Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Multi-wavelength maser observations of the Extended Green Object G19.01–0.03

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Abstract. We report the detections of NH_3(3,3) and 25 GHz and 278.3 GHz Class I CH_3OH maser emission associated with the outflow of the Extended Green Object G19.01–0.03 in sub-arcsecond resolution Atacama Large Millimeter/submillimeter Array (ALMA) and Karl G. Jansky Very Large Array (VLA) observations. For masers associated with the outer outflow lobes ($> 12.5''$ from the central massive young stellar object; MYSO), the spatial distribution of the NH_3(3,3) masers is statistically indistinguishable from that of previously known 44 GHz Class I CH_3OH masers, strengthening the connection of NH_3(3,3) masers to outflow shocks. In sub-arcsecond resolution VLA observations, we resolve the 6.7 GHz Class II CH_3OH maser emission towards the MYSO into a partial, inclined ring, with a velocity gradient consistent with the rotationally supported circumstellar disc traced by thermal gas emission.

Keywords. masers, stars: individual: G19.01–0.03, stars: formation, stars: massive, stars: protostars, techniques: interferometric

1. Introduction

Masers are well-established tracers of massive young stellar objects (MYSOs) and their outflows, with high-resolution Karl G. Jansky Very Large Array (VLA) and Atacama Large Millimeter/(sub)millimeter Array (ALMA) observations ongoing over the past decade continuing to lead to the identification of new maser lines in these environments. In this proceeding, we summarise our recent sub-arcsecond resolution ALMA and VLA observations of maser emission towards the Extended Green Object (EGO) G19.01-0.03, an MYSO that drives a well-collimated bipolar outflow (Williams *et al.* 2022, 2023).

2. Outflow-tracing maser emission, and a 6.7 GHz Class II methanol maser ring

The $CH_3OH(9_{-1,9} - 8_{0,8})$ line at 278.3 GHz is known to exhibit maser behaviour (e.g. Yanagida *et al.* 2014). Our ALMA peak intensity map of this line (Figure 1a) shows it generally traces the morphology of the bipolar outflow driven by the central MYSO

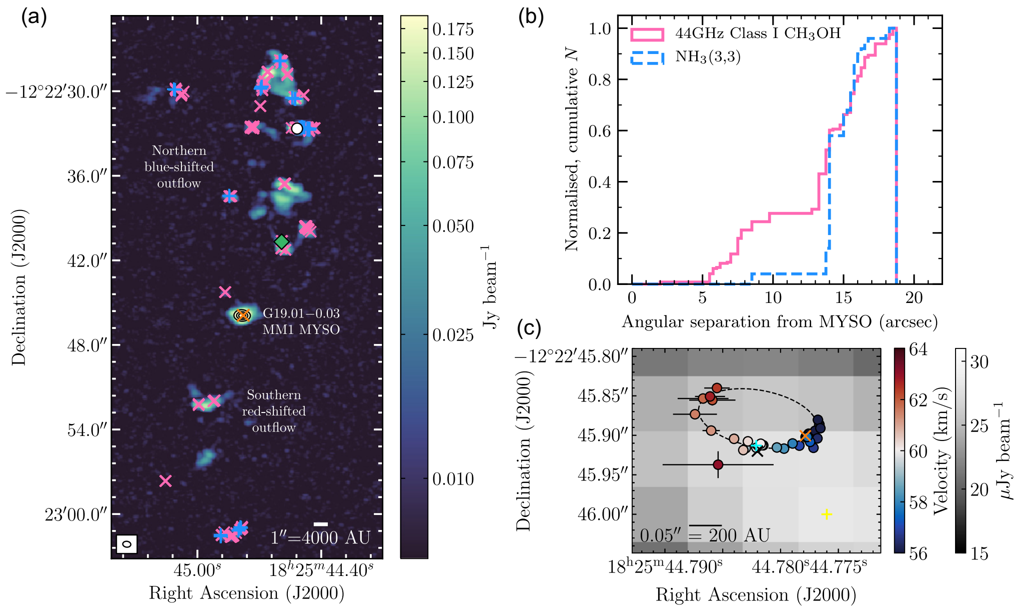

Figure 1. **(a)** ALMA peak intensity map of the $CH_3OH(9_{-1,9} - 8_{0,8})$ line at 278.3 GHz towards G19.01−0.03. The white circle marks the position of peak emission. ALMA 1.05 mm continuum contours are shown in black towards the MYSO at 64, 256 and 600σ. The orange cross marks the intensity-weighted 6.7 GHz Class II CH_3OH maser position (as in Fig.1c). Blue pluses denote new $NH_3(3,3)$ maser spots, and pink crosses denote 44 GHz Class I CH_3OH masers (Cyganowski *et al.* 2009). The green diamond marks the 25 GHz Class I CH_3OH maser. **(b)** Histogram of the angular separation of the $NH_3(3,3)$ and 44 GHz Class I CH_3OH maser spots (blue and pink respectively; as in Fig.1a) from the MYSO's ALMA 1.05 mm continuum peak (Williams *et al.* 2023). **(c)** Fitted 6.7 GHz Class II CH_3OH maser positions, coloured by velocity, overplotted on the VLA 5.01 cm continuum (adapted from Williams *et al.* 2022). The black cross and yellow and cyan pluses show the 1.05 mm, 5.01 cm and 1.21 cm continuum peak positions respectively.

(previously observed in ^{12}CO, SiO and HCO^+ by Cyganowski *et al.* 2011). We classify the brightest 278.3 GHz CH_3OH emission as a candidate maser, due to (i) its narrow spectral profile, (ii) its brightness temperature being an order of magnitude higher than that of thermal CH_3OH lines in our spectral tuning, and (iii) its coincidence, both spatially and kinematically, with known 44 GHz Class I CH_3OH masers (Cyganowski *et al.* 2009) and newly identified $NH_3(3,3)$ masers.

$NH_3(3,3)$ is known to exhibit maser behaviour thought to arise due to outflow-induced shocks (e.g. Brogan *et al.* 2011). With our $\sim 0.5''$ resolution VLA observations, we detect 50 $NH_3(3,3)$ maser emission spots to the $> 5\sigma$ level in the outflow (Figure 1a). These spots are coincident spatially and kinematically with the outflow-tracing 278.3 GHz CH_3OH emission. At large angular separation from the MYSO ($> 12.5''$), their spatial distribution is statistically indistinguishable from that of known 44 GHz Class I CH_3OH masers (Figure 1b).

The 25 GHz CH_3OH $(5_{2,3} - 5_{1,4})$ line can exhibit thermal and/or Class I maser emission towards EGOs (e.g. Towner *et al.* 2017). We tentatively detect (i) thermal emission towards the MYSO ($5.5\sigma \sim 36.8$ K), and (ii) candidate maser emission towards the outflow ($7.8\sigma \sim 52.3$ K) that is positionally and kinematically coincident with 44 GHz and 278.3 GHz Class I CH_3OH maser emission (Figure 1a).

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With VLA 2.8″ resolution observations, Cyganowski *et al.* (2009) detected 6.7 GHz Class II CH_3OH maser emission towards the central MYSO. With our new $\sim 0.6''$ resolution VLA observations, the maser spot distribution exhibits a partial ellipse, consistent with an inclined ring (Figure 1c). The strongest maser emission is blue-shifted with respect to the systemic velocity of the MYSO ($\sim$60 km s^{-1}; Cyganowski *et al.* 2011), and the maser velocities follow that of the Keplerian circumstellar disc traced by thermal gas emission (Williams *et al.* 2022).

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