THE ASTROPHYSICAL JOURNAL, **203**:124–131, 1976 January 1

INVERSION OF THE OH 1720-MHz LINE

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Received 1975 March 12; revised 1975 May 14

ABSTRACT

It is shown that the OH 1720-MHz line can be strongly inverted by collisions which excite the rotation states, preferentially the $^2\pi_{3/2}$ ladder. It is also argued that radiative pumps (of any wavelength) can strongly invert only the 1612-MHz line. Inversion of the 1720-MHz line with $|\tau| \lesssim 1$ can be achieved by either collisional or radiative pumps at low OH densities ($n_{OH} \lesssim 10^{-3}$–10^{-4} cm^{-3}).

Subject headings: interstellar: molecules — masers — molecular processes

I. INTRODUCTION

Emission from the ground state of the OH molecule has been a puzzle ever since it was first detected. The observed line intensities indicate that the level populations are almost never in thermal equilibrium and that inversion is quite a common occurrence. Despite some theoretical effort, especially by Litvak (summarized by Litvak 1974), a general classification scheme for the conditions that lead to different inversions has not yet emerged. It is not clear as yet why and how different pumps invert certain lines.

An attempt toward such an understanding was made recently when a model for the 1612-MHz maser emission from IR/OH stars was constructed (Elitzur *et al.* 1974; hereafter called Paper I). Inversion of the maser emitting levels is achieved in this model by pumping with far-infrared photons. The analysis of the pump mechanism (which relies heavily on photon trapping effects) suggests that the 1612 line is usually inverted in the case of pumps that excite the $^2\pi_{1/2}$ ladder. Inversion of the 1720 line requires a preferential excitation of the $^2\pi_{3/2}$ ladder.

The purpose of the present paper is to try to develop further these ideas for *satellite* line inversions. (Main line inversions are somewhat more complicated and will be discussed elsewhere.) Various pumping mechanisms were checked extensively, and the conclusion is that the only efficient mechanism to preferentially excite the $^2\pi_{3/2}$ ladder and strongly invert the 1720 line is collisions (with H_2 molecules) at temperatures above 25 K. The collision rates that give the most efficient pumps are 10^{-7}–10^{-5} s^{-1} (corresponding to H_2 densities of 10^3–10^5 cm^{-3}). It was found that collisions can also strongly invert the 1612-MHz line. The temperatures and (OH and H_2) densities required for this are higher than for the 1720 line inversion. It was also found that radiative (infrared and ultraviolet) pumps can strongly invert only the 1612 line. In the case of weak 1720-MHz inversions (with $|\tau| < 1$) the situation is somewhat more involved. Such inversions can be achieved at low OH densities ($n_{OH} \lesssim 10^{-3}$–10^{-4} cm^3) by either radiative or collisional pumps.

It is therefore suggested that the only pumping mechanism that can produce *strong* ($-\tau > 1$) 1720-MHz line inversions is collisions.

Some general considerations with regard to satellite line pumps are given in § II, where a description of the calculations is also given. The results of the numerical calculations are presented in detail in § III. Applications to different astrophysical objects are made in § IV, which also contains a summary of the results.

II. THE PUMP MODEL

a) *General Remarks*

We are looking for a pump mechanism that can produce a sizable and systematic inversion of the OH 1720-MHz line over a certain range of the relevant physical parameters. In particular, we are looking for gains which can be larger than unity. The pump should therefore operate also in the region where rotational transitions to the ground state are optically thick, since they have B-coefficients similar to those for hyperfine radio transitions. A detailed discussion of OH satellite line inversion under such circumstances was already given in Paper I. The main ingredients which go into the analysis are:

1. Most of the molecules are in the ground state.
2. The populations of different sublevels of any level are nearly equal to each other.
3. Downward transitions are due to radiative decays.
4. The rate of depopulation of a level i by radiative transitions to level j when the i–j line is optically thick is proportional to

$$W_{ij} = A_{ij}/\tau_{ij}\,, \tag{1}$$

where A_{ij} is Einstein coefficient and τ_{ij} the line optical depth. The rate is thus independent of the transition dipole moment, due to photon trapping.

Inversion is achieved in the following way: molecules are pumped in some way from the ground state ($^2\pi_{3/2}[J=3/2]$; see Fig. 1) into higher levels. When the cascade down is completed via $^2\pi_{3/2}(J=5/2) \rightarrow {}^2\pi_{3/2}(J=3/2)$, the $F = 2$ levels of the ground state overpopulate and the 1720 line is inverted. This happens because the $F = 2$ levels are connected to both $F = 2$ and $F = 3$ levels of $^2\pi_{3/2}(J = 5/2)$, whereas $F = 1$ levels connect only to $F = 2$ (due to the dipole selection rules). On the other hand, when the cascade is completed by $^2\pi_{1/2}(J = 1/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$, the $F = 1$ levels overpopulate (and the 1612 line is inverted), since they couple to both $F = 0$ and $F = 1$ of $^2\pi_{1/2}(J = 1/2)$, whereas the $F = 2$ levels couple only to $F = 1$.

It is easier to invert the 1612 line since it is easier to overpopulate the sublevels of an $F = 1$ level, where the population is divided among fewer states, than the sublevels of an $F = 2$ level (the population per sublevel is of course the relevant quantity for the optical depth). The inversion of the 1612 line will therefore dominate whenever the two inversions are *a priori* equally likely. In order to invert the 1720 line it is thus necessary to selectively excite $^2\pi_{3/2}(J = 5/2)$ more than other states. As this is the lowest state in energy above the ground state, a natural way to achieve this is by collisions at low temperatures. For temperatures below about 200 K, the Boltzmann factor ($\exp[-h\nu/kT]$) favors $^2\pi_{3/2}(J = 5/2)$ excitations over $^2\pi_{1/2}(J = 1/2)$ by 40 percent at least. This is therefore the region in which a systematic inversion of the 1720-MHz line by collisions is expected.

b) *The Model*

The calculations are performed in a manner similar to that of Goldreich and Kwan (1974) and Scoville and Solomon (1974), taking for a model a uniform spherical cloud with a large-scale radial velocity field. The equations of statistical equilibrium for such a case are discussed in details in Paper I and are reproduced here without elaboration (using the same notations). The number density (n_k) per sublevel of OH molecules in level k is governed by

$$\frac{dn_k}{dt} = \sum_{j>k} \left[\!\!\left[\frac{g_j}{g_k} A_{jk}\beta_{jk}\{n_j - (n_k - n_j)[F(T_{BB}, \nu_{jk}) + WF(T_b, \nu_{jk})]\} + Cg_j[n_j - n_k \exp(-h\nu_{jk}/kT)] \right]\!\!\right]$$
$$- \sum_{j<k} [\![A_{kj}\beta_{kj}\{n_k - (n_j - n_k)[F(T_{BB}, \nu_{kj}) + WF(T_b, \nu_{kj})]\} + Cg_j[n_k - n_j \exp(-h\nu_{kj}/kT)]]\!] , \qquad (2)$$

where g_k is the level degeneracy.

The function $F(\theta, \nu)$ is the photon occupation-number distribution,

$$F(\theta, \nu) = [\exp(h\nu/k\theta) - 1]^{-1} ;$$

T is the kinetic temperature; T_{BB} the temperature of the cosmic blackbody radiation; W and T_b the dilution factor and brightness temperature, respectively, of any external source of radiation which is included as a radiative pump. When the radiation is due to dust which is embedded in the cloud, the function $\beta_{jk}WF(T_b, \nu_{jk})$ is replaced by the function D_{jk} which is described in detail in Paper I.

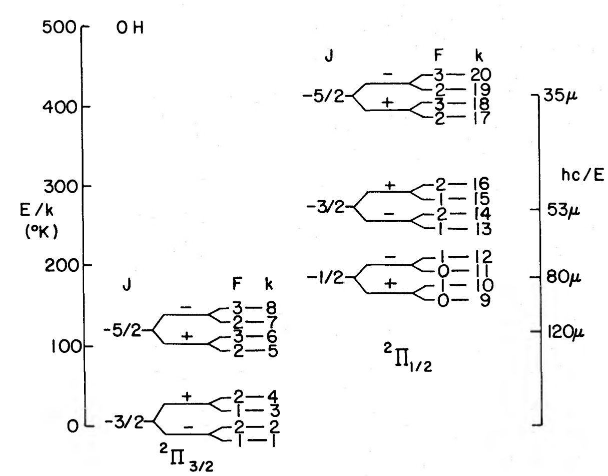

FIG. 1.—Energy-level diagram of all the rotational levels in the ground vibration state that couple radiatively to the ground state. Hyperfine- and Λ-doublet splittings are not to scale.

The escape probability β_{jk} is given by:

$$\beta_{jk}(r) = \int \frac{d\Omega}{4\pi} \beta_{jk}(r, \mu) ,$$

$$\beta_{jk}(r, \mu) = \{1 - \exp[-\tau_{jk}(r, \mu)]\}/\tau_{jk}(r, \mu) ,$$

$$\tau_{jk}(r, \mu) = \bar{\tau}_{jk}/[1 - \mu^2(1 - \epsilon)] , \quad (3)$$

$$\bar{\tau}_{jk} = \frac{1}{4\pi} hc\left(\frac{r}{v}\right) B_{jk} g_j (n_k - n_j) ,$$

$$\epsilon = \frac{d \ln v}{d \ln r} ,$$

where $\theta = \cos^{-1} \mu$ is the angle measured from the radius vector r. Equation (1) clearly follows from equations (3).

The collisions that are considered here are with H_2 molecules. All downward collision rates between magnetic sublevels are assumed equal. The rate C is given by:

$$C = C_0/\lambda ,$$

$$C_0 = N_{H_2}\langle\sigma V_{th}\rangle = 7 \times 10^{-12} T^{1/2} N_{H_2}(S^{-1}) , \quad (4)$$

$$\lambda = \sum g_i \exp(-h\nu_i/kT) .$$

Here, a geometric cross section of 10^{-15} cm^2 is assumed and λ is the total number of final states that can be reached by collisions (Goldreich and Kwan 1974). Other forms of collisions were also checked and are discussed below.

Overlapping of hyperfine-split components, when it exists due to large enough velocity gradients, is treated by adding together the corresponding optical depths. Here the simplifying approximation is made of either complete overlap or no overlap at all. Line overlap may play an important role in mechanisms of main-line inversions, as mentioned already in Paper I.

III. RESULTS

Equations (2) are solved numerically for steady state using Newton's method. The convergence criterion is that $\Delta n_k/n_k < 10^{-4}$ on successive iterations for all levels. The energy levels which are included in the calculation are the ground state and all the rotational states that can decay radiatively directly into it. These are (Fig. 1) the $J = 5/2$ level on the $^2\pi_{3/2}$ ladder and the levels with $J = 1/2$, 3/2, and 5/2 on the $^2\pi_{1/2}$ ladder. When ultraviolet and near infrared radiative pumps were checked, the corresponding excited vibration and electronic excitation levels were also included.

a) *Collisional Pump*

Collisions with H_2 molecules of the form given in equation (2) were found to be the source of an efficient pump for the inversion of the 1720-MHz line. Figure 2 displays the optical depth (averaged over angles) of the 1720 line in the region of OH densities where inversion is achieved. The curves in this figure are the results of calculations with different temperatures and with $\epsilon = 0.033$ and $N_{H_2} = 10^4$ cm^{-3}. The only source of external radiation is the cosmic blackbody background. The OH density enters the equations (eqs. [3]) only in the combination $N_{OH}/(V/R)$ (V/R is the overall velocity gradient in the cloud), which is therefore taken as an independent variable. A typical velocity gradient in a cloud is believed to be about 1 km s^{-1} pc^{-1} (Scoville and Solomon 1974). It then follows that inversion is achieved at OH densities which agree with the estimates usually found in the literature (e.g., Zuckerman and Palmer 1974).

The sharp transition from inversion to anti-inversion which occurs at large OH densities is due to effects of collisions across the Λ-doublet components of the $^2\pi_{3/2}(J = 5/2)$ state. As evident from equation (1), the de-excitation rate of a level by radiation decreases when the line becomes more optically thick, due to the trapping of the photons. The rates for transitions between the levels by collisions, on the other hand, are independent of the level populations. As a result, when the OH density increases, the importance of collisions across the Λ-doublet components of the $^2\pi_{3/2}(J = 5/2)$ state is increased with respect to the downward radiative de-excitations into the ground state. This opens an alternative route for the molecules which competes with the one that produces inversion. Since the entire inversion is never an effect of more than a few percent, it suffices for the collision rates to be only a fraction of the radiative decay rates to annihilate the inversion. It was found that the transition from inversion to

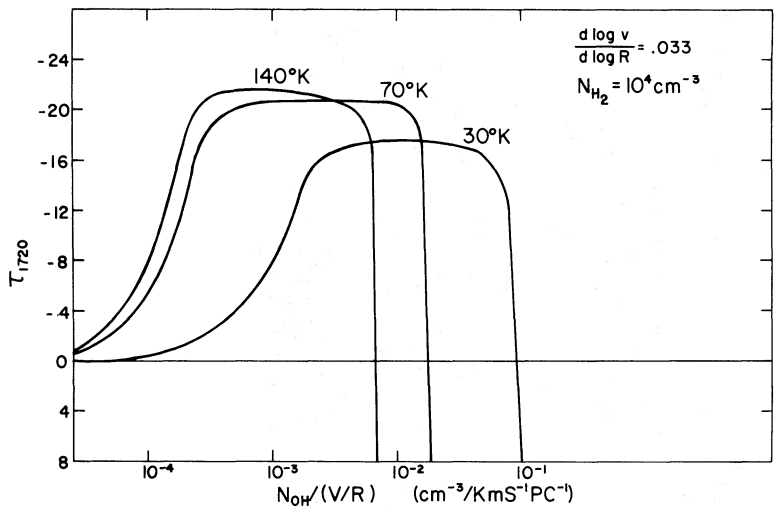

FIG. 2.—Optical depths of the 1720-MHz line in the region in which it is inverted by collisions with H_2 molecules. The parameters on the curves are the kinetic temperatures.

anti-inversion takes place when the collision rates are about 5 percent of the radiative rates for $^2\pi_{3/2}(J = 5/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$. Equating the expressions for the rates, the value of N_{OH} where the transition takes place is found to be approximately

$$N_{OH} \approx \text{const} \times (N_{H_2}T^{1/2})^{-1} . \quad (5)$$

Figure 2 displays the inverse dependence of the transition OH density on temperature. This transition was not accompanied by an inversion of the 1612 line.

When the temperature increases beyond about 200 K, the excitation of the $^2\pi_{1/2}(J = 1/2)$ state becomes sufficient to make the route for inversion of the 1612 line operative when the $^2\pi_{1/2}(J = 1/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ transition becomes optically thick. However, since the A-coefficients for this transition are about an order of magnitude smaller than those for $^2\pi_{3/2}(J = 5/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$, the 1720 line inverts first and the inversion switches over to the 1612 line only at higher OH densities. The solution for $T = 250$ K is shown in Figure 3. The transition of inversion from the 1720 line to the 1612 line takes place when the weakest transition from $^2\pi_{1/2}(J = 1/2)$ to $^2\pi_{3/2}(J = 3/2)$ becomes optically thick.

When the temperature decreases, the efficiency of the pump is slowly decreasing, but it is still operative down to low temperatures. Sizable inversion of the 1720 line could still be achieved at $T = 25$ K, but at lower temperatures it was found impossible to achieve inversion. However, as long as the temperature is above ~ 15 K, the pump produces an excitation temperature higher than the kinetic temperature for the 1720 line. Below 15 K the pump does not operate anymore, and all the ground-state levels are in thermal equilibrium. It may be worthwhile to note that the Boltzmann factor for $^2\pi_{3/2}(J = 3/2) \rightarrow {}^2\pi_{3/2}(J = 5/2)$ is 2×10^{-2}, 2×10^{-3}, and 6×10^{-6} for $T = 30$, 20, and 10 K, respectively.

Calculations were performed also for different values of $\epsilon = d \ln v/d \ln r$. It is evident from equations (3) that ϵ provides a scale measure for variations of τ_{jk}. As a result, for smaller values of ϵ the optical depths are expected to vary more rapidly with N_{OH}. This is verified by the calculations which are displayed in Figure 4. Evidently, as ϵ becomes larger[1] the inversion increases more slowly, and the transition to anti-inversion may occur even before the line has saturated. Also, since the rate of change of the optical depths depends inversely on ϵ, the proportionality factor in equation (5) increases with ϵ. As a result, the transition to anti-inversion occurs at higher OH densities for higher values of ϵ, as evident also from Figure 4.

The pump was also checked against variations in the H_2 density. It was found that the pump operates most efficiently for N_{H_2} in the range of 10^3–10^5 cm^{-3}. When N_{H_2} decreases below 10^3 cm^{-3} the efficiency of the pump is slowly decreasing. Sizable inversions are still obtained for N_{H_2} of the order of unity. The transition to anti-inversion occurs at higher values of N_{OH} (for smaller N_{H_2}), in agreement with equation (5). When N_{H_2} is increased above 10^5 cm^{-3} the inversion is quenched, since collisions across all the higher rotation levels begin to compete effectively with the downward radiative de-excitations. As a result, the saturated gain of the 1720 line decreases. The transition to anti-inversion moves to lower OH densities, in accordance with equation (5). If in addition to N_{H_2} the temperature is also increased, the transition to anti-inversion occurs at even lower OH densities (eq. [5]). At $T \gtrsim 70$ K, this transition is accompanied by an inversion of the 1612 line with a large gain ($-\tau \approx 20$). We have therefore

[1] Note that gravitational collapse corresponds to $\epsilon = 1$.

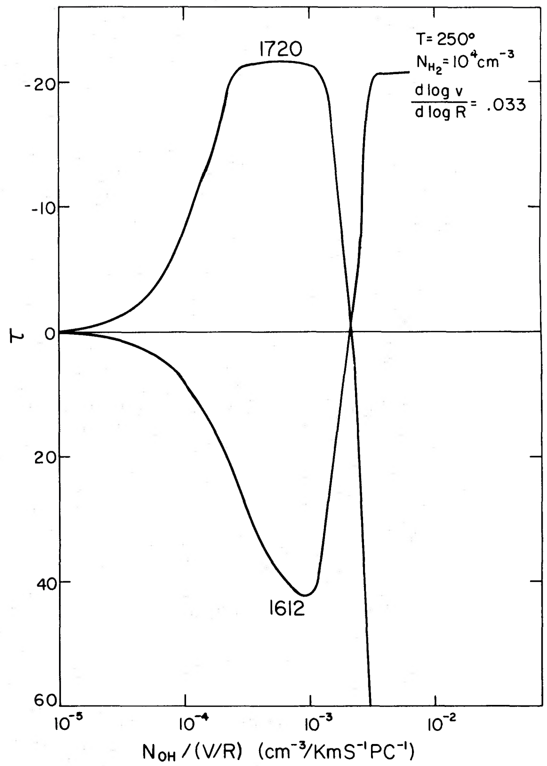

FIG. 3.—Optical depths of the 1612- and 1720-MHz lines at a temperature of 250 K. Notice the different scale for positive and negative optical depths.

discovered yet another region where collisions strongly invert the 1612 line. A simple explanation for the inversion was not found in this case. The collision rates are not small, so the populations of the higher levels are not entirely negligible. The downward collision rates compete with the radiative rates, and the populations of different sublevels of any rotation levels are substantially different from each other. The conditions are therefore widely different from the ones under which the general analysis of § II*a* was carried out. An understanding of the inversion was obtained only from the detailed numerical solution where the entire cycle that the molecules take was followed. At any rate, the inversion of the 1612 line is strong for $T \gtrsim 70$ K, $N_{H_2} \approx 5 \times 10^5$–$5 \times 10^6$ cm^{-3}, and OH densities above the value obtained from equation (5). For $\epsilon = 0.033$, $N_{H_2} = 10^6$ cm^{-3} and $T = 70$ K, the OH density that

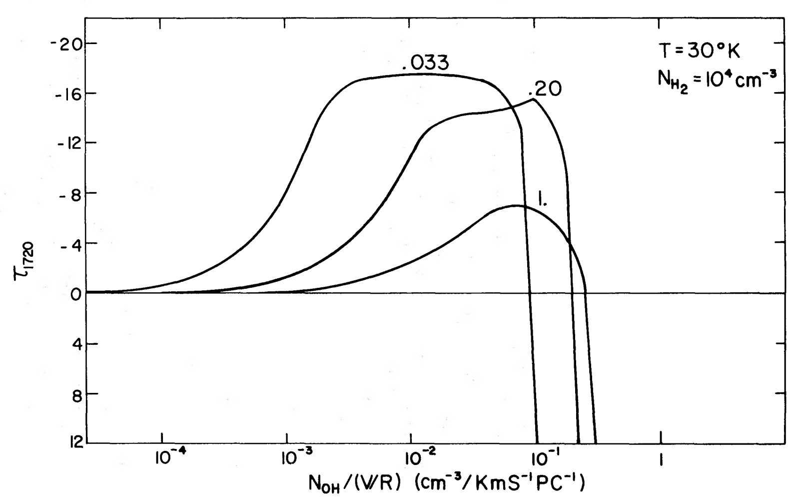

FIG. 4.—Results of the 1720-MHz line inversion for different values of $\epsilon = d \ln v / d \ln r$ which are indicated on the curves

gives strong 1612 inversion is given by

$$N_{\rm OH}/(V/R) \gtrsim 5 \times 10^{-3}\,{\rm cm}^{-3}\,({\rm km\,s}^{-1}\,{\rm pc}^{-1})^{-1}\,.$$

When N_{H_2} is further increased, both the 1720 and 1612 line inversions are decreasing, because of the downward collisions. Finally, at $N_{H_2} \gtrsim 10^9\,{\rm cm}^{-3}$, all the levels thermalize, as expected (since collisions dominate all the downward transitions).

b) *Other Collision Laws*

A basic weakness of every pump model based on collisions is the present poor understanding of molecular collision mechanisms. Other forms of collisions which are sometimes used in the literature were therefore also checked.

Two collision laws which are based on dipole selection rules are (*a*) when all downward collision rates of allowed transitions are equal, and (*b*) when they are scaled with the transition dipole moment. It is easy to construct simple models for both cases which can be solved analytically. The results are that in case (*a*) the 1612 line is inverted, and in case (*b*) the 1720 line is inverted with a gain that increases with the optical depth of the rotation transitions.

The numerical calculations confirm the results of the simple analytical model. The results in case (*b*) turn out to be very similar to the ones discussed in the previous section when collisions connect all the levels with equal downward rates. The situation can therefore be summarized as follows: if case (*a*) is appropriate for collisions with H_2 molecules, then inversion of the 1720 line cannot be produced; if case (*b*) is operative, the detailed results described in the previous section are valid.

Another collision law is that found by Gwinn *et al.* (1973). They suggest that as a result of collision, OH is preferentially excited into the upper Λ-doublet components. Their results, however, show no preference for a particular hyperfine component or for one ladder over the other. Hence it is clear that this collision law cannot affect the inversion of satellite lines, although it is important for the main lines. Numerical calculations show that these collisions do indeed provide an adequate mechanism for inversion of the main lines and do not change the results for the 1720 line inversion, described previously. Detailed results for this collision law will be included in a forthcoming publication on pumps which can invert the main lines.

A selection effect which may be operative is the possible enhancement of $\Delta J = 0$ collisions. This could reduce the 1720 line inversion by pumping relatively more molecules into the ${}^2\pi_{1/2}(J = 3/2)$ state which then decay into the ${}^2\pi_{1/2}(J = 1/2)$ state and initiate the competing 1612 line inversion cycle. Such a possible effect is reduced, however, by the Boltzmann factor which suppresses excitations into the ${}^2\pi_{1/2}(J = 3/2)$ state (with $h\nu/k = 270$ K) as well as by the many other decay modes opened to this level, notably into the ground state itself with similar strength.

The numerical calculations in fact show that enhancing the $\Delta J = 0$ collisions by as much as a factor of 5 does not reduce the 1720 line inversion at all. The only effect it had on the previous results was to decrease the OH density at which the transition to anti-inversion occurs. It was found that the proportionality constant in equation (5) became smaller by about 15 percent; otherwise the results remain the same.

A controversial point is the value of collision cross sections among the different components of the same energy level. In all of the above calculations they were subjected to the same rules as collisions between the levels. Some think, however, that they may be stronger than collisions which excite the rotation levels, and others think that they may be weaker when corresponding to quadrupole transitions (e.g. Litvak and Dickinson 1972). Clearly, if any of the collisions within the multiplets are weaker they will do nothing to the inversion, but if made sufficiently strong they will finally equalize the populations and annihilate the inversion. On the other hand, in all the above calculations (especially at low temperatures) the rates for collisions within the levels are already much higher due to the Boltzmann factor, and it is obvious that one should be able to increase them somewhat further before the inversion is annihilated.

It was found indeed that at a temperature of 30 K the collisions among the components of the same level could be increased by a factor of 8 with inversion still persisting. Upon further increase the inversion disappeared, but the excitation temperature of the 1720 line was still anomalously high. At higher temperatures the increase before the inversion disappeared was of course larger, and the critical value of the enhancement factor varied in fact as $\exp(-120/T)$, as expected ($h\nu/k = 120$ K for ${}^2\pi_{3/2}[J = 5/2]$). We therefore see that if collisions among the components of the same level are enhanced by more than a factor of 8, the only effect on the results of the previous section is to increase the value of the minimal temperature at which inversion of the 1720 line can be produced.

c) *Radiative Pumps*

It is evident from the rate equations (eqs. [2]) that a radiative pump can operate if there is an external source of radiation such that $F(T_b, \nu_{jk}) \approx 1$ and $WA_{jk} > C$ for a typical A-coefficient of the appropriate radiative transitions.

There is a fundamental difference between radiative and collisional pumps. When collisions dominate, it is possible to get an inversion even if only two levels interact so that molecules are excited by collisions to the upper level and then directly decay back radiatively. The difference between collisional excitation rates and radiative-decay rates can in principle redistribute the molecules between the sublevels of the lower state. When the molecules are excited by radiation, on the other hand, the excitation and decay rates are always proportional to each other (as evident also from eqs. [2]), and it is impossible to change the populations in the lower levels if only one upper state is involved. In order to affect the lower sublevel populations, the cycle must now include at least two steps before the final decay back; hence there must be at least two upper levels involved. Since more than one upper level is reached, the route involving $^2\pi_{1/2}(J = 1/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ will always be activated and, as a result, radiative pumps tend to systematically invert the 1612-MHz line.

When the pumping radiation is in the far-infrared, all the upper levels which participate in the cycle are on the $^2\pi_{1/2}$ ladder (apart from the $^2\pi_{3/2}[J = 5/2]$ state) and the 1612 line is strongly inverted. The numerical calculations for this case are described in detail in Paper I. It was found that there is a small range of OH densities in which the 1720 line is weakly inverted. This is the region in which the $^2\pi_{3/2}(J = 5/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ transitions are optically thick but the $^2\pi_{1/2}(J = 1/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ ones are still thin since their line strengths are about an order of magnitude smaller. This is exactly the same situation as that found in § III*a* for collisions with $T \geqslant 200$ K. The obvious difference is that in the case of a collisional pump the 1720 line can be strongly inverted (and even saturated) in this region, since the pump rate is independent of the optical thickness of the rotational transitions. For a radiative pump, on the other hand, a region of thin radiative transitions corresponds also to a high transparency to the pumping photons, leading to a low efficiency for the pumping mechanism. This explains why the calculations in Paper I always gave only small optical depth for the 1720 line in the region in which it was inverted. The situation is quite similar for pumping by near-infrared or ultraviolet photons. In both cases the numerical calculations show that the 1612-MHz line is strongly and systematically inverted for sufficiently high OH densities. The 1720 line is weakly inverted in the density region where the $^2\pi_{1/2}(J = 1/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ transitions are thin and the $^2\pi_{3/2}(J = 5/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ are thick. In these cases, the inversion of the 1720 line is even weaker than for a far-infrared pump since the line strengths for vibrational and electronic transitions are smaller than for rotational excitations. As a result, all the rotational transitions are optically thick by the time the cloud is efficiently absorbing the (near-infrared or ultraviolet) pump photons and the 1612 line is inverted. Also, due to the smaller line strengths, the inversion of the 1612 line is appreciable only at higher OH densities than in the case of a far-infrared pump.

In conclusion, (i) as a systematic effect, radiative pumps invert the 1612 line; (ii) the 1720 line is only weakly inverted over a limited range of OH densities, and (iii) far-infrared provides a more efficient pump than either near-infrared or ultraviolet.

IV. DISCUSSION

a) *Applications*

The results of the calculations presented above suggest that whenever high-gain ($-\tau > 1$) maser emission of the 1720 line is observed, the inversion is due to collisions. Sources which apparently fall under this category are W28 and W44 (Goss and Robinson 1968), which emit the 1720 line quite strongly and show absorption in the three other OH lines. It is suggested that the 1720 line is inverted in these sources by collisions with H_2 molecules and the maser amplifies background radiation, probably emitted from the supernova remnants associated with these sources.

A similar case is the OH emission from the source associated with the star V1057 Cygni where the 1720 line is observed, but not the three other lines (Lo and Bechis 1973; 1974). There seems to exist a correlation between changes in the intensity of the OH emission from the source and the star luminosity. It is suggested that the OH emitting region is heated by the radiation from the star and the 1720 line is then inverted by collisions. The changes in the intensity of the 1720 line reflect changes in the gain which are due to the varying temperature. A detailed model for this source including a study of the different contributions to the heating and cooling of the OH emitting region is now in preparation.

In the case of molecular clouds associated with H II regions, emission is sometimes observed in the 1720 line and sometimes in the 1612 line. It is suggested that the particular type of emission is determined by the relative magnitudes of the rates for collisions and radiative excitations in the particular source. When collisions dominate, the 1720 line is inverted since the physical conditions in the clouds ($T = 30$–100 K; $N_{H_2} = 10^4$–10^5 cm^{-3}; $N_{OH} = 10^{-4}$–10^{-3} cm^{-3}) are adequate for the operation of the collisional pump. When radiation dominates, the 1612 line should be inverted.

Observations seem to give some support to this conclusion. As a result of a survey, E. G. Hardebeck (1971) concludes that "the 1720-MHz lines of Class I sources do not seem to be associated with infrared sources." Also, the OH source G333.6-02 where the 1720 line is detected in absorption and 1612 in emission (Goss *et al.* 1970) is one of the brightest infrared H II regions in the sky (Becklin *et al.* 1973).

In dark clouds the OH emission pattern is as follows (Turner and Heiles 1971; Turner 1973): the main lines are usually seen in emission showing LTE characteristics; the 1720 line is seen in emission which is abnormally strong, relative to the main lines (with small absolute antenna temperature, however), and the 1612 line is seen in absorption or weak emission. Turner and Heiles (1971) also conclude that in these clouds the collision rate is much larger than the infrared pump rate. It would therefore seem that the collisional pump suggested above is in operation. There is a problem, however, with the low temperatures of the clouds. The temperatures are derived under the assumption that the main lines are thermalized by collisions (Heiles 1969). As pointed out by Turner (1973), this assumption may fail due to excitation by collisions which obey the selection rules derived by Gwinn *et al.* (1973). When kinetic temperatures are below ~ 15 K, however, all collisional excitations of higher rotational states are completely negligible. It therefore seems that the derivation of kinetic temperatures by Heiles (1969) is correct as long as $T \leqslant 15$ K. The calculations performed for the present work support this conclusion—at temperatures below ~ 15 K collisional pumps cannot operate at all. We are thus led to the suggestion that whenever anomalous 1720-MHz emission comes from clouds with $T \leqslant 15$ K, the inversion (or high excitation temperature) is produced by radiative (probably far-infrared) excitation with OH density such that the transitions ${}^2\pi_{3/2}(J = 5/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ are optically thick but ${}^2\pi_{1/2}(J = 1/2) \rightarrow {}^2\pi_{3/2}(J = 3/2)$ transitions are thin. There exists a somewhat peculiar situation where the radiative pump dominates even though the collision rates are higher. This is because the low temperature suppresses collisional excitation.

The conclusions of our model are that molecular and dust clouds which show the 1720 line in absorption and the 1612 line in emission are associated with infrared sources. When anomalous satellite line emission is detected from a source with $T \leqslant 15$ K it is due to a (far-infrared) radiative pump. In this case the OH density determines which line is inverted.

One situation that cannot be explained by our models is strong 1720 inversion (with $|\tau| > 1$) in a cold cloud (with $T < 25$ K). It does not seem that such a case has yet been detected; if observed, however, the explanation is clearly outside the scope of the models presented here.

Another point which is worth mentioning is that whenever a satellite line is weakly inverted, the other satellite line is anti-inverted with an optical depth which has roughly the same size. This feature is common to all the pumps and it agrees with the pattern that is usually observed.

b) *Summary*

We summarize by pointing out again that the only mechanism found here to achieve a *high gain inversion* of the 1720-MHz line is by collisional excitation of the lowest rotation state. Radiative excitations were able to produce only weak inversion of the 1720 line. Small gains ($|\tau| < 1$) can therefore be produced by either pump at low OH densities.

The calculations demonstrate the importance of photon trapping to the understanding of level populations. Due to trapping, radiative rates become independent of the line strengths, and the only relevant point is the number of available transitions in each step. The numerical calculations were performed using the formalism of escape probability and assuming that a large-scale radial-velocity gradient exists in the emitting region. Zuckerman and Evans (1974) have recently questioned the applicability of such a model to molecular clouds. The formalism of escape probability, however, can be applied also when only thermal motions are present. The escape probability itself is proportional to τ^{-1} (for large τ) in this case, too (Avrett and Hummer 1965). This, together with the general discussion of § II*a*, is the source of a feeling that the main properties of the inversion mechanisms worked out in this paper may hold in the case of models other than the particular one used here for the numerical calculations.

The formalism does not apply, however, to differential phenomena of radiative transfer. In particular, it cannot be applied to effects which vary with the distance from the edge of the cloud. This makes it impossible to compare our results with those of Jefferies (1971), who relies on such effects, although he also based his models on collisions. It is also clear that the formalism in this form can be applied to the turbulent case.

The weakest point of the model is probably the uncertain form of the collision law. Although most of the laws which are commonly used yield similar results for the 1720 line inversion, the results cannot be considered conclusive. Radiative pumps do not suffer from similar uncertainties. The most solid result of the paper, therefore, seems to be the conclusion that radiative pumps can never produce large gain inversions of the 1720-MHz line.

This work was initiated by a collaboration with P. Goldreich at Caltech.

REFERENCES

Avrett, E. H., and Hummer, D. G. 1965, *M.N.R.A.S.*, **130**, 295.
Becklin, E. E., Frogel, J. A., Neugebauer, G., Persson, S. E., and Wynn-Williams, C. G. 1974, *Ap. J.* (*Letters*), **182**, L125.
Elitzur, M., Goldreich, P., and Scoville, N. 1974, California Institute of Technology, preprint No. 2542 (Paper I).
Goldreich, P., and Kwan, J. 1974, *Ap. J.*, **189**, 441.
Goss, W. M., and Robinson, B. J. 1968, *Ap. Letters*, **2**, 81.
Goss, W. M., Manchester, R. N., and Robinson, B. J. 1970, *Australian J. Phys.*, **23**, 559.
Gwinn, W. D., Turner, B. E., Goss, W. M., and Blackman, G. L. 1973, *Ap. J.*, **179**, 789.
Hardebeck, E. G. 1971, *Ap. J.*, **170**, 281.
Heiles, C. 1969, *Ap. J.*, **157**, 123.
Jefferies, J. T. 1971, *Astr. and Ap.*, **12**, 351.
Litvak, M. M. 1974, *Ann. Rev. Astr. and Ap.*, **12**, 97.
Litvak, M. M., and Dickinson, D. F. 1972, *Ap. Letters*, **12**, 113.
Lo, K. Y., and Bechis, K. P. 1973, *Ap. J.* (*Letters*), **185**, L71.
———. 1974, *ibid.*, **190**, L125.
Scoville, N. Z., and Solomon, D. M. 1974, *Ap. J.* (*Letters*), **187**, L67.
Turner, B. E. 1974, *Ap. J.*, **186**, 357.
Turner, B. E., and Heiles, C. 1971, *Ap. J.*, **170**, 453.
Zuckerman, B., and Evans, N. J. 1974, *Ap. J.* (*Letters*), **192**, L149.
Zuckerman, B., and Palmer, P. 1974, *Ann. Rev. Astr. and Ap.*, **12**, 279.

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