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A MODEL FOR
EXTREMELY POWERFUL EXTRAGALACTIC
WATER MASERS

Ying-Cheng Wu
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EXTREMELY POWERFUL EXTRAGALACTIC WATER MASERS

by

YING-CHENG WU

SUBMITTED TO THE DEPARTMENT OF PHYSICS
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE
DEGREE OF
DOCTOR OF PHILOSOPHY

at the

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To the Memory of My Mother,

the greatest mother in my mind.

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ABSTRACT

This dissertation is composed of two separate papers concerning Extremely Powerful Extragalactic Water Masers. The masing phenomenon is fairly common in astronomical environments; a large number of molecules have been observed to exhibit varying degrees of masing. Among the three molecules, OH, SiO, and H₂O, which are the only ones that have been observed to exhibit strong maser emission, H₂O displays the strongest emission. Recently several extremely powerful extragalactic water masers (henceforth referred to as EPEWMs), whose luminosities are two or more orders of magnitude greater than those of the most powerful H₂O masers in our Galaxy and which are the most powerful cosmic water masers yet observed, have been detected. The maser radiation of an EPEWM is so intense that it emits up to several hundred solar luminosities with a narrow bandwidth. Their spectra show strong emission lines, rapid time variations, and features with various heights or widths. All EPEWMs are found close to the directions of the active nuclei of the galaxies and in galaxies which are strong infrared emitters. Some people think that EPEWMs could indicate a burst of star formation, but it is impossible that an EPEWM is simply an assembly of masers like the strongest Galactic water masers; at least some parts of an EPEWM are much more powerful than those strongest Galactic masers. Moreover the pump mechanism is a big question and EPEWMs are rare. Therefore it is likely that there are special astrophysical conditions associated with EPEWMs, which have some common characteristics among themselves and can be classified as a peculiar kind of astrophysical H₂O masers. All existing models of astrophysical masers apparently fail to explain this peculiar phenomenon. This is a great challenge to theorists. In conjunction with other observations, maser radiation is a very powerful tool for studying the emitting source and other astrophysical phenomena. Therefore studying EPEWMs may provide much useful information not only about EPEWMs themselves but also about those galaxies in which EPEWMs are found and, perhaps, help us understand most galaxies and many other astrophysical phenomena. Hence I, under the guidance of Professor Alcock, set out to investigate the astrophysics of EPEWMs and plan to present a series of papers on these peculiar objects.

In the first paper a model for EPEWMs is proposed in which an EPEWM region consists of more than one subregion with various velocities, sizes, masses, densities, etc. Active star formation occurs in this region, which is located near an active nucleus of the galaxy. Each subregion contains a normal, a massive, or a supermassive newly-formed central star as well as a disk-like envelope of molecular clouds in which H_2O masers reside. The saturated H_2O masers provide the most efficient maser operation; the (partially) unsaturated H_2O masers amplify the background radiation coming both from the active nucleus of the galaxy and from the newly-formed central stars, but have a lower conversion efficiency. There are usually more than one maser spot in a subregion. A spectral feature may be composed of one or more individual maser components, each of which is produced by a maser spot and arises from a spatially distinct position. Although the spots producing a spectral feature must have about the same radial velocity with respect to the Earth, it is not necessary that they belong to the same subregion. The matter in a disk migrates toward the central star, and after some time a small part of it will be ejected from the inner disk by the stellar wind. This repetitive mechanism and stellar flares are two of the main causes for the rapid time variations of some features of EPEWMs. Occasionally the collisions between subregions, ejecta, or clouds may also produce features in spectra. It is likely that the pump mechanism for some parts of EPEWMs producing some strong features is the CCR (collisional excitation, collisional sink, and rotational transition) pump mechanism. The conditions as stated in this model (strong stellar wind [i.e., the stellar mass-loss rate is $\sim 10^{-3} M_\odot \text{yr}^{-1}$ and the velocity of the stellar wind is $\sim 1200 \text{ km s}^{-1}$, high density [i.e., the number density of hydrogen molecules is $\sim 10^{12} \text{ cm}^{-3}$], strong interaction between stellar wind and disk matter, etc.) could provide the environments for this pump mechanism. The reasons that EPEWMs are so much more powerful than strong Galactic H_2O masers are perhaps as follows. First, an EPEWM region is probably larger than the region of a strong Galactic H_2O maser, it perhaps contains more newly-born massive stars or even some newly-born supermassive stars, and it perhaps has more active star formation. Second, the masses of central stars embedded in clouds (subregions) of EPEWMs may usually be larger than those of the central stars inside strong Galactic H_2O maser clouds. Moreover, in EPEWMs, stellar mass-loss rates may be higher, stellar winds may be faster and stronger, stellar radiation may be stronger, and so on. Third, the active galactic nucleus near an EPEWM probably contributes significantly to the peculiar behavior of the EPEWM.

Because of the unusual conditions of EPEWMs, it is possible that the local stimulated emission rate exceeds the local bandwidth for the radiation. In this case the standard expression relating the photon emission rate to the profile averaged mean intensity does not apply. In the second paper a new expression for the stimulated emission rate in this case is derived.

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EXTREMELY POWERFUL EXTRAGALACTIC WATER MASERS I. A MODEL

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ABSTRACT

A model for extremely powerful extragalactic water masers (EPEWMs) is proposed in which an EPEWM region consists of more than one subregion with various velocities, sizes, masses, densities, etc. Active star formation occurs in this region, which is located near an active nucleus of the galaxy. Each subregion contains a normal, a massive, or a supermassive newly-formed central star as well as a disk-like envelope of molecular clouds in which H_2O masers reside. The saturated H_2O masers provide the most efficient maser operation; the (partially) unsaturated H_2O masers amplify the background radiation coming both from the active nucleus of the galaxy and from the newly-formed central stars, but have a lower conversion efficiency. There are usually more than one maser spot in a subregion. A spectral feature may be composed of one or more individual maser components, each of which is produced by a maser spot and arises from a spatially distinct position. Those spots producing a spectral feature have close velocities with respect to LSR; it is not necessary that they belong to the same subregion. The matter in a disk migrates toward the central star, and after some time a small part of it will be ejected from the inner disk by the stellar wind. This repetitive mechanism and stellar flares are two of the main causes for the rapid time variations of some features of EPEWMs. The ejecta may also produce features. Occasionally the collisions between subregions, ejecta, or clouds may also produce features in spectra. It is likely that the pump mechanism for some parts of EPEWMs producing some strong features is the CCR

pump mechanism. The conditions as stated in this model could provide the environments for this pump mechanism. The reasons for the differences between EPEWMs and strong Galactic H_2O masers are discussed. This model quite successfully explains many important characteristics of EPEWMs: the rapid time variations, the broad range and random velocity distribution, the extremely high luminosities, the various heights or widths of features in spectra, the strong infrared radiation from the galaxies, how an active nucleus contributes to an EPEWM, how some parts of EPEWMs producing strong features are pumped, why this pump mechanism can work, and why EPEWMs are different from strong Galactic H_2O masers.

I. INTRODUCTION

Since the first astrophysical maser was detected in our Galaxy (Weinreb, *et al.* 1963), the study of astrophysical masers has been an exciting and rapidly growing area of research (for reviews on astrophysical masers see Reid and Moran 1981; Elitzur 1982; Downes 1985). The masing phenomenon is fairly common in astronomical environments; a large number of molecules have been observed to exhibit varying degrees of masing. Among the three molecules, OH, SiO, and H₂O, which are the only ones that have been observed to exhibit strong maser emission, H₂O displays the strongest emission. Since 1969 the water vapor masers have been found throughout our Galaxy in late-type stars and in regions of active star formation. H₂O maser emission was first detected in an external galaxy (M33) by Churchwell, *et al.* (1977). This H₂O maser as well as several others (see e.g., Lepine and Dos Santos 1977; Huchtmeier, *et al.* 1978; Scalise and Braz 1981) was comparable in luminosity to the strongest Galactic H₂O masers (i.e. $\lesssim 1 L_{\odot}$).

Recently several extremely powerful extragalactic water masers (henceforth referred to as EPEWMs), whose luminosities are at least an order of magnitude greater than those of the most powerful H₂O masers in our Galaxy, have been detected (Dos Santos and Lepine 1979; Gardner and Whiteoak 1982; Claussen, Heiligman, and Lo 1984; Henkel, *et al.* 1984; Haschick and Baan 1985; Moran 1984; Claussen and Lo 1986; Whiteoak and

Gardner 1986). The maser radiation of an EPEWM is so intense that it emits up to several hundred solar luminosities with a narrow bandwidth. Their spectra show strong emission lines, rapid time variations, broad ranges and random velocity distributions, and features with various heights or widths. All EPEWMs are found close to the directions of the active nuclei of the galaxies and in galaxies which are strong infrared emitters (e.g., Henkel, *et al.* 1984). Some people think that EPEWMs could indicate a burst of star formation (see, e.g., Claussen, Heiligman, and Lo 1984; Haschick and Baan 1985). However the region of an EPEWM would be too small to contain excessively many massive stars and it is impossible that an EPEWM is simply an assembly of W49-like masers (see, e.g., Moran 1984; Claussen and Lo 1986); at least some parts of an EPEWM are much more powerful than W49. Moreover the pump mechanism is a big question (e.g., Moran 1984) and EPEWMs are rare (Henkel, *et al.* 1984). Therefore it is likely that there are special astrophysical conditions associated with EPEWMs, which have some common characteristics among themselves and can be classified as a peculiar kind of astrophysical H_2O masers. In conjunction with other observations, maser radiation is a very powerful tool for studying the emitting source and other astrophysical phenomena. Therefore studying EPEWMs may provide much useful information not only about EPEWMs themselves but also about those galaxies in which EPEWMs are found and, perhaps, help us understand most galaxies and many other astrophysical phenomena. Hence we set out to investigate the astrophysics of EPEWMs and will present a series of papers on these peculiar objects. In this paper, the first paper of

this series, we present a model which is quite successful in explaining many important characteristics of EPEWMs. In later papers of this series, we will give more detailed discussions on some subjects presented in the model given in this paper.

While EPEWMs become a new exciting field for theoretical exploration, the theoretical study of strong Galactic H_2O masers has not yet been completed. There has been no consensus about the structures and the dynamics of those masers. Some people propose a model of an expanding and rotating disk or an expanding shell (Genzel, *et al.* 1978), some people propose a model of a quasi-stationary disk (Elmegreen and Morris 1979), some people propose a model of a non-stationary disk (Strel'nitskij 1984), some people propose a model of high-velocity collisions between clouds (Tarter and Welch 1986), some people propose a model of outflows to explain some outflows in some Galactic sources (Downes, *et al.* 1981; Genzel, *et al.* 1981), and some people propose a model of a single massive star to explain some bipolar flows in some Galactic sources (Walker, *et al.* 1982), among others. Similarly many pump mechanisms have been proposed for strong Galactic H_2O masers. To be short, we adopt the brief three-letter designation (Strel'nitskij 1980a, b, 1984): the first letter giving the type of the energy source (C, collisional; R, radiative), the second the type of the energy sink, and the third the type of the transitions constituting the pump cycles (r, rotational; v, vibrational). There are five most elaborated pump models: RRv model (Litvak 1969), RCv model (Goldreich and Kwan 1974), CRv model (Norman

and Silk 1979), CCr model (Turner 1970; Strel'nitskij 1971, 1973; de Jong 1973; Shmied, *et al.* 1976), and CCr model (Strel'nitskij 1980a, b, 1984; Ky-lafis and Norman 1986). We will show in this paper as well as in some later papers of this series that a model in which an EPEWM region consists of more than one subregions with various radial velocities and in which some strong H_2O masers are pumped by the CCr pump mechanisms would be the most appropriate explanation for EPEWM phenomena. From some points of view, part of this model appears to be the combination of the appropriate points (which may have been modified to satisfy the conditions of EPEWMs) of some best models for strong Galactic H_2O masers. However, we stress the peculiar conditions of EPEWMs and the differences between EPEWMs and strong Galactic H_2O masers, and we discuss the reasons for these difference

The plan of this paper is as follows. In Section II some phenomena of EPEWMs are described, and the main difficulty for understanding EPEWMs is mentioned and explained. In Section III the principle of building this model is stated. In Section IV we propose a model for EPEWMs, which is quite successful in explaining many important characteristics of EPEWMs. Our conclusions are summarized in Section V.

II. PHENOMENOLOGY AND THE MAIN DIFFICULTY FOR UNDERSTANDING EPEWMS

a) Phenomenology

The first EPEWM was found toward NGC 4945 on 1978 September 20-22 (Dos Santos and Lepine 1979); its isotropic luminosity⁴

⁴The isotropic luminosity of an H₂O maser is $L_{H_2O} = 4\pi D^2 S_{H_2O} \Delta\nu$,

where D is distance, S_{H_2O} observed maser flux density, $\Delta\nu$ maser linewidth.

is $165 L_{\odot}$ in a total bandwidth of 24 MHz (320 kms^{-1}) (Batchelor, Jauncey, and Whiteoak 1982). The second EPEWM was found toward the Circinus galaxy in 1982 April (Gardner and Whiteoak 1982); its isotropic luminosity is $37 L_{\odot}$ with a total velocity range of $370\text{--}725 \text{ kms}^{-1}$ covered (Gardner and Whiteoak 1982). In 1984 Claussen, Heiligman, and Lo (1984) reported that they had found two more EPEWMs — NGC 4258 and NGC 1068 with luminosities of $120 L_{\odot}$ and $350 L_{\odot}$, respectively, in a bandwidth of 100 MHz. The most powerful maser yet detected is NGC 3079 with isotropic luminosity of $520 L_{\odot}$ in a bandwidth of 50 MHz (Henkel, *et al.* 1984) or $\sim 500 L_{\odot}$ in a bandwidth of 20 or 40 MHz (Haschick and Baan 1985). These five EPEWMs are all EPEWMs yet reported and confirmed. (We have used, and will usually use, the name of the astronomical object such as a star, an

H II region, or a galaxy toward which the maser is detected as the name of the maser).

In the following we will describe some characteristics of EPEWMs, which we try to explain and/or discuss in next sections; they include most of the important characteristics yet observed.

1. Each EPEWM emits an extremely high luminosity, which is one to three orders of magnitude greater than the most powerful H₂O maser in our Galaxy, within a narrow bandwidth.
2. Some strong features have rapid time variations, which can be seen in Figures 1-5. We cite NGC 4258 (Figure 1(a)) as an example for a brief description. The feature at 455 km s⁻¹ is in a level of ~4 Jy in 1982 November. Then the observed intensity of this feature decreases to ~2 Jy in 1983 January. In 1984 April it increases to ~10 Jy. However in 1984 August it decreases to ~5 Jy (Haschick and Baan 1985, and a reference therein). In 1984 September it re-increases to ~6 Jy.
3. Each spectrum shows a complicated, apparently random distribution of features, widely spread in velocity (see Figure 1-5).
4. The parent galaxies are strong infrared emitters (e.g., Henkel, *et al.* 1984). For NGC 1068, NGC 3079, NGC 4945, and the Circinus galaxy, the nuclear IR luminosities are $\gtrsim 10^{10} L_{\odot}$, and for NGC 4258 the

nuclear luminosity is $\sim 6 \times 10^8 L_{\odot}$ (Claussen, Heiligman, and Lo 1984; Claussen and Lo 1986 and references therein).

5. Each EPEWM appears to be located near (within at most a few tens of arcseconds) the nucleus of its parent galaxy; the precise angles or distances between them need further higher-resolution observations (Haschick and Baan 1985; Henkel, *et al.* 1984; Dos Santos and Lepine 1979; Gardner and Whiteoak 1982; Claussen, Heiligman, and Lo 1984; Batchelor, Jauncey, and Whiteoak 1982; Claussen and Lo 1986).
6. All nuclei associated with EPEWMs show signs of activity (e.g., Claussen, Heiligman, and Lo 1984; Henkel, *et al.* 1984; Claussen and Lo 1986, and references therein): NGC 1068 is the prototypical Type 2 Seyfert galaxy; NGC 4258 is classified as having a spectrum intermediate between Seyfert galaxies and Liners; NGC 4258 has anomalous 'arms' detected in H α and the radio continuum, which may be indicative of some past nuclear activity; (Claussen, Heiligman, and Lo 1984 and the references therein) the Circinus galaxy, NGC 4945, and NGC 3079 also show evidence for nuclear activity (Moorwood and Glass 1984; Henkel, *et al.* 1984; Haschick and Baan 1985; Claussen and Lo 1986, and references therein).
7. EPEWMs are rare; a large number of galaxies showing star bursts and/or nuclear activities are undetected in EPEWMs (Claussen, Heiligman, and Lo 1984; Henkel, *et al.* 1984; Haschick and Baan 1985; Claussen and Lo 1986; Whiteoak and Gardner 1986).

b) The Main Difficulty for Understanding EPEWMs

Because of the limitation of present instruments and techniques of observations, we currently can obtain much less information about EPEWMs than that about the Galactic H_2O sources.⁵

⁵This situation could be quite improved when VLBI experiments can be made with an antenna on a space probe; they could be done after 1992 (Moran 1984).

Therefore most data and parameters, which can be obtained for Galactic counterparts, can not be obtained for EPEWMs at present or in the near future. This is the main difficulty for understanding EPEWMs. Hence in this series of papers we certainly can not make so quantitative and detailed studies for EPEWMs as for Galactic H_2O masers. With all known information we make every effort to estimate carefully the parameters which are necessary or helpful for the studies. Under this difficult situation we set out to investigate the important problems, with the hope that this series of papers could contribute to further observational and theoretical studies on the problems of EPEWMs.

III. THE PRINCIPLE OF BUILDING THE MODEL

The model is built according to the observational characteristics mentioned in Section II. For internal structures and mechanisms about which observational information cannot be obtained thus far, the best way is to consider the probable similarities and differences between EPEWMs and the strongest Galactic H_2O masers, to consider the observational characteristics of EPEWMs, and then to create a model which is most suitable for EPEWMs.

IV. A POSSIBLE EXPLANATION FOR PROPERTIES OF EPEWMS

According to the phenomena described above, a possible explanation for various characteristics of EPEWMS is as follows.

a) A Gross Description of An EPEWM

Each EPEWM resides in a region of active star formation, which produces strong IR radiation. This region is near the nucleus of the parent galaxy. An example of the size of an EPEWM is ~ 1.3 pc for NGC 4258 (by a VLA measurement) (Claussen and Lo 1986).⁶

⁶Time variation and preliminary VLBI observations suggest that the extent may be smaller than the VLA limits given here by another factor 10-100 (Claussen and Lo 1986).

This region consists of more than one, say, several to dozens of, subregions (see Figure 6), each of which comprises a normal(say, $< 5 M_{\odot}$), a massive(say, $\gtrsim 5 M_{\odot}$; this is the most plausible), or a supermassive(say, $> 60 M_{\odot}$) newly-born star as well as a disk-like envelope of molecular clouds in which H_2O masers reside. Normally subregions are separated from each other and have varied radial velocities with respect to LSR (V_{LSR}) within a broad range,

and they also have varied sizes, masses, densities, and many other physical properties. The ejecta ejected from these disks may also produce features.

All or some of the subregions of an EPEWM might be collected gravitationally in a central well, might move at random, might be in (an) outflow(s) from or in (an) inflow(s) toward one or more sources (e.g., the nucleus of the parent galaxy), might be expanded from a central source so that they move in a bipolar flow or in a great shell, ..., and so on. The observational information thus far (and probably in the near future) can not rule out or confirm any of the possibilities mentioned above. Therefore in this paper we will not discuss detailedly the gross motion of the subregions of an EPEWM, which will be detailedly discussed in a later paper. We will treat an EPEWM as an assembly of subregions.

b) Saturated and Unsaturated Masers

The saturated regime provides the most efficient mode of maser operation in which each pumping event leads to a maser photon with a constant efficiency which is determined by the details of the pumping scheme. In a saturated maser there is production of radiation, and the linear growth is the result of the contribution of additional emitting volume, with constant photon production rate, in the line of sight. Unsaturated masers have an exponential gain but have a lower conversion efficiency. An unsaturated maser can amplify background continuum radiation. As the line radiation field in

the maser gets stronger, the maser will eventually saturate. The presence of a background continuum may bring this about earlier. An observer will then see the (saturated or unsaturated) masers superposed on the continuum source. Without a background source the masers may not saturate at all and even be unobservable. We refer interested readers to Alcock and Ross (1985) for a more general discussion on this topic.

c) The Structure of A Disk Surrounding A Massive Star

The disk in a subregion orbits around a massive or a supermassive (young) star that has a strong wind (say, the stellar mass-loss rate $\sim 10^{-3} M_{\odot} \text{yr}^{-1}$ and the wind velocity $\sim 10^3 \text{ kms}^{-1}$). The wind pushes on and drives turbulence in the topmost, exposed layers of the circumstellar disk. The turbulence will create a viscous torque on the differentially rotating gas that will lead to a slow influx of material toward the central star. The action of the wind is not to push the whole disk away from the star; in fact, most of the disk will be drawn in toward the star. At any one time, both outward and inward motions can occur in the disk (as a result of drifts and wind-forced motions), but these will be much smaller than the orbital motion around the central star. Some of the disk material brought close to the star by the action of viscous friction will break off from the rest of the inner disk and get pushed away from the star by the tremendous pressure of the wind (Elmegreen 1978; Elmegreen and Morris 1979).

The gas density is higher(e.g., 10^{12} cm^{-3}) near the star and lower(e.g., 10^8 cm^{-3}) far from the star. Although the whole disk would roughly uniformly receive the radiation continuum from the nucleus of the galaxy, the inner disk receives stronger radiation from the central newly-born star and receives more energy caused by the interaction between the stellar wind and the clouds than the outer disk (Figure 7). Therefore, as explained above, the inner disk will saturate earlier. However, near the star(e.g., the distance $< 10^{14} \text{ cm}$) the H_2O masers either do not exist or cannot operate in some conditions. At great distances(e.g., $> 10^{17} \text{ cm}$) from the star, the density in the disk would become too low to permit a maser. At intermediate distances (see below for a quantitative estimate), a maser could, in principle, occur. As a result, a simplified structure of the disk could be divided into four regions: (from the inner disk to the outer disk; see below for a quantitative estimate for distance ranges; see Figure 8) the region A in which no H_2O masers can exist and operate, the region B in which H_2O masers are almost fully saturated, the region C in which H_2O masers vary from the partially saturated region to the mostly unsaturated region, and the region D in which the gas density is too low to permit a maser.

The distance ranges of a region B and a region C could be roughly estimated as follows:

As stated above, the gas density is higher near the star and lower far from the star. We assume that the range of the number densities of hydrogen molecules, n_{H} , is 10^{11} cm^{-3} to 10^{13} cm^{-3} in a region B. This assumption will

be justified in a later paper (Wu and Alcock 1988*b*). Here we make a comment for this assumption. In the past people thought that an H_2O maser should be quenched for $n_H > 10^{11} \text{ cm}^{-3}$. However, this case should not occur when the pump mechanism is the CCr pump, which probably works in B regions (Wu and Alcock 1988*b*). In this inherently non-LTE process, thermalization does not occur no matter how high the density is, as long as the ionization fraction is approximately equal to the ratio of the collision rate coefficient due to the neutral particles to that due to the electrons (Kylafis and Norman 1986; Strel'nitskij 1984). We will make more discussions on this subject in the Subsection(k) (pump mechanisms) as well as in a later paper (Wu and Alcock 1988*b*). For the region C, we assume that $10^7 \text{ cm}^{-3} \lesssim n_H \lesssim 10^{11} \text{ cm}^{-3}$, which is the usual range of n_H taken for Galactic H_2O masers in the past (e.g., Shmely, Strel'nitskij, and Muzylev 1976; Elmegreen and Morris 1979 and references therein).

The number densities of hydrogen molecules, $n_H(r)$, a function of the distance r from the star measured along the plane, can be written as

$$n_H(r) \sim \frac{S(r)}{h(r)b}, \quad (1)$$

where $b = 2.36 m_H$ is the mean molecular weight, $m_H = 1.66 \times 10^{-24} \text{ gm}$, the mass of a hydrogen atom or a.m.u. (atomic mass unit); $h(r)$ is the height of the circumstellar disk at the distance r from the star (Ward 1976):

$$h(r) \sim 2c_s \left(\frac{r^3}{GM_*} \right)^{\frac{1}{2}}, \quad (2)$$

where $c_s (\sim 10^5 \text{ cm s}^{-1})$ is the speed of sound, G the gravitational constant, M_* the mass of the embedded star; $S(r)$ is the surface (mass) density of the disk.

We take $S(r) \propto r^{-1}$, for example, for a disk density distribution (see, e.g., Elmegreen 1978). Then

$$S(r) = \frac{M_D}{2\pi r_D r}, \quad (3)$$

for the total disk mass M_D and the disk radius r_D . Therefore

$$n_H(r) \sim \frac{G^{\frac{1}{2}} M_*^{\frac{1}{2}} M_D}{4\pi c_s r_D r^{\frac{5}{2}} b}. \quad (4)$$

Then the distance range for a region B can be roughly estimated by

$$10^{11} \text{ cm}^{-3} \lesssim n_H(r) \lesssim 10^{13} \text{ cm}^{-3}, \quad (5)$$

and for a region C,

$$10^7 \text{ cm}^{-3} \lesssim n_H(r) \lesssim 10^{11} \text{ cm}^{-3}. \quad (6)$$

Hence, for $r_D \sim 10^{17} \text{ cm}$, $M_D \sim 5 M_\odot$, and $M_* \sim 40 M_\odot$, for example, the distance range for a region B is roughly

$$1.2 \times 10^{14} \text{ cm} \lesssim r \lesssim 7.4 \times 10^{14} \text{ cm}, \quad (7)$$

and the distance range for a region C is roughly

$$7.4 \times 10^{14} \text{ cm} \lesssim r \lesssim 3.0 \times 10^{16} \text{ cm}. \quad (8)$$

Of course, the real ranges for various B regions vary from disk to disk, and depend on the parameters of B regions.⁷

⁷In above discussions, for simplicity, we have used $c_s \sim 10^5 \text{ cms}^{-1}$ for all cases. In real situation, of course, c_s would vary under different conditions. However this effect is not significant. $c_s \propto T^{1/2}$ for the temperature T; for $T \sim 1600 \text{ K}$ and 400 K , for example, the factor of variation is only ~ 2 .

d) The "Spot-Cloudlets"

Considering the observational results of strong Galactic H_2O masers, the history of the development of the knowledge of strong Galactic H_2O masers, and the similarities between EPEWMs and strong Galactic H_2O masers, it is reasonable to predict that maser spots in EPEWMs like the Galactic counterparts would be observed when observations of sufficiently high resolution and sensitivity are available.⁸

⁸Resolution of extragalactic masers will have to wait until VLBI experiments can be made with an antenna on a space probe; these experiments could be done as early as 1992 (Moran 1984).

Besides the variations of densities with respect to the distances from the central stars as discussed in last subsection, the densities also vary from location to location and the "spot-cloudlets" are formed. A spot-cloudlet is defined as a dense maser cloudlet which produces one or more maser spots. Because of the beaming effect (Appendix A), a maser spot mentioned here is not necessary to be an observed (in the future) maser spot; the number of observed maser spots is not necessary to be the number of spot-cloudlets (Alcock and Ross 1985*a, b*, 1986*a, b*). The whole spot-cloudlet moves with an (almost) single velocity; different spot-cloudlets usually have different velocities. The velocity of a maser spot corresponds to the velocity of its associated spot-cloudlet. There are usually more than one spot-cloudlet, usually with different but relatively close velocities, in a subregion. The velocity dispersion is possibly due to a combination of hyperfine splitting (the hyperfine structure of the transition has six components spread over 5.9 km s^{-1} [Kukolich 1969]) and of turbulence caused by a stellar wind impacting on molecular clouds, and the turbulence is the dominant factor. A spectral feature may be composed of one or more individual maser components, each of which is produced by a maser spot and arises from a spatially distinct position. Those spots producing a spectral feature usually have close velocities with respect

to LSR; it is not necessary that their associated spot-cloudlets belong to the same subregion. Among those spots producing a feature, some are stronger and some are weaker. (Figure 9)

The size of an H_2O maser spot-cloudlet can be estimated by (Strelnitskij 1984; Dyson and Williams 1980; Kaplan and Pikelner 1970; Strelnitskij 1987, private communications)

$$d \sim \left(\frac{3}{2}\right) n_H K T_c v_c / R_c, \quad (9)$$

where K is the Boltzmann's constant, T_c is the gas temperature in the condensation in the spot-cloudlet compressed by the shock [see Subsection(k)], v_c is the velocity of the gas in the condensation, and R_c is the cooling rate:

$$R_c \sim n_H n_{\text{H}_2\text{O}} q_H^v X_H^v E_v \exp\left(-\frac{E_v}{K T_H}\right), \quad (10)$$

where $n_{\text{H}_2\text{O}}$ is the number density of H_2O molecules, q_H^v the rate of collisional de-excitation of an H_2O vibration-rotational transition by the H_2 molecules, E_v the energy of the typical pump photon, T_H the H_2 kinetic temperature, $X_H^v \sim 5$ is the typical number of transitions induced by collisions with H_2 from a given rotational level of the (000) state to the rotational levels of the (010) state. Substituting $n_H = 10^{12} \text{ cm}^{-3}$, $n_{\text{H}_2\text{O}} = 10^8 \text{ cm}^{-3}$, $q_H^v \sim 10^{-14} \text{ cm}^3 \text{ s}^{-1}$, $E_v/K \sim 2000\text{K}$, $T_H \sim 1500\text{K}$ (Strelnitskij 1984), $T_c \sim 3000\text{K}$, and $v_c \sim 50 \text{ kms}^{-1}$ for H_2O spot-cloudlets in the B regions of EPEWMs, one

finds that the order of the size of an H_2O maser spot-cloudlet in B regions of EPEWMs is

$$d \sim 10^{13} \text{ cm.} \quad (11)$$

The validity of the result of the estimate might be reinforced if the estimated size of a spot-cloudlet, d , does not exceed the estimated height of the disk, h , as there are no reasons that $d > h$ and it is reasonable that $d \lesssim h$. As in Figure 10, we define r_1 as the distance of the inner edge of a region B; e.g., $r_1 \sim 1.2 \times 10^{14} \text{ cm}$ [equation (7)]. When we obtained equation (11), we took $n_E = 10^{12} \text{ cm}^{-3}$. Since $n_E(r) \propto r^{-5/2}$ [equation (4)], by equation (5), this number density corresponds to $r_2 \sim 2.5$, $r_1 \sim 3 \times 10^{14} \text{ cm}$. Using equation (2) and the same parameters as those for equation (7) and (8), one obtains

$$h(r_2) \sim 1.4 \times 10^{13} \text{ cm} \gtrsim 10^{13} \text{ cm.} \quad (12)$$

This result reinforces the validity of equation (11).

Because $h(r) \propto r^{3/2}$ [equation (2)],

$$h(r) \gtrsim 1.4 \times 10^{13} \text{ cm for } r \gtrsim r_2. \quad (13)$$

As in Figure 10, when an H_2O spot-cloudlet moves from the region C toward the region B, or from $r = r_4$ toward $r = r_1$, its volume may become smaller

and its density may become greater; it may become stronger. Note that different spot-cloudlets may have somewhat different sizes, so a spot-cloudlet in the inner region may have greater size than another spot-cloudlet in the outer region.

e) The Time Variations of Some Features

Each of the ejecta from a disk is composed of a part of a spot-cloudlet in the region B. After the ejection the spot-cloudlet is destroyed and its velocity is altered so that its original associated maser spot will not contribute to the original spectral feature. Therefore the observed intensity in the feature will decrease after ejection. The amount of decrease depends on the original strength of the maser spot, and the fraction of decrease depends on the fraction of the contribution to the original feature by the original spot. The almost unsaturated and partially saturated clouds in C regions (in many subregions) migrate toward the central stars, and will saturate and become almost fully saturated masers in B regions. It is likely that one or more these maser clouds will form one or more spot-cloudlets which produce maser spots which in turn produce the feature components with velocities close to that of the feature whose observed intensity has decreased (remember that spot-cloudlets in a subregion usually have relatively close velocities), and the observed intensity in that feature will then increase. This scenario will be repeated again and again. This would be one of the main causes for the rapid time variations of some features of EPEWMs. Note that, although a

spectral feature may be composed of more than one (e.g., ~ 10) components, usually it may not be composed of too many (e.g., > 100) components, and components of a spectral feature have different intensities.⁹

⁹For example (see Figure 9 and Appendix B), the area of a spectral feature in the spectra of $F_{H_2O}-\Delta\nu$ is 100 in an appropriate unit. This feature is composed of 5 components, whose areas in the spectra of $F_{H_2O}-\Delta\nu$ at some time are 5, 10, 15, 20, 50; i.e., the components have different intensities.

Therefore, usually it does not occur that random variations of the individual components produce a negligible variation of the whole spectral feature, although the superposition of the random variations of the individual components do affect the pattern, the amplitude, and the period of the variation of the whole spectral feature. If there is no newly-formed spot-cloudlet producing a feature component with velocity close to that of the feature whose observed intensity has decreased, then the observed intensity in that feature will not increase and the feature will even disappear; the two features at 542 and 572 kms^{-1} in the top profile of Figure 4 are possibly two examples. Some very strong features, whose observed intensities increase rapidly and decrease slowly, are possibly produced under the actions of stellar flares, which contribute greater stellar mass-loss rates and stronger stellar winds and result in greater densities, pump rates, and maser luminosities (see Wu

and Alcock 1988b). The duration of each cycle varies from cycle to cycle. The lifetime of features varies from feature to feature; typically it is several weeks for features produced under the actions of stellar flares and several years to tens of years for features produced by spots in normal cases. Some features, whose observed intensities increase rapidly and decrease slowly and are not repetitive, are possibly produced by ejecta or collisions as described later.

f) The Unsaturated Masers

The (mostly) unsaturated masers in C regions amplify the background continuum radiation coming both from the active nucleus of the galaxy and from the embedded newly-born stars, and contribute a small part of the total luminosity of an EPEWM. This may be one of the differences between EPEWMs and strong Galactic H_2O masers, for each EPEWM is associated with an active galactic nucleus and its embedded newly-born stars may contribute more radiation (as explained later) so that the contribution to the luminosity of an EPEWM by the (mostly or partially) unsaturated masers may be much greater than the Galactic counterpart.

g) The Ejecta

The velocities, sizes, and densities of the ejecta ejected from disks could be estimated as follows:

We employ a radially directed wind from the central star as the source of accelerating pressure. We assume that the number density in the ejecta, n , scales adiabatically as the material decompresses with increasing distance from the star, then $c_s \propto n^{(\gamma-1)/2}$ and the wind pressure

$$P_w = bnc_s^2 \propto n^\gamma, \quad (14)$$

for adiabatic index γ . For a constant-velocity wind,

$$P_w \propto R^{-2} \quad (15)$$

for the distance, R , from the star. Therefore,

$$n \propto R^{-\frac{2}{\gamma}}. \quad (16)$$

Assuming that the ejecta expand spherically,¹⁰

¹⁰This assumption is an idealization, which simplifies the subsequent treatments. Actually the cloudlets of ejecta may become flattened along the direction of the wind, but the effect is small.

then the diameter of a cloudlet of the ejecta

$$L \propto n^{-\frac{1}{3}} \propto R^{\frac{2}{3\gamma}}. \quad (17)$$

Under these conditions one obtains the radial velocity, v , in terms of R (see Elmegreen and Morris 1979),

$$\frac{v^2}{2} = \frac{c_0^2 R_0}{L_0} \left[\frac{1 - (R_0/R)^{1-4/(3\gamma)}}{1-4/(3\gamma)} - \frac{\beta_0}{2} \left(1 - \frac{R_0}{R} \right)^2 \right], \quad (18)$$

where the subscript 0 represents the initial conditions, c_s is the speed of sound (c_0 is the initial c_s), and the dimensionless quantity β_0 is the initial ratio of the gravitational acceleration in the disk to the acceleration by the wind. Since the column density $S_c = \Sigma L$, the wind-driven acceleration of the cloudlet of ejecta is

$$\frac{P_w}{S_c} = \frac{c_s^2}{L}, \quad (19)$$

and

$$\beta_0 = \frac{GM_* S_{c0}}{R_0^2 P_{w0}} = \frac{GM_* L_0}{R_0^2 c_0^2}. \quad (20)$$

For ejecta with sufficiently large S_{c0} (then β_0 is sufficiently large), v goes to zero at some R , where $0 < R_0/R < 1$. Therefore, unless those ejecta break apart, they will never escape the system. They will eventually fall back onto the disk at some large distance and then begin to migrate back inward again. Ejecta with sufficiently small column density (then β_0 is sufficiently small) could accelerate to great distances from the star. The internal pressure of escaped ejecta cloud constantly adjust to the local pressure in the wind until

they get so far from the star that the ram pressure of their motion through the surrounding molecular cloud slows them down.

Let's take the reasonable (approximate) initial conditions:

$R_0 = r_1$ = the distance of the inner edge of the region B (see Figure 10)

$$\sim 1.2 \times 10^{14} \text{ cm [equation (7)]}, \quad (21)$$

$$L_0 \sim \left(\frac{3}{4}\right) h(R_0) = \left(\frac{3}{4}\right) h(r_1), \quad (22)$$

and

$$c_0 \sim 5c_s, \text{ for } \gamma = 7/5, . \quad (23)$$

For $M_* \sim 40 M_\odot$ and $c_s \sim 10^5 \text{ cm s}^{-1}$, by equation (2),

$$L_0 \sim 2.7 \times 10^{12} \text{ cm}. \quad (24)$$

R is an instantaneous parameter, which would be observable in the future.

For $R \gtrsim r_d \sim 10^{17} \text{ cm}$, by equation (18), $v \gtrsim 91 \text{ km s}^{-1}$ for $\gamma = 7/5$.

Note that these velocities obtained above are not the velocities of the corresponding features shown in the spectra of EPEWMs (Figure 1-5). These velocities are the ones with respect to the disk system, and are caused by the

ejections. We have assumed that $v_0 = 0$ when we derived the equation (18). Moreover, note that velocities of ejecta may have various components along the line of sight. Therefore the V_{LSR} 's along the line of sight of the features produced by ejecta are not necessary to be much different from those of the features produced by the spots in the region B.

Equation (16) implies

$$\frac{n}{n_0} = \left(\frac{R_0}{R} \right)^{\frac{2}{\gamma}}, \quad (25)$$

and equation (17) implies

$$\frac{L}{L_0} = \left(\frac{R}{R_0} \right)^{\frac{2}{\gamma}}. \quad (26)$$

Equation (26) could determine the size of the ejecta at a distance from the star. For a given n_0 , n could also be determined as a function of R by equation (25). For example, for $R \gtrsim r_D \sim 10^{17}$ cm, $n_0 \sim 10^{13}$ cm $^{-3}$, and $\gamma = 7/5$, $L \gtrsim 6.6 \times 10^{13}$ cm and $n \lesssim 6.7 \times 10^8$ cm $^{-3}$.

h) Collisions

Occasionally, when two subregions with high velocities collide with each other, or when ejecta collide with other clouds, high energy may be produced and excites H₂O maser emission (Tarter and Welch 1986). It is possible that a small portion of features, strong or weak, of EPEWMs are produced by this

kind of actions. These features have short life times and have no systematic time variations (although their observed intensities decrease rapidly) as those produced by maser spots in disks; they barely repeat the variation of flux density at the same V_{LSR} . Of course they are not constants, either.

i) Lifetimes of EPEWMs

Producing an EPEWM probably needs simultaneously both a region of active massive star formation and an active nucleus of the galaxy. This sets a constraint on the life time of an EPEWM. Since the presence of a nuclear radio source is a necessary, but not sufficient, condition for an EPEWM — a relatively large number of non-detections of EPEWMs in galaxies having active nuclei, the life time of an EPEWM may be short compared with the timescale for nuclear activity.

j) Some Examples of Features

We now discuss the possible structures or ways for producing the various features of individual EPEWMs.

NGC 4258 (see Figure 1). The strongest feature at 455 km s^{-1} (V_{LSR}) has rapid time variation (its observed intensity became double or half in a few months). This feature is probably mainly produced by some maser spots in B regions of one or more subregions, and it is also possible that this feature is produced under the action of a stellar flare. The feature at ~ 490

kms^{-1} varied relatively much more slowly (its observed intensity was almost constant). This feature is probably composed of many narrower features which varied roughly independently — random variations of the individual masers produce a slow variation in a resultant feature. Other secondly strong features may be produced by ejecta or by collisions, and weak features may be produced by the C regions of the disks of subregions, by ejecta, by collisions, or by subregions with small volumes.

NGC 3079 (see Figure 2). The feature at $\sim 960 \text{ kms}^{-1}$ has rapid time variation (its observed intensity became double in a few months). This feature is probably mainly produced by some maser spots in B regions of one or more subregions, and it is also possible that this feature is produced under the action of a stellar flare. Secondly strong features may be produced by ejecta, or by collisions. Weak features are the same as described for NGC 4258.

NGC 1068 (see Figure 3). The features around 1420 kms^{-1} (V_{Solar}) have rapid time variations (its observed intensity became half or double in a few months) (note that they rose again (to the 0.7 Jy) in the profile taken in September 1984 [Henkel, *et al.* 1984]), and are probably mainly produced by some maser spots in the B regions of disks. These spots have higher V_{Solar} 's than most others in NGC 1068 region so that these features are located on the higher V_{Solar} side of the spectra. Other features are the same as described for NGC 3079.

The Circinus galaxy (see Figure 4). The features at 519, 552, 569, 590, and 626 kms^{-1} are probably mainly produced by maser spots in B regions of disks. The strongest but very narrow features in the top profile in Figure 4

(542 and 572 kms^{-1}) disappeared in the next profile and didn't appear again in subsequent profiles. They may be produced by collisions, ejecta, or spots in B regions as mentioned in Subsection(e). Other features are the same as described for NGC 3079.

NGC 4945 (see Figure 5). The features at 558, 675, 699, 703, 706, 717, and 722 kms^{-1} are probably mainly produced by maser spots in B regions of disks. Other features are the same as described for NGC 3079.

k) Pump Mechanisms

Because of some characteristics of EPEWMs, it is likely that the pump mechanism for some regions of EPEWMs producing strong features is the CCr pump mechanism (Wu and Alcock 1988b). CCr pumping is possible if there are two kinds of particles, e.g., H_2 molecules and electrons, with different kinetic temperatures T_{H} and T_{e} . Collisions with the hot particles provide the excitation of molecules in the pump cycles, whereas collisions with the cold particles provide the energy sink. (Strel'nitskij 1980a, b, 1984). The minimum pump power of the strongest maser spot necessary to explain the observed energy flux in a spectral feature of fully saturated masers is

$$\left[\left(\frac{n_1}{\text{cm}^{-3}} \right) \left(\frac{\Delta P}{\text{s}^{-1}} \right) \right]_{\text{min}} \sim 5 \left(\frac{z}{\text{AU}} \right)^{-3} \left(\frac{D}{\text{kpc}} \right)^2 \left(\frac{F}{\text{Jy}} \right) \left(\frac{\Delta\nu_{12}/\nu_{12}}{10^{-6}} \right), \quad (27)$$

where n_1 is the number density of molecules at the lower level, $\Delta P = P_{12} - P_{21}$ the net rate of pumping from the lower to the upper signal level,

$n_1 \Delta P$ the specific pump power, ν_{12} the frequency of the signal transition, $\Delta\nu_{12}$ the observed linewidth, z the length of the region emitting the observed photons, D the distance to the region, F the flux density (see Wu and Alcock 1988*b*). By means of this equation we estimated (Wu and Alcock 1988*b*) that the minimum required pump powers for the strongest sources of EPEWMs are around of orders $\sim 10^4 - 10^6 \text{ cm}^{-3}\text{s}^{-1}$ provided that the amplification length of each source is 50 AU and that the distances to the sources are those assumed in the associated references. Under this condition, most models (except the CCr) of pump mechanism proposed for explaining Galactic H_2O masers are inadequate for pumping the strongest sources of EPEWMs (Wu and Alcock 1988*b*). The basic problem with these proposed pump mechanisms is thermalization. By increasing the collision rates, the emitted power increases only up to a point, after which the population inversion is destroyed and thermodynamic equilibrium sets in. An important advantage of CCr pump mechanism over other pump mechanisms is that non-LTE collisions can produce greater power than ordinary pump mechanisms for similar conditions. In this inherently non-LTE process, thermalization does not occur no matter how high the density is, as long as the ionization fraction is approximately equal to the ratio of the collision rate coefficient due to the neutral particles to that due to the electrons (Kylafis and Norman 1986; Strel'nitskij 1984).

As described above, a strong stellar wind from the central star is stopped by the matter of a disk, and a density condensation is created there. The

matter of the density condensation is compressed to a high density ($n_H \gtrsim 10^{11} \text{ cm}^{-3}$) by the ram pressure of the wind and heated by MHD-turbulence (see Norman and Silk 1979), and MHD shocks are produced there (see McKee and Hollenbach 1980). The generated energy will diffuse in the disk and provide most of the energy for CCr pumps. In the magnetic precursors of MHD shocks, it occurs naturally that the temperature of electrons is much larger than that of neutral hydrogens (Draine 1980, 1981; Draine, Roberge, and Dalgarno 1983; Kylafis and Norman 1986). The degree of ionization in the H_2O condensations could be much high — up to $\sim 10^{-6}$ – 10^{-5} (Strelnitskij 1984). In these environments the CCr pump mechanism for H_2O masers can work (see Kylafis and Norman 1986). Hence, the structures and dynamics of some regions of EPEWMs proposed in this section could provide the environments for the CCr pump mechanism.

*1) The Reasons for the Differences between EPEWMs and
Powerful Galactic H_2O Masers*

The reasons that EPEWMs are so much more powerful than strong Galactic H_2O masers, that is, their luminosities are so much higher than those of strong Galactic H_2O masers, are as follows. First, an EPEWM region is larger than the region of a strong Galactic H_2O maser, it contains more newly-born massive stars or even some newly-born supermassive stars, and the star formation rate is greater. This very active star formation may be triggered by tidal interactions with nearby galaxies or may be associated with

the activities of the active nucleus of the parent galaxy. Second, the masses of central stars embedded in clouds of EPEWMs may be larger than those of the central stars inside strong Galactic H_2O maser clouds. Moreover, in EPEWMs stellar mass-loss rates are higher, stellar winds are stronger, stellar radiation is stronger, ..., and so on. Therefore the maser powers produced by subregions are higher than those produced by corresponding Galactic sources. Third, each EPEWM is strongly affected by the associated nucleus of the parent galaxy. For example, the kinematics and energetics of the outflow from (or the inflow toward) the nucleus affect the strength and distribution of an EPEWM. The (mostly or partially) unsaturated masers of an EPEWM amplify the background radiation coming both from the active nucleus of the galaxy and from the newly-born stars which may contribute more radiation than Galactic newly-born stars, so that the contribution to the luminosity of an EPEWM by (mostly or partially) unsaturated masers may be much greater than the Galactic counterpart. Moreover, it is possible that by some direct or indirect ways this active nucleus contributes to the active star formation, to the formation of an EPEWM region, to the dynamics of subregions, and to the saturation of H_2O masers and lead to an unusual environment for producing extremely powerful H_2O masers and the structures, dynamics, and mechanisms as stated above. The detailed discussion on how active galactic nuclei affect EPEWMs will be given in a later paper.

The second and the third reasons greatly reduce the required number of

newly-formed stars and/or the required volume of the region of an EPEWM, and, therefore, they are the possible solutions to the problems of the numbers of newly-born massive stars stated in the Section of Introduction.

m) Some Comments and Remarks

The observed properties of EPEWMs can be explained by the model given above. This is not surprising in view of the relatively large number of unknown parameters due to the limitation of present observations. It is possible that some different models may have a comparable degree of success. Nevertheless the model given in this series of papers is very promising. Observations with higher resolution and sensitivity will help us check our model and understand EPEWMs, and, therefore, they extremely deserve to be done. We hope that our investigations could contribute to further observational and theoretical studies on the problems of EPEWMs.

V. CONCLUSIONS

We have proposed a model for EPEWMs in which each EPEWM region consists of more than one subregions with various V_{LSR} , sizes, masses, densities, etc.. Active star formation occurs in this region, which is located near an active nucleus of the galaxy. Each subregion contains a normal, a massive, or a supermassive newly-formed central star as well as a disk-like envelope of molecular clouds in which H_2O masers reside. The saturated H_2O masers provide the most efficient maser operation; the (partially) unsaturated H_2O masers amplify the background radiation coming both from the active nucleus of the galaxy and from the newly-formed central stars, but have a lower conversion efficiency. The inner disks saturate earlier. A disk could be divided into four regions: (from the inner disk to the outer disk) the region A in which no H_2O masers can exist and operate, the region B in which H_2O masers are almost fully saturated, the region C in which H_2O masers vary from the partially saturated region to the mostly unsaturated region, and the region D in which the gas density is too low to permit a maser. The distance range of each region has been estimated. There are usually more than one maser spots in a subregion. A spectral feature may be composed of one or more individual maser components, each of which is produced by a maser spot and arises from a spatially distinct position. Those spots producing a spectral feature usually have close velocities; it is not necessary that they belong to the same subregion. The size of a strong H_2O maser spot-cloudlet has been estimated. The matter in a disk migrates toward the central star,

and after some time a small part of it will be ejected from the inner disk by the stellar wind. This repetitive mechanism and stellar flares are two of the main causes for the rapid time variations of some features of EPEWMs. The ejecta from a disk may also produce features in EPEWM spectra. The velocities, sizes, and densities of the ejecta have been estimated. Occasionally the collisions between subregions, ejecta, or clouds may also produce features in spectra. Producing an EPEWM probably needs both active star formation and an active nucleus of the galaxy. This sets a constraint on the life time of an EPEWM, which may be short compared with the time scale for nuclear activity. It is likely that the pump mechanism for some parts of EPEWMs producing some strong features is the CCr pump mechanism. The conditions as stated in this model could provide the environments for this pump mechanism. The reasons that EPEWMs are so much more powerful than strong Galactic H_2O masers are perhaps as follows. First, an EPEWM region is probably larger than the region of a strong Galactic H_2O maser, it perhaps contains more newly-born massive stars or even some newly-born supermassive stars, and it perhaps has more active star formation. Second, the masses of central stars embedded in clouds (subregions) of EPEWMs may usually be larger than those of the central stars inside strong Galactic H_2O maser clouds. Moreover, in EPEWMs, stellar mass-loss rates may be higher, stellar winds may be faster and stronger, stellar radiation may be stronger, and so on. Third, the active galactic nucleus near an EPEWM probably contributes significantly to the peculiar behavior of the EPEWM.

This model quite successfully explains many important characteristics of EPEWMs: the rapid time variations, the broad range and random of velocity distribution, the extremely high luminosities, the various heights or widths of features in the spectra, the strong infrared radiation from the galaxies, how an active nucleus contributes to an EPEWM, how some parts of EPEWMs producing strong features are pumped, why this pump mechanism can work, why EPEWMs are different from strong Galactic H_2O masers, and some other characteristics of EPEWMs.

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APPENDIX A

The radiation from a typical cloud will be highly beamed, because the shape of a typical cloud is not symmetric (Alcock and Ross 1985*a*). The maser radiation emerges from a spot-cloudlet predominantly in two narrow cones (Figure 11). We refer interested readers to Alcock and Ross (1985*a*, *b*, 1986*a*, *b*). The subject of beaming in EPEWMs will be discussed in a later paper.

APPENDIX B

In terms of the observed quantities F_{H_2O} , the flux density; D , the distance to the source; and $\Delta\nu$, the linewidth, the H_2O maser luminosity L_{H_2O} of a single feature can be written as

$$L_{H_2O} = 4\pi D^2 F_{H_2O} \Delta\nu. \quad (A1)$$

Therefore

$$L_{H_2O} \propto F_{H_2O} \Delta\nu \quad (A2)$$

for a spectral feature of EPEWMs since D can be considered as the same for all places in an EPEWM. $F_{H_2O} \Delta\nu$ is the area of the feature in the spectra of $F_{H_2O} - \Delta\nu$. Hence, when the size (intensity) of a feature becomes double, the corresponding H_2O maser luminosity also becomes double.

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FIGURE CAPTIONS

Figure 1: (a) Spectra of EPEWM NGC 4258 in a, 1982 November and b, 1983 January (the velocity resolution is $\sim 2.6 \text{ kms}^{-1}$) (Claussen, Heiligman, and Lo 1984); c, 1984 April (the velocity resolution is 1.3 kms^{-1}) (Haschick and Baan 1985); d, 1984 September (the velocity resolution is 0.8 kms^{-1}) (Henkel, *et al.* 1984). (b) Spectra of water maser emission toward NGC 4258 for five epochs. The spectral resolution is 200 kHz. Note that the two spectra on the right have the same scale as the three spectra on the left. (Claussen and Lo 1986). (c) A spectrum of the water maser emission toward NGC 4258 made with an autocorrection spectrometer. The spectral resolution is 20 kHz (Claussen and Lo 1986).

Figure 2: Spectra of EPEWM NGC 3079 in a, 1984 March, April or May (the velocity resolution is 1.3 kms^{-1}) (Haschick and Baan 1985). b, 1984 September (the velocity resolution is 0.4 kms^{-1}) (Henkel, *et al.*, 1984).

Figure 3: Spectra of water maser emission toward the nucleus of NGC 1068 for three different epochs. The spectral resolution is 200 kHz. (Claussen and Lo 1986).

Figure 4: The H_2O profiles observed towards the nucleus of the Circinus galaxy. The velocity resolution is 0.5 kms^{-1} . (Whiteoak and Gardner 1986).

Figure 5: The H_2O profiles observed toward the nucleus of NGC 4945. The

velocity resolution is 0.5 kms^{-1} . (Whiteoak and Gardner 1986).

Figure 6: A schematic sketch of the location of an EPEWM. An EPEWM consists of more than one, say, several to dozens of, subregions, each of which comprises a normal, a massive, or a supermassive newly-born star as well as a disk-like envelope of molecular clouds in which H_2O masers reside. Normally subregions are separated from each other. For NGC 4258, for example, the region is confined to $\theta \lesssim 0''.035$ (Claussen and Lo 1986), which corresponds to a physical diameter $d \lesssim 1.5 \text{ pc}$ at the distance assumed, $R \sim 6.9 \text{ Mpc}$. Each EPEWM is within at most a few tens of arcseconds of the associated nucleus (Claussen, Heiligman, and Lo 1984). For example, the Circinus galaxy EPEWM is within 10-15 arcsec of the nucleus, which corresponds to a distance $D \sim 190 - 290 \text{ pc}$ at the distance assumed, $R \sim 4 \text{ Mpc}$ (Gardner and Whiteoak 1982). The sizes of the EPEWM, subregions, R , d , D , and θ are not to scale.

Figure 7: Energy flow chart. H_2O maser clouds receive energy (radiation) from the active galactic nucleus, the embedded star, and the interaction between the stellar wind and clouds.

Figure 8: A schematic sketch of the simplified structure of a disk. From the inner disk to the outer disk: the region A in which no H_2O masers can exist and operate, the region B in which H_2O masers are almost fully saturated, the region C in which H_2O masers vary from the partially saturated region to the mostly unsaturated region, and the region D in which the gas

density is too low to permit a maser. The disk orbits around a massive or a supermassive young star that have strong winds. The spot-cloudlets moving toward the central star by the action of viscous friction will break off from the rest of the inner disk and get pushed away from the star by the tremendous pressure of the wind and become ejecta. The notation r is the distance from the central star. The distance range of each region could be roughly estimated as in the text. Generally the maser emission from a subregion is roughly isotropic. The sizes of region A, B, C, D, and spot-cloudlets are not to scale.

Figure 9: A spectral feature may be composed of one or more individual maser components, each of which is produced by a maser spot and arises from a spatially distinct position. Those spots producing a spectral feature usually have close velocities; it is not necessary that they belong to the same subregion. Among those spots producing a feature, some are stronger and some are weaker.

Figure 10: A schematic sketch of the simplified geometry used in Subsection IV(d): r_1 is the distance of the inner edge of the region B from the central star, r_2 is that of a position ($r_2 \sim 2.5r_1$) in the region B, r_3 is that of the surface of the division between the region B and the region C, r_4 is that of an (arbitrary) position in the region C, $h(r)$ is the height of the disk at the distance r , and d is the size of a spot-cloudlet. The sizes of spot-cloudlets, region A, B, C, and $h(r)$ are not to scale.

Figure 11: A schematic sketch of the beaming effect of spot-cloudlets. The maser radiation emerges from a spot-cloudlet predominantly in two narrow cones.

Figure 1(a)

Figure 1(b)

Figure 1(c)

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

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**VERY HIGH STIMULATED EMISSION RATES
IN ASTROPHYSICAL MASERS**

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ABSTRACT

Recent observations of extragalactic water masers which have extremely high luminosities raise the possibility that the stimulated emission rate in the maser emission line in these regions is much higher than in Galactic masers. It is possible that the local stimulated emission rate exceeds the local bandwidth for the radiation. In this case the standard expression relating the photon emission rate to the profile averaged mean intensity does not apply. A new expression for the photon emission rate is derived.

I. INTRODUCTION

Recent observational work has led to the discovery of water vapor masers of extraordinary luminosity (Dos Santos and Lepine 1979; Gardner and Whiteoak 1982; Claussen, Heiligman, and Lo 1984; Henkel, *et al.* 1984; Haschick and Baan 1985; Moran 1984; Claussen and Lo 1986; Whiteoak and Gardner 1986). These extremely powerful extragalactic water masers (henceforth referred to as EPEWMs) have been observed to radiate $> 100 L_{\odot}$ in maser radiation in lines of width $> 100 \text{ kms}^{-1}$.

Specifically, these objects have the following remarkable characteristics:

1. Each EPEWM emits an extremely high luminosity, which is one to three orders of magnitude greater than the most powerful H_2O maser in our Galaxy, within a narrow bandwidth.
2. Some strong features have rapid time variations, which can be seen in Figures 1-5. We cite NGC 4258 (Figure 1(a)) as an example for a brief description. The feature at 455 kms^{-1} is in a level of $\sim 4 \text{ Jy}$ in 1982 November. Then the observed intensity of this feature decreases to $\sim 2 \text{ Jy}$ in 1983 January. In 1984 April it increases to $\sim 10 \text{ Jy}$. However in 1984 August it decreases to $\sim 5 \text{ Jy}$ (Haschick and Baan 1985, and a reference therein). In 1984 September it re-increases to $\sim 6 \text{ Jy}$.
3. Each spectrum shows a complicated, apparently random distribution of

features, widely spread in velocity (see Figure 1-5).

4. The parent galaxies are strong infrared emitters (e.g., Henkel, *et al.* 1984). For NGC 1068, NGC 3079, NGC 4945, and the Circinus galaxy, the nuclear IR luminosities are $\gtrsim 10^{10} L_{\odot}$, and for NGC 4258 the nuclear luminosity is $\sim 6 \times 10^8 L_{\odot}$ (Claussen, Heiligman, and Lo 1984; Claussen and Lo 1986 and references therein).
5. Each EPEWM appears to be located near (within at most a few tens of arcseconds) a nucleus of the parent galaxy; the precise angles or distances between them need further higher-resolution observations (Haschick and Baan 1985; Henkel, *et al.* 1984; Dos Santos and Lepine 1979; Gardner and Whiteoak 1982; Claussen, Heiligman, and Lo 1984; Batchelor, Jauncey, and Whiteoak 1982; Claussen and Lo 1986).
6. All nuclei associated with EPEWMs show signs of activity (e.g., Claussen, Heiligman, and Lo 1984; Henkel, *et al.* 1984; Claussen and Lo 1986, and references therein): NGC 1068 is the prototypical Type 2 Seyfert galaxy; NGC 4258 is classified as having a spectrum intermediate between Seyfert galaxies and Liners; NGC 4258 has anomalous 'arms' detected in H α and the radio continuum, which may be indicative of some past nuclear activity; (Claussen, Heiligman, and Lo 1984 and the references therein) the Circinus galaxy, NGC 4945, and NGC 3079 also show evidence for nuclear activity (Moorwood and Glass 1984; Henkel, *et al.* 1984; Haschick and Baan 1985; Claussen and Lo 1986, and references therein).

7. EPEWMs are rare; a large number of galaxies showing star bursts and/or nuclear activities are undetected in EPEWMs (Claussen, Heiligman, and Lo 1984; Henkel, *et al.* 1984; Haschick and Baan 1985; Claussen and Lo 1986; Whiteoak and Gardner 1986).

These objects are rich with theoretical possibilities. A model of EPEWMs will be given in another paper (Wu and Alcock 1988b). Here we address an interesting technical issue that arises when the mean intensity of maser radiation is very high. Specifically, an expression is derived for the photon emission rate that is valid when the stimulated emission rate (R) exceeds the local bandwidth for the radiation ($\Delta\nu$).

The possibility that $k > \Delta\nu$ in some astronomical masers was recognized by Goldreich, Keeley, and Kwan (1973), by Litvak (1974), and by Goldreich (1975). However, improved observation revealed that this circumstance was unlikely to occur in any of the known Galactic masers, and no further work on this problem seemed necessary. The situation for some representative Galactic masers is shown in Table 1; further numbers are given in the review of Reid and Moran (1981). The discovery of the EPEWMs raises this possibility once again; as shown by the last entry in Table 1. This is why we decided to perform this calculation.

As a final remark, laboratory masers generally operate under even more extreme conditions than these under discussion here. The mathematical description of the interaction of intense radiation fields with spectral lines

is highly developed. This paper represents a particular application of this apparatus to the problem at hand; we refer interested readers to Yariv (1968, 1975) for a more general discussion.

II. THE CALCULATION OF THE STIMULATED EMISSION RATE

If $R \gtrsim \Delta\nu$, will some physical conditions be different from the usual case that $R < \Delta\nu$? First, will the expression of R in terms of the Einstein B coefficients,

$$R = \frac{J}{n}(N_2 B_{21} - N_1 B_{12}) \quad (1)$$

which is valid in the usual case that $R < \Delta\nu$, be still valid if $R \gtrsim \Delta\nu$? We are considering a system in which the interaction under consideration can be limited to two levels only. We label these levels 1 and 2, where the level 2 is the higher level. In equation (1), n is the number density of the specific molecule and

$$J = \int_0^\infty J_\nu \phi(\nu) d\nu, \quad (2)$$

where

$$J_\nu = \frac{1}{4\pi} \int I_\nu d\Omega \quad (3)$$

is the mean intensity, I_ν is the specific intensity or brightness, $\phi(\nu)$ is a normalized profile function, i.e.

$$\int_0^\infty \phi(\nu) d\nu = 1, \quad (4)$$

N_1 , N_2 are the volume density population of the lower and upper level, respectively, B_{21} the Einstein B coefficient for stimulated emission, B_{12} that for true absorption, ν the frequency, and Ω the solid angle. In the non-degenerate case, the degeneracies $g_1 = g_2 = 1$, so that equation (1) can be expressed as

$$R = \frac{BJ}{n}(N_2 - N_1) \quad (5)$$

where

$$B = B_{21} = \frac{g_1}{g_2} B_{12} \quad (6)$$

The equation of radiative transfer is

$$\frac{dI_\nu}{dz} = -\alpha(\nu)I_\nu + j_\nu, \quad (7)$$

where $\alpha(\nu)$ is the absorption coefficient, j_ν is the volume emission rate, and z measures distances along the ray. The relation between $\alpha(\nu)$ and R is

$$R = -\frac{1}{n} \int_0^\infty d\nu \int d\Omega \frac{I_\nu}{h\nu} \alpha(\nu). \quad (8)$$

Both equation (7) and equation (8) generally hold no matter $R < \Delta\nu$ or $R \gtrsim \Delta\nu$.

When $R < \Delta\nu$, by equation (8),

$$\alpha(\nu) = (N_1 \frac{g_2}{g_1} - N_2) \frac{c^2}{8\pi\nu^2 t_{spont}} \phi(\nu)$$

if and only if

$$R = \frac{J}{n} (N_2 B_{21} - N_1 B_{12}). \quad (9)$$

The expressions (8) and (9) can be obtained in the standard manner using time dependent perturbation theory using a classical description of the radiation field. The time-independent wavefunctions of these levels u_1 and u_2 are the eigenfunctions of the unperturbed Hamiltonian H_0 so that

$$\begin{aligned} H_0 u_1 &= E_1 u_1 \\ H_0 u_2 &= E_2 u_2 \end{aligned}, \quad (10)$$

where E_1 and E_2 are the level energies.

We take the perturbation Hamiltonian as

$$H'(t) = \begin{cases} H' e^{-i\omega t} + (H')^\dagger e^{i\omega t}, & \text{if } t > 0; \\ 0, & \text{if } t < 0. \end{cases} \quad (11)$$

so that $H'(t)$ is hermitian. Since H_0 is hermitian, the total Hamiltonian

$$H(t) = H_0 + H'(t) \quad (12)$$

is hermitian.

By Fermi's Golden Rule, which is valid when $|H'_{fi}|/\hbar \ll \Delta\nu$,

$$W_{21} = \left(\frac{|H'_{12}|}{\hbar} \right)^2 \phi(\nu), \quad (13)$$

where W_{if} is the transition rate from the initial state i to the final state f , and H'_{fi} is the matrix element of the perturbation Hamiltonian connecting i and f states. The relation between W_{21} and W_{12} is

$$W_{12} = \left(\frac{g_2}{g_1} \right) W_{21}. \quad (14)$$

For stimulated emissions

$$\frac{dQ_\nu}{dz} = (N_2 W_{21} - N_1 W_{12}) \hbar \nu, \quad (15)$$

where Q_ν is the energy flux (power per unit area), and

$$\alpha(\nu) = -\frac{dQ_\nu/dz}{Q_\nu}. \quad (16)$$

Therefore we have

$$R = K \left(\frac{|H'_{12}|}{\hbar} \right)^2, \quad (17)$$

where K is a positive (finite) constant for masers. Hence $|H'_{12}|/\hbar \ll \Delta\nu$ implies $R < \Delta\nu$.

Since

$$R = \frac{J}{n}(N_2 B_{21} - N_1 B_{12})$$

if and only if

$$\alpha(\nu) = \left(N_1 \frac{g_2}{g_1} - N_2 \right) \frac{c^2}{8\pi\nu^2 t_{spont}} \phi(\nu),$$

which implies $|H'_{12}|/\hbar \ll \Delta\nu$ (see, e.g., Yariv 1968), which in turn implies $R < \Delta\nu$, we obtain that $R = (J/n)(N_2 B_{21} - N_1 B_{12})$ is not valid when $R \gtrsim \Delta\nu$. Similarly, in the non-degenerate case, $R = (BJ/n)(N_2 - N_1)$ is not valid when $R \gtrsim \Delta\nu$.

Now we set out to derive the expression of R in terms of the Einstein B coefficients for the case when $R > \Delta\nu$.

The case when $R > \Delta\nu$ would occur when the field is sufficient strong and/or when $\Delta\nu$ is small, and in this case $|H'_{12}|/\hbar > \Delta\nu$ (see, e.g., Litvak 1974; Yariv 1968). Hence we may not use Fermi's Golden Rule; higher-order terms may not be neglected and the first-order approximation may not be used. Therefore we will not use the traditional methods to derive the expression of P in terms of the Einstein B coefficients.

In this case, the most general solution which considers n -level systems is complicated. A two-level system is suffice for our purpose. Therefore in

the following we will consider a two-level system as described above with the transition frequency $\nu_{21} = \omega_{21}/2\pi$.

We assume the field frequency ω as

$$\omega \cong \omega_2 - \omega_1 = \frac{E_2 - E_1}{\hbar} \equiv \omega_{21} = 2\pi\nu_{21}, \quad (18)$$

The H' , in equation (11) is the amplitude of the interaction Hamiltonian for the case that an atom interacts with a single radiation mode

$$H' = -eE_{rx}(z, t)x, \quad (19)$$

where, for simplicity, we assume that at the position of the electron the field has an x component only and the position of the atom is z ; r represents the r -th radiation mode. Therefore the ω in equations (11) and (18) will be expressed as ω_r , the angular frequency of the r -th mode.

The electric field E_{rx} can be expressed in terms of the photon creation operator $a_r^\dagger(t)$ and the photon annihilation operator $a_r(t)$ as

$$E_{rx} = -2i\sqrt{\frac{\pi\hbar\omega_r}{V}}\sin(k_r z)(a_r^\dagger - a_r), \quad (20)$$

where V is the volume of the enclosure whose dimensions are very large compared to the transition wavelength (see Appendix A), and k_r the wave number of the r -th mode, so that

$$H' = 2ie\alpha\sqrt{\frac{\pi\hbar w_r}{V}}\sin(k_r z)(a_r^\dagger - a_r). \quad (21)$$

By equation (21), H' is hermitian, that is

$$(H')^\dagger = H'. \quad (22)$$

Therefore, when $t > 0$, $H'(t)$ can be written

$$H'(t) = 2H' \cos(w_r t). \quad (23)$$

In the presence of the perturbation we take the time-dependent eigenfunction as

$$\psi(t) = a_1(t)u_1 e^{-i\omega_1 t} + a_2(t)u_2 e^{-i\omega_2 t}, \quad (24)$$

where $\psi(t)$ satisfies the time-dependent Schrödinger equation

$$[H_0 + H'(t)]\psi(t) = i\hbar \frac{\partial \psi(t)}{\partial t}. \quad (25)$$

Substituting equation (24) into equation (25) and multiplying by u_2^* and integrating, we have

$$i\hbar \dot{a}_2 = H'_{12}^* a_1 e^{-i\Delta t}, \quad (26)$$

where

$$H'_{12} = \langle 1 | H' | 2 \rangle \quad (27)$$

and

$$\Delta = w_r - (w_2 - w_1) = w_r - w_{21}. \quad (28)$$

In deriving equation (26) we assumed that $\langle 1 | H' | 1 \rangle = \langle 2 | H' | 2 \rangle = 0$ and neglected $a_1 \langle 2 | H' | 1 \rangle e^{-i(w_r - w_1)t}$ from the right side since its time averaged contribution to a_2 is negligible.

In the same way we have

$$i\hbar\dot{a}_1 = H'_{12}a_2e^{i\Delta t}. \quad (29)$$

Assume that at $t = 0$ the system is in the upper level,

$$\begin{aligned} a_1(0) &= 0 \\ a_2(0) &= 1, \end{aligned} \quad (30)$$

then the equations (26) and (29) can be solved to yield $a_1(t)$ and $a_2(t)$, and then the transition rate W' , in a straight-forward manner. We get, for intense and highly (or quasi-) monochromatic fields,

$$W' = \frac{4|H'_{12}|^2}{\pi\hbar^2\Omega}, \quad (31)$$

where

$$\Omega = \sqrt{\Delta^2 + (w')^2}, \quad (32a)$$

and

$$(w')^2 = \frac{4|H'_{12}|^2}{\hbar^2}. \quad (32b)$$

We consider a transition from an initial state $|2, n_r\rangle$ in which the atom is in level 2 and the mode r has n_r quanta to a final state $|1, n_r + 1\rangle$ in which the atom is in the lower level 1 while the field has gained a photon. The states are orthonormal. By equation (21),

$$|H'_{12}|^2 = \frac{4e^2\pi\hbar w_r}{V} \sin^2 k_r z |<1, n_r + 1| x a_r^\dagger |2, n_r>|^2. \quad (33)$$

Since

$$<n_r + 1| a_r^\dagger |n_r> = \sqrt{n_r + 1}, \quad (34)$$

and we define

$$X_{12}^2 = |<1|x|2>|^2, \quad (35)$$

then

$$|H'_{12}|^2 = \frac{4\pi e^2 \hbar w_r X_{12}^2}{V} \sin^2(k_r z)(n_r + 1). \quad (36)$$

Substituting equation (36) into equation (31), we have

$$W' = \frac{16e^2 w_r X_{12}^2}{\hbar \Omega V} \sin^2 k_r z (n_r + 1). \quad (37)$$

It follows that the spontaneous transition rate into the single mode r is

$$W'_{spont} = \frac{16e^2 w_r X_{12}^2}{\hbar \Omega V} \sin^2 k_r z, \quad (38)$$

and the rate of induced emission into this mode is

$$W'_{induced} = \left[\frac{16e^2 w_r X_{12}^2}{\hbar \Omega V} \sin^2 k_r z \right] n_r. \quad (39)$$

The total spontaneous transition rate can then be evaluated. We get

$$W_{spont} = \frac{16e^2 X_{12}^2 g_1}{\pi \hbar \epsilon^3} Z, \quad (40)$$

where

$$Z = \left\{ \left[\frac{1}{3} \left(w + \frac{\Delta w}{2} \right)^2 - \frac{2}{15} (a - 2w) \left(w + \frac{\Delta w}{2} \right) + \frac{5}{8} (a - 2w)^2 - \frac{2}{3} w^2 \right] \sqrt{\left(\frac{\Delta w}{2} \right)^2 + a \left(w + \frac{\Delta w}{2} \right)} \right\} \\ - \left\{ \left[\frac{1}{3} \left(w - \frac{\Delta w}{2} \right)^2 - \frac{2}{15} (a - 2w) \left(w - \frac{\Delta w}{2} \right) + \frac{5}{8} (a - 2w)^2 - \frac{2}{3} w^2 \right] \sqrt{\left(\frac{\Delta w}{2} \right)^2 + a \left(w - \frac{\Delta w}{2} \right)} \right\}$$

$$- \left\{ \left[\frac{5}{16}(a-2w)^3 - \frac{3}{4}w^2(a-2w) \right] \ln \frac{2\sqrt{(\frac{\Delta w}{2})^2 + a(w + \frac{\Delta w}{2})} + a + \Delta w}{2\sqrt{(\frac{\Delta w}{2})^2 + a(w - \frac{\Delta w}{2})} + a - \Delta w} \right\}, \quad (41)$$

where w is the frequency of the applied monochromatic field, Δw is the uncertainty in the value of the transition frequency (see, e.g., Loudon 1983), and

$$a = \frac{8\pi e^2 X_{12}^2}{V\hbar} (n_r + 1). \quad (42)$$

Similarly the induced transition rate from level 2 to level 1 due to a traveling (quasi-) monochromatic wave at frequency $\nu = (w/2\pi)$ is

$$(W_{21})_i = \frac{8e^2 X_{12}^2 g_1 n_r \nu g(\nu = \nu_r)}{hV} P \quad (43)$$

where $g(\nu)$ is the normalized line shape function for the transition, and P is

$$\begin{aligned} \nu P = & \sqrt{(\frac{\Delta w}{2})^2 + a(w + \frac{\Delta w}{2})} - \sqrt{(\frac{\Delta w}{2})^2 + a(w - \frac{\Delta w}{2})} \\ & - \frac{a-2w}{2} \ln \frac{2\sqrt{(\frac{\Delta w}{2})^2 + a(w + \frac{\Delta w}{2})} + a + \Delta w}{2\sqrt{(\frac{\Delta w}{2})^2 + a(w - \frac{\Delta w}{2})} + a - \Delta w}. \end{aligned} \quad (44)$$

The energy flux

$$Q_\nu = \frac{cn_r h\nu}{V}, \quad (45)$$

so

$$(W_{21})_i = \frac{8e^2 X_{12}^2 g_1 P}{h^2 c} Q_\nu g(\nu). \quad (46)$$

Since

$$t_{spont}^{-1} = W_{spont}, \quad (47)$$

$$(W_{21})_i = \frac{c^2 \pi P}{2h Z t_{spont}} Q_\nu g(\nu). \quad (48)$$

By defining

$$\bar{P}(\nu) = P(w), \quad \bar{Z}(\nu) = Z(w) \quad (49a)$$

and

$$H(\nu) = \frac{\bar{P}(\nu)}{\bar{Z}(\nu)}, \quad (49b)$$

$(W_{21})_i$ can then be written

$$(W_{21})_i = \frac{c^2 \pi H}{2h t_{spont}} Q_\nu g(\nu). \quad (50)$$

By using equation (50) as well as equations (14), (15), (16), Einstein's relations, and $t_{spont}^{-1} = A$, we get the absorption coefficient,

$$\alpha(\nu) = (N_1 B_{12} - N_2 B_{21}) \pi \nu^3 H g(\nu). \quad (51)$$

Finally, by using equation (8), we get the stimulated emission rate for the case that $R > \Delta\nu$,

$$R = \frac{M}{n} (N_2 B_{21} - N_1 B_{12}), \quad (52)$$

where

$$M = \frac{\pi}{h} \int_0^\infty d\nu \int d\Omega \nu^2 I_\nu H(\nu) g(\nu) \quad (53)$$

(here Ω is the solid angle), and for H_2O molecules, $n = n_{\text{H}_2\text{O}}$.

Comparing with the R in equation (1), where $R < \Delta\nu$, and where

$$J = \int_0^\infty d\nu \int d\Omega \frac{I_\nu}{4\pi} g(\nu), \quad (54)$$

we know that the integrand in equation (54) is changed by a multiplicative quantity, a function of ν , $(4\pi^2/h)\nu^2 H(\nu)$, when the stimulated emission rate exceeds the bandwidth of the maser radiation.

The plot of $H(w)$ near $w \sim w_{21} \sim 1.4 \times 10^{11} \text{ s}^{-1}$ is shown in Figure 6, and an approximate and simplified plot of $\log R$ versus $\log J$ for both $R > \Delta\nu$ and $R < \Delta\nu$ is shown in Figure 7. The description and discussion for these figures is given in Appendix B).

III. CONCLUSION

The principal conclusion of this paper is equation (52) (together with equations (53) and (54)). The stimulated emission rate when $R > \Delta\nu$ is given by this simple expression. This expression will be useful in the construction of models of extremely powerful extragalactic water masers.

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APPENDIX A

Since we consider the plane-wave quantization, the enclosure chosen is one whose dimensions are very large compared to the transition wavelength. For the strongest spot of NGC 4258 (see Wu and Alcock 1988*b*, *c*), $a \sim 2 \times 10^8 / V \text{ s}^{-1}$, where V is the volume of the enclosure [equation (42)]. For the volumes whose dimensions $\gg$ the transition wavelength of H_2O masers, $\lambda = 1.35 \text{ cm}$, taking $V > 2 \times 10^8 \text{ cm}^3$, for example, $a < 1 \text{ s}^{-1}$. For the same spot mentioned above, the upper limit of Δw is $\sim 3.6 \times 10^6 \text{ s}^{-1}$ (see Wu and Alcock 1988*c*). For convenience, we take $\Delta w \sim 10^6 \text{ s}^{-1}$. For $w \sim w_{21} \sim 1.4 \times 10^{11} \text{ s}^{-1}$, therefore

$$w \gg \Delta w \gg a. \quad (A1)$$

Under this condition

$$H(\nu) = P/Z \sim 1/4\pi^2 \nu^3, \quad (A2)$$

which is true for any value of V (or a) as long as the requirement that dimensions $\gg \lambda = 1.35 \text{ cm}$ is fulfilled. Hence the final results of the value of R (as well as H) are practically independent of the value of a or the size (and the shape and nature) of the enclosure assumed (as long as the requirement that the dimensions are very large compared to the transition wavelength of H_2O masers is fulfilled).

APPENDIX B

$H(w)$ is approximately proportional to w^{-3} as shown in the approxi-

mation — equation (A2). H is practically independent of the value of a as long as the requirement that $a < 1$ is fulfilled (see Appendix A). In low intensity (and low density) R increases approximately linearly as J increases, with the assumed approximation that $\Delta N/n$ is constant. When $R \gtrsim \Delta\nu$, R becomes much greater and $\Delta N/n$ drops quickly so that the curve is not approximately linear any more. Remember that, as mentioned above, when $R \gtrsim \Delta\nu$ the physical situation is different from that $R < \Delta\nu$ so that we can not use the traditional methods to derive the expression of R . Hence the expression of R in the case when $R \gtrsim \Delta\nu$ can not imply the R in the case when $R < \Delta\nu$.

TABLE 1

Typical Parameters of Strong Masers

Type	Example(the strongest spot of)	$\Delta\nu$ (s ⁻¹)	R (s ⁻¹)
OH-stellar(1612MHz)	VY Canis Majoris(1)	2.7×10^4	1×10^3
SiO-stellar(43GHz)	VY Canis Majoris(1)	1.0×10^3	2×10^2
H ₂ O-interstellar	W51 MAIN(1)	1.4×10^5	3×10^0
EPEWM	NGC 4258(2)(3)	5.7×10^5	$\gtrsim 2 \times 10^7$

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FIGURE CAPTIONS

Figure 1: (a) Spectra of EPEWM NGC 4258 in a, 1982 November and b, 1983 January (the velocity resolution is $\sim 2.6 \text{ kms}^{-1}$) (Claussen, Heiligman, and Lo 1984); c, 1984 April (the velocity resolution is 1.3 kms^{-1}) (Haschick and Baan 1985); d, 1984 September (the velocity resolution is 0.8 kms^{-1}) (Henkel, *et al.* 1984). (b) Spectra of water maser emission toward NGC 4258 for five epochs. The spectral resolution is 200 kHz. Note that the two spectra on the right have the same scale as the three spectra on the left. (Claussen and Lo 1986). (c) A spectrum of the water maser emission toward NGC 4258 made with an autocorrection spectrometer. The spectral resolution is 20 kHz (Claussen and Lo 1986).

Figure 2: Spectra of EPEWM NGC 3079 in a, 1984 March, April or May (the velocity resolution is 1.3 kms^{-1}) (Haschick and Baan 1985); b, 1984 September (the velocity resolution is 0.4 kms^{-1}) (Henkel, *et al.*, 1984).

Figure 3: Spectra of water maser emission toward the nucleus of NGC 1068 for three different epochs. The spectral resolution is 200 kHz. (Claussen and Lo 1986).

Figure 4: The H_2O profiles observed towards the nucleus of the Circinus galaxy. The velocity resolution is 0.5 kms^{-1} . (Whiteoak and Gardner 1986)

Figure 5: The H_2O profiles observed toward the nucleus of NGC 4945. The

velocity resolution is 0.5 kms^{-1} . (Whiteoak and Gardner 1986)

Figure 6: The plot of $H(w)$ near $w \sim w_{21} \sim 1.4 \times 10^{11} \text{ s}^{-1}$, taking $\Delta w \sim 10^6 \text{ s}^{-1}$ and $a < 1 \text{ s}^{-1}$ (H is practically independent of the value of a as long as the requirement that $a < 1$ is fulfilled; see Appendix A).

Figure 7: An approximate and simplified plot of $\lg R$ versus $\log J$ for both $R > \Delta\nu$ and $R < \Delta\nu$. We take the approximation that $M \sim 4\pi^2\nu^2 JH(\nu = \nu_{21})/h$ and $g_1 = g_2 = 1$ so that $B_{21} = B_{12}$ and $N_2 B_{21} - N_1 B_{12} = B\Delta N$. Furthermore we adopt a simplified and approximate model: when $R < \Delta\nu$, $\Delta N/n$ is approximately constant; when $R \gtrsim \Delta\nu$, $\Delta N/n$ becomes much smaller and decreases as J increases. As in Figure 6, we take $\Delta w \sim 10^6 \text{ s}^{-1}$ and $a < 1 \text{ s}^{-1}$.

Figure 1(a)

Figure 1(b)

Figure 1(c)

Figure 2

Figure 3

Figure 4

Figure 5

H vs. ω Plot

Figure 6
 $H(10^{-34})$

Figure 7

$\text{Log}_{10} R$

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