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# A Possible Pumping Mechanism for Interstellar Class II 107 GHz Methanol Masers

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**Abstract** It is recognized that the interstellar methanol-107 GHz masers and OH-4.765 GHz masers towards Class II sources are associated with each other and coexist towards ultracompact HII regions. Therefore we suggest a new pumping mechanism – methanol masers without population inversion. It can explain the formation of 107 GHz methanol masers, with the 4.765 GHz OH masers acting as a driving coherent microwave field. It is argued that this mechanism is compatible with the astronomical conditions.

**Key words:** H II regions — masers — radiation mechanisms: non-thermal — ISM: molecules — line: formation

## 1 INTRODUCTION

Over more than thirty years dozens of transitions of interstellar methanol masers have been found in directions of star-forming regions, especially massive star-forming regions. All such masers can be divided into two distinct classes (Batrla et al. 1987; Menten 1991): in no case does a Class I methanol maser emit in a Class II maser line, and vice versa. While Class I sources show enhanced absorption at frequencies of 6.7, 12.2 and 107 GHz, Class II sources show prominent emission at those frequencies. Class I sources are usually situated away from compact continuum sources, while Class II masers are usually found close to ultracompact H II regions, or near their edges.

In addition, a new methanol masers – the $3_1 \rightarrow 4_0A^+$ transition at 107 GHz has been discovered in several galactic sources recently (Val'tts et al. 1995). In general these sources are in the same regions as the Class II 6.7 and 12.2 GHz masers emitters and all of them are associated with H II regions and OH masers. Therefore Caswell et al. (1995) suggested that the OH and methanol masers are commonly in very close association. Towards Class I methanol maser sources, however, the 107 GHz line is found in absorption or in weak, quasi-thermal

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emission. These findings make the pumping mechanism of the 107 GHz maser still a matter of debate.

One of the major goals of researchers on astrophysical masers is to understand maser pumping mechanisms in interstellar clouds. Extensive surveys have shown that the Class II methanol maser phenomenon is very widespread. This result adds to the importance of understanding the nature of Class II methanol maser sources, which may be done through detailed studies of particular masers in various transitions. In this paper we will follow the hints above and argue for a new pumping mechanism for the interstellar Class II 107 GHz methanol masers, which can be used to explain the formation and behavior of the Class II sources. The proposed mechanism is complementary to other mechanisms. We shall also demonstrate that this new mechanism is compatible with the astronomical conditions.

## 2 THE PUMPING OF CLASS II METHANOL $3_1 \rightarrow 4_0 A^+$ MASERS

### 2.1 The Relevant Level Structure of the Methanol Molecule

Methanol is one of the simplest molecules displaying hindered internal rotation, and it is a slightly asymmetric top, as the OH group does not lie on the principal molecular axis. Ioli et al. (1955) proposed that the energy levels of the methanol molecule sharing all the same quantum numbers except $J$ can be expanded into a Taylor series in $J(J+1)$:

$$E(q,J) = \Sigma a_m(q)[J(J+1)]^m \pm [(J+K)!/2(J-k)!][S(q) + J(J+1)T(q)]\,, \tag{1}$$

where $q$ stands for the common quantum numbers of a given sequence, i.e., $v, n, \tau$, and $K$. For the vibrational quantum number $v$, because the frequencies corresponding to pure vibrational modes are of the order of $1000\,\mathrm{cm}^{-1}$, only the ground level ($v = 0$) is of interest here; $n$ is the torsional vibration quantum number; $\tau$ may have the values 1, 2 and 3, and arises from the threefold nature of the hindering potential; $J$ is the total angular momentum quantum number, and $K$ is the projection of $J$ along internal axis. It is worth pointing out that the transitions may only occur between states belonging to the same symmetry species – $A$ or $E$. The terms including $S$ and $T$ describe the asymmetry doubling, designated by + or −, and are present only for levels belonging to $A$ symmetry with small but nonzero $K$ values. The summation in Eq. (1) can be truncated at $m = 4$, but in a few cases $m = 3$ is sufficient while in other cases $m = 5$ is required.

At the moment we are only interested in the transition of $3_1 \rightarrow 4_0 A^+$, $v = 0$, $n = 0$. The latest relevant parameters, according to Moruzzi (1998), are as follows (all values are in $\mathrm{cm}^{-1}$, and the energy of $J = 0$, $K = 0$ has been set equal to zero):

| $K$ | $a_0$ | $a_1$ | $a_2(\times 10^6)$ | $S(\times 10^2)$ | $T(\times 10^7)$ |
|---|---|---|---|---|---|
| 0 | 0.00001 | 0.806777 | −4.95644 | | |
| 1 | 10.10520 | 0.806825 | −3.26136 | −1.39152 | 1.40647 |

Thus we can calculate the separation of asymmetry doubling of level $3_1$, and it will be 5005.4 MHz. The experimental value has been confirmed to be 5005.321(6) MHz (Xu et al. 1997a).

Some relevant levels are shown in Fig. 1. The relative selection rules are:

$$+ \longleftrightarrow + \text{ and } - \longleftrightarrow -, \text{ for } \Delta J = \pm 1,\ \Delta n = 0;$$

$$+ \longleftrightarrow - \text{ and } - \longleftrightarrow +, \text{ for } \Delta J = 0,\ \Delta n = 0.$$

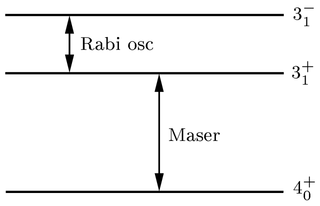

Fig. 1 Relevant energy levels of the methanol molecule.

### 2.2 Equations of Motion and Masers Without Inversion

There has been considerable interest in the study of lasing without population inversion. Many schemes have been proposed. One of them is the ladder system with coherent pumping proposed by Prasad (1991). Consider a three-level system with non-equidistant, non-degenerate levels $|\mathrm{a}\rangle$, $|\mathrm{b}\rangle$ and $|\mathrm{c}\rangle$, and with energies 0, $\hbar_{\omega_{ab}}$ and $\hbar_{\omega_{ac}}$, respectively, as shown in Fig. 2. Here $\gamma_1$ ($\gamma_2$) are the spontaneous decay rates, and $\lambda_1$ ($\lambda_2$), the incoherently pumping rates by thermal radiation. There is no direct dipole coupling between states $|\mathrm{a}\rangle$ and $|\mathrm{c}\rangle$. The transition $|\mathrm{b}\rangle - |\mathrm{c}\rangle$ of frequency $\omega_{bc}$ is driven by a strong coherent field of frequency $\omega_1$ with Rabi frequency $2G$, $\Delta_1 = \omega_{bc} - \omega_1$, and

$$G = E_{10}|p_{bc}|/2\hbar\,, \tag{2}$$

where $E_{10}$ is the amplitude of the strong coherent field, $p_{bc}$ is the dipole transition matrix element.

A probe field of frequency $\omega_2$ with Rabi frequency $2g$ is applied to the transition $|\mathrm{a}\rangle - |\mathrm{b}\rangle$ of frequency $\omega_{ab}$, $\Delta_2 = \omega_{ab} - \omega_2$.

$G$ and $g$ may be assumed to be real and positive for simplicity, and we let $\Delta_3 = \Delta_1 + \Delta_2$.

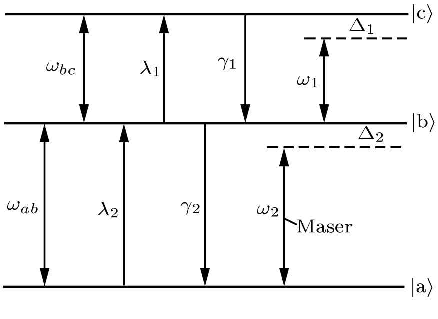

Fig. 2 Ladder system with coherent pumping.

The equations of motion for the particle density matrix in the rotating frame can be written as:

$$\left.\begin{aligned}
\dot{\rho}_{aa} &= \gamma_2\rho_{bb} - \lambda_2\rho_{aa} + ig(\rho_{ba} - \rho_{ab}),\\
\dot{\rho}_{bb} &= \gamma_1\rho_{cc} - (\gamma_2 + \lambda_1)\rho_{bb} + \lambda_2\rho_{aa} + iG(\rho_{cb} - \rho_{bc}) + ig(\rho_{ab} - \rho_{ba}),\\
\dot{\rho}_{cc} &= -\gamma_1\rho_{cc} + \lambda_1\rho_{bb} + iG(\rho_{bc} - \rho_{cb}),\\
\dot{\rho}_{cb} &= -(\gamma_{12} + i\Delta_1)\rho_{cb} + iG(\rho_{bb} - \rho_{cc}) - ig\rho_{ca},\\
\dot{\rho}_{ca} &= -(\gamma_{13} + i\Delta_3)\rho_{ca} + iG\rho_{ba} - ig\rho_{cb},\\
\dot{\rho}_{ba} &= -(\gamma_{23} + i\Delta_2)\rho_{ba} + iG\rho_{ca} + ig(\rho_{aa} - \rho_{bb}),
\end{aligned}\right\} \tag{3}$$

along with the equations of their complex conjugates, where

$$\gamma_{12} = (\gamma_1 + \gamma_2 + \lambda_1)/2,\ \gamma_{13} = (\gamma_1 + \lambda_2)/2,\ \gamma_{23} = (\gamma_2 + \lambda_1 + \lambda_2)/2. \tag{4}$$

The density matrix Eqs. (3) can be solved for the steady state, though the solving is cumbersome:

$$\left.\begin{aligned}
\rho_{aa} &= [2\gamma_{12}G^2 + \gamma_1(\gamma_{12}^2 + \Delta_1^2)]\gamma_2/W,\\
\rho_{bb} &= [2\gamma_{12}G^2 + \gamma_1(\gamma_{12}^2 + \Delta_1^2)]\lambda_2/W,\\
\rho_{cc} &= [2\gamma_{12}G^2 + \lambda_1(\gamma_{12}^2 + \Delta_1^2)]\lambda_2/W.
\end{aligned}\right\} \tag{5}$$

$$\begin{aligned}
\rho_{ba} &= g/(W_1^2 + W_2^2)\\
&\quad \times\big\{[G^2(\gamma_{12}W_2 + \Delta_1 W_1)(\rho_{bb} - \rho_{cc})/(\gamma_{12}^2 + \Delta_1^2) + (\gamma_{13}W_2 - \Delta_3 W_1)(\rho_{aa} - \rho_{bb})]\\
&\quad + i[G^2(\gamma_{12}W_1 - \Delta_1 W_2)(\rho_{bb} - \rho_{cc})/(\gamma_{12}^2 + \Delta_1^2) + (\gamma_{13}W_1 - \Delta_3 W_2)(\rho_{aa} - \rho_{bb})]\big\},
\end{aligned} \tag{6}$$

where

$$\left.\begin{aligned}
W &= [2\gamma_{12}G^2 + \lambda_1(\gamma_{12}^2 + \Delta_1^2)]\lambda_2 + [2\gamma_{12}G^2 + \gamma_1(\gamma_{12}^2 + \Delta_1^2)](\gamma_2 + \lambda_2),\\
W_1 &= G^2 + \gamma_{13}\gamma_{23} - \Delta_2\Delta_3,\\
W_2 &= \gamma_{13}\Delta_2 + \gamma_{23}\Delta_3\,.
\end{aligned}\right\} \tag{7}$$

The equation of motion for the probe field amplitude $E_{20}$ can be written as:

$$\dot{E}_{20} = -kE_{20} + 2\pi i\omega 2Np_{ab} \times \rho_{ba}\,, \tag{8}$$

where $k$ is the loss rate of propagation, $N$ the number density of molecules, and $p_{ab}$ the matrix element of dipole transition. Therefore, if the loss rate $k$ is so small as can be ignored, amplification of the probe field is obtained with

$$\mathrm{Im}\,(\rho_{ba}) < 0. \tag{9}$$

That is, due to quantum coherence effect, the spontaneous emission from the upper state $|\mathrm{b}\rangle$ to the lower state $|\mathrm{a}\rangle$ will be restrained, while the stimulated emission is not affected significantly. Therefore even when there is no population inversion between the upper and lower levels, there will still be net coherent light amplification — laser (or maser). As a matter of fact, the strong coherent field acts as a trigger or a stimulant.

Of course, it should be noted that Eq. (9) is only a necessary condition for amplification of coherent radiation. In order to explain the observed maser intensities in detail, large enough gain coefficients are needed. Thus besides $\rho_{ba}$, the interstellar conditions, such as the gas density and coherent path length of maser region must also be right. In the next section we will show that, in principle, the energy levels $4_0^+$, $3_1^+$ and $3_1^-$ in Fig. 1, as the energy levels $|\mathrm{a}\rangle$, $|\mathrm{b}\rangle$ and $|\mathrm{c}\rangle$ in Fig. 2, make up a ladder system with coherent pumping for gain without inversion.

### 2.3 The Pumping of Interstellar Class II 107 GHz Methanol Masers

We argue in this section that the 107 GHz methanol masers are masers without inversion driven by the interstellar OH 4.765 GHz masers, neglecting the origin of the latter temporarily.

As mentioned in Subsection 2.1, the levels $3_1^-$, $3_1^+$ and $4_0^+$ are pure non-degenerate, non equidistant levels. They constitute the three-level ladder system as in the model proposed by Prasad et al. (1991). Astronomical observations and statistics show that the Class II sources of interstellar methanol maser are always associated with HII regions, but Class I sources are not. The VLBI observations indicated that (Menten 1992a) Class I masers are located at distances of at least $0.1 - 1\,\mathrm{pc}$ from ultracompact HII centers, but Class II masers are located in the dense envelopes of ultracompact HII regions. Hartquist (1995) has also pointed out that Class II methanol masers occur in the immediate vicinity of ultracompact H II regions and seem to be closely related to hydroxyl masers. Virtually all known Class II methanol maser sources show maser action in OH coincidently, with the emissions of both species always covering similar velocity ranges. Especially, 107 GHz methanol masers are always projected on ultracompact H II regions (Mehringer et al. 1997). Therefore, following his measurements, Caswell (1995) suggested that the OH and methanol masers are commonly in very close association. He even suggested that a global model is required to incorporate both masers and their association with ultracompact H II regions. A similar proposal for Class II 6.7 GHz and 157 GHz methanol masers was made in Liu et al. (1997, 1998, 2002).

In regard to the methanol-107 GHz masers, Val'tts et al. (1995) pointed out that while there are strong methanol-6.7 GHz masers toward the sources $G9.62{+}0.19$, W33(A) and $G23.01{-}0.41$, there are no methanol-107 GHz masers in these directions. We also noticed that there are no OH-4.765 GHz masers found in the three strong methanol-6.7 GHz maser sources. It seems that there is something connection between the methanol-107 GHz and OH-4.765 GHz masers.

The W3(OH) region, one of compact H II regions and the prototype of Class II methanol masers, can be selected as an example. Menten (1992b) showed from VLBI data that many methanol masers and OH masers observed toward W3(OH) appear to be spatially coincident. As a matter of fact, the position coordinate of methanol-107 GHz maser source in W3(OH) is $\alpha = 02^{\mathrm{h}}23^{\mathrm{m}}17.3^{\mathrm{s}}$, $\delta = +61^\circ 38' 58''$ at the $V_{\mathrm{LSR}} = -43.3\,\mathrm{km\ s^{-1}}$ with a $3''$ rms pointing accuracy and half-power beamwidth $35''$ (Val'tts et al. 1995), and that of OH-4.765 GHz maser source at the similar $-43.21\,\mathrm{km\ s^{-1}}$ is $\alpha = 02^{\mathrm{h}}23^{\mathrm{m}}16.45^{\mathrm{s}}$, $\delta = +61^\circ 38' 57.51''$ from high resolution VLBI observations (Baudry 1988; Baudry & Diamond 1991). Despite the large difference of resolution and pointing accuracy, we consider both masers in W3(OH) to be spatially related.

Following the above hints, we propose a picture in which the 107 GHz methanol masers and 4.765 GHz OH masers co-emit in the W3(OH) region around an O-type star which excites the compact H II region. The 4.765 GHz masers can drive the local methanol molecules as a coherent field. In W3(OH) the associated infrared source is W3-IRS8, its total infrared luminosity is $\approx 2 \times 10^5\ L_o$ (Schaifers et al. 1982). We estimate the temperature of central star is $\approx 4.5 \times 10^4\,\mathrm{K}$, on assuming the infrared source is a zero-age main sequence (ZAMS) star. Because of the strong thermal radiation, the excitation levels of methanol molecule will be populated moderately. The separation of K-doublet of level $3_1$ is 5005.321 MHz (Xu et al.

1997a), therefore the doublet of level $3_1$ can produce Rabi oscillation driven by the 4765.562 MHz OH maser, with $\Delta_1 = 5005.321 - 4765.562 = 239.759$ MHz. The relative frequency deviation is only $\Delta_1/5005.321 \approx 4\%$.

Observations of the 4.765 GHz OH masers toward W3(OH) show a terrestrial antenna peak flux density of $\approx$ 3.69 Jy at $-43.21$ km s$^{-1}$ (Baudry 1988). The spectrum bandwidth of the maser spot $\Delta V = 43.58 - 42.84 = 0.74$ km s$^{-1}$, corresponding to 12 kHz. The distance from W3(OH) to the Earth, $D$, is 2.2 kpc (Migenes et al. 1999). The angular size of the source spot is $< 10$ mas, so its linear size is $d \approx 10^{14}$ cm. Hence the energy flux density of the source region will be:

$$S = (3.69 \times 10^{-26}\,\mathrm{W\ m^{-2}\ Hz^{-1}}) \times 1.2 \times 10^4\mathrm{Hz} \times (D/d)^2 = 2.04101 \times 10^{-6}\,\mathrm{W\,m^{-2}}.$$

Thus the energy density in the maser source region will at least be

$$w = S/c = 6.80336 \times 10^{-15}\ \mathrm{J\ m^{-3}},$$

where $c$ is the light speed. Since the relationship of $w$ and electric field $E$ is:

$$w = \varepsilon_0 \langle E^2 \rangle /2 = \varepsilon_0 E_{10}^2/4,$$

where $E_{10}$ is amplitude of electric strength, $\varepsilon_0$ is dielectric constant,

$$\varepsilon_0 = 8.85 \times 10^{-12}\mathrm{C^2N^{-1}m^{-2}},$$

we have

$$E_{10} = (4w/\varepsilon_0)^{1/2} = 5.54524 \times 10^{-2}\mathrm{N\,C^{-1}},$$

also, $p_{bc}$ of $CH_3OH \approx 1$ Debye (Xu et al. 1997b). Substituting these values into Eq. (2), we obtain:

$$G = 2.64059 \times 10^3\mathrm{s^{-1}}.$$

In general, the size of the central star $r \approx 10^{13}$ cm, and, according to quantum mechanics, the incoherently pumping rate by thermal radiation is

$$\lambda = Bw(\omega) = A/[\exp(\hbar\omega/kT) - 1](r/d)^2, \tag{10}$$

where $w(\omega)$ is the radiative energy density at frequency $\omega$. The methanol molecules are irradiated by re-radiated starlight, the radiation temperature can be estimated as 100 K (Sobolev et al. 1994). From Pei et al. (1988), the Einstein Coefficient $A$ of transition $3_1^-$—$3_1^+$ is $9.765 \times 10^{-11}\,\mathrm{s^{-1}}$, transition frequency 5.005 GHz, those of $3_1^+$—$4_0^+$ are $5.811 \times 10^{-6}\ \mathrm{s^{-1}}$ and 107 GHz. Thus we obtain:

$$\lambda_1 = 4.05613 \times 10^{-10}\mathrm{s^{-1}}, \qquad \lambda_2 = 1.1016 \times 10^{-6}\,\mathrm{s^{-1}}.$$

The theoretical value of $\omega_{ab} = 107.01377$ GHz (De Lucia et al. 1989), the observational value of $\omega_2 = 107.01382$ GHz (Sobolev et al. 1997), thus $\Delta_2 = -0.05$ MHz. As before, $\Delta_1 = 239.759$ MHz, $\Delta_3 = 239.709$ MHz.

Substituting all the above values into Eqs. (4), we obtain

$$\gamma_{12} = 2.90575 \times 10^{-6}\,\mathrm{s^{-1}}, \qquad \gamma_{13} = 5.50846 \times 10^{-7}\,\mathrm{s^{-1}}, \qquad \gamma_{23} = 3.4565 \times 10^{-6}\,\mathrm{s^{-1}}.$$

Substituting them into Eqs. (7), we have

$$W_1 = 1.19855 \times 10^{13}\,\mathrm{s}^{-2}, \qquad W_2 = 8.28572 \times 10^{2}\,\mathrm{s}^{-2}, \qquad W = 64.4884\,\mathrm{s}^{-4}.$$

Substituting the same into Eqs. (5) and (6), we obtain

$$\mathrm{Im}\,(\rho_{ba}) = -8.14116 \times 10^{10} \times g/(W_1^2 + W_2^2)\,. \tag{11}$$

There is always $g/(W_1^2 + W_2^2) > 0$, thus we have verified finally $\mathrm{Im}\,(\rho_{ba}) < 0$, and Eq. (9) is satisfied. As mentioned above, it will cause coherent amplification between states $|\mathrm{a}\rangle$ and $|\mathrm{b}\rangle$. Therefore levels of $3_1^-$, $3_1^+$ and $4_0^+$ together constitute a typical three-level system with coherently pumping. It can result in masers without the requirement of inversion. That is just the mechanism of $3_1 \rightarrow 4_0A^+$ 107 GHz masers associated with astronomical 4.765 GHz OH masers.

## 3 DISCUSSION

Maser emission from interstellar methanol is a widespread phenomenon, observed toward many dense molecular cloud cores in regions of massive star formation. The search for new methanol maser transitions is still in progress. Methanol masers are observed in transitions between energy levels in different $K$ ladders. The pumping mechanisms of two classes of methanol masers are not yet well understood, though the collision mechanism is more successful in Class I sources (Walmsley et al. 1988). We note that for $A$-species levels of methanol, the lowest level has quantum numbers of $J = 1, K = 0$. A strong preferential process is $\Delta K = 0$ for collision excitation (Lees et al. 1974). That can become the population inversion mechanism for $J_0 \rightarrow (J-1)_1A^+$ masers, such as the $7_0 \rightarrow 6_1A^+$, $8_0 \rightarrow 7_1A^+$, and $9_0 \rightarrow 8_1A^+$ masers at 44, 95, and 146 GHz, respectively. This mechanism also produces enhanced absorption in the 107 GHz of $3_1 \rightarrow 4_0A^+$ transition and 6.7 GHz of the $5_1 \rightarrow 6_0A^+$ transition which is characteristic of the Class I sources. Whereas in Class II masers the situation is reversed: the $3_1 \rightarrow 4_0A^+$ and $5_1 \rightarrow 6_0A^+$ transitions present strong maser emissions toward Class II methanol sources. That cannot be explained at all by collision mechanism.

We propose that the two classes of interstellar methanol masers may have different pumping mechanisms and physical conditions. In compact H II regions, radiative processes are likely to be a main source of pumping up Class II methanol masers. We suppose that the Class II masers should be radiatively pumped, so it is seen toward the W3(OH) region. In that region, the strong thermal emission of central star populates the excitation levels of the methanol molecule and, the 107 GHz and 4.765 GHz masers are well associated with each other. The $4_0$ level and $3_1A$ doubling co-form a typical three-level, non equidistant, ladder system with coherent pumping. The 4.765 GHz masers drive strongly the $3_1$ doubling. It acts as a trigger. Those create the $3_1 \rightarrow 4_0A^+$ masers without inversion.

The mechanism we argued for here is associated with astrophysical conditions. The physical environments of maser-forming regions are various. Perhaps, there are different mechanisms for different masers and, there are several mechanisms which co-operate on one maser: they do not contradict, but complement each other. Following this reasoning, we can obtain a true understanding of astronomical masers.

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