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OH inversions in star-forming regions and ALI radiation transfer

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Abstract. I introduce a new model of OH maser pumping in star-forming regions, based on exact radiation transfer models of the interface between an expanding ucHII region and undisturbed molecular material. The model incorporates the most recent set of rate-coefficients for collisions of OH with molecular hydrogen, and an improved model of continuum emission from dust. FIR line overlap is incorporated into the model in a manner which avoids the inconsistencies associated with the Sobolev approximation.

1. Introduction

It is now approximately five years since the last major attempt to model the OH maser pumping schemes in star-forming regions (Pavlakis & Kylafis 1996a,b,c). These most recent models, and earlier efforts all used the Sobolev or LVG approximation at various levels of sophistication. The present work is an attempt to upgrade the previous models by discarding the LVG approximation in favour of the exact radiation transfer treatment provided by the Accelerated Lambda Iteration (ALI) method. A major advantage of the present model over those which relied on LVG is the ability to model sets of conditions which involve small or zero velocity shifts across the maser region.

2. Included Effects

Any successful model of OH needs to include far-infrared (FIR) line overlap, as this very often makes an important contribution to maser pumping. The fact that the LVG approximation is essentially local, but line overlap includes non-local velocity gradients, means that any method of incorporating FIR line overlap within the LVG formalism looks somewhat artificial. In the current model, line overlap is included by a natural extension of individual transitions to overlapping transition groups, each composed of a number of velocity bins which deal with the Doppler effect as a function of depth through the model.

Kinetic collisions are modelled using the most recent comprehensive set of rate coefficients for collisions of OH with H_2 (Offer, van Hemert & van Dishoeck 1994). This set of rate coefficients allows for interactions with both the ortho- and para- forms of H_2. At this stage, I consider only transitions at the hyperfine

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level, and the model does not go on to consider magnetic hyperfine splittings, either for the collisions or polarization of the radiation.

The grey-body approximations for dust radiation fields used in earlier models have been replaced in the present work by tables of optical constants for a mixture of graphite and astronomical silicate particles, provided by Laor & Draine (1993). The tables contain data for 80 grain radii, ranging from 0.001 to $10\,\mu$m, and cover a wavelength range from 1 to $1000\,\mu$m. These data have also replaced the observational extinction data from Mathis (1990) used in some earlier work with the ALI code. An alternative dust model based on the Greenberg unified theory is also available, in which the dust is represented by a silicate core and various coatings of organic materials, and at low enough temperatures, ices. The Mie theory for a coated sphere has been extended to an arbitrary number of coatings in order to generate the radiation field from dust of this type (Gray 2001).

3. The Radiation Transfer Model

The model is based upon the Scharmer & Carlsson (1985) ALI code, as modified to OH by Jones et al. (1994). A slab geometry is used as a reasonable representation of the interface between the molecular cloud and the expanding ucHII region of the young stellar object (YSO). Typically eighty slabs or depth points are used in a given model, with rays at 5 angles. The slabs are fitted to a standard interface thickness of 20 AU, but values as low as 1 AU have been used to model the 13 GHz maser in W3(OH) (Gray 2001). To accelerate the slow linear convergence of the model, the acceleration method by Ng is applied at every 4th (or 6th for the higher order version) iteration, to ensure that the model is not forced to an apparently converged answer which is not a solution of the original equations.

4. The HII Region/Cold Cloud Interface

The model of the interface is based on the standard five-zone model by Tielens and Hollenbach (1985), but the two end zones, the undisturbed cold gas, and the ucHII region itself are excluded, as is the thin region of atomic hydrogen on the neutral side of the ionization front. The model thus consists of a warm molecular zone behind the leading fast shock (see Figure 1) and a PDR with a somewhat higher temperature.

5. Conclusions

I have carried out the initial study at zero velocity gradient, where the performance of LVG models is the poorest. The largest gain coefficients appear at 1667 MHz, but I expect competitive effects to transfer these to 1665 MHz in many cases, given sufficient gain length for saturation. The behaviour of 1667, 1665 and 1720 MHz is broadly similar (see Figure 2 and Figure 3) with a generally increasing gain with rising dust temperature and OH abundance, though the quantitative effect is much weaker at 1720 MHz than in the main lines. The

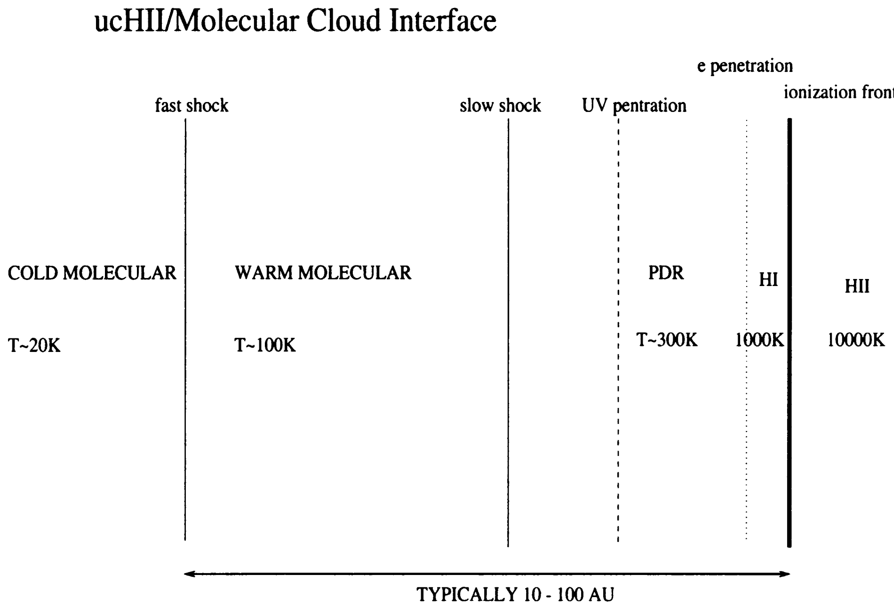

Figure 1. Slab model of the ucHII region/molecular cloud interface.

1612 MHz line has a significantly different behaviour, needing dust temperatures below 40 K for inversion. A useful feature of the ALI models is that gains near zero velocity shift tend to be larger than for high shifts, making it possible to get higher gains from shorter masers than predicted by previous models. Future work needs to include studies with at least modest velocity shifts to compare results with LVG work.

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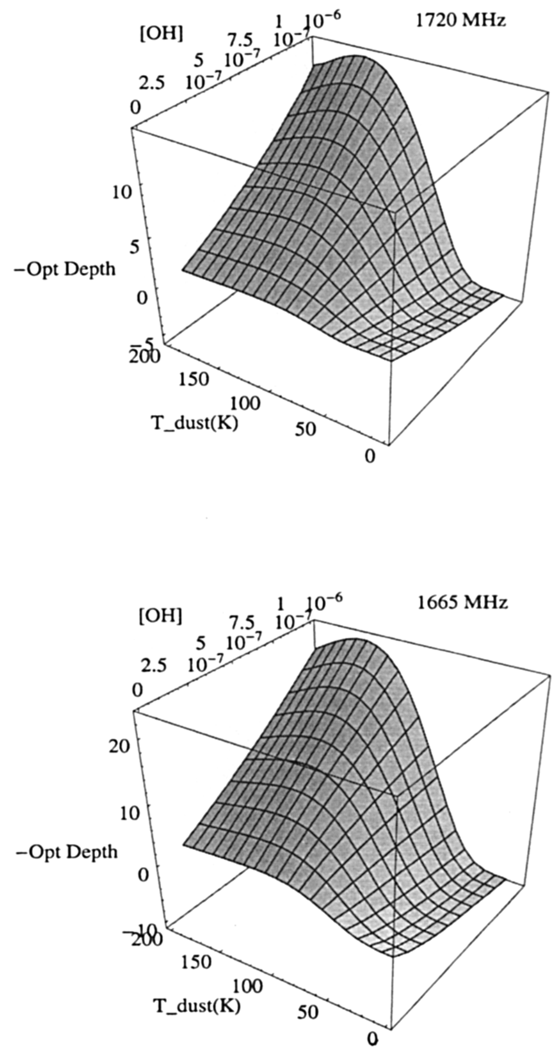

Figure 2. Integrated unsaturated gains for the 1720 and 1665 MHz lines of OH at a kinetic temperature of 100 K in the warm molecular gas region. Any gain over 10 is potentially saturating.

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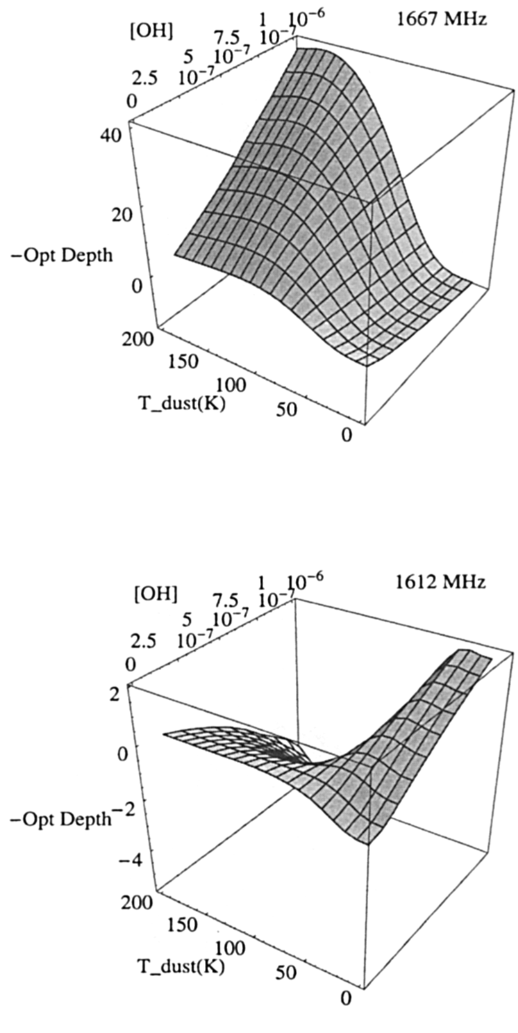

Figure 3. Integrated unsaturated gains for the 1667 and 1612 MHz lines of OH at a kinetic temperature of 100 K in the warm molecular gas region. Any gain over 10 is potentially saturating.