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Absorption against the cosmic 2.7 K background

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Abstract. Two interstellar lines, $1_{10} \rightarrow 1_{11}$ of formaldehyde at 4.831 GHz, and $2_{20} \rightarrow 2_{11}$ of cyclopropenylidene at 21.590 GHz, have so far been observed in absorption against the cosmic 2.7 K background. Observation of an interstellar line in absorption against the cosmic 2.7 K background is an unusual phenomenon, and can only be possible under rather peculiar conditions developed in the molecule, generating the line. We predict that two more lines, $3_{30} \rightarrow 3_{21}$ at 27.100 GHz, and $3_{31} \rightarrow 3_{22}$ at 59.550 GHz of cyclopropenylidene, and three lines, $2_{20} \rightarrow 2_{11}$ at 15.600 GHz, $3_{30} \rightarrow 3_{21}$ at 23.100 GHz, and $3_{31} \rightarrow 3_{22}$ at 39.700 GHz of ethylene oxide, may show absorption against the cosmic 2.7 K background. We speculate that such peculiar conditions are characteristic for b-type asymmetrical top molecules. – The observation of these lines may be used to place upper bounds to the density in the absorbing region.

Key words. molecular processes – ISM: molecules – Cosmology: cosmic microwave background – radio lines: ISM

1. Introduction

Observation of an interstellar line in absorption against the cosmic 2.7 K background is an unusual phenomenon. The intensity, I_ν, of a line generated in an interstellar cloud, with homogeneous excitation conditions, is given by

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

where $I_{\nu,\mathrm{bg}}$ is the intensity of the continuum against which the line is observed, τ_ν the optical depth of the line, and S_ν the source function, which is the Planck's function at the excitation temperature T_{ex}, i.e., $S_\nu = B_\nu(T_{\mathrm{ex}})$. For positive optical depth (which is a usual situation for most of the lines), a line is observed in absorption when $S_\nu < I_{\nu,\mathrm{bg}}$. The lower limit of $I_{\nu,\mathrm{bg}}$ is given by the cosmic 2.7 K background. Observation of an interstellar line in absorption against the cosmic 2.7 K background, obviously, implies $T_{\mathrm{ex}} < 2.7$ K, which requires rather peculiar physical conditions in the molecule, generating the line.

Up to now, only two lines have been reported in absorption against the cosmic 2.7 K background. The first one is the $1_{10} \rightarrow 1_{11}$ transition of formaldehyde at 4.831 GHz, which was found in absorption in several directions (Palmer et al. 1969). However, in some cases, it has been seen in emission, and even as a maser line (Foster et al. 1980; Whiteoak & Gardener 1983). The second line found in absorption against the cosmic 2.7 K background, in a large number of cosmic objects, is the $2_{20} \rightarrow 2_{11}$ transition of cyclopropenylidene at 21.590 GHz (Madden et al. 1989). Cox et al. (1987), however, reported the observation of this line in emission in the Planetary Nebula NGC 7027.

Under interstellar conditions, the relative occupation of the levels in a given molecule is controlled by the competition between collisional and radiative transitions, between the energy levels in the molecule, and in general, it cannot be described by the Boltzmann distribution law. There are, however, two simple limiting cases: (i) For very high densities in the line forming region, the collisional transitions dominate the radiative ones, and thus, one gets a Boltzmann distribution corresponding to the local kinetic temperature, T_{kin}. (ii) When the density in the region is so low that the collisional transitions may be neglected in comparison to the radiative ones, and the external radiation field is just the microwave background, one gets the Boltzmann distribution corresponding to 2.7 K. (This, in fact, is one way to measure the temperature of the cosmic background radiation, Crane et al. 1990.) For intermediate densities, one finds, in the two level approximation, 2.7 K $\leq T_{\mathrm{ex}} \leq T_{\mathrm{kin}}$. This shows that in order to find out physical conditions, under which $T_{\mathrm{ex}} < 2.7$ K may occur, one has to account for a multilevel system of the molecule under investigation.

2. Formulation of the problem

In the present work, we have investigated two molecules, cyclopropenylidene (C_3H_2), and ethylene oxide (C_2H_4O). Cyclopropenylidene was identified in the interstellar space by Thaddeus et al. (1985) and has been found in many objects (Madden et al. 1989). Out of the thirteen lines

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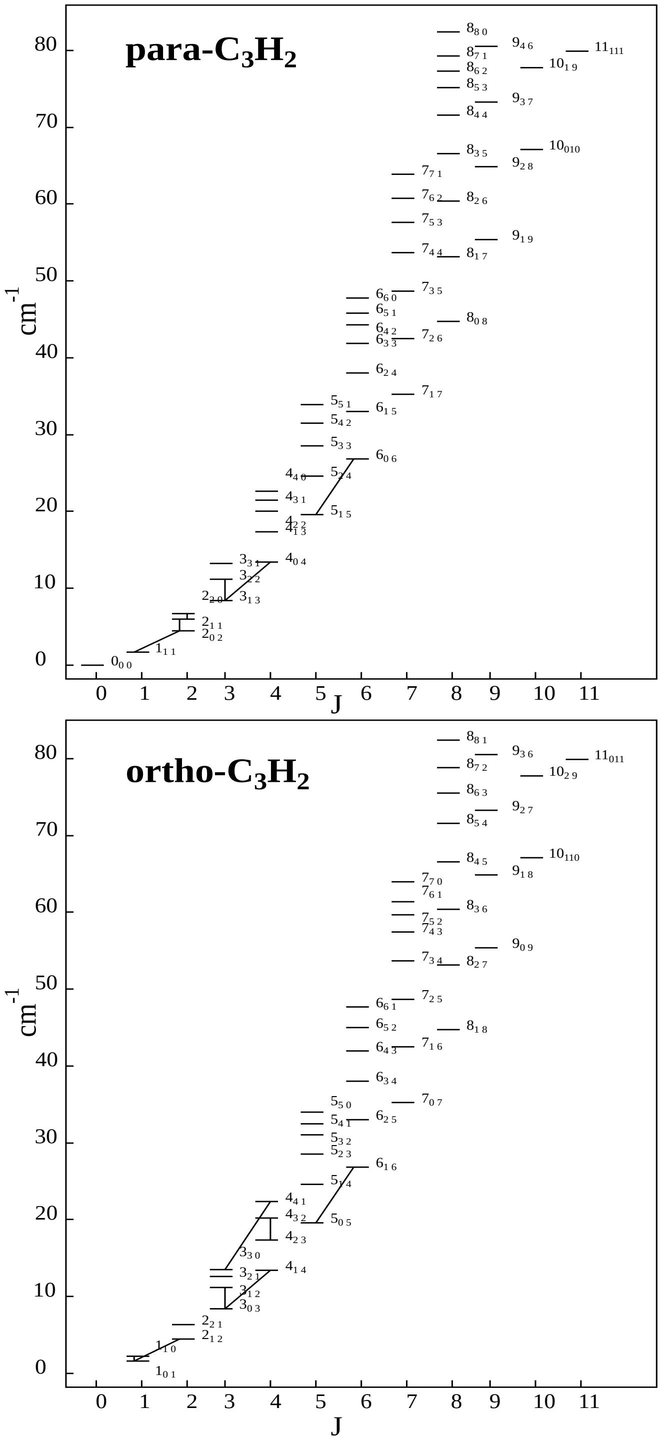

Fig. 1. Rotational energy levels in the ground vibrational state of para- and ortho-cyclopropenylidene (C_3H_2). The transitions shown correspond to the observed lines in the interstellar clouds

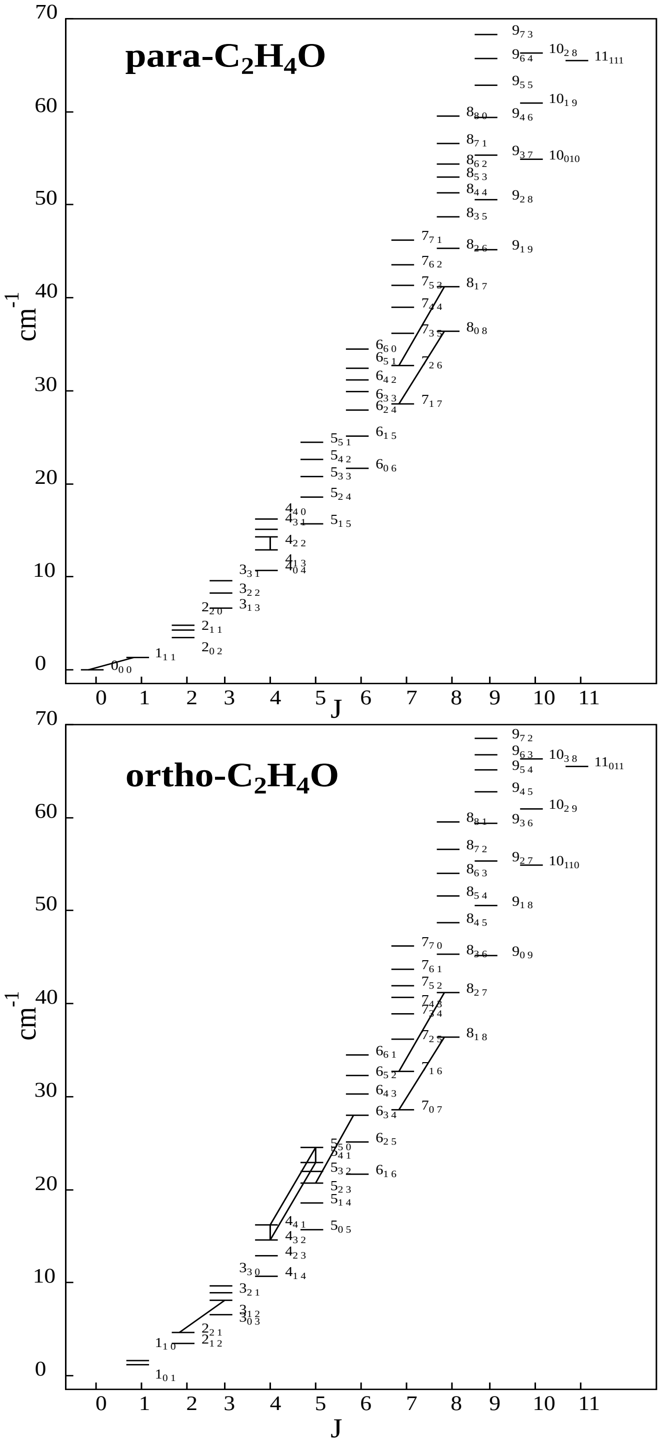

Fig. 2. Rotational energy levels in the ground vibrational state of para- and ortho-ethylene oxide (C_2H_4O). The transitions shown correspond to the observed emission lines in Sgr B2N

observed (see, Fig. 1) only the $2_{20} \rightarrow 2_{11}$ transition has been found in absorption. Ethylene oxide has been observed recently (Dickens et al. 1997), in Sgr B2N, through its twelve emission lines (see, Fig. 2). Both molecules are *b*-type asymmetric oblate rotors, having two distinct species, ortho and para.

With the aim to determine the physical conditions required for occurring the anomalous absorption against the cosmic 2.7 K background, we performed NLTE radiative transfer calculations for cyclopropenylidene (C_3H_2), and ethylene oxide (C_2H_4O), using a large velocity gradient (LVG) code (Cox et al. 1987; Rausch et al. 1996;

Table 1. Value of the minimum excitation temperature (Col. 4) achieved for the lines, showing absorption against the cosmic 2.7 K background, around the molecular hydrogen density n_{H_2} (Col. 5) at the kinetic temperature of 30 K. Columns 6 and 7 give the radiative life time of the upper and lower levels, respectively, of the line

Specie	Transition	Frequency (GHz)	T_{ex} (K)	n_{H_2} (cm^{-3})	Radiative Life Time (s)	
					Upper level	Lower level
para-C_3H_2	$2_{20} \rightarrow 2_{11}$	21.590	1.1	$5\ 10^4$	$1.79\ 10^4$	$3.61\ 10^5$
ortho-C_3H_2	$3_{30} \rightarrow 3_{21}$	27.100	1.6	$5\ 10^4$	$3.76\ 10^3$	$1.56\ 10^4$
para-C_3H_2	$3_{31} \rightarrow 3_{22}$	59.550	2.1	$2\ 10^4$ (at large γ)	$3.06\ 10^3$	$7.94\ 10^3$
para-C_2H_4O	$2_{20} \rightarrow 2_{11}$	15.600	0.8	$3\ 10^4$	$1.39\ 10^5$	$6.12\ 10^6$
ortho-C_2H_4O	$3_{30} \rightarrow 3_{21}$	23.100	1.1	$1\ 10^5$	$2.74\ 10^4$	$1.25\ 10^5$
para-C_2H_4O	$3_{31} \rightarrow 3_{22}$	39.700	1.5	$3\ 10^4$	$2.43\ 10^4$	$5.86\ 10^4$

de Jong et al. 1975; Goldreich & Kwan 1974), where the physical model is that of a homogeneous collapsing cloud. Owing to its simplicity, the present model allows to vary the physical parameters over wide ranges, with a moderate numerical efforts. The molecular data required as input parameters are: (i) Einstein coefficients for the various radiative transitions between the rotational energy levels accounted for (Figs. 1 and 2), and (ii) the rate coefficients for collisional transitions between the levels due to collisions with H_2 molecules. The Einstein A-coefficients are taken from Sharma & Chandra (1996) for cyclopropenylidene, whereas for ethylene oxide are calculated by using the molecular and distortional constants derived by Pan et al. (1998); the collisional rate coefficients for the transitions in cyclopropenylidene are taken from Avery & Green (1989), and Chandra & Kegel (2000), whereas for the downward transitions $J'k'_ak'_c \rightarrow Jk_ak_c$ in ethylene oxide at the kinetic temperature of 30 K, are approximated by the relation

$$C(J'k'_ak'_c \rightarrow Jk_ak_c) = 1\ 10^{-11}/(2J'+1).$$

Since this relation has no particular selections, it cannot from its own generate any NLTE situation. The rate coefficient for the corresponding upward transitions $Jk_ak_c \rightarrow J'k'_ak'_c$ has been calculated with the help of the detailed equilibrium equation.

As a background radiation field, we accounted only for the 2.7 K microwave radiation. The value of the molecular hydrogen density, n_{H_2}, which determines the collisional rates, and the quantity $\gamma \equiv n_{\mathrm{mol}}/(\mathrm{d}v_r/\mathrm{d}r)$ (where n_{mol} is the density of the molecule and $\mathrm{d}v_r/\mathrm{d}r$ the velocity gradient in the region), which corresponds to the column density of the molecule for the distance over which the Doppler shift is equal to the thermal line width, and determines the optical thickness in the various lines, have been varied over the ranges shown in Fig. 3. For cyclopropenylidene, the calculations were performed for $T_{\mathrm{kin}} =$ 10, 20, 30, 60, and 120 K. We found anomalous absorption, i.e., $T_{\mathrm{ex}} < 2.7$ K, in both the molecules for three lines, $2_{20} \rightarrow 2_{11}$, $3_{30} \rightarrow 3_{21}$, and $3_{31} \rightarrow 3_{22}$ (Fig. 3, Table 1).

3. Results

Since the line $2_{20} \rightarrow 2_{11}$ of cyclopropenylidene has already been observed in anomalous absorption, let us first, discuss, in brief, the results for this transition. In the present investigation, the basic excitation is evidently caused by collisions. Since the anomalous absorption is observed for a line connecting two excited levels, one would expect, at low densities, the effect to increase with the increase of n_{H_2}, and in fact this is what our numerical results show. The value of T_{ex} initially decreases with increasing n_{H_2}, reaches a minimum value and then increases. For $T_{\mathrm{kin}} = 10$ K, the minimum value of T_{ex} is 1.3 K, which occurs around $n_{\mathrm{H}_2} \approx 10^5$ cm^{-3}. For $n_{\mathrm{H}_2} \geq 10^6$ cm^{-3}, we found $T_{\mathrm{ex}} > 2.7$ K. Since the rate coefficients for collisional excitations increase with the kinetic temperature, the effect is expected to increase with the kinetic temperature. Our results are found in agreement with this expectation. At $T_{\mathrm{kin}} = 60$ K, we find a minimum excitation temperature of 1.1 K occurring around $n_{\mathrm{H}_2} = 5\ 10^4$ cm^{-3}. In the optically thin limit, i.e., when all lines are optically thin, the relative occupation numbers are independent of the column density. In this case, the optical depth, at a given molecular hydrogen density, increases linearly with the column density of the molecule. According to our results, optical thickness effects become important when $\gamma \geq 10^{-6}$ cm^{-3}(km s)$^{-1}$ pc. For larger values of γ, the excitation temperature of the $2_{20} \rightarrow 2_{11}$ transition is found to increase with the increase of the column density of the molecule.

As an illustration, Fig. 3 gives the intensities calculated for $T_{\mathrm{kin}} = 30$ K, where iso-lines of $(I_\nu - I_{\nu,\mathrm{bg}})/B_\nu(T_{\mathrm{kin}})$ have been plotted. The iso-line for the value -10^{-2}, for example, corresponds to the absorption of 0.3 K in brightness temperature.

We find qualitatively similar results for the $3_{30} \rightarrow 3_{21}$ and the $3_{31} \rightarrow 3_{22}$ transitions. At $T_{\mathrm{kin}} = 30$ K, the effect seen in the intensity (Fig. 3) is an order of magnitude smaller for the $3_{30} \rightarrow 3_{21}$ transition as compared to the $2_{20} \rightarrow 2_{11}$ transition. The anomalous absorption in the $3_{31} \rightarrow 3_{22}$ transition is about two orders of magnitude

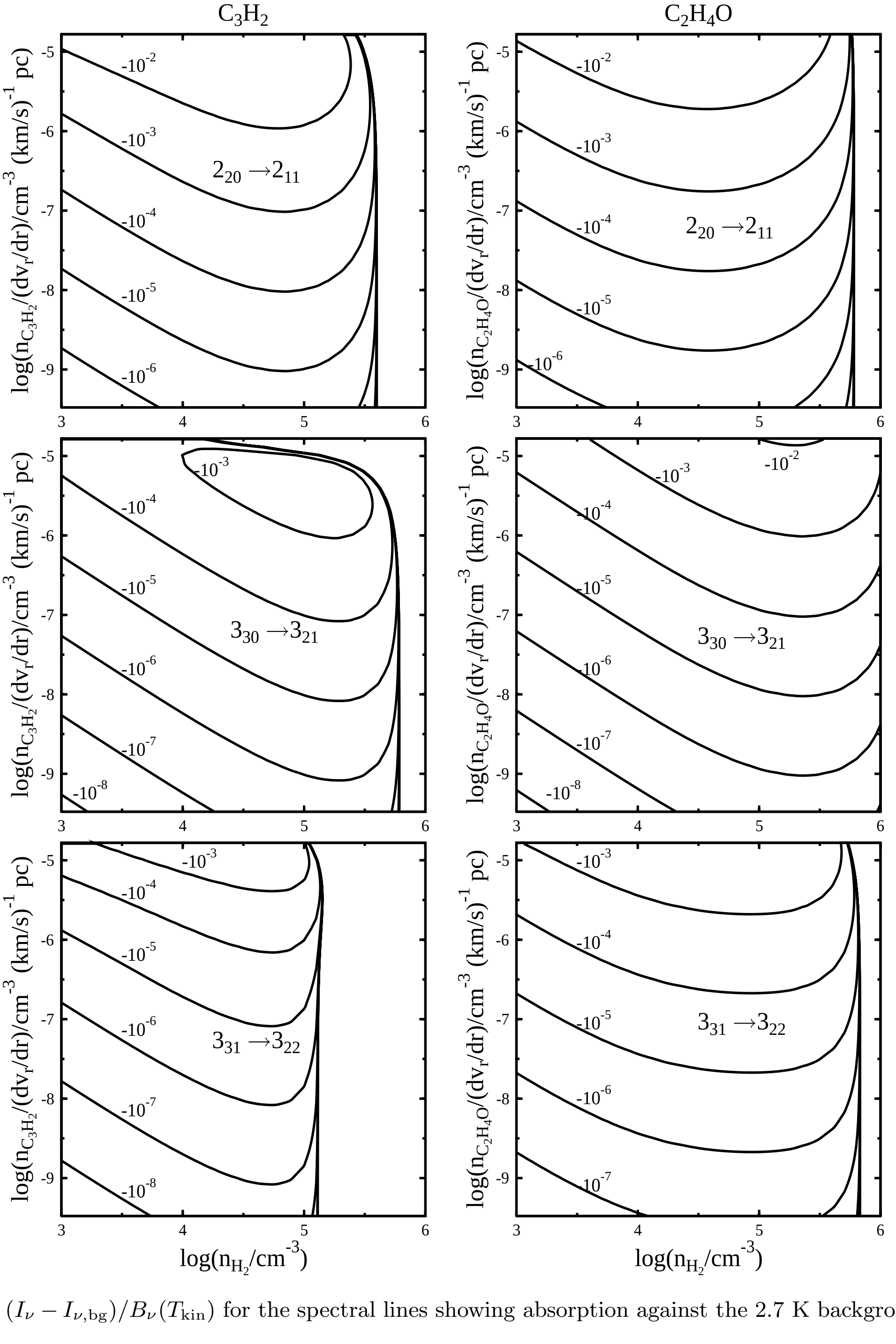

Fig. 3. Iso-lines for $(I_\nu - I_{\nu,\mathrm{bg}})/B_\nu(T_{\mathrm{kin}})$ for the spectral lines showing absorption against the 2.7 K background, computed for $T_{\mathrm{kin}} = 30$ K

weaker than in the $2_{20} \rightarrow 2_{11}$ transition and its detection will be difficult.

It appears worthwhile to discuss the numerical results in a qualitative manner in order to identify the main physical effect leading to anomalous absorption in the case studied here. We concentrate on the $2_{20} \rightarrow 2_{11}$ transition for which the effect is strongest. – At first we note that the pump mechanism is distinct from that leading to anomalous absorption in H_2CO. In the latter case anomalous absorption is observed for the line connecting the two lowest energy levels of ortho-H_2CO. To have an overpopulation of the 1_{11} state there must be an effective way to transfer molecules in the 1_{10} state to the 1_{11} state. According to Townes & Cheung (1969) this is achieved by the selectivity of the collision cross-sections, which favour the excitation of the 2_{12} state over that of the 2_{11} state. Subsequent radiative decay leads to an overpopulation of the 1_{11} state. – In the case studied here, we found anomalous absorption for transitions connecting two excited levels for which the lifetime against radiative decay of the lower level is substantially larger than that of the upper level. In the case of the $2_{20} \rightarrow 2_{11}$ transition the ratio of the lifetimes is

20 (Table 1). Anomalous absorption occurs in a density regime in which the lifetime of the upper level against collisional transitions is larger than that against radiative transitions. We further note that in the approximation used by Avery & Green (1989), the cross-section for collisional excitation of the 2_{11} level as well as of the 3_{22} level from the ground state 0_{00} is zero. Therefore, the sum of the rates of collisional excitation from the two lowest levels (0_{00} and 1_{11}) is smaller for the 2_{11} level than for the 2_{20} level. This implies that the collisions by themselves have the tendency to favour an overpopulation of the upper level rather than of the lower one. (In fact for very large densities our numerical results indicate population inversion.) These facts show that anomalous absorption in the present case is caused essentially by the differences of the radiative lifetimes of the upper and the lower level and not – as in the case of H_2CO – by the selectivity of the collisions. The main role of the collisions is to give a general excitation of the molecules, while the unequal distribution over the different levels is mainly caused by the radiative transitions.

Avery & Green (1989) investigated cyclopropenylidene accounting for 16 and 17 rotational energy levels for ortho- and para-C_3H_2, respectively, and found anomalous absorption, besides the transition $2_{20} \rightarrow 2_{11}$, for $3_{30} \rightarrow 3_{21}$ and $3_{21} \rightarrow 3_{12}$ transitions. Our calculations, accounting for 47 and 48 energy levels for ortho- and para-C_3H_2, respectively, (see, Fig. 1), however, did not find anomalous absorption for the $3_{21} \rightarrow 3_{12}$ transition. We note in passing that we found population inversion for the $1_{11} \rightarrow 0_{00}$ transition for n_{H_2} in the range from 10^5 cm^{-3} to 10^6 cm^{-3}, and for the $3_{13} \rightarrow 2_{20}$ transition in the range from 10^5 cm^{-3} to 3 10^5 cm^{-3}. The inversion is, however, so weak that it would not be recognized from the line profiles.

The results obtained for ethylene oxide are qualitatively very similar to those for cyclopropenylidene (see, Fig. 3), in particular we found anomalous absorption for the corresponding transitions. We relate this to the similarity of the energy level diagrams (Figs. 1 and 2) and the relative values for the Einstein A-coefficients for both the molecules. According to the arguments given above this implies that the occurrence of anomalous absorption against the cosmic 2.7 K background in these two systems is primarily related to peculiarities of the energy level diagram and the relative values of the Einstein A-coefficients, and to a lower degree to the collisional rate coefficients. In Table 1, we have given the minimum value of the excitation temperature T_{ex}, achieved for the line, around the molecular hydrogen density given in Col. 5 of the table.

A necessary condition for the mechanism discussed above to work, is that the radiative life-time of the upper level of the line must be smaller than that of the lower one. The larger the ratio of the life-times of the lower to the upper levels, the larger the absorption against the cosmic 2.7 K background. In case of anomalous absorption, the ratio of the population densities of the upper to the lower levels of the line satisfies the condition, $(n_{\mathrm{u}}/n_{\mathrm{l}})_{T_{\mathrm{ex}}} < (n_{\mathrm{u}}/n_{\mathrm{l}})_{2.7}$. As can be seen from Fig. 3, there is a rather sharp upper limit in density above which anomalous absorption does not occur. Thus the observation of anomalous absorption of the lines discussed is a rather direct way to place an upper bound to the density. At the critical density the collisional life-times of the levels become comparable to the radiative ones.

Based on the similarity of our numerical results for cyclopropenylidene and ethylene oxide, and based on the qualitative arguments given above, we expect that the occurance of anomalous absorption against the cosmic 2.7 K background, in particular for the $2_{20} \rightarrow 2_{11}$ transition may be a characteristic of *b*-type asymmetric top molecules.

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References

Avery, L. W., & Green, S. 1989, ApJ, 337, 306

Chandra, S., & Kegel, W. H. 2000, A&AS, 142, 113

Cox, P., Güsten, R., & Henkel, C. 1987, A&A, 181, L19

Crane, P., et al. 1990, in The Quest for Fundamental Constants in Cosmology, ed. J. Audouze, & J. Than Van (Éditions Frontières)

de Jong, T., Chu, S.-I., & Dalgarno, A. 1975, ApJ, 199, 69

Dickens, J. E., Irvine, W. M., Ohishi, M., et al. 1997, ApJ, 489, 753

Foster, J. R., Goss, W. M., Wilson, T. L., Downes, D., & Dickel, H. R. 1989, A&A, 84, L1

Goldreich, P., & Kwan, J. 1974, ApJ, 189, 441

Madden, S. C., Irvine, W. M., Matthews, H. E., et al. 1989, AJ, 97, 1403

Palmer, P., Zuckerman, B., Buhl, D., & Snyder, L. E. 1969, ApJ, 156, L147

Pan, J., Albert, S., Sastry, K. V. L. N., et al. 1998, ApJ, 499, 517

Rausch, E., Kegel, W. H., Tsuji, T., & Piehler, G. 1996, A&A, 315, 533

Sharma, A. K., & Chandra, S. 1996, J. A&A, 17, 41

Thaddeus, P., Vrtilek, J. M., & Gottlieb, C. A. 1985, ApJ, 299, L63

Townes, C. H., & Cheung, A. C. 1969, ApJ, 157, L103

Whiteoak, J. B., & Gardner, F. F. 1983, MNRAS, 205, 27p