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Class I Methanol Maser Emission in NGC 4945

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Abstract. We have detected maser emission from the 36.2 GHz ($4_{-1} \rightarrow 3_0$E) methanol transition towards NGC 4945. This emission has been observed in two separate epochs and is approximately five orders of magnitude more luminous than typical emission from this transition within our Galaxy. NGC 4945 is only the fourth extragalactic source observed hosting class I methanol maser emission. Extragalactic class I methanol masers do not appear to be simply highly-luminous variants of their galactic counterparts and instead appear to trace large-scale regions where low-velocity shocks are present in molecular gas.

Keywords. masers, galaxies: starburst, stars: formation

1. Introduction

Methanol maser emission has been observed in over 1200 sources throughout our Galaxy (e.g., Ellingsen *et al.* 2005; Caswell *et al.* 2010, 2011; Green *et al.* 2010, 2012; Voronkov *et al.* 2014; Breen *et al.* 2015). The rich masing spectrum of this species makes it a powerful tool for investigating high-mass star-formation. Two different pumping mechanisms, collisional and radiative, divide the various transitions of methanol into class I and class II masers respectively. Class I methanol masers within our Galaxy are typically associated with the interface of molecular clouds, low-velocity shocks from cloud-cloud interaction, extended green objects (EGO) or expanding HII regions (Kurtz *et al.* 2004; Cyganowski *et al.* 2009, 2012; Voronkov *et al.* 2010, 2014). Class I methanol masers are observed towards low- and high-mass star-formation regions, however, the class II transitions are exclusively associated with high-mass star formation (Breen *et al.* 2013). Galactic class I methanol masers are generally observed in numerous individual spots across each star-formation regions, in comparison class II methanol masers are closely associated with the location of the young-stellar objects (Ellingsen 2006; Breen *et al.* 2010; Caswell *et al.* 2010).

Extragalactic methanol masers are much less commonly observed than their Galactic counterparts. Confirmed detections of extragalactic class I masers have previously only been reported in three sources (NGC 253, NGC 1068 and Arp 220; Ellingsen *et al.* 2014;

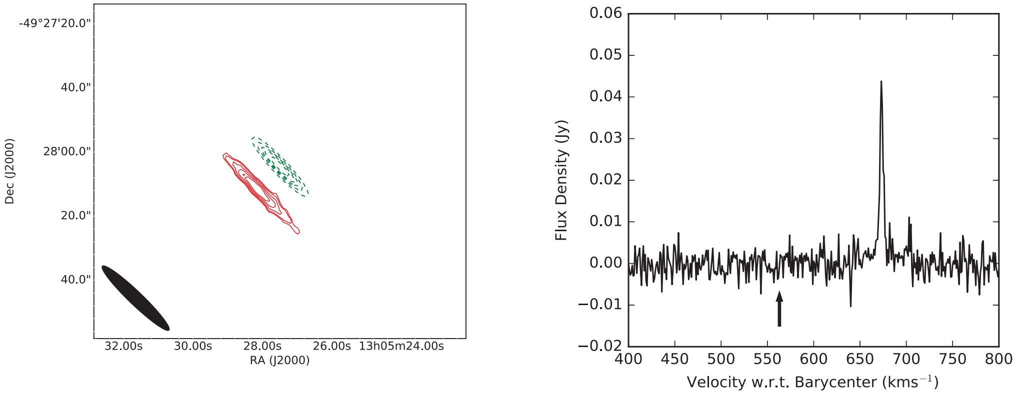

Figure 1. Left: 36.2-GHz emission methanol emission (solid contours 45%, 50%, 60%, 70%, and 80% of the 256 mJy km s^{-1} beam^{-1}) and the 7mm continuum emission (dotted contours 15%, 30%, 45%, 60%, and 80% of the 385 mJy km s^{-1} beam^{-1}). The black ellipse describes the synthesised beam size for our observations. Right: 36.2-GHz spectrum from the region of peak emission within our spectral line cube (imaged at 1 km s^{-1}). Vertical arrow indicates the systemic velocity of NGC 4945.

Wang *et al.* 2014; Chen *et al.* 2015), and extragalactic class II masers in two local group galaxies (Sjouwerman *et al.* 2010, for M31; Green *et al.* 2008 and Ellingsen *et al.* 2010, for the LMC). The extragalactic class II masers appear to be highly luminous versions of their Galactic equivalents, in contrast, the extragalactic class I methanol masers do not appear to result from the same phenomenon as those observed towards star-formation regions in our Galaxy.

Widespread emission from the 36.2-GHz $4_{-1} \rightarrow 3_0$E methanol maser transition is observed towards the centre of our galaxy (Yusef-Zadeh *et al.* 2013). The integrated luminosity of this emission is > 5600 Jy km s^{-1} spread over more than 350 unique sites within a 160×43 pc region. Yusef-Zadeh *et al.* (2013) suggested that the mechanism producing an abundance of methanol in the central region of the Milky Way is photo-desorption of methanol from cold dust grains. It is unlikely that such a phenomenon is exclusive to our Galaxy and, therefore, should be present in the central regions of other galaxies.

NGC4945 is a nearby (3.7$\pm$0.3 Mpc; Tully *et al.* 2013) barred-spiral galaxy, with a hybrid starburst and AGN nucleus. The starburst process in NGC 4945 is the primary source of energy for exciting photo-ionized gas, with infrared observations revealing that the AGN is heavily obscured (Spoon *et al.* 2000, 2003). We report observations towards this source at both the 36.2-GHz class I and 37.7-GHz class II methanol maser transitions.

2. Observations

The observations utilised the Australia Telescope Compact Array (ATCA) on 2015 August 25 and 26. The ATCA was configured in the EW352 array, with a minimum baseline of 31 metres and maximum baseline of 352 metres. Limited hour angle coverage, combined with this east-west array, caused an elongation of the synthesised beam (26×4 arcseconds at 36.2 GHz). The hybrid mode CFB 1M/64M was used for the Compact Array Broadband Backend (Wilson *et al.* 2011). We centred both 2048 MHz bands on 36.85-GHz and configured two zoom bands in the 64 MHz IF that covered the rest frequencies of 36.169265 and 37.703700 GHz, for the $4_{-1} \rightarrow 3-0$E and $7_{-2} \rightarrow 8_{-1}$E masing transitions respectively. The velocity range of our observations is -350 to 1200 km s^{-1}(barycentric) with a spectral resolution of 0.26 km $s^{-1}$for the 36.2-GHz transition. The FWHM of the primary beam of the ATCA antennas at 36.2-GHz is approximately 70 arcseconds which corresponds to a linear scale of 1200 pc a the assumed distance of 3.7 Mpc for NGC4945. As our observations consisted of only a single pointing, centred on the galactic nucleus, we are only sensitive to maser emission within 600 pc of the centre of the galaxy.

All data reduction was completed using MIRIAD, following standard techniques and procedures for 7-mm ATCA spectral line observations. PKS B1934-648 and PKS B1253-055 were used as the amplitude and bandpass calibrators respectively. Two minute observations of J1326-5256 were interleaved with the 10 minute source scans in order to perform phase calibration. Phase and Amplitude self-calibration were implemented using the continuum emission from the central region of NGC 4945. We used continuum subtraction to isolate the continuum emission component from the spectral line emission. The velocity range we imaged over was 200 to 1000 km s^{-1}barycentric (molecular line emission in NGC 4945 is observed between 300 and 800 km s^{-1}; Ott *et al.* 2001) with a spectral resolution of 1 km $s^{-1}$and average RMS noise of $\sim$2.2 mJy beam^{-1} in each channel.

3. Results

Emission from the 36.2-GHz methanol transition was detected towards NGC 4945, along with 7-mm continuum emission. No emission was detected from the methanol 37.7-GHz line. This result was expected, and the transition was observed 'for free' as it falls in the same IF as the 36.2-GHz transition. The 36.2-GHz emission (coordinate of 3:05:28.093 and −49:28:12.306 in right ascension and declination respectively) is observed offset by 10 arcsec from the galactic nucleus, perpendicular from the position angle of the galactic disk and the 7-mm continuum emission is observed at the nucleus of NGC 4945 (see Figure 1). The angular offset of the 36.2-GHz emission corresponds to 174 ± 14 pc at the assumed distance of 3.7 Mpc. The 36.2-GHz emission has a peak flux density of 43.8 mJy at a position of 674 km s^{-1}, with the emission spread over a velocity range of 50 km s^{-1}, from 660 to 710 km $s^{-1}$with a total integrated flux density of 256 mJy km s^{-1}.

Despite the elongation of our beam, we can be confident in the observed offset from the galactic nucleus as it is perpendicular to the major-axis of elongation. Initial analysis of a second epoch of observations from 2017 June 30 have confirmed that both the position and offset measured from the original observations are accurate.

4. Discussion and Implications

It is important to first convincingly attribute the observed emission to a maser process. There are numerous pieces of evidence supporting this, the strongest of which is the narrow line width of the primary component of the emission ($\sim$ 8 km s^{-1}). Narrow line widths are a characteristic property of maser emission within Galactic sources and have also observed in NGC 253 (Ellingsen *et al.* 2014, 2017b). In addition to the emission being narrower than typical thermal emission, it is also offset from any previously reported thermal emission in the source. From our observed integrated intensity of 0.258 Jy km s^{-1} we determine an isotropic luminosity of 4.44×10^7 Jy km s^{-1} kpc^2 for the methanol emission in NGC 4945. This is approximately a factor of two less than the isotropic luminosity of NGC 253 (9.0×10^7 Jy km s^{-1} kpc^2; Ellingsen *et al.* 2014). The combination of these factors strongly indicates that the 36.2-GHz emission we are observing is a maser.

The maser emission in NGC 4945 is the fourth confirmed detection of class I methanol maser emission in an extragalactic source. This small sample size has made it difficult to determine what morphological features or phenomena these extragalactic methanol masers are associated with. High-resolution observations of NGC 253 have determined that the two regions of methanol maser emission in this source appear to be associated with inner interface of the galactic bar either side of the galactic nucleus (Ellingsen *et al.* 2017b). Presently the dynamics of the galactic bar in NGC 4945 are poorly understood. However, a position angle of 33 degrees, and azimuth angle of 40 degrees (with respect to the galactic plane) is reported by Ott *et al.* (2001). The position of our maser emission does not appear to be associated with a bar of these properties, however, the accuracy of the bar dynamics is still under discussion.

Monje *et al.* (2014) reports the possible presence of a molecular inflow in NC 4945, detected in hydrogen fluoride (HF) absorption. The properties of this possible inflow, upper limit on radius of 200 pc and velocity range of 560 − 720 km s^{-1}, match with those of the methanol maser emission. This detection is only tentative, and the observed properties could be explained by other phenomena. Ellingsen *et al.* (2017b) speculate that extragalactic class I methanol maser emission is associated with large-scale molecular infall, therefore, association between the maser emission observed towards NGC 4945 and this possible molecular inflow would be consistent with this explanation.

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