

DIFFUSION OF CO AND CH MOLECULES IN THE SOLAR ATMOSPHERE

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The calculated rates of photodissociation, radiative association and the diffusion of CH and CO molecules show that the diffusion rates are many orders of magnitude smaller than the photodissociation and radiative association rates, both in the photosphere and spots. Moreover, the diffusion velocities are much smaller than the turbulence velocities in the photosphere and spots. Thus, the diffusion of diatomic molecules (with dissociation energies in the range 3.47 eV to 11.01 eV) is not possible in the solar atmosphere.

Диффузия молекул СО и СН в солнечной атмосфере

Вычисленная скорость фотодиссоциации, радиационного слияния и диффузии молекул СН и СО показывает, что скорости диффузии на много порядков меньше скоростей фотодиссоциации и радиационного слияния как в фотосфере так и в пятнах. Кроме того скорости диффузии гораздо меньше скоростей турбулентности в фотосфере и пятнах. Таким образом диффузия двухатомных молекул (с энергией диссоциации в пределах от 3,47 эв до 11,01 эв) в солнечной атмосфере не возможна.

1. Introduction

The strength and the shape of molecular line profiles depend on the depth variation of the ratio between the line opacity and the continuum opacity for a considered line. The line opacity is basically determined by the concentration-optical depth run for the selectively absorbing species. Consequently, if this species, taken as a minor constituent of the atmosphere, happens to diffuse, then the ratio of the line to continuum opacities will be altered. In such a case the calculations of the profile parameters and equivalent widths based on models may need to use properly altered concentration-optical depth curves.

Pande (1966) considered the diffusion of CO in URP (Heintze et al., 1964) with a view to find out whether the thin photospheric molecular CO layer gets spread due to diffusion of CO molecules and concluded that no such spread occurs. The criteria used were that the photodissociation and the radiative association processes occur much faster than the diffusion process (i.e. the diffusing species loses its identity before it could diffuse) and that the velocity of diffusion of CO molecules is too small to overcome the mixing up of the layers produced by the large photospheric turbulence velocities.

A generalisation of the results given by Pande (1966) for other photospheric molecules is not possible without further detailed investigation because of the following reasons. The known diatomic molecules possess a wide range in dissociation energies between 2.4 eV (MgH) to 11.01 eV (CO). Further, for different molecules the probability of dissociation, which depends on the product of the density of the dissociating radiation and the oscillator strength, will

not be the same. With this in view, we selected the molecules CH and CO for investigating the problem of molecular diffusion in sunspots and photosphere.

We report here the results of such an investigation for BCA photosphere (Gingerich and De Jager, 1968) and Zwaan's (1965) sunspot model (ZSM).

2. Calculations of the Diffusive Flux

Briefly, the assumptions made are (Pande, 1966):

(1) CH and CO have small concentrations in an atmosphere primarily composed of hydrogen and helium atoms.

(2) Diffusion of the minor constituent does not affect the overall gas pressure.

(3) The diffusion coefficients can be obtained from the kinetic theory of gases.

(4) The initial concentration-optical depth curves for CH and CO in URP, BCA and ZSM and also the radiation field density maintaining the photodissociative equilibrium can be obtained under LTE.

Following Pande (1966), the equations (2.1), (2.2), (2.3) below give the diffusion velocity and the coefficients of diffusion $d(AB)$ respectively.

$$(2.1) \quad W = d(AB) \left[\frac{1}{N(AB)} \frac{dN(AB)}{dz} + \frac{1}{N} \frac{dN}{dz} \cdot (1 + \alpha) + \left(1 + \frac{m(AB)}{m} \right) \frac{1}{H} \right],$$

$$(2.2) \quad \log d(\text{CO}) = 6.332 + \log \frac{T^{3/2}}{Pg},$$

$$(2.3) \quad \log d(\text{CH}) = 6.328 + \log \frac{T^{3/2}}{Pg},$$

where AB represents CH or CO as the case may be. The quantity α represents thermal diffusion coefficient and an estimation of its role in the same manner as in Pande (1966) shows that it can be neglected in equation (2.1). The other symbols are explained in the referred paper. Finally, $S_d(\text{AB})$, the diffusive flux of species AB is:

$$(2.4) \quad S_d(\text{AB}) = \delta[N(\text{AB})]/\delta t = \delta[N(\text{AB}) W]/\delta z.$$

3. Estimation of the Photodissociation Rates

Following Kaplan and Pikelner (1970), the probability of photodissociation is given by:

$$(3.1) \quad \beta_d(\text{AB}) = 4\pi B(\nu_0) e^2 f \pi / h \nu_0 m c \quad (\text{sec}^{-1}),$$

where e , m , c , and h are the electronic charge and mass, velocity of light and Planck's constant respectively. $B(\nu_0)$ is the Planckian at the dissociation limit frequency ν_0 .

For photodissociation of CO in URP Pande (1966) obtained:

$$(3.2) \quad \log \beta_d(\text{CO}) = 7.72 - 55.350/T^*$$

and for CH in ground state $^2\Pi$, $h\nu_0 = 3.47$ eV and $f = 1/30$ (Kramers and ter Haar, 1946). So we have:

$$(3.3) \quad \log \beta_d(\text{CH}) = 7.24 - 17.470/T^*.$$

4. Results in BCA and URP Models

The diffusive flux $S_d(\text{CO})$ in URP $\sim 10^2$ particles $\text{cm}^{-3} \text{sec}^{-1}$ and the rate of disappearance of CO molecules for $T = 5000$ K and $N(\text{CO}) \sim 10^{11} \text{cm}^{-3}$ due to photodissociation is $\sim 10^8$ particles $\text{cm}^{-3} \text{sec}^{-1}$. Moreover, the W values are $(1-6) \times 10^{-2} \text{cm sec}^{-1}$ i.e. much smaller than the turbulence velocities in the photosphere. These facts show that the CO molecules lose their identity in the photodissociative equilibrium pretty rapidly thus inhibiting diffusion.

For CH the gas pressure and temperature runs against geometrical depth z used to obtain W and $S_d(\text{CH})$ in the manner outlined in Pande (1966) with one exception that $N(\text{CH}) - Z$ curve was obtained following Pande et al. (1969). $S_d(\text{CH})$ is $\sim 10^3$ particles $\text{cm}^{-3} \text{sec}^{-1}$. The $\beta_d(\text{CH})$ values are rather large, namely $10^3 \text{cm}^{-3} \text{sec}^{-1}$ at 4600 K and increase only by an order of magnitude upto 7000 K. The reciprocal of $\beta_d(\text{CH})$ is 10^{-3} sec and represents the characteristic time for a single act of photodissociation t_p under the physical conditions of BCA. Similarly, $N(\text{CH})/S_d(\text{CH})$ represents the characteristic time for a single act of diffusion of CH molecules and in our case:

$$(4.1) \quad t_d = N(\text{CH})/S_d(\text{CH}) \sim 10^3 - 10^6 \quad (\text{sec}).$$

A comparison of t_p and t_d shows that the photodissociation and radiative recombination acts (equal under stationary state) for a given time interval are 10^6 to 10^9 times more frequent than the acts of diffusion. In other words, diffusion of CH molecules is not possible in BCA specially because in this case the $W(\text{CH})$ values are much smaller than the turbulence velocities in the photosphere.

Pande (1966) and also we evaluated the coefficient of rate of recombination of the process $A + B \rightleftharpoons AB + h\nu$, denoted as $\beta_r(\text{AB})$, according to the formulation by Kramers and ter Haar and checked them for LTE according to the equation (Sitnik and Pande, 1968):

$$(4.2) \quad \beta_r(\text{AB}) = \frac{kT}{K(\text{AB})} \beta_d(\text{AB}).$$

For CO both the values agreed (Sitnik and Pande, 1968). In case of CH, $\beta_r(\text{CH}) \sim 10^{-17} \text{sec}^{-1}$ as against a value 10^{-18}sec^{-1} from the formulation by Kramers and ter Haar (1946). Keeping in mind the uncertainties involved, the two values agree in this case also.

5. Results in ZSM

As $\beta_d(\text{AB})$ is a function of the local Planckian it should decrease sharply in sunspots and may be that the photochemical processes are not in a position to check the diffusion of molecules. Without further investigation it is difficult to say whether the negative evidence about the diffusion of molecules in the photospheric models can be extended to sunspots also.

Therefore, the same investigation was done for one of the representative sunspot models i.e. ZSM.

In case of CH molecules in ZSM, our calculations show that t_p ranges from 10^{-1} to 10^{-5} sec., while from equation (4.1) t_d lies within 10^8 to 10^9 sec., and consequently, the diffusion of CH molecules is not possible.

For CO molecules t_d and t_p values as functions of depth Z in ZSM are summarized in Fig. 1. These results show that in upper layers of ZSM diffusion may occur as the characteristic times for a single act of diffusion and photodissociation are comparable. We can not give much weight to this result because most of the sunspot models are really very uncertain in the higher layers, specially in the regions above the level with optical depth at $\tau(5000) = 0.1$. Moreover, the small values of $W(\text{CO})$ compared against the large turbulence velocities in sunspots show that the referred diffusion may not occur at all. The $W(\text{CO})$ values

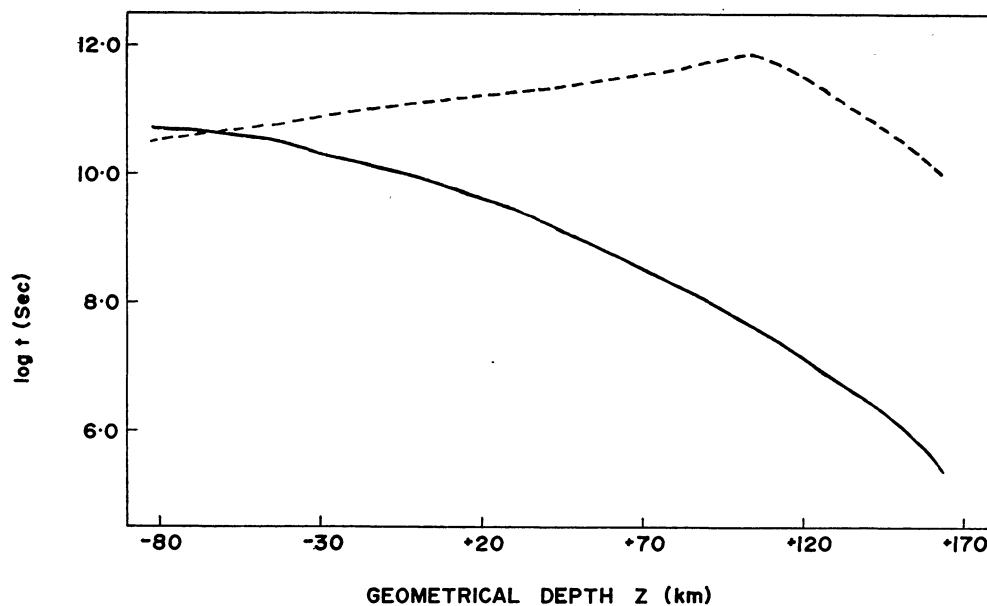


Fig. 1. The characteristic times t_d (broken line) and t_p (solid line) for CO molecules as functions of geometrical depth Z in ZSM.

range between 6.89×10^{-3} and 0.06×10^{-3} cm sec $^{-1}$, while the microturbulence velocity may be about 1.8 km sec $^{-1}$ in sunspots (Brückner, 1965).

6. Conclusions

In spots as well as in the photosphere the molecules CH and CO, possessing dissociation energies of 3.47 and 11.01 eV respectively, do not suffer any appreciable diffusion because of the very rapid photochemical processes and large turbulence velocities in these features. As faculae are hotter than the photosphere, the diffusion of molecules is much less probable. Summing up, diatomic molecules with dissociation energies in the range 3.47 to 11.01 eV will not suffer any appreciable diffusion in the solar atmosphere.

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