Upgrade Paths for Mopra

A discussion paper for the Australia Telescope User Committee

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Overview

This paper discusses a series of upgrades for the Mopra millimetre-wave telescope which are aimed at maintaining its position as a world class facility for single dish, long-wave millimetre astronomy (i.e. 2.6mm < λ < 12 mm), the premier such facility in the southern hemisphere. In these bands lie the ground state transitions of most molecules studied in the interstellar medium, as well as the transition from dust-dominated to free-free continuum emission from the associated gas. Three enhancements are discussed, of increasing complexity and expense, which provide for an upgrade path for the facility. These are, in turn:

1. Implementation of "fast-mapping"; made possible by the ability to sample data with a cycle time of at least a factor 10 faster than the current 2s limit.
2. An ultra-wide bandpass correlator, able to sample the entire 3mm waveband simultaneously, with both wide-band and zoom modes.
3. A 7-element multibeam detector for the 3mm band, and associated wide-band correlator.

These upgrades are described further below, with an outline of the science capabilities they would enable. We also discuss evaluation of their feasibility and where additional support may be found for their implementation, both from the Australian university community as well as from the international community.

Mopra Today

The Mopra telescope is uniquely capable of undertaking mapping surveys in multiple molecular lines of the southern skies at millimetre wavelengths. This is the result of its location, its receiver suite covering the 3, 7 and 12mm wavebands, its ability to scan the sky rapidly through "on-the-fly" (OTF) mapping and, most importantly, its 8 GHz wide-bandpass digital filter bank spectrometer. This capability has arisen as a result of a series of modest CSIRO and University-funded upgrades over the past decade. Four large molecular mapping surveys have been initiated with Mopra since the introduction of this spectrometer, the DQS, CMZ, HOPS and MAGMA programs, each making a use of a different combination of wavelength / bandpass options to undertake wide-field surveys in a variety of spectral lines[1]. Two capabilities are lacking, however – the ability to map over galactic-scale regions with reasonable time allocations, and the ability to include all the measurable spectral features when mapping in these three spectral bands. This document discusses how these capabilities may be realised.

[1] These are surveys of, respectively, the G333 giant molecular cloud complex (~20 lines at 3mm), the Central Molecular Zone of the Galaxy (all lines from 85-93 GHz), the southern galactic plane (all lines in the 12mm band) and the Magellanic Clouds (in CO).

“Fast-mapping” at 3mm

What is “Fast-Mapping”?

“Fast-mapping” involves scanning the telescope more rapidly than currently possible without degrading spatial resolution. To do so requires the cycle time of the telescope to be reduced from the current 2s period to one of no more than 0.2s. This will allow larger regions of sky to be mapped than presently, albeit with a somewhat reduced sensitivity.

Current Limitations

While Mopra is capable of mapping multiple molecular lines simultaneously, the area of sky that can be covered is limited by the single-pixel receivers that are available on the telescope. OTF mapping further restricts the telescope to being scanned at no faster than a quarter of the beam width during a cycle time, lest the spatial resolution be degraded. At 3mm, with a beam size of 35″, this limits the telescope to surveying areas of ~1 square degree in the typical 3-4 week time allocation a large proposal might be granted in a single semester. This then limits science programs to mapping, at most, a few GMC-sized complexes unless the telescope is dedicated to a particular project.

For many molecular lines of interest, the sensitivity achieved during the 2s cycle time of the system, $T_A^* \sim 0.3$K per 0.1 km/s channel, is in fact reasonably well matched to the typical line strengths in galactic sources, for instance allowing ~20 separate molecular lines maps to be obtained in the DQS and CMZ surveys. In this case, faster mapping would not be beneficial as the S/N achieved would be poor over much of the emission region. This, however, is not the case for measurements of CO line emission, which can typically be an order of magnitude brighter in the main ^{12}CO line at 115.3 GHz than in other bright 3mm band molecules such as HCN and HCO^+. The other two principal isotopologues of CO, ^{13}CO at 110.2 GHz and $C^{18}O$ at 109.8 GHz, can also be brighter than the HCN or HCO^+ lines, particularly when the ^{12}CO line is optically thick. The S/N obtained would thus still be adequate for the mapping of CO line emission if the telescope cycle time were to be reduced by a factor of 10 from its current value.

What is needed and what would be possible?

The intent of “fast-mapping” is to achieve this gain, by reducing the cycle time from 2s to 0.2s. The S/N would be three times worse, but this is perfectly adequate for CO line maps. There will likely by a trade-off required, reducing the number of zoom modes, and/or the bandpass, so as to decrease the data rate in the shorter cycle time. However, even if only 3 zooms are available, this will not impact the science, as only the CO molecule is bright enough for this mode to be used over extensive fields of view. The sensitivity is sufficient for the 3 main isotopologues to be measured over giant molecular clouds complexes. Furthermore, their line ratios enable the optical depth to be determined, and so the column density of the molecular gas to be inferred. Aside from in the densest cores, when CO can be depleted onto the surfaces of dust grains, this will allow large-scale maps of the distribution of molecular gas to be obtained over the southern Galactic plane. The 0.5′ angular resolution will be an order of magnitude better than the best existing large-scale data sets of the southern sky, the 9′ resolution survey of Dame, Hartmann & Thaddeus (2001; obtained using a 1.2m telescope) or the 4-8′ NANTEN-1 survey by the Nagoya group (in preparation; obtained using a 4m telescope). Furthermore, these two surveys only measured the ^{12}CO line and so it is not possible to correct their data for optical depth to infer the column density. With “fast-mapping” Mopra could survey ~10 square degree-sized regions for CO in ~4 weeks of observing time, rather than the ~1 square degree it can currently achieve.

Our calculations suggest that, for “fast-mapping”, achievable 1σ line detections should be ~0.7, 0.4 & 0.3 K km/s at 115, 110 and 88 GHz, respectively (this assumes a line width of 5 km/s, and corrects for the dish efficiency at the 3 frequencies; i.e. T_{MB} not T_A^*). This compares with the “normal” mapping sensitivity of 0.2, 0.14 and 0.09 K km/s at the same three frequencies.

Science: the formation of molecular clouds

"Fast-mapping" makes possible the mapping of many square degrees of sky in the CO lines, although it should be noted it will not make it possible to map the entire southern galactic plane unless the telescope were to be dedicated to such a project over several years. In this section we describe a project that requires "fast-mapping" for it to be undertaken, the search to find where and how molecular clouds are formed from the atomic medium.

The evolution of our much of our Galaxy can be understood through following the star-gas cycle. This is the cycle of materials that takes the elements produced by nucleosynthesis in the cores of the most massive stars, ejects them in stellar death and passes them through the phases of the interstellar medium, finally incorporating them into the next generation of stars. A critical part of the cycle that is not understood is how the molecular clouds form during it, the environment from which stars are then born (e.g. Bally, 2001).

The reason for this is that we have lacked the capability to make the necessary measurements until now, for key processes cannot be studied with any diagnostic lines from the principal components of the gas, the atomic and molecular hydrogen. For H_2, the energy levels are too widely spaced for the molecule to be excited in the typical environment where it is found, unless the gas has been heated to temperatures of order ~1,000K, e.g. by shock waves. For atomic gas, while there is a line at 21cm from the spin-flip transition of HI, its emission is not sensitive to the gas density and so cannot be used to discriminate between the cold (T ~ 70K) atomic clouds and the warm (T ~ 8,000K) neutral medium.

It is necessary to follow the cycle using rarer species that trace the physical processes at work. In particular, these involve carbon, which can be found in ionized form (C^+), where it emits in THz bands, in neutral form (C), emitting in sub-mm, and in molecular form (as CO), emitting in the millimetre. Ionized nitrogen (N^+), also emitting in the THz, is the other crucial diagnostic species, arising from the warm ionized gas. The C^+ and N^+ lines are dominant coolants in the ISM (Bennett et al., 1994). They provide probes of where molecular cloud formation is occurring (C^+) and of the rate of star formation (N^+) across the Galaxy. Despite their importance, these lines have barely been studied as the atmosphere is virtually opaque to them, unless a telescope is placed in an extremely dry location or in space.

The manner in which atomic gas is gathered into molecular clouds has yet to be observed. It is clear, however, that from observations in some other galaxies, where the entire atomic and molecular structures can be overviewed, that molecular clouds are formed from large structures of atomic gas that envelope spiral arms (e.g. as in the galaxy M33; Engargiola et al., 2003). Such observations, however, lack the spatial resolution to resolve the processes by which this occurs. To do so we need to be able to distinguish between emission from regions of ionized gas, from cold atomic gas, from "small" molecular clouds (where CO is absent due to photodissociation from energetic photons) and from "giant" molecular clouds (where CO is shielded, and is the dominant tracer). The difficulty is in determining where the ionized C^+ emission arises, as this ion emits from all these regimes. However this problem can be resolved through comparison of the C^+ emission with data on the distribution of all the above species, *when taken at similar spatial and spectral resolution*. The reasoning is as follows. Ionized gas will contain N^+, atomic gas will also contain H, and giant molecular clouds CO. The "small" clouds will have C^+ and C, but no CO or H, and so will be distinguishable from the surfaces of the giant molecular clouds. To find such regions we need to survey, in each of these species, a region of sufficient size to include the complete range of conditions encountered across a galactic spiral arm. Here gas is compressed, molecular clouds form, and stars are born. The process of molecular cloud formation from the atomic substrate will then be discernable, for the first time, by mapping the distribution of all these species across a spiral arm of the Galaxy.

We thus need the tools able make observations at comparable spatial and spectral resolutions in the millimetre, sub-mm and THz bands. These tools are now available, through Mopra, NANTEN2 (a sub-mm telescope on the Atacama plateau of Chile, in which Australia is a partner) and the Stratospheric Terahertz Observatory (STO, a balloon-borne telescope to be launched from the Long Duration Balloon Facility at McMurdo, Antarctica, in 2011). To these we add the 21cm HI data gathered by Parkes and ATCA as part of the SGPS (McClure-Griffiths et al., 2005). The molecular line observations obtainable by Mopra are crucial here. This is because C^+ emission can arise from all phases of the gas. Without the CO that Mopra can provide, it will not be possible to distinguish between emission from atomic clouds and from the surfaces of molecular clouds. We would thus not be able to determine where the formation of molecular clouds is taking place.

The Stratospheric Terahertz Observatory will survey the C^+ and N^+ emission from a 35°x1° strip of the southern galactic plane, from *l*=-20° to -55° (305°-340°) in a mission scheduled to fly in 2011. This, then, is the region that Mopra needs to survey. With “fast-mapping” this would take 3 seasons, if granted 4 weeks of time per year. With the current mapping rates, however, it would require Mopra to be solely dedicated to this survey for the next ~5 years to tackle this project.

An Ultra-Wide Bandpass Correlator

What is it?

This is a digital filter bank spectrometer capable of processing spectral line data across the entire bandpass of the 3mm band, able to be used in both broad-band (i.e. in ~2 GHz wide bands) and in zoom mode (i.e. multiple ~150 MHz wide bands) operation. Such a spectrometer would thus be capable of measuring all the lines emitted from 68 – 116 GHz window simultaneously with a single receiver, in addition to being used with receivers for 7mm (30 – 52 GHz) and 12mm (18 – 30 GHz) for complete coverage in these bands too.

Current Limitations

The current 8 GHz FFTS[2] spectrometer used Mopra is impressively wide, using 8 x 2-GHz polyphase digital filterbanks (i.e. FPGAs[3]). It provides for dual polarization across the entire 8 GHz (i.e. broad-band, with 32,768 channels per polarization), as well as upto to 16 zoom modes (each with 4,096 channels over 137 MHz per polarization, and with 4 zooms per 2 GHz band). It was built by the CSIRO-ATNF, supported by an ARC LIEF grant to UNSW, Sydney and Monash universities. Its introduction on Mopra in 2006 has revolutionised the telescope, and led to the current international interest in the facility and the subsequent high demand on time. Nevertheless, it is only able to cover one-sixth of the 3mm band, and one-third of the 7mm band, forcing choices to be made on observing programs regarding which set of lines to cover, when invariably emission from across the entire band is relevant to the study at hand.

What could be provided and what are the issues?

An ultra-wide-bandpass correlator with 48 GHz instantaneous would permit the entire 3mm bandpass to be processed simultaneously (or the 7mm, or the 12mm, bands). The cost of a single 2 GHz FFTS is now several K, rather than the tens of 10K when the 8 GHz spectrometer was built, making it possible to replace it with a new spectrometer that covers the entire 3mm band for similar cost as the current 8 GHz system. Furthermore, the capability of FFTSs continues to improve; it is now possible to have a 2.5 GHz FFTS with > 8K channels, and shortly this will be possible for a 4 GHz wide FTTS. Thus 12 x 2 x 4-GHz wide FFTSs would be able to cover the entire 3mm band with dual polarization operation.

There are, however, issues with the receiver which need to be considered before detailed planning for a new spectrometer begins. What instantaneous bandwidth can the current MMIC receivers take? Is this limited by the IFs or by the receivers themselves? The number of channels used in the zoom modes also needs to be sufficient to provide at least 0.1 km/s spectral resolution at 3mm, and when used in broadband mode ~ 1 km/s resolution; i.e. similar to the performance of the current Mopra spectrometer.

An ultra-wide bandpass correlator would also contribute towards the increased bandwidth required for operation of a multibeam beam array spectrometer, as is discussed in the next section.

How might this be done?

The ATNF have already demonstrated their capability to undertake such a project through their development of the current 8 GHz Mopra spectrometer as well as the CABB on the ATCA. An initial study first needs to be carried out by the CSIRO to determine the performance capabilities and limitations for an ultra-wide bandpass correlator at Mopra, and to identify the issues which any design must overcome.

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[2] FFTS = Fast Fourier Transform Spectrometer.

[3] FPGA = Field Programmable Gate Array.

Australian universities may be able to contribute to funding such a correlator through the ARC LIEF program, in a similar manner to the way they funded the current system. There is a yearly opportunity to seek funding in April-May of each year.

The MPIfR in Bonn also have a particular interest in wide-bandwidth FFTSs, having developed similar capability for the APEX telescope in the sub-millimetre. They may be interested in constructing FFTSs on contract and/or participating in a scientific collaboration, providing them, in return, access to the telescope for science. Discussion between the CSIRO and MPIfR is encouraged to determine what form of collaborative venture might work best for all interested parties.

Science

Thee are two principal forms of science that could be undertaken using a spectrometer that covered the entire 3mm band.

- The first is complete chemical studies of a source, permitting deep observations that are able to measure the entire range of spectral lines that are emitted across the band. For the weaker lines, emitted from the more complex molecules, detections of multiple lines of a particular species are indispensible if reliable identifications are to be made from the forest of emission lines that are always present. This new capability would provide a factor of 6 improvement on the current performance.

- Simultaneous mapping of all bright emission lines in a source. At 3mm there are three frequency settings where the majority of the bright lines are to be found, those that ideally would be mapped through a single OTF-survey. These are around 112 GHz (the CO isotopologues and CN), 98 GHz (CS, OCS, CH_3OH, SO) and 90 GHz (HCN, HCO^+, HNC, N_2H^+, HC_3N); spectral tracers that cover a range of density, temperature and dynamical conditions within which the bulk of molecular gas within a GMC is found. Currently it would take 3 separate setting of the spectrometer to cover these lines; hence this would represent an effective improvement in mapping speed of a factor of 3 over current performance.

A 7-element, 3mm Multibeam

What is it?

A 7-pixel, multibeam heterodyne receiver operating at 3mm, covering the focal plane of the Mopra telescope, thereby increasing mapping speeds by a factor of seven.

Current Limitations

Mopra is equipped with single-pixel receivers, and with OTF mapping this effectively limits the telescope to mapping ~degree-sized regions in a 3-4 week time allocation period if observing in the 3mm band. Even with "fast-mapping" for the CO lines, this only improves to ~10 square degree-sized regions. This therefore restricts mapping studies to a few selected GMC-complexes rather than of the southern galactic ring (e.g. for comparison to the Galactic Ring Survey – the GRS – mapped in ^{13}CO for the northern galactic plane by the 14m FCRAO). It is not possible to consider a legacy project to map the entire molecular distribution of the southern galactic plane at present.

What could be provided

Mopra's shaped antenna limits the field of view of the telescope; however a study by the CSIRO shows that adequate performance can be obtained at 3mm across a close-packed hexagonal-shaped field, allowing for a 7-element multibeam array. While phased focal plane arrays might make it possible to correct for the optical distortions over much wider fields of view, their development for 3mm band operation lies in the future, whereas multibeams can be built now.

The CSIRO undertook a concept design study for a Mopra 3mm multibeam system in 2008, under contract to UNSW, to examine possible configurations for receivers and correlators. The study found that a 7-element system is feasible, but only looked in detail at a simpler 4-element system, finding that it may be implemented by essentially replicating the systems for the current MMIC receiver and FFTS correlator. The simplest such system would make use of a single polarization and provide a 4 GHz bandwidth, or alternatively a 2 GHz, dual-polarization system, through re-programming the current 8 GHz correlator (and with the addition of an extra 2 GHz FFTS). A 4-element multibeam, however, is not regarded as sufficiently scientifically compelling to pursue now, so that investigation of a 7-element system is warranted.

The University of Arizona have developed a 7-element focal plane array called DesertSTAR operating at 345 GHz for the Heinrich Hertz Telescope (Groppi et al., 2008). The design could readily be adjusted for the optics associated with Mopra at 3mm. In particular, the group have the ability to both undertake the optical design of the feedhorns and fabricate the complex waveguides through laser micromachining.

A particular issue is that the beams for Mopra need to be adjacent, rather than being separated by ~1 beam width, as is usually the case for multibeam arrays. This has the potential of increasing cross-talk between detectors.

Complexity is increased by providing more bandwidth and dual polarization operation, and so the design will have to undertake a cost-benefit analysis to determine what specifications should be provided. An absolute minimum is 2.2 GHz, permitting the HCN, HCO^+, HNC lines to be measured simultaneously. However a 6 GHz bandwidth is required to measure the 3 main CO isotopologues. This is beyond what could be provided using the current spectrometer, but might be provided by re-configuration of a 2-polarization, 48 GHz bandwidth spectrometer, if such an ultra-wide band width spectrometer were to be developed first.

Science

The science that a 3mm multibeam will permit is that associated with large-scale mapping of the galactic plane and galactic ring in molecules that sample the full distribution of physical conditions found within the molecular medium. When also combined also with "fast-mapping", a multibeam would make it possible to obtain a complete map of the southern galactic plane in the three main CO isotopologues with 0.5 arcminute resolution, an improvement of nearly 20 better over the best maps that are now available. This would then provide a molecular view of the Galaxy at comparable resolution to that which we already have of the ionized and neutral gas, and shortly, will have of the dust continuum (in the sub-mm with JCMT and APEX, and in the far-IR with Herschel). A proper inventory of the gaseous phase of the interstellar medium could then be determined, and its evolution followed.

In this regard, investigation of the provision of a 100-element, 3mm multibeam array for the Green Bank Telescope has recently commenced at the NRAO, indicating the interest in such an instrument. The GBT, though, has cannot reach the southern galactic plane.

What is Needed

The upgrades described above represent three different levels of project for the Mopra Telescope. However they all need to be begun by conducting feasibility studies, including discussions with the interested parties, to assess the scientific requirements in relation to the performance constraints. Taking each project in turn:

- "Fast-mapping" appears to be a relatively straightforward project for which there is an immediate scientific demand and reward, as well as a minimal cost. We recommend that it be implemented as soon as is reasonably possible.

- Capabilities for ultra-wide bandpass performance at millimetre wavelengths have developed to the point where it is now possible to build spectrometers that sample the entire bandwidth of each of the millimetre bands, for a cost similar to that of the current 8 GHz Mopra spectrometer. We recommend that CSIRO conduct a study to consider the best route forward, and to properly cost such an upgrade. This should also include the possibly of involvement with Australian universities as well as with international partners. We suggest that informal discussions are held with the MPIfR to explore possible collaborations.

- The development of a 3mm multibeam is the most complex of these upgrades, as well as the most expensive. The capabilities of a multibeam instrument will also depend on what kind of wide bandpass correlator is available. We recommend that concept design studies be continued to explore the options further, and that informal discussions with potential partners, such as the University if Arizona, are initiated.

Any collaborative ventures with Australian universities that emerge from these considerations must also be mindful of the once-yearly funding opportunities that universities have to support new initiatives, in particular through the ARC LIEF scheme. Funding proposals for this scheme need to be prepared in April each year.

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