The Methanol Multibeam (MMB) Survey

Jimi Green
CSIRO Astronomy & Space Science
Science with Parkes @ 50 years young
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Overview

• Introduction (background and motivation for the survey)

• Techniques (observing with the Parkes Radio Telescope and the Australia Telescope Compact Array)

• Survey Results (source distributions, flux densities and completeness)

• Survey Science (Magellanic Clouds, tracing structure of the inner Milky Way with methanol masers)

• The future (astrometry through Very Long Baseline Interferometry, magnetic fields through Zeeman splitting)
Introduction: 6.7-GHz Methanol Masers

- Methanol forms through hydrogenation of ice mantles on dust grains.

- Evaporates into gas.

- Masers originate in gas surrounding high-mass stars in the process of formation.

- Pumped by mid-infrared emission from heated dust.

- Require high density \((10^5 \text{ to } 10^8 \text{ cm}^{-3})\), high methanol abundance and dust temperatures of \(~100-200 \text{ K}\).

(transition between the rotational energy levels of \(J=5, K=1\) to \(J=6, K=0\) in the A+ methanol)
Introduction:
Previous observations of 6.7-GHz methanol masers

- Targeted searches
  - e.g. colour-selected infrared sources
- unbiased surveys
  - e.g. large, but limited in coverage
- unbiased surveys
  - unbiased

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Sensitivity Survey Reference Telescope

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Vel. Resolution

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Introduction:
Understanding high-mass star formation

• High-mass (> 8-10 Solar mass) stars form:
  • in dense molecular clouds
  • at large distances (several kpc)
  • in complex clusters

• Observations difficult due to heavy shrouding in dust.

• Theory/processes not fully understood:
  • core nuclear reactions occur whilst in the primordial accreting phase.
  • radiation pressures inhibit accretion.
Introduction:
Understanding Galactic structure
Introduction: How can masers help with Galactic structure?

- 6.7-GHz methanol masers exclusively associated with high-mass star formation (Minier et al. 2003, Xu et al. 2008)

- masers constrained to spiral arms & prominent features of Galactic structure.

- expect high densities of high-mass star formation at the origins of the spiral arms & the ends of the bar.

- Central velocity of 6.7-GHz methanol masers are within 3 kms$^{-1}$ of the systemic velocity (Szymczak et al., 2007, Pandian et al. 2009, Green et al. 2011).
The Methanol Multibeam (MMB) Survey

The first unbiased, systematic Galactic plane survey for 6.7-GHz methanol masers

- Galactic longitudes -174° to +60°
- Galactic latitudes ±2°
- Commissioned January 2006, first new detection Australia day.
- ~120 days observing with Parkes Radio Telescope (2006-2009)
- ~1000 detections, ~40% new sources
- all new sources positioned with the Australia Telescope Compact Array (to 0.4 arcsec accuracy)
Survey Techniques:
Observing characteristics & strategy

• purpose built 7-beam receiver capable of dual-circular polarisation (*thanks to Mal Sinclair, Graham Moorey, Pat Sykes, Graeme Carrad and the engineering team*)

• Galactic plane scanned with the multibeam receiver – fast and efficient method to cover large area with good sensitivity.

• targeted follow-up of detections for deeper spectra.

• system noise ~ 60 Jy (~20 K).
• 3σ survey sensitivity of 0.7 Jy.
• FWHM 3.2 arcmin @ 6.7-GHz.
• beam spacings 6.46 arcmin, footprint 15 arcmin.
• 2048 frequency channels across each 4 MHz band, at each line frequency and each polarization.
• spectral resolution of 0.11 km/s.
Survey Results:
Longitude - Latitude Distribution

Dashed: Known sources; Solid: MMB detections, Grey: northern hemisphere
Survey Results:
Flux Distribution & Completeness

Peak Flux densities

Pandian et al. 2009

Shading: 3 sigma sensitivities
Red-lines: completeness estimates

Survey Completeness

MMB
Survey Science:
Small and Large Magellanic Cloud survey

- Blind survey of both Magellanic clouds (initial sensitivity of 0.22 and 0.13 for Large and Small respectively).

- New detections of 6.7-GHz methanol and 6-GHz hydroxyl masers in Large Magellanic Cloud.

- 11 sites of star formation maser emission in total, with varying combinations of species (water, ground-state hydroxyl, excited-state hydroxyl, and methanol).

- Comparison of abundances shows maser populations factor of 10-50 smaller in Large Magellanic Cloud.

- Star formation rates account for ~10, hydroxyl and water maser populations accounted for, but methanol still under-abundant.
Survey Science:
Star-formation in the inner Galaxy – the 3-kpc arms

• Near arm: van Woerden et al. 1957, Oort et al. 1958.

• Far arm: Dame & Thaddeus 2008.

• Question over existence of star formation? Some evidence (e.g. Caswell and Haynes (1987), Cersosimo (1990), Busfield et al. (2006)).

• Both arms shown by 6.7-GHz methanol maser detections of the MMB to clearly exhibit high-mass star formation.
Survey Science:
Tracing a 3-kpc arm “ring”

'Expanding' ring: Rougoor 1964; van der Kruit 1971; Cohen & Davies 1976
Non-'expanding' ellipse: de Vaucouleurs 1970
Survey Science:
Inner Galactic structure in the longitude-velocity domain

Orange: Crux-Scutum
Green: Norma
Yellow: Perseus
Purple: Carina-Sagittarius
Grey: 1 kpc, 7 km/s
Circles: 3 kpc arm
Stars: Galactic bar
Triangles: Sgr B2
Diamonds: Galactic Centre Zone

HI: Southern Galactic Plane Survey, McClure-Griffiths et al. 2005
CO: Dame et al. 2001, Dame & Thaddeus 2011
Survey Science:
Inner Galactic structure in the longitude-velocity domain

- Majority of the 6.7-GHz methanol maser longitude-velocity domain is attributable to the spiral arms.

- Both longitude-velocity distribution and structure function demonstrate structures on small (<0.03°) and large (>3°) scales – former due to multiple sources within molecular cloud complexes, latter a signature of Galactic scale structures.
Survey Science:
12.2-GHz methanol follow-up

• Targeted observations of 6.7-GHz methanol for 12.2-GHz methanol.
• 250 detections towards 580 targets, 43.1% detection rate.
• 12.2-GHz companions have smaller velocity ranges and lower flux densities.
• 80% coincidence of velocity of maser peaks.
• 12.2-GHz associated with later evolutionary stage.
• Increase in velocity range and luminosity with age.
Future prospects:
Very Long Baseline Interferometry

• Bright and compact nature of sources ideal for astrometry with Very Long Baseline Interferometry (VLBI).

• Accurate distances (±10 micro arcsec parallaxes) and full 3-dimensional motion (±1 km/s).

• Maser astrometry can provide valuable data for both the structure of our Galaxy and its velocity field.

• NRAO Very Long Baseline Array, European VLBI Network and Japanese VLBI Network currently being used (~30 parallaxes now published).

• Southern hemisphere observations with Long Baseline Array underway..
Future prospects:
Magnetic field measurements

- Magnetic field measurements through Zeeman splitting of hydroxyl maser emission.
- Targeted follow-up of all MMB detections for four ground state transitions of hydroxyl maser emission.
Future prospects:
Magnetic field measurements

Within regions of high-mass star formation:

- masers typically exhibit consistent line-of-sight field directions with comparable field strengths (e.g. Fish & Reid 2007, Nammahachak et al. 2006, Caswell et al. 2010, Vlemmings et al. 2010)
Future prospects:
Magnetic field measurements

On Galactic scales:

- Davies (1974) first suggestion of coherent fields across 8 sites.
- Reid & Silverstein (1990) coherence over a few kpc for 17 sites.
- Fish et al. (2003) coherence in 2\textsuperscript{nd} & 3\textsuperscript{rd} quadrants, and locally in 1\textsuperscript{st} and 4\textsuperscript{th} and levels up to 80% in the spiral arms (about 40 sites observed in study plus previous).
- Han & Zhang 2007 compilation.
Summary

• Parkes survey completed with ~1000 Galactic 6.7-GHz methanol masers detected – established an important legacy resource.

• 6.7-GHz methanol masers highlight regions of enhanced star formation indicating the starting points of the spiral arms and the interaction of the (long, thin) Galactic bar.

• The masers also provide many candidates for tracing the full 3-kpc arm structure.

• Multi-wavelength studies and astrometric distances through VLBI will further enhance the importance of this species of maser as a tool in understanding the structure of our Galaxy.
Publications & Data Release

• Survey Publications:
  • 12.2-GHz methanol maser MMB follow-up catalogue - I. Longitude range 330 to 10, Breen et al. MNRAS submitted.

• 6.7-GHz Catalogue Publications:
  • V: 20° – 60° (~250 sources) Fuller et al., MNRAS, in prep.

• Data will be available online [www.astromasers.org]
Thanks to the staff at Parkes and the ATCA for smooth observations


**MAGMO collaborators:** N. McClure-Griffiths, J. L. Caswell, L. Harvey-Smith, T. Robishaw

MMB data website: www.astromasers.org

contact: james.green@csiro.au