ANARE Research Notes, 88, *Australian upper atmospheric and space physics research in Antarctica*, 1992, Ed: G Burns and M Duldig

29. THE POTENTIAL OF NEAR-INFRARED ASTRONOMY IN ANTARCTICA

M.G. Burton(1), D.A. Allen(1), P.J. McGregor(2)

(1) Anglo Australian Observatory
Epping Laboratory
Epping NSW 2121
Australia

(2) Mt Stromlo and Siding Springs Observatories
The Australian National University
Weston Creek ACT 2611
Australia

ABSTRACT

The highest part of the Antarctic Plateau (Dome A) holds the promise of providing a superlative site for near-infrared (IR) astronomy and, in particular, for observations in the 2.27 - 2.45 μm waveband. This is a result of the intense cold, which reduces the thermal background by 6 magnitudes compared to a mid-latitude site, the absence of OH airglow emission between these wavelengths and the minimum in the zodiacal emission which occurs in the near-IR. The prospects exist for the darkest site for astronomy at any wavelength, anywhere in the inner solar system. Some possible scientific projects to exploit this potential, particularly deep cosmological surveys, are outlined.

29.1 INTRODUCTION

During the past few years it has become increasingly evident that the Antarctic plateau may be the best site on the planet for astronomical observations at infrared (IR), sub-mm and mm wavelengths. This is a result of the combination of high altitude, extreme cold and low water vapour content of the atmosphere. The 'seeing', or atmospheric-turbulence-limited resolution, may also be exceptional. Research groups from a number of countries have now conducted astronomical experiments from the South Pole, mainly focusing on the research areas of the microwave background and cosmic rays, and their experiences confirm the general expectations that Antarctica may provide an exceptional site for astronomy. In this paper we discuss the scientific potential of the Antarctic plateau for near-IR astronomy, and some of the plans that are being made to exploit it. There are fundamental astrophysical problems which might only be tackled from Antarctica. Other papers in this volume discuss the prospects for Antarctic astronomy at other wavelengths (see Gillingham 1992, Smith 1992, Storey and Hyland 1992).

29.2 NEAR-IR ASTRONOMY

IR astronomy can loosely be described as encompassing all observations spanning the wavelength range from 1 μm to 1 mm, and is subdivided into several regimes resulting from differences in detector capability and observational difficulty with wavelength. The near-IR regime covers the 1–5 μm waveband, and several factors conspire to make it an integral part of astronomy. First is the cosmological redshift, whereby distant (and therefore young) objects in the universe recede from us at ever greater speeds and thus have their radiation Doppler shifted into IR wavelengths. Second, the extinction of light waves passing through interstellar material is vastly reduced in the IR compared to the optical, a factor of 10 between 5500Å and 2.2 μm. Hence we are able to peer into and through the numerous dark clouds of dust and gas that lie along the plane of our galaxy. We can witness star formation, which otherwise would be hidden from us, and explore the dynamic and often violent interstellar medium through the many atomic and molecular emission lines that are radiated in these wavelengths. Third, the exponential leading edge of the blackbody function, that moderates most astronomical emission mechanisms. Many types of object are intrinsically cool and radiate only in the IR and most of the photon energy of the universe is emitted in the IR. Figure 1 illustrates some of these points by showing the blackbody emission from a 300 K source and a 10 000 K body subject to 100 magnitudes of visual extinction.

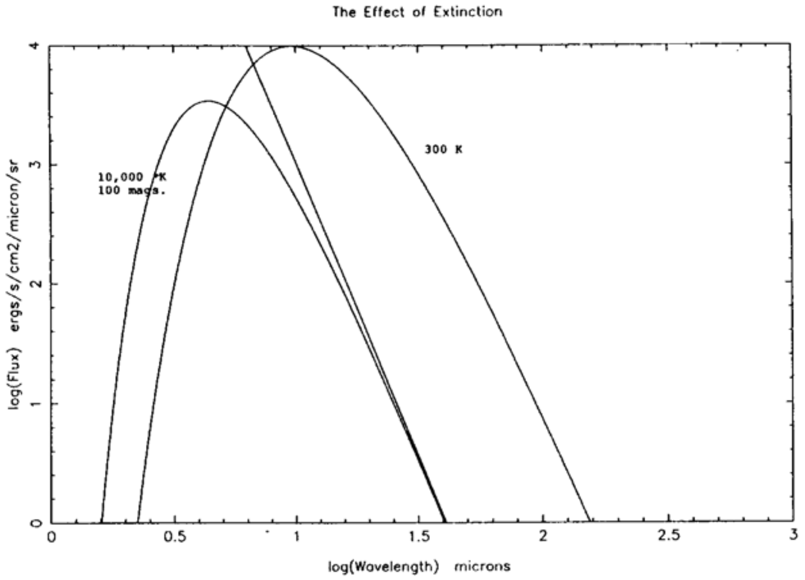

Figure 1. The Blackbody emission flux from sources at 300 K (right-hand curve) and at 10 000 *K (left-hand curve) but subjected to 100 magnitudes of visual extinction (and divided by a factor of 1000). Also shown is the intrinsic (unextinguished) emission from the 10 000 K body. The figure illustrates that both cool bodies and heavily reddened objects are observable only at IR wavelengths.*

29.3 SENSITIVITY LIMITATIONS IN IR ASTRONOMY

Three factors have been limiting the achievements of IR astronomy, as compared to the optical. These are:

1. Inferior technology
2. Poor atmospheric transmission
3. High thermal background

The first of these restrictions is now, however, receding. In the past five years, in what has been dubbed the 'infrared revolution', two dimensional array-format near-IR detectors, the equivalent of CCDs used in the optical, have replaced single element detectors and led to improvements of 10^3 to 10^4 in observational efficiencies. Although there still remains another order of magnitude improvement to equilibrate with the optical, it is realistic to expect that within the next decade IR arrays will be comparable in capability to optical CCDs. We are thus free to pursue the other two factors that limit performance.

The best IR observatories in the world are on high, dry mountain top sites, where the low water vapour content improves the atmospheric transparency over a lower altitude site and the low temperature reduces the IR thermal background radiation from both atmosphere and telescope. On the Antarctic plateau these gains are multiplied still further. Near-IR (1 – 5 μm) wavelengths lie on the Wien side of the blackbody radiation spectrum emitted by the earth. The decrease in temperature in Antarctica from a mid-latitude site results in an enormous decrease in the background. This is illustrated in Figure 2, which compares the blackbody emission fluxes in the near-IR at 273 K and 210 K, representative of a mountain top site, such as Mauna Kea, and the South Pole, respectively. The drop in the thermal emission from the sky in Antarctica is over two orders of magnitude over much of the near-IR spectrum. At longer wavelengths, although the drop in background levels are not so dramatic, the very low water vapour density over the Antarctic plateau considerably improves the atmospheric transparency, even opening some new 'windows' which are opaque at other observing sites (Smith 1992, Storey and Highland 1992).

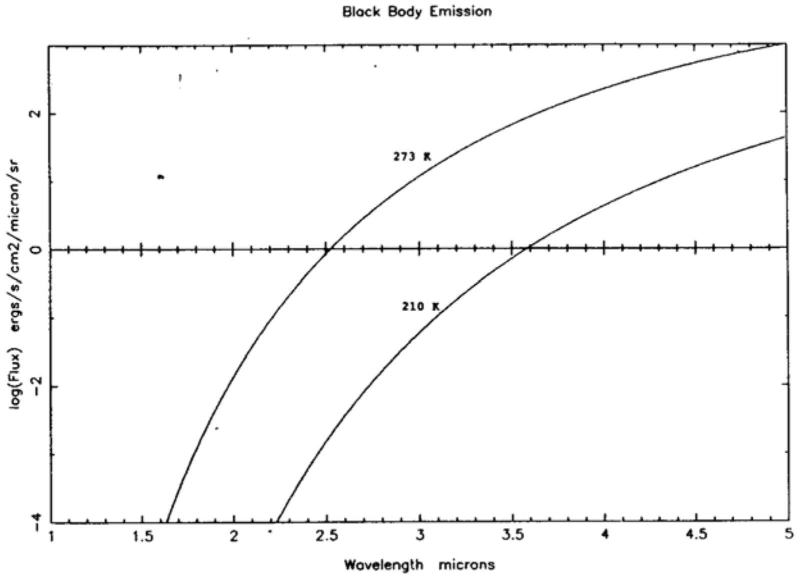

Figure 2. Blackbody emission fluxes in the near-IR (1 – 5 μm) regime for an atmosphere at 273 K (upper curve) and 210 K (lower curve), illustrating the relative thermal backgrounds at Mauna Kea and the South Pole.

In the near-IR, sensitivity is limited by a combination of airglow emission from OH radicals at altitudes of 80 – 90 km and thermal emission from the telescope and atmosphere. As demonstrated above, a small decrease in the ambient temperature results in a large decrease in the thermal background. Ultimately, if these could be reduced, we would be limited by the zodiacal emission (scattered and thermally re-emitted sunlight off solar system dust). This itself is at a minimum in the near-IR (Figure 3). Furthermore, and fortuitously, the 2.27 to 2.45 μm region is devoid of airglow emission. Model calculations (Figure 4) indicate that at the South Pole, with an air temperature of -60°C, the background is reduced by a factor of 220 from Mauna Kea, the best observing site currently in use, to a level close to the zodiacal emission itself. Even larger reductions can be expected above 4000 m, at the highest point on the Antarctic plateau (Dome A), where the temperature may drop to -90°C. The Antarctic plateau may therefore provide a site with as dark a sky background as can be found anywhere within the inner solar system.

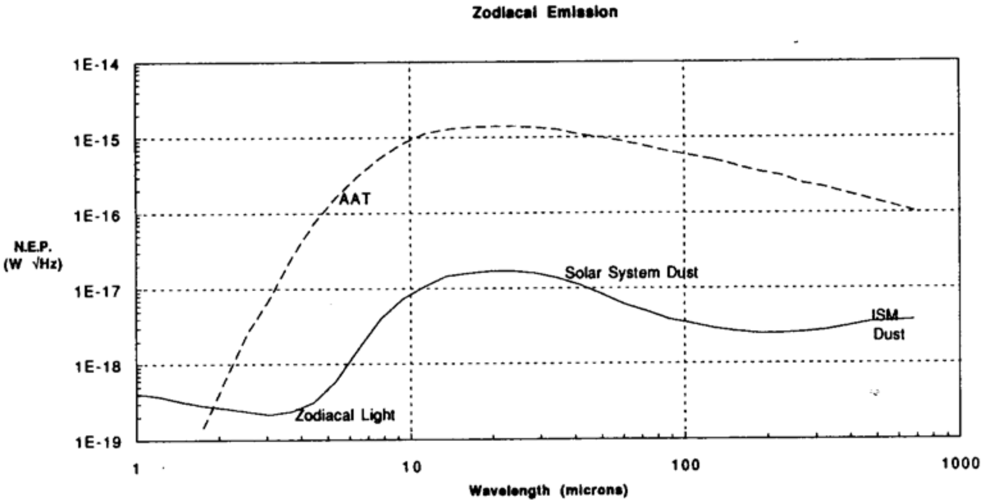

Figure 3. The Zodiacal emission in the IR, comprised of scattered sunlight off interplanetary dust in the optical and near-IR, thermal emission from interplanetary dust in the mid-IR, and thermal emission from interstellar dust in the far-IR. The minimum occurs in the near-IR regime. Also shown, for comparison, is the thermal emission from a 300 K site, representative of the background at Anglo Australian Telescope. (Adapted from Lee et al. 1990).

The reduced background can be translated into significant improvements in observing efficiencies. For a background limited observation between 2.27 and 2.45 μm, a decrease of a factor 220 in background corresponds to the following gains for a telescope in Antarctica compared to Mauna Kea (Harper 1989):

1. With the same size telescope and integration time, to observing a source 2.9 magnitudes fainter in Antarctica with the same signal-to-noise ratio;
2. To achieve the same signal-to-noise ratio on the same source, with the same integration time, requires a telescope 15 times larger in diameter on Mauna Kea;
3. With the same size telescope, to achieve the same signal-to-noise ratio on the same object, requires an integration time 220 times longer on Mauna Kea.

In other words, for such observations a 1 m telescope in Antarctica is equivalent to a 15 m telescope on Mauna Kea, with a price vastly smaller! A 1 m class telescope can be constructed from kit form, whereas building a 15 m class telescope is at the very limits of current technological capability.

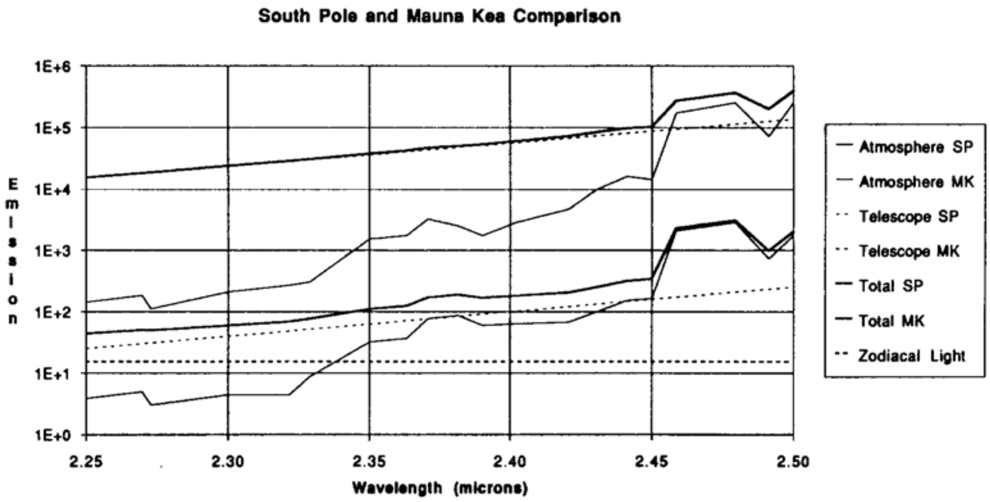

Figure 4. Comparison of the background at the South Pole (lower curves) and Mauna Kea (upper curves) in the 2.25 – 2.50 μm region. Contributions from the atmosphere are shown as thin solid lines, from the telescope as thin dashed lines and from the zodiacal light as a thick dashed line. The total background at each site is shown by the thick solid line. At the South Pole the background is close to the fundamental limit set by the zodiacal emission. (Adapted from Lubin 1988 and Harper 1989).

For the very deepest observations there is an additional and perhaps even more important gain. The ultimate sensitivity achievable depends on how accurately it is possible to flatfield the data in order to measure a signal which is a tiny fraction of the sky background. Practical experience shows that this is about 0.1% of the background level. In this case an Antarctic telescope will enjoy an advantage in signal-to-noise ratio directly proportional to the decrease in background, an improvement in limiting flux density of some 5.9 magnitudes. This has significant implications for cosmological surveys.

29.4 SCIENCE PROJECTS

Several key problems in cosmology, star formation, the physics of the interstellar medium and the galactic centre might be addressed by high sensitivity observations from the Antarctic plateau. Despite great strides in our understanding of the universe in the past few decades, major questions remain unanswered. How did galaxies form from an initially smooth and expanding primordial gas and when? How do stars actually form and what is the mass spectrum and formation rate? What is the role of the interstellar medium in regulating this process? Is there a massive black hole at the centre of our galaxy? Significant progress can be made on these issues through observations at IR wavelengths from the Antarctic plateau. Some example projects which can be tackled are described below.

29.4.1 *Early Star Formation in Galaxies*

How did the first stars form from a gas of only hydrogen, helium and a little lithium? Without dust and metals the usual mechanisms of star formation observed in our galaxy cannot operate. Molecular hydrogen must have formed at some point and the heat of gravitational contraction be radiated away through its cooling lines, mainly at mid-IR wavelengths. After the first generation of stars formed and heavy elements built up, collapsing clouds could cool through fine structure

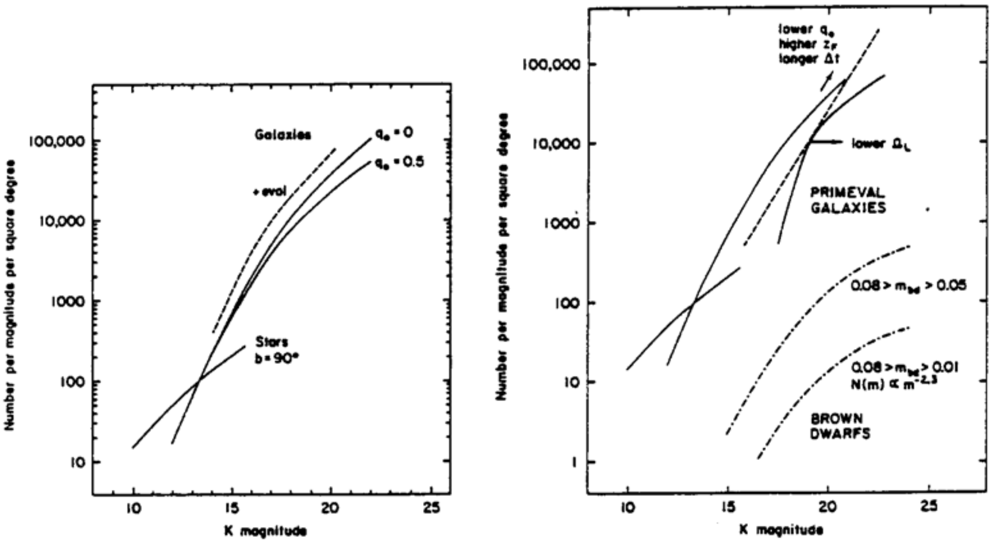

Figure 5. (a) Left. A predicted number-magnitude relation at K (2.2 μm) for stars and galaxies, as would be observed at high galactic latitude, based on K-corrections determined at low redshift and for two different cosmological models. The number counts are dominated by galaxies in the faint IR sky. For an equivalent survey, a sensitivity gain of nearly 3 magnitudes will be achieved from the Antarctic Plateau compared to Mauna Kea.

(B) Right. As for (a), but also including possible populations of brown dwarf stars and high redshift proto-galaxies. The curves for brown dwarfs represent the field populations for different mass ranges which will account for the local 'missing mass'. The dashed line for proto-galaxies represents a locus along which plausible luminosity functions will slide depending on model parameters. The very deepest surveys might reach limits 0.1% of the sky level, or 7.5 magnitudes fainter than the K = 13 magnitudes per square arcsec background of Mauna Kea. On the Antarctic plateau the background is reduced a further 6 magnitudes at K. (Both figures from Lilly and Cowie 1987.)

lines of elements such as O and C, emitted at far-IR wavelengths. For redshifts in the range z = 3 - 10, where Galaxy formation probably occurred, the peak of mean stellar spectrum can be observed at near-IR wavelengths. Deep near-IR surveys are required to search for and detect these proto-galaxies.

Figure 5(a) (Lilly and Cowie 1987) shows a prediction of the number-magnitude relation at K (2.2 μm) for stars and galaxies for a field at high galactic latitude, extrapolated from measurements at shorter wavelengths and lower sensitivity. Galaxies will clearly dominate any faint survey. Assuming a sensitivity improvement of 2.9 magnitudes over a similar survey conducted from Mauna Kea, as discussed above (i.e. with the same size telescope and integration times), an order of magnitude more sources will be detected for the same effort.

For the very deepest survey of a small region we may expect to do even better. A practical limit to such a survey is 0.1% of the sky background, which for Mauna Kea, where the background is K = 13 magnitudes per square arcsec, corresponds to K~20.5. On the Antarctic plateau, if we are able to achieve such a limit, this would take us down by a factor of 220, to K~26.5! In Figure 5(b) (Lilly and Cowie) are shown the same number-magnitude relation predictions but this time including contributions from possible brown dwarf stars, postulated to account for the 'missing mass', and from high-redshift proto-galaxies. It is clear that with these sensitivity levels, not only are the prospects of discovering orders of magnitude more proto-galaxies than from Mauna Kea excellent but that a significant number of brown dwarfs would be detected too, if they exist. The brown dwarf yield for a similar survey from Mauna Kea is too low to result in a significant chance of detection.

29.4.2 Formation of Stars and Planets

Some of the nearest and richest star forming regions lie in the southern sky and their embedded stars are only observable at IR wavelengths. In the near-IR the extinction is at most a few magnitudes to such regions and the sensitivity high enough that a complete population census of the cluster membership of several nearby star forming regions, such as Rho Ophiuchus and R Coronae Australis, can be undertaken to determine the distribution and range in mass of the young stars. The strongest lines from shocked and fluorescent molecular hydrogen, which trace the energetic activity associated with young stellar objects, are also emitted near 2.4 μm.

29.4.3 The Galactic Centre

The study of the stars at the centre of our galaxy is the domain of IR astronomy, as they are totally obscured by intervening gas and dust in the visible. The stars are readily apparent by 2.4 μm, but the region is so crowded at the highest spatial resolutions achieved that we still do not know what lies at the very centre of our galaxy. With the prospects of super-seeing, combined with high sensitivity at 2.4 μm, we may hope to understand the nature of the galactic nucleus.

29.5 CURRENT PLANS

A number of countries have expressed interest in Antarctic astronomy and undertaken exploratory experiments. The most developed plans come from the Center for Astrophysical Research in Antarctica (CARA) in the USA, which has been funded and has initial plans for three telescopes at the South Pole; a sub-millimetre telescope, a cosmic background microwave detector, and a near-IR telescope. The latter, the South Pole Infrared Explorer (SPIREX), is a 60 cm transportable telescope which will be used with a near-IR array camera and spectrometer and is designed to exploit the minimum of zodiacal emission in 2.27 - 2.45 μm window. There are only proto-designs at present, however, for a 2 m-class telescope, which also offers the potential of benefiting from 'super-seeing', as well as from the low background in the near-IR and yet remains relatively simple to construct.

29.6 SUMMARY

The combination of extreme cold and minimal atmospheric water vapour content mean that the summit of the Antarctic plateau (Dome A) might prove to be the preeminent site on the Earth for astronomical observations across the entire IR and sub-mm wavebands with superior atmospheric transparency and reduced background to any other site on the Earth. The thermal background in the near-IR is reduced by over two orders of magnitude from mid-latitude sites like Mauna Kea. In particular, in the 2.27-2.45 μm regime, devoid of atmospheric airglow emission, observations will be limited only by the natural zodiacal background which is itself at a minimum in this region. Thus, the background against which observations must be made is at a minimum for a site anywhere within the inner solar system. This offers us an unprecedented window to peer out upon the universe and pursue fundamental astrophysical problems in star formation and cosmology.

REFERENCES

Harper, D.A. (1989). Infrared astronomy in Antarctica. In: Mullan, D.J., Pomerantz, M.A. *and* Stanev, T. (Eds). Astrophysics in Antarctica. *American Institute of Physics Conference Proceedings 1988*. Pp. 123 - 129.

Lee., T.J., Hawarden, T.G., Thronson, H.A., Mountain, C.M., Davies, J.K. *and* Longair, M.S. (1990). Radiatively cooled telescopes for infrared space astronomy. *Proceedings of the 24th Liege International Astrophysical Colloquium, July 1990, ESA SP 314:373* - 379.

Lilly, S.J. and Cowie, L.L. (1987). Deep infrared surveys. In: Wynn-Williams, C.G. *and* Becklin, E.E. (Eds). *Infrared Astronomy with Arrays*. Pp. 473 - 482.

Lubin, D. (1988). Masters Thesis. University of Chicago.