The Millimetre White Paper: a strategy for high-frequency radio astronomy in Australia

Contributors to this document

Peter Barnes (U Sydney), Kate Brooks (ATNF), Michael Burton (UNSW), Maria Cunningham (UNSW), John Dickey (U Tasmania), Phil Edwards (ISAS), Ron Ekers (ATNF), Yasuo Fukui (U Nagoya), Annie Hughes (Swinburne U), Ilana Klamer (U Sydney / ATNF), Vincent Minier (CEA Saclay), Erik Mueller (ATNF), Juergen Ott (ATNF), Bob Sault (ATNF), Mark Thompson (U Hertfordshire), Andrew Walsh (UNSW), Tony Wong (UNSW / ATNF).

Edited by Michael Burton.

Overview

This document describes a strategy for high frequency radio astronomy in Australia. It has resulted from process of public consultation in the Australian astronomical community, together with some input and advice from colleagues overseas. It has been produced through submissions made via a wiki page established at mmscience.atnf.csiro.au. The process also involved presentations at three meetings and workshops:

❖ Millimetre Astronomy Science Meeting: the 2005 Season
Held at UNSW on 30/11/05, presenting results from the 2005 millimetre-wave observing season using Australia's radio telescopes. The first draft of this report was presented there.

❖ Australia Telescope Users Committee
Held at ATNF, Epping on 01/12/05, during the public session of this meeting. The first draft was presented to ATUC.

❖ Future Directions for Southern Hemisphere Millimetre Wave Astronomy
A workshop held at the Sydney Harbour Institute for Marine Studies (SHIMS), at Chowder Bay in Sydney on 30-31/03/06. The second draft of the white paper was presented there. The workshop examined the status of current facilities and their future science programs, both in Australia and elsewhere. An international perspective on the future role for Australia's millimetre wave facilities was also provided by an number of overseas visitors who attended. The meeting finished with a discussion on future priorities for millimetre astronomy in Australia.

This final document was presented to the Australia Telescope Users Committee at its meeting on June 5-6, 2006.

Contents

Future Priorities for Millimetre Wave Astronomy in Australia for the Next Decade (2006-2016)

Vision

Millimetre-wave astronomy will provide the primary focus for developments in radio astronomy for at least the next decade, offering the promise of furthering our understanding of the formation of planets, stars and galaxies across the universe. In Australia, using our current facilities and their new mm-wave instrumentation, we will be able to make significant contributions to these fields of study. This includes conducting effective searches for new molecules in interstellar space, including those which might provide the seeds for life, the unveiling of star formation across the Galaxy, and a comparative examination of the environment in which stars form in nearby galaxies to that in the Milky Way, as well as in the distant universe.

When completed around 2012, ALMA will become the principal instrument used by the international radio astronomy community. Its large collecting area and comprehensive baseline coverage will provide an ability to image in the millimetre bands with far higher sensitivity and spatial resolution than has been achieved before. ALMA will not provide, however, a comprehensive view of the millimetre-wave universe. It must work with other facilities that have differing capabilities in order to obtain the full picture that is available. This provides an important opportunity for Australia, to meet this need.

Wide-field imaging, undertaken with wide bandpasses, and access to the long-wavelength end of the millimetre spectrum, are domains which ALMA will not serve well. Such capabilities can be provided by Australia's millimetre facilities if they are maintained with leading-edge technologies over the next decade. They would serve to keep Australia's facilities internationally competitive for a relatively modest investment, in comparison to that being made in ALMA and associated facilities in Chile. The ATCA, fitted out with phased focal plane arrays that could operate across bands at 3 mm and longward, would be a uniquely powerful facility that would serve Australia's science community well in the ALMA-era. Supported for open time allocation, it would continue to attract the best from the rest of the world to Australia to use it. It would maintain the vitality and reputation of our radio-science community, and provide us with access to the best facilities elsewhere through the collaborations this would engender. It would also serve to make Australia a provider of focal plane array technology, together with the commercial opportunities that offers.

Wide field capability is also a route that has been successfully demonstrated at the Anglo Australian Observatory. The 4m AAT has remained one of the most productive optical/IR telescopes in the world despite the operation of 8m class telescopes overseas for the past decade. It managed this through the development of wide-field spectroscopic instrumentation, enabling extensive sky surveys to be undertaken with the telescope. Providing such a capability has proved to be financially beyond the ability of the 8m telescopes to match, so maintaining the AAT's own competitiveness.

Our challenge is to make this vision happen for the radio community too, while at the same time continuing along the path towards the SKA, the international radio telescope that will follow ALMA. We need to keep open the doors to opportunities in the millimetre bands, while also working towards opening news doors in the centimetre bands.

The challenge can be met by following a staged development path that takes advantage of synergies with the technologies needed for the SKA, as well as the needs of the international radio community. It involves completing projects currently underway, undertaking a few modest enhancements which will improve the efficiency of operation of our facilities, and re-deploying resources to ensure that the path towards developing phased focal plane arrays at millimetre wavelengths is followed. We outline this approach below.

Current Developments

There are four current instrumentation projects underway that should be completed.

- The 8 GHz digital filter bank (MOPS) for the Mopra Telescope. This will provide a uniquely powerful instrument for line surveys in the 3 and 12 mm bands using existing receivers.
- The 2 GHz backend (CABB) for the ATCA. This provides greatly increased coverage for spectral line studies and increased sensitivity for continuum imaging in both millimetre and centimetre wavebands.
- The 7 mm upgrade for both the ATCA and Mopra, with the receiver band extending to at least 49 GHz. Used with either the CABB or the MOPS, this provides a correspondingly powerful instrument for line and continuum studies in this band.
- The 12 mm single-element receiver designed for Parkes, with the project also addressing some of the performance issues related to the future development of focal plane arrays operating at 12 mm for that telescope.

Modest Future Developments

There are several smaller projects which should be continued under ongoing maintenance and development programs of the national facility, and in the broader community.

- The study regarding the use of water vapour radiometers for phase correction at 3 mm for the ATCA should be completed and recommendations regarding its suitability made. This might be conducted, for instance, as a student project. Real time phase correction offers the promise of 3 km baselines at 3 mm, yielding sub-arcsecond resolution imaging.
- Noise diode calibrators for use at 3 mm should be installed on the receivers of the ATCA. This would not only improve observing efficiency and the accuracy of flux calibration, but would make possible polarization measurements in the band as well.
- The net of calibrators available for 3 mm observation with the ATCA needs to be expanded, in order to improve phase correction by using calibrators nearby to all objects under study, and to facilitate fast switching between source and calibrator.

- Automated tilting of sub-reflectors as the elevation angle varies would improve telescope efficiency at millimetre wavelengths, in particular the beam profiles. It is a cost effective (though somewhat inferior) alternative to actively controlling antennae shape.
- Site testing on the Antarctica plateau for THz frequency astronomy should proceed, at South Pole, Dome C, Dome A and other high plateau sites, as well as including comparative measurements from the Atacama plateau, all conducted with identical instrumentation.

Extending the frequency coverage of all ATCA dishes at 3 mm to the same as available at Mopra (i.e. 77–116 GHz) is desirable and an eminently feasible project. It would facilitate studies of the molecular environment in nearby galaxies, where the 115 GHz transition of CO may often be the only molecular line bright enough to be readily observable. However, this is a project that cannot be started until the current mm-wave projects (i.e. MOPS, CABB, 7 mm, 12 mm-Parkes) are completed. At this stage this project should be prioritised, taking into account the then projected timeline for 3 mm operation with ALMA, and the outcomes of the focal plane array engineering studies discussed below. Alternative sources should also be explored for funding an extension of the frequency coverage at 3 mm.

Future Priorities and Strategies

The development of phased focal plane arrays (pFPA) for millimetre-wave astronomy would have far reaching consequences. Provision of such arrays with >100 elements on the ATCA would guarantee its competitiveness in the ALMA-era, enabling wide-field imaging that could not readily be undertaken using ALMA. It would also position Australia as a supplier of such devices to observatories elsewhere. pFPAs would, for instance, be a powerful addition to the total power antennae planned for the ALMA-ACA, where they could provide essential zero spacing information needed by the main array. We believe the ATNF should devote resources to investigating how such arrays could be built, and estimating the costs involved. Such an effort would also have synergies with the need to develop FPAs for use at centimetre wavelengths with the SKA.

While it would be desirable, we rate as a lower priority, in relation to that of FPA development, the broad-banding of current operations at 3 mm in order to make possible the measurement of the entire 40 GHz wide window at a single setting. The MOPS will make it possible to observe the entire 3 mm band at Mopra with five settings, partially meeting the capability needed here.

We propose that resources be deployed to develop a technology roadmap for FPA studies that includes the needs for mm-band, and well as cm-band, devices.

Initially, we recommend studying the merits of two systems:

- A 4- or 7-element 3 mm wavelength multibeam (i.e. multiple feed horns) for the Mopra telescope. This is the maximum size array that could be built without serious beam efficiency losses due to the shaping of the antenna. Larger arrays would either require it to be re-shaped, or a pFPA installed. However, even such a modest system would greatly improve the ability to undertake mapping projects.

- A pFPA at 12 mm for the Parkes telescope. Given that this would be installed at prime focus, this is an easier option than building a pFPA for ATCA or Mopra (the number of elements goes as $(f/D)^2$, giving a gain of ~25 for Parkes). The size of the pFPA would also be considerably smaller than a corresponding device working at 21cm, as for instance needed by SKA, and so may prove easier to construct?

A prototype then needs to be built.

The study should also examine the challenges and needs to produce a pFPA with ~100 elements, first working at 12 mm on Parkes, and then working at 3-12 mm with the ATCA and Mopra. It should also consider the prospects for extending these to higher frequency operation beyond this, to sub-mm wavelengths (e.g. for use with ALMA total power antennae) and to THz frequencies (e.g. for use in Antarctica).

The study should result in an options paper so that decisions regarding future developments to the mm-wave capability can be quantitatively assessed. The study should also consider what aspects might be outsourced, and what needs to be developed in-house at CSIRO.

Additional resources should be identified for funding such developments beyond those available from the CSIRO. This could include university partners, through, for instance, the ARC-LIEF scheme, and international partners, perhaps as the provider of instrumentation for other observatories.

By preparing such an engineering white paper on pFPAs, it will allow us to properly assess the feasibility of, and options for, future developments for mm-wave systems in Australia. It will allow a path to be mapped out for the next decade that will allow the ATCA to remain an internationally competitive facility, and to continue Australia's influential role in the radio astronomy community worldwide.

Introduction – Goals of the White Paper

Australian radio astronomy has a long history of accomplishment. Recent high-frequency upgrades to the ATNF facilities promise to usher in a new era of scientific productivity. We seek to establish a broad strategy for maintaining and extending Australia's capabilities in high-frequency radio astronomy. We will lay out some ideas for high-impact science, discuss possibilities for future upgrades, and identify resources needed to make these visions a reality. For purposes of this document we focus on capabilities in the 15–115 GHz range, though related developments at lower and higher frequencies are important to bear in mind as well.

A key component of this strategy is international collaboration, for three reasons. First, Australian experience in this field is still limited. We have much to learn from colleagues overseas who have operated high-frequency radio facilities for several decades. Second, a new generation of telescopes is emerging in northern Chile, at sites higher and drier than any available in Australia. We need to be complementing rather than competing with these facilities. Finally, since a large fraction of our telescope users are from overseas, providing an essential boost to our community's vitality, we need to be responsive to their wishes and needs as well.

This "white paper" has been compiled through the contributions of those listed on the cover page, making use of a wiki. It was divided into several themes, each with a separate wiki page and an organiser who coordinated the contributions to the themes. The first draft of the white paper was presented at a meeting on 30/11/05 at UNSW on science results from Australia's millimetre facilities in 2005, followed by a presentation the following day to the Australia Telescope User Committee. The second draft developed through responses to that document, and was presented at a workshop on future directions for southern hemisphere millimetre wave astronomy, held in Sydney on 30-31/03/06. Further input to the document was sought at the workshop, in particular an international perspective on the future use and role of Australia's facilities, and on the prioritisation of future developments. This final document was presented to the Australia Telescope User Committee at its June 2006 meeting.

Overview of Current Capabilities

Stocktake of Current Facilities

Currently, millimetre telescopes in Australia fit into two wavelength regimes:

- 12 mm facilities, including the ATCA, Mopra, Tidbinbilla and Parkes,
- 3 mm facilities, including the ATCA and Mopra.

A summary comparison of these facilities and their capabilities is given below.

12 mm Facilities

	ATCA	**Mopra**	**Tidbinbilla**	**Parkes**	**Tid 34m**
Frequency Range (GHz)	16 – 25	16 – 25	19.9 – 20.5 21.8 – 22.4 23.6 – 24.2	21 – 24	31.8 – 32.3
Wavelength Range (mm)	19 – 12	19 – 12	14.8 13.5 12.6	14 – 12.5	9.4 – 9.3
Diameter (m)	6 x 22	22	70	45	34
Primary Beam (arcsec)	175 – 112	120	48	80	61
Maximum Synthesised Beam (arcsec)	0.5	–	–	–	–
Typical System Temperature (K)	30 – 38	45	50	140	30
Maximum Bandwidth (MHz)	2 x 128	8000	64	128	64
Maximum number of Channels	1024	8192	4096	8192	2048
Continuum Sensitivity (1 sec) (mJy/beam)	5	–	9	590	160
Line Sensitivity (10min, 10km/s) (mJy/beam)	12	24	3.4	320	

3 mm Facilities

	ATCA	Mopra
Frequency range (GHz)	85 – 105	77 – 116
Wavelength range (mm)	3.5 – 2.9	3.9 – 2.6
Diameter (m)	5 x 22	22
Primary beam FWHM (")	35	37 – 33
Maximum synthesised beam (")	2	–
Typical system temperature (K)	310 – 440	140 – 290
Maximum bandwidth (MHz)	2 x 128	8000
Maximum number of channels	1024	8192
Continuum sensitivity (1s) (mJy/beam)	100	–
Line sensitivity (10min, 10 km/s) (mJy/beam)	24	60 – 155

ATCA 12 mm Facility

Currently works with all 6 antennas over a broad frequency range. Highest signal to noise characteristics in the mm-bands. High spectral resolution is excellent for Galactic line astronomy. 128 MHz bandwidth is acceptable for extragalactic work, as it typically translates to 1700 km/s. High spatial resolution is often tempered by poor phase stability for CA06, which has the longest baselines.

Mopra 12 mm Facility

It has not so far been used much outside of water maser VLBI due to the narrow frequency range available. However, the new receiver (installed in March 2006) has broader frequency coverage. Taken with the wide bandwidth (8 GHz) correlator, this will make Mopra a sensitive and versatile line detector in this waveband.

Tidbinbilla 12+7 mm Facility

Three narrow bands are available, which include the important water maser as well as ammonia lines. Excellent line sensitivity means it is well suited to Galactic line work, although limited bandwidth makes it difficult for extragalactic work. The large dish diameter makes it an excellent complement to the ATCA when zero UV spacing observations are needed. Currently the telescope only works in a pointed mode, but on-the-fly mapping will be available in the near-future. Only a small fraction of the time is available to astronomers, however.

The Tidbinbilla 34m also provides a facility for 7 mm work, though only in the narrow frequency range from 31.8-32.3 GHz. A number of molecular lines are accessible in this range (these include C_6H, H_2COH^+, $HCC_{13}CCN$, HC_5N and HC_9N). Such species are typically found in hot molecular cores, and might be used to provide an internal clock measuring the progress of star formation within them.

Parkes 12 mm Facility

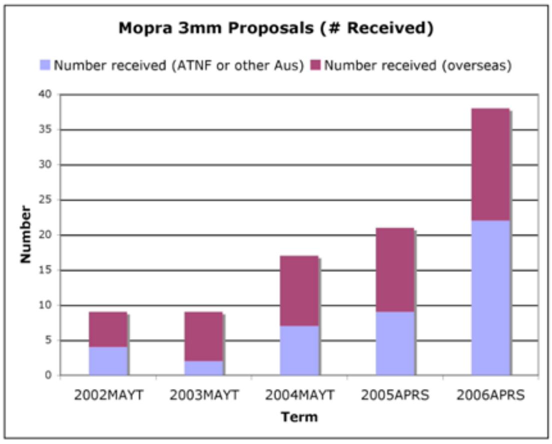
High system temperatures lead to poor sensitivity in this band, relative to other telescopes. Broader frequency coverage than Tidbinbilla may make it useful for lines that Tidbinbilla cannot see. The inner 45 metres of the dish is used for 12 mm observations. An improved receiver that illuminates 55m of the dish will be installed in 2007.

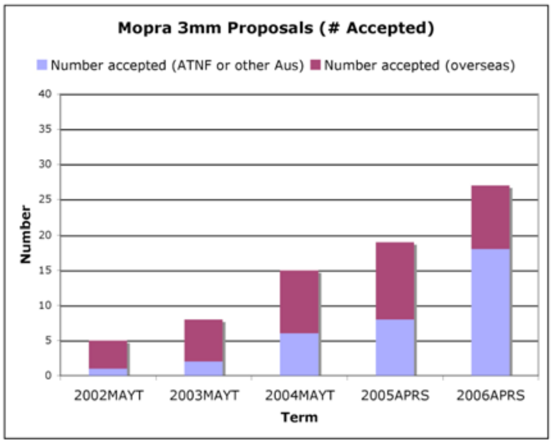
ATCA 3 mm Facility
Five antennas can be used to observe with the ATCA at 3 mm over a broad frequency range. Currently two frequencies can be observed, as long as they are within 2.7 GHz of each other. However, available correlator configurations limit the maximum bandwidth to 128 MHz. This is not good for extragalactic work, but works well for Galactic line work. With two frequency windows, 200 MHz bandwidth is currently available for continuum measurements, but the sensitivity will be greatly enhanced when the 2 GHz backend is available.

Mopra 3 mm Facility
Mopra has recently been upgraded so that it will now work over the frequency range 77-116 GHz. The new MOPS correlator will also allow observations across an 8 GHz bandwidth. This is excellent for Galactic observations of more than one line, as well as for extragalactic line work. On-the-fly mapping has recently been introduced and works well.

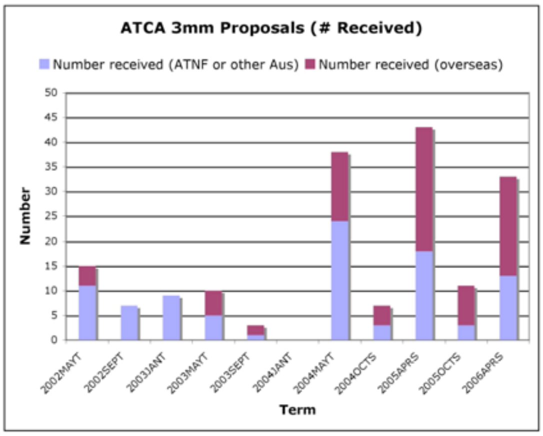
Demand for ATCA and Mopra

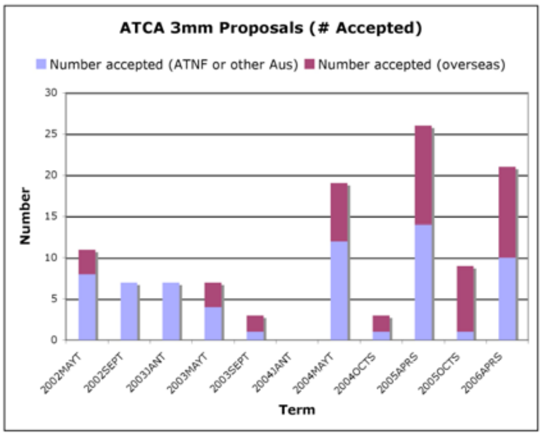
Demand for Mopra 3 mm time has increased dramatically over the past 5 years, from 9 proposals per year in 2002 and 2003 to 38 in 2006, reflecting growing interest from the astronomy community, both within Australia and internationally.



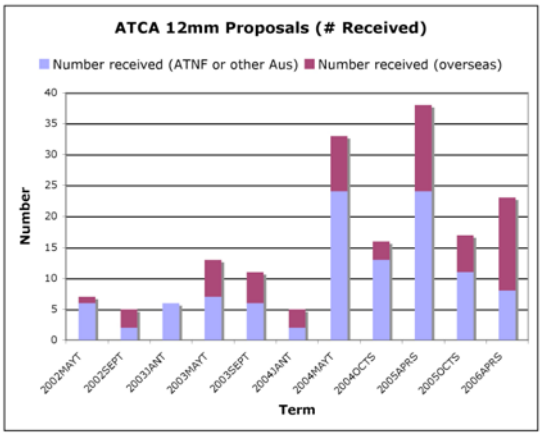


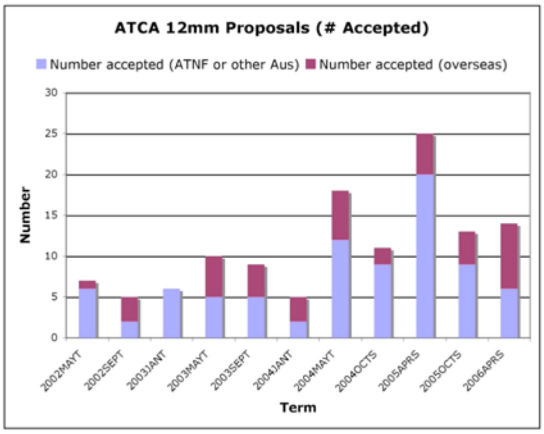
Demand for ATCA time at 3 mm has been high since 2004, when the 5-element system was completed. However, the number of hours requested fell by 40% in 2006, reflecting a drop in the number of proposals from both Australian and overseas PIs. The saw tooth demand reflects that most millimetre observations occur during the winter months.

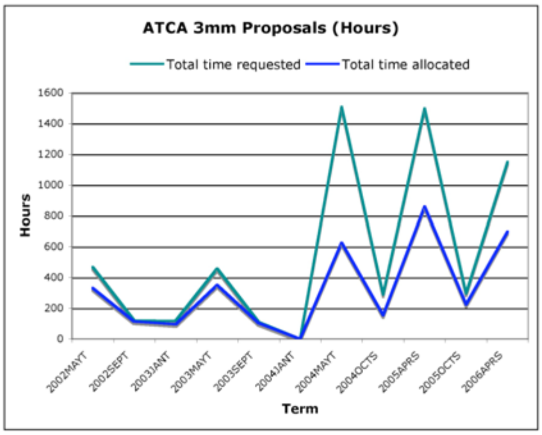


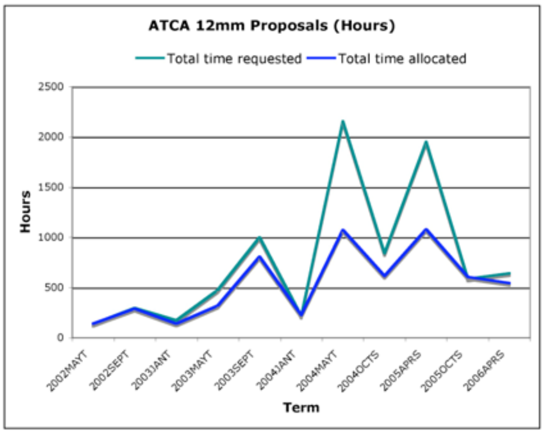


Demand for ATCA time at 12 mm was highest in the winter terms of 2004 and 2005, but dropped in 2006.









Science Drivers for Millimetre Wave Astronomy

Introduction

Millimetre-wave astronomy is a young field in comparison with optical and even radio astronomy, and so readily provides new opportunities for exploring the cosmos and furthering understanding of many fundamental phenomena. The millimetre regime is rich in observational signatures. Line densities are highest in the mm-bands for many categories of source, with the corresponding continuum fluxes also peaking at the short-wave end of the band. Yet the spectrum has remained little studied to date as observation has been impeded by the atmosphere and by immature detection technologies. Both these adversities can now be addressed through technology development, and this is driving the rapid growth of millimetre facilities world-wide in the twenty first century. The challenge of opening new windows for viewing the cosmos through is a particular attraction of the field, providing opportunities across broad ranges of study. It has also been the driving rationale behind the development of ALMA, the world's major ground-based astronomical project of the coming decade. The science potential has also spurred construction of a range of other mm-wave facilities, both in Australia and overseas. These will provide a focus for initiating some science that will later be tackled in depth by ALMA, but they will also provide complementary capability to ALMA, in a similar way that a suite of 1-4m class optical/IR telescopes are needed to support the science tackled by the 8m facilities.

Millimetre-wave science can be divided into four broad arenas, aimed at studying formation processes and events throughout the Universe. These are to study when:

- *planets are young*, measuring the millimetre continuum emission from cold dust, to probe the protoplanetary environment as the process of planetary construction begins,

- *stars are young*, probing the rich chemical environment within the cores of protostellar clouds, and the organic chemistry driven by the incipient protostar, as evident through the plethora of molecular lines emitted in the millimetre bands,

- *galaxies were young*, probing the nature of protogalaxies in the first billion years of the universe, through the red-shifted emission from lines and continuum, now peaking in the (sub-)millimetre regime,

- *the Universe was young*, measuring ripples in the cosmic microwave background radiation emanating from the era of when hydrogen first formed, 300,000 years after the Big Bang, whose thermal spectrum now peaks in the millimetre regime.

These four arenas cover some of the most challenging subjects of investigation in astronomy today. Our particular challenge in Australia is to find a way to ensure that we play an active role in their pursuit, and do not miss out on the opportunities that will arise as the field grows internationally. We can do this by ensuring that the science that Australia's millimetre-wave facilities conduct is both focussed on important questions in the field and is also designed to be complementary to the capabilities that the international facilities will provide. In the pages ahead we outline some of the major science areas that can be tackled from Australia.

From this list we are then able to determine what capabilities are needed to ensure that this program can be achieved. Other nations will be committing extensive resources to the field, and so international collaboration is the best way to leverage the geographic advantage of our facilities.

The Evolution of Circumstellar Disks around Young Stellar Objects: from nebulae to proto-planetary disks

Detection and study of planetary systems and proto-planetary disks around nearby stars is an exciting and rapidly growing area of research. These can be studied in various ways across the spectrum from optical to radio wavelengths. The coming decade will certainly lead to advances in all of them. Over the past ten years this branch of astrophysics has developed from a situation of hardly any data, to the present startling diversity of planetary systems and circumstellar disks. The physical, chemical, and ultimately biological questions raised by this rich new observational field are attracting wide theoretical interest. In the next few years the subject will mature, with observational advances guiding theoretical efforts to establish new paradigms for the formation and evolution of planetary systems.

There are several niche topics where Australian telescopes can have a large impact. One example is contributing to the Spitzer space infrared telescope legacy program "from molecular cores to planet-forming disks" (or c2d). This involved mapping five nearby molecular clouds and ~80 isolated dense cores from 3.6 to 70 μm, providing information on the location of energy sources down to 5 Jupiter-mass substellar objects, young stellar objects, and disks with a few earth-masses. To complement this data, continuum maps at 1.2 mm have been obtained from the SEST and IRAM telescopes, as well as line maps for the northern sample in the N_2H^+ and CS molecules from the FCRAO telescope. The Mopra telescope is now undertaking corresponding line work for the southern cores. It is only with such a large sample as the c2d program has that it will be possible to study the full range of core evolution, from chemically young starless cores (these are strong in CS, weak in N_2H^+, and weak in mm-continuum emission), to evolved starless cores close to forming a protostar (which have a high column density in mm dust, and are strong in N_2H^+), to protostellar cores (which can exhibit CS outflows, strong mm dust emission, N_2H^+ and/or CS emission, depending on their age and luminosity). As a bonus, the new 8 GHz Mopra spectrometer will enable a number of other molecular tracers to be sampled at the same time, a project not feasible at any other facility.

Determining the physical conditions of starless cores is critical for these studies as these define the initial conditions of star formation. The initial conditions in turn define the collapse dynamics, the likely mass of the star, and the evolutionary timescales. Another aspect of this problem is the origin of binarity in stars. Most stars in the sky are in fact not single, but part of a multiple (usually binary) system. For low-mass stars, the main physical characteristic that seems to determine whether a protostellar core will produce a single star or a binary appears to be how the gas sheds its angular momentum. Why some systems have high specific angular momentum (the binaries) and why some shed enough angular momentum to become single stars remains a mystery. To make progress it will be necessary to measure the properties of the disks that form.

The molecular gas in disks can be detected through observations in the millimetre regime. The recent upgrade of the ATCA to operate at 3 mm wavelength has made it the only millimetre interferometer in the southern hemisphere and one of the most sensitive instruments of its type in the world. It will play a major role in the next five years in making high-resolution observations of the molecular gas in disks in nearby low-mass star forming regions. Information on the molecular gas content for disks of different ages can be used to determine temperatures, densities and chemical compositions, and from these used to infer the evolution of the disk. Our knowledge of how planetary systems form from disks is poor and such observations will constitute a major advance and provide constraints for theoretical modelling. Similar observations are possible with northern millimetre interferometers, but the ATCA has an important role to play in the Southern Hemisphere in undertaking the first such observations, for later follow-up by ALMA in Chile.

Habitable planetary systems are not likely to occur around high-mass stars, as they have lifetimes of the order of millions of years, rather than billions of years for stars like the Sun. How these high-mass stars form remains very much an open question. Once a star reaches a mass approximately eight times greater than the Sun, the pressure from the intense radiation it produces is sufficient to halt the further accretion of material. However, many such stars with masses are observed in the Galaxy, so there must be some means to create them. One possibility is that they form through coalescence, alternatively accretion may proceed through a thick or flared disk. To date, few disks have been detected around high-mass stars and their detection and study at radio and millimetre wavelengths is another area where Australia can reasonably expect to play a role through observations with the ATCA and through long baseline interferometry with the Long Baseline Array. In particular, with the completion of the wide band (2 GHz) correlator, sensitivities for the detection of cold dust emission from disks will be greatly enhanced.

The Search for Biogenic Molecules: organic chemistry from comets to hot molecular cores

Few questions challenge the imagination more than the question of whether there is life in the Universe, other than the Earth. Could there be, or was there once, life elsewhere in the Solar System? Does life also exist elsewhere in the Galaxy? If so, could life on Earth have been seeded from the interstellar environment? Could there then be common genetic traits across the Galaxy? In the coming decade humanity can go beyond simply raising such questions, and begin the quest in earnest of conducting experiments which try to answer them.

To do so, we need to address the question of what environments life might exist in, and how these environments come to be, in order that we can determine what it is best to look for. A natural starting point for the search is our own Earth. How might we find similar objects, whose surfaces are covered in liquid water and lie within a habitable zone around another star? However, that may be too confining for the search of parameter space. As the discovery of liquid methane on Titan shows, liquids other than water may be abundant elsewhere on a planetary surface, and exist within a hydrocarbon environment. While life may require a fluid medium to sustain the transport of materials to it, and the waste from it, perhaps that medium need not only be water?

These environments on planets and satellites have themselves formed from processes that take place within the dusty disks that surround protostars, molecular cloud cores which have gravitationally collapsed within cold clouds of gas. The extended surface areas of the disks and clouds make their detection and dissection easier than that of the planets which they ultimately produce. The clouds themselves are also rich in molecules, with a complex organic chemistry underway, taking place on the surfaces of dust grains and in the gas phase as the protostar heats up and evaporates material from the grain mantles. Do biogenic molecules exist inside these clouds? Species such as acetic acid, glycoaldehyde (a sugar), and ethylene glycol (anti-freeze) have been found in some sources. Even glycine (the simplest amino acid) has been found in a few meteorites (and controversially claimed to have been detected in the interstellar medium). Do chiral molecules exist and if so what is the balance between right-handed and left-handed versions of the molecules? Can these molecules then seed planets with the organic material needed for the precursors to life? If so, are the origins of life similar across the Galaxy?

These questions may all be addressed through precise observations at infrared, millimetre and centimetre wavelengths. They demand high spatial resolution, to resolve structures on scales of a few arcseconds to milliarcseconds, high dynamic range to simultaneously measure faint objects adjacent to bright stars, and large collecting areas to provide the sensitivity to discern the necessarily weak emission signatures.

To study the organic chemistry inside a molecular cloud it is necessary to measure the plethora of spectral lines emitted from the molecules across the sub-millimetre and millimetre regimes. In the sub-millimetre, higher rotational levels are evident, arising from warmer (and therefore smaller) regions, closest to the protostellar objects where, presumably, the 'hot core' chemistry is also being driven. The more complex, and therefore rarer, the molecule, the more emission lines are present, a facet of the complexity of the partition function. The lowest energy lines are also shifted towards the low frequency end of the millimetre spectrum the heavier the molecule; i.e. in the 3, 7 and 12 mm bands. To be sure of detecting a rare species many lines therefore need to be measured to distinguish it from the line 'jungle' of all the species present. Wide correlator bandpasses are essential to achieve this. The ability to observe across an entire mm-window at once, with spectral resolutions sufficient to resolve down to thermal line widths, would greatly facilitate the search for biogenic molecules, allowing a complete inventory of the species present in many protostellar environments to be undertaken. Current correlators have around 10,000 channels, but million channel devices would be needed to provide such a capability. Such investigations can readily be undertaken using single dish millimetre-wave telescopes. In addition, interferometry further helps the process of identification, by providing validation, or otherwise, of whether candidate lines arise from the same region of space, within the beam of the single dish telescope. Typically the emitting regions would be expected to be very much smaller (a few arcseconds) than the beam size of Mopra, and so the role of the ATCA mm-wave interferometer will be crucial in locating and characterising the emitting regions where such molecules reside.

The Evolutionary Sequence for Massive Star Formation: from cold core to massive star

Massive star formation is the crucible through which the Galactic ecology is driven. Massive stars dominate the luminosity of our Galaxy, even though they only comprise a small fraction of its mass. They return the bulk of the products of stellar nucleosynthesis through which the chemical enrichment of the Galaxy occurs. They are the source of energy flows which both drive further star formation, and regulate the rate at which it occurs. Yet the process of massive star formation remains shrouded from us, literally and metaphorically. For example, in a massive cluster the typical separation between the stars is significantly less than the Jeans length in Giant Molecular Clouds (GMC). Distance, rapidity, multiplicity and overlapping physical processes mean the passage from a cold core to a massive star is unclear. While it seems clear that stages such as cold dust core, hot molecular core and ultra-compact HII region must be passed through before a main sequence star is reached, the relation of these stages to each other, and the timescales they last for, is not adequately understood.

Furthermore, how do these timescales vary with mass for different aspects of the formation process, such as core assembly, mass accretion, disk formation and outflow generation? Is this apparent though the chemical evolution that accompanies these stages? It will only be by identifying and studying a uniform and unbiased population of massive, cold, dense cores at different evolutionary stages that these questions can be properly addressed.

Many of the events, especially at the earliest stages of the process, are evident through mm-wave emission, both in lines and continuum. Cold cores, with sizes of a few tenths of a parsec, masses from tens to hundreds of solar masses, densities exceeding 10^5 cm^{-3} and temperatures of ~20K, are only evident through mm emission, in particular from thermal continuum in the sub-mm and mm bands. These cold cores may also correspond to the 'Infrared Dark Clouds', which have been discovered through absorption of mid-IR radiation by a cold foreground clouds by two space satellites (MSX and Spitzer). However, even if they do, only a fraction will be found this way, while all will be evident through their mm emission.

Some of these cores will develop into protoclusters, though which ones do, and why, is unknown. Those that do not form protoclusters may simply be transient phenomena which do not produce stars. It is important to determine which will in order to establish the initial conditions for massive star formation.

Those that do form protoclusters appear to pass through the hot molecular core phase, where a rich organic chemistry is evident. It is driven by the heat of a massive protostar which evaporates molecules from grain surfaces, so creating a chemical soup which evolves on $\sim 10^4$ year timescales. The signature of this process, emission from molecular species like methanol, methyl cyanide and formaldehyde, provides a chemical clock through which the evolutionary state of the core can be ascertained, though as yet the hands of the clock are too blurred to be reliably read. Intense maser emission from species like methanol and water signpost these cores.

The central source continues to heat up, eventually producing UV photons, and forming an ionized bubble. This expands through the hyper-compact, ultra-compact and finally HII region stages, though the timescale for this, particularly the first stages, is in considerable doubt. It depends on how the UV radiation is quenched by the dust, and that depends how the radiation is escaping whilst infall is still occurring. In other words, it depends on the unknown internal structure of the core and protostar.

Australia's millimetre-wave facilities can contribute to these studies in several ways:

Massive Cold Cores and Infrared Dark Clouds are newly discovered phenomena, and little is known about their physical state. A survey has begun with Mopra to characterise their conditions – the Census of High and Medium-mass Protostars (or CHaMP), involving Japanese collaborators. Using the new MMIC receivers and 8 GHz correlator, a sample of GMCs over 20° of the Galactic Plane, in up to 16 different molecular tracers in the 3 mm band will be obtained. This project can be tackled despite the lack of a focal-plane/multibeam imaging system at Mopra because CHaMP bootstraps from the highly successful NANTEN surveys of the Milky Way. Indeed, since massive star formation behaviour may well be different near the solar circle than in the galaxy's centre, eventually it will be necessary to cover the entire fourth quadrant of the Galaxy. To make this feasible a wide-field imaging system will be needed.

At higher resolution, direct temperature and density measurements for extremely cold gas will be possible through interferometric imaging of NH_3 lines in the 12 mm band, and other species in the 7 mm band, with the ATCA. In particular, if the cores are as cold as presumed there will be few molecular tracers available to probe them since they are frozen onto the dust grains. However NH_3 will be one of the last molecules to deplete, and so provide a tool with which the physical state can be characterised. At even earlier stages, molecules like HC_3N appear to trace prestellar material in their lower–J transitions (36 and 45 GHz), and so could give detailed pictures of the initial conditions in the massive dense gas, once the 7 mm capability of the ATCA is available.

Hot molecular cores are rich repositories of organic molecules, and these are evident through the spectral lines across the mm spectrum, particularly in the 3 and 7 mm bands. To determine whether there is a chemical clock which signposts the evolutionary state it is necessary to undertake an inventory of the molecules present. This can be done through high spectral resolution measurements across the entire 3, 7 and 12 mm bands, necessitating broad band correlators. The 8 GHz correlator for Mopra will allow the complete 3 mm spectrum to be obtained with 5 settings at 3 km/s resolution, close to the typical line width in hot cores (though more than the line width of the coldest sources). This will provide a powerful tool for such chemical studies. A million-channel spectrometer, with 40 GHz bandwidth, would allow the entire band to be measured at once, with 0.1 km/s resolution, sufficient for even the coldest source. It would permit a systematic study of such environments across the Galaxy. The ATCA 3 mm interferometer can contribute to this work through imaging the brighter lines that are detected and examining their relative spatial distribution, which is expected to depend both on distance to the heating source as well as the time since the source switched on. However, with a spatial resolution of a few arcseconds, most sources as expected to be unresolvable, making this a prime topic for investigation using ALMA. However the ATCA can serve as a finder telescope for ALMA, by picking out suitable sources for such detailed examination in the future.

Hyper-compact HII regions: when an HII region first turns on it is evident as a 'hyper-compact HII region'. It will be a few mpc in size, with density greater than 10^6 cm^{-3}. This results in a very high emission measure, with the critical frequency for the transition from optically thick to optically thin emission lying in the 40 – 100 GHz regime; i.e. in the 3 and 7 mm bands. Since the optically thick (longer wavelength) emission flux varies as frequency-squared, it rapidly drops at cm-wavelengths, rendering hyper-compact HII regions undetectable at cm-wavelengths. In contrast, ultra-compact HII, as well as ordinary HII regions, have lower emission measures and critical frequencies of a few GHz, and so have been well studied at cm-band wavelengths. The 7 mm band addition to the ATCA will thus allow us to study the birth of HII regions through investigating the characteristic features of hyper-compact HII regions.

Turbulence and Star Formation: what determines its efficiency and regulates its rate?

A comprehensive theory of star formation remains one of the major unsolved problems of astrophysics (e.g. Klein et al. 2003, Larson 2003). Although much has been learnt about how low-mass stars (i.e. solar mass and below) form in isolated mode, this accounts for only about 10% of all star formation. Recently a new turbulent model for star formation has emerged which holds the promise of providing a unified explanation for star formation from the smallest to the largest scales (Mac Low & Klessen 2004). This model is so far only based on numerical simulations that are highly dependent on initial conditions and has yet to be constrained by observations.

Any successful model of star formation must be able to explain the low star formation efficiency of molecular clouds in the Galaxy – in other words the relatively long timescale on which gas is converted into stars, compared with the time that it would take for a molecular cloud to collapse under the influence of gravity alone.

Over the past two decades a 'standard model' of star formation has emerged that invokes magnetic fields to slow down the collapse of gas and reproduce observed star formation rates (e.g. Shu, Adams & Lizano 1987). This model works well for low mass stars forming in isolated mode but efforts to extend it to star formation in cluster mode, or to massive star formation, have not been successful.

On the other hand, recent 'turbulent' models for star formation seem to provide an explanation for star formation at all scales (see Mac Low & Klessen 2004). In these models, supersonic turbulence is driven on large scales (tens of parsecs or more) and generates turbulence on smaller scales via an energy cascade. The supersonic gas motions quickly compress regions of gas, which may then undergo collapse in these denser clumps (leading to short lifetimes before collapse). Furthermore, the frequent disruption of clouds by turbulence (preventing collapse in many clumps) can account for the low observed star formation efficiency, which is ultimately set by the rate and characteristic scale of the energy injection. It is proposed that turbulent energy is continually replenished by energy sources whose origin remain unclear, but may include expanding supernova bubbles and large-scale galactic flows of gas.

One of the key questions that can be answered by observations is whether there is a relationship between star formation and turbulence? To address this question it is necessary to characterise turbulence within the ISM, and also to determine the protostellar and stellar content. There are specific predictions arising from the modelling that has been conducted into this, as we describe below.

The star formation efficiency increases as the driving scale of the turbulence increases (Klessen, Heitsch & Mac Low 2000). Strongly-driven turbulence leads to larger density fluctuations about the mean density than does weakly-driven turbulence (Ballesteros-Paredes & Mac Low 2002). This may be seen observationally using emission tracers sensitive to different densities, which are predicted to have quite different relative distributions regions where the turbulence is strongly, rather than weakly, driven. For example, in weakly-driven turbulence a low-density tracer, such as CO, will have a much wider distribution compared to a higher-density tracer, such as CS, whereas strongly-driven turbulence leads to a more similar spatial distribution between the high and low-density tracers.

These are predictions that are testable – mapping of molecules that trace widely different density regimes can be used to determine the dominant size scale of density structures in a particular region.

A major investigation in this field began in 2004 using the Mopra Telescope and the newly developed on-the-fly (OTF) mapping technique. The distribution of ^{13}CO (J=1–0) line emission was mapped in a degree-sized region of the southern galactic plane centred on the molecular cloud complex G333.6-0.2. The region is in the Fourth Quadrant of the Galaxy, and the field passes through the ring of molecular clouds that circle the Galaxy at 3–5 kpc from its centre. As the fore-runner of what would eventually become a survey of the entire quadrant, the project has been dubbed the 'Delta Quadrant Survey' or *DQS*.

The region selected for the initial survey is large enough to contain a varied sample of molecular regions within the Galactic plane. It contains a variety of high mass star forming clouds, surrounded by diffuse molecular and atomic gas. It is, however, a discrete region in the plane whose boundaries can be specified. It also needs to be contrasted with surveys conducted of nearby, low-mass star forming clouds (e.g. Chamaeleon I and II) which lie away from the galactic plane. These two clouds exhibit quite different characteristics, in particular in their SFEs (13% in Cha I but only 1% in Cha II), so providing a clear contrast to the DQS field in evaluating the role of turbulence in the regulation of the star formation occurring in each.

While the Mopra survey cannot compete in size with that conducted in the First Quadrant by the FCRAO mm-antenna in Massachusetts (the Galactic Ring Survey), once the new digital filter bank is installed at Mopra it will be possible to conduct the survey in several lines simultaneously. In 2005, $C^{18}O$, CS and $C^{34}S$ were mapped (making use of the first 2 GHz of the 8 GHz correlator). In future years the intention is to map in N_2H^+, HCO^+, HCN, SO, CH_3CN and CH_3OH, as well as in several of their optically thin isopotomers. These lines have critical densities ranging from 10^3 to 10^6 cm^{-3}, and so will allow the distribution of the molecular gas, as well as the turbulence, to be determined across the full range of environments present.

The scientific objectives of this program require data to be obtained of the distribution of a variety of atomic and molecular lines, as well as infrared and sub-mm wave continuum data, in order to complete this characterisation. These include:

- ❖ Atomic data through the ATCA HI Galactic plane survey (McClure-Griffiths et al 2001).

- ❖ Mid-IR imaging data through the public release of the Spitzer GLIMPSE survey along the Galactic plane (Benjamin et al 2004).

- ❖ Sub-mm continuum data from a survey that could be conducted by the APEX telescope.

- ❖ Sub-mm line data of higher rotational lines that could be obtained by a survey conducted by the NANTEN2 telescope (e.g. J=4-3 CO), to measure the temperature distribution within the gas.

There are clear synergies with the capabilities of other facilities that need to be established in order to achieve the goals of this program. The installation of the complete 8 GHz correlator system on Mopra will allow the survey to be conducted in up to 8 lines simultaneously, a capability that no other telescope provides. The area mapped, however, will remain limited to degree-sized regions unless a focal plane array can be added at Mopra.

References
Ballesteros-Paredes & Mac Low, 2002, Ap J, 570, 734.
Klein et al., 2003. Rev. Mex. A&A, 15, 92.
Klessen, Heitsch & Mac Low, 2000, Ap J, 535, 887.
Larson, Rep. Prog. Phys., 66, 1651.
Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125.
McClure-Griffiths et al., 2001, Ap J, 551, 394.
Shu, Adams & Lizano, 1987, ARA&A, 25, 23.

Star Formation in the Magellanic System as a low-metallicity analogue for the early Universe

Did stars form in the same way at high redshift as they do today? The small angular sizes of distant galaxies means that only integral star forming properties can be derived. Moreover, their faintness limits observation to intrinsically luminous objects. The detected galaxies are consequently exceptional objects and not representative of typical galaxies at the dawn of galaxy formation. Fortunately, there is a type of nearby galaxy which may have similar properties to those in the early Universe: dwarf irregular galaxies. In particular, the nearby Magellanic Clouds are excellent testbeds due to the following properties: low metallicity (LMC: 30% solar, SMC: 10% solar), proximity (with about 50-60 kpc distance they are among our closest neighbours), and the high UV radiation in the LMC. In addition, the LMC harbours the most massive star forming region in the Local Group – 30 Doradus. The conditions in the Magellanic system may thus emulate conditions in the early Universe. Importantly, the Magellanic system can only be observed from the southern hemisphere, which makes it a prime target for Australian millimetre facilities.

Observations of molecular gas in the Magellanic Clouds can teach us much about the physics and chemistry of interstellar matter under low metallicity, high UV-field conditions. Not surprisingly, the ISM of both Clouds has been a topic of intense study, with virtually every infrared and radio facility undertaking surveys of both galaxies. Indeed, a survey of the LMC with Spitzer is currently underway. Perhaps the best-known single image from the ATCA is the HI synthesis map of the LMC.

Building on the complete CO survey produced by the 4-m NANTEN telescope, a program is underway at Mopra to map some of the molecular clouds identified at the higher spatial resolution of ~10 pc, making use of the newly implemented on-the-fly mapping technique. These improved CO maps will, in turn, stimulate follow-up observations of selected regions in additional lines with Mopra and ATCA. Some of the scientific goals for this program are described below. These studies can readily be augmented with measurements of higher-frequency transitions using Chilean or Antarctic facilities, to provide temperature and chemistry information, where appropriate.

The Cloud Mass Spectrum for Molecular Clouds

The mass spectrum of molecular clouds, $dN/dM \sim M^{\alpha}$, is a standard empirical test for numerical models of ISM structure (e.g. Wada et al. 2000). The low-mass end of cloud mass spectrum is sensitive to the ambient UV field, and is used to constrain models of energy feedback by young stars and supernovae. The upper mass limit of clouds, on the other hand, reflects the efficiency of turbulent mixing in the ISM. The cloud mass spectrum for the LMC has recently been calculated with the NANTEN ^{12}CO survey data, and was found to be steeper ($\alpha = -1.9$) than for molecular clouds in the Milky Way disk ($\alpha = -1.6$, Fukui et al. 2001). While a possible explanation is that the molecular clouds in the LMC are strongly dissipated by an intense interstellar radiation field, the NANTEN ^{12}CO survey did not have sufficient spatial resolution to accurately characterise the low-mass end of the mass spectrum. At 115 GHz, the Mopra beam is 33″, corresponding to a spatial scale of 8 pc at

50 kpc, so resolving clouds ~6 times smaller than NANTEN. This will allow the low-mass end of the LMC cloud mass spectrum to be determined with confidence.

Measuring the Size-Linewidth Relation for LMC and SMC Molecular Clouds

In the Milky Way, molecular clouds are observed to exhibit highly supersonic motions and a wealth of structure on all scales (e.g. Larson 1981, Elmegreen & Scalo 2004). The supersonic motions are such that the velocity dispersion of molecular clouds has been found to vary as the square root of the length scale (e.g. Heyer & Brunt 2004). Reproducing the observed size-linewidth relation has become an important test for theoretical models of ISM kinematics, especially those that investigate potential driving mechanisms for interstellar turbulence (see e.g. Mac Low & Klessen 2004, Bonnell et al. 2005). The size-linewidth relation for molecular clouds in the LMC was measured with the NANTEN ^{12}CO survey data. It was found to be steeper, but roughly consistent with the relation found for Galactic molecular clouds. The major limitation of the NANTEN result is the small dynamic range of cloud sizes that can be probed (Mizuno et al. 2001). By contrast, a significant fraction of the LMC's small molecular cloud population can be resolved with Mopra at 115 GHz. The SMC habours an ISM of metallicities even lower than that of the LMC. High resolution measurements are imperative to resolve the small-angle structure; molecular observations using the ATCA can achieve a spatial resolution of a few parsecs.

Determination of the X Factor in Different Environments

The conversion factor, $X=N(H_2)/I(CO)$, is an empirical scaling factor from the velocity-integrated intensity of the ^{12}CO emission to the column density of molecular hydrogen. It is an extremely important parameter in observational cosmology, where it is used to estimate the total molecular mass of high-redshift objects. Previous Milky Way studies have determined X for Galactic molecular clouds using a variety of approaches, with most methods converging on $X \sim (1\text{-}3) \times 10^{20}$ cm^{-2} (K km/s)$^{-1}$ for the inner Galaxy (e.g. Solomon et al. 1987). However, the application of this standard value for X to low metallicity systems remains controversial, since those systems have low C and O abundances, high ambient radiation fields (i.e. enhanced CO photodissociation) and low dust-to-gas ratios (i.e. reduced shielding). As the nearest, low-metallicity ISM that we can observe, the Magellanic System represents a unique opportunity to directly measure X in conditions that may resemble those in the early Universe. Preliminary results from a Mopra survey of the molecular gas near 30 Doradus in the LMC suggest that X varies as function of the radiation field surrounding 30 Doradus. Measuring X for a large population of molecular clouds in the LMC and other nearby galaxies will provide a critical reference value for this result.

References

Bonnell, I.A. Bate, M.R., 2005, MNRAS, 362, 915
Elmegreen, B.G.; Scalo, J., 2004, ARA&A, 42, 211
Fukui, Y., Mizuno, N., Yamaguchi, R., Mizuno, A., Onishi, T., 2001, PASJ, 53, L41
Heyer, M.H. & Brunt, C.M., 2004, ApJ, 615, L45
Larson, R.B., 1981, MNRAS, 194, 809
Mac Low, M.-M., Klessen, R.S., 2004, RvMP, 76, 125
Mizuno, N., Yamaguchi, R., Mizuno, A., Rubio, M., Abe, R., Saito, H., Onishi, T., Yonekura, Y., Yamaguchi N., Ogawa, H., Fukui, Y., 2001, PASJ, 53, 971

Solomon, P.M., Rivolo, A.R., Barrett, J., Yahil, A., 1987, ApJ, 319, 730
Wada, K., Spaans, M., Kim, S., 2000, ApJ, 540, 797

Star Formation and the Interstellar Media of Galaxies

Star formation in galaxies is observed to follow two simple empirical laws. The first is a correlation between the star formation rate and the average gas density, known as the Schmidt law: Σ_{SFR} proportional to Σ_{gas}^{N}, where N ~ 1.4 (Kennicutt 1998). The second is that below some "threshold" gas surface density, star formation is observed to fall off sharply. These simple laws are often incorporated into galaxy evolution recipes, yet their origin is poorly understood. For instance, studies which spatially resolve the gas distribution in galaxy disks (Wong & Blitz 2002, Heyer et al. 2004) find a wide range of Schmidt law indices *within* galaxies, making it unclear why on a galaxy-wide basis the Schmidt law is obeyed. These studies also emphasize that it is the molecular, not atomic, gas that is correlated with recent star formation, a fact which may be relevant to the origin of the star formation threshold. There is evidence that the star formation threshold is related to gravitational instability (Martin & Kennicutt 2001, Dalcanton et al. 2004), suggesting that molecular clouds can only form in gravitationally unstable disks. On the other hand, molecular clouds may not necessarily be gravitationally bound entities, and their formation may instead depend more on the external pressure. In this interpretation, the star formation threshold is a result of insufficient pressure to allow cold gas to exist in equilibrium with warm gas.

High-resolution studies of nearby galaxies in tracers of different interstellar gas densities will help us to understand large-scale star formation. Studies of the Milky Way emphasise that the efficiency of star formation is low in a molecular cloud as a whole, but high on the scale of dense (> 10^5 cm^{-3}) molecular cores. With the sensitivity of millimetre arrays like ATCA, and eventually ALMA, it will be possible to map out the distribution of dense molecular gas in nearby galaxies using tracers such as HCN, HCO^+ and CS. The HCN luminosity of galaxies has been argued to be a linear tracer of the star formation rate (Gao & Solomon 2004), though these conclusions are still based on global averages. Comparison of HCN maps with infrared and CO maps at ~5" resolution will help to verify this claim and give us deeper insight into how the dense gas mass can be predicted from the overall gas content (traced by HI and CO) and other galaxian properties.

Finally, an important, but poorly understood relation in extragalactic astronomy, is the correlation between the far–IR and radio continuum emission in star-forming galaxies. This correlation is so strong that radio emission is often used as a measure of the star formation rate as well as a tool to pinpoint high-redshift submillimetre galaxies. Yet its origin remains puzzling, given that it ties together a thermal process (radiation from young stars) with a non-thermal process (diffuse synchrotron emission). One possibility that is often discussed to explain this correlation is a coupling between magnetic field strength and gas density, but direct evidence for this coupling is still scarce. With ATNF facilities it is possible to attack both sides of this relation: measuring the cm-band radio continuum as a probe of the magnetic field strength, and measuring the HI, CO and denser gas tracers as a probe of the gas density. Such a study has already been underway for the LMC, where the resolution allows the relation to be readily investigated over the scale of individual giant molecular cloud complexes (Hughes et al. 2006). Such studies could readily be expanded to other well-resolved galaxies.

References

Dalcanton, J.J., Yoachim, P., & Bernstein, R.A. 2004, ApJ, 608, 189

Gao, Y., & Solomon, P.M. 2004, ApJ, 606, 271

Heyer, M.H., Corbelli, E., Schneider, S.E., & Young, J.S. 2004, ApJ, 602, 723

Hughes et al. 2006, MNRAS, in press

Kennicutt, R.C. 1998, ApJ, 498, 541

Martin, C.L., & Kennicutt, R.C. 2001, ApJ, 555, 301

Wong, T., & Blitz, L. 2002, ApJ, 569, 157

The Star Formation History of the Universe: molecular clouds at high redshift

Constraining the epoch of maximum star formation for both Milky Way-type galaxies and the more massive elliptical galaxies is vital in distinguishing between the various galaxy formation and evolution models. To do this, one looks to the molecular gas, which provides both the fuel for ongoing star formation as well as pinpointing the sites of chemical enrichment from earlier stellar populations. The most abundant molecule (by four orders of magnitude) is H_2, but it cannot be observed directly. Instead we observe the tracer dipolar molecule CO, whose rotational transitions are caused primarily by collisions with H_2. The relative strengths of the transitions allow us to probe hitherto unknown astrophysics, for example, characterising the temperature, density and kinematics of the massive gas reservoirs.

Thanks to the increased sensitivity of radio telescopes and interferometers over the last decade, it is now possible to observe CO emission in galaxies at cosmologically important distances. To date, there have been 36 detections of CO from galaxies above $z > 1$ (see Solomon & vanden Bout 2005 for a detailed review of high redshift molecular gas). The interferometers capable of detecting CO redshifted into an observable passband are all in the northern hemisphere, aside from the ATCA. With the advent of the new millimetre systems at the Compact Array, the southern hemisphere has been opened up to the high redshift universe for molecular line studies.

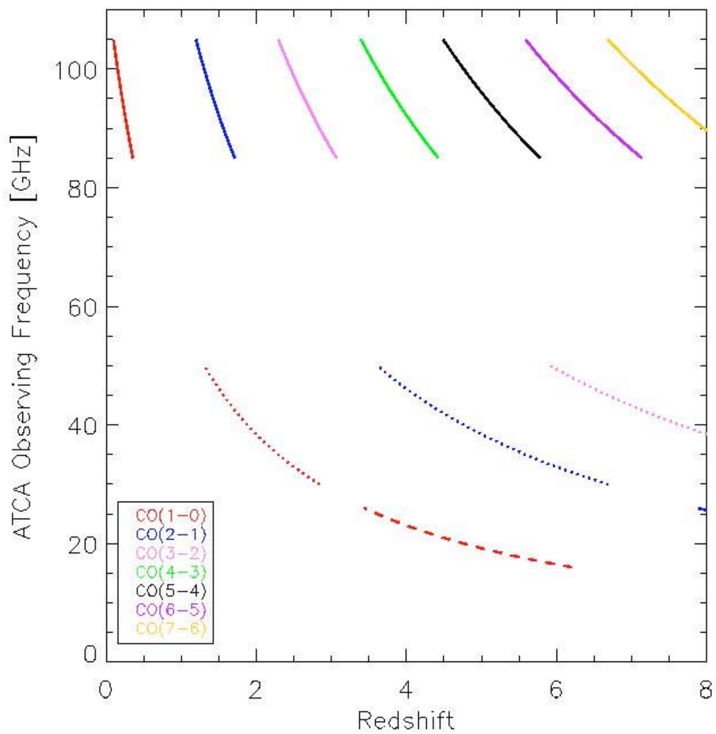
The present state of high redshift CO observations

The majority of the high redshift CO detections have been made with northern hemisphere millimetre interferometers at frequencies which place the lines in the 100 GHz (3 mm) band. The lowest CO transition accessible in this band, for sources at redshift > 2, is the CO J=3–2 line, with a rest frequency of 346 GHz and a critical density of $\sim 10^5$ cm^{-3} for its excitation. However, it is important to realise that the critical density of the lowest CO J=1–0 line is more than an order of magnitude lower than this. Thus, while higher–J transitions of CO will therefore be most luminous in the densest regions of the molecular gas reservoirs, they may not necessarily trace the entire molecular distribution if the reservoirs are replete with gas which is below their critical density. If the molecular gas in these galaxies is distributed over different spatial scales, in the sense that there are high density regions contained within a pool of low density gas, then observations of high–J transitions will miss most of the molecular gas. This will lead to mass estimates which are lower, and to higher densities, than those which apply to the global distribution of the molecular gas (Papadopoulos et al. 2001). This is especially important for those sources where the CO emission from a compact region is amplified by a foreground gravitational lens, because any extended low-density gas would go undetected.

In order to trace the total extent of the molecular gas in a galaxy, as well as the molecular gas which is relevant for star formation, it is vital to observe both high and low–J transitions of CO in a given galaxy. In this regard, the ATCA has the distinct advantage over other millimetre telescopes and can greatly enhance our current understanding of chemical enrichment and star formation in the distant universe.

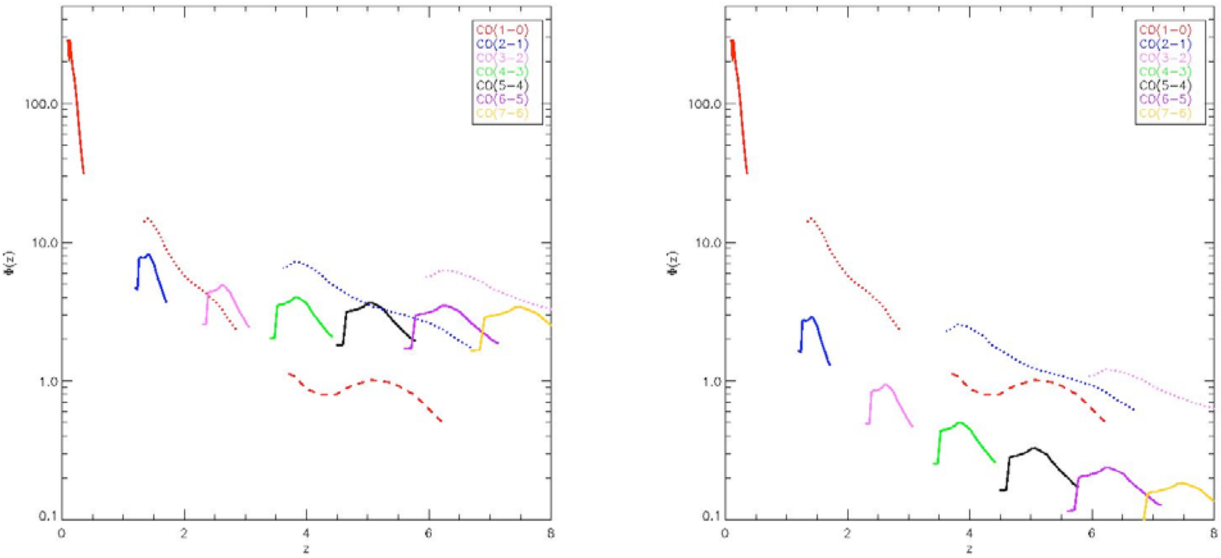
High Redshift CO windows with the ATCA

The lowest rotational transition of the CO molecule is CO J=1–0 at 115 GHz, with higher transitions increasing in a geometric progression of a factor of two. Since the 3 mm system is (currently) not capable of observing at frequencies above 105 GHz, any CO observations made with the ATCA must be targeted at sources located beyond a redshift of about 0.1, where the observed emission / absorption line is redshifted into an available observing window. These redshift windows, which include the anticipated 7 mm system, are illustrated in the Figure below.



High Redshift CO windows accessible to the ATCA with the 3 mm (solid line), 7 mm (dotted lines) and 12 mm (dashed lines) systems. These correspond to the three bands on the y-axis, from 85-105, 30-50 and 16-25 GHz, respectively. CO transitions start from J=1-0 at the left, and increase (i.e. 2-1, 3-2 etc) with redshift.

For a galaxy whose redshift lies in the range where more than one CO transition is accessible at the ATCA, it is useful to know a priori which transition should be pursued in the initial detection experiment. The normalised relative CO detection sensitivity for CO searches with the ATCA is shown in the Figures below for targetted searches (when the source redshift is known) and for blind searches (when it is not, and the complete bandpass needs to be searched). Larger efficiencies mean that is easier to detect the line. In making these calculations the system temperatures of the ATCA are 3, 7 and 12 mm are used, together with the assumption that the molecule is thermally populated with the same excitation temperature for all levels being studied (this implies that their intensity varies as J^2). For example, at a redshift of 5.2, three lines might be observed; CO 1–0 in the 12 mm window, 2–1 at 7 mm and 5–4 at 3 mm. For a targeted search these Figures suggest that the 3 and 7 mm bands will be equally efficient, however for a blind search the 7 and 12 mm bands provide a better combination to use.



Left: The normalised relative CO detection efficiency using the 2 GHz backend with the ATCA at 3 mm (solid lines), 7 mm (dotted lines) and 12 mm (dashed lines), as a function of redshift, for a targetted survey (i.e. when the source redshift is known). CO lines measurable at each redshift are indicated by the colour code, with J=1–0 on the left and increasing to right. The source brightness temperature is assumed to be the same for all lines at a given redshift. Right: The same figure, for a blind search. In this case the source redshift is unknown, so that measurements have to be made across the entire observing band.

References

Papadopolous, P., Ivison, R., Carilli, C., Lewis, G., 2001, Nature, 409, 58.
Solomon, P.M. & vanden Bout, P.A., 2005, ARAA, 43, 677.

The Cosmic Microwave Background Radiation

The 2.7K cosmic microwave background radiation (CMBR) provides the observational basis for our understanding of cosmology, including the advent of structure in the universe leading to the formation of galaxies and the first stars. Of particular interest is measuring the polarization of the CMBR and correlating this with temperature anisotropies in the CMBR signal, for this provides constraints on the structure, evolution and ionization history of the universe. In addition, polarization measurements will enable degeneracies in critical cosmological parameters obtained from the temperature anisotropy power spectra to be broken. The amplitude of the polarization is exceedingly small, only about 10^{-6} of the CMBR signal itself. The Planck satellite, to be launched in 2007, has as its main objective to determine the polarization, mapping the CMBR across the sky at nine frequencies simultaneously from 30 to 857 GHz with angular resolutions greater than 10 arcminutes, to an accuracy of one microkelvin. The separation of the Galactic and extragalactic foreground radiation from the primordial cosmological background signal is critical to achieving the scientific objectives of the mission. This provides an opportunity for Australian facilities to contribute. The Planck data needs to be calibrated, requiring polarization calibrators across the millimetre wavebands to be determined. Polarized foreground signals then have to be removed from the dataset. Observations with the ATCA at high angular resolution at 20, 40, 80 and 100 GHz are extremely important for achieving this in the southern hemisphere. No other facility will be capable of these measurements until ALMA is completed.

Unique Objects

SN1987A in the LMC

SN1987A in the Large Magellanic Cloud was the nearest and brightest supernova in nearly 400 years. In the radio it was a short-lived supernova, fading rapidly below detection limits (Turtle et al. 1987). It re-appeared in 1990, around day 1200, found with the MOST telescope at 843 MHz (Stavely-Smith et al. 1992). Since then it has been steadily brightening in the radio, with a power law index of -0.9 consistent with optically thin synchrotron radiation (Ball et al. 2001, Manchester et al. 2002). The SNR is expanding at ~3000 km/s, and slowing down as it encounters a density enhancement in the surrounding ISM. The radio emission is generated by the shock wave associated with interaction of the ejecta with circumstellar gas from the red giant phase of the pre-SN star. There is a clear shell-structure to the radio emission, arising from a barely-resolved region ~1.6″ across. The shell is enhanced on its east and west sides, corresponding to optical emission from a ring resolved by the HST, where the interaction of the ejecta with the pre-SN circumstellar material is occurring. As more and more material continues to be overrun, the radio flux will continue to increase – we are witnessing the birth of a radio SNR.

At 8.6 GHz the ATCA can achieve a resolution of 1.6″, and with super-resolution imaging applied to high S/N data, achieve 0.5″ (though with lower dynamic range). This is barely sufficient to resolve the emission. At higher frequencies the achievable spatial resolution is higher. With the new 12 mm system, Manchester et al. (2005) have imaged the SNR at 19 GHz with a diffraction limit of 0.5″ (0.25″ after super-resolution). A thick equatorial ring is seen, with a string of knots around its circumference.

In the 7 mm band the resolution would be a factor of two higher; i.e. 0.25″ diffraction limit, and ~0.1″ after super-resolution. Based on the 20 mJy flux at 12 mm, the flux should be ~10 mJy at 7 mm, sufficient to apply super-resolution. At 3 mm the flux will be ~5 mJy, sufficient for imaging with reasonable S/N. However with only a 300m baseline available the resolution of 2.5″ is insufficient to resolve any structure. If 3km baselines could be achieved at 3 mm this would improve the resolution to 0.25″, so allowing the structure to be studied at this wavelength. The flux itself at 3 mm provides a constraint on shock models, in particular on where the synchrotron spectral index turns over.

The increasing flux density of SN1987A over the next decade will improve the quality of imaging, allowing more detailed comparison of the optical, X-ray and radio images as the SNR expands. This should help our understanding of the relationship between the emission processes observed in these different wavebands, in particular whether the acceleration of the radio synchrotron electrons occurs at the reverse shock where the ejecta overruns the circumstellar shell.

References

Ball, L., Crawford, D.F., Hunstead, R.W., Klamer, I. & McIntyre, V.J., 2001, ApJ, 549, 599.

Manchester, R.N., Gaensler, B.M., Wheaton, V.C., Staveley-Smith, L., Tzioumis, A.K., Bizunok, N.S., Kesteven, M.J. & Reynolds, J.E., 2002, PASA, 19, 207.

Manchester, R.N., Gaensler, B.M., Staveley-Smith, L., Kesteven, M.J. & Tzioumis, A.K., 2002, ApJL, 628, L131.

Staveley-Smith, L. et al., 1992, Nature, 355, 147.
Turtle, A.J. et al. 1987, Nature, 327, 38.

The Central Molecular Zone of the Galaxy

The central regions of our Galaxy provide a unique region for studying for a variety of phenomena, one of which is the "Central Molecular Zone". As described by Morris & Serabyn (1996), extending approximately 1.5° either side of the Galactic Centre along the plane, and 0.8° out of it (i.e. ~450 x 240 pc), lies a molecular zone prominent in CO (carbon monoxide) line emission, as well as in far-IR dust emission. Containing ~10^8 $M_\odot$ of molecular gas, this is about 10% of the total molecular content of the Galaxy, with the IR emission accounting for about 10% of the Galaxy's luminosity. It is quite different in nature to molecular clouds found elsewhere in the Galaxy, such as in the 3–5 kiloparsec Galactic Ring. Temperatures are higher (up to 200 K), densities exceed 10^4 cm^{-3} throughout, turbulent velocities are high (in the range 15–50 km/s) and molecular surface densities are several hundred $M_\odot$ pc^{-2} (more than a order of magnitude greater than in the galactic ring). Elsewhere in the Galaxy such densities are only found in cloud cores rather than extended over entire cloud complexes, but this is necessitated by the need to withstand tidal shearing in the central regions. The Central Molecular Zone is a very different environment to that in which star formation has been studied in either nearby clouds to the Sun or in the GMCs of the Galactic Ring.

Perhaps most surprisingly the Central Molecular Zone (CMZ) is rich in organic molecules, and these appear to be widespread throughout it. Yet, while the prominent cloud of Sgr B2 in the CMZ is well studied (it contains about 10% of the CMZ's mass, the largest column density along any site line in the Galaxy, as well as every exotic molecular species so far found in the interstellar medium), the rest of the CMZ is little studied outside the CO lines. However, it is clear from CH_3OH (methanol) measurements made at 834 MHz (a K-doubling 1^+ - 1^-) transition) made with a 40 arcminute beam, that the emission is extended even on this scale (Gottlieb et al 1979). From HNCO (isocyanic acid) mapping at 110 GHz with a 9 arcminute beam by Dahmen et al (1997), made fortuitously at the same time as a $C^{18}O$ map of the CMZ (the line fell in the same bandpass), the organic species are seen to be extended on much the same scale as the far more abundant CO molecule. This is completely unexpected and unexplained. While organic reservoirs have indeed been found to be common in molecular clouds, they have been confined to hot molecular cores associated with massive star formation - i.e. regions of order 0.1 pc in size, not the ~10 pc scales associated with GMC-complexes, let alone the ~100 pc size-scale associated with the CMZ.

The composition and distribution of the molecular content of the CMZ, as discussed by Menten (2004), provides a unique environment to study in our Galaxy, though it may perhaps be closer in physical characteristics to that found in the molecular clouds in starburst galaxies? This distribution needs to be mapped in a variety of molecules before it can be understood, to see how they compare and contrast, in particular with conditions in the very much smaller hot molecular cores. Why are organic molecules so widespread throughout the CMZ? Which ones are present? However there have been no facilities able to undertake this project until now, as it requires a combination of large area coverage, multi-line capability and good spatial resolution. With the new 8 GHz correlator on Mopra it is now possible to conduct such a mapping survey in several lines simultaneously, utilising OTF mapping and a 35 arcsecond beam. For instance, in one setting, lines from HC_3N, CH_3OH, OCS, C_3H_2, CH_3CCH, $H^{13}CO$, SiO, CCH, HNCO, HCN and HCO^+ could be measured from 81–89 GHz, while with a second setting from 90–98 GHz, lines from HNC, HC_3N, CH_3CN, N_2H^+, CH_3OH, OCS, CH_3OH and CS. However to map the full extent of the CMZ will remain a time consuming task if using a single beam receiver. It would take 3-4 seasons to complete even with 2 months of allocation per season. This is a project which calls for a multi-beam device, or a focal plane array, for its efficient conduct.

References

Dahmen, G. et al., 1997, AASup, 126, 197.
Gottlieb, C. et al., 1979, Ap J, 227, 422.
Menten, K., 2004, Proc 4th Cologne-Bonn-Zermatt Symposium on the Dense Interstellar Medium in Galaxies.
Morris, M. & Serabyn, E., 1996, ARAA, 36, 645.

Sgr A^*

Sgr A^*, the radio source at the centre of the Galaxy, also provides a unique object for study. It is the only black hole in the universe with potentially observable event horizon effects. Detection of the linear polarization at 3 mm provides constraints on the accretion rate and accretion process within several hundreds of Schwarzchild radii of the Black Hole (e.g. Aitken et al. 2000). VLBI measurements at mm and sub-mm wavelengths can provide resolutions comparable to the Schwarzchild radius. These are challenging observations, as Sgr A^* lies behind a screen of turbulent interstellar plasma that scatters radio waves and broadens the images obtained by VLBI. VLBI at 7 mm (Bower et al. 2004) has detected a 24 R_{sch} size object for Sgr A^*, and a limit of 20 R_{sch} at 3.5 mm obtained. Sparse UV-coverage and low elevations, due to the northern hemisphere location of all telescopes so far used for these types of studies, limits their utility. Polarized emission is expected from an accretion disk, with a level of about 1% at 3 mm. ATCA would be the best telescope available for making such observations due to its southerly location if it was equipped with noise diodes that would allow it to make 3 mm polarization measurements.

References

Aitken et al. 2000, Ap J, 535, L173.
Bower et al. 2004, Science, 304, 704.

Capabilities and Needs

The table below summarises the capabilities required to tackle the science programs described in this section.

Driver	Disks	Bio Mol	Early MSF	Turb SF	MC SF	SF Gals	High-z SF	SN 87A	CMZ	SgrA*	CMBR
3 mm	X	X	X	X	X	X	X	X	X	X	X
7 mm	X	X	X	X	X		X	X	X	X	X
12 mm	X	X	X	X	X		X	X	X		X
Line	X	X	X	X	X	X	X		X		
Continuum	X		X		X			X		X	X
Mopra		X	X	X	X				X		
ATCA	X	X	X	X	X	X	X	X	X	X	X
Tidbinbilla / Parkes			X	X							
OTF mapping			X	X	X				X		
Wide correlator MOPS/CABB	X	X	X	X	X	X	X	X	X	X	X
Noise Diode 3 mm	X	X	X	X	X	X	X	X	X	X	X
WVR 3km @ 3mm	X	X	X		X	X		X		X	X
Tilt sub-reflector	X	X	X	X	X	X	X	X	X	X	X
77-116 extension	X		X		X	X	X	X			
10^6 ch correlator 2sidebandMOPS		X	X	X	X		X		X		
pFPA / multi-beam			X	X	X	X	X		X		

Facility Developments

Here we discuss a number of technology developments at ATNF that are underway or in the planning stage.

Receivers

ATCA 7 mm receivers

This project will expand the frequency coverage of the Australia Telescope Compact Array (ATCA) by providing a new observing capability within the frequency band 26 to 50 GHz, the so-called 7 mm band. It will be achieved by installing a new feed horn and receiver channel in the existing ATCA mm-wave receiver packages. These receiver packages were designed to accommodate three frequency bands in the one cryogenic dewar, at 12, 7 and 3 mm wavelengths. The 12 and 3 mm band receivers are installed and operating. This project will retrofit the 7 mm band.

There are two main drivers for a 7 mm capability on the ATCA. A major goal of the project will be to satisfy these requirements in one receiver system.

- Astronomy, where the basic requirement is for maximum possible frequency coverage in the band 26 to 50 GHz. Science areas include redshifted CO, molecular spectroscopy (e.g. CS and SiO).
- NASA Deep Space Network spacecraft tracking, where the requirement is to meet a specified performance over a narrow frequency band from 31.8 to 32.3 GHz.

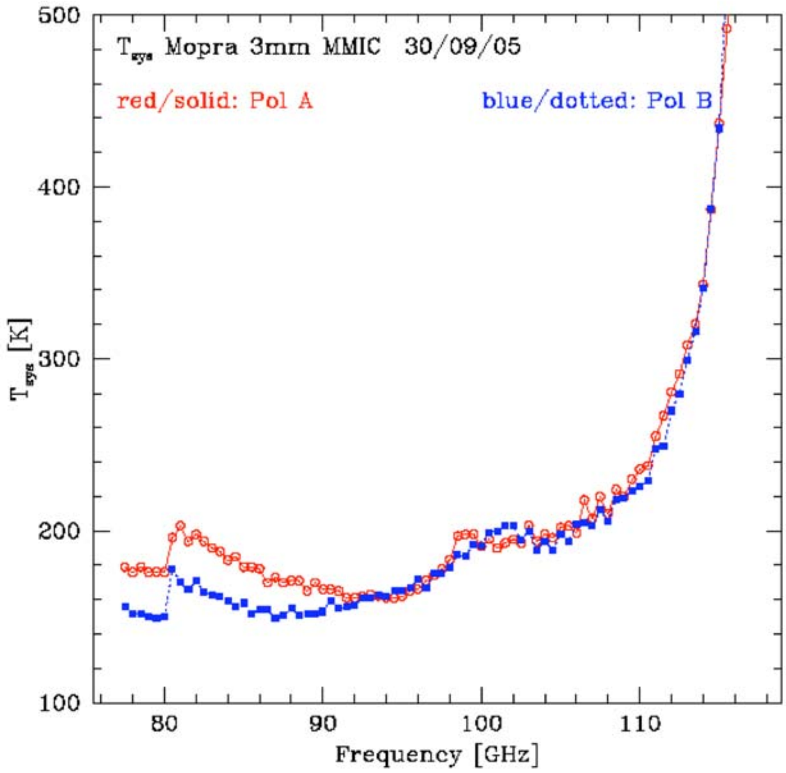
Completion is expected in 2007, with the receivers expected to cover 30–43 GHz, with somewhat degraded performance to higher frequencies, up to 50 GHz. Provision has been made for 2 spares, one of which can be installed at Mopra. The IF bandwidth is 8 GHz, of which CABB can process 4 GHz.

Parkes 12 mm receiver

A new single beam 16–26 GHz receiver, based on the ATCA receivers, will replace the outdated system currently at Parkes. Sensitivity should be improved by a factor of 3, and a larger part of the dish would be illuminated. The science case includes ammonia, water masers, VLBI and continuum imaging. Parkes is not as sensitive as Tidbinbilla in terms of effective aperture at this frequency, but has a better suite of correlators and is more routinely available for science.

Completion is expected in 2007. A second feed horn will allow dual circular polarization measurements for VLBI at 22 GHz. The main feed horn will service the 16–26 GHz band with dual linear polarization.

ATCA 3 mm bandwidth upgrade



The successful operation (since 2005 October) of the Mopra receiver from 77–116 GHz (see T_{sys} plot above) motivates a similar upgrade to the ATCA. This would nearly double the ATCA's current frequency range of 85–105 GHz and provide access to CO and its isotopes, transitions of several deuterated species, and improved sensitivity to dust emission. The upgrade would also include noise diodes for improving calibration and enabling polarimetry. The ATCA is currently the only mm interferometer that simultaneously measures two orthogonal polarisations.

Specific parts of the science case for 115 GHz extension:

- *Redshifted CO*: Several gaps in redshift space (1–1.2, 2–2.3, 3–3.4) could be filled in, and continuous coverage for $z > 2$ would become possible. Moreover, galaxies at $z < 0.1$ would become observable, including most sources detected by 2dFGRS and HIPASS.

- *Nearby galaxies*: Observations of CO and its isotopes enable studies of molecular gas and star formation, galaxy dynamics and chemical abundances. For the Magellanic Clouds these would enable unique, high-impact studies as no other interferometer can target these sources.

- *Photochemistry with CN*: This molecule has an important line at 113.3 GHz. Since CN is formed by the photodissociation of HCN – a process which can be modelled using detailed radiative transfer codes – it can be used as an indirect tracer of UV radiation in regions from which UV photons themselves cannot escape.

- *Methanol masers*: an important 107 GHz maser line, as well as thermal methanol line at 108.9 GHz will become accessible.

- *Dust continuum*: rises steeply with frequency ($\sim\nu^4$), more than offsetting the increase in T_{sys} until the top end of the band is reached.

ATCA 3 mm polarization upgrade

This would involve installing noise sources for polarimetry, a subset of the bandwidth upgrade above. The science case includes measurement of magnetic fields in the interstellar medium (a key test of turbulent vs. isolated star formation theories), high frequency polarization and Faraday rotation in Sgr A^*, and measurement of polarization of calibration sources and CMB foregrounds for Planck.

To calibrate the ATCA polarization it is only necessary to install the noise injection system on one telescope. Antenna based self-calibration ties all the antenna phases for X and for Y, then any one antenna can tie all the X's to all the Y's. The upgrade of one receiver could be performed during the 7 mm installation period in 2007; the parts for this are already in hand.

Spectrometers

Mopra Spectrometer (MOPS)

MOPS will be a broadband spectrometer for Mopra, with 32,000 channels across 8 GHz of bandwidth. The 8 GHz band will be divided into four overlapping 2.2 GHz windows. Each of the four windows can have two "zoomed" sub-windows of 137.5 MHz bandwidth. Both linear polarizations are processed. A future upgrade would be to allow both sidebands to be processed, giving a total bandwidth of 16 GHz with an 8 GHz gap in the middle (e.g. 89–97 GHz and 105–113 GHz).

This project is near completion, with operations scheduled for June 2006. A 2 GHz system was successfully commissioned in 2005.

Compact Array Broadband Backend (CABB)

This project will expand the maximum bandwidth of the ATCA from 128 MHz to 2 GHz, a factor of 16 improvement. Since ATCA is a dual-frequency system, the total bandwidth that could be covered simultaneously is 4 GHz. This will lead to improved sensitivity to continuum emission, multi-bit sampling for RFI mitigation, and zoom modes for multi-line studies. The technology is based on the polyphase digital filter bank demonstrated with the MOPS. It provides excellent isolation between channels and versatility to allow multiple sub-bands at different frequency resolutions.

This project is now underway. Early commissioning tests are scheduled for July 2007.

Million-channel Spectrometers

There is growing interest in wide-bandwidth spectrometers. Major science drivers include searches for molecular lines from sources of unknown redshift and of chemically rich regions in the Galaxy. Searches for biologically important molecules, which produce a "forest" of transitions, would become feasible. Ongoing developments include the 8 GHz ATCA analogue correlator and the 14 GHz Green Bank Telescope Zpectrometer, also an analogue device. The spectral resolution of these instruments is limited, however. By increasing to 10^5 to 10^6 channels across 10 to 50 GHz, it will enable efficient line surveys to be conducted. There is some confidence that the DFB architecture used in MOPS and CABB will eventually allow such developments over their 2–8 GHz bandwidths.

Other telescope upgrades

Active subreflector

The Mopra and ATCA dishes deform as a function of elevation and temperature, leading to changes in beam shape and efficiency. Installing an active primary surface would be expensive, but some improvement could be realised by allowing the subreflector to tilt in order to compensate for the dish deformation. Ideally this would be done with minimal user intervention. It would improve amplitude calibration, and assist mosaicing and scanning modes such as on-the-fly mapping.

An ATCA experiment using a tilting subreflector on one antenna has been tried with rather poor results, however the issues are now better understood so this could be revisited.

Water Vapour Radiometers

A major limitation of the ATCA is that baselines beyond 300 m have not been achieved when operating at 3 mm because of rapid phase fluctuations induced by water vapour fluctuations in the atmosphere. This limits resolutions at 3 mm to 3–5", which is insufficient to resolve many objects of interest. For instance, structure inside some circumstellar disks may be evident on 1" scales, as would be chemical stratification within hot molecular cores. If the maximum baseline of 3 km could be used, sub-arcsecond resolution would become possible at 3 mm. At the BIMA array at Hat Creek in California baselines as long as 2 km have been achieved for wavelengths of 1 mm, suggesting that it is not unreasonable to expect that 3 km could be achieved at 3 mm at Narrabri in the best conditions.

Real time phase correction might be implemented using a water vapour radiometer, through measuring the total power of the signal received from the atmosphere at each antenna, relating power fluctuations to those in the column of water vapour. A system for mm-VLBI has been successfully installed on the Effelsberg 100m telescope in Germany, and it might be possible to recover the loss of correlation using such a system with the ATCA.

Focal Plane Arrays / Multibeams

The small fields of view of millimetre-wave telescopes strongly motivate the ability to place multiple beams on the sky with a single reflector. The usual approach is a "multibeam" system like the Parkes 21 cm multibeam, where multiple independent feed horns are placed in the focal plane. This has been very successful with mm/sub-mm bolometer arrays (SCUBA, SIMBA, MAMBO). In addition, heterodyne array systems have become widespread, with the 32-pixel SEQUOIA array for FCRAO, the 9-pixel HERA array for the IRAM 30m, the 16-pixel CHAMP array for the CSO and APEX, and the 25-pixel BEARS array for the Nobeyama 45m all producing excellent results in recent years. The problem with installing such a system on Mopra is the relatively small focal plane due to the shaped reflector. Any system with more than 7 feedhorns would suffer degraded performance from the outer beams.

A "next-generation" alternative to traditional multibeam systems is a "phased array" which fully samples the focal plane. This requires a large number of closely spaced small elements, with signals from several adjacent elements combined to yield a beam that can be "steered" relatively freely across the sky. Within some limits, it is possible to correct for optical distortions (e.g. astigmatism and coma) by clever weighting of the element signals.

There are several issues particularly relevant for high-frequency work that need to be investigated further. How would an array receiver be cooled? Would it have to sit at the prime focus (probably – short focal ratios ~0.4-0.5 are preferred to reduce costs)? How many probes of the EM field are needed, and at what cost (probably a 10 x 10 array forming ~30 beams would be the minimum useful for science)? If the array is at the prime focus, how can spillover be minimised (can be eliminated by weighting schemes)? What are the LO power requirements, especially for 100 GHz? What are the advantages over traditional FPA's + OTF mapping (potentially better RFI cancellation and handling of antenna deformations)?

A 5 x 5 sub-array is under development at ATNF, to cover approximately 0.3–1.8 GHz. If successful, this would be incorporated into a 10 x 10 array for the NTD and xNTD. Subsequently one might consider developing a 22 GHz system for Parkes and possibly overseas telescopes. It seems unlikely that a 3 mm FPA for Mopra could be developed quickly (large number of receivers + large correlator requirements to get GHz bandwidths) – FPAs need first to developed that operate at longer wavelengths. A 12 mm pFPA at Parkes, would be the first device that might be constructed for mm-operation. This is because for operation at prime focus the number of elements needed is less than for cassegrain operation (as at Mopra or ATCA), since the number of elements scales as $(f/D)^2$.

Operations and Support

An important key to the longevity of ATCA and Mopra is fostering a strong international and national user community that will drive leading-edge science projects in the era leading up to and beyond ALMA becoming fully operational (in 2012?). This is facilitated by implementing innovative millimetre operation, calibration and data analysis techniques that make ATCA and Mopra extremely efficient, reliable and easy to use. The discussion in this section is devoted to how all of these requirements can be met at a relatively low cost compared to the initial A$9M already invested in millimetre receiver technology.

Operations at Mopra

In the past all Mopra observations had to be conducted at the telescope, due to the slow internet link to the site. This led to several difficulties: the lodge has only two bedrooms, making it difficult for several people to use the telescope around the clock, and access to staff support is generally only by telephone. Also, the lodge is only self-catering, and the supermarket is some distance away. To improve on this situation, several options are under consideration:

- Remote observing from Narrabri Observatory should be possible starting in mid-2006, with the recent introduction of a fast link. Narrabri offers ample accommodation, catering and computing.

- Remote observing from other sites. Relies most importantly on having an experienced user community that needs little support, and relatively robust software. It is unclear whether observers would process their data on Narrabri machines or request their data on DVD. This should be possible.

- Automated (robotic) operations. Not entirely clear how suitable this would be for smaller projects. It is certainly an attractive option for large surveys, but a great deal of effort on the software side would be needed to manage this. A particular challenge is the large data rates expected from the MOPS spectrometer. Even harder would be implementing weather-dependent observing programs.

We recommend that remote observing be trialled in 2006 from Narrabri, with careful attention paid to issues and problems raised by observers. If all goes well, remote observing from other sites could be trialled the following year. Robotic observations should be considered only if there is a clear constituency for long-term projects and if it would not place an extra burden on the observatory. The cost for visiting observers is a consideration, however, as university groups may not be able to afford to stay at the Narrabri lodge for extended periods.

Operations at ATCA

The ATCA is a mature telescope with a large, experienced user base. It is generally well-documented, and users report little difficulty with the observing system. There are a few areas where some improvement could be envisaged. We discuss these below.

It is difficult to specify a program entirely from start to finish. This is because the observing typically begins with a delay calibration that is performed interactively outside the normal observing program, and also because the current observing program is relatively limited in its capabilities. For example, it cannot loop over some sources and not others, it cannot make decisions about when to open and close datafiles, it cannot decide where to "pick up" after an interruption, and it cannot adjust observing times to end exactly at a chosen time. Thus the observer typically observes from two or more schedule files and switches between them manually. Enabling new capabilities would require some investment, but their feasibility has been demonstrated for many years by other arrays such as BIMA.

Data reduction, especially for spectroscopy, can be quite involved, and thus reducing archival data is difficult. This is especially the case at high frequencies. The situation has improved somewhat with the introduction of some data pipelines (e.g. the atcalib.csh script). However, there remains a fundamental limitation of discerning the observer's intentions when reducing archival data (which source is a phase calibrator, etc.). Operator error and system problems can also be an issue. This gets back to the first problem: by giving users the freedom to modify their observations in real time, it can become more difficult to figure out their observing strategy (if they have one!). On the other hand, some degree of flexibility encourages users to stretch the system in new and creative ways.

We recommend that high priority be given to enabling more automated observing and reduction. This should not be made so opaque that students do not have the opportunity to learn the basics, or so restrictive that experienced users cannot implement new observing modes. However, it should facilitate the use of the instrument by non-experts and remote observers, as well as re-use of archival data. In addition, it enables, though does not require, more flexible, weather-dependent scheduling in the future, as even an inexperienced observer or operator can run a schedule that has been well planned and specified.

Flexible scheduling at ATCA

At high frequencies especially, the success of observations depends critically on the weather. Ideally, there would be a queue of "backup" cm projects which could be observed when the weather is not suitable for mm observing. These projects could be inserted when necessary, i.e. if the weather was unsuitable for the original program. Conversely, one could override a low-frequency project with a high-frequency one if weather conditions were especially good. In such a system a fixed schedule is not possible, but efficiency is maximized and most highly rated projects will be observed in suitable weather. Many telescopes (mm, sub-mm and optical/IR) now operate in such a mode. However, it does require a significant up-front investment in software, good weather diagnostics, and detailed specification by proposers of what conditions they require.

The current mode of ATCA operation, where investigators supervise their own observations, does not permit fully flexible scheduling. As a compromise, a "swap" system is used by which mm and cm proposals are paired (the mm proposal being scheduled a few days earlier), and if the weather is unsuitable for mm observing the cm swap is observed instead. If the swap is invoked, the mm observer is in principle responsible for conducting both the cm and mm observations. Based on an analysis of the 2002 season, the provision of a swap increases the chances of observing in "good" weather from about 60% to about 80% in the winter.

A problem with the swap system is identifying suitable cm projects to swap with. This is especially a problem in very compact configurations such as H75, where the resolution is often too coarse for cm data to be in demand. There are a number of possible responses:

- Limit observing time in H75 to snapshot observations or more northerly sources that really require it. Many users like the high brightness sensitivity of H75 and not having to observe at low elevation. However, for longer integrations it is relatively inefficient at covering the visibility.

- Treat more broadly what qualifies as a possible swap partner. Current policy favours 1–5 GHz observations for swap partners, but there are few such projects that want compact arrays.

- Assign Director's time as swap partners. This keeps everyone happy, but it does mean that some time is spent doing unranked projects. However, given that oversubscription rates at the ATCA are fairly modest (1-2), it may be a practical alternative.

User support

An issue of some relevance to the mm community is maintaining a core of experienced mm observers on the ATNF staff. One might argue that this requirement is being met, but only marginally. Such people are needed to sound out the wishes of the larger community, interact with the engineering groups, and ensure that longer-term efforts to improve capabilities are carried out. At present many requests for support and documentation are directed towards postdoctoral fellows who may have the appropriate skills but must focus primarily on short-term research productivity.

Facilities in the Global Context

The key to the success of millimetre astronomy in Australia is the forging of international collaborations that give access to the best instruments, and to the complementary scientific expertise, needed for doing great science.

A Brief History of Millimetre Astronomy in Australia

The first millimetre-wave observations in Australia were in fact undertaken with the Anglo-Australian 3.9-metre optical telescope (AAT) at Siding Spring near Coonabarabran in northern NSW in 1975 and 1976. A receiver from Queen Mary College in London mounted at the Coudé focus of the telescope (Gillespie et al. 1977) was used to observe the 115 GHz J=1–0 transition of CO in southern molecular clouds and in the Large Magellanic Cloud (LMC). These observations resulted in the first detection of CO in the LMC.

Australia's first actual millimetre telescope was four metres in diameter (Gardner et al. 1978) and was constructed in 1976 at Epping, NSW, in the grounds of CSIRO's Division of Radiophysics (now the ATNF). First light was in 1977, using a receiver shared with the Parkes radio telescope that was able to observe frequencies around 85 to 90 GHz, and surveys of the J=1–0 transitions of HCO^+ and HCN were undertaken during 1977 and 1978 (Gardner et al. 1978). During this time the Parkes telescope was also used for millimetre operations, with the inner 16-metres having been resurfaced in 1976.

A strong science driver for the 4-metre telescope had been the desire to undertake a 115-GHz CO J=1–0 survey of the southern Galactic plane and so a CO receiver was fitted in 1980 and a survey of the Galactic plane undertaken (McCutcheon, Robinson & Whiteoak 1981).

In the early 1980's, when the Australia Telescope (AT) was being planned, a stand-alone telescope capable of single dish operation and suitable for millimetre operations was made part of the AT so that a millimetre receiver could be fitted in the future. This dish was situated at Mopra, close to the Siding Spring Observatory. The Mopra telescope is a 22-metre dish, but only the inner 15-metres was millimetre-capable. The SIS millimetre receiver itself was finally added in 1994, operating between 86 and 115 GHz, and Mopra was used for spectral line observations of Galactic molecular clouds and the LMC.

Funding received through the 1996 MNRF round then allowed the process of upgrading and equipping the ATCA antennas for operation at 3 mm and 12 mm to begin. This included replacing the outer mesh of the telescope with panels capable of 3 mm operation, building a north-south spur for the array to permit more rapid UV-coverage, the development of MMIC receivers for 3 mm and of a broad band correlator (i.e. the CABB), and the installation of a fibre optics network to all antennae to distribute the local oscillator reference signals.

In 1999 the University of New South Wales provided the resources to resurface the dish to use the full 22 metres for millimetre astronomy, and also provided a "Friend" of the telescope to assist with operations. In 2004 the capabilities of the telescope were further extended with the development of an on-the-fly mapping mode of observations allowing large-scale maps to be made quickly. In 2005 the SIS receiver was replaced by a MMIC receiver, extending the frequency range from 77–116 GHz.

The latest development for Mopra will commence operations at the beginning of this winter: an 8-GHz, 32,000 channel digital filter bank will exploit the wide bandwidth of the MMIC receivers and allow simultaneous observations of up to eight transitions simultaneously. This has been funded by a university consortium through an ARC LIEF grant.

What Australia Can Offer

Australia has much to offer overseas astronomers in collaborative activities:

- ❖ An established and highly regarded cm-band interferometer that is used extensively by international investigators, as well as a vibrant radio astronomy community.

- ❖ Excellent instrumentation for the 3-mm and 12-mm bands at high spectral resolution (Mopra, ATCA, Parkes and Tidbinbilla), and soon at 7 mm. These wavebands provide complementarity to those that will be available with ALMA, APEX, ASTE and NANTEN2 (see below). From 2006 the Mopra telescope will have 8 GHz of bandwidth available at 3 and 12 mm, giving the telescope an unmatched capability to undertake multi-line surveys.

- ❖ Instruments that are currently available, several years ahead of the commissioning of ALMA. This provides a window of opportunity to undertake the surveys that will be used as pathfinders for ALMA science, as well to form the collaborations that will allow Australian participation in the facility.

- ❖ Great strengths in developing and using cutting-edge instrumentation, as evidenced by the many outside contracts held by ATNF (e.g. the technology developed for the Parkes HI multibeam translated into contracts for the Alpha multibeam for Arecibo, the methanol multibeam for Jodrell Bank and the 8 GHz digital filter bank for Mopra). The community needs to consider how to use this expertise to develop new instrumentation (e.g. focal plane arrays), particularly those that may complement the capabilities of overseas facilities. ARC LIEF grants are one mechanism that could be used to help fund such developments, leveraging international collaboration in such ventures to make them attractive to funding agencies.

Synergies with Other Telescopes

Synergies with telescopes in the northern hemisphere exist for southern telescopes to provide full-sky coverage. This has been used many times over the history of astronomy in Australia to gain collaborations, instruments and facilities, and remains relevant today (e.g. as currently planned for Sky Mapper and the University of Wisconsin H-alpha mapper at Siding Spring).

There are also a number of telescopes in the southern hemisphere that have potential synergies with Australian millimetre-wave facilities, and it is on these that this discussion concentrates. Their capabilities are summarised below.

Synergies with Chilean Telescopes

There are four Chilean Telescopes that have obvious relevance:

Atacama Pathfinder Experiment (APEX)
http://www.apex-telescope.org/

APEX, the Atacama Pathfinder Experiment, is a collaboration between Max Planck Institut für Radioastronomie (MPIfR) at 50%, Onsala Space Observatory (OSO) at 23%, and the European Southern Observatory (ESO) at 27%. The APEX telescope is a 12-metre sub-millimetre telescope located on the 4,800 m high Chajnantor plateau in the Atacama Desert (Chile).

APEX has been operational since the austral winter 2005, and is currently equipped with a heterodyne receiver tunable in the range 279–381GHz. LABOCA is a 295-pixel, 870 μm bolometer array under construction at MPIfR.

In the future APEX will be equipped with SIS heterodyne receivers covering the bands at 211–275 GHz, 275–370 GHz and 385–500 GHz, a heterodyne HEB receiver operating at 1.25–1.39 THz, and a bolometer array operating at 350 μm.

Partners	MPIfR, Sweden (Onsala) and ESO.
Description	Vertex 12-m "ALMA" antenna used as a single dish and modified to accommodate Naysmith foci. Surface RMS 20 – 25 μm. Open air telescope.
Frequencies	1300 and 850 μm MPIfR bolometer arrays, 460/490 GHz heterodyne array, other single beam heterodyne receivers.
Site	Chajnantor Plateau (5000 m).
Science Program	Facility telescope for European community to replace SEST.
Status	Operational. Official opening September 2005.

NANTEN2 Telescope
http://www.ph1.uni-koeln.de/workgroups/astro_instrumentation/nanten2/

The NANTEN2 telescope is located at an altitude of 4,800 metres at Pampa la Bola in the Atacama desert in northern Chile. It is a 4m telescope that will operate between 230 and 880 GHz and be used to survey the southern sky in molecular and atomic spectral lines between 230 and 880 GHz. It is expected to commence operations in early 2006.

Australia has been invited to join the NANTEN2 consortium, and an ARC LIEF grant has been submitted in 2006 by the Universities of New South Wales, Sydney and Macquarie to provide a ground station in order to accept this invitation.

Partners	Japan (Nagoya University and Osaka Prefecture University, Germany (University of Cologne and University of Bonn), South Korea (Seoul University), Chile (University of Chile). Australia (UNSW) and Switzerland (ETH Zurich) are negotiating membership.
Description	4 m Cassegrain system.
Frequencies	Frequencies between 230 and 880 GHz. The highest observing frequencies are covered by the KOSMA SMART receiver, a dual-frequency, 2x8 pixel array receiver operating between 460 and 880 GHz. KOSMA Acousto Optical Spectrometers (AOS) are used as backends.
Site	Pampa la Bola (4850 m).
Science Program	NANTEN2 will be used to survey the southern sky in molecular and atomic spectral lines between 230 and 880 GHz.
Status	Operations to commence 2006.

Atacama Submillimeter Telescope Experiment (ASTE)
www.ursi.org/Proceedings/ProcGA05/pdf/JB2.1(01099).pdf

The Atacama Submillimeter Telescope Experiment (ASTE) is a 10 metre Japanese submillimetre telescope also located at Pampa La Bola, a few metres from the NANTEN2 telescope. ASTE began operations in 2002. ASTE is equipped with single-beam heterodyne receivers that cover four bands between 350 to 950 GHz.

Partners	Japan (NAOJ).
Description	10-m single dish used for technology tests of hardware NAOJ will provide to ALMA. RMS surface accuracy no better than 30 microns.
Frequencies	100 - 850 GHz in 4 frequency bands for spectroscopy and 3 for continuum. Heterodyne systems, single beam.
Site	Pampa la Bola (4850 m).
Science Program	Some student research programs, particularly involving CI (492 and 809 GHz). Primary ASTE goal is not science but technology demonstration.
Status	Operational.

Atacama Large Millimeter Array (ALMA)
http://www.alma.info/

The Atacama Large Millimeter Array, or ALMA, is a US–European–Japanese collaboration to develop a sub-millimetre interferometer in Chile. Each of ALMA's 64 antennae has 12 m diameter. They are movable. At its largest, the array will measure 14 km, and at its smallest, only 150 m. Receivers will cover the range from 30 to 950 GHz. The ALMA correlator, a specialized computer that combines the information received by the antennas, will perform an astounding 16,000 million-million operations per second. ALMA's location in the Atacama Desert is one of the driest places on Earth. When completed (in 2012?), ALMA will be the largest and most capable imaging array of telescopes in the world.

ALMA will be located in the Atacama desert of northern Chile on the high-altitude (5000m) Zona de Chajnantor, east of the village of San Pedro de Atacama in Chile.

The current timeline (see http://www.cv.nrao.edu/naasc/) has ALMA commencing operations in 2010 as a six-to-eight element interferometer working in two bands, with full science operation by December 2012 (64 commissioned antennas, 4 bands). ALMA will dominate activities within the international radio astronomy community for the next decade.

Australia's mm- and cm-wave facilities are the key to providing local access to ALMA, as they will provide complementary information for a wide variety of investigations. It is therefore important to strongly support continued development of these facilities, including the 7 mm receivers and wideband 1–3 GHz ATCA upgrade.

The specifications for ALMA (see http://www.eso.org/projects/alma/specifications/) are as follows:

Requirement	**Specification**
Frequency	All atmospheric windows between 30 and 950 GHz.
Bands	10 bands; initial priority to band 3 = 84 to 116 GHz, band 6 = 211 to 275 GHz, band 7 = 275 to 373 GHz and band 9 = 602 to 720 GHz. Band 4 = 150 to 200 GHz and Band 8 = 400 to 550 GHz are also funded.
Spectral resolution	Sufficient (0.01 km/s) at 100 GHz to resolve thermal line widths.
Flux sensitivity	Sub-mJy point source at all frequencies within 10 min under median atmospheric conditions.
Site	Llano de Chajnantor at 5000 m altitude.
Antennas	50 antennas of 12 m diameter.
Antenna surface	rms deviations of 25 μm.
IF bandwidth	8 GHz per polarization in continuum mode.
Dynamic scheduling	Optimization following scientific priority and required / current conditions.
High fidelity	On spatial scales of degrees to 0.01 arcsec.
Total power	4 antennas equipped with nutating subreflectors.
Configurations	Continuous from within 150 m to maximum baseline of 18.5 km.
Pointing	Accurate to 0.6 arcsec using reference pointing.
Antenna locations	Determined to 65 μm
Polarization	All polarization cross-products measured simultaneously.
Calibration	Accurate to 3% below 300 GHz and 5% at higher frequencies. Absolute calibration to 5%.

Synergies with Antarctic Telescopes

There are also a number of millimetre and submillimetre telescopes either existing or planned in Antarctica.

Antarctic Submillimeter Telescope and Remote Observatory (AST/RO)
http://cfa-www.harvard.edu/~adair/AST_RO/

AST/RO is a 1.7 metre diameter off-axis telescope for research in astronomy and aeronomy at wavelengths between 200 microns and 2 mm. The instrument has operated at the South Pole since 1994, equipped with a series of heterodyne receivers. The receivers operate at frequencies of 230 GHz, 492/810 GHz and 800–820 GHz. Important spectral lines that can be observed include CO 4–3, CO 7–6 and the 492 and 809 GHz [CI] lines. One goal is to survey the southern Galactic plane in these lines.

South Pole Telescope (SPT)
http://spt.uchicago.edu/

A 10 m diameter telescope currently under construction at the South Pole. It is designed to conduct large-area millimetre and sub-millimetre surveys of faint, low contrast emission, as required to map primary and secondary anisotropies in the cosmic microwave background. The telescope will employ an off-axis primary and will have a surface accuracy better than 20 microns rms. The telescope will be surrounded with a large reflecting ground screen to reduce sensitivity to thermal emission from the ground and from local interference. The optics of the telescope will support a square degree field of view at 2 mm wavelength and will feed a 1000-element bolometric focal plane array. The first project will be to conduct a survey in four bands (90, 150, 220 & 270 GHz) over ~4000 square degrees for galaxy clusters using the Sunyaev-Zel'dovich Effect. This is expected to find many thousands of clusters with a mass selection criteria that is remarkably uniform with redshift. Combined with redshifts from optical and infrared follow-up, the survey will enable the state parameter for dark energy to be determined to an accuracy of 5%. This parameter governs the rate of acceleration of the expansion of the Universe.

High Elevation Antarctic Telescope (HEAT)
HEAT is a 0.5m THz frequency telescope for fully-automated remote operation at the summit of Dome A, the highest point on the Antarctic plateau. The unparalleled stability, exceptional dryness, low wind and bitter cold make Dome A a ground-based site without equal for astronomy at infrared and submillimetre wavelengths. HEAT, the High Elevation Antarctic Terahertz Telescope, will operate in the atmospheric windows between 150 and 400 microns, in which many spectral diagnostics of the formation of galaxies, stars and planets are found. At these wavelengths HEAT will have higher aperture efficiency than any other telescope. The receiver will be comprised of 0.8 THz, 1.4 THz and 1.9 THz channels, to observe the pivotal J=7–6 line of CO, the J=2–1 line of atomic carbon, and the far-infrared fine structure lines of N^+ and C^+, the brightest emission lines in the entire Milky Way Galaxy. HEAT is seeking funding from the US NSF as well as the ARC, and would be deployed on an Australian AASTINO at Dome A.

Synergies with Space and Airborne telescopes

The Herschel Space Observatory
http://www.rssd.esa.int/herschel

The European Space Agency's Herschel Space Observatory (formerly called Far Infrared and Sub-millimetre Telescope, or FIRST), is equipped with a 3.5 metre mirror and will cover the full far infrared and sub-millimetre waveband. It is scheduled for launch in 2007 and will perform photometry and spectroscopy in the 60–670 μm range. It is the fourth of ESA's "cornerstone" missions, and will be located 1.5 million kilometres away from Earth, at the second Lagrange point of the Earth-Sun system.

The instruments planed for Herschel are:

- IFI (Heterodyne Instrument for the Far Infrared) Very high resolution heterodyne spectrometer.

- PACS (Photodetector Array Camera and Spectrometer) Imaging photometer / medium resolution grating spectrometer

- SPIRE (Spectral and Photometric Imaging Receiver) Imaging photometer / imaging Fourier transform spectrometer

The Stratospheric Observatory for Far Infrared Astronomy
http://www.sofia.usra.edu

SOFIA, the Stratospheric Observatory for Far Infrared Astronomy, would be a 2.5m airborne telescope, carried by a 747 aircraft into the stratosphere, able to be flown to any location on the Earth. At these heights there is only a few tens of microns of precipitable water vapour in the atmosphere, thus opening windows across nearly all the infrared and sub-millimetre bands that are closed from even the best ground based sites. SOFIA would operate as an Observatory, with a range of facility instruments available via a peer-reviewed proposal process. Regular southern hemisphere deployments would provide access to the southern skies.

SOFIA is managed for NASA by the Universities Space Research Association. Despite having been virtually completed SOFIA has, unfortunately, been indefinitely postponed by NASA.

Synergies with SKA development

http://www.skatelescope.org/

A vibrant science community utilising these mm-wave facilities over this decade will be needed to ensure the continued vitality of the Australian radio science community leading into the next decade, when the development of the SKA will begin in earnest. It is important that Australia maintains its respected standing in the international radio community in order to play a leading role in the SKA. This can only occur if Australia remains an active player in the major developments of the coming decade, i.e. we contribute to ensuring that ALMA is a scientific success.

References

Gardner F.F., Batchelor R.A., McCulloch M.G., Simons L.W., Whiteoak J.B., 1978, PASAu, 3, 264

Gillespie A.R., Huggins P.J., Sollner T.C.L.G., Phillips T.G., Gardner F.F., Knowles S.H., 1977, A&A, 60, 221

Huggins P.J., Gillespie A.R., Phillips T.G., Gardner F., Knowles S., 1975, MNRAS, 173, 69P

McCutcheon W.H., Robinson B.J., Whiteoak J.B., 1981, PASAu, 4, 243

Whiteoak J.B., Gardner F.F., 1978, MNRAS, 185, 33P

Wilson RW, Jefferts KB and Penzias AA 1970 Astrophys. J. 161 L43

An International Perspective

This section contains perspectives from the international community on future science opportunities for the field, and the role that Australia may be able to play.

Galactic star formation up to the high-mass regime: wide field surveys at 200-450 microns from Antarctica

Vincent Minier, CEA Saclay, France

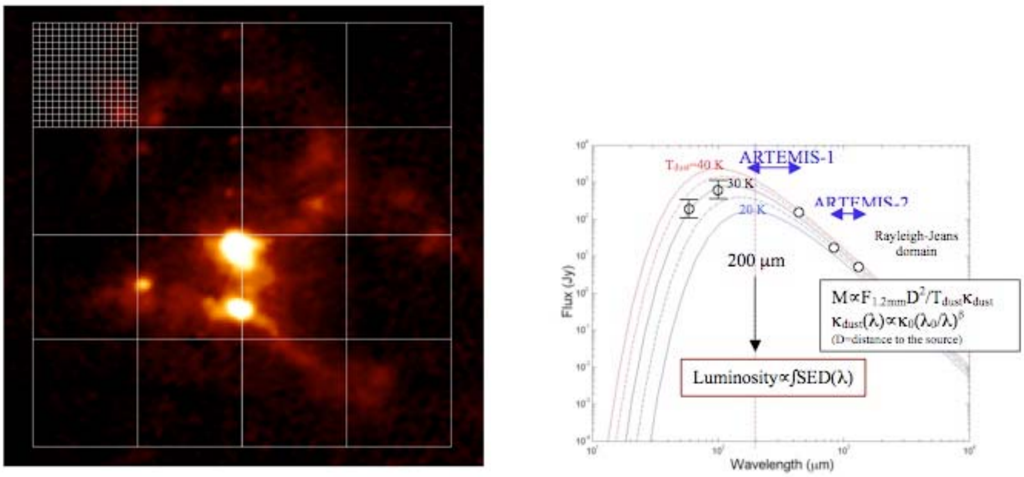
The problem of the origin of the distribution of stellar masses at birth (i.e. the 'initial mass function' or IMF) remains an open issue in astrophysics. It is a central part of galactic star formation research. It is also important to understand whether the IMF is truly universal, including in starburst galaxies and at high redshift, and/or whether it depends on parameters in the local environment, such as its metallicity, pressure or temperature. As prestellar cores and young (Class 0) protostars emit the bulk of their energy longward of 100 microns (André et al. 2000; see Figure), far-infrared and sub-millimetre continuum mapping is a unique tool to address these questions. Recent ground-based dust continuum surveys of nearby compact cluster-forming clouds (Rho-Ophiuchi, Orion B) at millimetre wavelengths have uncovered complete (but small) samples of prestellar condensations (i.e. starless core), whose associated mass distributions resemble the IMF (Motte, André, Neri 1998). These findings suggest that the IMF of solar-type stars is largely determined by pre-collapse cloud fragmentation, prior to the protostellar accretion phase. The studies are, however, seriously limited by small-number statistics at both the low- and high-mass ends of the mass spectrum, due to both sensitivity and angular resolution limitations of current telescopes.

A Herschel Space Observatory key project from the SPIRE and PACS consortia will probe the prestellar core mass function from the proto-brown dwarf ($M \sim 0.01\ M_{\odot}$) to the intermediate-mass ($M < 8\ M_{\odot}$) regime. This will be based on a sensitive survey of the nearest ($d < 0.5$ kpc) molecular cloud complexes of our Galaxy, mostly belonging to the Gould Belt (André & Saraceno 2005). This study will, however, be limited to nearby regions because the 15" resolution of Herschel at 200µm is only adequate to probe individual (~0.05 pc) star-forming cores up to 500 pc away. This is the distance of the nearest massive star forming region in Orion. Thus, there will be few prestellar cores found in the survey that will be progenitors for high mass stars.

High-mass ($M_{star} > 8\ M_{\odot}$) stars appear to form only in closely-packed stellar protoclusters located in large molecular cloud complexes within the Galactic plane. Aside from Orion, they are at distances greater than 1 kpc. The lack of arcsecond angular resolution at 200µm has essentially precluded the determination of accurate luminosities and dust temperatures for high-mass prestellar cores and protostars. There is thus a clear need for other sub-mm instruments providing (1) better angular resolution than Herschel around 200µm and (2) wider-field mapping capabilities than ALMA. Large (> 10 m) aperture sub-mm telescopes, with bolometer-array cameras that can operate in all atmospheric windows between 200µm and 1.2 mm, would enable this field to be advanced. Single dish sub-mm telescopes such as APEX and ASTE on Chajnantor plateau will allow observations in the 350-1200µm range. However the 200µm window, that is essential to obtain good luminosity and temperature estimates, will not open more than 10% of the time. Such a goal could be achieved with a 12-m Antarctic plateau sub-mm telescope placed at, for instance, Dome A or Dome C, where atmospheric conditions allow 200μm observations for a large fraction of the time.

The ArTeMiS project at CEA Saclay aims to develop a large-format (4000 pixels) bolometer-array camera for ground-based submillimetre-wave telescopes, using the expertise of the CEA teams on the PACS bolometer arrays for the ESA Herschel Space Observatory. Placed on a 12-m single-dish telescope in Antarctica, with an angular resolution 3.5 times better than Herschel at 200μm, this camera could directly image individual protostars and prestellar condensations up to 2 kpc away. It would provide access to the high-mass regime of the protostellar core mass and luminosity functions for the first time. A total of ~700 prestellar precursors to OB stars are expected within 2 kpc of the Sun, as opposed to only 20 such condensations at d < 0.5 kpc. As a specific example of what a 200μm bolometer camera could achieve in this area, a 15' x 15' cluster-forming region could be imaged to a rms sensitivity of 40 mJy per 4"-beam at 200 microns in 1 hour of observing time. This would provide a 10 sigma mass sensitivity of 0.7 $M_\odot$ in high-mass star-forming complexes at about 2 kpc, assuming a typical dust temperature of 15 K for starless condensations in massive star-forming clouds.

Such sub-mm observing programmes in coordination with spectral line observations with the ATNF millimetre telescopes (Mopra, ATCA) will provide a foundation for the scientific utilisation of the Atacama Large Millimetre Array, the largest submillimetre interferometer in the Southern Hemisphere.



Left: NGC7538 at 1.2mm: an infrared dark cloud where high-mass stars are born. The square corresponds to the size of the 16x16 ArTeMIS bolometer array, with the individual pixels shown in the top left corner. Right: Observed spectral energy distributions (SEDs) for this massive protostellar core located at 2 kpc (Minier et al.2005). The 5 white dots are data points from 60 microns to 1.2 mm. The SED is fitted with a grey-body function. Five fits are shown with T_{dust} = 20, 25, 30, 35 and 40 K. The best fit is for T_{dust} = 30 K. The luminosity can be derived by integrating the SED function over wavelengths that strongly depend on the temperature. The SED is not well constrained due to the poor angular resolution of IRAS at 60 and 100 microns (~2'). Many protostellar objects are probably included in the beam. Data from 200–450μm would provide strong constraints on the SED peak, especially for cold sources (10–30 K) and hence on determinations made for the temperature and luminosity.

References
André, P., Ward-Thompson, D. & Barsony, M. 2000, in Protostars & Planets IV, p. 59
Minier, V., Burton, M.G. & Hill, T. 2005 in The Dusty and Molecular Universe, Ed. A. Wilson, ESA SP-577, p. 201
Motte, F., André, P. & Neri, R. 1998, A&A, 336, 150

The JCMT Legacy survey programme and the context for southern mm-wave telescopes

Mark Thompson, University of Hertfordshire, UK

The James Clerk Maxwell Telescope (JCMT) is a 15m aperture telescope located on Mauna Kea, Hawaii. The JCMT is specifically designed to operate at sub-mm wavelengths and over 2006 is substantially improving its instrument suite. Two new instruments are being fitted to the JCMT which will dramatically improve the wide-field mapping capability of the JCMT: SCUBA-2, a successor to the SCUBA bolometer array with over 1000 times the mapping power of SCUBA; and HARP-B, a sensitive 16-pixel heterodyne focal plane array working in the 350 GHz band. HARP-B is currently in the process of being commissioned and SCUBA-2 is on schedule to be delivered to the telescope in November 2006.

To capitalise on these instruments the JCMT community are planning a series of ambitious Legacy Surveys. Consortia of astronomers from the JCMT partner countries joined to submit projects to the JCMT Board and seven Survey programmes have been approved by the Board to commence in July 2007. The survey programmes that have been awarded time are: the SCUBA-2 Cosmology Survey, the JCMT Nearby Galaxies Survey, the JCMT Galactic Plane Survey, the Gould Belt Survey of Local Star Formation, the SCUBA-2 Debris Disc Survey, The JCMT Spectral Legacy Survey and the SCUBA-2 "All-Sky" Survey. Initially the surveys will run until the end of 2009, with a further 3-year survey period to be approved at a later date. The survey data is proprietary to the survey consortia for one year after final survey observations and after that the survey data, metadata and advanced data products will be released to the wider community.

There are many clear and compelling roles that southern-hemisphere mm-wave telescopes could play in the JCMT Legacy Survey programme. Even though the JCMT is a northern hemisphere telescope, its location close to the equator means that many of the survey fields are available to telescopes from Australia and Chile. Indeed, many of the survey programmes contain southern fields by design so that follow-up observations can be performed with telescopes such as the VLT, APEX, ATCA, Mopra and eventually ALMA. The wide-field mapping capability of SCUBA-2 means that it is most effectively used as a pathfinder instrument to locate continuum sources that can be further studied at other wavelengths or via spectroscopy. However, even though SCUBA-2 will be a powerful sub-mm continuum imager, its sub-mm continuum images cannot inform about the chemistry, kinematics, embedded stellar content, virial mass or even the distance of the objects that are detected. Follow-up at the radio, mm and IR wavelengths is crucial to extract the maximum scientific potential from the survey data.

One possible key role for Australian mm-wave facilities lies in the determination of kinematic distances for Galactic Plane sub-mm and FIR continuum surveys. The star formation community is in the rather unique position that four major sub-mm and FIR surveys of the Galactic Plane are currently being planned. In the north there are the JCMT Galactic Plane Survey and the pilot phase of the SCUBA-2 "All-Sky" Survey, which will map the northern plane and galactic centre at 450 and 850μm. In the south is the APEX ATLASGAL survey which will map the southern plane and galactic centre at 870μm. And finally, a proposal to map the entire galactic plane at 5 wavelengths from 70 to 500μm from the Herschel Space Observatory is currently under development (the Herschel HiGAL survey). All four surveys will be carried out at comparable sensitivities and angular resolutions, and the combination of their data will be a powerful resource in the study of massive star formation. The surveys will provide an almost complete census of massive star formation in our Galaxy, ranging from the currently poorly understood Infrared Dark Clouds (IRDCs) to well-developed protoclusters and embedded clusters of high-mass stars. In addition to the census of star-forming regions, the multi-colour nature of the combined surveys means that for the first time we will have well selected samples of massive star-forming regions with well sampled spectral energy distributions (SEDs) and hence bolometric temperatures. This is crucial to understanding the evolution of massive star formation from cold dark pre-clusters to embedded high-mass stellar clusters.

However, although the continuum surveys will give us our first glimpse of the bolometric temperatures of a statistical sample of massive star forming regions, a key part of the puzzle is missing - the distance of each region. The well-sampled SED provided by the continuum surveys does not provide any information regarding the distance of the object, which means that the luminosity of the objects detected in the surveys cannot be determined. This is an obvious problem which must be overcome if we are to assemble samples of massive star-forming regions with high luminosities. The usual manner in which distances to these regions is determined is via millimetre-wave spectroscopy to determine their radial velocity and hence kinematic distance (with a model of Galactic rotation). Much progress has been recently made with this technique by using HI absorption spectra to remove the near/far distance ambiguity for inner Galaxy objects (Busfield et al. 2006).

In the north, we are well served by existing moderate angular resolution spectroscopic data sets that have been obtained with the FCRAO 14m telescope and the SEQUOIA focal plane array (the Galactic Ring Survey; Jackson et al. 2006 and the FCRAO Outer Galaxy Survey; Heyer et al. 1998). But paradoxically in the south, although there are large-scale HI surveys available to resolve the distance ambiguity (McClure-Griffiths et al. 2005), there is no spectroscopic survey of sufficient angular resolution to determine kinematic distances for the planned JCMT, APEX or Herschel Galactic Plane surveys. The highest angular resolution survey available is the Japanese NANTEN CO J=1–0 Galactic Plane Survey, which is an under-sampled survey with 4 arcminute grid spacing. This is completely inadequate to resolve the objects observed in the JCMT, APEX or Herschel surveys, which will be of 10-20 arcseconds resolution.

There is thus an important opportunity for Australian mm-wave facilities (particularly Mopra) to provide the spectroscopic data that will allow kinematic distances to be found for objects detected in the JCMT, APEX and Herschel surveys. The CO or ^{13}CO J=1–0 line is readily available from the Mopra 3 mm MMIC receiver and is easily excited, hence readily observable in the Galactic Plane. The other sub-mm wave facilities in the southern hemisphere (APEX, ASTE, NANTEN2) are predominantly pathfinder experiments and it is unlikely that these facilities could devote sufficient observing time for large-scale spectroscopic surveys. In any case, the focus of these facilities is very much on high-frequency spectroscopy and currently, none of these telescopes can observe the low-frequency low-excitation 3 mm lines of CO that are the preferred lines of choice for this experiment. Mopra is thus relatively unique in its capability (both in time and instrumentation) to provide kinematic distances for the planned Galactic Plane surveys.

We thus strongly urge that consideration be given to using Mopra to provide spectroscopic support to the planned continuum surveys of the galaxy. The combination of Mopra spectroscopy with JCMT, APEX and Herschel continuum measurements will result in a "Luminosity Engine" for the surveys, allowing their maximum scientific potential to be reached. The bare minimum required to achieve this is single-position spectroscopy of each object detected in the continuum surveys – we estimate that somewhere in the region of 5000 spectra may be required, or on the order of 500 hours of Mopra time. However, significant extra benefits can be gained if mapping observations are made, which will allow statistics on cloud morphology, turbulence, extent of outflows and their momentum to be compiled. A multi-beam receiver at 3 mm is however required for mapping observations to be completed over a significant section of the Galactic Plane.

References
Busfield et al. 2006, MNRAS 366, 1096
Heyer et al. 1998, ApJS 115, 241
Jackson et al. 2006, ApJS 163, 145
McClure-Griffiths et al. 2005, ApJS 158, 178

VSOP-2 and the need for the Millimetre

Phil Edwards, ISAS, Japan

VSOP-2 is a next generation space VLBI (Very Long Baseline Interferometry) mission being planned in Japan in collaboration with international partners for a launch as early as 2012. The VSOP-2 mission follows the successes of the VLBI Space Observatory Programme (VSOP) mission, which was realised with the launch of the HALCA satellite by Japan's Institute of Space and Astronautical Science (ISAS) in 1997.

The scientific objectives of the VSOP-2 mission include high angular resolution imaging of the cores, jets, and accretion disks of active galactic nuclei (AGN), galactic and extragalactic water vapour maser sources, and the coronae of young stellar objects. With a planned apogee height of 20,000 to 25,000 km above the Earth's surface, an angular resolution of about 40 micro-arcseconds will be achievable in the 43 GHz band.

The VSOP-2 spacecraft will employ a 9-m off-axis paraboloid antenna. It is assumed the VSOP-2 satellite will be launched on a M-V rocket, and the dimensions of the nose fairing place strong constraints on the size of the deployable antenna. The observing bands will be

8, 22 and 43 GHz and the receivers for the 22 and 43 GHz bands will be cryogenically cooled. The satellite will be able to receive both left- and right- circular polarizations simultaneously. Observing requires a two-way link between the satellite and a tracking station for the wideband VLBI data downlink at 1-Gbps, and the uplink of a reference signal. The frequency band for the 1-Gbps VLBI data down-link is 37 to 38 GHz, and the up-link reference frequency is 40 GHz.

The main improvements over the VSOP mission will be: an order of magnitude increase in the maximum observing frequency, from 5-GHz to 43-GHz, allowing detailed imaging deeper into the emitting plasma; an order of magnitude increase of maximum angular resolution; and an order of magnitude increase in interferometer sensitivity for continuum observations. This is accomplished mainly by the 8 times higher bit rate and the lower system noise temperatures.

A phase-referencing capability, to remove atmospheric phase fluctuations, increase the coherence time and hence the sensitivity, is being considered. Nodding of the whole spacecraft quickly between the calibrator and target sources may be possible with the addition of 2 Control Moment Gyroscopes to the 4 momentum reaction wheels.

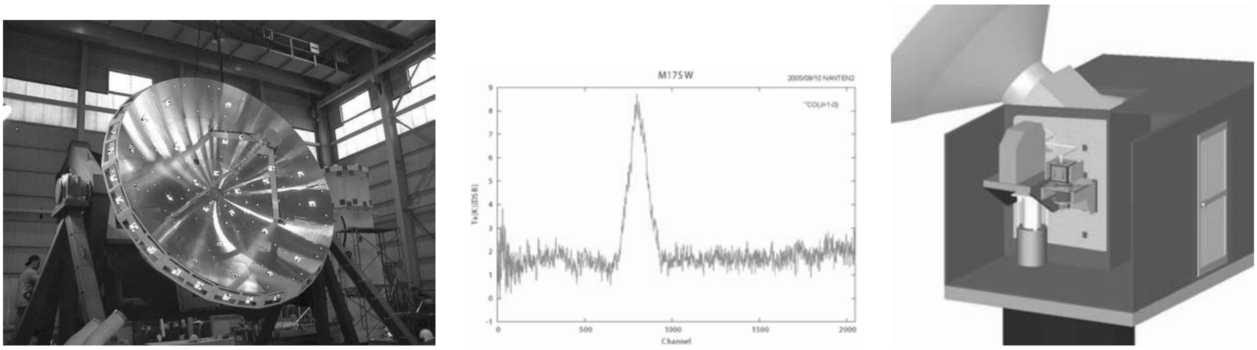
The VSOP mission was realized through a large international collaboration in terms of ground telescope arrays, correlators, and tracking stations, and a similar degree of collaboration will be essential for the success of VSOP-2. As with VSOP, the involvement of Australian ground radio telescopes is critical for imaging VLBI observations of southern hemisphere sources. This is particularly true at 43 GHz, where the ATCA and Mopra may be the only southern hemisphere telescopes able to co-observe with the VSOP-2 satellite.

Sub-millimetre Surveys of the Southern Galactic Plane: NANTEN2 and the need for the millimetre

Yasuo Fukui, University of Nagoya, Japan

The NANTEN2 telescope is a 4m diameter sub-millimetre-wave telescope under construction at the 4,800m elevation Pampa la Bola on the Atacama high plateau of northern Chile. From this exceptionally dry site, atmospheric windows in the sub-millimetre wave bands are opened for observation from the ground, rather than requiring the telescope to be placed in space or in high-altitude flight. The telescope is being equipped with state-of-the-art array-format receivers for these bands. Combined with the large beam size, this will enable it to efficiently map the sky in the sub-mm bands. NANTEN2 will undertake the first surveys of the southern skies in a number of molecular and atomic species emitting between 0.3 and 1 mm wavelength, in particular measuring the distribution of the warm gas using moderately excited spectral lines.

The southern Milky Way and the Magellanic Clouds will be mapped in excited lines of carbon monoxide (CO J=2–1, 3–2, 4-–3 and 7–6 lines) and the two fine-structure lines of carbon. These maps will make possible large-scale studies of the processes of star formation within our Galaxy and the Magellanic Clouds, including the dynamical effects of energetic explosive events like supernovae and supershells on the interstellar medium. The structures they produce are extended over many degrees on the sky, meaning that they can only be studied properly through wide-field mapping, so needing a facility like NANTEN2 for their investigation. The maps will then be compared to maps obtained in the lowest excitation line of carbon monoxide with the original NANTEN telescope and, at five times higher resolution, to what can now be obtained with Mopra. These target the coldest gas emitting in the lowest transitions of the same molecules.



The NANTEN2 dish, after re-surfacing with adjustable aluminium panels, is shown at left. The first spectrum it obtained, of the ground state transition of carbon monoxide line in the star forming region M17, is shown in centre. To right is a CAD drawing showing where the new receivers that are being built will be located at the focus of the telescope. These are the Cologne KOSMA SMART 16 channel dual frequency receiver array for short-wavelength, and the Nagoya receiver for long-wavelength, sub-mm wave operation.

NANTEN2 is an international university consortium, led by the University of Nagoya in Japan, who have built the telescope and are providing the longer-wavelength receivers. The principal partner is the University of Cologne in Germany, who are providing the array-format receiver and backends needed for operation at the shortest wavelengths of the sub-millimetre spectral bands. The other collaborating institutions are Osaka Prefecture University in Japan, Seoul National University in Korea, Bonn University in Germany and the University of Chile in Santiago. ETH Zurich University in Switzerland is currently negotiating membership of the consortium. Australia has been invited to join, and the Universities of New South Wales, Sydney and Macquarie jointly submitted an ARC LIEF proposal in 2006 to seek funding to do so.

As the only country operating its own millimetre-wave facilities in the southern hemisphere, Australian expertise is valuable to the NANTEN2 partners. Australian telescopes could obtain key data at millimetre-wave to NANTEN2, which will allow one to derive density and temperature through comparing different spectra of a given molecule.

Workshop Programs

Millimetre Astronomy Science Meeting

UNSW, 30/11/05

Time	Length	Speaker	Subject
13:00	10	Michael Burton	Welcome
13:10	5	Andrew Walsh	Overview of Australia's MM-Wave Facilities
13:15	10	Cormac Purcell	ATCA and Mopra observations of the molecular cores in NGC3576
13:25	10	Steven Longmore	Ammonia cores in massive star formation
13:35	10	David Blank	Search for a debris disk around GJ 876
13:45	10	Chris Wright	ATCA millimetre observations of young dusty disks
13:55	10	Paul Jones	Deep Impact on a comet
14:05	10	Andrew Walsh	Uncovering cores in G305
14:15	15	Maria Cunningham / Nadia Lo	The DQS: Dense Gas in the G333 Molecular Cloud Complex
14:30	10	Peter Barnes	Surfing the mm-wave spectrum: the era of large-scale surveys
14:40	20	All	Tea Break
15:00	15	Juergen Ott	The ATCA ammonia survey of the Galactic centre
15:15	15	Annie Hughes	A Mopra survey of the molecular gas in the LMC
15:30	10	Erik Muller	High resolution CO mapping of star forming regions in the SMC
15:40	15	Tony Wong	Dense gas in circumnuclear rings
15:55	5	Chris Phillips (Juergen Ott)	3mm VLBI - first fringes
16:00	15	Graeme Carrad	Right on SISta (an ode to the 3mm SIS receiver)
16:15	15	Warrick Wilson	Future developments at ATNF
16:30	15	Michael Burton	The Millimetre White Paper.
16:45	15	All	Open Discussion
17:00	15	Finish	
17:30		*Post-Meeting Meeting*	Coogee Beach Palace Hotel (Aquarium Bar)

Future Directions for Southern Hemisphere Millimetre Wave Astronomy

Sydney Harbour Institute for Marine Studies, Chowder Bay, Mosman, 30-31/03/06

The full workshop program can be found at URL:
www.atnf.csiro.au/whats_on/workshops/mmworkshop2006/ with the talks at URL
www.atnf.csiro.au/whats_on/workshops/mmworkshop2006/thetalks/

Future Directions in Southern Hemisphere Millimetre Wave Astronomy					
Reception & Registration: ATNF, Epping			29/03/06		
Workshop: SHIMS, Chowder Bay, Mosman			30-31/03/06		
Dinner: Aqua Dining, North Sydney			30/03/06		
Time	**Wednesday March 29**				
15:30	Radio, millimetre & submillimetre astronomy: exciting new opportunities for the southern hemisphere	Karl Menten	MPIfR, Bonn		
	A colloquium at the ATNF headquarters in Epping				
17:00	Workshop Reception and Registration, ATNF Epping				
Time	**Thursday March 30**	**Speaker**	**Institution**	**Length**	**Questions**
08:45	**Registration and Coffee**				
09:15	**Opening Address**	Mike Archer	Dean, Faculty of Science, UNSW	10	
09:30	**Setting the Scene**	Chair: Tony Wong			
	The Millimetre White Paper	Michael Burton	UNSW	20	5
	The ATNF and its future	Brian Boyle	ATNF	20	5
10:20	**Coffee**				
10:45	**Current Millimetre Facilities**	Chair: Erik Muller			
	Australia's millimetre wave telescopes	Tony Wong	UNSW / ATNF	15	5
	Science possibilities with Australia's millimetre telescopes	Andrew Walsh	UNSW	10	5
	APEX, the Atacama Pathfinder Experiment	Karl Menten	Max-Planck-Institut fuer Astronomie	20	5
	NANTEN2 and ASTE	Yasuo Fukui	Nagoya University	20	5
	JCMT legacy programs and the role for southern telescopes	Mark Thompson	University of Hertfordshire	20	5
12:35	**Lunch**				
13:30	**Future Southern Facilities**	Chair: Michael Burton			
	THz astronomy from Antarctica	John Storey & Vincent Minier	UNSW & CEA, Saclay	20	5
	ALMA, the Atacama Large	Tony Beasley	ALMA	30	20

	Millimetre Array				
14:45	**Coffee**				
15:15	**Science Opportunities I**	Chair: Juergen Ott			
	Turbulence-regulated star formation	Maria Cunningham	UNSW	10	5
	Studies of high-mass star formation from the southern hemisphere: NGC6334, G327.3-0.6, SgrB2 and the Orion Bar	Sven Thorwirth	MPIfR	15	5
	Hot molecular cores	Cormac Purcell	UNSW	15	5
	Science with HEAT in Antarctica	Wilfred Walsh	UNSW	15	5
	Should we use Australian millimetre telescopes for VLBI experiments	Roopesh Ojha	USNO	15	5
	VSOP-2 and opportunities for millimetre astronomy	Phil Edwards	ISAS, Japan	10	5
17:05	**Finish**				
18:30	**Dinner, Aqua Dining, North Sydney**				
	Friday March 31				
09:15	**Science Opportunities II**	Chair: Maria Cunningham			
	Star formation's most wanted	Mark Wardle	Macquarie University	15	5
	Line surveys at 3 & 12mm	Andrew Walsh	UNSW	10	5
	Unbiased surveys of dense molecular clumps in the Galactic plane	Yoshinori Yonekura	Osaka Prefecture University	15	5
	Large scale surveys of low and high mass star formation	Peter Barnes	University of Sydney	10	5
	Opportunities at 7mm for star formation	Kate Brooks	ATNF	10	5
10:40	**Coffee**				
11:10	**Science Opportunities III**	Chair: Andrew Walsh			
	Investigating grain growth in southern protoplanetary disks	Sarah Maddison	Swinburne	5	
	The initial conditions for massive star formation	Michael Burton	UNSW	10	5
	The Galactic centre at millimetre wavelengths	Juergen Ott	ATNF	10	5
	Molecular clouds and star formation properties in the LMC	Akiko Kawamura	Nagoya University	15	5
	Studying the early universe in our galactic neighbourhood: Mopra observations of the Magellanic Clouds	Annie Hughes	Swinburne University	15	5

12:25	**Lunch**				
		Chair: Kate Brooks			
13:30	Sub-millimetre observations of the Magellanic Clouds	Tetsuhiro Minamidani	Nagoya University	15	5
	High redshift molecular gas	Elaine Sadler, Ilana Klamer	University of Sydney	15	5
	The ATCA 20 GHz survey and mm follow-up	Roberto Ricci	ATNF	10	5
14:25	**Technology Opportunities**				
	Emerging opportunities for millimetre heterodyne receivers and arrays	Warwick Wilson	ATNF	10	5
	Water Vapour Radiometry	Bob Sault	ATNF	5	
	Terahertz radio systems	Trevor Bird	CSIRO	15	5
15:05	**Coffee**				
		Chair: Michael Burton			
15:30	**The Science Drivers**	*Three wise rapporteurs*	*3 x 10min*		
	Line	Karl Menten	MPIfR	10	
	Continuum	Mark Thompson	University of Hertfordshire	10	
	Extra-galactic	Tony Wong	UNSW/ATNF	10	
	Anything else?	The Floor			10
16:10	**Strategies for Millimetre Wave Astronomy**	Round Table Discussion			
	Panel: Beasley, Cunningham, Fukui, Menten, Norris	Chair: Storey		60	
	The Millimetre White Paper: what now?	Burton		10	
17:30	**Finish**				
	Refreshments: Mosman Rowers Club				