Radiative excitation of CS molecules in atmosphere of a star*

Suresh Chandra

School of Physical Sciences, S R T M. University,
Nanded-431 606, Maharashtra, India

E-mail . suresh492000@yahoo co.in

Abstract We have investigated radiative excitation of CS molecules in atmosphere of a carbon star Besides those of the observed lines of CS molecule, intensities of some other lines, in the ground $v = 0$ as well as vibrationally excited $v = 1$ states, are computed. Intensities of other lines are found comparable to those of the observed ones, in the corresponding vibrational state, and therefore, those lines are probable candidates for their detection The lines in the vibrationally excited state, as well as between higher rotational levels in the ground vibrational state, are found to have a tendency of their formation in the regions close to the photosphere of the star, whereas the reverse has been found for the lines between lower rotational levels in the ground vibrational state

It is found that lines in the vibrationally excited state cannot be generated, even in a high density and high temperature region, unless external infrared radiation field is present

Keywords . CS molecule, radiative excitation, steller atmosphere

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1. Introduction

Interstellar CS was discovered by Penzias *et al* [1] through its transition $J = 3 \rightarrow 2$ in the ground vibrational state ($v = 0$), in Ori A, W 51, DR 21 and IRC + 10216 astronomical objects. Since then, various rotational transitions of CS have been observed in a number of astronomical objects. Some rotational transitions have been observed in the vibrationally excited ($v = 1$) state also The observed transitions of CS are marked by putting an asterisk on the frequency in Table 1. Molecules are found in vibrationally excited states either near the regions of star formation or in the atmosphere of an evolved star. Hence, vibrationally excited molecules may play an important role for finding out physical conditions near star forming regions and in the atmosphere of an evolved star.

In the present investigation, we are interested in the CS molecules observed in the atmosphere of a carbon star. Carbon stars show a substantial mass-loss rate, and thus, their envelopes are expanding. Since the details of pumping processes of the lines depend on the velocity difference between the photosphere

of the star and the emitting volume element, intensities of the observed lines may be used as a useful tool to study the velocity field in the envelope of the star. We, in particular, have investigated the influence of the photospheric spectrum of the star on the pumping mechanism.

Table 1. Frequency (in GHz) of transitions of CS molecule in the ground ($v = 0$) and vibrationally excited ($v = 1$) states, The observed lines are marked by putting an asterisk on the frequency.

Transition	$v = 0$	$v = 1$
$J = 1 \rightarrow 0$	48.991*	48.636
$J = 2 \rightarrow 1$	97.981*	97 271*
$J = 3 \rightarrow 2$	146 969*	145 904*
$J = 4 \rightarrow 3$	195.954	194.534
$J = 5 \rightarrow 4$	244.035*	243.161*
$J = 6 \rightarrow 5$	293.912*	291.782*
$J = 7 \rightarrow 6$	342 883*	340.398*
$J = 8 \rightarrow 7$	391.847	389.007
$J = 9 \rightarrow 8$	440.803	437.608
$J = 10 \rightarrow 9$	489 751*	486.201*

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*Dedicated to Professor A W Joshi on the occasion of his sixtieth birth-day.

To the best our knowledge, there is no theoretical investigation for the CS molecule in atmosphere of an evolved star. However, studies for the molecules in interstellar molecular clouds have been done by Turner *et al* [2], Liszt and Linke [3] and Martin and Barrett [4], Turner [5] and Highberger *et al* [6].

2. Basic formulation and input parameters

Non-Local Thermal Equilibrium (NLTE) occupation numbers of CS molecules in atmosphere of the star are calculated in an on-

the-spot approximation, by using the escape probability method (see, e.g., Rausch *et al* [7]), where the external radiation field $I_{v,bg}$ impinging on the volume element emitting the lines, has two components : (i) the cosmic 2.7 K background, and (ii) the radiation coming from the photosphere of the star. Hence,

$$I_{v,bg} = (1 - f) \, B_v (2.7K) + f \, F_{phot} (v, \Delta v_r),$$

where πF_{phot} is the Doppler shifted photospheric flux and f is the dilution factor.
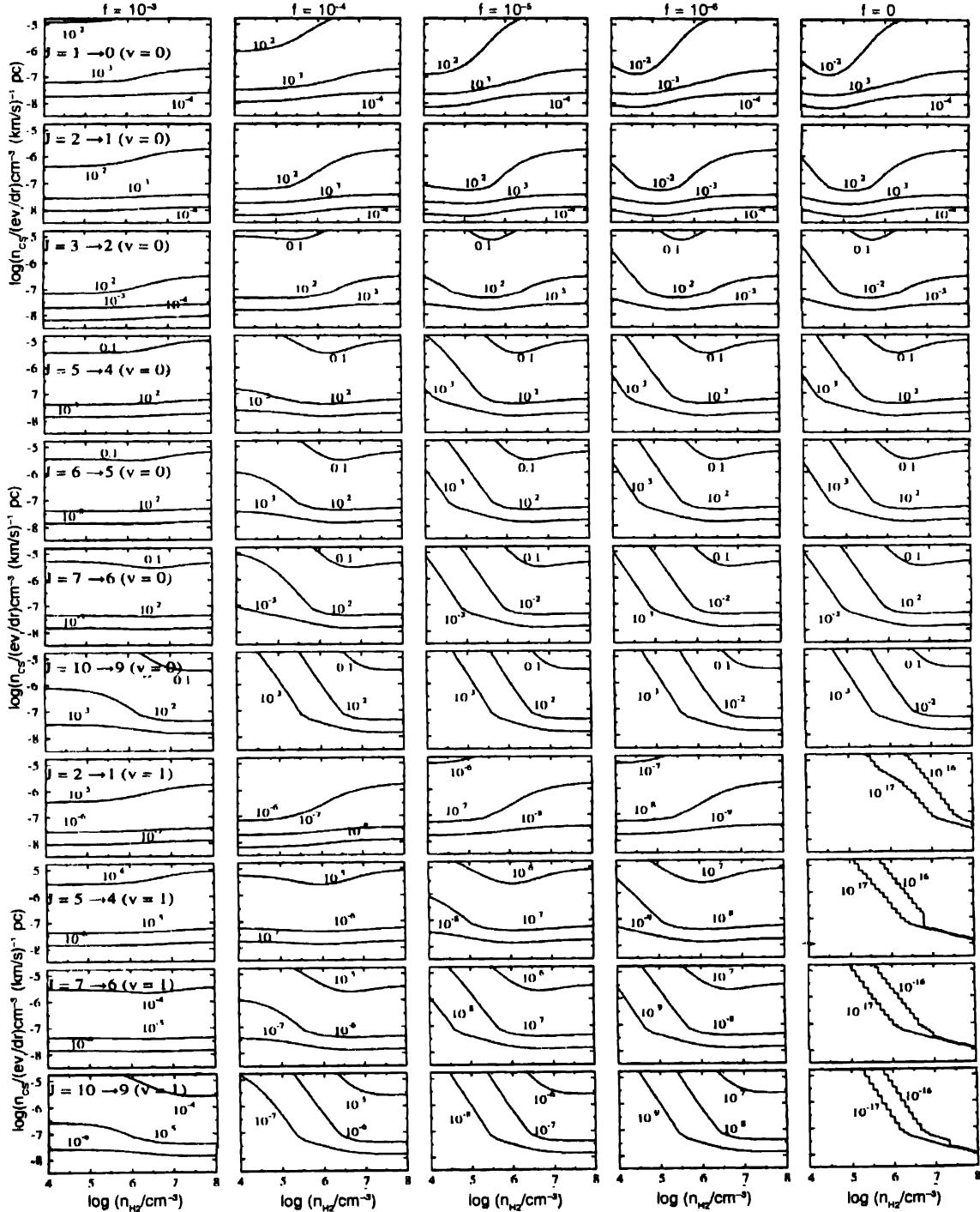

Figure 1. Iso-lines for the intensity in the units of Planck's function at kinetic temperature of 100 K, of some lines, for various values for the dilution factor f. The dilution factor $f = 0$ corresponds to the case (ii).

In our investigation, we have considered a carbon star IRC + 10216 (the source of infrared (IR) radiation field) having a photospheric temperature of 2300 K reported by Keady *et al*[8]. The star is considered to behave like a black-body. Temperature in the atmosphere of the star varies, and we considered a kinetic temperature of 100 K for the volume element, which may exist some where at a distance in between from $15R_*$ to $500\ R_*$, (R_* being the radius of the star). Therefore in our calculations, the dilution factor f has been varied from 10^{-3} to 10^{-6} in order to cover a wide range. Molecular clouds are dust-rich and the radiation from the star are reprocessed by the dust grains. The effect of the dust grains would be cared through the dilution factor f. Moreover, the on-the-spot approximation being rather crude one, present results show qualitative behaviour.

In order to limit the numerical efforts in the investigation, we accounted for three vibrational states, $v = 0$, 1 and 2 of the CS

molecule. In these states, we considered those rotational levels which lie below the next higher vibrational state, and hence, we accounted for the rotational levels up to $J = 39$, 38, and 38, in the vibrational states, $v = 0$, 1 and 2, respectively. Thus, in all, our system consists of 118 energy levels, which are connected through 345 radiative transitions. For these 345 radiative transitions, we used the Einstein A-coefficients, calculated by Chandra *et al* [9]. Collisional rate coefficients between all the levels are computed by using standard formulae discussed by Chandra and Sharma [10]. Though the validity of these formulae at 100 K is questionable, to some extent, we have no other options due to absence of other data.

3. Results and discussion

We performed calculations for two situations : (i) when there is radiation field from the star having photospheric temperature of
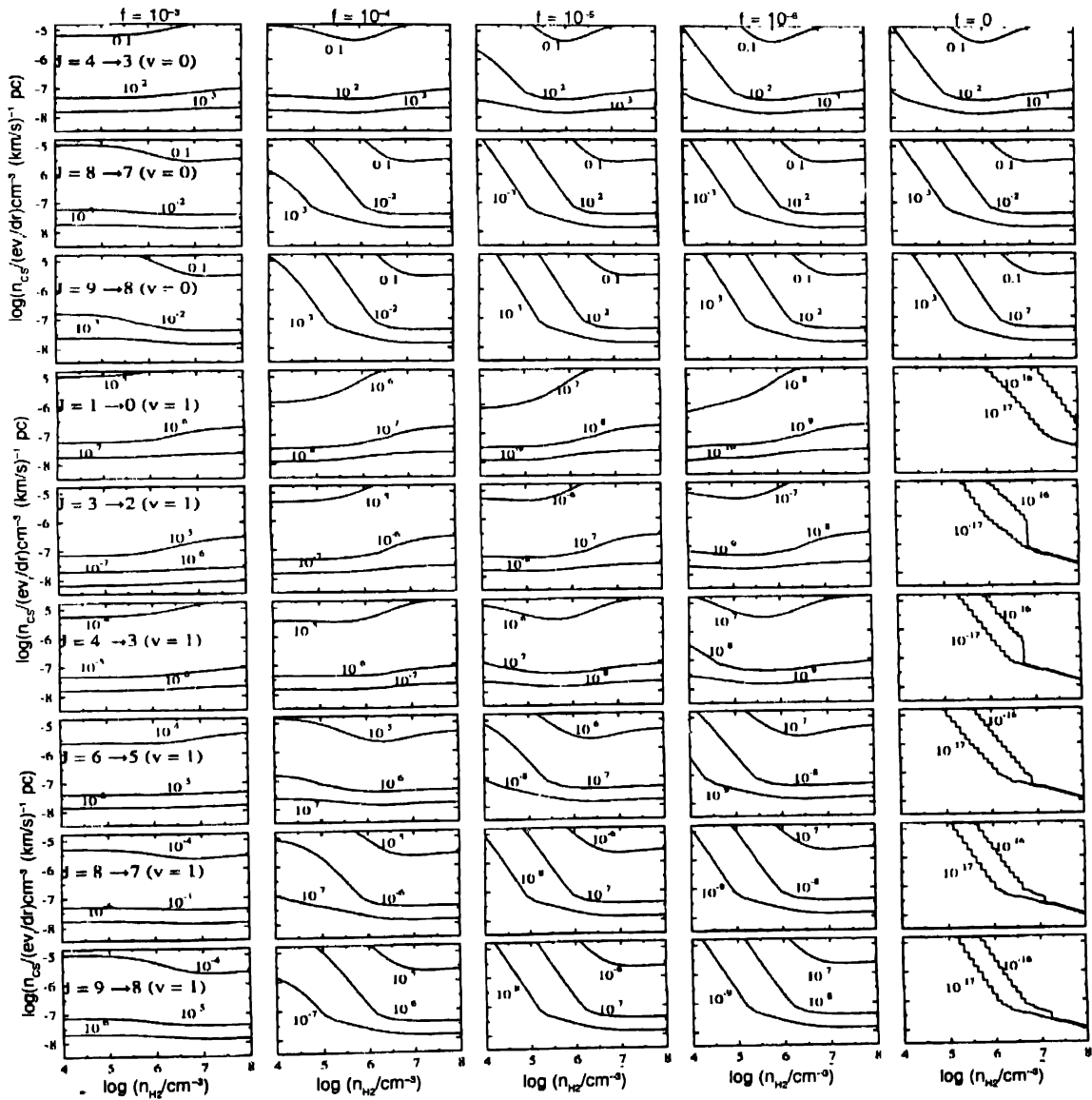

Figure 2. Iso-lines for the intensity in the units of Planck's function at kinetic temperature of 100 K, of other lines, for various values for the dilution factor f. The dilution factor $f = 0$ corresponds to the case (ii).

2300 K, besides the cosmic 2.7 K background, and (ii) when only the cosmic 2.7 K background is present. Effect of the atmosphere in between photosphere of the star and the volume element including dust is accounted for, through the dilution factor f. Case (ii) obviously, corresponds to the situation when the dilution factor f is zero in the case (i). The molecular hydrogen density is varied over the range from $10^4\,cm^{-3}$ to $10^8\,cm^{-3}$

The free parameters in our investigation are the molecular hydrogen density n_{H_2} and $n_{CS}\,/\,(dv_r/dr)$, where n_{CS} is density of CS molecules, and (dv_r/dr) the velocity gradient. Intensities in the unit of Planck's function at kinetic temperature of 100 K, of the lines given in Table 1, are calculated. Iso-lines of intesities for the lines are given in Figures 1 and 2. Various lines show different behaviour for variation of intensity with molecular hydrogen density and with the parameter $n_{CS}/(dv_r/dr)$. Intensities of the lines in the ground vibrational state are about three orders of magnitude larger than those in the vibrationally excited state, showing that observation of lines in the vibrationally excited state is a rather difficult task.

Interesting to note that intensities of the unobserved lines are comparable to those of the observed ones, in the corresponding vibrational state, and therefore, these lines may also be observed. The lines in the vibrationally excited state, as well as between higher rotational levels in the ground vibrational state, are found to have a tendency of their formation in the regions close to the photosphere of the star, whereas the reverse is found for the lines between lower rotational levels in the ground vibrational state. Since the nature of variation of intensity is different for various lines, ratio of intensities of two lines observed in a common region may provide information about molecular hydrogen density in the region and/or about density of the molecule of CS for the known velocity gradient.

When the external IR field is absent ($f = 0$), intensity of the lines in the vibrationally excited state ($v = 1$) is practically zero. Thus, for a molecule to be in a vibrationally excited state, external IR field is essential. Further, in absence of the IR field, molecular

hydrogen density does not help in formation of lines in the vibrationally excited state. Collisional rates are the only parameters where kinetic temperature is utilized. We repeated the calculations for a kinetic temperature of 1000 K in the region for the case when external IR field is absent ($f = 0$). Intensities of the lines in the vibrationally excited state were still found practically zero, showing that in absence of the external IR field, high density and high temperature of the region, cannot support the formation of the lines in the vibrationally excited state. It may therefore, be concluded that lines in vibrationally excited states cannot be found, even in the regions having high density and high kinetic temperature, unless external IR field is present

Finally, we would like to state that on-the-spot approximation is rather crude one, and therefore, the present investigation is qualitative in nature.

Acknowledgments

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