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Opportunities in Infrared Astronomy from Dome C

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Abstract. Infrared astronomy has come to maturity over the last 5 years with the availability of large format near-infrared detectors and sophisticated instruments mounted on 8 to 10-m telescopes. These will be followed by more capable second generation instruments before the end of the decade. Deep infrared surveys will begin next year following upon the 2MASS and Denis surveys with the UKIRT and CFHT IR cameras and the VISTA instrument in 2006. At mid-infrared wavelengths, imagers and spectrometers are becoming available on 8-m telescopes while SIRTF is due to be launched later this year. In the longer term, ambitious space missions such as the Next Generation Space Telescope operating in the infrared will be launched. Here, I review the current capabilities and developments in infrared astronomy and compare these to the opportunities presented by development of antarctic sites. It seems that the greatest opportunity for major scientific impact will come either from continuous monitoring campaigns permitted by Antarctica's location or from dedicated observations in the 3–5 μm wavebands where the low thermal background gives very significant advantages over existing mountain-top sites. A telescope with a diameter >2 m is needed to realise sensitivities greater than those offered by existing 8 m telescopes.

Key words. Infrared Astronomy – Infrared Background – Instrumentation

1. Introduction

Infrared observations are now at the core of many astronomical programmes. Cool objects, such as low mass stars and planets, emit strongly in the infrared wavebands. Extinction due to interstellar dust, which obscures many objects at visible wavelengths, decreases rapidly with increasing wavelength. Transitions from vibrational and rotational states in molecules and dust grains become accessible and the redshift effect means that we detect emission from short wavelength transitions in distant objects in the infrared. Breakthroughs in astronomy often result from the application of new techniques or instruments which provide gains in sensitivity, depth, resolution, or area coverage, and opportunities to

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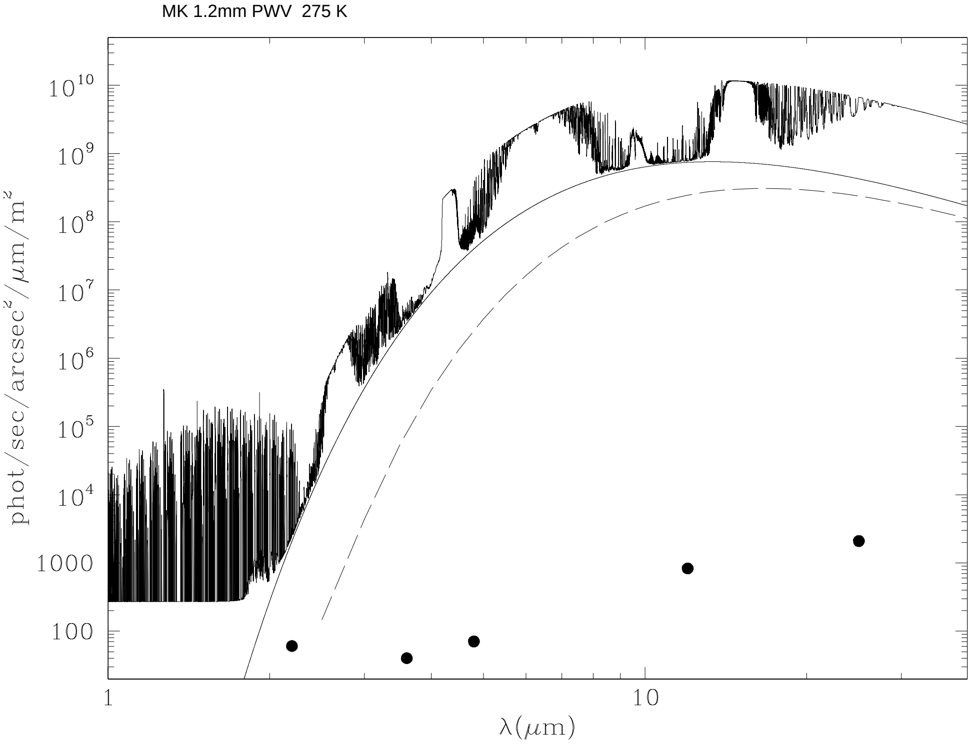

Fig. 1. A model of the infrared photon flux from the atmosphere above Mauna Kea, Hawaii at a temperature of 275 K is shown together with that from the telescope and instrument with a combined emissivity of 7% (Roche & Glasse (1990)). The contribution from the telescope and instrument is taken to follow a Planck curve and is shown by the lower smooth curve. At wavelengths below 2 μm, the dominant emission is from strong narrow airglow emission lines at low spectral resolution, but the interline continuum is at a much lower level and covers most of this spectral region at spectral resolving powers R >2000. At longer wavelengths thermal emission dominates and peaks near 13μm. A 7% emissivity Planck curve at a temperature of 220 K is shown as a dashed line to indicate the much lower thermal background levels that could be achieved from Dome C, where the flux is lower by factors of ∼4 at 10 μm, ∼14 at 4.8 μm and ∼30 at 3.8 μm. The zodiacal background fluxes appropriate for cooled space telescopes are shown as large filled circles.

test new ideas. The ambitious and complex instruments exploiting large format detectors that have been delivered to large diameter telescopes over the last few years, and are anticipated in the next 5 years, mean that ground-based infrared astronomy will reach maturity with sensitivities approaching the ultimate attainable from the existing telescope sites (e.g. Bergeron & Monnet (2001), Simons et al. (2003)). Improved detector performance has led to increased sensitivity, expecially for observations at high spectral resolution where the detector noise properties become increasingly important. At the same time, larger detector formats, with buttable 2k x 2k detectors, have become available at near-infrared wavelengths with the promise of mosaics up to 4k x 4k pixels and beyond. These larger area detectors permit wider field and/or higher spatial resolution imaging instruments and higher spectral resolution and/or greater wavelength or spatial coverage for spectrographs. At longer wavelengths, the detector formats available have increased more slowly, but large gains in sensitivity have been realised by coupling mid-infrared detectors to large aperture (8 m and 10 m diameter) telescopes. Whilst blurring from atmospheric 'seeing' dominates the delivered image size at short wavelengths, diffraction by the telescope aperture imposes a lower limit to the image size at long wavelengths. Because of the reduced diffraction limit, 8-m class telescopes can deliver images of half the angular width of 4-m telescopes at wavelengths greater than ~6 μm under good seeing conditions. This means that the sensitivity of measurements at thermal infrared wavelengths improves dramatically with telescope aperture, scaling as D^2 for point sources, and giving large gains in sensitivity with large aperture telescopes for observations of compact objects.

2. Current Developments in Infrared Astronomy

2.1. Ground-Based Telescopes

Infrared astronomy undertaken from ground-based sites is confined to atmospheric windows of good transmission. At several wavelengths between 1 and 25 μm, the atmosphere is opaque, with almost complete absorption between 30 and 200 μm. Radiation absorbed by molecules in the Earth's atmosphere is re-emitted in the infrared, producing an emission spectrum at the characteristic temperature of the atmosphere, which is typically between 270 and 285 K on the high mountain summits in Hawaii and Chile (see Fig. 1) For most observations made from the Earth, the dominant source of background emission arises from airglow in the upper atmosphere or from thermal emission from the sky and telescope. The sensitivity achieved for measurements of faint astronomical objects is limited by the light collected from the astronomical target which increases as the square of the telescope diameter, divided by the noise associated with the background emission. The sensitivity achieved can be expressed as the signal to noise ratio which goes as:

$$S/N \propto D\sqrt{t_A t_i}/\theta\sqrt{\epsilon}$$

where D is the telescope diameter, θ the delivered image size, ϵ the background emission from the sky and telescope, and t_A and t_i the throughputs of the atmosphere and the instrument and telescope respectively. In practice, the field of view covered by the instrument and the detector properties and formats are often very important parameters in determining the effectiveness of the instrument for specific programmes. For maximum sensitivity, we require clean, low-emissivity, large-aperture telescopes on cold, dry, stable, cloud-free sites. This is reflected in the profusion of large aperture telescopes built or under construction on the best developed mountain top sites in the northern and southern hemispheres. The Keck 10m diameter telescopes were completed on Mauna Kea in 1993 and 1996, and have since been joined by the Gemini-North and Subaru 8 m telescopes. In Chile, the four 8 m VLT telescopes operated by ESO were joined by the Gemini-South 8 m telescope in 2001. Under the best observing conditions from these high mountain tops, the column of precipitable water vapour above the site falls below 1mm and the temperature can drop below 0 C.

At wavelengths longer than 2 μm, the dominant source of background is the thermal emission from the atmosphere above the site, the telescope optics and the instrument window. In the most transparent atmospheric windows, near 2.2 μm, 3.7 μm and 10.5 μm, the atmospheric emission is very low and can have an effective emissivity ¡1% under the best conditions. Careful design to ensure that the detectors see minimal warm emissive structures together with particular attention to cleanliness is required to minimise the emissivity of the telescope and the instrument warm optics to take maximum advantage of the low atmospheric background. In practice, telescope emissivities below 5% have been difficult to maintain, but regular mirror cleaning programmes and the development of robust protected silver mirror coatings will reduce the emissivity further over the coming years. However, even the most optmistic estimates for the telescope emissivity indicate that the thermal emission from the telescope and instrument will be higher than that from the atmosphere in the most transparent atmospheric windows. In turn, this means that the ultimate sensitivity of observations will be determined by the telescope and instrument emissivity, which places a premium on high reflectivity coatings and maintaining cleanliness during operations. The 8-m class telescopes are equipped with comprehensive optical/infrared instrumentation, with further enhancements planned over the next few years. Most of the exisiting instruments exploit fields of $<$ 1 arcmin at 10 and 20 μm and up to a few arcmin at 1–5 μm for imaging, spectroscopy and/or polarimetry. The availability of large format detectors (4k x 4k) is leading to ambitious new instruments with larger ($\sim$8 arcmin) field imagers at 1–2.5 μm. These instruments could be available by $\sim$2006. Design studies are underway for near infrared multi-object spectrographs based upon multiple deployable integral field units to obtain areal spectroscopy over 20–40 regions each of $\sim$3 x 3 arcsec, primarily aimed at collecting deep spectra of faint high redshift galaxies. These spectrographs will operate at resolving powers of R$\sim$5000 to allow maximum sensitivity in the low-background regions between the bright OH airglow emission lines, and will attain sensitivities within a factor of a few of those achievable from space. Mid-infrared instruments operate over much smaller fields and use a chopping technique where the secondary mirror is tilted rapidly about the axis to chop between two nearby positions ($\sim$30 arcsec) on the sky to minimise the effect of atmopheric emission fluctuations. This leads to high sensitivity for compact objects, with detections at flux levels below 1 mJy at 10 μm (e.g. Perlman et al. (2001)), but the relatively small chop displacement compromises measurements on angular scales $>$30 arcsec. Adaptive optics can provide real time compensation for turbulence in the Earth's atmospheres to deliver image qualities approaching the diffraction limit at infrared wavelengths over narrow ($<$30 arcsec fields), with planned developments to increase the field of view to $\sim$1.5 arcmin using multiple laser guidestars and deformable mirrors. The spatial resolution delivered on 8 m telescopes is $<$0.1 arcsec at $\lambda < 2$ μm, but at the penalty of decreased throughput and increased thermal background from the additional optical components. Very high order AO systems which concentrate more than 90% of the light into the diffraction-limited image core, are being proposed for use with imagers and coronagraphs for planet detection around nearby bright stars.

2.2. Near-Infrared Surveys

With the advent of the 8 m telescopes, several 4 m telescopes are introducing wide field cameras to undertake near-IR survey programmes. These include 1–2.5 μm cameras on the UKIRT, CFHT and NOAO telescopes in the northern hemisphere and the VISTA telescope in Chile with fields of hundreds of square arcminutes. These surveys will use substantial fractions of the available observing time over the next few years and will build upon, and go several magnitudes deeper than, the pioneering surveys undertaken by the 2 μm sky survey in the 1960s, and the 2MASS and DENIS surveys undertaken over the last few years. Strategies vary among the teams but, for example the UKIRT programme, UKIDSS, includes an ultradeep extragalactic survey to K = 23 mag over 0.7 degrees, a deep survey to K=21 mag and wide field surveys to K$\sim$ 20 mag (see Warren & Lawrence (2003)). These surveys will identify hundreds of thousands of objects for spectroscopic follow-up as well as complementing deeper imaging over smaller fields with 8-m telescopes. A parallel development that may be of interest for Antarctic programmes is the deployment of 2 m Robotic Telescopes in Hawaii, La Palma and Australia (e.g. Steele (2001)). These telescopes will initially be instrumented with optical CCD cameras. In addition to monitoring programmes for professional astronomers, they will devote large amounts of observing time to projects for schools and public outreach.

2.3. Infrared Interferometry

Following on from techniques developed at radio frequencies, light from arrays of physically separated telescopes can be combined coherently to gain high spatial resolution from the the long baselines separating the individual telescopes. These techniques have been demonstrated on small-scale prototype arrays (e.g. COAST; Haniff & Buscher (2001)), but are now moving into full scale facilities including those on Cerro Paranal (the VLTI) and Mauna Kea (the Keck interferometer), which will combine beams from 2-m class telescopes with the 8 m or 10 m telescopes, and on Magdalena Ridge. The technology needed to implement interferometry at these sites is formidable, with multiple beam combiners and real-time pathlength compensation, requiring highly controlled motion of optical relays. Each telescope has to be equipped with an Adaptive Optics module to maintain coherence across the beam, and here there may be an interesting potential for improved performance from Dome C. The stable atmosphere, with relatively low turbulence from the upper layers (Travouillon et al (2003)) is potentially a very attractive feature for interferometry, not only reducing the requirements for the AO modules on the individual telescopes, but also potentially increasing significantly the isoplanatic patch within which bright phase-reference sources can be located to allow long integrations on faint objects

2.4. Space-based IR Astronomy

Satellites above the turbulence, emission and absorption from the Earth's atmosphere have many advantages over ground-based facilities. They can provide access to the whole elecromagnetic spectrum, can deliver diffraction-limited resolutions and with a cooled telescope, can have low levels of background emission, limited by zodiacal emission from interplanetary dust grains in the mid-infrared and the diffuse background at shorter wavelengths. This leads to backgrounds up to 6 orders of magnitude lower than a ground-based telescope in the mid-infrared, but less than a factor $\sim$10 lower for spectroscopic observations in the 1–2 μm region (see Fig. 1). However, the apertures of telescopes launched into space have been restricted by rocket payloads, with the result that the cryogenic telescopes cooled by liquid helium tanks in the IRAS and ISO missions launched in 1983 and 1995 had telescope diameters of only 60cm, while SIRTF due to be launched later in 2003 has an 85cm aperture, and ASTRO-F has a 67cm aperture telescope due for launch in 2004. These relatively modest (by current ground-based telescope standards) apertures limit the spatial resolution to $>$3 arcsec at 10μm, but because of the very low background from the telescope optics, (which are cooled to temperatures of $\sim$5 K), they still have much greater sensitivity at mid-infrared wavelengths than the ground-based 8 m telescopes by 2 or more orders of magnitude. In a real sense, space and ground-based facilities are complementary with the former delivering huge advantages in sensitivity, especially for weak, extended emission, and the latter offering higher spatial resolution for probing the structure of relatively bright, compact objects or those extended on scales of a few arcsec such as circumstellar disks around newly formed stars. Current plans for space missions include the successor to the 2.4 m Hubble Space Telescope, the James Webb Space Telescope with a 6 m class primary mirror and instruments operating in the infrared wavebands. This satellite will combine the advantages of high sensitivity and high spatial resolution for the instrument capabilities that are available when it is launched in ∼2012. We should bear in mind however, that some uncertainty must remain over the performance of a space telescope until it has been launched and begins operations. The Wide-Field Infrared Explorer satellite, WIRE, was launched in 1999, but the mission failed when all the coolant was evaporated during initial check-out. It is obviously important to maintain awareness of space missions, but equally important not to allow a kind of planning blight to set the agenda for science programmes because of concerns that a particular mission may be selected. A thermal infrared survey mission WISE, operating between 3.5 and 23 μm is currently being evaluated by NASA as a possible MidEx mission; a decision is expected in 2004.

2.5. IR astronomy from Aircraft and Balloons

Many of the pioneering measurements in the far-infrared were made with telescopes suspended below high altitude balloons or in aircraft such as the Kuiper Airborne Observatory (e.g. Larson (1995)). The balloon borne instruments have largely been superseded by satellites, although they are still used very effectively for observations of the cosmic microwave background. The KAO housed a 90cm diameter telescope which was operated for more than 20 years before being decommissioned to make way for SOFIA, the stratospheric observatory for infrared astronomy. This will provide a 2.5 m telescope in a modified Boeing 747SP (Erickson (1995)), which will fly at altitudes above 12,000m at a temperature below 250K, opening up much of the far-infrared spectrum. However, the facility is limited to realtively short duraction flights (<8 hr) and so the maximum integration time on a field will be ∼3 hr. In common with ground-based telescopes, it does offer opportunities to mount innovative new instrumentation with relatively short lead times. SOFIA is scheduled to begin operations in 2005.

3. Options for Antarctica

Antarctica offers two main advantages over the best mountain top observatory sites developed to date: the coldest and driest site on the Earth's surface and the extended observing periods that allow uninterrupted monitoring of some objects. Antarctica is potentially a much cleaner, less dusty, site than the arid Chilean and Hawaiian summits and this could have substantial advantages in reducing the emissivity of telescope surfaces. It would be wise to install witness samples at Concordia now for evaluation of contamination (e,g, from diamond dust). A telescope in Antarctica will have to compete with 8 m telescopes equipped with comprehensive near- and mid-infrared imagers and spectrometers, 4 m survey telescopes equipped with arrays of 2k infrared detectors and spacecraft such as SIRTF and ASTRO-F in the near-term, followed by JWST in a decade's time. Ground-based telescopes are currently investing heavily in 1 to 2.5 μm and 10 and 20 μm imaging and spectroscopic instruments. Most of these instruments will operate under natural seeing conditions, but there are also substantial investments in small field Adapative Optics systems and instruments to exploit them. An infrared telescope on Dome C must make a real impact with high-profile science programmes, which will almost certainly come from exploitation of the areas where the gain from the Concordia site is largest. The largest gains occur at wavelengths between 2 and 5 μm on the Wien side of the Planck curve, where the low temperature significantly lowers the thermal background, or at 4.7 to 5.5 μm or 16 to 35 μm where high atmospheric transmission opens up the atmospheric windows. A sensitivity gain in itself however is not sufficient to motivate astronomy from the Antarctic; it must be accompanied by a telescope with a sufficiently large aperture to realise the gain compared to existing facilities.

3.1. A Telescope for Dome C

It is likely that the first substantial astronomical facility deployed on Dome C will have a telescope aperture significantly smaller than the 8 m telescopes now operating in Chile and Hawaii. The image quality will probably be similar, particularly bearing in mind that the diffraction-limited image size for a 2 m telescope is 0.4 arcsec at $\lambda = 3$ μm. The instrument throughput will be similar, but the atmospheric transmission will be higher, and very much so at some wavelengths. The background will be lower by factors of >20 at 3 μm and >3 at 10 μm, *BUT* at $\lambda > 5$ μm, images will be diffraction-limited, so image sizes will be larger from Antarctica, reducing the overall gains, particularly for observations of compact objects.

Of course, operations will be more demanding than at more temperate and accessible sites, and this must have a substantial effect on the operating model that could be adopted ar Dome C. Clearly reliability and low-maintenance will be essential and this suggests that instruments with limited modes of operation, and minimal moving parts will be required. In turn, this suggests that the telescope and instrument should be considered from the outset as an integrated facility rather than a more general purpose telescope. It seems that the best option may be for imaging, and perhaps at a later stage for spectroscopy, at 3 to 5.5 μm. The lower thermal background has some distinct advantages here. Not only does the reduced background improve the sensitivity attainable, but it also delivers a significant gain in detector operability in the L and M bands (3.8 μm and 4.7 μm). An 8 m telescope with 0.1 arcsec pixels needs detector read rates greater than 5 Hz and 20 Hz with broad-band L and M filters respectively in order to read out the pixels before the detector wells approach saturation. In turn, this imposes severe constraints on the detector read-out and control systems and the number of data channels needed for each detector array. The lower background at Dome C means that say a 2-m telescope with 0.2 arcsec pixels only has to read out every few seconds. The longer integration times and/or wider filter band passes offer greater efficiency and much simpler read-out electronics. These features make wide-field thermal imaging very attractive from Antarctica offering the possibility of initiating wide field surveys to complement those at 1–2.5 μm getting underway on the 4 m telescopes and operating in a niche not currently exploited or planned for the VLT or Gemini 8 m telescopes, while building on the early results obtained with SPIREX by Burton et al. (2000). Significant gains in sensitivity are also possible at 20 μm, where improved transmisson opens up the window considerably. However, the diffraction-limited image sizes mean that the gains from the lower background are compensated by the requirement to use larger apertures, restricting the overall gains to particular parts of the mid-infrared spectrum.

3.2. The Minimum Telescope Diameter

In general, larger telescopes offer greater sensitivity, but as the telescope aperture increases, it becomes increasingly difficult to deliver a wide field of view, and design solutions using 3 powered telescope mirrors have been proposed for 8-m class wide field telescopes (e.g. for the LSST, Tyson

Table 1: Comparison between a 2.5-m telescope on Dome C and an 8-m telescope in Chile

Waveband λ_0 (μm)	Background Flux Ratio	Image Size Ratio	Telescope Diameter	Overall Gain
L Band 3.8 μm	30	1.0	0.3	1.8
M Band 4.8 μm	16	1.2	0.3	1.2
N Band 10 μm	04	2.4	0.3	0.3

(2003)). For surveys, the figure of merit usually taken is the product of the telescope collecting area and the field of view, AΩ. The real gains then depend on the science programmes to be conducted, but a goal might be to have a telescope that is more sensitive than an 8 m for some projects. The image size sets the area of background emission that must be included when detecting an object, and so sharper images help enormously for most projects. The diffraction limited image size of a 2 m telescope is $\lambda/D > 0.6$ arcsec at $\lambda > 5$ μm, so for comparable image quality to other facilities, a 2 m telescope is a fairly firm lower limit. We can compare the sensitivity of a 2.5 m telescope on Dome C with an 8 m telescope in Chile. The gains from increased throughput are small in most atmospheric windows, except at the edges of the windows and between 4.5 and 5.5μm and 16 to 35 μm. However, the reduced thermal background provides big gains at 3 to 5.5 μm where a telescope diameter >2.5m has higher sensitivity in the L and M bands than an 8-m, and potential for a wider field. At these wavelengths, the sensitivity is enhanced by the square root of the background reduction (5.5 and >4 respectively), beating the factor of 3 loss in sensitivity from the smaller mirror diameter. These factors are summarised in Table 1.

4. Conclusions

A telescope operating at 3–5.5 μm with an aperture of 2.5 m or more on Dome C would open up many fields of research including: detection and characterisation of brown dwarfs and other low luminosity objects, investigation of stellar disks and envelopes and Young Stellar Objects in regions of star formation, studies of the Interstellar Medium, and observations of Active and Starburst Galaxies etc. It could provide observations of unprecedented depth, and would complement the 1–2.5 μm survey facilities coming on line over the next couple of years.

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