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Anomalous absorption in H_2CO molecule

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Abstract. Snyder et al. (1969) detected H_2CO through its transition $1_{10} - 1_{11}$ at 4.829 GHz in absorption in the interstellar medium in a number of galactic and extragalactic sources (M17, W3, W3(OH position), W49, NGC 2024, DR 21, W43, W44, W51, Sgr A, Sgr B2, W33, NGC 6334, Cas A, and 3C 123). This transition of H_2CO was found in anomalous absorption by Palmer et al. (1969) in the direction of four dark nebulae. In some objects, this transition has however been detected in emission and even as a maser line (Forster et al. 1980; Whiteoak et al. 1983). Evans et al. (1970) reported detection of H_2CO molecule through its transition $2_{11} - 2_{12}$ at 14.488 GHz in absorption in some cosmic objects. This transition was also found in anomalous absorption by Evans et al. (1975). Since the transition $1_{10} - 1_{11}$ is considered as a unique probe of high density gas at low temperature, the study of H_2CO in cosmic objects is of great importance. Garrison et al. (1975) investigated the problem of anomalous absorption of $1_{10} - 1_{11}$ and $2_{11} - 2_{12}$ transitions of H_2CO where they accounted for 8 energy levels connected by 10 radiative transitions and considered a kinetic temperature of 5 - 20 K. They found weak anomalous absorption of $1_{10} - 1_{11}$ and $2_{11} - 2_{12}$ transitions of H_2CO.

Here, we have investigated the transfer of radiation in H_2CO accounting 22 rotational energy levels connected by 47 radiative transitions in ground vibrational and ground electronic state. Further, we considered a kinetic temperature of $10 - 40$ K, as the kinetic temperature in some regions may be rather high. Thus, the present work may be considered as an extension of the work of Garrison et al. (1975) where the investigation is carried out in more detail. We have obtained remarkable anomalous absorption of $1_{10} - 1_{11}$, $2_{11} - 2_{12}$ and $3_{12} - 3_{13}$ transitions of H_2CO. In order to include a large number of cosmic objects, where H_2CO may be found, parameters in our investigation are varied over wide ranges.

Keywords : Interstellar material - H_2CO - anomalous absorption

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1. Introduction

Formaldehyde is the first organic molecule identified in some cosmic objects by Snyder et al. (1969) through its transition $1_{10} - 1_{11}$ at 4.829 GHz. This transition $1_{10} - 1_{11}$ was found in absorption against the Cosmic Microwave Background (anomalous absorption) by Palmer et al. (1969), showing H_2CO to be the first candidate for anomalous absorption in cosmic objects. Anomalous absorption is obviously an unusual phenomenon and may be used as a technique for identification of asymmetric top molecules in cool cosmic objects, as the kinetic temperature there may not be sufficient to generate emission spectrum of the molecule. Identification of a large number of molecules in cosmic objects would undoubtedly help in understanding the physical condition prevailing there and the chemical processes going on. Therefore, it is of great interest to identify as many molecules as possible in cosmic objects.

In the present investigation, we have considered H_2CO molecule where we accounted for 22 rotational energy levels of ortho-species. These levels are connected by 47 radiative transitions. Temperature in cool cosmic objects is generally low, but in some regions may be rather high and therefore, we have accounted for a kinetic temperature of $10 - 40$ K. We found remarkable anomalous absorption of $1_{10} - 1_{11}$ and $2_{11} - 2_{12}$ transitions. We also found anomalous absorption of $3_{12} - 3_{13}$ transition at 28.974 GHz.

2. Theoretical details

For a kinetic temperature $10 - 40$ K in the cosmic objects, it is sufficient to account for 22 rotational energy levels of ortho-H_2CO (Table 1). In our investigation, we solved a set of statistical equilibrium equations coupled with equations of radiative transfer given as the following.

$$n_i \sum_{\substack{j=1 \\ j \neq i}}^{22} P_{ij} = \sum_{\substack{j=1 \\ j \neq i}}^{22} n_j \ P_{ji} \qquad i = 1, 2, \ldots, 22$$

where n's are population densities of the levels and P's as the following.

(i) For optically allowed transitions

$$P_{ij} = \begin{cases} (A_{ij} + B_{ij} \ I_{\nu,bg})\beta_{ij} + n_{H_2} \ C_{ij} & i > j \\ B_{ij} \ I_{\nu,bg}\beta_{ij} + n_{H_2} \ C_{ij} & i < j \end{cases}$$

Table 1. Energy levels of ortho-H_2CO

J	k_a	k_c	$E(\mathrm{cm}^{-1})$	J	k_a	k_c	$E(\mathrm{cm}^{-1})$
1	1	1	10.5390	6	1	5	60.8605
1	1	0	10.7001	7	1	7	73.8907
2	1	2	15.2369	7	1	6	78.3949
2	1	1	15.7202	3	3	1	88.2382
3	1	3	22.2822	3	3	0	88.2383
3	1	2	23.2487	8	1	8	92.6337
4	1	4	31.6729	4	3	2	97.9576
4	1	3	33.2835	4	3	1	97.9578
5	1	5	43.4067	8	1	7	98.4197
5	1	4	45.8220	5	3	3	110.1086
6	1	6	57.4804	5	3	2	110.1092

(ii) For optically forbidden transitions

$$P_{ij} = n_{H_2}\ C_{ij}$$

where A's and B's are Einstein coefficients,

$$A_{ul} = \frac{2h\nu^3}{c^2}\ B_{ul} \qquad\qquad B_{ul} = \frac{g_l}{g_u}\ B_{lu}$$

C's the collisional rate coefficients, n_{H_2} the density of hydrogen molecules, and the escape probability β for the transition is

$$\beta_{lu} = \beta_{ul} = \frac{1 - \exp(-\tau_\nu)}{\tau_\nu}$$

where optical thickness τ_ν is

$$\tau_\nu = \frac{hc}{4\pi(\mathrm{d}v_r/\mathrm{d}r)}\left[B_{lu}n_l - B_{ul}n_u\right]$$

where $(\mathrm{d}v_r/\mathrm{d}r)$ is velocity gradient in the region. By solving these equations, populations of the levels are calculated. Here, external radiation field, impinging on a volume element generating the lines, is the CMB only. This set of equations is solved through iterative procedure for given values of n_{H_2} and $\gamma \equiv n_{\mathrm{mol}}/(dv_r/dr)$, where n_{mol} is density of the molecule.

Input data required in present investigation are radiative transitions probabilities (Einstein A-coefficients) and collisional rate coefficients.

2.1 Einstein A-coefficients

The Einstein A-coefficients for 47 radiative transitions between 22 energy levels of H_2CO molecule were calculated by Jaruschewski et al. (1986). These values are used in the present investigation.

2.2 Collisional rate coefficients

In the present investigation we have used the collisional rate coefficients calculated by Green et al. (1978) for downward transition ($J'_{k'_a k'_c} \rightarrow J_{k_a k_c}$). For upward collisional rate coefficients, we accounted for the fact that downward and upward collisional rate coefficients are related through detailed equilibrium (Chandra et al. 2000).

$$C(J_{k_a k_c} \rightarrow J'_{k'_a k'_c}) = C(J'_{k'_a k'_c} \rightarrow J_{k_a k_c})\,\frac{2J'+1}{2J+1}\,\exp\Big(-\frac{\Delta E}{kT_K}\Big)$$

where k is Boltzmann constant and ΔE the energy difference between upper and lower energy level.

2.3 Anomalous absorption

Intensity, I_ν, of a line generated in an interstellar cloud, with homogeneous excitation conditions, is

$$I_\nu - I_{\nu,bg} = (S_\nu - I_{\nu,bg})(1 - e^{-\tau_\nu}) \tag{1}$$

where S_ν is the source function, $I_{\nu,bg}$ the background intensity against which the line is observed and τ_ν the optical depth of the line. Equation (1) can also be expressed as

$$B_\nu(T_B) - B_\nu(T_{bg}) = \big[B_\nu(T_{ex}) - B_\nu(T_{bg})\big](1 - e^{-\tau_\nu})\big] \tag{2}$$

where B_ν represents a Planck's function corresponding to various temperatures, T_{bg} the background temperature, and T_B and T_{ex} the brightness and excitation temperatures, respectively, of the line. For absorption against CMB, we have $T_B < T_{bg}$. This obviously shows that for optically thin case, $\tau_\nu \approx 0$ and we have $T_B = T_{bg} \equiv$ 2.73 K. Further, in the Rayleigh-Jeans limit [ν(GHz) $<<$ 21 T(K)], Equation (2) can be written as

$$T_B = T_{ex} + (T_{bg} - T_{ex})e^{-\tau_\nu}. \tag{3}$$

For anomalous absorption, we have $T_{ex} < T_{bg}$ and $\tau_\nu > 0$, and therefore, $T_B > T_{ex}$.

When τ_ν is very large, then for anomalous absorption, we have $T_B = T_{ex}$. It shows that for anomalous absorption, brightness temperature of the line lies in between T_{ex} of the line and T_{bg} ($T_{ex} < T_B < T_{bg}$).

3. Results and Discussion

In our model, free parameters are the hydrogen density n_{H_2} and γ. In order to include a large number of cosmic objects, where H_2CO molecule may be found, numerical calculations are carried out for wide ranges of physical parameters. In present investigation, we have taken $\gamma = 10^{-5}$, 10^{-4} and 10^{-3} cm^{-3} (km/s)$^{-1}$ pc. The molecular hydrogen density n_{H_2} is varied over the range from 10^2 to 10^5 cm^{-3}, and calculations are performed for kinetic temperatures of $10 - 40$ K. The results are given in Figures 1 - 3 for the three lines.

All energy levels of ortho-H_2CO are in the form of K-doublets. The observed lines in absorption are due to transitions between the levels of doublets. In cosmic objects, the value of Δv varies from 1 to 7 km s^{-1} and column density of H_2CO is generally larger than 3 $\times 10^{15}$ cm^{-2} and therefore the value of γ is well covered in our investigastion. With increase of the value of γ, probability of detection of anomalous phenomenon increases. However, in our programme we find some instabilities and consequently, the results show either kinks or sudden change in the value. However, there should be smooth variation of the parameters.

Our results show that the transition $1_{10} - 1_{11}$ can be seen in anomalous absorption at $n_{H_2} \approx 10^{3.5}$ cm^{-3} and kinetic temperature of about 30 K. The transition $2_{11} - 2_{12}$ can be seen in anomalous absorption in a bit dense and rather cool cosmic objects. Besides these two transitions, already observed in anomalous absorption, we found that the transition $3_{12} - 3_{13}$ at 28.974 GHz can be seen in anomalous absorption at $n_{H_2} \approx 10^{4.5}$ cm^{-3} and kinetic temperature of about 20 K. Thus, detection of these three lines in anomalous absorption can provide information about density as well as kinetic temperature in the region.

4. Conclusion

It is interesting to note that anomalous absorption of three lines $1_{10} - 1_{11}$, $2_{11} - 2_{12}$ and $3_{12} - 3_{13}$ can provide information about density as well as kinetic temperature in the region. Thus, not only one line $1_{10} - 1_{11}$, but other two transitions $2_{11} - 2_{12}$ and $3_{12} - 3_{13}$ of H_2CO can also be used as probe of high density gas at low temperature. Further, the anomalous absorption can be used as a technique for identification of H_2CO in the cosmic objects.

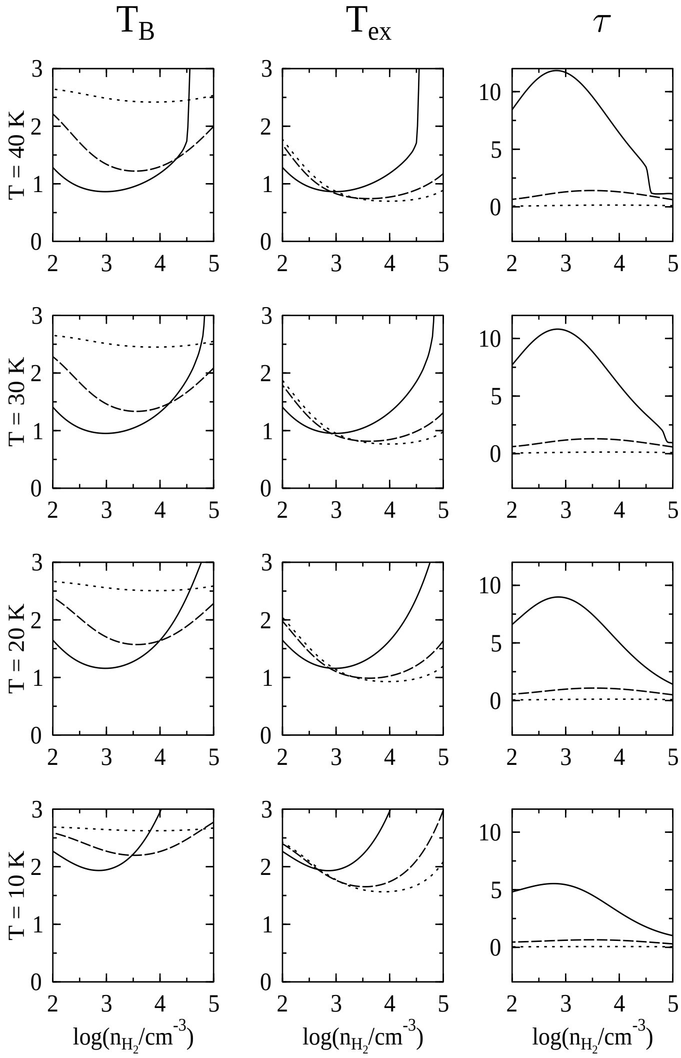

Figure 1. Variation of brightness temperature T_B (K), excitation temperature T_{ex} (K) and optical depth τ versus hydrogen density n_{H_2} of the line $1_{10} - 1_{11}$ for kinetic temperature T = 10 - 40 K. Solid line is for γ =10^{-3} cm^{-3} (km s)$^{-1}$ pc, the dashed line for $\gamma = 10^{-4}$ cm^{-3} (km s)$^{-1}$ pc and the dotted line for $\gamma = 10^{-5}$ cm^{-3} (km s)$^{-1}$ pc.

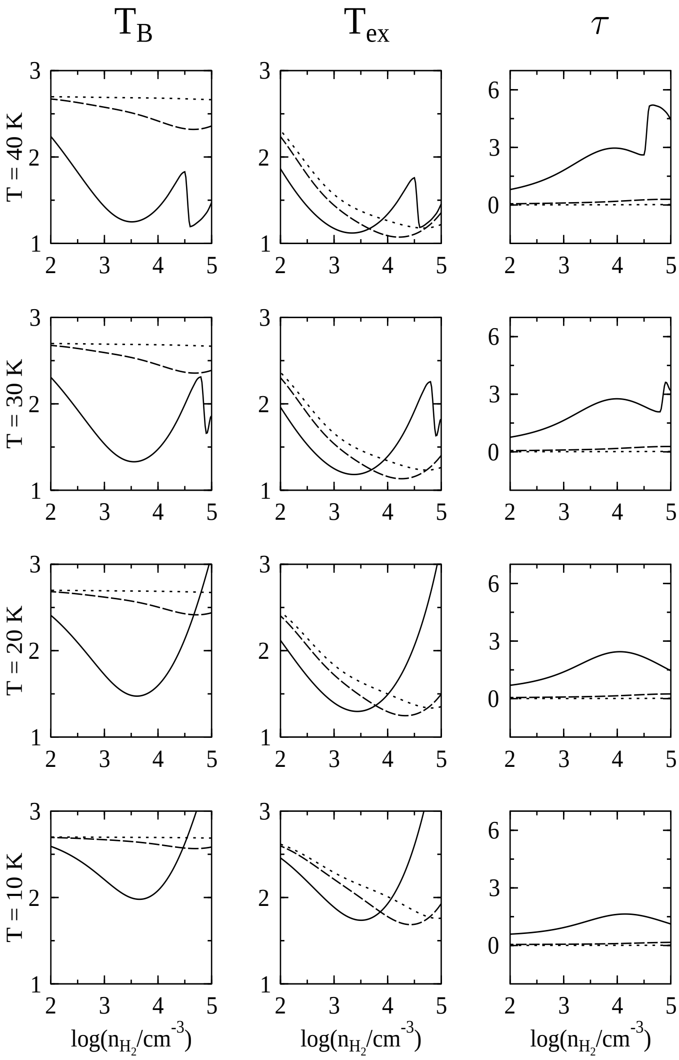

Figure 2. Variation of brightness temperature T_B (K), excitation temperature T_{ex} (K) and optical depth τ versus hydrogen density n_{H_2} of the line $2_{11} - 2_{12}$ for kinetic temperature T = 10 - 40 K. Solid line is for $\gamma = 10^{-3}$ cm^{-3} (km s)$^{-1}$ pc, the dashed line for $\gamma = 10^{-4}$ cm^{-3} (km s)$^{-1}$ pc and the dotted line for $\gamma = 10^{-5}$ cm^{-3} (km s)$^{-1}$ pc.

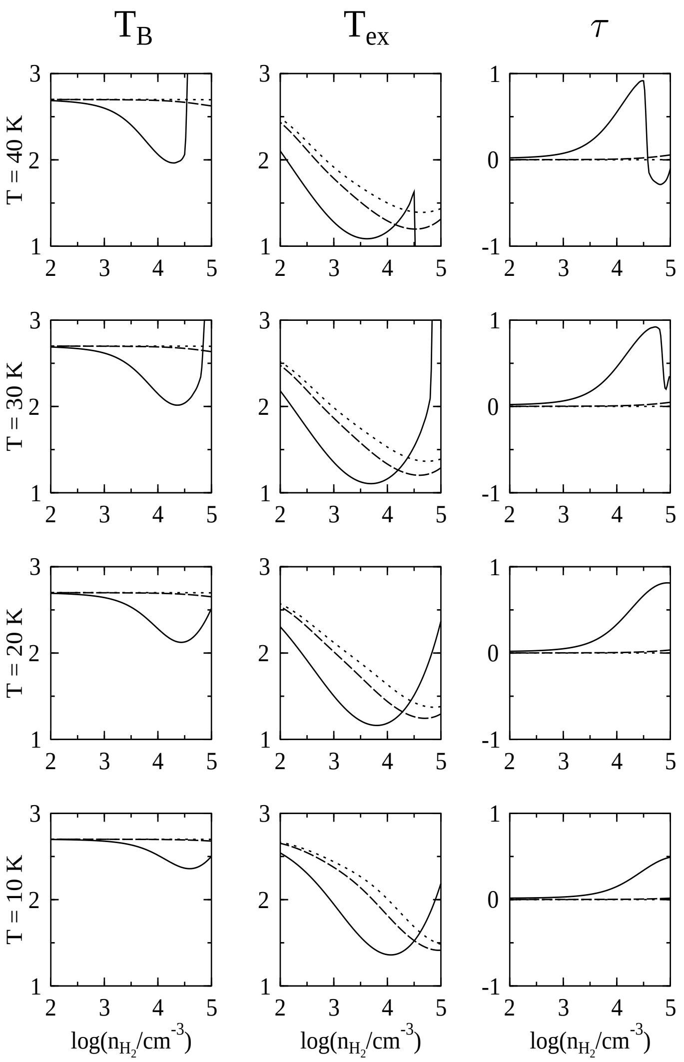

Figure 3. Variation of brightness temperature T_B (K), excitation temperature T_{ex} (K) and optical depth τ versus hydrogen density n_{H_2} of the line $3_{12} - 3_{13}$ for kinetic temperature T = 10 - 40 K. Solid line is for $\gamma = 10^{-3}$ cm^{-3} (km s)$^{-1}$ pc, the dashed line for $\gamma = 10^{-4}$ cm^{-3} (km s)$^{-1}$ pc and the dotted line for $\gamma = 10^{-5}$ cm^{-3} (km s)$^{-1}$ pc.

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