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Pumping the interstellar methanol masers

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ABSTRACT

The pumping of interstellar methanol masers is studied, covering a range of excitation conditions. The Class I (Class A) masers result from collisional excitation followed by spontaneous radiative decay. Masers appear in low-frequency transitions where the upper state is strongly favoured by large Einstein A coefficients, associated with high-frequency transitions, or by slower loss rates. Absorption (anti-inversion) is seen when the lower state is so favoured. The Class II (Class B) masers appear when there is a source of continuum radiation warmer than the gas kinetic temperature. Here the high-frequency transitions selectively populate or depopulate levels by preferential absorption of submillimetre photons. This radiative pumping leads to just the opposite behaviour: masing in transitions which show absorption in the Class I case, and vice versa. In particular the very strong 12.2-GHz 2_0–$3_{-1}E$ and 6.6-GHz 5_1–6_0A^+ masers are qualitatively accounted for, and predictions are made of other masing lines.

This simple model accounts successfully for all the diverse methanol masers, switching between Class I and Class II behaviour, and explains naturally the phenomenon of lines which are seen as masing in some sources and in absorption in others; it also enables us to predict the occurrence of some additional methanol maser transitions not yet observed.

Key words: masers – molecular processes – interstellar medium: molecules – radio lines: molecular: interstellar.

1 INTRODUCTION

Many lines of methanol have been observed in molecular clouds, due to its rich spectrum and high abundance in warm cloud cores. Of particular interest are the maser transitions of this molecule which fall into two types, denoted Class A and Class B by Batrla et al. (1987). Here we follow the convention introduced by Menten (1991a), and relabel these Class I and Class II respectively, to avoid confusion with the A and E symmetry species of CH_3OH.

The Class I masers in E-species methanol include the 25-GHz J_2–J_1 ($J=2$–10) series (Barrett, Schwartz & Waters 1971; Chui et al. 1974; Barrett, Ho & Martin 1975; Hills, Pakonin & Landecker 1975; Matsakis et al. 1980; Menten et al. 1986a; Menten et al. 1988d; Johnston et al. 1992), and the 84-GHz 5_{-1}–4_0 and 36-GHz 4_{-1}–3_0 transitions (Turner, Gordon & Wrixon 1972; Zuckerman et al. 1972; Nagai et al. 1979; Morimoto, Ohishi & Kanzawa 1985; Menten et al. 1988b; Haschick & Baan 1989; Haschick, Menten & Baan 1990). In A-species methanol they include the 147-GHz 9_0–8_1 A^+, 95-GHz 8_0–7_1 A^+ and 44-GHz 7_0–6_1 A^+ masers (Lovas et al. 1976; Morimoto et al. 1985; Ohishi et al. 1986; Plambeck & Wright 1988; Bachiller et al. 1990; Haschick et al. 1990; Plambeck & Menten 1990; Menten 1991b). Class I masers may be accompanied by absorption in the 12-GHz 2_0–3_{-1} E line (Whiteoak et al. 1988; Whiteoak & Peng 1989) and the 6.6-GHz 5_1–6_0 A^+ line (Menten 1991a). These features have been observed in various combinations in Orion, Sgr B2, and a variety of other galactic molecular clouds, where they are generally separated from compact H II regions, strong IR sources and OH or H_2O masers (Menten et al. 1986a; Plambeck & Wright 1988; Bachiller et al. 1990; Plambeck & Menten 1990).

The Class II masers include the 19-GHz 2_1–3_0 E, 37-GHz 7_{-2}–8_{-1} E, 23-GHz 9_2–10_1 A^+, 38-GHz 6_2–5_3 A^+ and 38-GHz 6_2–5_3 A^- transitions (Wilson et al. 1984; Menten et al. 1985; Wilson et al. 1985; Menten et al. 1988a; Haschick, Baan & Menten 1989; Menten & Batrla 1989). Until recently the 12-GHz 2_0–3_{-1} E transition was the most intense and widespread methanol maser observed, comparable in intensity with OH (Batrla et al. 1987; Norris et al. 1987; Kemball, Gaylard & Nicolson 1988; Koo et al. 1988;

McCutcheon et al. 1988; Norris et al. 1988). Subsequently, Menten (1991a) and MacLeod, Gaylard & Nicolson (1992) have found the 6-GHz 5_1–6_0 A^+ line to be even more luminous. Class II masers are sometimes accompanied by absorption in the Class I maser lines (Wilson et al. 1985; Menten 1991a). These features are seen predominantly in W3(OH) and NGC 6334, as well as other star-forming regions where they are associated with compact H II regions and OH/H_2O masers, but not OH/IR stars (Norris et al. 1987; Kemball et al. 1988; Koo et al. 1988; Menten et al. 1988a; Menten et al. 1988b; Norris et al. 1988).

The 25-GHz J_2–J_1 Class I masers have been studied by Zeng, Lou & Li (1987), who modelled Orion, including dust cooler than the gas kinetic temperature, and by Johnston et al. (1992). The other Class I masers are understood to be a result of fast Einstein coefficients which funnel molecules down to $k=-1$ for the E species and $K=0$ for the A species (Lees 1973; Pelling 1975). Indeed, many authors have found these transitions to be inverted in statistical equilibrium calculations (Morimoto et al. 1985; Menten et al. 1988c; Zeng & Lou 1990). The 12-GHz anomalous absorption in cold clouds has been modelled by Walmsley et al. (1988) and Peng (1990) in a similar fashion, with collisional excitation at appropriate density, and radiation from the 2.7-K cosmic background with or without a continuum source cooler than the gas. In this paper we explore further the range of this model for the Class I masers, and examine the influence of collisional selection rules.

Until now there has been no model in the literature explaining the existence of all the Class II masers. Here we propose a pumping mechanism which accounts for these features, based on a source of continuum radiation which is warmer than the gas kinetic temperature. The 9_2–10_1 A^+ maser in W3(OH) has been modelled by Zeng & Lou (1990) in this fashion. This pumping mechanism was found to work for the 12-GHz 2_0–3_{-1} E maser in calculations by R. S. Peng (private communication 1991).

It has been suggested by Menten et al. (1986a) that the methanol masers result from IR excitation to torsionally excited states, followed by spontaneous radiative decay, which tends to couple together alternate K ladders in the ground state. Thus all even K may become overpopulated with respect to odd K, or vice versa, leading to masers or absorption in the $\Delta K=1$ μ_b type lines. Torsionally excited methanol has been observed in a number of sources (Lovas et al. 1982; Hollis et al. 1983; Menten et al. 1986b), and some observations seem to agree with the odd/even-K hypothesis. Detailed modelling is required to substantiate this idea further; here we show that it is possible to account for both Class I and Class II masing by excitation within the ground state alone, without recourse to special excitation conditions.

2 MODELLING

We have carried out statistical equilibrium calculations on both A- and E-species methanol using the large velocity gradient method of Goldreich & Kwan (1974), as previously implemented for ammonia masers (Brown & Cragg 1991). Since the A and E symmetry species are not interconverted by radiative or collisional processes, we model them as separate species of equal abundance. The energy levels and Einstein coefficients for the torsional ground state were obtained for levels up to $J=12$ from Pickett et al. (1981), truncated at 140 cm^{-1} (200 K). This set of energy levels is likely to be adequate at kinetic temperatures greater than ~ 50 K, where the highest levels carry approximately 0.1 per cent of the total population.

The model includes absorption, spontaneous and stimulated emission radiative processes. In all cases the 2.7-K cosmic background radiation is included. An undiluted Planck function at temperatures ranging between 0 and 50 K is also included as a continuum source of submillimetre photons available for radiative pumping. Radiative transfer is treated in the Sobolev approximation for a spherical cloud of uniform density and temperature with infall velocity proportional to radius. Neither the geometry, nor the distribution of radiation from warm dust, is likely to be entirely realistic. However, we believe that this simple model provides insight into the qualitative features of maser excitation, although quantitative agreement may require a more elaborate model involving many uncertain parameters.

Collisional excitation rates for CH_3OH colliding with H_2 or He are unfortunately unknown. Here we use the 'hard sphere' model of Goldreich & Kwan (1974), setting all downward rates between magnetic sublevels equal to a constant, $1.5\times10^{-10} N_{H2} T_K^{1/2}/Q$, where N_{H2} is the molecular hydrogen density, T_K is the gas kinetic temperature, and Q is the partition function. Upward rates come from detailed balance. This model represents the extreme case of totally unselective collisions. For comparison, we also did calculations with a model based on double-resonance data from Lees & Haque (1974), in which some account is taken of propensity rules favouring small ΔK.

This model approximately reproduces the results of Nagai et al. (1979), Zeng et al. (1987) and Walmsley et al. (1988) at kinetic temperatures up to 50 K, the differences being attributable to differences in the collision models employed. Our set of energy levels is inadequate at the higher kinetic temperatures modelled by Zeng & Lou (1990) and Johnston et al. (1992), and so we have not attempted to reproduce their results in detail. However, the results of Zeng & Lou do differ qualitatively from ours, in that we are able to generate the 7_0–6_1 A^+ maser with *no* continuum radiation field, and we find that it does not occur under the same conditions as the 9_2–10_1 A^+ maser. This difference may be due to the inclusion by these authors of an extra temperature in their continuum radiation expression, making the variation with radiation temperature less clear cut.

3 RESULTS

We ran the statistical equilibrium calculations for five values of kinetic temperature T_K between 10 and 50 K, six values of H_2 density N_{H2} between 10^2 and 10^7 cm^{-3}, and six values of continuum temperature T_C between 0 and 50 K, giving 180 calculations in all for each symmetry species. The CH_3OH column density was set to 3×10^{16} cm^{-2} for both A and E species with an assumed linewidth of 1 km s^{-1}. These parameters give moderately strong maser intensities (maximum 6×10^4 K), allowing us to map the incidence of masing. Stronger masers can be generated with higher methanol column density. In contrast to previous work by other authors, we are not here seeking to model quantitatively any particular source, but rather to explore the behaviour over a range of parameters. The major results of these calculations are summarized below.

Over much of the range of parameters covered, the model predicts emission or absorption against the continuum background. Here we focus specifically on the incidence of masing. Two regimes are apparent: the Class I masers appear for $T_C < T_K$, while the Class II masers appear for $T_C > T_K$, over an intermediate range of density. We define (somewhat arbitrarily) as a maser an inverted transition with predicted line temperature exceeding 10 K; the actual intensity will be a sensitive function of methanol abundance and other model parameters. This excludes the weakly inverted lines, which are less likely to be observable masers.

When there is no source of continuum radiation other than the cosmic background, and when the continuum temperature is less than the kinetic temperature, the lines listed in Table 1 and displayed in Fig. 1 become masers on the chosen criterion. These include all the observed Class I masers, and a number of new maser candidates which warrant further investigation. Depending on the model temperatures, the masers appear for densities in the range 10^2–10^5 cm^{-3}, this being a function of the assumed collision cross-section. Some of these lines have been observed in molecular clouds (Lovas 1986), but not identified as masers. Some transitions mase over a wider range of model conditions than others; these are obviously better candidates for observation. Particularly promising potential masers are the 28-GHz 4_0–3_1 *E* line, and the 834-MHz 1_1–1_1 *A* (Ball et al. 1970) and 2.5-GHz 2_1–2_1 *A* asymmetry doublet transitions.

Table 1. Predicted Class I methanol masers.

transition	frequency[1] MHz	model[2] intensity	transition	frequency[1] MHz	model[2] intensity
$9_{-1}-8_{-2}$ E	9932	178 i	7_0-6_1 A^+	44070 m*	1356 i
$10_{-1}-9_{-2}$ E	57285	33 i	8_0-7_1 A^+	95169 m	282 i
$11_{-1}-10_{-2}$ E	104286	7 i	9_0-8_1 A^+	146619 m	119
$4_{-1}-3_0$ E	36169 m*	2557 i	1_1-1_1 A	834 *	64 i
$5_{-1}-4_0$ E	84521 m	432 i	2_1-2_1 A	2503 *	21 i
$6_{-1}-5_0$ E	132891	184	3_1-3_1 A	5005	13 i
4_0-3_1 E	28316 *	365 i	4_1-4_1 A	8342	9 i
5_0-4_1 E	76509	124 i	10_1-9_2 A^-	23445	18 i
2_2-2_1 E	24934 m*	143 i	11_1-10_2 A^-	76247	4
3_2-3_1 E	24929 m*	671 i			
4_2-4_1 E	24933 m*	881 i			
5_2-5_1 E	24959 m*	736 i			
6_2-6_1 E	25018 m*	357 i			
7_2-7_1 E	25125 m*	124 i			
8_2-8_1 E	25294 m*	39 i			
9_2-9_1 E	25541 *	14 i			
10_2-10_1 E	25878	5 i			
11_2-11_1 E	26313	1 i			
2_2-1_1 E	121690	106			

m: observed Class I maser – see text for references. *: mases over a wide range of model conditions. [1]Frequencies from empirical formula of Pickett et al. (1981). [2]Line intensities in K from calculation with $T_K = 50$ K, $N_{H2} = 10^4$ cm^{-3}; $T_C = 10$ K, other parameters as described in text. i: transition inverted in specified model calculation.

Table 2. Predicted Class II methanol masers.

transition	frequency[1] MHz	model[2] intensity	transition	frequency[1] MHz	model[2] intensity
$5_{-2}-6_{-1}$ E	133606	113 i	4_1-5_0 A^+	57033	22
$6_{-2}-7_{-1}$ E	85569	113 i	5_1-6_0 A^+	6668 m*	12150 i
$7_{-2}-8_{-1}$ E	37706 m*	70 i	5_2-6_1 A^-	183853	73 i
1_0-2_{-1} E	60531	1181 i	6_2-7_1 A^-	132622	67 i
2_0-3_{-1} E	12179 m*	61810 i	6_2-7_1 A^+	156128	37 i
1_1-2_0 E	68306	392 i	7_2-8_1 A^-	80993	42 i
2_1-3_0 E	19968 m*	708 i	7_2-8_1 A^+	111290	28 i
3_1-2_2 E	120197	160 i	8_2-9_1 A^-	28970	23 i
4_1-3_2 E	168578	109 i	8_2-9_1 A^+	66948	18 i
6_3-7_2 E	191735	18 i	9_2-10_1 A^+	23121 m	10 i
7_3-8_2 E	143173	16 i	2_2-2_2 A	2	86 i
8_3-9_2 E	94550	12 i	3_2-3_2 A	11	35 i
9_3-10_2 E	45859	9 i	6_2-5_3 A^+	38453 m	-0.7
			6_2-5_3 A^-	38293 m	-0.08

m: observed Class II maser – see text for references. *: mases over a wide range of model conditions. [1]Frequencies from empirical formula of Pickett et al. (1981). [2]Line intensities in K from calculation with $T_K = 10$ K, $N_{H2} = 10^4$ cm^{-3}; $T_C = 50$ K, other parameters as described in text. i: transition inverted in specified model calculation.

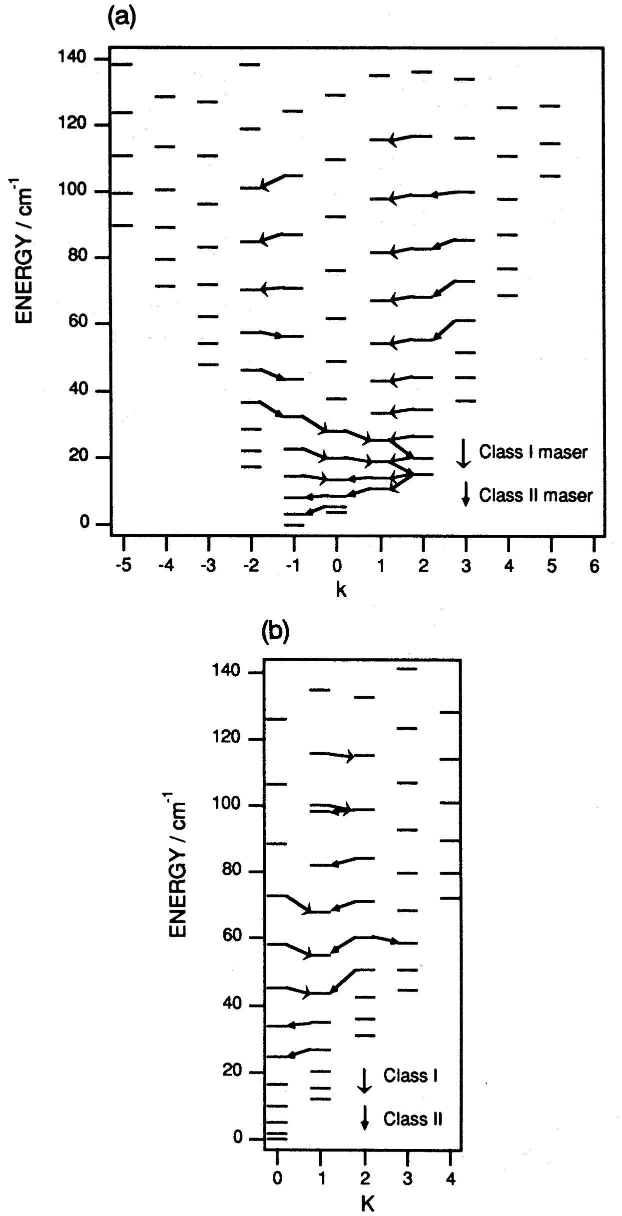

Figure 1. Predicted maser transitions in the Class I and Class II regimes for (a) *E*-species CH_3OH and (b) *A*-species CH_3OH. *A*-species asymmetry doublets are not shown, except for the 10_1 levels, where the splitting is exaggerated.

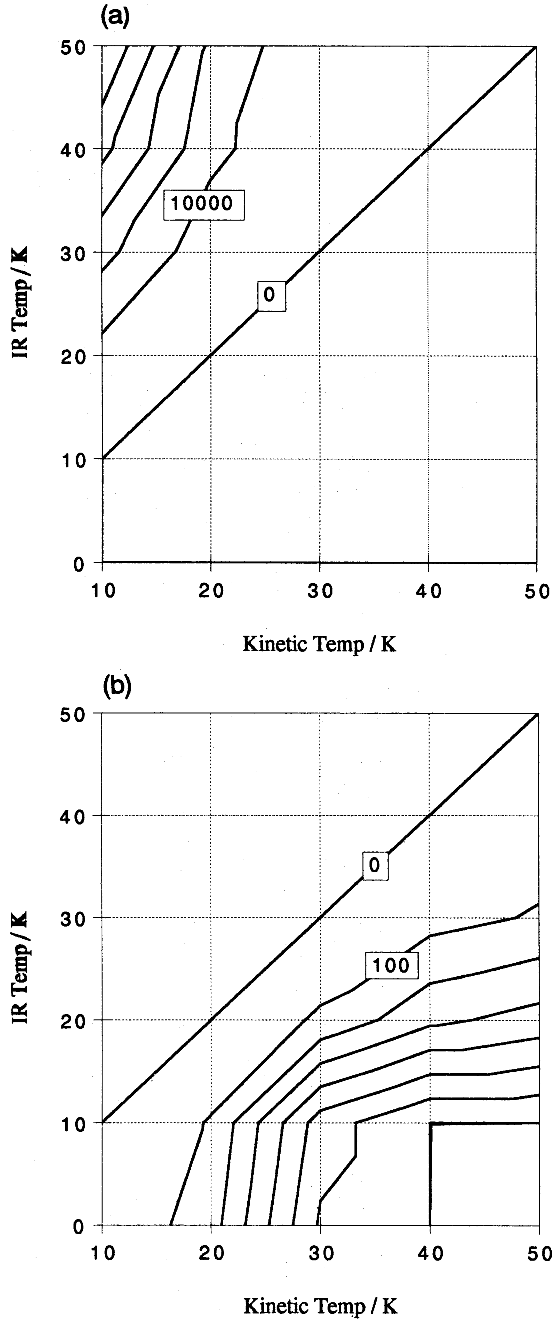

Figure 2. Contours of line intensity (in K with respect to the continuum) as a function of gas kinetic temperature and IR continuum temperature. (a) The 12-GHz 2_0–3_{-1} *E* line appears in absorption in the lower right part of the diagram and masing in the upper left (contour interval 10^4 K). (b) The 25-GHz 5_2–5_1 *E* line is in absorption in the upper left part of the diagram and masing in the lower right (contour interval 10^2 K).

Strong absorption in the 12.2-GHz 2_0–3_{-1} *E* and 6.6-GHz 5_1–6_0 A^+ lines is also a feature of the model in this regime.

When the continuum temperature exceeds the kinetic temperature, our model switches over to Class II behaviour. In this case the lines listed in Table 2 and displayed in Fig. 1 become masers, while the Class I maser lines show absorption. Once again this is in complete qualitative agreement with observations. The 12.2-GHz 2_0–3_{-1} *E* maser and 6.6-GHz 5_1–6_0 A^+ maser occur over the widest range of model conditions (densities between 10^2 and 10^5 cm^{-3}, depending on T_C and T_K). Other masers occur over a narrow range of parameters, but since several of the predicted masers which are less widespread in our model have already been observed, the list includes many possible candidates for observation.

Tables 1 and 2 include predicted line intensities for a specific example of a Class I and a Class II model. The way in which the 12-GHz 2_0–3_{-1} *E* maser intensity varies with T_C and T_K at density 10^4 cm^{-3} is illustrated in Fig. 2(a), showing the switch from Class II masing to absorption. The reverse behaviour is apparent for the 25-GHz 5_2–5_1 *E* Class I maser line, as seen in Fig. 2(b). Further numerical data may be obtained from the authors.

The ratio of the 6.6-GHz 5_1–6_0 A^+ to 12.2-GHz 2_0–3_{-1} E maser intensities varies between 10^{-2} and 10^1 depending on the model conditions. Once again the numerical values will be a sensitive function of model parameters, and these can be 'tuned' to fit the observations in a particular source. However, Menten (1991a) has observed that in all cases the 6-GHz line is stronger. The 6-GHz line turns on and peaks at a lower density than the 12-GHz line in our model. Thus it may be that the observed intensity ratio comes about through sampling more of the low-density region of the molecular clouds.

These results are achieved with non-selective collisions, but similar results come from the alternative collision model. With selection rules favouring $\Delta K = \pm 1$ based on the Lees & Haque (1974) recommendations, broadly the same results are obtained, when the total cross-section is scaled to be the same for the two models. The same transitions become inverted under the same conditions, although the selective collisions result in slightly weaker masers, and a few lines fail to meet our maser criterion. This demonstrates unequivocally that the masing is due to radiative selection rules, not collisional selection rules.

4 DISCUSSION

The Class I methanol masers displayed in Fig. 1 come about through collisional excitation followed by spontaneous radiative decay, the latter providing the selection effect. Spontaneous emission will tend to overpopulate levels which have fast channels in, or slow channels out. Examination of the Einstein coefficients (which are largest for high-frequency transitions) shows that this process favours the $k=2$ over $k=1$ and 3, and the $k=-1$ over $k=0$ and -2 ladders in the E species, and the $K=0$ over $K=1$, and $K=1$ and 3 over $K=2$ ladders in the A species, leading to the distribution of masers seen in Fig. 1 and the 12- and 6-GHz absorption. Note that collisional selection rules have little impact on the incidence of masing, and the vital role of the Einstein coefficients has sometimes been overlooked.

A detailed analysis of the rates of creation and destruction of molecules in the maser levels helps to explain the pumping process. This is best achieved when the maser is not of sufficient intensity that the absorption and stimulated emission of maser photons dominates its excitation (i.e. it is unsaturated). For example, we have examined the rates for the 3_{-1}, 2_0, 5_1 and 5_2 E-species levels for a Class I run with $T_K = 30$ K, $N_{H2} = 10^4$ cm^{-3}, $T_C = 0$ K. Collisional channels contribute significantly to the total rates, but the collisional pump and loss rates are about equal for the 3_{-1} and 2_0 pair of levels, and for the 5_1 and 5_2 pair. In each case, spontaneous emission dominates the radiative processes. The 3_{-1} level has a faster radiative pump rate than the 2_0 level, and a slower loss rate. These effects combine to give absorption in the 2_0–3_{-1} transition. For the 5_1 and 5_2 levels the radiative pump rates are approximately equal, while the 5_1 has a faster loss rate, resulting in masing in the 5_2–5_1 transition. These trends are apparent from examination of the Einstein A coefficients, the effects of which are moderated by collisions.

The Class II methanol masers displayed in Fig. 1 are radiatively pumped and collisions are essentially irrelevant to their excitation, except that they keep the system slightly away from equilibrium with the radiation field. In this case absorption of continuum photons is an important excitation process. In the optically thin limit the rate of change of population due to absorption is the Einstein B coefficient multiplied by the Planck function at the continuum temperature, and in the Rayleigh–Jeans limit this rate varies with ν^2. Again, the largest rate occurs for high-frequency transitions. In the reverse of the Class I case, the absorption processes depopulate the $k=2$ and -1 E-species ladders, and the $K=0$ A-species ladder, while overpopulating $K=2$. This accounts broadly for the pattern of masing and absorption.

Again for a specific Class II run ($T_K = 30$ K, $N_{H2} = 10^4$ cm^{-3}, $T_C = 50$ K), we have examined the rates into and out of the 3_{-1}, 2_0, 5_1 and 5_2 E-species levels. Collisional channels are insignificant. Both absorption and spontaneous emission are important radiative processes. Creation channels are dominated by spontaneous emission from higher levels, which favours 3_{-1} over 2_0, and 5_2 over 5_1 as before. Opposing this, the destruction channels are dominated by absorption, and the 3_{-1} and 5_2 levels both have a faster loss rate than their corresponding partners. In the overall balance the destruction processes win, giving the 2_0–3_{-1} maser and the 5_2–5_1 absorption.

5 CONCLUSIONS

It is striking that all the observed Class I and II methanol masers are accounted for by our model. The range of behaviour spanning both Class I and Class II methanol masers can be qualitatively explained under modest excitation conditions of T_K, $T_C < 50$ K, $10^2 \le N_{H2} \le 10^5$ cm^{-3}. The important characteristics generating these masers are related to the topography of the energy level diagrams, and so other pumping processes which exploit these features may also be possible. The model may be made more realistic by incorporating a better CH_3OH–H_2 collision model, torsionally excited states, optically thick dust and more appropriate geometry. Some or all of these features may be required for good quantitative agreement with observations for particular sources. However, our aim has been to discover the essence of masing of interstellar methanol by devising the simplest model that contains the general features of the variety of observed methanol masers. We leave the detailed modelling of individual methanol masers to future investigations.

The attractive feature of our investigation is that the full range of Class I and II methanol masers can be qualitatively understood in terms of a simple model in which the temperature of the continuum radiation, relative to the gas kinetic temperature, is decisive in the switch from Class I to II, and the details of the collision model are of little significance.

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