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On Satellite Lines Anomalies in OH Excited States

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Summary

It is argued that different pumps produce similar distributions of populations in the first two excited states of OH. The pattern observed recently in G 219.3 - 07 by Whiteoak and Gardner can be due either to radiative or collisional pump.

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I. Introduction

Recent observations of Whiteoak and Gardner (1976) and Gardner and Whiteoak (1975) draw attention again to radio emission from excited states of OH. In these observations an emission pattern is emerging in the $^2\pi_{3/2}(J = 5/2)$ state which is similar to the familiar one in the ground state, namely: the main lines appear in absorption, approximately in LTE; one sattelite line (the counterpart of 1612) shows anomalous absorption while the other one (the counterpart of 1720) is enhanced relative to the main lines. In the particular source where this pattern is observed (G 291.3 - 07) the ground state exhibits the analogous pattern. Whiteoak and Gardner interpret this as supporting the IR - pumping model calculated by Litvak, Zuckerman and Dickinson (1969).

I would like to point out that the observations are also compatible with collisional excitation of the $^2\pi_{3/2}$ (J = 5/2) state. The pattern follows in fact just from the structure of the energy levels diagram and photon trapping effects rather than any particular pump. Hence, the emission pattern is not enough and one must invoke some additional arguments to decide which is the dominant pumping process in any particular source.

II. The $^2\pi_{3/2}$ (J = 5/2) State

The first point to realize is that during excitation, whichever pump is operating, the different levels of the $^2\pi_{3/2}$ (J = 5/2) state are more or less equally populated. This is clear for pumping by collisions with neutrals directly from the ground state, unless some peculiar selection rules govern the collisions. If such selection rules were operative, however, their effect should show up in the final population distribution after the decay back to the ground state in, e.g., producing main lines anomalies. Since this is not observed in most, and probably even all, clouds this possibility is dismissed, at least as long as the temperature is bellow about 100°K. When radiative pumps dominate, the $^2\pi_{3/2}$ (J = 5/2) state is populated both by direct excitation from the ground state and by cascades from the higher states. Altogether, this tends to distribute the population equally between the different levels of $^2\pi_{3/2}$ (J = 5/2). It is during the cascade back to the ground state that the non-LTE population distribution is produced: the levels with F = 3 decay only to the F = 2 levels of the ground state whereas those with F = 2 decay both to the F = 2 and F = 1 of the ground state. As long as the IR - transitions $^2\pi_{3/2}$ (J = 5/2)$\rightarrow$$^2\pi_{3/2}$ (J = 3/2) are optically thin, the total rates for cascade out of the F = 2 and F = 3 levels are equal; however, when photon trapping effects become important, the decay rates become independent of the A - coefficients and depend only on the number of decay modes. Hence, the F = 2 levels of $^2\pi_{3/2}$ (J = 5/2) are emptied at a rate which is twice as fast as that for F = 3. The population per sub-level of F = 3 is about 50% higher than that for a sub-level of F = 2.

The result is that the 6049 MHz line (F = 3 → F = 2) of $^2\pi_{3/2}$ (J = 5/2) (the counterpart of the 1720 - MHz line) will be inverted whereas the 6016 MHz line (F = 2 → F = 3 ; counterpart of 1612 MHz line) will be anti-inverted, as observed in G 291.3 - 0.7. It is also evident that the same pattern should exist in any other source, independent of the nature of the dominant pumping process, provided the transitions $^2\Pi_{3/2}$ (J = 5/2) → $^2\Pi_{3/2}$ (J = 3/2) are optically thick. That this is indeed the case is evident from the expression for the optical depth of the transition:

$$\tau_{IR} = 8 \cdot 10^4 \frac{NR}{V} \qquad (1)$$

where N(cm^{-3}) is the OH density, R(pc) the linear dimension of the cloud and V(km/sec) the OH line width. Since V/R is typically about 1 km/sec/pc it is evident that for commonly observed OH densities τ_{IR} will in fact be larger than unity.

The scheme described above was verified in actual numerical calculations. The statistical equilibrium equations were solved in the manner described by Elitzur (1976). It was found that collisional and radiative pumps lead to similar results for equal pumping rates. Hence, the distribution of population in the $^2\Pi_{3/2}$ (J = 5/2) state is determined during the decay back to the ground state rather than the pumping process, in agreement with the claim made above.

To establish the relative importance of different pumps in a particular source we note that the population per sublevel of the excited state, N_1, is related to the OH density via:

$$P\,N = \beta_{ir}\,A_{IR}\,N_1$$

where P is the pump rate, β_{ir} the IR-photon escape probability and A_{IR} (≈ .1 sec^{-1}) the A-coefficient for the IR transitions

$^2\Pi_{3/2}$ (J = 5/2) → $^2\Pi_{3/2}$ (J = 3/2). Since $\tau_{IR} > 1$, β_{IR} is equal to τ_{IR}^{-1}.

The optical depth of an excited state main line is then related to its ground state counterpart through:

$$r \equiv \frac{\tau(6035)}{\tau(1667)} = 2.5\cdot 10^2 \, \frac{T_x(1667)}{T_x(6035)} \cdot \frac{P}{\beta_{IR}} \qquad (3)$$

and T_x is the excitation temperature of a particular line. The ratio of excitation temperatures on the r.h.s. of eq. (3) is usually of the order of unity and is henceforth set equal to 1.

The optical depth of the 1667-MHz line is calculated from:

$$\tau(1667) = 1.3\cdot 10^4 \, \frac{NR}{V} \cdot \frac{1}{T_x(1667)} \qquad (4)$$

$T_x(1667)$ is usually of order of magnitude 10°K and if $\tau(1667)$ is about 1 as suggested by Whiteoak and Gardner (1976), the OH density is of order 10^{-3} cm^{-3} and $\tau_{IR} \simeq 80$.

We can finally calculate the collisional pump rate, P_c, for G291.3 - 07 and at a temperature T of, say, 50°K we find:

$$\frac{P_c}{\beta_{IR}} = \tau_{IR}\cdot 7\cdot 10^{-12} N_H \sqrt{T} \exp(-120/T) = 5\cdot 10^{-10} N_H \qquad (5)$$

We see that in order to get a value of 10^{-1} for r, as quoted by Gardner and Whiteoak (1975), the density must be 10^6cm^{-3}. A more plausible density of 10^4cm^{-3} (corresponding to H_2/OH = 10^{-7}) yields only r = 10^{-3}.

In checking whether radiative pumps can do much better, attention can be restricted to far - IR radiation since the B - coefficients for electronic and vibration excitations are smaller than those for rotational excitations by factors 10^2 and 10^4, respectively. Hence, UV and near - IR radiations are usually important only close to the radiation sources which are point sources. On the other hand, far - IR can submerge large volumes of space due to the re-radiation of dust.

The pump rate, P_R, for a far - IR pump is itself proportional to β_{IR} so that:

$$\frac{P_R}{\beta_{IR}} = A_{IR} \cdot W[\exp(120/T_R)-1]^{-1} \approx 10^{-2}W$$

where T_R is the radiation brightness temperature and the last equality is for $T_R = 50^{\circ}K$. The dilution factor W is equal to the optical depth of the dust around 100 μ and to get $r = 10^{-1}$ a value $W = 10^{-2}$ is needed. This is again a pretty large value since a λ^{-2} behavior for the dust opacity leads to an optical depth of more than 100 for the dust in the visual. A visual extinction of order unity leads to $W = 10^{-4}$ and $r = 10^{-3}$ again. Hence, both collisional and far - IR pumping are equally hard pressed in explaining the value of r quoted by Gardner and Whiteoak. Since the quality of their estimate is not known we will not speculate about this point any further here.

III. The $^2\pi_{1/2}$ (J=1/2) state.

The behaviour of the $^2\pi_{1/2}$ (J=1/2) state under different pumping conditions was also examined. It was found that the F=1 levels are more populated than the F=0 ones, again irrespective of the particular pump used. The reason now is that this is the lowest state of the $^2\pi_{1/2}$ ladder and cascades are done preferentially within the ladder, with little crossing. Now, the F=0 levels are the cascade target only of the F=1 levels of $^2\pi_{1/2}$ (J=3/2) whereas the F=1 levels are the target of many more levels. Hence, the F=1 levels of $^2\pi_{1/2}$ (J=1/2) are overpopulated and the emission pattern is similar to that in $^2\pi_{3/2}$ (J=5/2). It is therefore predicted that the analogous pattern to 1612 enhancement and 1720 anomalous absorption will never be found either in $^2\pi_{3/2}$ (J=5/2) or $^2\pi_{1/2}$ (J=1/2).

In conclusion, the results obtained here are in agreement with the patterns found by Litvak, Zuckerman and Dickinson (1969) both for the $^2\pi_{3/2}$ (J=5/2) and $^2\pi_{1/2}$ (J=1/2) states even when differing from them with regard to the ground state. The claim is that these patterns are really independent of the pumping process. When observed, they therefore cannot tell us which excitation mechanism is in operation without using some additional observational material.

References

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