MASER SOURCES IN H II REGIONS

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Abstract. When OH and H_2O sources are found in H II regions, a compact source of radio continuum and infrared emission is usually, perhaps always, found nearby, $\lesssim 10^{17}$ cm away (approximately the conjectured size of a prestellar condensation). Whether the masers are self-excited, are amplifying the background radiation, or are themselves associated with an exciting star is clearly model-dependent, and observations have not yet given the answer. H_2O masers occur less frequently than OH masers. When they occur together they appear as a cluster of compact sources of line radiation, exhibiting the same range of radial velocities, The OH sources nearly always are strongly polarized, while the H_2O maser is not. Both classes of maser are probably saturated, and some care is needed in inferring the maser geometry from the observations. The period of stability of neither OH nor H_2O can be much more than 10^3 yr, and this fact can be used as an estimator of stellar formation rate.

I. Introduction

The OH and H_2O emission-line sources associated with H II regions exhibit such high surface brightness that it is virtually certain they arise from regions where natural maser processes can occur. This means that the upper levels of the molecular transition have a larger population than the lower states, i.e., the state temperature, T_s, defined by the Boltzmann equilibrium $n_2/n_1 = g_2/g_1 \exp(-h\nu/kT_s)$, must be negative. The stimulated emission rate predominates over the stimulated absorption rate, and amplification rather than absorption occurs. In other words, the emission lines are characterized by a negative optical depth.

The present status of our observational knowledge is in some ways sufficiently detailed to allow one to draw a few conclusions about the nature of the maser sources. Very-long-baseline interferometry (VLBI) has provided quantitative information on the frequency of occurrence, angular sizes and distributions, and association with phenomena observed at other wavelengths. There still are many more questions than answers about their nature, however, and this review will consist mostly of an attempt to formulate these questions. The OH and H_2O masers will be treated in parallel, although it is not clear to what extent the two phenomena are related.

II. What Is the Geometry of the Sources, and Where Do They Occur?

Surveys of dense, highly excited H II regions, where only those H II regions with emission measures greater than 10^6 cm^{-6} pc are considered, have demonstrated that OH maser sources are more common than H_2O sources. Studies of OH masers have shown that about one third of the dense H II regions have associated OH line sources, although the actual probability of occurrence may be somewhat higher if weak lines are searched for. The H_2O masers are less common, and a survey of the literature reveals that the probability of maser occurrence is about 10%.

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The maser sources do not occur independently of other objects in H II regions. Wynn-Williams *et al.* (1972) have shown that there is a high probability of finding an infrared source within a few arcseconds of a line maser, and this probability may be 100%. It is not yet certain whether the coincidence must be exact, and in fact the infrared sources in the Orion nebula seem to lie to one side, although they are probably not separated by more than 10^4 AU, more or less. Furthermore, the maser sources are also associated with compact knots of continuum radio emission, as first shown by Baldwin *et al.* (1973), for the case of W3, and then in great detail for a number of sources by Matthews *et al.* (1973). It has been suggested that the maser sources lie at the outer edges of the continuum condensation, but the generality of this rule is not clear. In the example cited by Baldwin *et al.* (1973), not all of the maser sources of the W3 complex were included, and a substantial number do in fact lie in the interior. A more careful statistical study must be made before the suggestion is acceptable.

Both the OH and H_2O maser complexes in H II regions share the common characteristic of occurring in compact groups. The emission line shape typically exhibits a number of components, each of which comes from a different position. The diameter of the entire group is 20″ for the Orion nebula and 1″ for W49, which corresponds in linear dimensions to 1.3×10^{17} cm and 2×10^{17} cm, respectively, as determined from VLBI work by Moran *et al.* (1973).

The individual apparent sizes are much smaller. In general, the OH masers have larger apparent sizes, and there is a strong suspicion that scattering by the interstellar medium may not be negligible for OH. The H_2O masers have apparent sizes in the range 0″.001 to 0″.003 for M42, while the sizes are of the order of 0″.0002 to 0″.0005 for W49. The apparent diameters, then, correspond to linear dimensions of the order of 1/2 to a few astronomical units.

The apparent source shapes may not be round. Typically, in M42, the fringe visibilities vary with hour angle in a way that suggests lack of circular symmetry, as reported by Moran *et al.* (1973). The effect may be due to a blending of separate features, however, and so the conclusion is not yet certain. It should be emphasized that the *apparent* shape may not be the true shape. Since the maser is basically an amplifier, it is capable of amplifying the plane wave from a distant emitter, and thus one might observe merely the amplified image of a distant radio source. The problem of the excitation of the maser is such an important matter that it must be treated as a separate question later.

The positions of the OH and H_2O masers do not change greatly with time, although the intensity of the H_2O masers varies dramatically with a characteristic time-scale of a few months. The turn-on time may, in fact, be much shorter. Some of the OH sources have been reported to vary slowly in intensity, but the well-studied W3 OH source has been essentially constant over the last four years (Moran, private communication).

The question of velocity variation with time is an interesting one. Although there have been velocity changes reported, the line velocity never has changed by more than a line width, so varying intensity within a blend of several lines cannot be excluded.

The observations provide a useful upper limit, however, that has direct physical significance since change of velocity with time, d*v*/d*t*, is an acceleration. The observations give an upper limit of 0.03 cm s^{-2} for all cases, and for most of the lines the upper limit is 3×10^{-3} cm s^{-2}. From this one may conclude that if each masering object is in the vicinity of a star of one solar mass, it is typically at least 45 AU distant. Thus the masering objects are not likely to be proto-planets in solar systems, although one cannot exclude the possibility that there are pressure forces that balance the effects of gravitation.

III. What Is the Pump Mechanism?

Despite the large amount of theoretical work expended on the problem, it is not easy to draw definite conclusions. The OH and H_2O molecules have very different energy level structures, OH having a set of hyperfine levels in a Λ-doublet spectrum, while the H_2O line arises from a pure rotational transition high above the ground state. It does seem probable, however, that ultraviolet pumping is not very likely, both because of the difficult energy requirement (spending one ultraviolet photon for each radio photon) and because of the dissociation of the molecules in the presence of the ultraviolet radiation unless a strong cutoff between the pumping wavelength and the photo-dissociation wavelength can be devised.

The OH problem is very complex, because of the large number of angular momenta that determine each state. In principle, it is a very rewarding problem because of the large number of observables. All ground-state hyperfine components are in principle observable, and the transitions between the Λ-doublets of the excited states of both the $^2\Pi_{3/2}$ and $^2\Pi_{1/2}$ ladders are observable. Infrared pumping appears to be very promising, especially in view of the observational fact that the masers occur in conjunction with infrared sources.

The H_2O masers present a severe problem, since the energy requirements are heavy. The energy output of 10^{31}–10^{33} erg s^{-1} actually observed requires a large supply of infrared photons. Since we know, observationally, the infrared flux in the vicinity of the sources, it has been shown that there are not enough infrared photons to supply the maser energy. The most promising mechanism appears to be collisional pumping. De Jong's (1973) collisional pumping model requires a molecular hydrogen density of 10^8–10^{10} H cm^3 and a kinetic temperature of 100–1000 K, although he had to use estimated cross-sections that may be very far from the actual value.

It is interesting to note that, for H_2O, in which the transition lies 465 cm^{-1} above the ground state, frequent collisions are absolutely necessary to populate the states, and one has a potentially valuable estimate of the local density and temperature if only one can understand the pump mechanism thoroughly.

IV. Are the Masers Saturated or Unsaturated?

The answer to this question has important implications for the next two questions. By definition, an unsaturated maser is one in which the induced transition rate is small compared to the other rates by which the molecules enter and leave the upper state. This means that the excitation temperature is independent of the radiation field, and the specific intensity will grow exponentially. In a saturated maser, on the other hand, the transition rate from the upper state is determined primarily by the induced radiative transition, and so the rate at which the specific intensity grows is controlled by the pump rate. Thus, the intensity grows linearly.

The observational evidence is not conclusive, but the strongest maser sources, such as W49, W3, and M42, probably are saturated. Each source exhibits 10 or so lines with intensity 5% or greater than that of the strongest line. If the masers are unsaturated, the (negative) optical depths are between 20 and 25, which would require the brightest 10 lines to have optical paths that differ from one another by only 10%. (In a domain of exponential growth, even small path differences become greatly exaggerated.) This does not seem to be a very likely situation, while, on the other hand, if the growth is linear the optical path lengthens greatly, even for the strongest lines. Unless the bright masers form an exceptionally uniform class, therefore, the evidence appears to favor saturated masers, at least for the strong ones.

V. How Are the Masers Excited?

The central point that must be addressed is the relation between the observations and the real physical objects. Following the suggestion of T. Gold that the physical size of the masers might be very different from the apparent size, both Litvak (1973) and Goldreich and Keely (1972) worked out simple models that demonstrated very clearly that this is the case. In this discussion, I shall follow the latter, who treat the development of the radiation field in a homogeneous, spherical, uniformly pumped two-state system. While the model is certainly an idealized one, the important difference between the apparent size and physical size is amply demonstrated.

The observed physical properties, derived from the considerations of the preceding questions, can be summarized in Table I. In all cases, entries refer to *observed* properties, although the luminosity is inferred under the assumption that the radiation is

TABLE I

Observed properties of OH and H_2O masers

Quantity	OH	H_2O
Occurrence in H II regions	1/3	1/10
Time scale	10^8 s	10^6 s
Velocity	$V(\mathrm{H\,II}) \pm 10\ \mathrm{km\ s^{-1}}$	
Line widths	0.5–2 km s^{-1}	
Polarization	Circular	None (or linear in Orion)
Energy	10^{-5}–10^{-3} $L_\odot$	10^{-4}–1 $L_\odot$
Brightness	10^{13} K	10^{15} K
Group size	10^3–10^4 AU	
Acceleration	$< 10^{-2}$ cm s^{-2}	
Apparent size	5–10 AU	0.5–2 AU

effectively isotropic. (For individual lines this may not be so, but since a number of different velocity components are usually observed simultaneously in a given maser, the average power output must be effectively isotropic.)

The maser properties themselves are not directly observed, and are of course model dependent. The Goldreich-Keely model assumes the following are given: a differential pumping rate for the two levels, $\Delta R/R$, a relaxation rate Γ which includes all non-radiation channels, and a molecular density n_x for the molecule under consideration. These quantities will be functions of the total (molecular hydrogen) density, the temperature, and the radiation field, and in general these relations are not well known, although estimates can be made. Goldreich and Keely then solve simultaneously the equations of radiative transfer and of detailed balance, in a dimensionless form where the natural unit is the scale length L required to give a factor e amplification in the unsaturated regime.

Interestingly, the ratio of apparent size to actual size of such a homogeneous maser is given by $(1/\alpha)^{1/4}$, α being the dimensionless quantity $(A/\Gamma)\,(R/\Delta R)$, where A is the Einstein spontaneous radiation probability. A typical set of physical parameters, consistent with the observations, is given in Table II. These masers consist of an unsaturated core, in which all rays are amplified, outside of which there is a transition region and then, for the bulk of the cloud, only the outgoing rays from the unsaturated core are amplified. Thus, most of the maser is saturated, and the induced transitions dominate all other radiation processes. Note that the apparent maser sizes, of the order of 1–10 AU imply physical sizes of about 100 AU, which corresponds very closely to the observed separations between different velocity components. The question of saturation of the masers is evidently a crucial one. Note, however, that the maser size to apparent size ratio is not sensitive to the assumptions about physical conditions because the fourth root of the parameter α is taken.

TABLE II

Typical parameters for maser regions

Quantity	OH	H_2O
L (unsaturated length)	2×10^{13} cm	5×10^{12} cm
T_{ex}	45 K	2500 K
$\alpha = RA/\Delta R\Gamma$	2.5×10^{13}	6×10^{6}
Size	50 AU	200 AU

Goldreich and Keely also considered models with cylindrical geometry. In this case, for a long cylinder, the apparent size is the same as the diameter of the cylinder. For H_2O masers, we see the spots turning on and off, turning on rather suddenly and off more slowly. It does not seem likely that this is caused by the narrow beams of filaments sweeping past us, and it therefore seems likely that the physical shapes of the masers are more nearly spheres than filaments.

VI. What Is the Magnetic Field?

From the observed polarization it should be possible to derive the magnetic field. Unfortunately, this cannot be done uniquely. The Goldreich theory for the observed polarization predicts that one should see the full Zeeman pattern. But since components are observed at a large number of velocities and since one is free to specify both the radial velocity and the Zeeman effect for each line, there are twice as many free parameters as observables. Solutions can be found, but not unique solutions.

One wants to have a sharper test than that, and the H_2O masers do give a sharper test. Goldreich and Keely found that there is a regime where linear polarization can arise. This is where the rate of radiation, r, is less than the gyrofrequency, ω_Z, which in turn is less than the natural line width, $\delta\omega$, i.e., $r < \omega_Z < \delta\omega$. For Orion this predicts a magnetic field $B \sim 10^{-2}$ G, a very high field indeed. For $B > 10^{-3}$ G the field would already separate out the Zeeman components for OH, but complete OH Zeeman patterns are not observed in a convincing way. One should note that Moran *et al.* (1973) have demonstrated that the H_2O masers in Orion are quite separate from the OH masers, and so the magnetic fields may not, in fact, be the same for both.

VII. What Use Are They?

The natural time scale seems to be something on the order of 300 years for an entire complex of these objects. This follows from noting that, for the observed velocities, a group cannot stay together in the sky for more than about 300 to 1000 yr. However, the lifetime of the H II regions is generally believed to be 10^5 to 10^6 yr. Therefore, we are dealing with an object that lives for only about 10^{-3} the lifetime of a given H II region, an observation recently made by de Jong (private communication).

We are seeing a transient phenomenon, but we also see something that is more common than the appearance of an O6 star. The apparent rate of about 1000 of these masers in the lifetime of one of these density-limited H II regions is more appropriate to the entire formation rate of all O and B stars. Therefore, in addition to the obvious interest in understanding the physics of these peculiar masering regions, it seems very likely that by surveying the Galaxy for all its OH and H_2O masers we may hope to locate all the new B stars in the Galaxy.

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DISCUSSION

Kaufmann: The physical parameters you assume for H_2O masers, such as molecular densities and pump rates, are they convenient because they provide adequate solutions to Goldreich equations, or because there are some other evidence or thoughts on physical conditions at the sources?

Burke: There is a wide range of acceptable values for the various parameters.

Van Woerden: What is the evidence that masers are related to the formation of O- and B-type stars only, and not to that of less massive stars?

Habing: I think one good reason to assume that OH masers are associated with early-type stars is that a sizeable fraction of the Class I OH masers (possibly up to 100%, but most likely more than 30%) is associated with H II regions, as Winnberg, Goss, Mathews and I discovered recently at Westerbork.

Townes: There is a variety of arguments which lead to the conclusion that many of the interstellar masers are probably saturated. The lack of weaker masers in a given field is not to me a very convincing one, since not many careful searches and statistical studies of weaker lines have been carried out.

An important feature which must be considered is dust; in fact, its presence seems to be required for some masers in order to allow any reasonable pumping scheme to function. Furthermore, the dust may be quite important in producing feedback and scattering which affects both saturation and polarization.

Burke: There are several strong maser sources with a large number of strong lines whose intensities are comparable.

Robinson: In type I OH masers, satellite line emission or absorption is commonly observed only an order of magnitude in intensity below the main line emission. Given the lower transition probabilities for the satellite lines, I take this as supporting evidence for saturated maser emission. For unsaturated maser emission we would, on the average, expect intensity ratios of 1665 MHz to satellite line emission of exp (20)/exp(4) for comparable degrees of inversion.