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Pumping regimes of Class I methanol masers

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Abstract. In the current paper we describe results of an extensive and refined analysis which shows that the beaming leads to considerable changes in the model line ratios and brightness estimates. For example, beaming shifts the locus of the brightest masers to the lower values of the gas densities. Recent theoretical paper by Leurini *et al.* (2016) presented extensive consideration of the Class I methanol maser (MMI) pumping. Their study allowed to distinguish only 3 of 4 MMI pumping regimes found in Sobolev *et al.* (2005) and Sobolev *et al.* (2007) on the basis of analysis of observational data combined with theoretical considerations. The regime when the line from the $J_{-2} - (J-1)_{-1}\ E$ series is the brightest was missing in Leurini *et al.* (2016) results. This may be explained by considering the fact that the authors did not take into account considerable beaming effects.

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

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In our earlier papers Sobolev *et al.* (2005) and Sobolev *et al.* (2007) we have provided observational examples and results of preliminary theoretical analysis that Class I methanol maser (MMI) pumping has at least 4 regimes defined by the series of lines containing the brightest maser line. Since then extensive surveys of the southern maser sources confirmed this conclusion.

Survey of the 36 and 44 GHz lines (lowest frequency lines of the $J_{-1} - (J-1)_0\ E$ and $J_0 - (J-1)_1\ A^+$ series) by Voronkov *et al.* (2014) have shown that these masers are bright and widespread and only 23% of detected maser features is detected in both transitions. These lines define the most widespread 1st and 2nd regimes of MMI pumping.

The lines $4_{-1} - 3_0\ E$ at 36.1 GHz and $5_{-1} - 4_0\ E$ at 84.5 GHz are likely to be weak masers under normal conditions of the massive star forming region (Berulis *et al.* 1991). Frequently, the maser nature of the lines in this regime is difficult to prove observationally. Anyhow, there are cases when the line profiles contain narrow spikes and the maser nature is proved interferometrically. The sources Sgr B2 and G1.6-0.025 (Salii *et al.* 2002) can be considered as representatives of this maser regime.

Lines of the $J_0 - (J-1)_1\ A^+$ series become prevalent in the other maser regime. Numerous sources in star forming regions manifest definitely maser lines arising in the $7_0 - 6_1\ A^+$ and $8_0 - 7_1\ A^+$ transitions at 44.1 and 95.2 GHz, respectively. Masers in the northern sources DR21 W, NGC 2264 and OMC-2 and numerous southern sources represent this regime. Theoretical analysis of the pumping shows that the lines of the $J_0 - (J-1)_1\ A^+$ series become brightest in the models with rather high beaming and moderate column densities.

Survey of the 25 GHz line from the $J_2 - J_1\ E$ series by Voronkov *et al.* (2007) have shown that these masers are widespread but mostly rather weak. However, bright example of OMC-1 clearly shows existence of this 3rd regime.

Survey of the 9 GHz line from the $J_{-2} - (J-1)_{-1}\ E$ series by Voronkov *et al.* (2010) have shown that though these masers are rare there are clear examples of existence of the 4th MMI pumping regime (Voronkov *et al.* 2006; Voronkov *et al.* 2011).

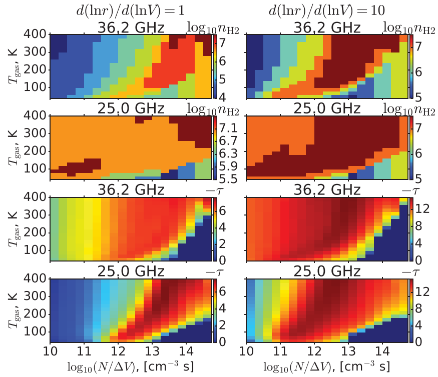

Figure 1. Effect of the beaming on the density, n_{H2}, column density and optical depth of the strongest masers at 36 and 25 GHz. Upper two panels show n_{H2} at which the maximum maser optical depth, τ_{max}, is reached. Lower two panels show τ_{max}.

In the current paper we describe results of extensive and refined analysis which tells that the beaming leads to considerable changes in the model line ratios and brightness estimates. For example, beaming shifts the locus of the brightest masers to the lower values of the gas densities (see Fig.1). The most refined present model of collisional excitation of methanol from Parfenov *et al.* (2016) was used.

The recent study of Leurini *et al.* (2016) of the MMI pumping allowed to distinguish only 3 of 4 MMI pumping regimes found in Sobolev *et al.* (2005) and Sobolev *et al.* (2007) on the basis of analysis of observational data combined with theoretical considerations. Leurini *et al.* (2016) results miss the regime when the line from the $J_{-2} - (J-1)_{-1}$ E series is the brightest. This can be explained by the fact that these authors did not take into account considerable beaming effects: clear example of the model with the beaming which matches observational data is published in Voronkov *et al.* (2006).

So, the beaming should be taken into account if one considers conditions of the MMI excitation. This is in accordance with suggestions from the paper "Modelling of Cosmic Molecular Masers: Introduction to Computation Cookbook" (Sobolev *et al.* 2012).

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