $S^0$ | $^3P_0 \rightarrow {}^3P_1$ | 56.3* | 0.0–10.4 | 826 | 0 |
| $N^{++}$ | $^2P_{3/2} \rightarrow {}^2P_{1/2}$ | 57.3* | 29.6–47.4 | 251 | 10 |
| $Cr^{++}$ | $^5D_3 \rightarrow {}^5D_2$ | 57.5 | 16.5–31.0 | 512 | 0 |
| $Ti^0$ | $^3F_3 \rightarrow {}^3F_2$ | 58.8 | 0.0–6.8 | 245 | 0 |
| $Sc^0$ | $^2D_{5/2} \rightarrow {}^2D_{3/2}$ | 59.4 | 0.0–6.5 | 242 | 0 |
| $Ti^+$ | $^4F_{9/2} \rightarrow {}^4F_{7/2}$ | 59.6 | 13.6–27.5 | 566 | 5 |
| $P^+$ | $^3P_1 \rightarrow {}^3P_0$ | 60.0 | 10.5–19.7 | 240 | 75 |
| $O^0$ | $^3P_1 \rightarrow {}^3P_2$ | 63.2* | 0.0–13.6 | 228 | 0 |
| $F^+$ | $^3P_0 \rightarrow {}^3P_1$ | 67.2 | 17.4–35.0 | 706 | 0 |
| $Si^0$ | $^3P_2 \rightarrow {}^3P_1$ | 68.5* | 0.0–8.2 | 321 | 35 |
| $Fe^{4+}$ | $^5D_1 \rightarrow {}^5D_0$ | 69.0 | 54.8–75.0 | 210 | 10 |
| $V^{++}$ | $^4F_{5/2} \rightarrow {}^4F_{3/2}$ | 69 | 29.3–46.7 | 210 | 10 |
| $V^0$ | $^4F_{5/2} \rightarrow {}^4F_{3/2}$ | 72.8 | 0.0–6.7 | 198 | 15 |
| $Ti^+$ | $^4F_{7/2} \rightarrow {}^4F_{5/2}$ | 76.0 | 13.6–27.5 | 324 | 0 |
| $V^+$ | $^5D_4 \rightarrow {}^5D_3$ | 76.7 | 6.7–14.7 | 488 | 25 |
| $Cr^{++}$ | $^5D_2 \rightarrow {}^5D_1$ | 82.0 | 16.5–31.0 | 262 | 0 |
| $Fe^+$ | $^6D_{1/2} \rightarrow {}^6D_{3/2}$ | 87.4 | 7.9–16.2 | 1405 | 70 |
| $O^{++}$ | $^3P_1 \rightarrow {}^3P_0$ | 88.4* | 35.1–54.9 | 163 | 60 |
| $Al^0$ | $^2P^0_{3/2} \rightarrow {}^2P^0_{1/2}$ | 89.2 | 0.0–6.0 | 162 | 5 |
| $V^+$ | $^5D_3 \rightarrow {}^5D_2$ | 97.8 | 6.7–14.7 | 300 | 0 |
| $Fe^{++}$ | $^5D_0 \rightarrow {}^5D_1$ | 105.4 | 16.2–30.7 | 1478 | 0 |
| $Ti^+$ | $^4F_{5/2} \rightarrow {}^4F_{3/2}$ | 106.4 | 13.6–27.5 | 135 | 5 |
| $Sc^+$ | $^3D_3 \rightarrow {}^3D_2$ | 110.0 | 6.5–12.8 | 256 | 5 |
| $Fe^0$ | $^5D_0 \rightarrow {}^5D_1$ | 111.2 | 0.0–7.9 | 1421 | 0 |
| $N^+$ | $^3P_2 \rightarrow {}^3P_1$ | 121.9* | 14.5–29.6 | 189 | 0 |
| $Si^0$ | $^3P_1 \rightarrow {}^3P_0$ | 129.7 | 0.0–8.2 | 111 | 25 |
| $V^+$ | $^5D_2 \rightarrow {}^5D_1$ | 141.7 | 6.7–14.7 | 153 | 40 |
| $O^0$ | $^3P_0 \rightarrow {}^3P_1$ | 145.5* | 0.0–13.6 | 326 | 20 |
| $Sc^+$ | $^3D_2 \rightarrow {}^3D_1$ | 147.8 | 6.5–12.8 | 97 | 30 |
| $C^+$ | $^2P^0_{3/2} \rightarrow {}^2P^0_{1/2}$ | 157.7* | 11.3–24.4 | 92 | 20 |
| $Cr^{++}$ | $^5D_1 \rightarrow {}^5D_0$ | 166.9 | 16.5–31.0 | 86 | 0 |
| $N^+$ | $^3P_1 \rightarrow {}^3P_0$ | 203.5* | 14.5–29.6 | 71 | 50 |
| $C^0$ | $^3P_2 \rightarrow {}^3P_1$ | 370.4* | 0.0–11.3 | 63 | 85 |
| $C^0$ | $^3P_1 \rightarrow {}^3P_0$ | 609.1* | 0.0–11.3 | 24 | 80 |

many species, currently observable only from the KAO, are accessible. For some, such as [O III] at 88 $\mu$m and several of the CO rotational transitions, the transmission is acceptable even with the average winter-time level of 0.3 mm ppt $H_2O$. Others will remain unobservable within our Galaxy. At selected redshifts, however, all lines can be studied. These lines are tracers of activity associated with massive star formation, reprocessing the energy of UV photons absorbed by the gas and dust grains. As such they can be used as signposts of star formation at high redshift, and in particular to search for the signatures of the earliest star formation in proto-galaxies at $z = 3$–10. These lines also provide the best tool for measuring the abundances of their parent species.

Observations from Antarctica will still be challenging, but it is the only ground-based site where they are at all possible. With a 60-cm telescope, competitive observations, currently possible only with the 90-cm KAO, could be performed. At some wavelengths, only a slight decrease in sensitivity relative to the KAO would be suffered, and would be more than compensated by the longer observing times available. A 60-cm telescope would also gather data on atmospheric transmission and stability, in

**Table 4.** Selected molecular transitions in the far-infrared

| Molecule | Transition | Wavelength ($\mu$m) | Transmission[A] |
|---|---|---|---|
| CO | $34 \rightarrow 33$ | 77·1 | 20 |
| | $31 \rightarrow 30$ | 84·4 | 15 |
| | $30 \rightarrow 29$ | 87·2 | 75 |
| | $27 \rightarrow 26$ | 96·8 | 5 |
| | $26 \rightarrow 25$ | 100·5 | 0 |
| | $22 \rightarrow 21$ | 118·6 | 45 |
| | $21 \rightarrow 20$ | 124·2 | 5 |
| | $20 \rightarrow 19$ | 130·4 | 20 |
| | $17 \rightarrow 16$ | 153·3 | 60 |
| | $16 \rightarrow 15$ | 162·8 | 35 |
| | $15 \rightarrow 14$ | 173·6 | 0 |
| | $14 \rightarrow 13$ | 186·0 | 5 |
| | $13 \rightarrow 12$ | 200·0 | 60 |
| | $12 \rightarrow 11$ | 216·7 | 0 |
| | $11 \rightarrow 10$ | 236·4 | 25 |
| $^{13}$CO | $18 \rightarrow 17$ | 152·9 | 65 |
| OH | $^2\Pi_{1\,2}\ 3/2^+ \rightarrow {}^2\Pi_{3\,2}\ 1/2^-$ | 53·3 | 0 |
| | $^2\Pi_{1\,2}\ 3/2^- \rightarrow {}^2\Pi_{3\,2}\ 1/2^+$ | 53·4 | 10 |
| | $^2\Pi_{3\,2}\ 7/2^+ \rightarrow 5/2^-$ | 84·4 | 15 |
| | $^2\Pi_{3\,2}\ 7/2^- \rightarrow 5/2^+$ | 84·6 | 5 |
| | $^2\Pi_{3\,2}\ 5/2^- \rightarrow 3/2^+$ | 119·2 | 45 |
| | $^2\Pi_{3\,2}\ 5/2^+ \rightarrow 3/2^-$ | 119·4 | 40 |
| | $^2\Pi_{1\,2}\ 3/2^+ \rightarrow 1/2^-$ | 163·1 | 40 |
| | $^2\Pi_{1\,2}\ 3/2^- \rightarrow 1/2^+$ | 163·4 | 40 |
| $^{18}$OH | $^2\Pi_{3\,2}\ 5/2^- \rightarrow 3/2^+$ | 120·0 | 20 |
| | $^2\Pi_{3\,2}\ 5/2^+ \rightarrow 3/2^-$ | 120·2 | 30 |
| CH | $^2\Pi_{3\,2}\ 3/2^+ \rightarrow {}^2\Pi_{3\,2}\ 1/2^-$ | 149·1 | 40 |
| | $^2\Pi_{3\,2}\ 3/2^- \rightarrow {}^2\Pi_{3\,2}\ 1/2^+$ | 149·4 | 60 |
| NH$_3$ | $4_3 \rightarrow 3_3,\ a \rightarrow s$ | 124·6 | 0 |
| | $3_2 \rightarrow 2_2,\ a \rightarrow s$ | 165·6 | 0 |
| HD | $1 \rightarrow 0$ | 112·1 | 0 |
| HeH$^+$ | $1 \rightarrow 0$ | 149·1 | 40 |

[A] Transmission for 0·1 mm ppt $H_2O$ (%).

order to quantify the importance of the far-infrared for future Antarctic telescopes. A 2·5-m telescope would provide a significant improvement both in sensitivity and spatial resolution over that obtainable with the KAO. For instance, on the 88 $\mu$m [O III] line a diffraction-limited resolution of 7 arcsec would be achieved. Although an airborne telescope of this diameter is planned, a significantly larger instrument is clearly impracticable. Higher spatial resolution is feasible only from Antarctica, where construction of a 10-m far-IR/sub-mm telescope (or an interferometric array of smaller dishes) could be considered after experience has been gained with smaller instruments.

A space-based platform provides the only alternative access to this region. The European Space Agency intends to launch the Infrared Satellite Observatory (ISO) in late 1995 to observe this spectral regime. ISO is limited by technology (small arrays and single-element detectors), aperture (60-cm), and lifetime (18 months). It will also leave a void, with many discoveries demanding follow-up observations that could readily be satisfied from the Plateau.
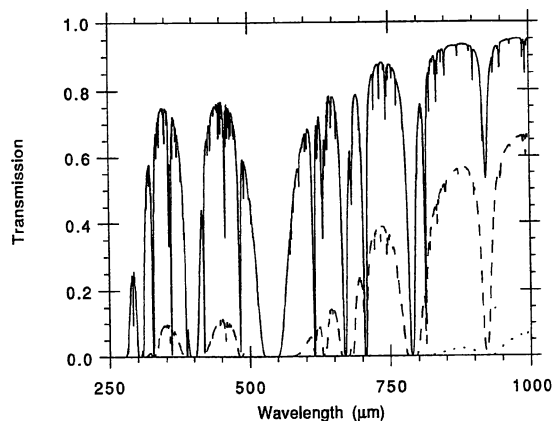


**Figure 4**—Atmospheric transmission in the sub-millimetre, from 250 $\mu$m to 1 mm, representative of typical observing conditions overhead for the Antarctic Plateau (solid curve), Mauna Kea (dashed curve) and Siding Spring Observatory (dotted curve) (as for Figure 2). The spectral resolution is $R = 500$.

### 3.2.3 Prospects for sub-millimetre astronomy

The arguments in favour of sub-millimetre astronomy are so compelling that the first major instrument to be deployed at the South Pole by the US Center for Astrophysical Research in Antarctica (CARA) will be the Antarctic Submillimeter Telescope and Remote Observatory (ASTRO; Bally 1989). CARA plans surveys with ASTRO of the CO $J = 4$–3 transition at 650 $\mu$m and the atomic carbon [C I] transition at 609 $\mu$m in the Galactic plane, with detailed studies of selected star-forming clouds, stellar outflows and nearby galaxies also to be undertaken. Figure 4 compares the transmission from 250 $\mu$m to 1 mm of the Plateau, Mauna Kea and Siding Spring. The gains are self-evident.

There are also opportunities for sub-millimetre interferometry, with the aim of achieving higher angular resolution. Measurements on Mauna Kea have shown a maximum achievable baseline of around 100 m at 900 $\mu$m, limiting resolution to $\sim$2 arcsec (Masson 1993). Phase stability has yet to be measured on the Plateau, but the improved conditions suggest it will be considerably better. Sub-arcsecond resolution might be attainable only from Antarctica.

For Australia, the attractions of an Antarctic observatory are even more compelling. On the Australian continent, no site exists which can give meaningful access to any part of the entire 14 $\mu$m to 2·6 mm spectral region. Australian astronomers are totally dependent on foreign-owned facilities to fill the gap between data obtained on our excellent optical and radio observatories. Thus Australia has no incentive to develop receiver and instrument technology in this important spectral region, and terahertz technology has been largely neglected.

***Stratospheric chemistry.*** In the far-infrared and sub-millimetre region lie not only many accessible ozone transitions, but also lines due to HCl, ClO, $HO_2$ and other species vital to our understanding of ozone chemistry and the formation of the ozone hole. A monitoring program could easily be put in place whereby daily measurement of the concentration of these species at various altitudes was carried out. This program could be performed even with a small telescope, as high spatial resolution is not required.
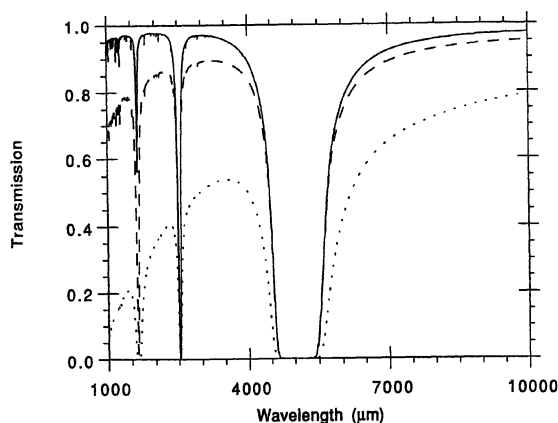


**Figure 5**—Atmospheric transmission in the millimetre regime, from 1 mm to 10 mm, representative of typical observing conditions overhead for the Antarctic Plateau (solid curve), Mauna Kea (dashed curve) and Siding Spring Observatory (dotted curve) (as for Figure 2). The spectral resolution is $R = 500$.

## 3.3 The Millimetre and Radio Wavebands

Millimetre astronomy, from 1 to 10 mm, has to contend with variable atmospheric attenuation from water vapour, and benefits from a dry site. Figure 5 shows the transmission from Siding Spring, Mauna Kea and the high Plateau, where the improvement as water vapour content is reduced is clear. For instance, the transmission at 2·6 mm, the wavelength of the ground state transition of the CO molecule, the $J = 1$–$0$ line, is 85% from the Plateau, 75% from Mauna Kea and less than 50% from Siding Spring in typical observing conditions. Australian expertise in millimetre astronomy is limited, but growing rapidly as the antennas of the Australia Telescope are equipped with 3-mm receivers. This is clearly an important and expanding area of astrophysics, for which the Plateau makes a prime site. Of particular interest are the possibilities for conducting millimetre-wave interferometry on the plateau.

At present, the only significant millimetre and sub-millimetre telescope in the southern hemisphere is the SEST 15-m antenna in Chile. The current development of a mm-wave interferometer in Aus-

tralia straddles an important window of opportunity: there is no other interferometer operating in the south, nor will any of the proposed (but as yet unfunded) Chilean-based instruments be operational within a decade. Thus Australia expects to operate a unique instrument for the next few years. However, while the first images from the Australian synthesis array will be invaluable scientifically, the poor sites available in continental Australia will ultimately limit image quality. Thus, while we can expect to obtain new science from this array this decade, in the next decade the facility will not be competitive with those in Chile. The Antarctic sites, with their low atmospheric water vapour and low wind speeds, promise superb conditions for interferometry, outperforming those in Chile. Indeed, as discussed in the last section, in the sub-millimetre band, high-quality interferometry may be possible only from Antarctica.

Gains for cm-wave radio astronomy from a Plateau site stem not only from improved observing conditions in the band, but also from the location on the Earth with respect to other antennas in a very long baseline interferometry (VLBI) network. A VLBI telescope close to the South Pole improves enormously the imaging capability of a southern VLBI array. A secondary gain is the ability for continuous monitoring of a source, discussed later.

### 3.3.1 Millimetre-wave astronomy

Millimetre-wave astronomy has had a major impact on virtually all areas of contemporary astronomy. It provides a testing ground for our theories of stellar evolution, galactic evolution, and the evolution of the universe itself. The continuum emission mechanism in the millimetre often changes from synchrotron, through free–free, to thermal dust emission across the band. All fundamental rotational transitions of diatomic molecules of the abundant elements C, O, S and N fall in the millimetre regime. Thus the chemistry and composition of the molecular gas in the interstellar medium is uniquely revealed by observations at millimetre wavelengths. The cold gas surrounding the earliest stages of star formation, and the internal kinematics of luminous galaxies are phenomena where the millimetre provides important contributions to our knowledge. The cosmic microwave background radiation peaks in this regime. Here we describe some areas where advances could be made with an Antarctic mm-antenna or mm-interferometer.

***Molecular gas in our galaxy.*** An area of great application is observation of the fundamental line of CO at 2·6 mm for the study of star formation. CO-line emission traces the earliest stages of star formation, revealing the kinematics of dark clouds through the stages of fragmentation and collapse

prior to the formation of a star. Most of the observable Galaxy lies in the southern celestial hemisphere and thus will be continuously observable with a millimetre telescope in Antarctica. Some particular areas amenable to study are:

- Molecular outflows in star-forming regions.
- Expanding molecular rings in planetary nebulae.
- Circumstellar accretion disks around young stellar objects.
- Continuum emission from cold ($\sim$15 K) dust around protostars.
- Determination of the mass spectrum of clumps in molecular clouds, to test the unproven inference that smaller-scale clumps evolve into stars.
- The interaction of supernova remnants with molecular clouds, and in particular the comparison of high-spatial-resolution near-infrared images of shocked molecular hydrogen with interferometric maps showing the dynamics of the accelerated gas in CO and HCO$^+$.
- Interferometry of SiO maser emission at 43 and 86 GHz (7 and 3·5 mm) associated with circumstellar shells around evolved stars, both probing the nature of the stellar envelopes and linking together the optical and radio reference frames.
- Composition of planetary atmospheres within our Solar System.
- Synthesis imaging of sunspots and filaments on the Sun.

*Molecular gas in active galaxies.* The CO molecule is also used to trace molecular gas in active galaxies. Through it we can study the distribution of gas in the vicinity of starburst cores, and measure its kinematics. The thermal radiation from cold dust in these same objects is frequently bright enough to be a valuable tracer of density in these objects. Observations so far have shown enormous masses of molecular gas and dust in such systems. Some projects of extragalactic interest include:

- The search for proto-galaxies through redshifted CO lines.
- Studying individual giant molecular clouds in nearby galaxies.
- Mapping the molecular distribution at kiloparsec scales in the Virgo cluster.
- Examining the core of the galaxy Centaurus A.
- Investigating the relation between molecular gas, spiral structure and star formation in spiral galaxies.
- Searching for bar morphology in the molecular cloud distribution, and measuring gas motions along the bar.
- Evolution of, and relationship between, merging, starburst and active galaxies.

*Cosmic microwave background anisotropy.* The cosmic microwave background (CMB) is the remnant radiation from the hot early universe in standard Big Bang cosmology. Anisotropies in its distribution on large angular scales are introduced by the collapse of proto-galaxies and proto-clusters at large redshifts, and on smaller scales by Compton scattering of the background by the hot gas in clusters of galaxies (the Sunyaev–Zel'dovich effect). Measurement of the CMB provides our most effective probe of the early universe. With a temperature of 2·7 K its emission peaks at 1 mm, so it is best studied in the millimetre and sub-millimetre regimes. The Antarctic Plateau provides the premier site on the Earth for its observation due to a combination of low atmospheric emission, high transmission, stability of observing conditions and low man-made interference. A secondary benefit for anisotropy experiments is the ability to observe the same part of the sky continuously at high elevations.

Anisotropy has now been detected in the CMB at a level of $\Delta T/T \sim 1 \times 10^{-5}$ by the COBE satellite at large angular scales (Smoot *et al.* 1992), but this result was statistical and did not map the level of the anisotropy across the sky. The potential for mapping the CMB anisotropy from the plateau is so good that experiments to this end have been conducted at the Pole since 1986. CARA is currently developing the Cosmic Background Radiation Anisotropy experiment (COBRA), designed to map the anisotropy on angular scales from 15 arcmin to 20° at wavelengths of 2 and 3·3 mm, with an order of magnitude better sensitivity than COBE. Early results indicate anisotropies at smaller angular scales than were measured by COBE, at levels from $\Delta T/T \sim 3 \times 10^{-5}$ to $1 \times 10^{-5}$ (CARA 1993).

Fluctuations in the CMB are also produced when photons are Compton up-scattered by electrons in the hot X-ray-emitting gas surrounding clusters of galaxies, distorting its spectrum from black-body form. This is the Sunyaev–Zel'dovich (SZ) effect. There are two contributions to the SZ effect, a thermal part dependent on the temperature of the gas in the cluster, and a kinematic part resulting from the peculiar velocity of the cluster along the line of sight. The thermal component causes a decrement in the CMB in the Rayleigh–Jeans part of the spectrum, and an excess in the Wien part. The sign of the kinematic SZ effect depends on the sign of the cluster's radial velocity. Measurement of the CMB decrement towards a cluster in the cm-band, and the increment in the sub-mm band, can disentangle the two effects and yield the peculiar velocity of a cluster by a distance-independent determination. A change of brightness temperature of order one part in $10^4$ is predicted, on spatial scales of around 3 arcmin. Sensitive observations with a synthesis telescope across the sub-millimetre and millimetre regimes are necessary to measure this effect. In Antarctica the method could be extended to measure

peculiar motions down to a few hundred km s$^{-1}$, and provide a considerably better estimate of the cosmological density parameter of the universe.

### 3.3.2 Very long baseline interferometry

The Australia Telescope contains a Long Baseline Array component consisting of three telescopes giving three baselines up to 300 km, and a bandwidth of 64 MHz. Collaboration with other institutions within Australia results in baselines up to 3000 km, and the capability to image complex radio sources. Further collaboration with observatories in other countries, particularly in the Asia–Pacific region and South Africa, results in baselines up to 10,000 km, and produces the highest resolution images possible with ground-based arrays.

The best images are obtained when the telescopes give baselines evenly distributed in length and angle as viewed from the source. Existing baselines are predominantly east–west, severely restricting the image quality of southern sources. A telescope in Antarctica would provide many north–south baselines. It would also significantly enhance the proposed space-VLBI satellites of Japan and Russia (VSOP and Radioastron, respectively). These satellites will have baselines of 20,000–80,000 km, giving resolutions down to micro-arcseconds. They will rely on ground-based facilities to complete phase coverage, and without an Antarctic telescope they will suffer in the south due to the lack of adequate north–south baselines.

Recent developments in VLBI have seen the technique pushed to higher and higher frequencies. VLBI has now been conducted at 43 and 100 GHz (7 and 3 mm) and shows unresolved components in quasars even at the corresponding sub-milliarcsecond resolutions. As a result, the millimetre region promises to be a productive area for VLBI in the future and so new facilities such as the Very Long Baseline Array (VLBA) in the USA are being equipped for millimetre VLBI. In Australia three antennas capable of mm-VLBI (Culgoora, Mopra, and Parkes) could profitably be used with an Antarctic antenna, together with other telescopes such as the VLBA antenna on Mauna Kea and SEST in Chile.

VLBI observations can be used to probe the nature of the active cores at the heart of distant galaxies and quasars, one of the central mysteries of astronomy. They can be used to study the emission from dense knots of molecular gas in star formation regions, probing the mechanism of cloud collapse, and the formation of stars and planets within them. VLBI techniques provide positions of radio sources to milli-arcsecond accuracy, better than any other method. They also provide the best method of determining baseline lengths, with accuracies better than a few millimetres over distances of thousands of kilometres, improving the monitoring of geodetic effects. Thus a telescope in Antarctica will significantly improve the accuracy of astrometric measurements from Australia, and one anchored on rock, perhaps at a coastal station, could be used to measure continental drift.

## 3.4 The Optical and Ultraviolet Wavebands

### 3.4.1 Optical astronomy

Optical astronomy can be performed only in the winter time in Antarctica, and must contend with the auroral emission, whose effect on observations needs to be quantified. The total amount of astronomically dark time (defined as when the Sun is 18° or more below the horizon, with no Moon) is approximately half that at mid-latitude sites, although this is concentrated into the winter months. With these provisos, the argument for an optical telescope on the Antarctic Plateau relies on the attainment of excellent seeing, superior to that at mid-latitude sites such as on Mauna Kea or in Chile. As discussed earlier (see Section 3.1.2), both superior intrinsic seeing and more favourable conditions for wavefront correction contribute to this case. While the arguments for this seem reasonable, it is essential to conduct appropriate site testing measurements to verify, or otherwise, this hypothesis. The following science case assumes it to be true.

Given 0·2 arcsec seeing, the minimum diameter of telescope needed to achieve this resolution is 60 cm, for which this is the diffraction limit at V (5500 Å). While such a telescope would undoubtedly prove its worth as a testbed for a larger facility, the amount of new science that could be achieved with it would be small. We consider a 2·5-m class telescope to be the minimum size necessary to produce competitive science. However, given the long lead time for its design and construction, it is important to keep in mind that such a telescope will be operating in an era when at least three very large optical telescopes should be operating in the southern hemisphere at sites whose median seeing is around 0·5 arcseconds. On the other hand, an Antarctic telescope can be operating beyond the first decade of the 21st century, when the only current or planned instrument capable of delivering 0·1 arcsec performance over a wide field of view, the Hubble Space Telescope, will no longer be operating.

It should also be noted that while adaptive optics systems recovering the full diffraction-limited resolution might be achieved by infrared systems located at mid-latitude sites in the future, this may never be the case for the optical. In Antarctica, however, where most of the seeing will be generated in the surface inversion layer, and there is no high-altitude jet-stream, the isoplanatic patch will both be larger and vary on slower timescales. Hence

adaptive wavefront correction will be considerably easier to implement.

An optical telescope in Antarctica should not be regarded as an alternative to the 8-m general-purpose telescopes now under construction, but rather as a complementary instrument for specialised applications. To compensate for the enormous collecting area advantage of the 8-m class telescopes, the science case at optical wavelengths for an Antarctic 2·5-m class telescope must therefore be squarely aimed at the unique features such a telescope can provide. These fall into two distinct categories.

*High spatial resolution spectroscopy.* With excellent optics and the hypothesised excellent seeing, such a telescope should allow optical spectroscopy at unprecedented spatial resolution. Over the last few years we have been made increasingly aware of details at the sub-arcsecond level thanks to the imaging from the Hubble Space Telescope. Many of the features shown by Hubble, plus others not yet revealed, are in need of spectroscopic study. More will undoubtedly be recognised as imaging studies at high resolution proceed, from space, from the ground, and eventually from Antarctica. Even without knowing what studies will be demanding attention a decade hence, we can identify some obvious examples of projects.

- Disks around young stellar objects, such as $\beta$ Pic.
- Emission from gas flows associated with wide interacting binaries such as RS CVn systems.
- Kinematic and compositional studies in the cores of compact clusters.
- Structure and stratification of emission lines in planetary nebulae and H II regions to improve ionisation and excitation models.
- Velocity studies of shock structures in supernova remnants and stellar jets.
- Kinematics of gas flows in the nuclear regions of normal and barred spirals, and active galaxies.

Another long-term advantage of intrinsic good seeing is the ability to match image sizes to the entrance slits of high-resolution spectrographs without the light losses incurred in adaptive optics. This advantage will be most critically felt when 8-m class telescopes are built in the anticipated good-seeing sites of the Antarctic Plateau.

*Wide-field broad-band imaging.* With appropriate attention to design, a telescope should be capable of delivering images that are seeing-limited over a field exceeding 1° in diameter. A suitable camera could contain a mosaic of CCDs, such as one hundred 2048 × 2048 CCDs, with a plate scale of 0·2 arcsec/pixel over a 1·1° × 1·1° field. With such an instrument the telescope would provide a unique capability for studying a number of problems. These include:

- Morphology and photometry in galaxy clusters up to moderate redshifts.
- Searches for faint supernovae.
- Surveys for high-redshift galaxy clusters.
- Surveys for QSOs.
- Surveys for faint high-proper-motion objects in the Galactic halo (i.e. cool white dwarfs or low-luminosity stars), or for objects in the Kuiper belt beyond the orbit of Pluto, similar to 1992QB1.
- Stellar population studies in crowded fields, such as the Bar of the Large Magellanic Cloud, to determine whether there is just an intermediate-age (~3 Gyr) population or an underlying older population as well.
- Population studies of the old component in the Small Magellanic Cloud.
- Population studies of southern Local Group and nearby galaxies (e.g. Sculptor group galaxies).
- Determination of the extragalactic distance scale, both through searches for RR Lyrae and Cepheid variables in galaxies beyond the Local Group, and through the use of techniques such as Tonry's surface brightness fluctuation method for more distant objects.
- Determination of the mass distribution in clusters of galaxies through searches for gravitationally-lensed objects, such as multiply-imaged QSOs and arcs.
- Colour–magnitude determinations at or near the centres of globular clusters to determine how the stellar population may be affected by the cluster dynamics.

### 3.4.2 Ultraviolet astronomy

At the short-wavelength end of the optical regime, atmospheric transmission on the Plateau will be higher than elsewhere on the Earth, due to a combination of reduced particulate concentration in the atmosphere, and high elevation. It will be possible to observe down to wavelengths approaching the 300 nm cutoff of the atmosphere. The wavelength range 300–340 nm is of particular interest to stellar abundance studies because of the large number of important diagnostic lines in this region. We describe here a few programs that would benefit when a large telescope with Coudé spectrograph is available in Antarctica.

*Beryllium.* As the fourth lightest element, beryllium is crucial to testing Big Bang models, through its abundance in the oldest stars, and for studies of nucleosynthesis in stars. The *only* spectral line of beryllium lies at 313 nm.

*CNO elements.* The abundances of the carbon–nitrogen–oxygen group are also crucial to our studies of nucleosynthesis. The CNO cycle is the catalytic reaction that supports hydrogen burning in stars

more massive than the Sun. In the late stages of their lives, convection dredges up the interior products of nucleosynthesis, allowing a study of the processes. Due to a shortage of spectral lines from CNO elements, their abundances have to derived from molecules, such as CO in the infrared. The most abundant and easily interpreted molecules are the hydrides, CH, NH and OH. Lines from these species are found at 314, 336 and 310–320 nm, respectively.

*Copper*. Copper is an s-process element, just above the iron group, that has been little studied to date. Indications so far suggest different behaviour to the iron-group elements, with inferences for supernovae types in the earliest history of the Galaxy (e.g. Sneden *et al.* 1991). The copper doublet occurs at 325, 327 nm.

### 3.5 Continuous Observations

From the Polar regions the vast majority of objects visible are circumpolar, and all have a small range in zenith distance over the course of 24 hours. Thus it is possible to observe an object continuously for very long spells. Such coverage is otherwise achieved by a network of telescopes around the planet (the Whole Earth Telescope). The advantage of Antarctica is that all measurements would use the same instrument, providing internally consistent data, and have near-constant zenith angle. Very long runs of continuous clear weather are statistically more likely for a single Antarctic telescope than a global network.

The projects that might benefit from continuous observation span the spectrum. In the radio, which is little affected by the weather, it would be possible to monitor a single object virtually all year, whereas in the optical, of course, observation would be confined to the winter months when the conditions were clear. Nevertheless, much longer observing periods will be possible than from a mid-latitude site. The possibilities for observing Venus in the near-infrared around inferior conjunction have already been discussed. The advantage of winter access to the Magellanic Clouds was also noted earlier. Examples of other projects that might be undertaken include:

- *Solar seismology*. Monitoring global oscillations of the Sun to probe its internal structure formed the rationale for the first astronomical activities at the South Pole in 1979 (Pomerantz 1986). The natural progression to other stars will constrain the theory of stellar evolution. It requires observations of extremely faint photometric variations, or of small line-of-sight velocity variations on the stellar surface, on timescales from a few minutes to several days. Uninterrupted data sets are optimal for precision.

- *Stellar activity*. Applying ideas from solar physics to similar stars probes the structure and energy transport in stellar atmospheres, and can test and develop models previously used for the solar atmosphere. Our lack of understanding of the nature of the solar dynamo represents one of the fundamental problems of modern astrophysics. Observations of stellar magnetic activity can help us critically test theories of the internal structure of solar-type stars and their dynamo generation of magnetic fields. Multi-colour micro-photometry and high-dispersion spectropolarimetry are required. Photometric and colour variations yield the distribution of darks spots and bright regions. Spectropolarimetry provides a picture of the differential rotation of the photosphere and the distribution of magnetic fields through the technique of Zeeman Doppler imaging. The particular advantage of an Antarctic site is the coverage of many successive stellar rotations, providing a continuous, reliable, unaliased data set. Hence we can monitor the evolution of active regions.

- *Complete time-series data of photometric variables*. The coverage avoids aliasing problems that hamper the analysis of discontinuous studies, particularly for phenomena with periods near a small multiple of 12 hours.

- *Simultaneous observations with satellites*. Most satellite observatories are constrained to point in directions nearly 90° from the Sun, giving a period of simultaneous visibility only 3–4 hours long from most ground-based sites, while following the source to high zenith angle. From Antarctica simultaneous observations could be conducted for much longer periods, and be better matched to satellite observing schedules.

### 3.6 Particle Astronomy

#### 3.6.1 Cosmic rays and gamma rays

Cosmic ray astronomy divides into three ranges. Neutron monitors respond to the lowest-energy cosmic rays capable of penetrating the atmosphere ($\sim$500 MeV$-$50 GeV) and are particularly sensitive to phenomena originating in explosive events at the Sun. Muon telescopes respond to higher energies ($\sim$10$-$1000 GeV) and are sensitive to large-scale heliospheric modulation and to local Galactic effects. Finally, air-shower and Cerenkov telescopes respond to the highest-energy cosmic rays (1000 GeV to $>10^{20}$ eV) and are sensitive to Galactic (and possibly extragalactic) phenomena but are not influenced by solar modulation. Air-shower experiments also respond to ultra-high energy (UHE) gamma rays through a similar atmospheric cascade generation.

*Neutron monitors.* Low-energy cosmic rays are significantly deflected in the geomagnetic field. The field of view of a neutron monitor is therefore complex. It is energy-dependent and bears little resemblance to the opening angle of the ground-based monitor. A neutron monitor located on the Plateau would significantly overlap the fields of view of other monitors already operating in Antarctica, although the altitude would result in a somewhat lower energy threshold. However, the energies observed in these overlapping directions would be quite different and thus valuable. A Plateau neutron monitor would also allow the gap in spectral coverage between satellite and ground-based instruments to be filled for the first time. Two important needs would be met by such an instrument.

Firstly, some apparent inconsistencies may be resolved between the responses of satellite and ground-based detectors to transient events such as Forbush decreases (FDs) and ground level enhancements (GLEs). FDs are decreases over timescales of several hours in the cosmic ray flux at the Earth caused by the passage of a shock and coronal mass ejection. The shock acts as a barrier to Galactic cosmic rays, and their flux has a slow recovery, over a period of about 10 days. GLEs are rapid increases in the low-energy cosmic ray flux at Earth on timescales of minutes to a few hours. They are caused by protons of solar origin being accelerated to low cosmic ray energies during solar flares.

Secondly, access to this spectral 'hole' will help to resolve the problem of poorly determined yield functions for neutron monitors at such energies. Studies of GLEs have demonstrated that the yield functions, based on theoretical calculations of high-energy particle interaction in the atmosphere, are not consistent with observations made by high-altitude neutron monitors at their lowest energies of response of $\gtrsim 500$ MeV (D. F. Smart, personal communication 1992).

Completing the gap in spectral coverage with such a neutron monitor should resolve these two problems, leading to deeper insights into the acceleration, scattering and propagation of high-energy particles by the solar magnetic fields, shocks and associated solar wind plasma during GLEs and FDs.

*Muon telescope systems.* Galactic cosmic ray modulation in the heliomagnetosphere at energies above 50 GeV can only be studied by ground-based and underground muon telescope systems. In the northern hemisphere there are a number of observatories in Japan, North America, the CIS and Europe which give the very good latitude and energy coverage necessary for the study of anisotropies generated by solar processes. By contrast the southern hemisphere, particularly viewing southward of 50°S, is only covered by observatories in Tasmania

and at Mawson to mid-latitudes, and Mawson alone further south. This coverage is reasonable up to 200 GeV but only the Poatina observatory in Tasmania, viewing to mid-southern latitudes, measures up to the 500 GeV necessary to establish the upper limiting energy of solar modulation (Duldig *et al.* 1985).

A novel approach to an underground system would be to place a telescope in a simple reinforced building under the ice on the polar plateau. A great advantage of such a system would be the perfectly determined overburden of absorber material. Underground muon telescope sites suffer from poorly determined overburdens with seasonally varying water content, varying structure with depth, and varying density of material, including water-filled or air-filled gaps and fissures. As a result it is difficult to correct for seasonal variations of local origin and to determine accurate energies of response. By contrast, an in-ice system would not suffer from any of these difficulties. Furthermore, muon systems could operate at the ambient in-ice temperature of −20°C, minimising the problem of the housing sinking into the ice and changing the depth with time. With no structure extending above the flat surface, snow drift accumulation would not affect this distribution of overburden. The only correction necessary to observational data would be for the very slow accumulation of snow over periods of years to decades, which would reduce the count rate and increase the energy of response over long timescales.

Such a system has been designed for the South Pole station (Duldig *et al.* 1985) but could equally well be placed at higher elevations. The energy coverage would be designed to extend beyond the range presently observed at Mawson so as to complement that experiment.

The present very sparse coverage of high southern latitudes causes difficulty in the interpretation of both heliospheric and Galactic modulation of cosmic rays. For example, there are indications of a latitudinal dependence to the north–south asymmetry. This dependence in the southern hemisphere does not appear to be consistent with similar northern observations. The addition of a high-latitude experiment of higher response energy than the Mawson experiment would be invaluable in unravelling this puzzling variation.

*Combined neutron monitor and muon telescope.* Cosmic ray experiments are, in general, integral energy detectors. Employing different different detector systems for effective energy windows is necessary if spectral and energetic parameters are to be found. This is particularly so for transient and time-varying phenomena. Combined neutron monitor and muon telescope analyses are important when attempting to understand the energetics of

heliospheric modulation and large FDs and GLEs. Where possible, both types of instruments should view the same region of sky from the same site. Such an experimental setup has been achieved at Mawson, and a Plateau site is equally amenable to these requirements. It is much more difficult to achieve them at lower-latitude sites where no advantage can be taken of the proximity of the magnetic pole.

The use of neutron monitors and the geomagnetic cutoff, which prevents particle access to Earth below a certain energy (~15 GeV at equatorial latitudes and zero at the magnetic poles) has assisted spectral studies of FD and GLE greatly but cannot be used to determine the effective maximum energy of these and other solar modulation processes. Most solar modulation phenomena cease to be effective between 50 and 250 GeV and the upper limit varies throughout the solar cycle. It is therefore essential to combine higher-energy muon systems with neutron monitors to gain insight into the underlying physical processes controlling cosmic-ray particle transport in the heliosphere. The Dome A site could host a combination system designed with these considerations in mind. The muon telescope could incorporate viewing directions coincident with the existing Mawson telescopes but at higher energies, thus extending and complementing those instruments and having a significant impact on southern hemisphere and inter-hemisphere investigations of the solar modulation processes.

*Air-shower and ultra-high energy (UHE) gamma ray astronomy.* A cosmic ray air-shower experiment (TeV–PeV energies) already operates at the South Pole (SPASE; van Steckelenborg *et al.* 1993). The atmospheric cascades of electrons produced by very-high-energy cosmic rays and by UHE gamma rays can be discriminated by the shower structures and by the heavier charged particle content of the shower using muon detectors. The air showers can also be studied by the Cerenkov light emitted by the shower particles. Such an experiment is also operating at South Pole in the winter months (GASP; Morse and Gaidus 1989). Both these techniques are restricted to within ~40° of the zenith, although a very-high-altitude site such as Dome A may be able to view to greater zenith angles. Increased altitude also improves the detection efficiency of such systems. The South Pole has the additional advantage that all sources remain at the same zenith angle, resulting in a constant energy threshold and simplifying determination of the energy spectrum.

Showers induced by cosmic ray particles carry information about the local Galactic magnetic field, particularly the field direction in the region immediately surrounding the nearest stars. UHE gamma ray showers have been observed from energetic

compact sources such as neutron stars and suggested black-hole binary systems. The UHE gamma ray generation process is not understood. Declinations south of ≃60° can be systematically searched only from Antarctica.

### 3.6.2 Neutrinos

During the 1991/92 southern summer a small neutrino experiment was established at the South Pole (AMANDA; Tilav *et al.* 1993). This involved the use of photomultipliers placed within the ice at depths ranging from 300 to 1000 m and counting light pulses resulting from neutrino interactions in the ice. Muon-generated Cerenkov radiation is also present. Antarctic ice is considered to be a better medium than water for this purpose because of the low concentration of naturally occurring radioactive isotopes, which increase background rates, and the complete lack of biological contaminants. This modest telescope system is an excellent first stage in the development of a large neutrino telescope for the Antarctic Plateau. If the technique proves to be as successful as expected, then a large system could be constructed anywhere on the Antarctic ice plateau but would logically be sited together with other operations. A Dome A astrophysical observatory would be most appropriate.

### 4. THE WAY FORWARD

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

A program for Antarctic astronomy should be drawn up. This program must recognise the challenges ahead and thus explore the technical limitations thoroughly before embarking on the building of astronomical facilities. It may prove too difficult to operate all that are desired and this should be understood before construction is initiated. The program should recognise and complement other developments that are occurring in astronomy worldwide, and be clearly focused to exploit those aspects of Antarctica which provide truly unique conditions for astronomy. It should follow a staged approach towards an observatory, starting with simple and limited facilities and gradually increasing the

degree of sophistication and performance as our technical capabilities develop and our expectations of the site quality are proven.

An Antarctic astronomy program should have as its long-term goal the construction of a major facility at the best site available, most probably the highest part of the Plateau, Dome A. We recognise that such a goal is indeed ambitious and beyond the resources of any one country. It will not take place within this century. We believe that Australia now has the opportunity to seize and play a leading role in the development of what may be one of the major international astronomical initiatives of the next century, and should endeavour to do so.

This document does not intend to propose the route that this program should follow. Some comments are, however, in order here. A likely sequence is as follows:

- Site testing.
- Operation of testbed facilities and development of infrastructure.
- Construction of intermediate-sized facilities. In this category we include the 2·5-m optical/IR telescope envisaged here, and a sub-mm/mm-wave facility.
- Construction of a major observatory at the premier site available.

Thorough site testing now is absolutely essential. Much of the argument given in this document assumes superlative observing conditions, but these need to be verified. In particular, the site seeing needs to be accurately measured and its dependence on local conditions understood. Secondly, the level of thermal background in the 2·27–2·45 $\mu$m window needs to be determined and the effect of any airglow or auroral lines on performance assessed. A third area of interest is the need to determine phase stability in the millimetre and sub-millimetre, and thus to quantify the prospects for interferometry at these wavelengths. A fourth area of concern is the level of optical sky brightness in winter. The outcome of site testing experiments will, of course, affect subsequent developments.

In parallel with a site testing program, activities aimed at furthering the study of astronomy may also have beneficial effects for other areas of science; these should be thoroughly explored. For instance, data obtained on night sky emissivity in the infrared can be related to the level of winter cloud cover over the Plateau. This is an important, but poorly known, parameter for modelling global climate, which this data will be able to constrain. Far-infrared and sub-millimetre spectroscopic observations of astronomical sources will simultaneously register the emission from many lines of ozone and other molecules in the atmosphere. Thus they would monitor the chemistry in the polar atmosphere, an essential ingredient for

studies of the formation and growth of the ozone hole above Antarctica.

Assuming a successful outcome to the site testing, the next stage is the development of small-scale facilities in order to gain the experience necessary to operate in the extreme environment. Concurrently, the level of infrastructure and logistical support needs to be built up. The US *Center for Astrophysical Research in Antarctica* is undertaking such an exercise at the Amundsen–Scott South Pole station. Under development are three facilities: the Cosmic Background Anisotropy Experiment (COBRA; Ruhl *et al.* 1993), consisting of a 2-m and a 0·5-m antenna designed to measure the microwave background anisotropy on angular scales from 15 arcmin to 20°; the Antarctic Submillimeter Telescope and Remote Observatory (ASTRO; Stark 1989), a 1·7-m offset-fed parabolic antenna capable of surveying spectral lines in the sub-millimetre window; and the South Pole Infrared Explorer (SPIREX; Hereld 1994), consisting of an infrared camera and spectrometer mounted on a 60-cm telescope capable of exploiting the low thermal background at 2·4 $\mu$m. A likely step for Australia at this stage is the development of a 60-cm telescope capable of being equipped with optical, infrared and sub-millimetre instrumentation. At 5500 Å the diffraction limit will be 0·2 arcsec and thus the instrument will be capable of exploring and exploiting conditions of 'super-seeing'. Construction and instrumentation of this telescope will provide essential experience we currently lack. The scientific potential of such a telescope is limited, but not negligible.

The third stage is the development of a significant facility, capable of undertaking whole new areas of science. Given the current expertise within the Australian community, likely interest will centre on a 2·5-m class optical/IR telescope. From 3000 Å to 2·5 $\mu$m this would be expected to achieve image performance of 0·2 arcsec over a wide field, and make the most sensitive observations achievable in the 2·27–2·45 $\mu$m window. This instrument would be located on the high plateau, and possibly even flown as the payload of a balloon tethered above the surface inversion layer. At this stage of development other facilities might be constructed concurrently. They include a millimetre and/or sub-millimetre antenna, a radio VLBI dish and a neutron monitor and muon telescope system.

Looking further ahead to the development of a major international facility, the possibilities are many and exciting. An 8-m class optical/IR telescope, an optical interferometer, a 10-m class mid-IR/sub-mm telescope, a 15-m class sub-millimetre antenna, a sub-millimetre and millimetre array, and a large neutrino telescope all seem promising projects. All can be more cheaply and effectively operated from Antarctica than from space platforms or the Moon.

If developed to this degree, the Antarctic Plateau could become one of the world's major astronomical observatories.

With its existing strengths in both astronomical and Antarctic science, and its claim over the best astronomical sites on the continent, Australia has the potential to be a major player in the development of such an observatory, and to remain at the forefront in the exciting pursuit of astrophysics.

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## References

Allen, D. A. and Crawford, J. W., 1984, *Nature*, **307**, 222.

Bahcall, J. N., 1991, *Physics Today*, **44**, 24.

Bally, J., 1989, in 'Astrophysics in Antarctica', D. J. Mullan *et al.* (eds), *Amer. Inst. Phys. Conf. Proc.* **198**, 100.

Burova, L. P., Gromov, V. D., Luk'yanchikova, N. I. and Sholomitskii, G. B., 1986, *Sov. Astron. Lett.*, **12**, 339.

Burton, M. G., Hollenbach, D. J. and Tielens, A. G. G. M., 1992, *Astrophys. J.*, **399**, 563.

CARA, in 'Renewal Proposal for the Center for Astrophysical Research in Antarctica', 1993, submitted to the National Science Foundation, USA.

Duldig, M. L., Jacklyn, R. M. and Pomerantz, M., 1985, *Proc. Astron. Soc. Aust.*, **6**, 48.

Gillingham, P. R., 1993, *ANARE Research Notes*, **88**, 290, Australian Institute of Physics 10th Congress, Melbourne University, February 1992 (publications of the Antarctic Division).

Harper, D. A., 1989, in 'Astrophysics in Antarctica', D. J. Mullan *et al.* (eds), *Amer. Inst. Phys. Conf. Proc.* **198**, 123.

Harvey, J., 1991, in 'Highlights of Astronomy, as presented at the Joint Commission Meeting #4 of the XXIst General Assembly of the IAU', Buenos Aires, 27 July 1991.

Hereld, M., 1994, in Proceedings of the 'IR Astronomy with Arrays: the Next Generation' conference, UCLA, July 19–23 1993, I. S. McLean (ed.), in press.

Herter, T., 1994, in Proceedings of the 'IR Astronomy with Arrays: the Next Generation' conference, UCLA, July 19–23 1993, I. S. McLean (ed.), in press.

Leger, A., d'Hendecourt, L. and Jolin, C., 1992, in 'Infrared Astronomy with ISO', Les Houches series, T. Encrenaz and M. Kessler (eds), Nova Science Publishers, p. 359.

Lord, S. D., 1993, 'A new software tool for computing Earth's atmospheric transmission of near- and far-infrared radiation', NASA–TM–103957.

Masson, C. R., 1993, in 'Millimeter and Sub-millimeter Wave Interferometry', *IAU Coll. 140*, Oct. 5–9, 1992, Hakone, Japan.

Morse, R. and Gaidus, J., 1989, in 'Astrophysics in Antarctica', D. J. Mullan *et al.* (eds), *Amer. Inst. Phys. Conf. Proc.* **198**, 24.

Nelson, L. A., Rappaport, S. A. and Joss, P. C., 1986, *Astrophys. J.*, **311**, 226.

Pomerantz, M. A., 1986, *Proc. Astron. Soc. Aust.*, **6**, 403.

Ruhl, J., Dragovan, M., Novak, G., Platts, S., Crone, S. and Pernic, R., 1993, *Bull. Am. Astron. Soc.*, **25**, 927.

Sholomitskii, G. B., 1993, presented at the IAU Asia–Pacific regional meeting, Aug. 1993, Pune, India.

Smoot, G. F. *et al.*, 1992, *Astrophys. J. (Lett.)*, **396**, L1.

Smythe, W. D. and Jackson, B. V., 1977, *Appl. Optics*, **16**, 2041.

Sneden, C., Gratton, R. G. and Crocker, D. A., 1991, *Astron. Astrophys.*, **246**, 354.

Stacey, G. J., 1993, in 'Astronomical Infrared Spectroscopy: Future Astronomical Directions', *PASP Conf. Ser.* **41**, 297.

Stark, A. A., 1989, in 'Astrophysics in Antarctica', D. J. Mullan *et al.* (eds), *Amer. Inst. Phys. Conf. Proc.* **198**, 67.

Taylor, M. J., 1988, *Sky & Telescope*, **76**, 351.

Tilav., S. *et al.*, 1993, in *Proc. 23rd Int. Cosmic Ray Conf.*, **4**, 561.

Townes, C. H. and Melnick, G. J., 1990, *Pub. Astron. Soc. Pac.*, **102**, 357.

van Steckelenborg, J. *et al.*, 1993, *Phys. Rev.* D **48**, 4504.