Astrophysical Masers:
Unlocking the Mysteries of the Universe
Proceedings IAU Symposium No. 336, 2017
A. Tarchi, M.J. Reid & P. Castangia, eds.

doi:10.1017/S1743921317010717

Ubiquitous millimeter-wavelength Class I methanol masers associated with massive (proto)stellar outflows: ALMA and SMA results

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Abstract. We report the discovery of widespread millimeter-wavelength Class I methanol maser emission associated with protostellar molecular outflows in the massive (proto)cluster G11.92−0.61. Our ∼0.5″-resolution SMA and ALMA observations of the 229 GHz and 278 GHz Class I transitions reveal seven and twelve candidate masers, respectively: all 229 GHz masers have 278 GHz counterparts, and five are also coincident with 44 GHz Class I masers previously detected with the VLA. For paired masers, the peak intensities at 229 GHz and 278 GHz are correlated. We also find tentative evidence for a correlation between the strength of millimeter-wavelength Class I maser emission and the energy of the associated molecular outflow.

Keywords. masers, ISM: individual objects (G11.92-0.61), ISM: molecules, ISM: jets and outflows, stars: formation, techniques: interferometric

1. Introduction

Numerous observational studies, spanning nearly three decades, have shown that Class I CH_3OH masers at 36, 44 and 95 GHz are associated with the outflows driven by high-mass protostars (e.g. Plambeck & Menten 1990, Kurtz *et al.* 2004, Cyganowski *et al.* 2009, Voronkov *et al.* 2014). More recently, Kalenskii *et al.* (2013) detected Class I CH_3OH masers (at 44, 84, and 95 GHz) towards outflows in low-mass star-forming regions, and found that Class I maser luminosities scaled with the luminosity of the driving protostar. The Class I maser series extend into the (sub)millimeter regime (e.g. Voronkov *et al.* 2012), but higher-frequency transitions were relatively unstudied prior to the commissioning of the Atacama Large Millimeter/submillimeter Array (ALMA). Here, we report observations of two millimeter-wavelength Class I CH_3OH maser transitions towards the massive protocluster G11.92−0.61. Located at a distance of $3.37^{+0.39}_{-0.32}$ kpc (Sato *et al.* 2014), G11.92−0.61 is notable for containing both high- and low-mass (proto)stars that are actively accreting and driving outflows (Cyganowski *et al.* 2017).

2. Observations

We have observed G11.92−0.61 with subarcsecond resolution in three Class I CH_3OH maser transitions: 44.069 GHz (with the Very Large Array (VLA)), 229.759 GHz (with

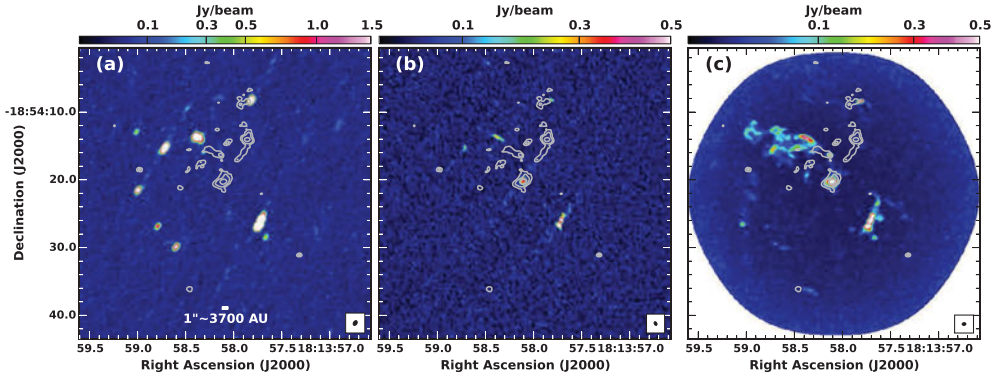

Figure 1. Peak intensity maps, in colorscale, of (a) VLA 44 GHz, (b) SMA 229 GHz, and (c) ALMA 278 GHz CH_3OH emission, overlaid with ALMA 1.05 mm continuum contours from Cyganowski *et al.* (2017) (levels: [5,15,100] × 0.35 mJy beam^{-1}).

the Submillimeter Array (SMA)), and 278.305 GHz (with ALMA). Details of the observations are given in Cyganowski *et al.* (2009), Cyganowski *et al.* (2014), and Cyganowski *et al.* (2017), respectively. The key parameters of the maser image cubes are: $\theta_{\rm syn}$ ∼0.6″ and $\sigma_{\rm line}$ ∼ 23 mJy beam^{-1} (VLA 44.069 GHz), $\theta_{\rm syn}$ ∼0.5″ and $\sigma_{\rm line}$ ∼ 23 mJy beam^{-1} (SMA 229.759 GHz), and $\theta_{\rm syn}$ ∼0.4″ and $\sigma_{\rm line}$ ∼ 3 mJy beam^{-1} (ALMA 278.305 GHz).

3. Results

Peak intensity maps of the 44.069 GHz, 229.759 GHz, and 278.305 GHz CH_3OH emission observed towards G11.92−0.61 are shown in Figure 1. From the image cubes, we identified 12 candidate 278.305 GHz and 7 candidate 229.759 GHz masers (based on T_B, line width, and line ratios). All of the 229.759 GHz candidate masers have 278.305 GHz counterparts, and five are also coincident with 44.069 GHz masers. Both the 229.759 and 278.305 GHz transitions are in the 36 GHz maser series (Voronkov et al. 2012); for 229/278 GHz maser pairs, the peak intensities of the two transitions are correlated.

The millimeter-wavelength Class I CH_3OH masers are associated with shocked gas at outflow-cloud interfaces (c.f. Figs. 2 and 3 of Cyganowski *et al.* 2017). The new masers are found in association with outflows from high-mass (MM1) and low-mass (MM7/9) protostars within the G11.92−0.61 protocluster; based on the limited data available, the maser strengths appear correlated with the outflow energy, as measured from ^{12}CO (Cyganowski *et al.* 2011, Cyganowski *et al.* 2017).

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https://doi.org/10.1017/S1743921317010717 Published online by Cambridge University Press