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INTERSTELLAR MASERS

INTRODUCTION: Why Interstellar Maser Action is not Surprising

The maser action we shall be talking about is that which amplifies spectral line radiation rather than continuum radiation. Such masers are well-known in the laboratory but until fairly recently their existence in the interstellar medium was considered very surprising.

Maser amplification occurs whenever the upper level of an atomic or molecular transition contains more population than the lower level. Then, the stimulated emission rate exceeds hhe absorption rate. (Stimulated emission occurs when an incident photon whose frequency is that of the transition in question interacts with a molecule in an excited (upper) state, causing it to decay to the lower state and emit a photon of the same frequency. This second photon is always emitted in exactly the same direction as the incident photon, thereby adding to the intensity of the incident beam of photons).

In LTE (local thermodynamic equilibrium) the lower level always has more population than the upper one. In fact, by Boltzmann's law, the ratio of populations in the upper (u) and lower (ℓ) levels is

$$\frac{n_u}{n_\ell} = \frac{g_u}{g_\ell} e^{-h\nu/kT_s}$$

where T_s is called the excitation temperature of the transition. In LTE, T_s is a positive number which is the same for all energy levels in the molecule. Under the anomalous excitation which apparently applies to many of the observed molecules in the interstellar medium, T_s may differ for each transition. For those transitions actually undergoing masering, T_s will be a negative quantity.

Before considering how such excitation may occur, we state that under the very low density conditions that apply in the interstellar medium, it is not surprising that the Boltzmann (LTE) population distribution is often not realized. This is because the collision rate of the molecules is very low compared with radiative rates, and it is the collisions that try to establish equilibrium populations. Radiative interactions, on the other hand, can produce completely anomalous population distributions because the radiation fields, especially around the molecular clouds themselves, are not those of a blackbody.

Furthermore, only a very small deviation of the populations from the Boltzmann distribution is needed to cause masering, especially if the frequency ν of the transition is small. This can be seen as follows. Spitzer (Diffuse Matter in Space, p. 16) gives an expression for the integrated atomic absorption cross section as

$$\sigma_{\ell u} = \sigma_u \left(1 - \frac{b_u}{b_\ell} e^{-h\nu/kT}\right) = \frac{h\nu B_{\ell u}}{c}\left(1 - \frac{b_u}{b_\ell} e^{-h\nu/kT}\right) = \frac{h\nu B_{\ell u}}{c}\frac{h\nu}{kT}\left\{\frac{b_u}{b_\ell} + \frac{kT}{h\nu}\left(1 - \frac{b_u}{b_\ell}\right)\right\}$$

in which a simple two-level transition $\ell \to u$ is considered, and where $\sigma_{\ell u}$ is related to the optical depth τ_ν by $\int_\nu \tau_\nu \, d\nu = N_\ell \sigma_{\ell u} \ell$. Again, under normal excitation, τ_ν is positive and leads to an absorption of radiation at the line frequency. Under masering, τ_ν is negative and then becomes the amplification factor. The point here is the "correction" term which has to be applied in $\sigma_{\ell u}$ to take account of non-LTE excitation. b_u is defined as the ratio of the actual population in level u to the population when LTE applies, i.e. when the excitation temperature equals the kinetic temperature. Similarly for b_ℓ. If $b_u/b_\ell \cong 1$, $\sigma_{\ell u}$ is reduced below σ_u, the value when stimulated emission is negligible, by a factor $h\nu/kT \sim 10^{-4}$ for transitions in the radio spectrum. But when $(b_u - b_\ell)/b_u$ exceeds $h\nu/kT$, the absorption coefficient becomes negative and we get maser amplification. We see that this is particularly easy to achieve when $h\nu \ll kT$.

For example, for the 21 cm line $kT/h\nu \approx 1500$ for $T = 100°K$. Then if the level u is overpopulated by only 1 part in 1000, i.e. $(b_u - b_\ell)/b_u \gtrsim 0.001$, we get $\{\ \}$ $\lesssim -0.5$, leading to maser action.

Energy level populations are controlled by collisions and by radiation fields. Normally, collisions simply cause a mixing of the level populations weighted by $\exp(-h\nu/kT)$ and hence serve to establish LTE. (Some special types of collisions that we will mention later may favor some levels over others, and could establish population inversions). Radiation fields may, if they have spectra radically different from black-body spectra, also cause population inversions or anti-inversions. If we just assume a blackbody spectrum and "normal" collisions, then it turns out that

$$\frac{b_u}{b_\ell} = \frac{r_{col}/A_{u\ell} + W e^{h\nu/kT}/(e^{h\nu/kT}-1)}{1 + r_{col}/A_{u\ell} + W/(e^{h\nu/kT}-1)}$$

where r_{col} is the collision rate, $A_{u\ell}$ the (Einstein A) spontaneous emission rate, and W is the dilution factor of the blackbody radiation field. Note that if $W = 1$ (no dilution) then we have $b_u/b_\ell = 1$, hence the populations follow a Boltzmann law.

Actually, in the interstellar medium, visible radiation acts like a 10,000°K blackbody diluted by a factor W of $\sim 10^{-15}$. Then the terms in W can usually be neglected, giving

$$\frac{b_u}{b_\ell} \approx \frac{1}{1 + A_{u\ell}/r_{col}}$$

Thus the populations will be close to LTE if $r_{col} \gg A_{u\ell}$ and very far from LTE if $r_{col} \ll A_u$. For optical transitions $A_{u\ell}$ is typically 10^8 sec^{-1} while $r_{col} \simeq 10^{-6}n$, n being the number density of colliding atoms. Since n is 10^3 cm^{-3} at most, we see that b_u/b_ℓ is very small: the upper levels of optical transitions are almost completely unpopulated. Among radio lines, the 21 cm line has $A_{u\ell} \sim 10^{-15}$ sec^{-1} and for (dominant) H-H collisions and small W leads to a correction factor of $1 + (37n_H)^{-1}$. This factor is ~ 1 for large n_H but can lead to significant departures in the absorption coefficient from LTE values if n_H is as small as 0.1, as it is between spiral arms. For the stronger OH lines, $A_{u\ell}$ is about 10^4 times larger and if r_{col} is about the same as for the 21 cm line, the correction factor becomes proportional to 1/W. Thus, on this ideal model, the OH absorption coefficient would be inversely proportional to the mean radiation temperature, T_R, rather than to the kinetic temperature, T.

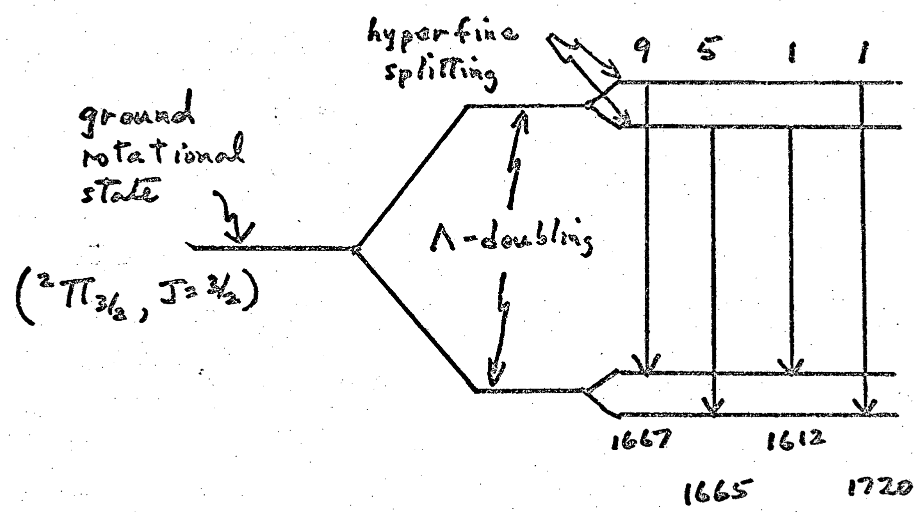
II. Interstellar OH and H_2O Masers: Observational

At the present time, 7 molecules have been detected in the interstellar medium at radio wavelengths: OH, H_2O, NH_3, H_2CO, CO, CN, and HCN. Of these, OH and H_2O display spectacular emission properties attributed to masering. H_2CO has equally anomalous excitation; the three transitions presently observed have anti-inverted population distributions, resulting in anomalously strong absorption against even the 3°K background. NH_3 is observed weakly in emission in only the Galactic Centre region, and its excitation also appears somewhat abnormal in the sense that the excitation temperatures for the inversion transitions increase with increasing rotational excitation. There is at present no evidence that CO, DN, or HCN are anomalously excited. It appears likely that collisions dominate radiative rates ($A_{u\ell}$) for these latter molecules.

OH MASERS

OH masers were discovered in 1965 in the direction of several HII regions in the Galaxy (W3, W49, W51, W75, NGC6334, SagB2, and several others). In its ground or lowest energy state, OH emits 4 characteristic lines as shown in the Figure (in MHx).

In LTE and at small optical depths, the 4 lines have relative strengths shown at the top. The 1667 and 1665 lines are referred to as "main" lines while the two weak lines are referred to as "satellite lines".



In the very first sources in which OH maser action was found, it was at once obvious that this was the only ready explanation. The properties dictating this choice were

a) the 1665 line is the most intense; none of the lines has anything like the relative strength characteristic of LTE.

b) the emission is very strong. Single dish observations were early able to establish brightness temperatures $\gtrsim$ 5000°K, too high a value to correspond to any kinetic temperature without destroying the OH.

c) the emission is polarized. The first observations established up to 90% linear polarization, a value exceeding the possible value produced by resonant scattering. Later, in 1966, the emission was also found to be circularly polarized, in patterns which cannot be explained by the Zeeman effect.

d) the linewidths of the emission features were very narrow, $\lesssim$ 2 kHz, which correspond under Doppler broadening to kinetic temperatures $\lesssim$ 50°K and in some cases

$\lesssim 8°K$. Such low temperatures are incompatible with the energy needed for the powerful emission, so that line narrowing must occur some other way, such as by maser amplification.

e) the emission intensity of some sources varies rapidly with time. This can most easily occur if small fluctuations occur in the gain of a amplifying system. Otherwise the rate of time variations imposes limits on the dimensions of the source sufficiently small that the large intensities observed would be impossible under normal emission.

Later on (1966-1968) other types of anomalous OH sources were found, in which the strongest emission occurred in either the 1612 or 1720 MHz line. The same very high brightness temperatures, and completely peculiar line ratios are found in these cases also. However the linewidths are somewhat wider ($\sim$10 to 15 kHz) and the lines are often not highly polarized, although some are.

As a larger number of OH emission sources has been discovered, one begins to see a pattern in the particular types of anomalies which occur among the various parameters describing the emission. We have defined three classes of OH emission. Table I summarizes the properties of the 3 classes, as apply to the 4 ground state lines.

Table I

Property	Class I	Class II(a)	Class II(b)
strongest emission line	1665 (1667 sometimes)	1720	1612
other emission lines	both satellites	none	main lines
absorption lines	none	1667, 1665, 1612	1720
polarization of strongest line	circular (sometimes linear)	$\sim$none	$\sim$none
polarization of other lines	circular (sometimes linear)	-	circular
physical association	H II regions	supernova remnants (a few H II regions)	IR stars
velocities	agree with H109α	not associated with continuum	bifurcated*
relation between lines	unrelated	all 4 have same velocity	main lines cover larger velocity range than 1612
emission linewidths	$\lesssim$ 2 kHz†	$\lesssim$ 15 kHz	$\lesssim$ 15 kHz††
examples	W3, W49, NGC 6334	W28, W44	NML Cyg, VYCMa

Significantly, this difference by class seems to be reflected in the difference in the origin of the emission. Most emission sources associated with H II regions are Class I, all emission sources associated with IR stars are Class II(b); and most sources associated (in projection at least) with non-thermal sources are Class II(a).

As a measure of the generality of this classification scheme, we note that the properties listed in Table I apply to all 39 well-studied OH sources with minor exceptions in three cases (in one of these cases, NGC 7538, the properties are Class I except that 1720 MHz emission is as strong as 1665 MHz emission; in the other two cases, which are Southern Hemisphere sources, properties are Class II(b) except that the 1612 MHz emission is significantly circularly polarized). Preliminary studies of 22 new OH emission sources (Turner 1970a) have uncovered no further discrepancies.

In addition to the strange line ratios and peculiar polarization, it is well-known that the third outstanding property of the OH emission sources is their high brightness temperatures (T_B). VLB measurements have established sizes of typically 10^{14} cm, corresponding to T_B as high as 10^{13} °K for the Class I emitters. More recently, similar techniques have led to values of $T_B \gtrsim 2 \times 10^{10}$ °K for two Class II(b) sources, NML Cyg and VYCMa. As in the class I sources, these latter sources show a large number of small emission centres within a region of size $\sim$2 arc sec. As yet, no definitive VLB results exist for Class II(a) sources, but we may anticipate that they have values of T_B within the range 10^{10} to 10^{13} °K, based on the received fluxes and estimated distances to these sources.

H_2O MASERS

The H_2O molecule has a somewhat more complicated energy level scheme than OH (see Figure 3). Maser emission has been detected in the interstellar medium from only one transition, the 6_{16} 5_{23} transition at 22235 MHz. It is not unlikely that several other transitions will also be found to maser at microwave frequencies, but they lie in presently inaccessible regions of the spectrum. The frequencies corresponding to the transitions between the different levels of a given J correspond to the near-infrared portion of the spectrum. They are often seen to show maser action in the laboratory under flash-photolysis excitation of water, but are not observable at present astronomically. Some facts relevant to choosing a theory are as follows.

Strong H_2O masering has at this time been observed in a total of 14 interstellar sources, 9 associated with H II regions and Class I OH emitters, and 5 with IR stars of which 3 are Class II(b) OH sources and the other two do not show OH. Among the Class I OH sources, the strongest usually correspond to the strongest H_2O emission. However both the radiated flux and the number of photons/sec generated by the sources are much greater for the H_2O masers than for the OH masers, by typically 100 times. W49 generates 6×10^{48} photons/sec in the H_2O line if the emission is isotropic. Since one microwave photon is generated per pumping event, it is very unlikely that radiative pumping can apply; for example the total IR emission from an M5 giant corresponds to a factor 10^5 less photons/sec than is generated by the H_2O in W49.

Observed linewidths are typically $\sim$40 kHz, corresponding to $T_K \simeq 120°K$ under pure Doppler broadening with no line narrowing. Such a temperature is entirely inadequate for the excitation of the masering 6_{16}-5_{23} transition which lies 477 cm^{-1} above ground. From a deduced total gain $\alpha\ell_o = 27.7$ (see below), the lines would be narrowed by a factor of 6.3 in W49 if the amplification is unsaturated. Then T_K can be as high as 4500 °K while producing the observed linewidths; such a temperature can also produce adequate rates of production of OH from H_2O according to the Gwinn et al. theory. Another indication that the H_2O masers are probably unsaturated is the rapid and large time variations observed in the emission, which have a time scale as short as a few days in some cases and produce a threefold or more change in intensity of some features. For an unsaturated maser of total gain $\alpha\ell_o = 27.7$, a 1% change in $\alpha\ell_o$ produces a 27.7% change in the output brightness T_B, while for a saturated maser T_B would only change by 1%.

Recent VLB measurements (Burke et al. 1970) reveal angular sizes of less than 0.003 arc sec for several features in W49, Ori A, W3 (OH), and VYCMa. The corresponding linear sizes are less than 1.5 A.U. in Ori A and 40 A.U. in W49. In W49, T_B exceeds 10^{13} °K, which means that the microwave interaction rate $W_m \sim 2 \times 10^4$ sec^{-1} for $\Omega = 4\pi$. Now in order that an anomalous population, rather than a Boltzmann distribution, can be set up between adjacent rotational levels connected by far IR transitions, the IR spontaneous rate W_{IR} must exceed the collision rate W_c. Since in H_2O, $W_{IR} \sim 1$ sec^{-1} for the relevant levels, we have that $W_c << W_m$. This also means that the pump rate $W_p << W_m$ so that the maser would seem to be saturated if a steady state applies, contrary to the above-mentioned requirements on the linewidths and kinetic temperatures. The dilemma is resolved by assuming that some storage mechanism operates to store up the pumping action to a critical point at which a burst of unsaturated amplification occurs with corresponding sharp time variations and narrow linewidths. One such storage process, involving trapped IR, is discussed below.

The H_2O emission is seen to be slightly linearly polarized (as high as 30% for one feature in Ori A but much less in all other cases). Circular polarization has never been detected. Linear polarization can occur through resonant scattering; for example if IR photons pump the J=5 level to the 6_{16} level which then decays by microwave emission to the 5_{23} level, the linear polarization can be as much as 30%, when the microwave radiation is perpendicular to the IR radiation, which would need to be highly directed. In a more realistic case the degree of polarization can be produced by saturation effects, but would occur only for $\Delta F = \pm 1$ transitions, not $\Delta F = 0$. Within the 6_{16}-5_{23} transition occur hyperfine transitions with both $\Delta F = \pm 1$ and $\Delta F = 0$, and these transitions are virtually unresolved in the data since the inherent linewidths exceed the frequency separation. Clearly the blended emission could be linearly polarized by this mechanism, especially since the three $\Delta F = \pm 1$ transitions have much larger (LTE) line strengths than the two $\Delta F = 0$ transitions. If a storage mechanism for the pump is operating, then during the depletion period after a burst of unsaturated microwave emission, the amplifier will momentarily saturate during which the radiation could become linearly polarized; if this polarized field can be partly preserved during the ensuing pumping period, it will be amplified in the next burst, and so on. However because of the requirements on linewidths and kinetic temperatures, it seems more likely that the amplification is unsaturated, and that the observed linear polarization arises from the amplification of a very small degree of linear polarization arising from a non-spherical geometry and resonant scattering.

THE CONCEPT OF AN INTERSTELLAR MASER

The high brightness temperature T_B, anomalous line ratios, and high degree of polarization preclude any thermal explanation of OH and H_2O interstellar emission. On a thermal basis the observed linewidths are also much narrower than is consistent with the observed values of T_B. It is now accepted that the populations of the energy levels are inverted and that maser amplification is occurring, either of background radiation or of spontaneous emission from the OH itself.

For most purposes it is adequate to neglect time-dependence in the equation of radiative transfer, which in the one-dimensional case is then

$$\frac{dI}{dx} = \frac{\alpha I}{c + bI} + \varepsilon \tag{1}$$

where α is the gain factor (negative absorption coefficient) for small stimulated rate and collision rate, $\alpha/(c+bI)$ is the (reduced) gain factor when these rates are not negligible, I is the specific intensity, $c = 1 + 2\, S_c/S_p$ with S_c the collision rate (per sec per molecule) which tries to thermalize the molecules, and S_p the pump rate producing the population inversion. $b = (2B/S_p)(\Omega/4\pi)$ with B the Einstein coefficient for stimulated emission and Ω the solid angle of the maser beam. $\varepsilon = n_u\, Ah\nu/4\pi\delta\nu$ is the usual emissivity. If we neglect the dependence of ε on I (through n_u) the solution at a given frequency is

$$I_x = \left(\frac{c\varepsilon}{\alpha+\varepsilon b} + I_o\right)\left\{\exp\left[\frac{(\alpha+\varepsilon b)x - b(I-I_O)}{c - c\varepsilon b/(\alpha+\varepsilon b)}\right] - 1\right\} + I_o$$

As a function of x, $I - I_o$ grows exponentially for small x, then decreases its rate of growth for larger x until in the limit of large x the growth is linearly dependent on x. The larger is b, the smaller is x at which the exponential growth goes over to linear growth, hence the smaller is $I - I_o$ at any given x.

It has been customary to limit theoretical discussion to the two limiting cases of unsaturated and saturated maser amplification. In the unsaturated case, $c >> bI$, and the solution of (1) is simply

$$I_x = I_o e^{\alpha x/c} + \frac{\varepsilon c}{\alpha} (e^{\alpha x/c} - 1) \qquad (2)$$

where the first term is the amplified background and the second term the amplified spontaneous emission. The gain factor $\alpha = \lambda^2 A \Delta n / 8\pi\delta\nu$ where $\Delta n = (n_u - \frac{g_u}{g_\ell} n_\ell)$ with n_u and n_ℓ referring to the population densities of the upper and lower levels of the transition in question, and A is the Einstein spontaneous emission coefficient. Very large values of $T_B = \lambda^2 I_x / 2k$ may result when αx is large. Relatively small differences in α for the various transitions result in large corresponding differences in I_x. A narrowing of the lines, by the factor $(\alpha x/\ln 2)^{1/2}$, is also accomplished by the exponential scaling of the frequency dependence of α. In current theories (see Litvak (1970) for a summary) the anomalous polarization does not arise under conditions of unsaturated growth, but requires at least the onset of saturation.

In the fully saturated limit ($bI >> c$) the solution is

$$I_x = I_o + (\Delta n\, S_p\, h\nu/\Omega\delta\nu + \varepsilon)\, x$$

where for simplicity we again take all quantities in parentheses as independent of path length x. Here, Δn is the population difference calculated under unsaturated conditions, and we assume that the saturation is homogeneous over the linewidth. Large values of T_B may still occur, but require much larger values of $\Delta n\, x$ than in the unsaturated case. No line narrowing occurs for a fully saturated maser; the narrow widths emerging from the unsaturated portion of a maser are broadened during the saturated part until they become equal in width to the unamplified lines. It is possible that the observed properties of narrow linewidths and high degree of polarization can occur in a maser which is only partially saturated, enough to produce the polarization if it indeed arises from the non linear suppression of one polarization mode by another, as current theories indicate, but not enough to overcome appreciably the line narrowing properties of the unsaturated growth. One difficulty with this picture is that, if a maser is even partially saturated at the end we actually observe, as is expected from the very large values of bI that correspond to observed values of T_B, then it must be at least partially saturated over the entire path length, assuming that a maser beam can propagate equally well in one direction as in the other. This situation is not altered by the fact that orthogonal polarization modes may be travelling in the opposite directions. Therefore if saturation is required to produce strong polarization, it is difficult to understand the very narrow observed linewidths, which correspond in Class I emitters to kinetic temperatures of typically 25 to 40 °K and as low as 7 °K.

Another difficult question is whether background radiation or spontaneous emission controls the number and direction of modes that are amplified. The answer depends among other things on the initial conditions in the maser. In a case in which the population inversion was established throughout a cloud in a time shorter than the light travel time through the cloud, the following possibilities occur. For large enough density and path length there will be an interior region in the cloud within which, after the onset of masering, the radiation fields built up by amplified spontaneous emission will be strong enough to cause saturation before the amplified background has penetrated this far. These modes, which are isotropically distributed, will tend to persist under saturated conditions, rather than be overridden by the background modes. Hence the maser output will be into a large solid angle if it is not restricted by turbulence to narrow, filamentary paths. Such filaments would be expected to be continually varying, and hence appear somewhat unlikely for the OH case, in which few instances of time varying emission are observed. On the other hand, if the initial population inversions are established slowly and in a not-too-dense cloud, saturation might be induced by the background source modes if the source is sufficiently strong, rather than by spontaneous emission modes, which would then be suppressed. The maser output in this case could be quite directional. In either case the background radiation will not compete with spontaneous emission unless $T_o \Omega_o / 4\pi \gtrsim h\nu n_u / k\Delta n \sim 0.1$ to 1 for typical OH pumping models. This criterion probably would be satisfied only for continuum sources near a masering cloud which subtend a fairly large angle Ω_o at the OH cloud. Thus the background sources would not impose a high degree of directionality on the maser output, as would also be the case for amplification of the 3°K background.

PUMPING OR EXCITATION THEORIES FOR INTERSTELLAR MOLECULES

In trying to explain the maser emission that comes from OH and H_2O, and the anomalous absorption from formaldehyde (H_2CO), it has been found that every molecule must be treated as an individual case, and that in the case of OH, even the different classes of emission are almost certainly caused by different pumping mechanisms. Since the (quantum mechanical) details of each molecule are involved, it makes constructing a theory fairly involved. We shall summarize only briefly the types of mechanisms presently thought to produce the various types of emission.

OH EMISSION: CLASS II(a) AND II(b)

Both of these types of anomalies are believed produced by infrared radiation fields which interact with several of the IR transitions in the OH molecules as they penetrate a cloud. If the IR is incident on the cloud from outside, certain spectral lines in the far-IR (120μ and 79μ particularly) get absorbed preferentially by the surface layers of the cloud, leaving a residual field which deviates increasingly from a black body field as it penetrates further into the cloud. This latter field can then anomalously excite the molecules lying further inside, in a way which inverts the 1720 MHz transition, anti-inverts the 1612 MHz line, and leaves the two main lines pretty much normal. Thus we get a 1720 MHz maser, normal main lines (in absorption or emission) and an anomalously strong absorption at 1612 MHz if there is a background source. This is exactly what is seen in Class II(a) sources.

For class II(b), a near-IR field is needed to interact with the v = 0-1 vibrational transition of OH at 2.8μ. Such a field again assumes a non-blackbody spectrum as it penetrates an OH cloud, either from the outside, or as it excapes from an internally generated region such as a shock front. This process inverts the 1612 line under a wide range of physical conditions and anti-inverts the 1720 line. It inverts the main lines only if the temperature is high ($\gtrsim$1500°K). This latter condition suits it to the conditions found in the atmospheres of the IR stars in which this type of emission is found. These stars also produce the large near-IR fluxes needed.

OH EMISSION: CLASS I

It is presently thought that when OH is formed by the collisional dissociation of H_2O according to

$$H_2O + H + 4.5 \text{ eV} \rightarrow OH^* + 2H$$

that the OH comes off in certain excited states. This comes about because the electron orbitals of the O atom in the OH fragment remain correlated, during a fast collision, with the orbitals of the O atom in H_2O. These aligned orbitals in turn are oriented in a definite way with the rotational axis of the OH fragment, which is always perpendicular to the H-O-H plane. All of this means, in short, is that the upper state of the Λ doublet is populated for most of the J levels including the ground state. This in turn leads to an overpopulation of all 4 ground state lines, but particularly the main lines.

Surprising as it may seem, this is the only theory among several which have been tried (UV pumping, electron collisional pumping, etc.) which succeeds in producing the 1665 line as the strongest. It also suggests that Class I OH emitters will be found where H_2O also exists, and this is what is observed. But how is the H_2O itself excited into maser action?

H_2O EXCITATION

Because only one masering transition is known for interstellar H_2O, it is harder to choose a theory unambiguously. We are therefore tempted most by the simplest possible theories. One of these requires only that we populate the various energy levels above the 6_{16} and 5_{23} levels, by any method at all, such as normal collisions. Assume only that the collision rate does not exceed the rate of decay from these levels by spontaneous IR emission. Then as the arrows in the Figure indicate, the decaying levels tend to pile up in the bottom levels of each vertical ladder, since these can decay only along the diagonal edge. The 6_{16} level is one of these. Levels like the 5_{23} however can decay in several directions and hence are less populated. Thus the $6_{16} \rightarrow 5_{23}$ transition is inverted, and can show maser action.

H_2CO DASARS

(DASAR $\equiv$ Dark Amplification by Stimulated Absorption of Radiation). As we mentioned, various pairs of levels in the H_2CO molecule are anti-inverted. The levels have given anomalously strong absorption in the 6,2,and 1 cm lines so far observed. Even the 3°K background gives an absorption line when there is no background source at all. This means that the excitation temperature T_s (see p.1) is $<$ 3°K, or the level is "refrigerated".

It has been found that such anti-inversion can be produced in H_2CO when H atoms collide with the molecules under conditions where the collision rates are less than the IR decay rates of these levels. The process is similar to the one mentioned for the Class I OH masers; the electron orbitals in the H_2CO are oriented only in certain ways relative to the rotation axis. The relative orientation in this case has the opposite effect to the OH case, however, and anti-inverts the doublets.

It should be pointed out that only a few types of molecules are thus affected by collisions. They must have splitting in the rotational levels caused by Λ-doubling in the case of diatomics like OH, or by so-called "asymmetric splitting" in the case of multi-atomics like H_2CO. The former requires that the molecules have Π electronic ground states, a criterion which the majority of diatomics do <u>not</u> satisfy. Some that do are SH,SiH,CH, and NO to mention some with astrophysically common atoms. However at least SH and NO have embarrassingly low ionization potentials and may not exist with enough abundance in the interstellar medium to be detected unless very anomalously excited. The "asymmetric" splitting in multiatomics is more common, and arisses because the molecules are not symmetric tops, which means that the electronic and rotational motions are coupled. Thus if the special collisions (with rates $<$ IR decay rates in each case) work in general as predicted for H_2CO, several of these multiatomic molecules might show anomalous excitation. The only problem is that the lowest rotational levels are <u>not</u> split in this way, only the higher ones. One must then look for molecules where the lowest of the split levels is not too far above the ground state, in order for the levels to be significantly populated.