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Studies of Clump Structure of Photodissociation Regions at Millimeter and Sub-millimeter Wavelengths

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Abstract. To interpret the millimeter and sub-millimeter line emissions of atomic and molecular species from galactic and extragalactic photodissociation regions, warm gas components and molecular clouds, generally, escape probability formalism of Tielens & Hollenbach (herein referred as TH) are employed which is based on the assumption of plane parallel geometry of infinite slab allowing photons to escape only from the front. Contrary to the assumption observationally it is found that these lines are optically thin except OI(63μm) and low rotational transitions of CO and some other molecules. This observational evidence led us to assume that emitting regions are finite parallel plane slab in which photons are allowed to escape from both the surfaces (back and front). Therefore, in the present study escape of radiations from both sides of the homogeneous and also clumpy PDR/molecular clouds are taken into consideration for calculating the line intensities at millimeter and sub-millimeter wavelengths (hereinafter referred as QA). Results are compared with that of the TH model. It is found that thermal and chemical structures of the regions are almost similar in both the formalisms. But line intensities are modified by differing factors. Particularly at low density and low kinetic temperature and also for optically thin lines line intensities calculated from TH and QA model differ substantially. But at density higher than the critical density and also for optically thick lines TH and QA models converge to almost same values. An attempt has been made to study the physical conditions of the M17 region employing the present formalism.

Key words. Photodissociation region—clump structure—cooling lines —fine structure transitions and rotational transitions.

1. Introduction

During the last two decades theoretical attempts to interpret the observations from the photodissociation regions (PDRs), HII regions and reflection nebulae at millimeter and sub-millimeter wavelengths [CI (370 & 609 μm); OI (63 & 146 μm); CII (158 μm); SiII (35 μm); FeII (26 μm)]; and rotational lines of CO ($\Delta J = 1$ up to $J = 20$) have been made by Tielens & Hollenbach (1985 a,b); Stutzki *et al.* (1988); Wolfire *et al.* (1990); Castets *et al.* (1990); Tauber & Goldsmith (1990); Howe *et al.* (1991); Meixner *et al.* (1992); Meixner & Tielens (1993); Robert & Pagani (1993); Bennet *et al.* (1994);

Steiman-Cameron *et al.* (1997); Luhman *et al.* (1997); and Hermann *et al.* (1997); Kemper *et al.* (1999); Jackson & Kramer (1999) and Strorzer & Hollenbach (1999).

In theoretical studies of photodissociation regions, the model of Tielens & Hollenbach (1958a) (hereafter TH) has been extensively used to calculate the temperature and chemical structure (abundances of atomic, ionic and molecular species) of the region and also to calculate the line intensities of fine structure and rotational transitions of some of the atoms, ions and molecules, especially CO molecule. The PDR in the TH model is a homogeneous, semi-infinite, plane parallel slab illuminated on the non-infinite side by large flux of FUV ($6 < h\nu < 13.6$ ev) radiations (G_0 times more intense than the average interstellar radiation field 1.2×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} of Habing 1968) and line emission takes place only towards the observer (semi-infinite assumption of deJong *et al.* (1980)). But now it has been established through the observations that most of the PDRs are clumpy in nature and some of the lines observed are also optically thin (i.e., line optical depth is less than unity). Therefore, homogeneous one-dimensional semi-infinite plane parallel geometry is no longer valid.

In the present study, PDR is supposed to be a finite plane parallel slab having clumps and inter-clumps mixed together. An attempt has been made to incorporate the escape of radiation from both sides of the region. To solve the radiative transfer in one-dimensional approach, the techniques of Averett & Hummer (1965) have been used. Further, the formalism of Boisse (1990) has been employed to compute the mean FUV radiation as a function of depth z, in two phase clumpy region. We apply them to solve radiation transfer through a region of high density, low filling material (clump) and low density, high filling factor (inter-clump). The nature of work is purely investigative, therefore, no attempt has presently been made to study the variety of PDRs. However, the present formalism has been employed to study the clumpy region of M17.

The mathematical formulation of the problem is discussed in section 2, physical parameters and assumptions presented in section 3 and results (hereinafter referred to as QA) and discussions are in section 4. The calculations are summarised in section 5.

2. Mathematical formulation of problem

The current interest in the problem of photodissociation regions, associated with the HII regions, requires methods to compute the following:

- Mean FUV intensity as a function of depth into the clumpy clouds to calculate the thermal and chemical structure of the region.
- Net radiation loss due to escape of radiation at millimeter and sub-millimeter wavelengths through the clumpy PDRs.

2.1 *FUV penetration through PDRs*

In the present study we use the formalism of Boisse (1990) to compute mean FUV intensity as a function of depth z, in a two phase clumpy region. We apply them to the case of UV radiative transfer through a region of high density, low filling factor material (the clump) and low density high filling factor (inter-clump). The derived solutions appear in pairs: one for the average intensity in the clump and other for average intensity in interclump phase.

According to Boisse (1990) the equation of radiative transfer for the case of isotropic scattering may be written as

$$\partial I(M,\theta,\varphi)/\partial S = -K(M)I(M,\theta,\varphi) + \omega K(M)J(M), \tag{2.1.1}$$

where $I(M,\theta,\varphi)$ is the specific intensity at a point M along a distance S defined by the angle θ and φ, $K(M)$ the extinction coefficient, ω the albedo of dust grains (K and ω being wavelength dependent) and $J(M)$ the mean intensity (average of I over θ and φ).

The average flux on a plane perpendicular to the incident photon as $\Psi^+(z)$ and $\Psi^-(z)$ in the forward and backward direction respectively are given by a pair of integrals with (i, $j = 0$ or 1) following Boisse (1990) as

$$\begin{aligned}\langle\Psi_i^+(z)\rangle = {}& \frac{2\pi\omega\, K_i}{K''-K'}\int_0^z G_{ii}(z-z')\langle J_i(z')\rangle dz' \\ &+ \frac{2\pi\omega\, K_j}{K''-K'}\int_0^z G_{ij}(z-z')\langle J_j(z')\rangle dz' + \langle\Psi_i^0(z)\rangle\end{aligned} \tag{2.1.2}$$

and

$$\begin{aligned}\langle\Psi_i^-(z)\rangle = {}& \frac{2\pi\omega\, K_i}{K''-K'}\int_z^L G_{ii}(z'-z)\langle J_i(z')\rangle dz' \\ &+ \frac{2\pi\omega\, K_j}{K''-K'}\int_z^L G_{ij}(z'-z)\langle J_j(z')\rangle dz \\ \langle\Psi^{\pm}(z)\rangle = {}& P_0\langle\Psi_0^{\pm}(z)\rangle + P_1\langle\Psi_0^{\pm}(z)\rangle.\end{aligned} \tag{2.1.3}$$

The subscripts 0 and 1 stand for clumpy and interclump. G_{ii} and G_{ij} are defined as $G_{ii} = G_{00}$ or G_{11} and $G_{ij} = G_{01}$ or G_{10} given as below:

$$G_{00}(x) = (\nu P_0 + K_1 - K')E_2(K' \mid x \mid) + (K'' - \nu P_0 - K_1)E_2(K'' \mid x \mid), \tag{2.1.4}$$

$$G_{01}(x) = (\nu P_1[E_2(K' \mid x \mid) - E_2(K'' \mid x \mid)], \tag{2.1.5}$$

$$G_{10}(x) = (\nu P_0[E_2(K' \mid x \mid) - E_2(K'' \mid x \mid)], \tag{2.1.6}$$

$$G_{11}(x) = (\nu P_1 + K_0 - K')E_2(K' \mid x \mid) + (K'' - \nu P_1 - K_0)E_2(K'' \mid x \mid). \tag{2.1.7}$$

The physical meaning of K'' is the transfer of radiation inside individual clump while K' describe the “clump to clump" transport. Its value is given by

$$\begin{aligned}K'^{('')} &= \frac{\nu + K_0 + K_1 - (+)\sqrt{(\nu + K_0 + K_1)^2 - 4K_0K_1 - 4\nu\langle K\rangle}}{2} \\ \langle K\rangle &= P_0K_0 + P_1K_1,\end{aligned} \tag{2.1.8}$$

where P is filling factor.

The average intensity of photons in the clump and interclump is simply given by

$$\begin{aligned}\langle J_i(z)\rangle = {}& \frac{\omega\, K_i}{2(K''-K')}\int_0^L F_{ii}(z-z')\langle J_i(z')\rangle \\ &+ \frac{\omega\, K_i}{2(K''-K')}\int_0^L F_{ij}(z-z')\langle J_i(z')dz' + \langle J_i^0(z)\rangle.\end{aligned} \tag{2.1.9}$$

The pair of subscripts i and j has the same meaning as defined earlier.

F_{ii} and F_{ij} have similar expression as the G_{ii} and G_{ij} except that $E_2(x)$ is replaced by $E_1(x)$. $\langle \Psi_i^0 \rangle$ is the unscattered photons equal to $4\pi \langle J_i^0(z) \rangle$. The initial value is taken as $\langle J_i^0(z) \rangle$ defined by

$$\langle J_i^0(z) \rangle = \frac{J_{in}}{(K'' - K')} \left[(\nu + K_j - K') e^{-k'z} + (K'' - \nu - K_j) e^{-k''z} \right], \qquad (2.1.10)$$

$$J_{in} = \frac{\Psi_{in}}{4\pi},$$

where Ψ_{in} is the incident flux; and pair (i and j) has the same meaning as defined earlier.

2.2 *Escape of radiation through PDRs*

The radiative transfer equation in a plane-parallel slab and isotropic source for distance z normal to the plane of stratification can be written as

$$\frac{\mu \, dI_\nu}{d\tau_\nu} = \Phi_\nu(x)[I_\nu(\tau_\nu, \mu) - S_\nu(\tau_\nu)], \qquad (2.2.1)$$

where

$$\tau_\nu = \int_z^\infty K_\nu(z) dz$$

and $\Phi_\nu(x)$ is a normalized profile function where x is a dimensionless variable measured with respect to the line center such that

$$\int_{-\infty}^{\infty} \Phi_\nu(x) \, dx = 1. \qquad (2.2.2)$$

Here

$$x = (\nu_s - \nu)/\Delta\nu_D$$

$$\Delta\nu_D = V_d \, \nu/c \quad \text{and} \quad V_d = (2KT + V_t^2)^{1/2},$$

ν is the frequency of the line observed $I_\nu(\tau_\nu, \mu)$ is the specific intensity of radiation for frequency ν at a point z in a direction of inclination $\theta (\mu = \cos\theta)$ to the normal and also depends on x but it is not shown as a function of x. The broadening of line is simply considered due to microturbulence (turbulence velocity V_t), which makes it convenient to work with in terms of Doppler width in the line profile. $S_\nu(\tau_\nu)$ is the local source function.

In case of an atmosphere with finite optical thickness t_ν equation reduces to

$$I_\nu^+(\tau_\nu, +\mu) = I_\nu^c(t_\nu, +\mu) e^{\frac{-(t_\nu - \tau_\nu)\Phi_\nu(x)}{\mu}} + \frac{\Phi_\nu(x)}{\mu} \int_{\tau_\nu}^{t_\nu} S_\nu(t) e^{\frac{-(t-\tau_\nu)\Phi_\nu(x)}{\mu}} dt, \qquad (2.2.3)$$

$$I_\nu^-(\tau_\nu, -\mu) = I_\nu^c(0, -\mu) e^{\frac{-(\tau_\nu)\Phi_\nu(x)}{\mu}} + \frac{\Phi_\nu(x)}{\mu} \int_0^{\tau_\nu} S_\nu(t) e^{\frac{-(\tau_\nu - t)\Phi_\nu}{\mu}} dt, \qquad (2.2.4)$$

for $0 \le \mu \le 1$,

where I^+ and I^- symbolize the intensity towards observer and away from the observer $I^c_\nu(0, -\mu)$ and $I^c_\nu(t_\nu, \mu)$ are external source radiation at two faces of cloud (defined in terms of optical depth 0 as front face and t_ν as back face). Hereinafter these will be used as $I^c_\nu(o)$ and $I^c_\nu(t_\nu)$. The total radiation at any point inside the cloud at optical depth τ_ν after integrating over μ may be written as

$$I_\nu(\tau_\nu) = \frac{1}{2} I^c_\nu(0) E_2(\tau_\nu \Phi_\nu(x)) + \frac{1}{2} I^c_\nu(t_\nu) E_2((t_\nu - \tau_\nu)\Phi_\nu(x)) + \frac{1}{2}\int_0^{\tau_\nu} S_\nu(t) E_1(\mid (\tau_\nu - t) \mid \Phi_\nu(x)) dt. \tag{2.2.5}$$

The total intensity of a line at frequency ν averaged over the width can be written as

$$J_\nu(\tau_\nu) \ = \ \int_{-\infty}^{\infty} \Phi_\nu(x) I_\nu(\tau_\nu)\ dx, \tag{2.2.6}$$

here, $I_\nu(\tau_\nu)$ is a function of x also.

Finally after integration it comes out to be as

$$J_\nu \ = \ \frac{1}{2} I^c_\nu(0)\kappa_2(\tau_\nu) + \frac{1}{2} I^c_\nu(t_\nu)\kappa_2(t_\nu - \tau_\nu) + \int_0^{\tau_\nu} \kappa_1(\mid t - \tau_\nu \mid) S_\nu(t) dt, \tag{2.2.7}$$

where κ_1 and κ_2 in equation (2.2.7) are called the Kernel Function defined as

$$\kappa_1(\mid \tau_\nu - t \mid) = \frac{1}{2}\int_{-\infty}^{+\infty} \Phi^2_\nu(x) E_1(\Phi_\nu(x)(\mid t - \tau_\nu \mid))\ dx, \tag{2.2.8}$$

$$\kappa_2(\tau_\nu) = \int_{-\infty}^{+\infty} \Phi_\nu(x) E_2(\Phi_\nu(x)\tau_\nu)\ dx, \tag{2.2.9}$$

$$\int_0^{t_\nu} \kappa_1(\tau_\nu - t)\ dt = 1 - \frac{1}{2}\kappa_2(\tau_\nu) - \frac{1}{2}\kappa_2(t_\nu - \tau_\nu). \tag{2.2.10}$$

For homogeneous and isothermal, which may exist locally, the above equations may be simplified as

$$J_\nu(\tau_\nu) = \beta(\tau_\nu) I^c_\nu(0) + \beta(t_\nu - \tau_\nu) I^c_\nu(t_\nu) + S_\nu(\tau_\nu)[1 - \beta(\tau_\nu) - \beta(t_\nu - \tau_\nu)], \tag{2.2.11}$$

where $\beta(\tau_\nu) = \frac{1}{2}K_2(\tau_\nu)$ is the escape probability that a photon escapes from a surface at an optical depth τ_ν from the surface. The value of J_ν for the semi-infinite plane parallel slab (i.e., $t_\nu \rightarrow \infty$) may be reduced as

$$J_\nu(\tau_\nu) \ = \ I^c_\nu(0)\beta(\tau_\nu) + S_\nu(1 - \beta(\tau_\nu)) \tag{2.2.12}$$

which is the expression used by deJong *et al.* (1980) (equation B-4 of Appendix B). Therefore, for optically thin cases where t_ν is finite the TH model can not be employed, instead the general expression as defined earlier (2.2.7) for J_ν should be used.

2.3 *Cooling efficiency*

The gas is generally cooled by hyperfine transitions of atoms, ions and rotational transitions of some of the molecules and its isotopes. The cooling efficiency is the function of level populations of different levels, which enter, in the cooling efficiency through the escape probability terms. To solve for level populations, statistical equilibrium for bound-bound levels m and n are established as

$$N_m(x)\left(\sum_{l=1}^{n} P_{lm}(x)\right) = \sum_{l=1}^{n} N_l(x)P_{lm}(x) \quad \text{for } l \neq m \tag{2.3.1}$$

where $N_m(x)$ is the number density of the species x in level m and $P_{lm}(x)$ is the rate coefficient for species x between levels l and m as

$$P_{lm} = B_{lm}J_\nu + C_{lm} \quad (m < l), \tag{2.3.2}$$

$$P_{ml} = A_{ml} + B_{ml}J_\nu + C_{ml} \quad (m > 1). \tag{2.3.3}$$

Here A and B are Einsteins coefficients for m and l transitions which correspond to frequency ν and C_{lm} and C_{ml} are the collisional excitation and deexcitation rates. The intensity of radiation J_ν is given by the expression as

$$\begin{aligned} J_\nu = {} & S_{ml}(\tau_\nu)[1-\beta(\tau_\nu)-\beta(t_\nu-\tau_\nu)] + I_\nu^c(0)\beta(\tau_\nu) + I_\nu^c(t_\nu)\beta(t_\nu-\tau_\nu) \\ & + \beta(\tau_\nu)\tau_\nu^d B(\nu, T_0) + \beta(t_\nu-\tau_\nu)\tau_\nu^d B(\nu, T_0), \end{aligned} \tag{2.3.4}$$

$$S_{ml} = 2h\nu_{ml}^3/(c^2(g_m N_l/g_l N_m - 1)). \tag{2.3.5}$$

Here $B(\nu, T_0)$ is the infrared radiation at frequency ν and temperature T_0, τ_ν^d is the optical depth at frequency ν due to dust.

Now the cooling efficiency in units of erg cm^{-3}sec^{-1} will become as

$$\Lambda_{ml} = N_m A_{ml} h\nu_{ml}\beta_{ml}^{\text{esc}}\left[1 - \frac{B(\nu, T_0)\beta(\tau_\nu)}{\beta_{ml}^{\text{esc}} S_{ml}}\right], \tag{2.3.6}$$

here, $\beta_{ml}^{\text{esc}} = \beta(t_\nu - \tau_\nu) + \beta(\tau_\nu)$.

In the limit $t_\nu \to \infty$ equation (2.3.6) is reduced to

$$\Lambda_{ml} = N_m A_{ml} h\nu_{ml}\beta(\tau_\nu)\left[1 - \frac{B(\nu, T_0)}{S_{ml}}\right]. \tag{2.3.7}$$

This is the same as equation (20) of deJong *et al.* (1980) used by Tielens & Hollenbach (1985a).

3. Physical parameters and assumptions

In the recent past a great deal of work has been done on M17 by Meixner & Tielens (1993). Madden *et al.* (1993); Robert & Pagani (1993); Meixner *et al.* (1992); Boreiko & Betz (1991); Stutzki *et al.* (1988); Harris *et al.* (1987); Rainey *et al.* (1987); Schulz & Krugel (1987); Zmuidzinas *et al.* (1986); Knee *et al.* (1985); and Thronson *et al.* (1983). Observationally it has been established that M17 is clumpy in nature. Most of the transitions at millimeter and sub-millimeter wavelengths e.g., CI(307 and 609μm), CII (158μm), OI (145μm), SiII(35μm) and high rotational transitions of CO molecules are optically thin except OI(63μm) and low lying rotational transitions of CO. In the light of these observational facts the semi-infinite slab of deJong *et al.* (1980), extensively used in the TH model, is not a safe assumption. Moreover, homogeneous cloud assumption is also not valid.

To take into account the observational facts the M17 is supposed to be clumpy in nature and to solve for escape probability the region is assumed to be finite slab. The relevant details of the mathematical formulations are discussed in section 2. The physical parameters of the study are discussed below.

- **FUV flux:** In order to study M17, FUV flux is taken 5.6×10^4 times more intense than the ambient interstellar field (1.2×10^{-4}ergs cm^{-2}sec^{-1} sr^{-1} of Habing (1968) from Meixner *et al.* (1992).
- **Line profile:** The line width is assumed to be mainly due to turbulent Doppler width in clump and interclump both. The turbulent velocities in clump and interclump are taken 1.5 and 7.8 km/sec respectively (Meixner & Tielene's 1992).
- **Density:** The clump and interclump are supposed to be imbedded and density of the regions are taken as a free parameter varied over a wide range ($100 \leq N \leq 10^7$ cm^{-3}). The purpose of variation in the density is only to see the qualitative behaviour of the cloud.
- **Attenuation:** The ultraviolet flux will be attenuated during the penetration deep into the cloud because of the dust and absorption by atoms, ions and molecules. The attenuation of radiation by dust is proportional to $\exp(-\tau_{uv})$ where τ_{uv} is the ultraviolet optical depth for ($912\ A^0 \leq \lambda \leq 2100 A^0$). The τ_{uv} depends upon the extinction coefficients K_ν and depth Z into the cloud from the boundary i.e., interface of HII/HI and for the present study we use

$$\tau_{uv} = 4.2 \times 10^{-3} \mathrm{N\ Z}\ (1000/\lambda), \tag{3.1}$$

(Meixner & Tielens 1993; Spitzer 1978).

  Further, to calculate the attenuation due to absorption in clump/interclump the abundances are first calculated by solving the coupled equations obtained from chemical equilibrium for atoms, ions and molecules. Absorption of radiation by neutral carbon, CO and H_2 has important bearing on the CII, CI, HI and H_2 abundances.
- **Thermal structure:** The heating mechanism discussed by Tielens & Hollenbach (1985) has been used. It is found that M17 is predominantly heated by FUV flux $\geq 912 A^0$ mainly through photoelectric emission from the surface of dust grains. Deep inside the cloud other mechanism may be important too. The gas is generally cooled by the hyperfine transitions of atoms (CI and OI), ions (CII, SiII and FeII) and rotational transitions CO ($\Delta J = 1$ up to 20) and its isotopes and some other molecules. The cooling is the function of populations of different levels, which enters into the cooling rate equation through the probability of escape of radiation. To solve the level populations statistical equilibrium coupled equations are solved for different levels as discussed in section 2. The collisional rates are taken from Tielens & Hollenbach (1985).
- **Abundance:** In order to calculate the abundances of different species chemical equilibrium is solved at every point inside the cloud. The required reaction rates are taken from Miller *et al.* (1993) and Tielen & Hollenbach (1985).

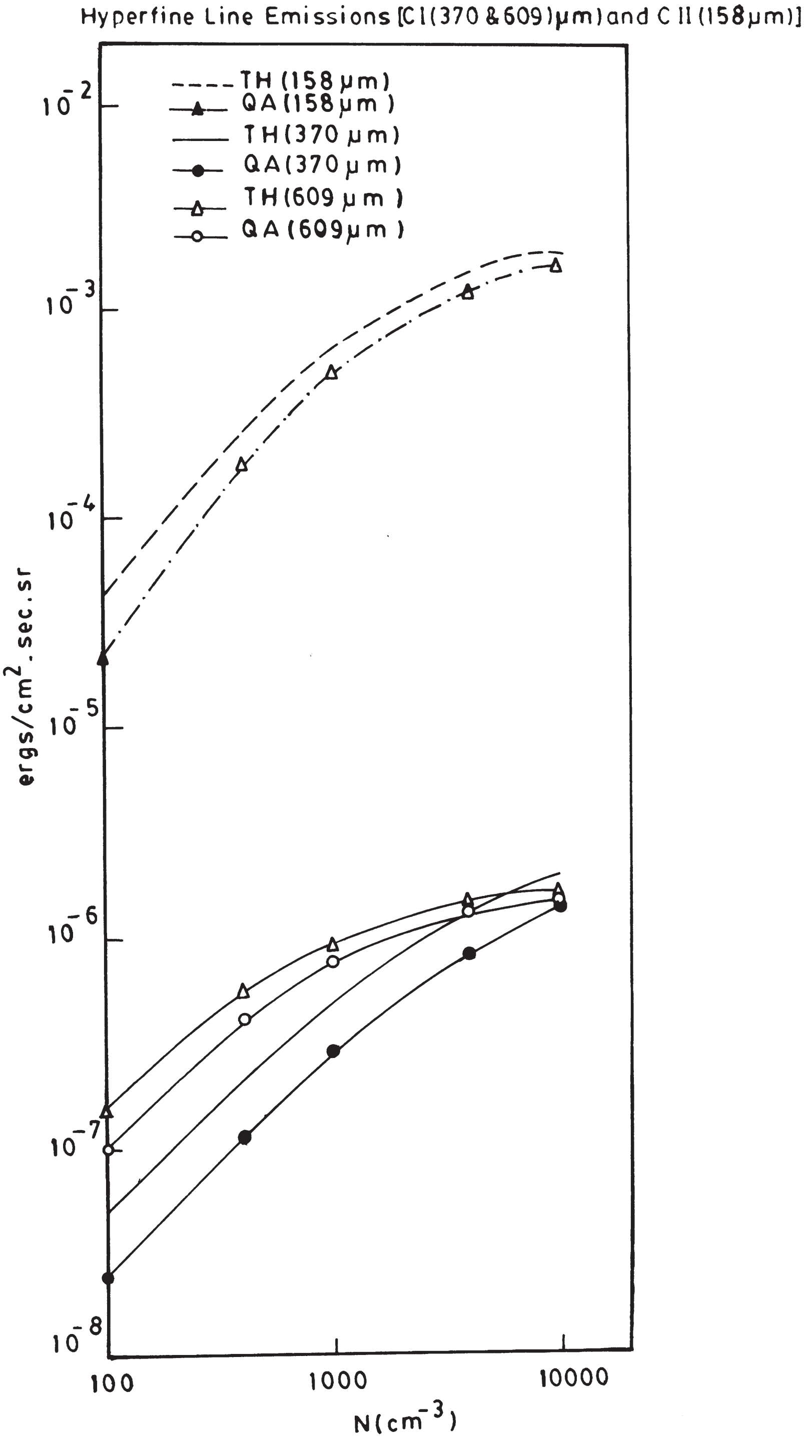

Figure 1. 'Intensity of line emission from interclump (ergs $sec^{-1}cm^{-2}$ sr^{-1})' vs 'interclump density N(cm^{-3})' for $G_0 = 5.6 \times 10^4$ and clump density of 10^5 cm^{-3}.

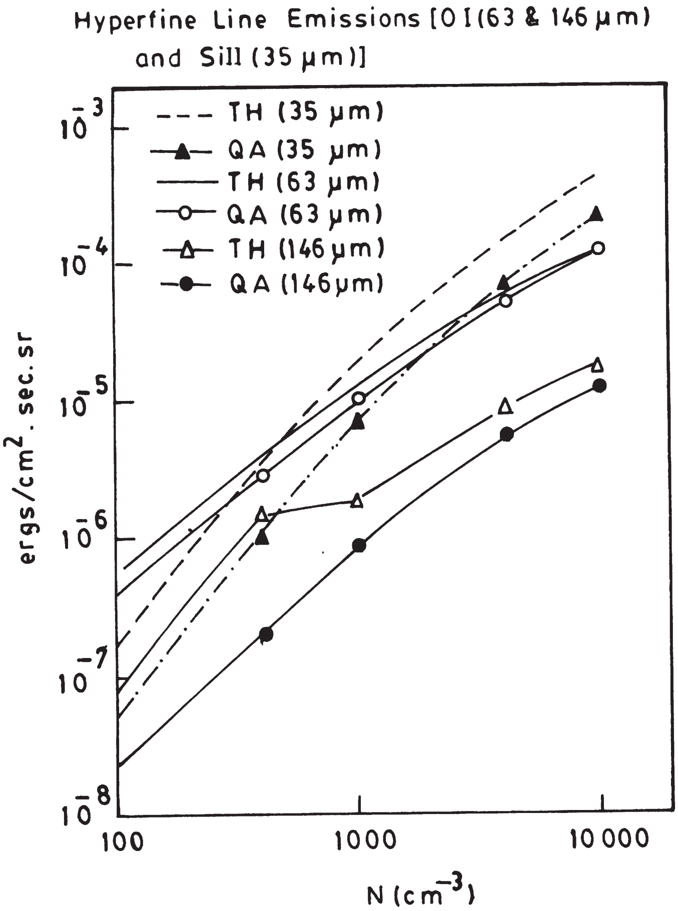

Figure 2. 'Intensity of line emission from interclump (ergs $\sec^{-1}$cm^{-2} sr^{-1})' vs 'interclump density N(cm^{-3})' for $G_0 = 5.6 \times 10^4$ and clump density of 10^5 cm^{-3}.

- **Filling factors:** The filling factors of the clump and interclump is based upon the size and density. If r_c is the average radius of the clump size distribution, the average length of the clump is defined as $4/3r_c \sim .32(P_0)^{1/3}$. Here P_0 is the volume filling factor. Generally the whole mass resides in clump as a result $P_0 n_c = n_{\text{avc}}$ (average density). The interclump filling factor P_1 equals $(1 - P_0)$.

4. Results and discussion

For a comparative study of the TH model and present formalism (referred to as QA), calculations have been performed for line intensities of different cooling agents [CI (609μm and 370μm), CII (158μm), OI (146μm and 63μm), SiII(35μm) and rotational transitions of CO molecules]. These are plotted as a function of number density in the Figs. (1–3). It is quite clear from the figures that present calculations differ from those of TH model. The difference is large at low density where the radiation term dominates over the collisional one but the difference is narrowing down as den-

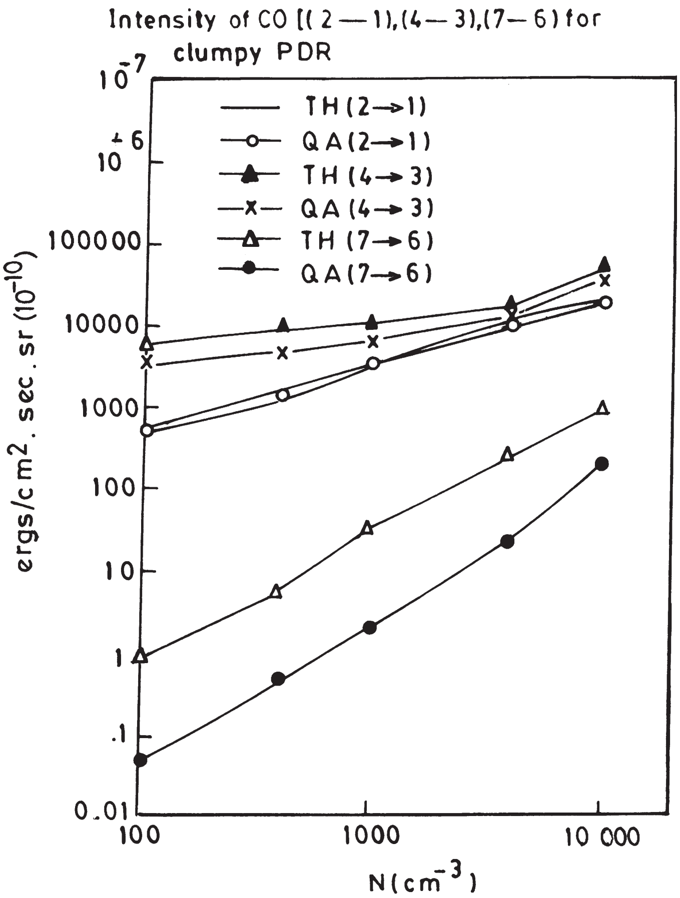

Figure 3. 'Intensity of molecular lines from interclump (ergs $sec^{-1}cm^{-2}$ sr^{-1})' vs 'interclump density N(cm^{-3})' for $G_0 = 5.6 \times 10^4$ and clump density of 10^5 cm^{-3}.

sity increases and finally both the curves merge together at densities higher than critical density. However, the behaviour of the optically thin lines differs from that of optically thick lines. Thus the optical depth parameter divides the PDR cooling lines into two groups: **(a)** Optically thin lines: [CI (609 μm and 370 μm) and CII (158 μm)] (Fig. 1), OI [(146μm) and SiII(35μm)] (Fig. 2) and [high rotational transitions of CO (e.g. 7→ 6 transitions)]: (Fig. 3) and **(b)** optically thick lines OI [(63μm)] (Fig. 2) and [low rotational transitions of CO (e.g., 2→ 1 and 4→3 transitions)] (Fig. 3).

It has been found that optically thin lines in QA model differ substantially (in some cases an order of magnitude) from that of TH model as long as radiation term dominates over the collisional one (Figs. 1, 2 and 3). In such circumstances assumption of semi-infinite slab will be erroneous and hence TH model cannot be employed. However, at density much higher than critical density of the line emission, line intensities calculated using TH and QA model yields the same value. However, for CO (14→13 transition) it has been observed that both the models differ by an order of magnitude even at sufficiently high density. For optically thick lines (Figs. 2, 3 and 4), no substantial

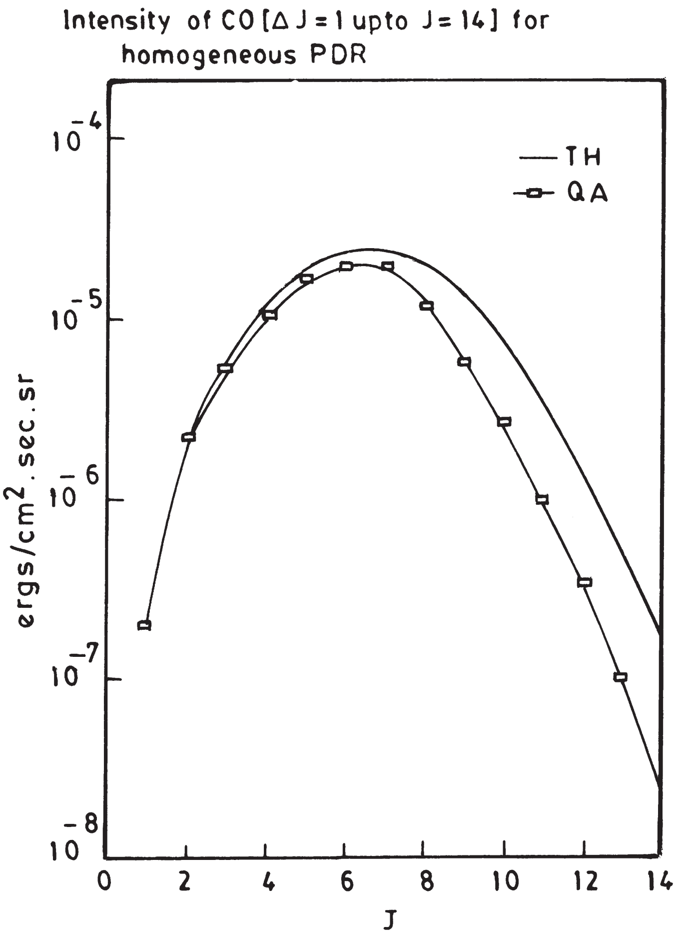

Figure 4. 'Intensity of lines (ergs $sec^{-1}cm^{-2}$ sr^{-1})' in homogeneous photodissociation region of density 10^5 (cm^{-3}) and $G_0 = 5.6 \times 10^4$.

difference is noticed. However, for sufficiently large optical depths ($t_\nu \rightarrow \infty$) the cloud is behaving like semi-infinite slab and equations (2.2.12 and 2.3.6) will be reduced to that of equations B-4 of Appendix B and 20 of deJong *et al.* (1980) and the present formalism will be reduced to TH model. Therefore for optically thick lines TH and QA model do not differ significantly. In Fig. 4, line intensity of various rotational transitions ($J + 1 \rightarrow J$) of CO molecule have been plotted for homogeneous PDR of density 10^5 cm^{-3} and $G_0 = 5.6 \times 10^4$. From the figure it is quite obvious that for high rotational transitions which are optically thin QA and TH models differ significantly, whereas the difference is narrowing down as we move towards the optically thick lines i.e., lower transitions.

The analysis of various fine structure lines and FIR continuum for $G_0 = 5.6 \times 10^4$ yields a density $\sim 4 \times 10^3$ and a temperature of ~ 300 K for atomic gas in homogeneous models. However, homogeneous models can not reproduce the spatial distribution of line emissions. The homogeneous PDR with typical density of 4×10^3 have an edge-on extension ~ 0.01 pc contrary to the observational facts. CII (158 μm)

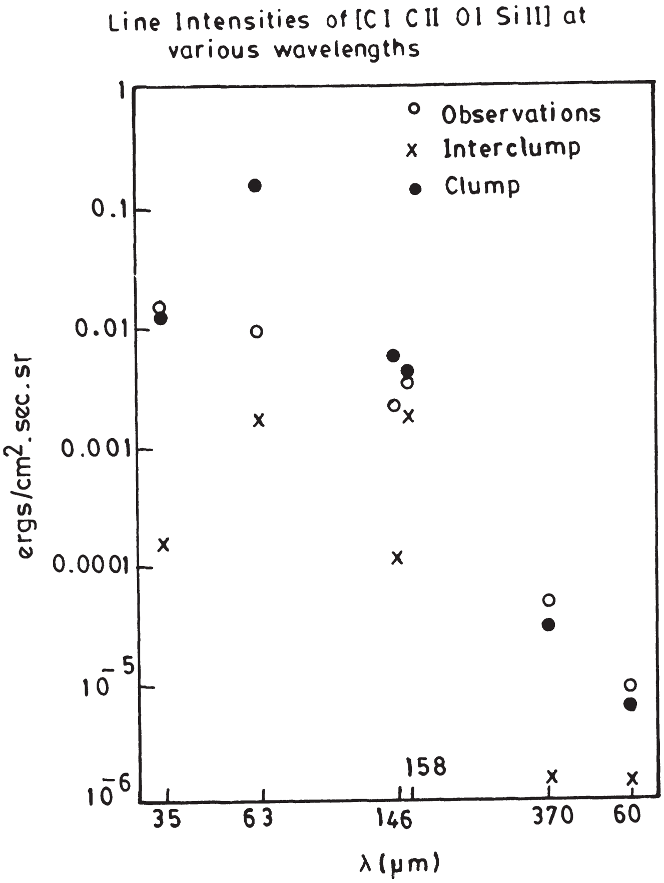

Figure 5. **Calculated** line intensities (ergs $\sec^{-1}\text{cm}^{-2}\ \text{sr}^{-1}$) of fine structure line emissions of CI (370 and 609 μm), CII (158 μm), OI (163 and 146 μm) and SiII (35 μm) at various wavelengths noted against each atom and ion or interclump density = 4×10^3 (cm^{-3}) and clump density $= 6 \times 10^5(\text{cm}^{-3})$ and $G_0 = 5.6 \times 10^4$.

Observed values (references): [CI (370 μm) Zmuidzinas *et al.* (1986)], [CI (609 μm) Knee *et al.* (1985)], [CII (158 μm) Stutzki *et al.* (1988)], [OI (63 μm) Meixner *et al.* (1992)], [OI (146 μm) Meixner *et al.* (1992)] and [SiII (35 μm) Meixner *et al.* (1992)].

emission when viewed edge-on extends 1 PC to 4 PC in NGC 1977, Orion, NGC 2023, W3 and M17W (Stacey *et al.* 1993; Stutzki *et al.* 1988; Howe *et al.* 1991). The spatial distribution of CII (158 μm) line emission indicate a deep penetration of UV radiation into the region. Further observed velocity distribution is also found to be drastically different at locations of CII emissions (Meixner *et al.* 1992). These facts led to the assumption of two-component models of PDRs in the form of clump and interclump by Meixner & Tielens (1993).

Theoretical calculations have been performed for line intensities of FIR and sub-millimeter transitions to study the M17 region using the present formalism. For that purpose density is taken as free parameter. But turbulent velocities for clump and interclump are taken as 1.5 and 7.8 km/sec and $G_0 = 5.6 \times 10^4$ from Meixner *et al.* (1992). The calculated and observed line intensities at millimeter and sub-millimeter

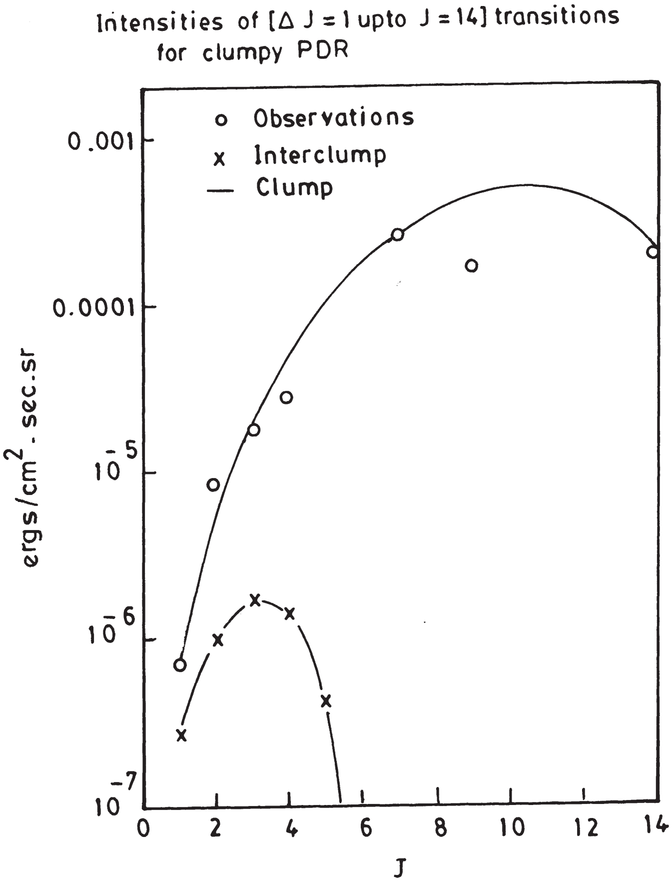

Figure 6. **Calculated** line intensities (ergs $sec^{-1}cm^{-2}$ sr^{-1}) for interclump density = 4 × 10^3 (cm^{-3}) and clump density $= 6 \times 10^5(cm^{-3})$ and $G_0 = 5.6 \times 10^4$ for various J and $\Delta J = 1$.

Observed values (references): [(1→ 0) Thronson *et al.* (1983)], [(2→ 1) Meixner *et al.* (1992)], [(3→ 2) Rainey *et al.* (1987)], [(4→ 3) Schulz & Krugel (1987)], [(7→ 6) Stutzki *et al.* (1988)], [(9→ 8) Boreiko & Betz (1991)] and [(14→ 13) Harris *et al.* (1987)].

wavelengths for hyperfine transitions of atoms [CI (370 and 609μm); OI (63 and 146μm)], ions [CII (158 μm); and SiII (35 μm)] and rotational transitions of CO ($1 \rightarrow 0$, $2 \rightarrow 1$, $3 \rightarrow 2$, $4 \rightarrow 3$, $7 \rightarrow 6$, $9 \rightarrow 8$ and 14→ 13) are compared with that of the observed values in Figs. 5 and 6. The following conclusions may be drawn from these two figures:

- The contribution to the line intensities from the interclump is negligibly small as compared to that of the clump except CII (158 μm) in which case both are comparable (Fig. 5). This explains the large spatial extent observed for CII (158 μm) line.
- The line intensities of almost all the listed fine structure transitions from clump agree fairly well with the observations except OI (63 μm) (Fig. 5). In case of OI (63 μm) the interclump intensity is low enough than the clump but it is close to the observed value. Since the temperature of the interclump is found to be lower

than the clump it is highly probable that line OI (63 μ m) originating from clump may be absorbed. In such circumstances calculated intensity will come out to be close to the observed one.

- The line intensities for the rotational transitions of CO molecule are plotted in Fig. 6 for the levels up to $J = 14$ for the clump and interclump both. Observed lines are also plotted in the same figure. It is found that the line intensities from the clump agree fairly with those of observed values. However line intensities from interclump are negligibly small as compared to clump except for the lowest transition. However, first transitions of CO may be observed from the extended region. Meixner *et al.* (1992) have shown that $7 \rightarrow 6$ and $2 \rightarrow 1$ transitions of CO peak together. This has been confirmed from the calculations that both originate from clump. Further spatial extended observation of rotational transitions of CO will give more insight to the clump structure of the M17 region.
- The agreement of calculated values with those of the observations over a wide range of fine structure line emissions and rotational transitions favour clumpiness in the region and favoured densities for the clump and interclump regions are 6×10^5 and 4×10^3 cm^{-3} respectively.
- The values obtained by QA closely match with the results of Meixner & Tielens (1993) obtained earlier with a similar model (TH and Boisse formalism) for optically thin lines.

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