Inversion of the OH 1720-MHz Line

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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 wave length) can invert strongly only the 1612-MHz line.

I. Introduction

Emission from the ground state of the OH molecule has been a puzzle ever since it was first detected The observed lines intensities indicate that the levels 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 has been made recently when a model for the 1612-MHz maser emission from IR/OH stars was constructed (Elitzur, Goldreich and Scoville, 1974; hereafter called paper I) Inversion of the maser emitting levels is achieved in this model by pumping with far-IR 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 sattelite lines inversions. Various pumping mechanisms were checked extensively and the conclusion is that the only efficient mechanism to excite preferentially the $^2\pi_{3/2}$ ladder and invert strongly the 1720-line is collisions (with H_2 molecules) at temperatures above 25°K. The collisions 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 invert strongly 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 (IR and UV) pumps can invert strongly only the 1612 line. In the case of weak

inversions (with $|\tau| < 1$) the situation is somewhat more involved, as discussed below.

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 lines 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 done at 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 sizeable 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 lines 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:

$$W_{ij} = A_{ij} / \tau_{ij} \qquad (1)$$

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) - $^2\pi_{3/2}$ (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) - $^2\pi_{3/2}$ (J=3/2), the F=1 levels overpopulate (and the 1612-line 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 in the case 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% 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 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 (same notations). The number density (n_k) per sublevel of OH molecules in level k is governed by:

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

$$- \sum_{j<k} \left\{ A_{kj}\beta_{kj}[n_k - (n_j-n_k)(F(T_{BB},\nu_{kj}) + WF(T_b,\nu_{kj}))] \right.$$
$$\left. + Cg_j(n_k - n_j \exp(-h\nu_{kj}/kT)) \right\}$$

where g_k is the level degeneracy.

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

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

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.

The escape probability β_{jk} is given by:

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

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

$$\tau_{jk}(r,\mu) = \overline{\tau}_{jk}/(1 - \mu^2(1 - \epsilon))$$

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

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

(3)

where $\theta = \cos^{-1}\mu$ is the angle measured from the radius vector r. Eq. 1 clearly follows from eqs. 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:

$$C = C_0/\lambda$$

$$C_0 = N_{H_2} < \sigma \ V_{th} > = > 10^{-12} \ T^{1/2} \ N_{H_2} (S^{-1})$$

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

(4)

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.

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 UV and near-IR 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 eq. 2 were found to be the source of an efficient pump for the inversion of the 1720-MHz line. Fig. 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 black-body 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 eq. 1, the deexcitation 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 levels 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 deexcitations 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 more than a few
percent effect, it suffices for the collisions rates to be only a fraction
of the radiative decay rates to annihilate the inversion. It was found that
the transition from inversion to anti-inversion takes place when the collisions
rates are about 5% 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:

$$N_{OH} \approx Const \times (N_{H_2} \ T^{1/2})^{-1} . \tag{5}$$

Fig. 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 Λ-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 $T \sim 250°K$ is shown in fig. 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 $T \approx 25°K$ but at lower temperatures it was found impossible to achieve inversion. However, as long as the temperature is above $\sim 15°K$, the pump produces excitation temperature higher than the kinetic temperature for the 1720-line. Below 15°K the pump does not operate any more 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 $2\cdot 10^{-2}$, $2\cdot 10^{-3}$ and $6\cdot 10^{-6}$ for $T = 30°$, $20°$ and $10°K$, respectively.

Calculations were performed also for different values of $\varepsilon = d\ln\nu / d\ln r$. It is evident from eqs. 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 fig. 4. Evidently, as ε becomes larger* 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 eq. 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 fig. 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}.

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*Note that gravitational collapse corresponds to $\varepsilon = 1$.

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 eq. 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 deexcitations. As a result the saturated gain of the 1720-line is decreasing. The transition to anti-inversion is moving to lower OH densities, in accordance with eq. 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 ($-\tau \sim 20$). We have therefore discovered yet another region where collisions invert strongly 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 sec. II.a was carried. 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 $T \gtrsim 70°K$, $N_{H_2} \approx 5 \cdot 10^5 - 5 \cdot 10^6$ cm^{-3} and OH densities above the value obtained from eq. 5. For $\varepsilon = .033$, $N_{H_2} = 10^6$ cm^{-3} and $T = 70°K$ the OH density that gives strong 1612-inversion is given by:

$$N_{OH}/(V/R) \gtrsim 5 \cdot 10^{-3} \text{ cm}^{-3}/(\text{kms}^{-1} \text{ pc}^{-1}) \ .$$

When N_{H_2} is further increased, both the 1720- and 1612-line inversions are decreasing, because of the downward collisions Finally, at $N_{H_2} \gtrsim 10^9$ 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 rotatio⁻ 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 summarised 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 1/20-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.

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 $F(T_b, \nu_{jk}) \sim 1$ 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 decay back radiatively directly. The difference between collision excitation - 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 sublevels populations the cycle must include now 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 invert systematically the 1612-MHz line.

When the pumping radiation is in the far-IR, 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 section III.a for collisions with $T \gtrsim 200°K$. 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-IR or UV 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 densities 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 far-IR 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 absorbing efficiently the near-IR or UV pump photons and the 1612 line is inverted. Also, due to the smaller lines strengths, the inversion of the 1612 line is appreciable only at higher OH densities than in the case of a far-IR 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-IR provides a more efficient pump than either
near-IR or UV.

IV. Discussion

a. Applications

The results of the calculations presented above suggest that whenever high-
gain (~τ > 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 Bechio, 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 antena temp., however) and the 1612 line is seen in absorption or weak emission. Turner and Heiles (1971) also conclude that in these clouds the collisions rate is much larger than the IR-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 $T \lesssim 15°K$. The calculations performed for the present work support this conclusion - at temperatures below ~15°K collisional pumps cannot operate altogether. We are thus led to the suggestion that whenever anomalous 1720-MHz emission comes from clouds with $T \lesssim 15°K$, the inversion (or high excitation temperature) is produced by radiative (probably far-IR) 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 $^2\pi_{1/2}(J=1/2)\rightarrow^2\pi_{3/2}(J=3/2)$ 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 IR-sources. When anomalous satellite line emission is detected from a source with $T \lesssim 15°K$ it is due to a (far-IR) radiative pump. In this case the OH density determines which line is inverted.

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 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. It is somewhat unfortunate that at small gains ($|\tau|<1$) the situation is not a clear cut case.

The calculations demonstrate the importance of photon trapping to the under-standing of levels 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 Humner, 1965). This, together with the general discussion of Sec II a are 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 weakest point of the model is probably the uncertain form of the collisions law. Although three out of the four 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

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Figure Captions

Fig. 1 - Energy levels 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.

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

Fig. 3 - Optical depths of the 1512- and 1720-MHz lines at a temperature of
250°K. Notice the different scale for positive and negative optical
depths.

Fig. 4 - Results of the 1720-MHz line inversion for different values of
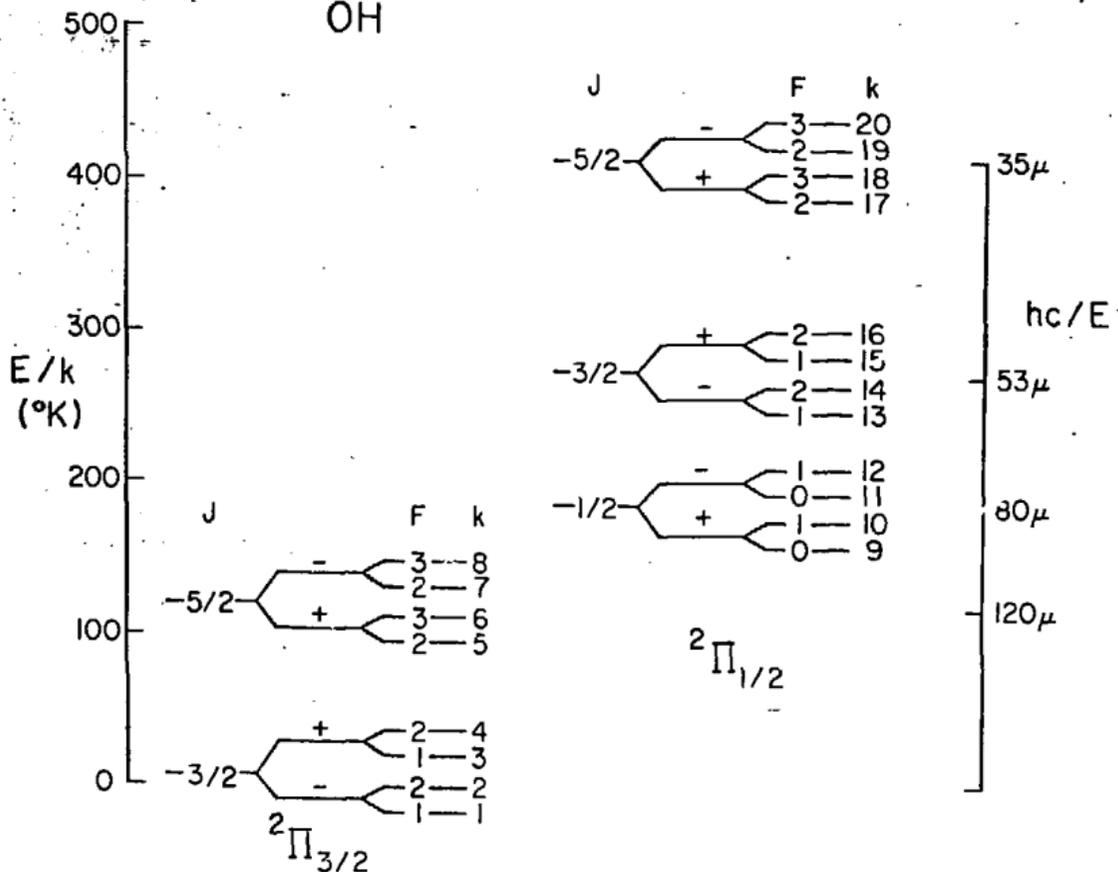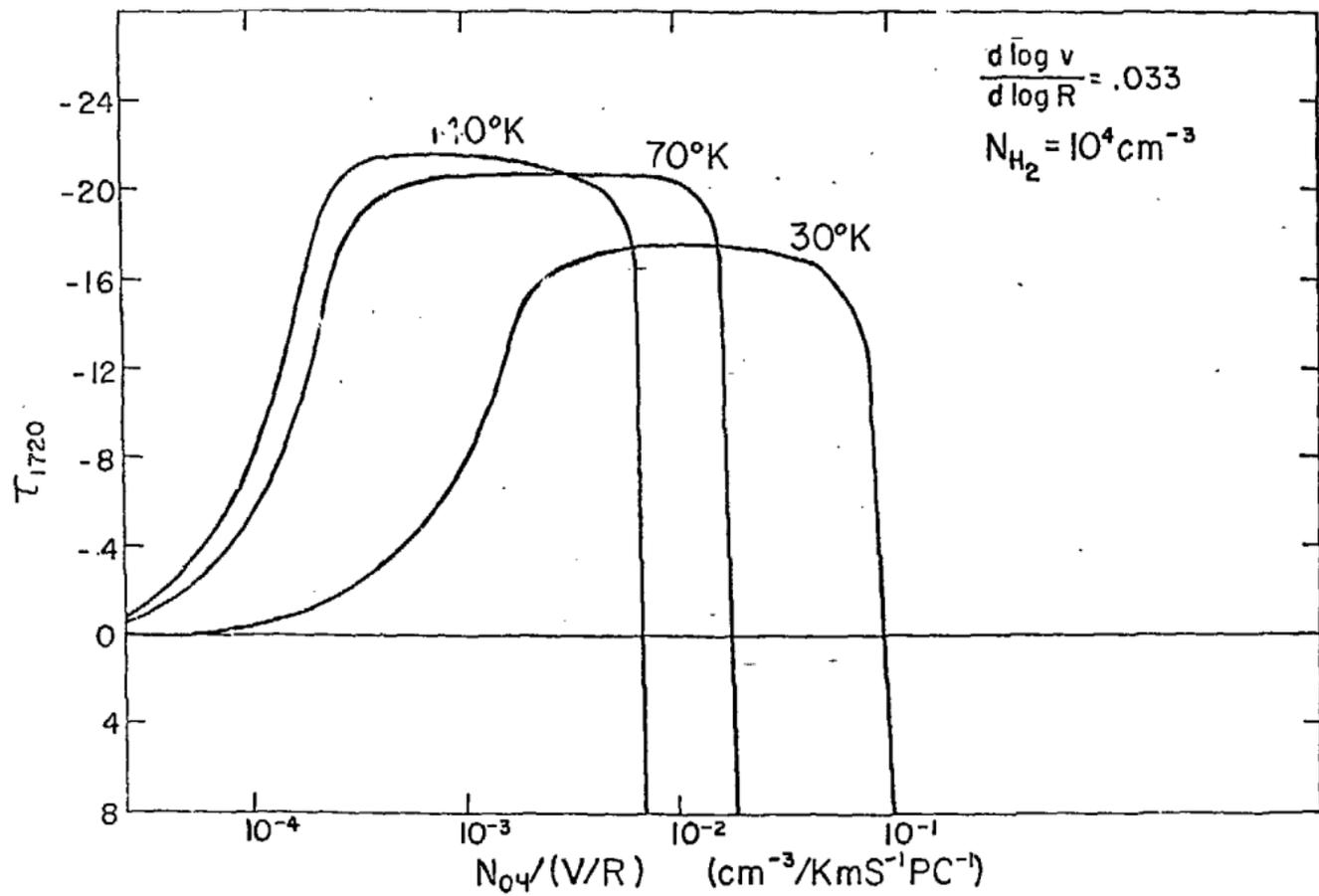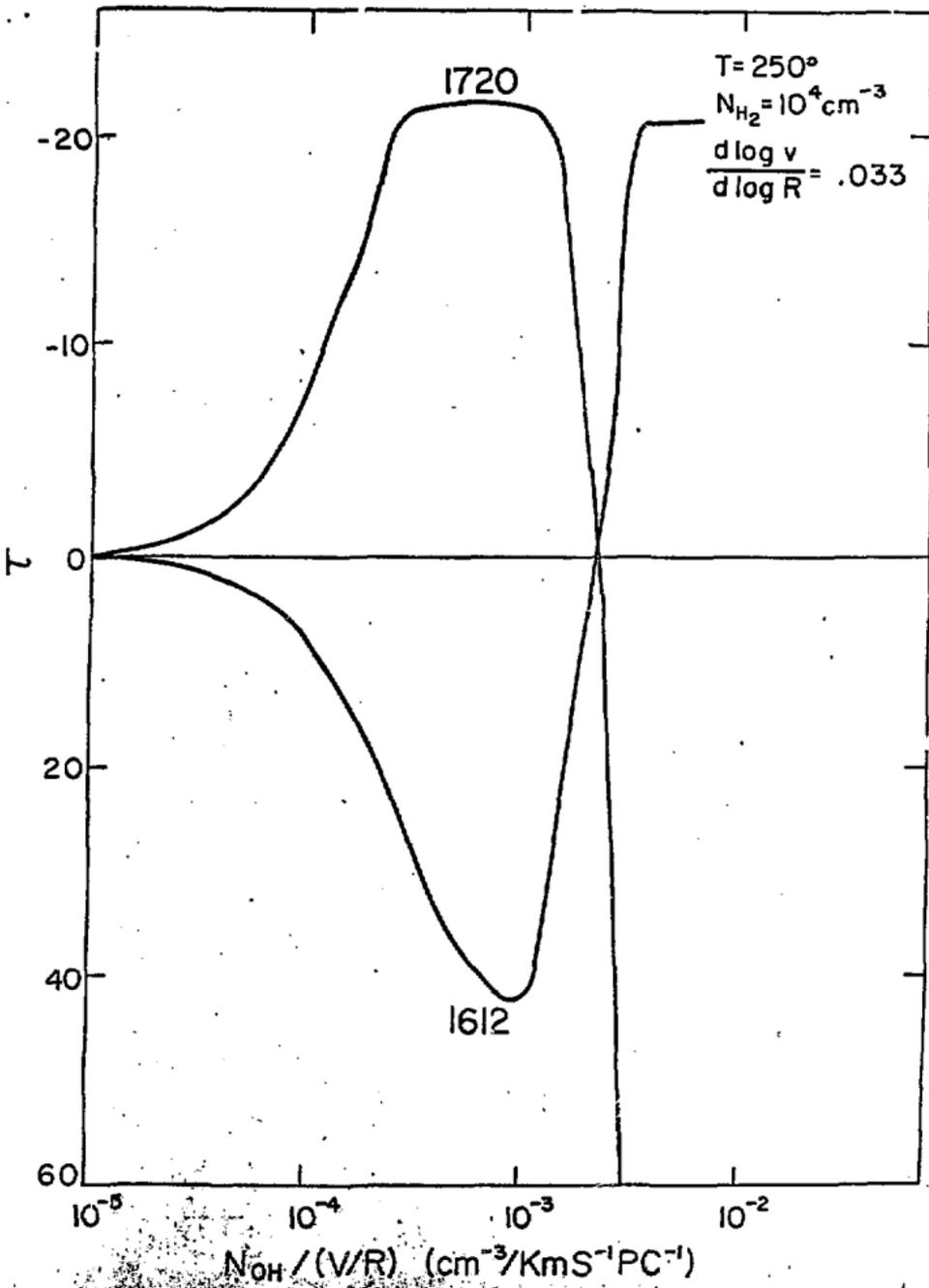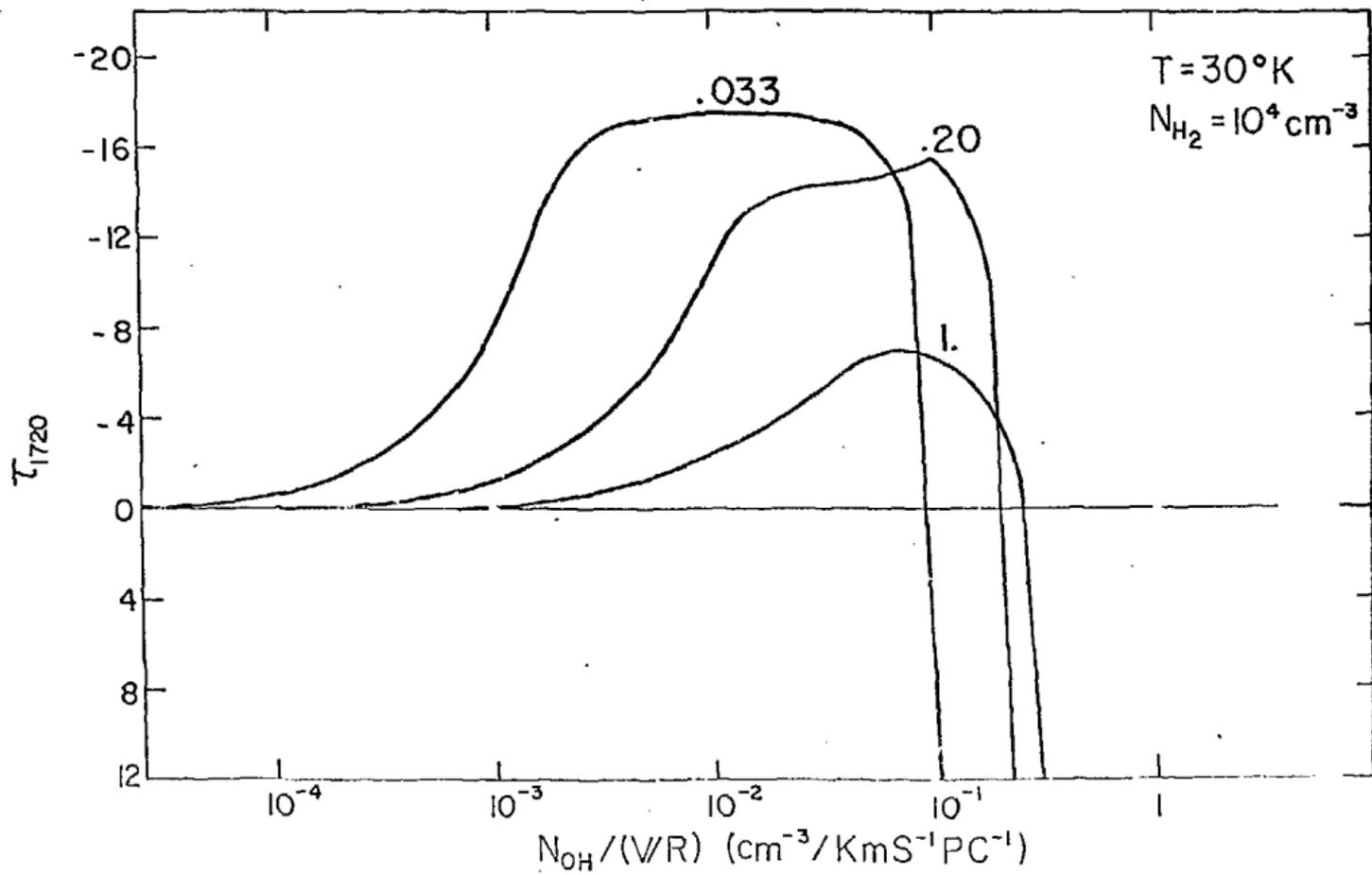$\varepsilon = \frac{d\ln v}{d\ln z}$ which are indicated on the curves

Fig. 1.

Fig. 2.

Fig. 4.