

A Survey and Statistics of Interstellar OH and H₂O Masers *

Han-Ping Liu¹, J. R. Forster² and Jin Sun³

¹ Department of Physics, Beijing Normal University, Beijing 100875; gaozm@bnu.edu.cn

² University of California, Berkeley, and Hat Creek Radio Observatory, 42231 Bidwell Road, Hat Creek, CA 96040

³ Department of Astronomy, Beijing Normal University, Beijing 100875

Received 2004 May 8; accepted 2005 March 10

Abstract We present a statistical analysis of a sky survey of interstellar H₂O and OH masers. These masers can be classified into three categories: isolated H₂O masers, isolated OH masers, and simple OH/H₂O maser associations. The total number of sources in each category is of the same order of magnitude, and as an evolutionary phase they can maintain $\sim 10^5$ yr. An improved radiative pumping mechanism is proposed. This model avoids some of the deficiencies of previous radiative models, such as shortage of exciting photons. The statistical results obtained from the survey can be interpreted by the new mechanism together with the evolutionary model in which the gravitational force of the central stellar objects is responsible for the HII region.

Key words: surveys – masers – radiation mechanism: non-thermal – HII regions

1 INTRODUCTION

Since the discovery of OH and H₂O masers more than 30 years ago evidence has been accumulating linking the masers to massive young stars and ultracompact HII (UCHII) regions. Various ideas concerning the formation of OH and H₂O masers associated with massive star-forming regions have been proposed, and a large amount of observational data and theoretical models have been presented. Most pumping models rely on an embedded young stellar object (YSO) to provide the excitation energy for maser action. It is suggested that the two molecular species might have formed under different conditions and their masers may not be closely related. On the other hand, regions containing OH masers appear to be the best sites for detecting H₂O maser emission, and many models of maser pumping excitation also imply a close association between the two masers. If H₂O masers reside in molecular fragments near an HII region, then the two species should be closely associated or even coincident (Forster et al. 1978). Argon et

* Supported by the National Natural Science Foundation of China.

al. (2003) have detected a class of interstellar OH masers in massive star-forming regions that are associated with embedded protostellar objects. The spatial coincidence of OH and H₂O masers may be explained by OH being produced by photodissociation of H₂O in the stellar or interstellar radiation field.

Forster & Caswell (1999) made a deep search toward 74 star-forming regions containing masers of both OH and H₂O molecular species with the Very Large Array (VLA). In this paper we shall carry out a statistical analysis of the VLA survey result. We shall also propose an improved radiative pumping model for the origin of these OH and H₂O masers, with which we shall interpret the results of our statistical analysis.

2 THE SURVEY STATISTICS

The survey mentioned above achieved an estimated accuracy of $\sim 0.5''$ rms in the absolute positions of OH and H₂O masers (Forster & Caswell 1999). This is the first time a statistically meaningful sample of associated OH and H₂O masers is available that was observed with similar resolution at both frequencies, and with good relative positional accuracy. We shall use the term “isolated group” to indicate a maser group which has no maser of other species within ~ 150 mpc ($1 \text{ mpc} = 10^{-3} \text{ pc}$); the term “simple maser association” to mean an association of one OH and one H₂O maser group with angular separation less than the position uncertainty, and generally distributed within an extent < 30 mpc. Finally, by a “complex association” is meant one that contains multiple groups of OH and H₂O masers within a region ~ 150 mpc. The complex associations will not be analysed in the present paper. According to these definitions, we found that there are 22 isolated OH groups (four with HII regions), 36 isolated H₂O groups (none with HII regions), 39 simple OH/H₂O associations (seven with HII regions) and 14 complex OH/H₂O associations (nine with HII regions). Note that the numbers in the first three categories are about the same, while only a small fraction of them contains detectable HII regions. For instance: two examples of isolated H₂O masers are 339.68–1.21 and 14.17–0.06, neither contains detectable UC HII regions; two examples of isolated OH masers are 347.63+0.15 and 11.90–0.14, and only the latter contains HII region; two examples of simple maser association are 359.14+0.03 and 23.44–0.18, and only the first contains HII region. Also, it seems that the H₂O masers are slightly closer to the HII regions than the OH masers. Previous theoretical models can hardly interpret these results.

Following our survey statistics, we now present a new pumping model for interstellar OH and H₂O masers, and shall use it to interpret our statistical results.

3 THE ROLE OF UV RADIATION

At present there is no consensus on the several rival pumping mechanisms of OH and H₂O masers proposed by Andresen (1986), Gray et al. (1992) and Elitzur (1996), etc. These models can be classified into two kinds, collisional and radiative models. The criticisms of the radiative pumping models involve a shortage of pumping photons and the fact that H₂O and OH would be dissociated by the radiation itself (Holtz 1968; Litvak 1974). Thus the collisional pumping model is more popular nowadays.

All of the results of our statistical survey demonstrate that the regions of interstellar masers are varied. This implies that the physics and environment of massive star-forming regions are diverse, suggesting that the pumping mechanism of different sorts of interstellar masers may also be diverse. Nevertheless, they have well-known common features, such as a central stellar object at the stage of nuclear burning, appearance of ultra-violet (UV) radiation, and surrounding dense molecular materials. Therefore, we will pursue the pumping mechanism of interstellar

OH and H₂O masers from two aspects: (1) interaction between UV radiation and interstellar molecules; (2) collision between surrounding interstellar species. Our mechanism belongs to the radiative type, but avoids the defects of former such models, such as the shortage of UV photons. We shall use our model to interpret the statistical results including the shortage of HII regions.

3.1 Generation of Interstellar H₂O Masers

It is well known that maser emission is a widespread phenomenon in massive star-forming regions, and OH and H₂O masers are common features of deeply embedded YSOs. Plenty of H₂O has been discovered in regions of star formation by the Infrared Space Observatory (van Dishoeck et al. 1998). There is strong radiation emitted from the central YSO. The photons with wavelengths $\lambda < 91.2\text{nm}$ may generate an HII region, while abundant photons with wavelengths $\lambda > 91.2\text{nm}$ will pass through the HII region and irradiate H₂O molecules. Thus, the H₂O molecules can be excited and dissociated. The UV absorption spectrum of H₂O vapor has been recorded long since (Watanabe & Zelikoff 1953; Ishiguro et al. 1978). The global feature is just a wide continuous absorption spectrum, which can be divided into several bands. There is an obvious predissociation feature with these bands: when a molecule absorbs a photon to jump up to discrete state i which is near to a repulsive state f , it may undergo a radiationless transition from states i to f , i.e. a predissociation. We use the notation $J_{k_a k_c}$ for the rotational quantum states of H₂O, here J is the total rotational quantum number, K_c is the projection quantum number of J on the axis perpendicular to the nuclear H-O-H plane, and K_a is the projection quantum number of J on the axis in the nuclear H-O-H plane. Following the theory of spectroscopy, the probability of a predissociation is proportional to K_a^2 ; for details, see e.g., Liu et al. (2004). Thus, molecules in levels with $K_a = 0$ will not undergo predissociation. It can be found that the higher the value of K_a , the stronger is the tendency to predissociate. For the famous $6_{16} \rightarrow 5_{23}$ astronomical maser transition of H₂O, for instance, the values of K_a is 1 or 2 for the upper or lower level, respectively. Thus the ratio of their predissociation probabilities is approximately $\leq 1/4$. This implies that the depopulation rate of 5_{23} will be roughly 4 times greater than that of 6_{16} , so that the populations are inverted and masering can occur. This is the origin of the astronomical H₂O masers in the regions of massive star formation.

Following this argument, we may expect further maser transitions, namely $5_{15} \rightarrow 4_{22}$ at 325 GHz, $4_{14} \rightarrow 3_{21}$ at 380 GHz, $3_{13} \rightarrow 2_{20}$ at 183 GHz, even $10_{29} \rightarrow 9_{36}$ at 321 GHz, $7_{53} \rightarrow 6_{60}$ at 437 GHz, $6_{43} \rightarrow 5_{50}$ at 439 GHz and $6_{42} \rightarrow 5_{51}$ at 471 GHz. All of these have been observed.

Furthermore, we have argued that nascent H₂O molecules in massive star-forming regions are born preferentially in the upper levels of maser transitions, available for enhancing the inversion of maser levels (Liu et al. 2004).

3.2 Generation of Interstellar OH Masers

Interstellar OH molecules are mainly the product of photodissociation of H₂O (Argon et al. 2003). The electron configuration of H₂O in the ground is $X(^1A_1): (1a_1)^2 (2a_1)^2 (1b_2)^2 (3a_1)^2 (1b_1)^2$. It is the most loosely bound $1b_1$ electron that will be excited and dissociated. From molecular orbital theory, the $1b_1$ electron orbital can be described as a non-bonding $2p_x$ orbital of Oxygen, with wave function whose $p\pi$ lobe is perpendicular to the H₂O plane. According to symmetry conservation, the nascent OH will have the orbital with the unpaired electron in the π^- state. This means that the upper Λ -doublet will be preferentially populated. Therefore,

a population inversion is created between the two Λ -doublet states, and masers can occur subsequently.

Of course, the actual situation is not so simple. There are complications with both Λ -doublet mixing and out-of-plane rotation of H_2O . However, both theory and experiment have confirmed that there is indeed a high degree of inversion between the masing levels at low temperature, which of course is just the case with interstellar space (Thissen et al. 1999).

The nascent OH is formed in higher energy levels, and drops to the lower levels by radiative relaxation. The selection rules are:

$$\Delta J = \pm 1, + \leftrightarrow -. \quad \Delta F = 0, \pm 1. \quad (1)$$

This means that the upper levels of the Λ -doublets are always preferentially populated. Therefore, the inversion can be maintained and the maser action is sustained.

3.3 Number of Available Photons

The radiative models have encountered strong criticisms. One concerns the shortage of UV photons. Holtz (1968) asserted that the huge UV fluxes required to explain sustained maser action are not produced in HII regions. Indeed, since the strong H_2O and OH masers emit up to $\sim 5 \times 10^{46}$ photon s^{-1} , there must be at least 5×10^{46} pumping photon s^{-1} available. Can such an enormous demand be met?

As a matter of fact, Holtz's calculation involved direct UV pumping of the $\Pi - \Sigma$ transitions of OH ground-state molecules at wavelength ~ 305 nm. This is a narrow spectral range, hence the UV photons are in short supply. On the contrary, our model reaches the OH excited states through pumping H_2O . Since the absorption of UV photons by H_2O is diffuse, the model can use photons in a wide spectral range from 90–180 nm which provides a sufficient supply of UV photons. Suppose the central stellar object has radius $R \sim 1.5 \times 10^{12}$ cm and surface temperature $T \sim 2.5 \times 10^4$ K. One can calculate the total number of photons that contribute to the pumping of the maser by integrating over λ from 90 to 180 nm as:

$$N_0 = 4\pi R^2 \int_{90 \text{ nm}}^{180 \text{ nm}} e(\lambda) d\lambda / h\nu \approx 3.5 \times 10^{49} \text{ photon s}^{-1}, \quad (2)$$

where $e(\lambda)$ is monochromatic emissive power, N_0 is far more than the required photon flux of 5×10^{46} per second.

Of course, there also are particles such as H, H_2 and dust in the same region as the masers and these will share the UV photons with the H_2O molecules. However, the absorption by H and H_2 occurs in sharp features below 100 nm, beyond the range used in our pumping mechanism.

With respect to the absorption by dust, the number density ratio of dust grains to gas molecules N_d/N_g is $\sim 2 \times 10^{-12}$ (Leung 1976). Thus $N_d \sim 2 \times 10^{-12} \cdot n(\text{H}_2)$, $n(\text{H}_2)$ is the number density of H_2 molecules. Since the typical radius of a dust grain is $\sim 10^{-5}$ cm, we obtain the maximum absorption coefficient due to dust as $\varepsilon_d \sim 2\pi 10^{-22} \cdot n(\text{H}_2) \text{ cm}^{-1}$. For H_2O , the absorption coefficient is $\varepsilon_{\text{H}_2\text{O}} = n(\text{H}_2\text{O}) \cdot \sigma_0 \text{ cm}^{-1}$. With a cross-section $\sigma_0 \sim 10^{-16} \text{ cm}^2$, and the fractional abundance of H_2O in star-forming regions $f_{\text{H}_2\text{O}} \sim 10^{-4}$ (Kylafis & Norman 1991), we obtain $\varepsilon_{\text{H}_2\text{O}} \sim 10^{-20} \cdot n(\text{H}_2) \text{ cm}^{-1}$, which is larger than ε_d by two orders of magnitude. Even if the number density of dust goes somewhat higher, our model for the required supply of UV photons will still be compatible with expected astronomical conditions.

4 THE ROLES OF NUMBER DENSITY OF MOLECULES

The number density of masing molecules is restricted by two conditions, namely, to offer more enough maser photons and to avoid the thermalization of the molecule levels. If the number density is too low, the amplification gain would be too small and the maser intensity would not meet the requirement of observation. If, on the other hand, the number density is too large, then numerous collisions would thermalize the population of maser molecules. Therefore, the collision effect should be taken into account for any reliable masing models. Since the fractional abundance of interstellar H₂O or OH species is thought to be constant, $f_{\text{H}_2\text{O}} \sim 10^{-4}$, $f_{\text{OH}} \sim 10^{-5}$, the number density of the H₂ molecules is restricted also.

4.1 Limit of Number Density in the Regions of H₂O and OH Maser Spots

The main roles of collision are: excitation, de-excitation, thermalization and maser quenching. If the radiative de-excitations dominate the collisional ones, it is likely that some transition will exhibit inverted populations. However, when the collisions dominate both the excitations and de-excitations, the molecules will be thermalized and the population inversion will be destroyed, to result in the Boltzmann distribution of the level populations. Therefore we need to consider the influence of collision in our model.

In general, one can have the following rate equations (N_i denoting the population of level i):

$$\frac{dN_i}{dt} = \sum_{j>i} R_{ji}N_j - \sum_{j<i} R_{ij}N_i + \sum_{j\neq i} (C_{ji}N_j - C_{ij}N_i), \quad (3)$$

$$N = \sum_{k=1}^n N_k$$

where $i = 1, 2, \dots, n-1$; $j = 1, 2, 3, \dots, n$. R_{ji} is the net radiation transition rate between levels j and i . C_{ji} is the collision rate from level j to level i due to the other particles (here H₂ molecules). Obviously, the condition for masing in the optically thick region would be:

$$C_{ji}/R_{ji} \leq 1. \quad (4)$$

When the ratio C_{ji}/R_{ji} becomes larger than 1, the molecular levels involved will be thermalized, and maser will be quenched.

Nevertheless, it is the UV radiation to pump the molecules up to higher electronic states in our model. To stress the simple scenario, we estimate the competition of radiation with collision for both OH and H₂O species.

For inelastic collisions of an H₂O molecule with other particles, only collisions with H₂ will be important since H₂ is the most abundant species in interstellar space. The general collision rate C of a H₂O molecule with interstellar molecules H₂ is

$$C = n(\text{H}_2) \cdot \sigma \cdot V_C, \quad (5)$$

where σ is the cross-section for inelastic collisions, and is approximately $\sim 10^{-16}$ cm², V_c is the relative velocity of H₂O and H₂, equal to $\sim 10^5$ cm s⁻¹. The smallest radiative transition rate of H₂O molecule is ~ 0.1 s⁻¹ (Herzberg 1966). Therefore, from Eqs. (4) and (5), the upper limit of $n(\text{H}_2)$ is $\sim 10^{10}$ cm⁻³. Higher density will thermalize the maser level populations and quench the masing.

As to the lower limit of $n(\text{H}_2)$, it comes from the requirement of maser intensity. The typical isotropic photon emission rate of H_2O maser is $\Phi_{\text{isotr}} \sim 10^{46}$ photon s^{-1} . We can obtain the effective isotropic rate by (Kylafis & Norman 1990):

$$\Phi_{\text{isotr}} = 4\pi R_{ji} N_j l^3, \quad (6a)$$

$$R_{ji} = A_{ji} \exp(|\tau_{ji}(\mu)|) \Omega / (4\pi |\tau_{ji}(\mu)|), \quad (6b)$$

where l is the length of the masing region along the line of sight, A_{ji} is the Einstein A-coefficient, $\tau_{ji}(\mu)$ is the optical depth and $\Omega = 2\pi\mu$. Because of the exponential dependence of maser radiative rate on $\tau_{ji}(\mu)$, one may find that the maser radiation is beamed within a solid angle Ω around $\mu=1$, or the $\tau_{ji}(\mu) \approx \tau_{ji}(1)$. For a typical $6_{16} - 5_{23}$ masers of interstellar H_2O species, $A_{ji} = 1.85 \times 10^{-9} \text{ s}^{-1}$, $|\tau_{ji}(1)| \approx 22$ (Kylafis & Norman 1990). Here N_j is the population of masing upper level, it is at about 600 K above the ground state. We can consider the temperature of the maser region as $T \sim 400$ K (Kylafis & Norman 1991) and take $l = 10^{14}$ cm. Substituting these data into Eqs. (6a), (6b) and (4), we obtain the lower limit, $n(\text{H}_2) \sim 10^6 \text{ cm}^{-3}$.

The number density $n(\text{H}_2)$ in the regions of OH maser spots is limited either by the thermalization effect or by the maser intensity. We can repeat the above argument for the OH species. In this case, σ is approximately $\sim 10^{-15} \text{ cm}^2$, V_c is the relative velocity of OH and H_2 , and is equal to $\sim 6 \times 10^4 \text{ cm s}^{-1}$. The smallest radiative transition rate of the OH molecule is $\sim 0.01 \text{ s}^{-1}$ (Huber & Herzberg 1979). Therefore, from Eqs. (4) and (5), the upper limit of $n(\text{H}_2)$ in the OH maser spots is $\sim 10^8 \text{ cm}^{-3}$.

As to the lower limit of $n(\text{H}_2)$, it comes from the requirement of maser intensity. A typical isotropic photon emission rate of OH maser is $\Phi_{\text{isotr}} \sim 10^{44}$ photon s^{-1} . For the typical 1665 MHz maser of interstellar OH species, $A_{ji} = 7.2 \times 10^{-11} \text{ s}^{-1}$ (Moran 1990), $|\tau_{ji}(1)| \approx 22$. For the length of the masing region along the line of sight, we have $l = 5 \times 10^{15}$ cm. Substituting these data into Eqs. (6a), (6b) and (4), we obtain the lower limit, $n(\text{H}_2) \sim 10^5 \text{ cm}^{-3}$.

4.2 The Contribution of Collision to Population Inversion

The collisional pumping model for the interstellar masers has been proposed for a long time. We have checked it carefully. To take H_2O as an example, the population n_i of quantum state i of a H_2O molecule increases by: (1) new formation through the reaction, $\text{OH} + \text{H}_2 \rightarrow \text{H} + \text{H}_2\text{O}$; (2) radiative relaxation from higher states to state i ; (3) collision ending up in the state i from other states. The population n_i decreases by: (1) radiative relaxation to lower states; (2) photodissociative destruction of H_2O molecules; (3) collision starting in the state i and ending up in other states. We calculated the population distribution n_i (the details can be found in Liu et al. (2004)). It was found that collisional pumping always yields less population in high-lying rotational states. This is not surprising because collisional pumping rates are much smaller, compared to the radiative relaxation rates, particularly for the high-lying rotational states.

This important result implies that in regions of interstellar masers collisions may have a negligible effect on the population distribution of high rotation states. This in turn implies that the FIR and microwave emission originating from these regions cannot be explained only by collisional pumping, as is often in the literature.

5 DISTRIBUTION OF MASERS AND HII REGIONS

The 74 regions we investigated represent a nearly complete sample of known OH/H₂O maser in the galactic longitude range 339 to 50, a region covering more than half of the galactic disk. The sample undoubtedly comprises a range of evolutionary stages. Most of them are unambiguously associated with young star-forming regions.

5.1 The Distribution of Masers

The general condition of maser emission requires a warm and dense environment. According to our observations and argument, the H₂O masers have a smaller spot size of ~ 0.01 mpc, a higher number density of $\sim 10^6$ to 10^{10} cm⁻³ and a higher temperature. The OH masers have a spot size of ~ 0.1 mpc, a lower number density of $\sim 10^5$ to 10^8 cm⁻³ and a lower temperature. Therefore, we can propose an evolutionary sequence for the formation of H₂O and OH masers in massive star-forming regions as follows. Isolated H₂O masers form first, and because of the high excitation conditions of the 22 GHz H₂O maser, it is generally believed that the shocks are probably required to achieve higher temperatures and higher densities. These conditions would be satisfied at the interface between an outflow and the ambient medium or in an accretion disk (or envelope). According to the observed separation of the masers and HII regions in the isolated H₂O masers and simple associations, these two types belong to the accretion envelope scenario. In the accretion envelope the density decreases with radius. Usually, H₂O masers represent the youngest phase of star formation, they mark the commencement of nuclear burning. The isolated OH masers may have arisen in the relatively more extended and lower density regions than the H₂O masers. They generally lie in an accreting envelope outside of the UC-HII region. While simple OH/H₂O association will exist at the intermediary distances, where the number densities are also in between 10^6 and 10^8 cm⁻³.

5.2 Timescale Sequence of Masers

The current embedded star model encounters difficulties, such as on the expected lifetime for the maser phase and the size of the associated HII region. In the current dynamical model, an HII region is first formed when a new massive YSO begins to ionize a surrounding cloud which is assumed to be static, uniform in density, and of infinite extent. The lifetime of the maser phase in these regions has been estimated at $\sim 10^5$ yr (Genzel & Downes 1979). If we assume that the compact HII regions have expansion velocities ~ 5 km s⁻¹, then maser emission should be present until the HII region reaches a diameter of ~ 1000 mpc if the H₂O and OH masers endure for $\sim 10^5$ yr. That is, of course, unreasonable and the OH/H₂O maser emission near HII regions with diameters as large as 1000 mpc has never been found.

As a matter of fact, the current dynamical model is not an adequate description of the evolution of a massive star-forming region. If one achieves a model to include the gravitational force of the stellar object responsible for the HII region, the scenario is quite distinctive. Keto (2002) has shown that if a YSO at the center of the HII region has an ionized flux such that a stationary radius of ionization equilibrium is within a so-called R-critical radius (see below), then the HII region cannot expand by thermal pressure. At this small radius, the infall velocities are everywhere higher than the sound speed of the ionized gas, the gravitational force of the central stellar object dominates over the thermal pressure. Once ionization equilibrium is achieved, the HII region can only expand by the increasing flux of ionizing photons. Because the increase of ionizing flux is tied to the accretion rate, the timescale for accretion through the HII region will be relatively long – on the order of the free-fall timescale of the molecular core. Since the

HII region grows with the increase of the ionizing flux of the YSO, the evolutionary timescale of the HII region in the trapped phase must be on the order of the accretion timescale, or quite slow compared to the current dynamical timescale of the HII region, it is certainly possible to match the observational value of $\sim 10^5$ yr. The HII region expands slowly, so that outside of the UC-HII region that the density changes due to the expanding HII region is also slow and smooth. Subsequently the states of the three sorts of masers we have observed are quite stable. They co-exist in the accretion envelope in comparable numbers.

In the model with gravity, the hydrodynamic equation can be written in nondimensional form using the scaling factors. The radius is

$$R = (GM/C_1^2)x, \quad (7)$$

where G is gravitation constant and C_1 is the sound speed. If $x = 0.5$, R would be the R -critical radius. For the modest values, $M = 20 M_\odot$, $C_1 = 6 \text{ km s}^{-1}$, $x = 1/2$, we have $R \sim 0.1 \text{ mpc}$. It agrees well with the observations.

5.3 The Shortage of HII Regions

Since strong OH and H₂O sources are generally associated with UC HII regions, it has been concluded that OH masers are associated with massive young (ionizing) stellar objects. However, it may well be that the “popular” picture of OH-UC HII region association emerged from a selection effect, caused by the fact that earlier searches for OH masers were conducted predominantly toward HII regions. Interstellar H₂O masers are often found in the same star-forming regions as OH masers

We searched the 3 cm continuum emission toward 26 star-forming regions containing both OH and H₂O masers (Forster & Caswell 2000). Of a total of 45 individual maser sites in these regions, compact HII region was detected at 17 sites, giving an overall detection rate of 38%. Fewer than a half of the maser groups have detectable HII regions. The survey statistics presented above were under the assumption that each maser site contains an embedded YSO and that continuum emission comes from a UCHII surrounding the YSO.

The common shortage of detectable HII regions can be understood as follows. The masers may be associated with a young HII region that is currently below the detection limit because of its small size. As mentioned above (see Section 5.2), in the earlier phase, the strong gravitational force of material in the vicinity of a massive YSO can significantly extend the lifetime of this phase ($\sim 10^5$ yr), and after a long period these HII regions can be expected to grow larger and become detectable.

6 CONCLUSIONS AND COMMENTARY

It is obvious from the observations that the central YSO, UV radiation, and H₂O and OH masers all coexist in some massive star-forming regions. All of these features have been accounted for in the new model introduced in this paper. This new radiative model can interpret the pumping of interstellar OH/H₂O masers, without the known deficiency of previous radiative models. Furthermore, particularly it can interpret the observational statistical results of these masers. The isolated interstellar H₂O masers appear first and form near the cores of massive YSO, where the molecular number densities would be about $10^6 - 10^{10} \text{ cm}^{-3}$. The isolated OH masers form later at locations farther from the central star with lower densities of $10^5 - 10^8 \text{ cm}^{-3}$. In between the times, simple H₂O/OH maser associations form in locations where the densities are also intermediate ($\sim 10^6 - 10^8 \text{ cm}^{-3}$). For understanding why these masers last $\sim 10^5$ yr, we tried

to take the gravitational force into consideration, which is not done in the current dynamical model.

It is known that the population inversion for H₂O masers is obtained also from pure collisional pumping models that neglect the H₂O formation completely (Elitzur 1992). In this case the H₂O molecules live for a long time. However, despite the high density considered here, we find in our calculations that collisional redistribution starts to modify the rotational state populations only if the photodissociation rates are less than 10^{-5} s^{-1} . For H₂O masers exposed to the UV radiation in star-forming regions with a large H₂O formation rate, it seems that the collisional pumping can be safely eliminated as a dominant pumping mechanism.

We speculate that the physical environments of the massive star-forming regions are diverse. Perhaps there are different mechanisms for different masers and several mechanisms operate together in a given maser. They are not contradictory but complementary to one another.

In general, the values of photon flux, H₂ number density, etc., required by our model, are fully compatible with the expected astronomical conditions. Moreover, the model is promising because of its simplicity.

Acknowledgements We gratefully acknowledge the financial support from the National Natural Science Foundation of China.

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