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THE PUMPING OF INTERSTELLAR METHANOL 6.7GHz MASERS

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I. INTRODUCTION

There are over 200 interstellar masers to be found toward numerous star–forming regions.They can be divided into two classes. In no case a Class I methanol maser emits in a Class II maser line, and vice versa. While Class I masers are found to be offset from HII regions, Class II methanol masers are observed toward ultracompact HII regions. While Class I sources show enhanced absorption at frequencies 6.7 and 12.2GHz, Class II sources emit prominent masers of these frequencies. Especially, the 6.7 and 12.2GHz masers always appear simultaneously. This is a surprising and peculiar event because the two transitions are from completely different excitation species, E species and A species. It is a puzzle of Astronomy. That should provide powerful constraints on the excitation mechanism of Class II methanol masers and, eventualy, on the physical conditions of masing regions.

In this paper, we argue a new mechanism to settle this puzzle, to give it a reasonable and associated interpretation.

II. THE PUMPING OF METHANOL $5_1 \rightarrow 6_0A^+$ MASERS

The energy levels and wavefunctions of methanol molecule have been the subjects of many studies in detail. The methanol is a slight asymmetrical–top molecule with hindered internal rotation. The OH–group is subject to a potential of CH_3–group to cause torsional oscillation, denoted by the quantum number n. Actually this potential barrier to internal rotation is not very high, the torsional level will split into three sublevels, denoted by quantum number τ, due to the tunneling–process of the OH–group through one of the barriers. And since the asymmetry of the OH–group with respect to the symmetry–axis of the CH_3–group, these sublevels will be further split(except $K = 0$). These doublet sublevels are designated by + or − according to the symmetry properties of the corresponding wave functions. Therefore the total energy of the rotational level of methanol can be written as follows:

$$E_{JK\tau n} = E_{JK} + E_{K\tau n} \pm \triangle_{jk\tau n}/2 \qquad (1)$$

where $\triangle_{JK\tau n}$ is the doublet separation of appropriate τ–sublevel, being a function of J, K and n. The separation $\triangle_{JK\tau n}$ can be calculated. Some levels related to transition $5_1 \rightarrow 6_0A^+$ are shown in Fig.1.

The appropriate selection rules are:

$$\triangle J = \pm 1, \quad \triangle K = \pm 1, \quad \triangle n = 0;$$
$$\tau = 1 \rightarrow 2, \quad 2 \rightarrow 3, \quad 3 \rightarrow 1.$$

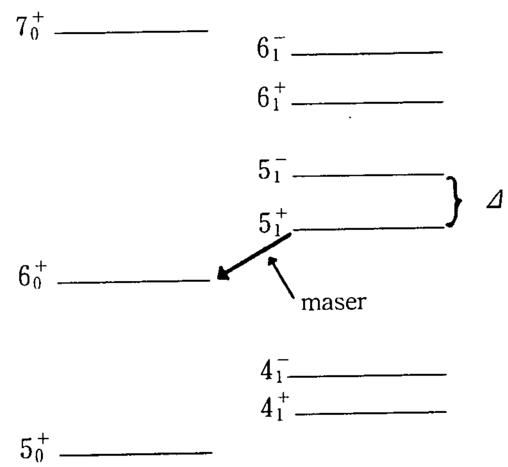

Fig. 1.— Energy levels related to the 6.7GHz methanol masers

The doublet separation depends upon quantum numbers J, K, n and τ. Let $J = 5$, $K = 1$, $\tau = 3$, $n = 0$, then the doublet separation of level 5_1 can be obtained:

$$\triangle = 1.39 \times 10^{-2} J(J+1)\,\mathrm{cm}^{-1} = 12.51\,\mathrm{GHz} \qquad (2)$$

Agarwal(1991) summarized various model systems which act lasers without population inversion. One of them is a Λ system with coherent pumping.

Suppose there is a three–level system: lowest level |a>, upper level |b> and uppermost level |c>. The upper levels are pumped by weak incoherent radiation, which is spectrally broad. And upper two levels are also driven by a coherent microwave field. We assume that medium is dilute and, the spontaneous radiation lifetimes of relative levels are longer. As a result, the microwave field will create Rabi oscillation between levels |b> and |c>. That means, a particle will oscillate between levels |b> and |c>. The oscillation rate will be:

$$W = (2b)^2/\left[(\omega - \omega_0)^2 + (2b)^2\right]^{1/2} \qquad (3)$$

where ω_0 is the permanent frequency between |b> and |c>, ω is microwave frequency.

$$b = E_{10}|p_{bc}|/2\hbar \qquad (4)$$

E_{10} is the amplitude of microwave field, p_{bc} is transition matrix element.

Imamoglu(1991) has proved that, provided W is more larger than the spontaneous transition rates: $W \gg A_{ab}$, $W \gg A_{bc}$, $W \gg A_{ac}$, then, based on the quantum interference effect, the spontaneous emission from upper states |b>, |c> to lower state |a> will be restrained, but stimulated emission is not effected much. Therefore even there is not population inversion between upper and lower levels, there will be still net coherent light amplifi- cation–laser (or maser).

Astronomical observations and statistics show that the Class II sources of interstellar methanol masers are associated with HII regions, but Class I sources of those are not. Moreover, recent VLBI observations indicate that(Menten 1992), Class I masers are located at distance of at least 0.1–1pc from ultracompact HII center, but Class II masers are located in the dense envelope of ultracompact HII regions. There is an O/B star at the center of ultracompact HII. The 6.6GHz masres have been detected toward all sources with known 12.2 GHz masers. In general, 6.6 and 12.2GHz spectra cover similar velocity ranges. For W3(OH), prototype of Class II masers, individual velocity components in the 12.2GHz spectra seems to have counterparts at identical velocities in the 6.7GHz spectra. Norris(1992) noticed also that the 6.7GHz and 12.2GHz masers are always coincident, and exhibit similar spectra.

Those imply that one maser spot is masing in both transitions, which are from completely different excitation. That is surprising and would place a tight constraint on pumping mechanism. This problem can be settled in the light of our mechanism. One can take W3(OH) as a example. The temperature of its central star is high up to 4×10^4 K. The excitation levels of methanol molecule will be populated moderately. The separation of K–doublet of level 5_1 is 12.51GHz. The relative frequency deviation from 12.2GHz is $\Delta f/f \approx$ 2.4%. Therefore the doublet of level 5_1 can produce Rabi oscillation since driven by 12.2GHz masers.

The antenna flux density of 12.2GHz masers toward W3(OH) is $\sim$ 850Jy, spectrum range is $\sim$ 3.6 Km/sec, it is $\sim$ 0.15MHz. The distance from W3(OH) to the Earth D $\approx$ 3.1Kpc, the size of source spot d$\approx 10^{13}$ cm, thus the radiation power from 12.2GHz maser per area at surface of source spot will be S= $(8.5 \times 10^{-24}$ W / m^2 Hz)$\cdot 1.5\times10^5$ Hz $\cdot$ $(d/D)^2 = 1.2$W/ m^2. The energy density of source spot region will be: $\rho = S/C$, where C is the light speed. And $\rho = \varepsilon_0$ $E_{10}^2/4$, dielectric constant $\varepsilon_0 = 8.85 \times 10^{-12} C^2 N^{-1} m^{-2}$. Thus $E_{10} = (4S/\varepsilon_0 C)^{1/2} = 43N/C$. And the p_{bc} of CH3OH $\sim$ 1 debay. From Eq.(4), one can obtain $b = 6.8\times10^5/$ sec. From Eq.(3), one can obtain W= $9.2 \times 10^2/$ sec.

From Pei et al.(1988), the Einstain Coefficient A of transition $5_1^- \rightarrow 5_1^+$ is 6.1×10^{-10}/sec., that of $5_1^- \rightarrow 6_0^+$ is 3.5×10^{-8}/sec., that of $5_1^+ \rightarrow 6_0^+$ is 1.5×10^{-9}/ sec. All of them are more less than volue W. Therefore levels of 5_1^-, 5_1^+ and 6_0^+ together constitute a Λ type three–level system. It can result in masers without population. That is just the mechanism of $5_1 \rightarrow 6_0A^+$ 6.7GHz masers associated with astronomic 12.2GHz methanol masers.

III. DISCUSSION

The Pumping mechanisms of two classes methanol masers have not been understood well yet, only the collision mechanism is more successful for Class I sources. We note that for A–species levels of methanol, the lowest level has quantum numbers of $J = 1$, $K = 0$. A strongly preferential process is $\Delta K = 0$ for collision excitation. That can become the population inversion mechanism for $J_0 \rightarrow (J-1)_1$ masers, such as the $7_0 \rightarrow 6_1A^+$, $8_0 \rightarrow 7_1A^+$, and $9_0 \rightarrow 8_1A^+$ masers. This mechanism also produces enhanced absorption in 6.7GHz $5_1 - 6_0A^+$ transition toward Class I sources which is the character of Class I. Whereas the $5_1 \rightarrow 6_0A^+$ transition presents strong maser emissions toward Class II methanol sources. That cannot be explained at all by collision mechanism.

We propose that the pumping mechanism and physical conditions of these two Classes of interstellar methanol masers might be different from each other. It seems that the Class II masers should be radiation pumping, it is so at least toward W3(OH) region. In that region, the strong thermal emission of central star populates fairly the excitation levels of methanol and, the 6.7 and 12.2GHz masers are associated well each other. The 6_0 level and 5_1A doublet co–form a Λ type three–level system. The 12.2GHz masers drive the 5_1 doublet strongly, to result in Rabi oscillation. Those create the $5_1 \rightarrow 6_0A^+$ masers without population inversion.

The mechanism we argued here is associated with astronomical conditions. The interstellar environments of maser–forming regions are variant. Perhaps, there are different mechanisms for different masers and, there are several mechanisms which co–work on one maser. They are not contradictory, but complementary each other. Follow this way, one can get the true understanding of astronomical masers.

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