30. THE POTENTIAL FOR MID-INFRARED ASTRONOMY FROM ANTARCTICA

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ABSTRACT

The Antarctic plateau, with its very dry and cold atmosphere, presents a number of advantages for astronomy in the thermal infrared region. With atmospheric temperatures 60 - 80° below zero, the thermal background drops by a factor of 5, compared with the best currently available observatory sites (e.g. Mauna Kea). More importantly however, the extremely low precipitable water vapour content in the Antarctic atmosphere (200 – 600 μm) means that the accessible region of the spectrum extends virtually all the way to 60 μm, compared with the almost complete cutoff at 22 μm for currently available observing sites. While the potential gains are significant, there are also some potential drawbacks, such as ice 'haze'. It is essential that site testing begin as soon as possible to determine the reality of the benefits from siting a telescope in Antarctica.

30.1 INTRODUCTION

For astronomical purposes the infrared (IR) spectral regime (1 – 500 μm) is generally divided into three parts:

Near-IR	1 – 5 μm
Mid-IR	5 – 60 μm
Far-IR	60 – 500 μm

This paper discusses some of the problems and possible solutions that are particular to the mid-IR.

The mid-IR is also called the thermal-IR, as it sits at the peak of the Planck function for a room temperature black body. Unfortunately, this makes the mid-IR one of the least sensitive spectral regions in which we can work, as the thermal background is higher here than any other part of the spectrum. In fact, if it wasn't for a host of interesting and important astrophysical phenomena which manifest themselves in the mid-IR we may not bother trying to use this spectral region at all. By way of an example, the astronomical sources that we observe are generally orders of magnitude fainter than the background due to the 'warm sky' and telescope.

The high background however, is not the only problem that besets us. The mid-IR (as are the near- and far-IR) is further sub-divided by atmospheric transparency effects, or atmospheric windows. At low altitude (< 2000 m) terrestrial observing sites, only the region from 8 – 13 μm is workable but from better sites (>2000 m) the region from 16 – 22 μm is also accessible.

These 'windows' are largely defined by the transparency (or rather, lack of it) of atmospheric CO_2 and H_2O, although other atmospheric gases also play their part. $C0_2$ is fairly uniformly distributed throughout the atmosphere and has a scale height of about 6 km. H_2O however, resides mainly in the lower regions of the atmosphere, and has a scale height of around 2 km. There is not much that can be done about $C0_2$ absorption other than observe from above the atmosphere with space-borne observatories such as IRAS, ISO and SIRTF. There are, however, some less expensive solutions to the water vapour problems.

So, the two major factors which limit ground based mid-IR astronomy at present are:

(a) the thermal background and
(b) the atmospheric transparency.

Mid-IR astronomy from Antarctica offers improvements in both of these areas.

30.2 THERMAL BACKGROUND

In a modem IR (photo conducting) array detector, the noise photocurrent (i_n), per beam, is defined as:

$$i_n = \left[NR^2 + 2G\left(i_s + i_{bg} + i_{dc}\right)T\right]^{1/2} e^- / s \qquad (1)$$

where i_s = signal photocurrent
i_{bg} = background photocurrent
i_{dc} = dark current
NR = read noise
G = photoconductive gain
T = temperature

The factor of 2 arises from both generation and recombination photo-electron noise in the detector.

We calculate the signal (photocurrent) as:

$$i_s = \frac{\eta\, G\, \tau\, A\, F_\lambda}{\frac{h}{2\pi}} \frac{\Delta\lambda}{\lambda} \qquad (2)$$

where η = detector quantum efficiency
τ = transmission by sky, telescope and instrument
A = telescope collecting area
F_λ = incident flux
$\Delta\lambda$ = band width
λ = observation average wavelength

and using typical numbers at a 4 m telescope this signal current is around 10^4 e^-/s.

The photocurrent due to the background is

$$i_{bg} = \frac{\eta \, G \, \varepsilon \, B(\lambda, T) \, A \, \Omega}{\frac{h}{2\pi}} \frac{\Delta\lambda}{\lambda} \; e^- / s \tag{3}$$

where ε = emissivity of sky and telescope
Ω = beamsize solid angle
$B(\lambda,T)$ = Planck function for λ,T

The emissivity of sky and telescope is typically about 15% and i_{bg} amounts to $10^9 - 10^{10}$ e^-/s at 10 µm and T ≅ 273K.

In the mid-IR the read noise and dark current are generally negligible compared with the background i.e. a few 100 – 1000 e^-/s: this is also true of the signal photocurrent. The system noise is therefore dominated by photon shot noise from the sky background.

So, ignoring i_s, i_d, and NR the system noise reduces to:

$$i_n = \left[2 \, G \, i_{bg} \, T \right]^{1/2} \; e^- / s \tag{4}$$

and substituting for i_{bg} gives:

$$i_n = G \left[\frac{2 \, T \, \eta \, \varepsilon \, B(\lambda, T) \, A \, \Omega}{\frac{h}{2\pi}} \frac{\Delta\lambda}{\lambda} \right]^{1/2} \; e^- / s \tag{5}$$

The noise is clearly a maximum in the mid-IR as B(λ,T) peaks here, for a room temperature blackbody. Given our estimates of i_s and i_{bg}, the typical signal is around 10^{-5} of the background.

A further problem with modem IR array detectors is that the detector well depth is generally limited to $10^5 - 10^7$ e^-/s and so with an i_{bg} of 10^{10} e^-/s we must read the array between 10^3 and 10^5 times per second in a broad band imaging mode. These detectors (with formats typically 128^2 or 256^2) have around 16000 and 65000 elements and so we need to be able to read individual pixels at around $1.6 \times 10^7 - 6.5 \times 10^9$ per second to avoid well saturation and this requires some fast readout electronics. This is only a technical problem and is already being resolved but the fast read rate can lead to non-negligible values for the read noise.

Another problem is that most mid-IR detectors show a non-white noise component in their noise, the origin of which is still a mystery, although carrier bunching and current noise at edge contacts have been suggested as possibilities. This introduces a component of noise that is proportional to the background, at least in high background conditions. Going to a lower background does help to reduce this effect.

Generally then, most mid-IR detectors fall short of being background limited by a factor of between 2 and 4, even though the general misconception is that the mid-IR is background limited. However, these last two problems are not fundamental and detector development and refinement is continuing. By the time a telescope is constructed in Antarctica these problems will hopefully have been resolved and any reduction in the thermal background will be fully utilised.

Ideally, to minimise noise, we would put telescopes in space where there is no thermal background from the sky and we could cryogenically cool the telescope. This however, is difficult and expensive for any reasonable size telescope and the lifetime of a cryogenically cooled telescope is always limited (e.g. IRAS, ISO, SIRTF). Next best are stratospheric aircraft, which get to heights of around 12 km above the earth and precipitable water vapour of 7 μm (e.g. KAO and SOFIA), although these observatories also suffer many of the problems of space borne telescopes, such as size, limited duration and expense. At the proposed observatory site in Antarctica, with an altitude of over 4000 m and telescope/sky temperatures of around 210 – 220 K there is a significant reduction in the thermal background at 10 μm (factor of 5), although this is not quite the spectacular gain available in the near-IR. Table 1 shows the ratio of background flux at 273 and 213 K at a number of infrared wavelengths. Also indicated is the reduction of limiting flux commensurate with the reduced background at the lower temperature.

Table 1. Effect of temperature on thermal background.

Wavelength (μm)	2.4	5	10	20	40	60
B(l, 273 K)/B(l, 213 K)	480	20	4.4	2.2	1.6	1.2
Reduction in limiting flux	22	4.5	2	1.5	1.25	1.1

Clearly there will be some gains (a factor of ~2 in S/N) at 10 μm but at wavelengths longer than 10 μm the reduction in thermal background becomes less significant. While these gains are valuable we would need to build a rather large (> 4 m) telescope in Antarctica to compete with the modern 8 and 10 m class telescopes being proposed and constructed elsewhere.

One potentially serious problem for mid-IR astronomy with an Antarctic telescope is the possible presence of ice haze, i.e. any suspended icy crystals, which cause observed phenomena such as sun haloes and sun dogs. If such icy crystals have optical depths of as little as 1% then the sky/telescope background (nominally 10%) increases by ~10%. While this increase may not seem catastrophic in itself, it represents something like 1000 times the limiting flux and any temporal or spatial structure in the haze/cirrus could easily negate the gains derived from the cold site. At present however, we do not have any firm data on the frequency or composition of the ice haze and so we clearly have a need for some proper site testing at the proposed observatory site before any informed decision can be made about the suitability of the Antarctic for mid-IR astronomy.

30.3 ATMOSPHERIC TRANSPARENCY

Thermal background is not the only factor and it is in atmospheric transparency that Antarctica wins out over any other terrestrial observatory. As noted previously, the main culprits in reducing atmospheric transparency are CO_2 and H_2O and there is little we can do about CO_2 from ground based observatories. We can however, beat down the effects of water vapour by going to a high, cold site. High to get above the water vapour and cold to minimise the amount of precipitable water vapour in the remaining atmosphere.

At the proposed observatory site in Antarctica (Dome A) the altitude is >4000 m, and the temperature is around -60°C. Under these conditions the precipitable water vapour (PWV) drops to around 500 μm in the Antarctic summer and 250 μm in winter, compared with ~2 mm on a

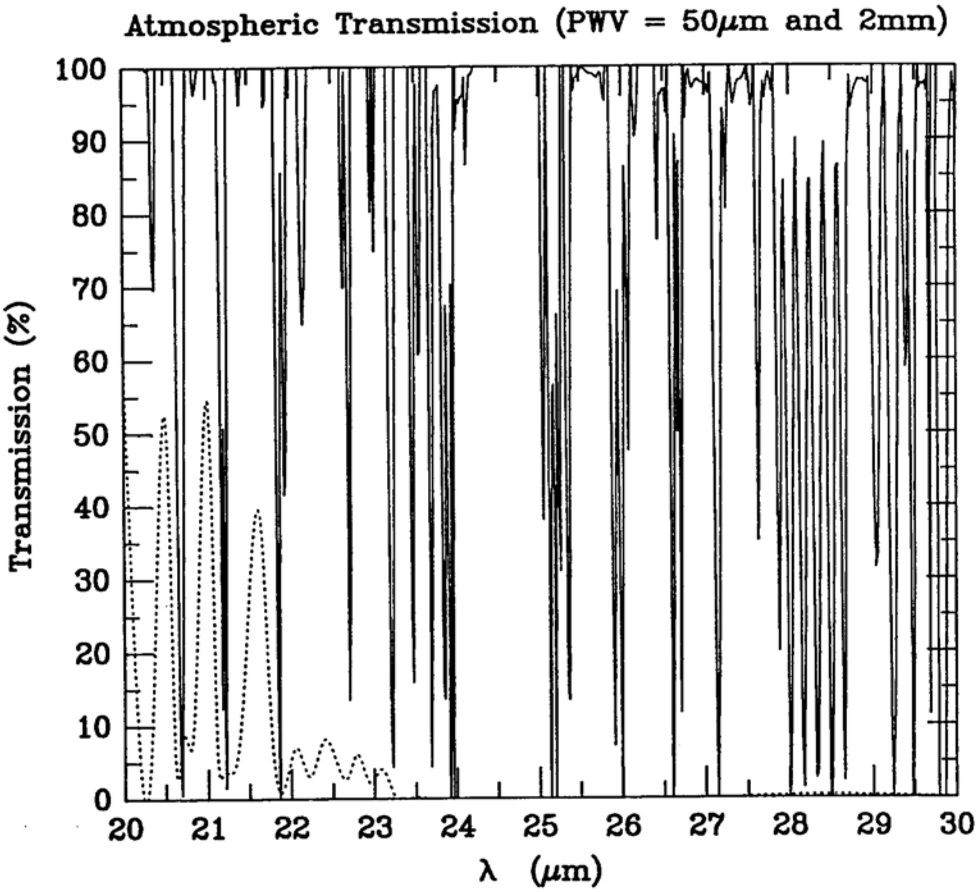

Figure 1. Atmospheric transmission curves for precipitable water vapour content of 50 μm (solid line) and 2 mm (dotted line) in the 20 – 30 μm wavelength region. Fifty μm PWV represents a 'good' day in Antarctica, and 2 mm PWV represents a 'good' day at a site like Mauna Kea. The improved transmission under Antarctic conditions is dramatic.

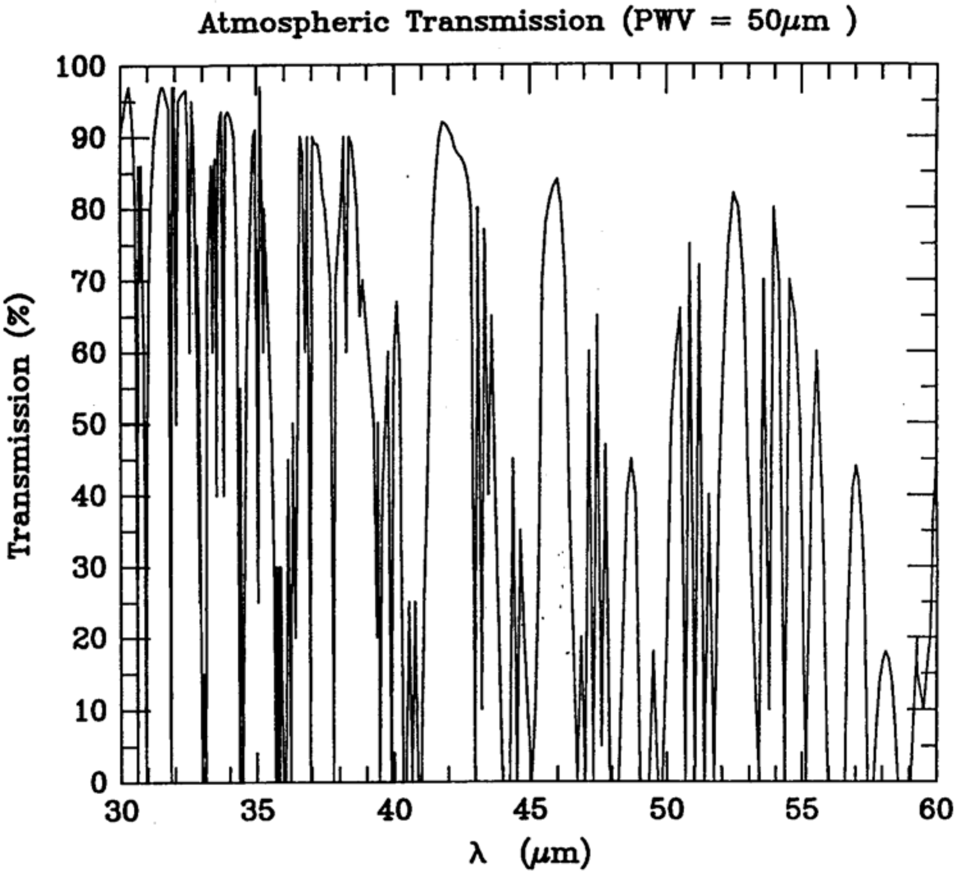

Figure 2. Atmospheric transmission curve for precipitable water vapour content of 50 μm *in the 30 - 60* μ*m wavelength region. Observations in this waveband are not possible from any other terrestrial observatory. While the transmission is still 'patchy, even at these low PWV levels, this spectral region would undoubtedly be useable for continuum and some line observations.*

good day at Mauna Kea, the best mid-IR observing site currently available. This leads to significantly improved transparency wherever water vapour is the limiting factor. Furthermore, the measurements of PWV that have been made in Antarctica were with radiosonde balloons and it seems there is a possibility that this measurement technique overestimates the PWV under Antarctic operating conditions. The PWV may well be even lower than the values adopted here, but again there is a need for site testing to determine the real PNW values.

Based on the currently available PWV estimates, we should be able to achieve photometry and polarimetry right out to 50 – 60 μm, whereas the previous limit is about 23 μm from Mauna Kea and 13 μm at the Anglo-Australian Telescope. Even in the 8 – 13 μm region the improved transparency will lead to meaningful spectra with 0.1% accuracy, free from telluric residuals, which is vital when trying to determine the detailed spectral structure.

The most significant gain however, may be in opening up spectral regions with previously unobservable, though important, spectral, atomic, ionic and molecular transition lines. Figures 1 and 2 show calculated atmospheric transmission curves from 20 – 60 μm for PWV of 50 μm and 2 mm. 50 μm PNW is perhaps a little optimistic for Antarctica, but possibly represents a 'good' day, and 2 mm PWV represents a good day at a site like Mauna Kea. Figure 1 clearly shows how the transmission falls rapidly to zero longward of 22 μm at common astronomical sites (i.e. PWV in the mm range), whereas the improved transmission under Antarctic conditions is dramatic. The transmission from 30 – 60 μm is still patchy, even under 'good' conditions, but quite useable for continuum work and line observations provided the desired line falls in one of the 'windows'. Some of the astronomically interesting spectral lines and their observability at various telescope sites are listed in Table 2. Access to these lines via an Antarctic telescope would be most valuable, though it is prudent to remember that all of the listed lines, including the 'No and Maybes' are already observable by the Kuiper Airborne Observatory (KAO), where the precipitable water vapour is around 7 μm. The disadvantages of the KAO of course are the small telescope aperture, the shorter integration times possible and the limited access for Australian astronomers. There is little improvement in transmission between 12 and 22 μm as the lack of transparency in this region is largely attributed to atmospheric CO_2.

Table 2. Observability of some mid-IR spectral lines (AAT = Anglo-Australian Telescope, MKO = Mauna Kea Observatory).

Spectral line	Wavelength (μm)	Observatory Site AAT	 MKO	 Antarctica
Ar III	9.00	Yes	Yes	Yes
S IV	10.52	Yes	Yes	Yes
C IV	11.70	Yes	Yes	Yes
Ne II	12.81	Yes	Yes	Yes
Ne III	15.56	No	No	No (CO_2)
S III	18.71	No	Yes	Yes
Ne V	24.28	No	No	Yes
O IV	25.87	No	No	Yes
S III	33.66	No	No	Yes
O III	51.81	No	No	Maybe
N III	57.33	No	No	Maybe
O I	63.17	No	No	Yes
H2 S(2) $J = 4 \rightarrow 2$	12.28	Yes	Yes	Yes
H2 S(l) $J = 3 \rightarrow 1$	17.03	No	Yes	Yes
H2 S(0) $J = 2 \rightarrow 0$	28.22	No	No	Maybe

30.4 CONCLUSION

There are significant gains to be made in both reduced thermal background and atmospheric transparency from siting a telescope in the high, cold, dry site of Dome A in Antarctica. If there were a telescope in Antarctica, we could undoubtedly gain good service from it in the mid-IR and probably improve sensitivity by about a factor of 5 when the reduced background and the improved transparency are considered, not to mention the increased spectral coverage and the new lines that this would allow us to observe. There are also some potential losses too and it is imperative that some site testing is commenced as soon as possible to determine whether the suggested gains are real.

Certainly, most of the gains for the mid-IR in Antarctica could also be achieved by a combination of the new generation of large telescopes and KAO/SOFIA airborne observatories, without the serious loss of sky coverage that must occur with an Antarctic based telescope. Of course, Australian astronomers do not have formal access to any of these facilities at present, although participation in such projects should be seriously considered. Nonetheless, an Australian Antarctic telescope, or at least a share in a telescope (with an aperture >2 m), could fulfil most of our requirements for Southern Hemisphere mid-IR astronomy for the next decade.