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Time-dependent numerical modelling of hydroxyl masers

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Abstract. The statistical rate equations are used to model the OH masers to see if they will always have a one-to-one correspondence with the variation of dust temperature. It is concluded that one has to be careful to argue that the masers will always follow the dust temperature variation profile, and it is possible that different maser transitions from the same molecule respond differently to the same dust temperature variations.

Keywords. stars: formation, masers, methods: numerical, ISM: molecules

1. Motivation

The origin of the periodic variability in the two brightest class II methanol masers (MMIIs), at 6.7- and 12.2-GHz, is yet to be determined but there are currently five hypotheses which had been proposed. Three of these five hypotheses use the dust temperature variation as the origin of periodicity (Array *et al.*, 2010, Inayoshi *et al.*, 2013 and Parfenov & Sobolev, 2014). In these hypotheses, it is assumed that the dust temperature variability has a one-to-one correspondence with maser variability. It is, therefore, the aim of this work to investigate if there is always a one-to-one correspondence between the dust temperature variations and maser variability. The OH molecule is used because it is less complex compared to methanol.

2. Overview

The rate at which level population N_i of a molecule in a molecular cloud changes can be modelled by the standard statistical rate equations (Elitzur & Netzer, 1985). For OH, some transitions overlap, which may populate and de-populate the involved level populations. Therefore, the angle-averaged intensity should be modified to incorporate line overlap and Elitzur & Netzer (1985) derived it to be:

$$\bar{J}_a = S_a\,(1-\beta_a)\,(1-f_a) + (1-\beta_{ab})\,f_a S_{ab} + W_d \beta_{ab} I_d + W_{\rm HII}\beta_{ab} I_{\rm HII}, \tag{2.1}$$

where f_a, W_d ($W_{\rm HII}$), I_d ($I_{\rm HII}$) and S_{ab} (S_a) are the fraction of the line width profile which overlaps with the line profile of transition b, geometric dust (HII region) dilution factor, radiative intensity from the dust (HII region) and source function for overlapping (non-overlapping) line, respectively. See Bujarrabal *et al.* (1980) for the overlapping lines.

3. Results and discussion

In this investigation, the 24-level OH data, from the Leiden Atomic and Molecular Database (LAMDA) (Schöier *et al.*, 2005), are used in finding the solution of the statistical rate equations with Heun's method. At each second, the previous level populations

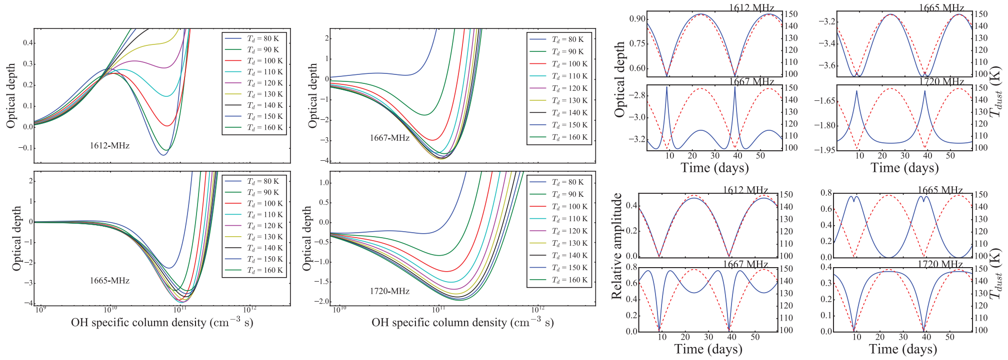

Figure 1. The *left* and *middle* panels are how the optical depths vary as a function of a specific column density at different dust temperatures (from 10 to 160 K). The dust's (HII region's) geometric dilution factor, molecular hydrogen density, fractional molecular abundance of OH, electron (kinetic) temperature, and emission measure were fixed at 0.1 (1.0×10^{-3}), 10^5 cm^{-3}, 10^{-5}, 9.0×10^3 (100) K and 3.0×10^8 cm^{-6} pc, respectively. *R*ight panel shows how the optical depth (top) and relative amplitude (solid line) changes to an absolute cosine-like dust temperature light curve (dashed line).

$N_i(t_{j-1})$ were used to calculate the t_j level populations, $N_i(t_j)$. The convergence criterion was such that $\frac{|N_i(t_j)-N_i(t_{j-1})|}{N_i(t_j)} < 10^{-7}$ (Cragg, Sobolev & Godfrey, 2005).

After testing the implementation of the code, the set of physical parameters which could result in one or more of the four rotational ground state transitions of OH in masing were searched at the specific column density of 1.0×10^6 to 2×10^{20} cm^{-3} s. The negative optical depths in Fig. 1 (*left* and *middle* panels) imply that the transitions are masing. At the specific column density of 1.5×10^{11} cm^{-3} s, the 1612-MHz line is not masing but the rest are masing. At this specific column density, the dust temperature was changed with time and independently of whether the system is in equilibrium or not. The 1665- and 1667-MHz lines do not show a one-to-one correspondence to the dust temperature variations (*right* panel in Fig. 1). On the other hand, the 1720-MHz maser shows a one-to-one correspondence to the dust temperature variations. Such behaviour had been observed even with different dust temperature profiles and at different specific column densities.

Therefore, we conclude that it is possible that the dust temperature variations do not have a one-to-one correspondence with the maser variation and different masing lines can behave differently to the same dust temperature profile. It is then reasonable to argue that different maser species of different molecules can respond differently from the same changes of the dust temperature.

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