Astrophysical Masers:
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Extragalactic class I methanol maser: A new probe for starbursts and feedback of galaxies

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Abstract. We report progress on research relating to 36.2 GHz extragalactic class I methanol masers, including a review of published work and new observations at high angular resolution. These observations reveal that extragalactic class I masers are excited in shocked gas and maybe associated with starbursts, galactic-scale outflows from active galactic nuclei (AGNs) feedback, or the inner-end region of the galactic bar. The current observational results suggests that extragalactic class I methanol masers provide a new probe for starbursts and feedback in active galaxies.

Keywords. masers – stars: formation – ISM: molecules – galaxies

1. Introduction

There are more than 30 methanol transitions known to exhibit maser emission in the radio frequency range (Ellingsen *et al.* 2012). These masers are widely excited in star forming regions (SFRs) within our Galaxy and are recognised to be one of the most effective tracers for investigating SFRs (e.g., Ellingsen *et al.* 2006). The methanol maser transitions are empirically classified into two types, which have been labelled as class I or class II transitions (e.g., Batrla & Menten 1988; Menten 1991). Class I methanol masers usually arise from multiple locations within a SFR, spread over areas of 0.1–1.0 parsec in extent (Voronkov *et al.* 2006). While the class II methanol masers are located close to (within $\sim 1''$) the high-mass young stellar object (YSO ; Caswell *et al.* 2010). More than 1000 methanol maser sources from class I and class II transitions have been detected in our Galaxy (e.g., Green *et al.* 2009; Chen *et al.* 2014; Yang *et al.* 2017).

Compared to the rich and active methanol maser phenomena in our Galaxy, discoveries of extragalactic methanol masers are limited to the class II transitions at 6.7 GHz or 12 GHz, which have only been detected in the Large Magellanic Cloud (LMC; Green 2008; Ellingsen et al. 2010) and Andromeda (M31; Sjouwerman *et al.* 2010). A number of extragalactic surveys for class II methanol masers are described in the literature (Ellingsen *et al.* 1994, Phillips *et al.* 1998 and Darling *et al.* 2003). These searches observed over one hundred sources showing OH and H_2O megamaser galaxies, and/or (Ultra-) Luminous Infrared emission, but no detections were made in any of these surveys.

More than 20 years ago Sobolev (1993) suggested that the $4_{-1} \rightarrow 3_0$ E 36.2 GHz class I methanol transition may be more likely to be observed as an extragalactic maser than any of the class II transitions. Recently, widespread methanol maser emission (from over 300 positions) in the 36.2 GHz class I transition have been detected toward the central Molecular Zone (CMZ) of the Milky Way (Yusef-Zadeh *et al.* 2013), providing evidence in support of Sobolev's conjecture. In contrast, in the same region there are only three positions where 6.7 GHz class II methanol masers were detected by the Parkes methanol multibeam survey (Caswell *et al.* 2010). This is consistent with the hypothesis that class I methanol transitions can be excited on large scales in the central regions of luminous galaxies (such as starburst galaxies and merging galaxies), where widespread shocks and enhanced cosmic rays may significantly boost methanol abundances on large scales. To test this hypothesis, we have performed a number of surveys for the extragalactic class I methanol masers at 36.2 GHz transition using interferometers, Australia Telescope Compact Array (ATCA) and Jansky Very Large Array (JVLA), and single dishes Green Bank Telescope (GBT). In this paper, we mainly focus on reporting the observing results from these surveys.

2. Overview of extragalactic class I methanol maser surveys

2.1. *First survey with the ATCA*

The first systemic survey for extragalactic class I methanol masers was undertaken with the ATCA in the H168 array configuration (angular resolution of $\sim 7''$). The survey targets were a sample of about ten OH maser emission selected galaxies. We detected emission in the 36.2 GHz methanol transition towards the central regions of two starburst galaxies, NGC 253 and Arp 220 from this survey (see Ellingsen *et al.* 2014 and Chen *et al.* 2015 for details). Interestingly, emission from $7_{-2} \rightarrow 8_{-1}$ E 37.7 GHz class II methanol transition was also detected in Arp 220. These observations represent the first detections of methanol emission from the 36.2 and 37.7 GHz from sources beyond the Milky Way.

Comparing the line width (a few 10s of km s^{-1}) of the detected methanol emission with other thermal molecular lines detected in the two galaxies, they are at least a factor of $2-3$ times narrower. In addition, the integrated emission we observed from the 36.2 GHz transition is at least 30 times stronger than that predicted for thermal methanol emission (based on previous observations of thermal methanol transitions in these sources). Figure 1 shows that the detected methanol emission from the 36.2 GHz (and for Arp 220 also the 37.7 GHz) transition is significantly offset from the centre of the two galaxies where the strongest thermal molecular emission is typically observed. In combination, these findings strongly suggest that the detected 36.2 GHz methanol emission in the two galaxies is produced by masing. The luminosity of the 36.2 GHz methanol emission in Arp 220 is well in excess of a million times stronger than that of typical star formation masers in this transition in the Milky Way, and so represents the first detection of a methanol megamaser.

As shown in Figure 1 (right panel), the 36.2 GHz methanol masers towards Arp 220 show that there is a good spatial alignment of the methanol and diffuse, soft X-ray emission in this system. Two hypotheses have been proposed which can explain this phenomenon. One is that the enhancement of the methanol abundance is due to the effect of the high-energy cosmic rays in these regions. This has been proposed to explain the production of widespread 36.2 GHz methanol masers in the CMZ of the Milky Way (Yusef-Zadeh *et al.* 2013) and NGC 253 (Ellingsen *et al.* 2014). Another hypothesis is that the X-ray plume in Arp 220 traces a starburst-generated superwind region wherein rapidly outflowing and inflowing shock-heated gases are produced. In this scenario a critical assumption is that the widespread shocks within the plume region play an important role in producing widespread 36.2 GHz class I methanol emission.

2.2. *Single dish survey with the Green Bank Telescope*

In order to clarify the pumping conditions required for extragalactic class I methanol masers (either outflow-driven shocks, cosmic rays or both), a systematic survey for the

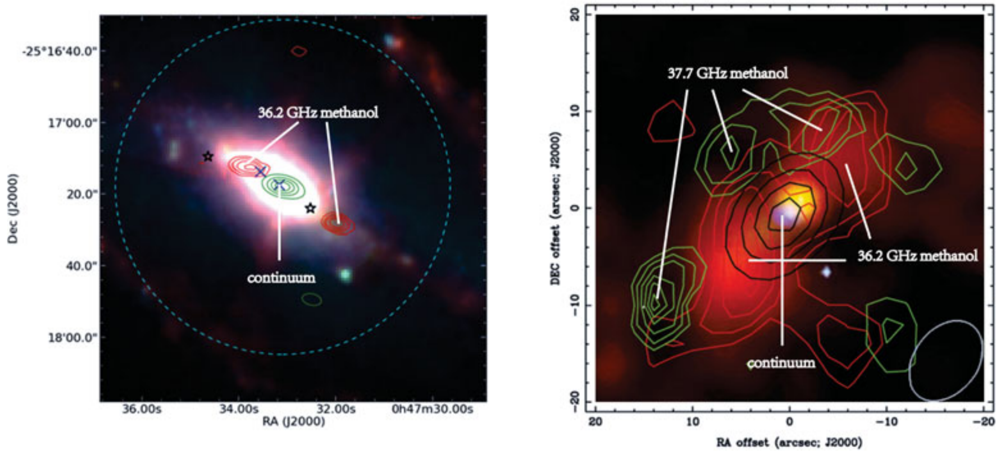

Figure 1. The 36 GHz continuum emission and 36.2 GHz methanol emission from towards NGC 253 (*left:* Ellingsen *et al.* 2014) and Arp 220 (*right:* Chen *et al.* 2015) detected with ATCA observations in H168 array. **Left panel**: for NGC 253 with 36 GHz continuum emission (contours at 20%, 40%, 60%, and 80% of 95 mJy beam^{-1}) and 36.2 GHz methanol emission (contours at 20%, 40%, 60%, and 80% of 310 mJy km s^{-1} beam^{-1}). The background image is from Spitzer IRAC data at the 3.6, 4.5 and 8.0 μm bands. **Right panel**: for Arp 220 with 36 GHz continuum emission (contours at 20, 40, 60, and 80 σ; 1σ=0.35 mJy beam^{-1}), and integrated methanol emission from both the 36.2 GHz and the 37.7 GHz transitions. Both methanol emission contours are starting at 2.5σ with increments of 1σ (1σ=0.4 Jy km s^{-1} beam^{-1}). The background image is the X-ray emission image extracted from McDowell *et al.* (2003).

36.2 GHz methanol masers was performed with the GBT towards 16 galaxies with both extended X-ray emission and megamaser emission (from water or OH). Extended X-ray emission may trace the physical environment of outflow-driven shocks or high-energy cosmic rays, allowing us to investigate these phenomena. In this survey, large baseline ripples in the GBT spectra limited the results to tentative detections towards 11 of the target galaxies (Chen *et al.* 2016). These tentative detections show that the peak flux densities of the methanol emission is weak (in a range of 2 – 8 mJy). The majority of them show a single component, with typical linewidth of $\sim$ 200 km s^{-1}. Most of them have a peak velocity located within or near the edge of the velocity range of the HI emission and OH or H_2O megamasers, suggesting that they are associated with the host galaxies. However, significant offsets of the methanol spectral features with respect to the systemic velocity are seen in Mrk 231. Figure 2 shows a comparison of the spectra of the methanol emission with those of the dense gas tracer HCO^+ 1–0 (89.2 GHz) for three galaxies. It can be clearly seen that in Mrk 231 two methanol spectral features are observed and these are blue- and red-shifted by approximately 1000 km s^{-1} with respect to the systemic velocity. The velocity offsets are consistent with the high-velocity outflow components revealed by millimetre CO observations (Cicone et al. 2012), supporting the hypothesis that class I methanol megamasers might be produced in galactic-scale outflows.

Investigation of possible relationships between the tentative methanol emission and the emission in other wavelength ranges of host galaxies indicates no correlation between the methanol and X-ray luminosities of the host galaxies (as shown in left panel of Figure 3), suggesting that the methanol megamasers are not related to galactic-scale high-energy cosmic rays. Whereas there are good correlations between the methanol luminosity, and that of the IR and radio luminosities of the host galaxies, i.e., $L_{methanol} \propto L_{IR} \propto L_{36GHz}$ (as shown in two right panels of Figure 3), suggesting that the methanol

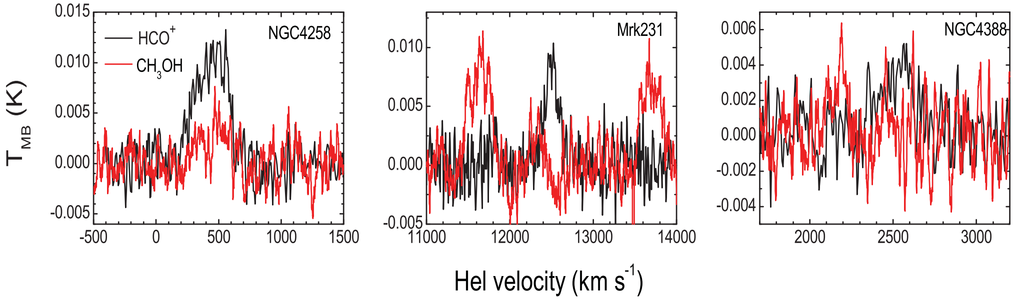

Figure 2. Comparison of spectra of the 36.2 GHz class I methanol detected in the GBT survey with HCO^+ 1–0 spectra for three galaxies.

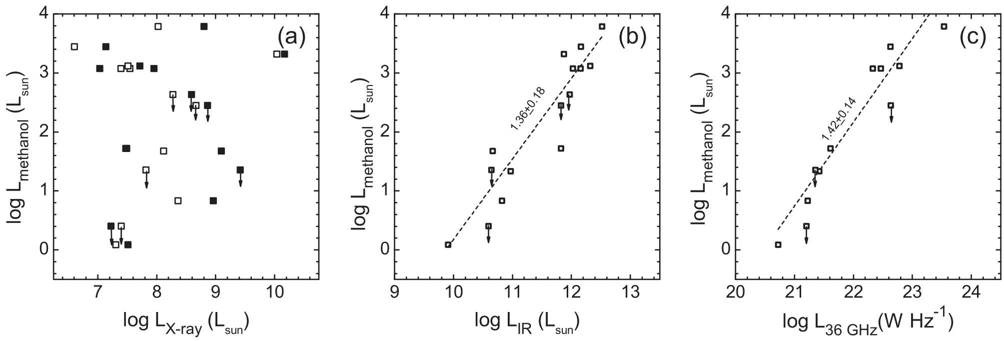

Figure 3. Relationships between the luminosity of the 36.2 GHz methanol megamasers detected from the GBT survey and that observed in other wavelength ranges for the host galaxies: (a) methanol vs. soft-x ray emission (0.5–2 keV; marked with open squares) and hard-x ray emission (2–10 keV; marked with filled squares) relations; (b) methanol vs. infrared; (c) methanol vs. radio (36 GHz) relation. Upper limits for the methanol luminosity are indicated by downward arrows for the four non-detections. Dotted lines are fits to the data labeled by their slopes.

emission may be related to the starburst activity of the host galaxy. Combining these investigations, we argue that class I methanol masers appear to be excited in galaxies with significant starburst and strong molecular outflow, and provide a potential probe of starburst activity and feedback process via wind-driven outflows of these active galaxies.

2.3. *Higher resolution observation with the JVLA towards NGC253*

Recently, follow-up higher angular resolution and sensitive observations of 36.2 GHz methanol towards NGC253 were undertaken with the ATCA in the EW367 and 1.5A arrays (Ellingsen *et al.* 2017; see also Ellingsen's paper in this proceeding). The combination of the previous ATCA H168 array and new EW367 and 1.5A array data reveal that the methanol shows compact emission from seven positions at an angular resolution of $\sim 1''$ (labeled MM1–MM7; see Ellingsen et al. 2017). With the angular resolution of the combined ATCA array data the derived brightness temperature is a few K (or 220 K) using the peak flux density (or the integrated intensity) for the brightest components (Ellingsen *et al.* 2017). Hence, considering the brightness temperature alone, these observations do not require that the methanol emission is from a maser (although there are other lines of evidence that leave little doubt that it is).

To investigate the compact components of the 36.2 GHz methanol transition, we used the JVLA in the A-array configuration to make observations of this line towards NGC253 (Chen *et al.* in prep.). The JVLA A-array observations have an angular resolution of

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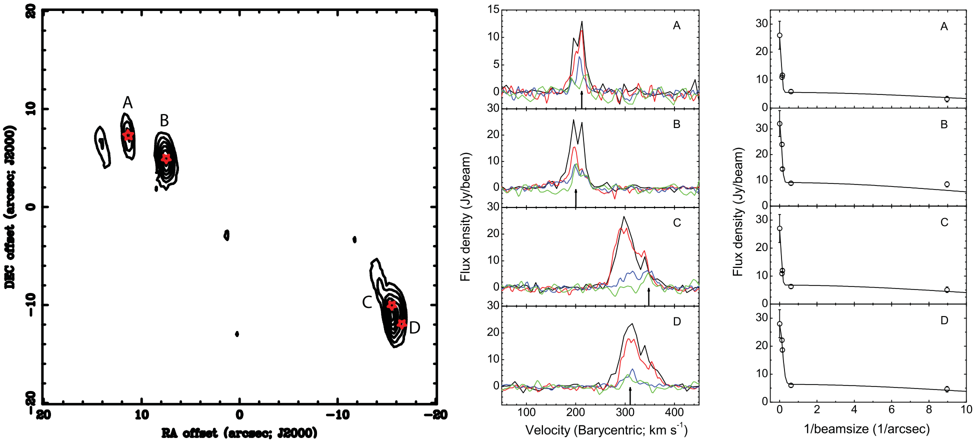

Figure 4. 36.2 GHz methanol emission detected with the ATCA and JVLA. **Left panel**: Overlaid the positions of the compact methanol emission (stars) detected with JVLA in the A-array configuration on the integrated methanol emission image (contours) obtained using the ATCA in the EW367 configuration. **Middle panel**: The peak flux densities of the four compact components detected at different angular resolutions with the ATCA in the H168, EW367 and 1.5A array configurations, and JVLA in the A-Array configuration. **Right panel**: The change in peak flux density of the four compact components versus the inverse of the beamsize. The solid lines represent the combined Gaussian profiles of both the extended and compact components with angular sizes of 6 arcseconds and 0.06 arcsenconds, in the distribution. Note, the zero-spacing data is obtained from the Shanghai Tianma 65-m telescope.

$\sim 0.1''$, one order of magnitude greater than the previous ATCA data. Compared to the previous ATCA observations, the JVLA data show four compact methanol components located within the regions of more extended emission detected with the ATCA (see left panel of Figure 4). The peak flux densities of the compact components detected with the JVLA are in the range of 3 – 9 mJy/beam, corresponding to typical brightness temperatures of >3000 K, which is far higher than the typical temperature ($\sim$ 100 K) of thermal methanol emission regions. These data provide unambiguous confirmation of methanol maser emission in extragalactic sources.

Figure 4 (middle and right panels) shows the peak flux densities of the methanol emission detected at different angular resolutions by the ATCA and JVLA. We can see that the flux density rapidly decreases as the angular scale decreases from a few arcseconds to 2 arcseconds, but the flux density does not change significantly when the angular scale decreases less than 2 arcseconds. This shows that the methanol emission consists of both extended and compact structures, with typical scales of 6 arcsecs and 60 mas, respectively.

3. Other new detections

Using the ATCA and JVLA, we have also made detections of 36.2 GHz methanol masers towards some other galaxies. We list some of these other detections here:

• Methanol maser emission with a narrow linewith ($<$ 10 km s^{-1}) has been detected towards NGC4945 (see McCarthy *et al.* 2017 and McCarthy's paper in this proceeding). The maser emission may be associated with molecular inflow, which is observed in HF absorption.

• Both extended and compact methanol maser emission are detected towards the Seyfert galaxy NGC 1068 with the ATCA and JVLA (Chen *et al.* in prep.). The detected maser emission is located at the edge of the galactic bar, suggesting that the shock

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produced in the region between the bar edge and inflow or outflow gas of the galaxy may excite the maser emission.

• JVLA observations in the D-array configuration have detected the methanol maser emission from four positions along the galactic bar of nearby galaxy Maffei2 (Chen *et al.* in prep.). The velocity of the methanol emission is consistent with the hot dense gas tracer NH_3, suggesting that the methanol maser might be associated with shocks in star forming clouds along the galactic bar.

4. Summary

We have performed searches for 36.2 GHz extragalactic class I methanol masers toward a number of galaxies with the ATCA, GBT and JVLA. Significant detections have been made towards some galaxies (including NGC253, Arp220, NGC 4945, NGC1068 and Maffei2). Follow-up higher resolution observations with the JVLA have revealed that the methanol emission consists of both the extended and compact components. However their pumping mechanism is still unclear. Current observations suggest that the masers might be excited in shocked gas triggered in the starburst region, bar edge, or AGN wind-driven outflow and inflow. We argue that class I methanol megamasers may provide a new tool for investigating the starburst and feedback processes of active galaxies.

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