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On the origin of methanol maser variability: Clues from long-term monitoring

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Abstract. High-mass young stellar objects (HMYSO) displaying methanol maser flux variability probably trace a variety of phenomena such as accretion events, magnetospheric activity, stellar flares and stellar wind interactions in binary systems. A long-term monitoring of the 6.7 GHz methanol line in a large sample of HMYSOs has been undertaken to characterize the variability patterns and examine their origins. The majority of the masers show significant variability on time-scales between a week and a few years. High amplitude short flares of individual features occurred in several HMYSOs. The maser features with low luminosity tend to be more variable than those with high luminosity. The variability of the maser features increases when the bolometric luminosity the powering star decreases. Statistical analysis of basic properties of exciting objects and the variability measures supports an idea that burst activity of methanol masers is driven mainly by changes in the infrared pumping rate.

Keywords. masers – stars: formation – ISM: clouds – radio lines: ISM

1. Introduction

Early information on the variability of 6.7 GHz methanol masers came from searching for new sources. Caswell *et al.* (1995) observed 245 objects on 4-5 occasions over 1.5 yr and found that 75% of features were not significantly variable while noticeable variability of amplitude <2 occurred in 48 sources. Their main suggestion was that the maser variations are related to changes in the maser path length or pump rate. Goedhart *et al.* (2004) monitored 54 sources over a period of 4.3 yr at 1−2 week intervals or shorter. Diverse variability patterns on time-scales of a few days to several years were reported for a majority of the targets including periodic (132−520 day) variability. A flare activity on time-scales of a few months together with long-term variations on a time-scale of years was reported in G351.78−0.54 (MacLeod & Gaylard 1996). Changes in the maser pumping or disturbances with the maser regions were postulated as possible causes of that peculiar variability. Episodic and short (<6 day) flares of only one feature in the spectrum of G33.641−0.228 were detected (Fujisawa *et al.* 2014). These flares likely arise in a region of size much smaller than 70 au and can be induced by energy release in magnetic reconnection. Here, we present some of the results of long-term monitoring of the 6.7 GHz maser line for a large sample of HMYSOs. A full description of the sample and data presentation can be found in Szymczak *et al.* (2018).

2. Observations and results

A sample of 166 maser sources with peak 6.7 GHz flux density greater than 5 Jy was drawn from the Torun methanol source catalogue (Szymczak *et al.* 2012). Each target was

† He was the speaker. Indeed, the expected presenter of this talk, Prof. M. Szymczak, could not finally attend the Symposium.

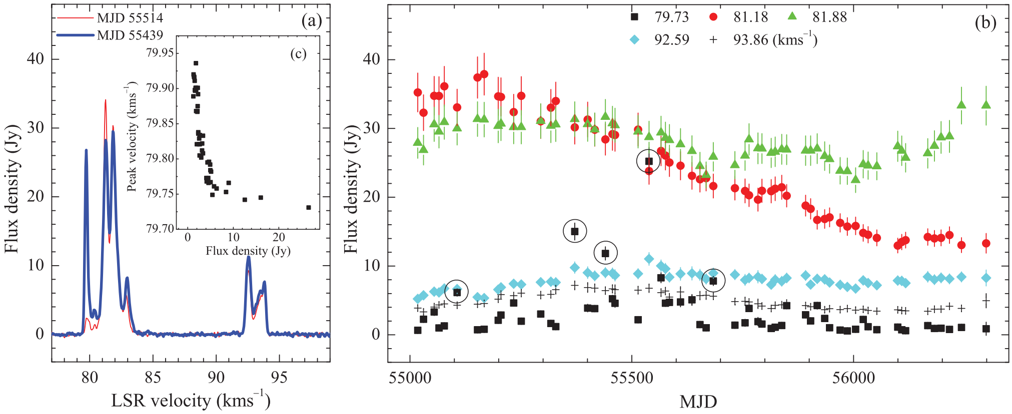

Figure 1. Short flares of 6.7 GHz maser feature at 79.73 kms^{-1} in G28.305−0.387. **(a)** The spectra taken before and during the flare are shown with the thin and thick lines, respectively. **(b)** The light curves of the maser features. The flaring events at 79.73 kms^{-1} are marked with open circles. Inset **(c)** shows the change in peak velocity of the flaring feature versus its flux density.

observed at least once a month between 2009 June and 2013 February using the Torun 32 m radio telescope. Several circumpolar sources were observed at 2−3 day intervals. The data were dual polarisation taken with frequency switching mode. The spectral resolution was 0.09 kms^{-1} and typical rms noise level was 0.20−0.35 Jy. Absolute flux density calibration was accurate to within 10% (Szymczak *et al.* 2014).

A wide range of variability patterns from non-varying to very complex changes in the shape and intensity of the spectra was observed. The types of behaviour such as monotonic increases or decreases, aperiodic, quasi-periodic and periodic variations seen in the sources of our sample are similar to those reported in Goedhart *et al.* (2004).

2.1. *Short flares*

In five HMYSOs we detected rapid flares with relative amplitudes higher than two. In most cases these events appeared as outliers in the light curve of individual maser feature, while other features showed smooth and slight variations. Figure 1 shows the light curves of selected maser features of G28.305−0.387. Five bursts with a relative amplitude of 2−13 occurred at 79.73 kms^{-1}. For instance at MJD 55439 the flux density of this feature was 25.2 Jy while it was only 2.2 Jy 25 days earlier. No significant changes were seen in the other features. We cannot uncover a profile of those bursts due to sparse observations. The peak velocity of the flaring feature was measured by a Gaussian fitting. During the bursts the peak velocity decreased by 0.12−0.18 kms^{-1} relative to the velocity during a quiescent state. Blending of two maser features with slightly different velocities appears as the most natural explanation of this relation. One maser feature has high velocity and relative stable intensity while low velocity feature experiences bursting activity.

Probably the same type of flares was observed in G33.64−0.21 where typical rise and fall times were one and five days, respectively (Fujisawa *et al.* 2014). The flux density rose by a factor of 7 and fell exponentially. Similarly as in G28.305−0.387 the peak velocity of the flaring feature slightly changed during the bursts and returned to its pre-flare value. The VLBI data suggest that an active region where the flares arise is much less than 70 au. Fujisawa *et al.* (2014) proposed that the bursts are powered by energy released in impulsive events of magnetic field reconnection; the particles accelerated in solar-like flares heat the environment of reconnection region and can influence rapidly the

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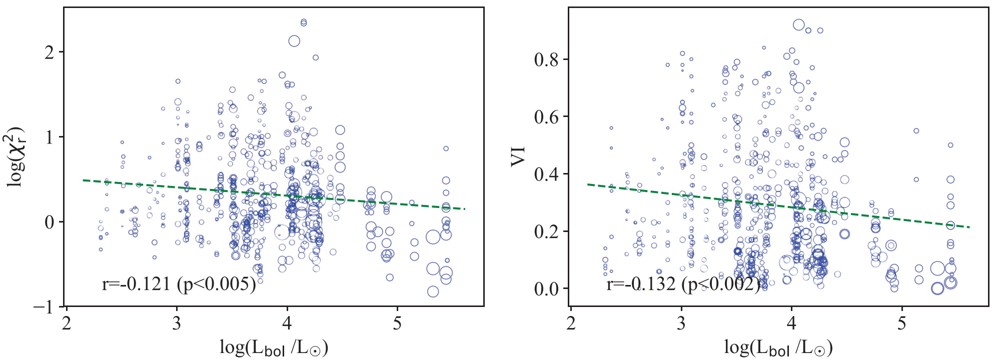

Figure 2. Reduced χ^2 (left) and variability index (right) of maser features vs. the bolometric luminosity of exciting star. The size of symbol is proportional to the square of 6.7 GHz maser luminosity of feature. The dashed lines represent the best-fitting results.

gas where the maser emission arises. Our survey indicates that short flares of the maser emission in restricted velocity range are not unique to G33.621−0.228. These bursts were observed for one feature of the spectrum or synchronously occurred for more features. We suggest that similar events may occur in more HMYSOs when monitored with high cadence.

2.2. *Variability measures vs maser and bolometric luminosities*

To quantify the variability we used the variability index as defined in Szymczak *et al.* (2014) and the reduced value of χ^2. We investigated the dependence of these variability measures on the luminosity of maser features and luminosity of exciting star. The distances were taken from trigonometric parallaxes (Reid *et al.* 2014) or else calculated from the Galactic rotation model (Reid *et al.* 2009). The kinematic distance ambiguity was resolved using the data published by Green & McClure-Griffiths (2011). For sources with known distances we have calculated the luminosity of each maser feature with well determined variability indices assuming the emission is isotropic. To determine the bolometric luminosity of powering star we used the SED fitting tool, SED models (Robitaille *et al.* 2006; 2007) and photometric data in the wavelength range from 3.4μm to 1.1 mm available from the public databases (see Sarniak *et al.* this volume).

Figure 2 displays the values of the reduced χ^2 and variability index (VI) versus the bolometric luminosity of exciting HMYSO for all the features not affected by the effects of confusion and offset observation. There is a weak anti-correlation between the star bolometric luminosity and both variability measures. It is clear that the variability of maser features increases in the sources powered by less luminous HMYSOs. We note that the significance of this correlation may be lowered by two factors: (i) the bolometric luminosity used is a measure of the total luminosity of the protocluster while the maser flux density likely depends on the intrinsic luminosity of a single HMYSO, (ii) the kinematic distance errors of the studied objects are much higher than those of a minority of maser sources with known trigonometric distances.

The size of symbols in Figure 2 is proportional to the square of the isotropic luminosity of maser features. There is a tendency that the maser features of higher luminosity are associated with the objects of higher stellar luminosity. It is possible that luminous exciting star provides higher pumping rate via infrared photons or longer path of maser amplification (Urquhart *et al.* 2013).

2.3. *Origin of variability*

In several periodic sources in the sample we observed a time delay (3−8 days) of the bursts between individual maser features. This indicates a radiative mechanism of pumping of the maser emission and a linear separation between group of maser clouds up to ∼1400 au which is comparable to the source size observed with VLBI. Thus changes in the pump rate appear as plausible cause of the maser variability. Recently observed giant flare in the 6.7 GHz maser emission toward S255 NIRS3 preceded by an increase in infrared luminosity (Caratti o Garatti *et al.* 2017; Moscadelli *et al.* 2017) possibly due to accretion event, provides a strong support for radiative pumping and indicates that changes in the infrared radiation drive the maser variability. High resolution observations suggest that the infrared radiation can enlarge the size of the excited region providing longer amplification path (Moscadelli *et al.* 2017).

Extraordinary outburst in G24.329+0.144 detected in our monitoring appears to be similar to that reported in S255 NIRS3 where the variability is driven by global changes in the pump rate. However, the burst peaks of two maser features showing the highest relative amplitude were delayed by ∼2.5 months and their shapes significantly changed (Wolak *et al.* this volume). Such large delays cannot be easily explained but suggest that local changes of physical conditions in the maser regions play a role. There are several sources in the sample which exhibited uncorrelated variability in a few spectral features. These may be caused by tiny fluctuations of the parameters which influence the maser optical depth or flux of seed photons. Correlations between the velocity fields and alignment of the structures along the line of sight in the environment of HMYSO may also cause changes in coherence velocity and path of maser amplification.

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