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PHOTODISSOCIATED REGIONS IN THE NEIGHBORHOOD OF ZAMS

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RESUMEN

Las regiones fotodisociadas en la vecindad de estrellas de secuencia principal tienen tamaños que están determinados por la temperatura efectiva de la estrella excitadora. El tamaño de estas regiones también está afectado por la metalicidad y densidad del gas. Mientras que las variaciones en las abundancias resultan únicamente en pequeñas diferencias en los resultados, la densidad del gas es determinante en la extensión de la zona en la cual la molécula de hidrógeno se disocia. Por otro lado, la expansión de la región ionizada que resulta de estrellas OB reduce la masa total de H I. Este no es el caso para las estrellas de masa intermedia, las cuales pueden tener una contribución importante a la masa total del material fotodisociado. Para entender mejor las nubes moleculares y la formación estelar, es importante un estudio detallado de estas regiones para un amplio intervalo de metalicidades y tipos estelares, así como para medios de diferentes densidades.

ABSTRACT

The photodissociated regions around Main-Sequence stars have sizes determined by the effective temperature of the exciting star. The size, however, is also affected by the metallicity and density of the medium. While the former has a lower effect, but no less important, on these regions, the later fix the outer boundary up to which atomic hydrogen can be found. On the other hand, expansion of the H II regions produced by massive stars can reduce a considerable amount of the total mass of atomic material. This is not the case for low mass stars, which can be an important source for the production of photodissociated regions due to its larger number within molecular clouds and longer Main-Sequence life times. A detailed study of these regions, for a wide range of stellar effective temperatures and metallicities and for mediums of different densities, is important in the study of molecular clouds and star-formation.

Key words: **ISM: MOLECULES — STARS: MAIN-SEQUENCE**

1. INTRODUCTION

When a star is formed in a molecular cloud, the ultraviolet (UV) radiation produces a region of ionized material and, further out, a photodissociated region (PDR) where the molecules are destroyed by the stellar flux. The photoionized and photodissociated regions heat and destroy the molecules of the cloud, perturbing the otherwise cold and dense medium ideal for star formation. Hot stars, with a strong UV radiation field, rapidly dissociate and ionize the medium close to the star. Outside this H II region the remaining radiative flux, with energies below the Lyman limit ($912\ \AA < \lambda < 1010\ \AA$), dissociates the molecular material and produces a photodissociated region of considerable size. Low mass stars, on the other hand, with negligible H II regions, still have large dissociating photon fluxes and their PDRs can be prominent. The large opacity of dust absorption in molecular clouds, however, can considerably reduce the size of the H II regions and PDRs. It must be quantified to correctly assess the effects of the H II regions and PDRs on the erosion of the molecules in the cloud.

Destruction of molecular gas by the expansion of the H II region and photodissociation will reduce even further the star forming capacity of molecular clouds. A previous study on the effects of expansion of H II regions in molecular clouds was done by Franco, Shore, & Tenorio-Tagle (1994) (FST). The dissociated region was then noted to be an important factor that could reduce even further the number of O stars formed in molecular clouds. At the moment, we are able to explore the consequences of PDRs produced in the static case; however, in the near future expansion of the photodissociating front will be included in the study.

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TABLE 1

FLUXES OF LYMAN AND DISSOCIATING PHOTONS

Teff	Log g	$\mathrm{Log}(R_*)^a$	Z⊙		0.1 Z⊙		0.01 Z⊙	
			Log S_{Ly}	Log S_D	Log S_{Ly}	Log S_D	Log S_{Ly}	Log S_D
(10^3K)	(cgs)	(cm)	(photons s^{-1})		(photons s^{-1})		(photons s^{-1})	
7.5	4	11.00	32.42	36.47	33.56	37.55	34.63	38.31
11.5	4	11.18	38.51	43.41	39.21	44.42	39.75	44.64
16	4	11.30	42.16	45.76	42.23	45.93	42.20	45.98
22	4	11.5	44.80	47.14	44.65	47.18	44.50	47.20
25	4	11.53	45.67	47.51	45.47	47.54	45.33	47.56
30	4	11.58	47.02	47.99	46.85	48.02	46.77	48.03
40	4	11.75	48.78	48.76	48.76	48.77	48.72	48.79
50	5	12.02	49.89	49.54	49.88	49.53	49.87	49.52

[a] Stellar radius from Thompson (1984). A more complete table is given in Diaz-Miller et al. (1997).

2. ATMOSPHERE MODELS

Several models have been developed, looking to match the characteristics known for different stellar types and evolution stages. However, the rate of ionizing and dissociation photons not only depends on the effective temperature of the star, but on its metallicity. In order to account for this, as well as to obtain the rates for a wide range of different stellar sources, we use the line blanketed LTE atmosphere models of Kurucz (1993). These models are the most widely used and proved to be the most versatile and reliable due in part to the large number of lines considered.

The rates of Lyman continuum photons, N_{Ly}, for zero-age main sequence stars with effective temperatures ranging between 7500 K and 50000 K and with stellar gravities log g = 4 – 5, is given in Table 1 for stellar metallicities of 1.0, 0.1 and 0.01 times solar (column 3, 5 and 7 respectively). The rate of dissociating photons, N_D, for the same stellar types and metallicities, are given columns 4, 6 and 8 of the same table. Differences in the rates of ionizing photons obtained here and those in the literature are mainly due to the atmosphere model used (e.g., Panagia 1973) or on the assumed stellar gravity and radius (Vacca, Germany, & Shull 1996). A more detailed discussion is given in Diaz-Miller, Franco, & Shore (1997).

3. THE MODEL

The structure and size of the H II and H I regions were obtained using the rates of ionizing and dissociating photons given in Table 1. The model is spherically symmetric and treats the radiative transfer through a molecular cloud with uniform density in the range of 10 to 10000 cm^{-3}.

The structure of the H II region was calculated following the schemes described by Hummer & Seaton (1964) and Flower (1969). The gas composition includes H, He, C, O, N and S, with the abundances of Anders & Gravesse (1989). The results for the same effective temperatures as in Table 1 are given in column 2 of Table 2.

The structure of the PDR is determined by the local equilibrium between the formation and the photodissociation of molecular hydrogen. Molecular hydrogen formation on dust grains seems to be the most likely way to reproduce the observational abundances. The rate at which H molecules are formed, depends mainly on the temperature of the region (Hollenbach & McKee 1979; Hollenbach & Salpeter 1971) and for a gas at 500 K it is $\alpha_f = 1.37 \times 10^{-17}$. The formation rate then can be expressed by $P_f(r) = \alpha_f n(HI)\, n(H)$, where n(HI) is the density of neutral hydrogen, and $n(H) = n(HI) + n(H_2)$, is the total hydrogen density.

In the HI regions, the principal dissociation mechanism is excitation from the ground electronic state to the Lyman electronic state followed by radiative decay to the vibrational continuum (Stecher & Williams 1967). Assuming a Voigt profile for the absorption cross-section of the different Lyman-band transitions, and using the "self shielding" function given by Hollenbach, Werner, & Salpeter (1971), the photodissociation rate of hydrogen molecules at a radius r from the star can be expressed by

$$P_D(r) = n(H_2) \sum_i k_i \int_0^\infty \frac{S_D(\nu, r)}{h\nu} \sigma_i(\nu) d\nu, \qquad (1)$$

where k_i is the dissociation probability of the i-th Lyman-band transition and $S_D(\nu, r)$ is the dissociating flux at frequency ν at radius r. Making $P_f(r) = P_D(r)$ we obtain the size of the PDR, the result are shown in column 3 of Table 2.

The size of the static PDR also can be obtained, assuming a medium of constant density and a fixed rate of dissociating photons (S_D), through the equation

$$R_{\rm PDR} = R_{\rm HII}\left[1 + \frac{N_D}{N_{Ly}}\left(\frac{n_e^2\alpha_B({\rm HI})}{n({\rm HI})n({\rm H})\alpha_f}\right)\right], \tag{2}$$

where n_e is the electron density and α_B is the hydrogen recombination rate. This equation agrees within a factor of two with the dissociation radius obtained with the detailed radiative transfer model hence can be used to obtain a first approximation to the size of the PDR.

3.1. Dust

Dust is crucial in interstellar chemistry both through attenuation of the UV radiation field and as a catalytic agent for the formation of molecular hydrogen and other molecules. Dust can absorb and scatter a considerable amount of the high energy radiation field. The degree of attenuation depends on the grain composition and on the incident spectrum. Here it is assumed that the grains are a mixture of silicates and graphite with a cross-section obtained using the mean extinction law formula of Cardelli, Clayton, & Mathis (1989). The sizes of the H II region and of the PDR for a dusty cloud are shown in columns 5 and 6 of Table 2. For comparison, the rate of atomic to ionized mass for a dust-free and a dusty cloud are given in columns 4 and 7 respectively.

A very simple approximation to the effects of dust in the H II region and PDR can be also obtained using the formula given by Franco, Tenorio-Tagle, & Bodenheimer (1990) for dusty H II regions and its analog for dusty PDRs. The results obtained this way are accurate to within 15% for the ionized region and to within 30% for the PDR (in addition to the errors introduced by using the approximation in eq. (2)).

4. DISCUSSION

We obtained the rates of ionizing and dissociating photons for a wide range of stellar sources. The rate of ionizing photons we calculated differs by up to 20% with the rates given in the literature (see Vacca et al. 1996). Comparing the rates of ionizing photons with those obtained by Thompson (1984) using the models of Kurucz (1979), it is clear that the improved LTE atmosphere models of Kurucz (1993) result in a considerable decrease of the ionization rates for low mass stars (due to the larger number of lines), while for hot stars they are practically unchanged. Roger & Dewdney (1995) calculated the rate of dissociating photons for OB stars using the same atmosphere models than Thompson. At these frequencies, the effects of line blanketing are more evident. Even for hot stars, the rates obtained are ~50 % below those of Roger & Dewdney. From Table 2 it can also be deduced that there is a lower limit to the effective temperature of a star that can produce a considerable amount of photodissociated material around 13 000 K.

As pointed out before, the effects of dust absorption on the size of the H II regions and PDRs must be quantified. As expected, the dust opacity decreases with the cloud density and its effect is almost negligible for a gas with $n = 10$ cm^{-3} and for cold stars. However, dust absorption in the H II regions produced by OB stars, and for the photodissociated regions of all the stellar types, is important and neglecting its effects will result in large errors. The values for a gas of density 10^5 cm^{-3} are given in columns 5 and 6 of Table 2.

The results of this study place constraints on the maximum star forming capacity of molecular clouds. As noted by FST, the limit on the number of massive stars that can be formed in a molecular cloud is set by the overlap of the internal H II regions and the evaporation of the cloud by the formation of peripheral blisters. Table 2 shows that the size of the PDR is at least one order of magnitude larger than the H II region, with and without dust, making clear the effects of these regions on the destruction of the molecular material. Comparing the H I to H II mass ratio for OB stars in column 4 and 7 of the same table, it is evident that the production of photodissociated material will modify considerably the estimates of FST in the static case. For a dust-free region it is overestimated by a factor of 10^5 while for a dusty region the factor is only 10^2.

However, the static region results are an upper limit to the total amount of dissociated material produced by a given star due to the large time scales over which dissociation equilibrium is reached. In particular, the time at which the $R_{\rm PDR}$ will reach its statistical equilibrium value ranges from 4×10^4 yr for a density of 10^5

TABLE 2

IONIZED AND DISSOCIATED RADIUS [a]

	Without Dust			With Dust		
Teff (10^3K)	Log R_{HII}	Log R_{PDR}	Log($\frac{M_{HI}}{M_{HII}}$)	Log R_{HII}	Log R_{PDR}	Log($\frac{M_{HI}}{M_{HII}}$)
7.5	12.03	13.68	5.60	12.73	13.68	5.59
11.5	13.77	16.02	7.37	13.77	15.96	7.18
16	14.76	17.00	6.93	14.76	16.67	5.93
22	15.60	17.52	5.79	15.58	16.91	4.03
25	15.88	17.66	5.34	15.84	16.96	3.39
30	16.33	17.85	4.55	16.22	17.02	2.41
40	16.90	18.12	3.67	16.62	17.11	1.47
50	17.27	18.39	3.34	16.81	17.18	1.07

[a] Radius given in cm. The tabulated values for R_{PDR} correspond to the radius where 2 n(H_2)/n(H) = 0.5 A more complete table is given in Diaz-Miller et al. (1997)

cm $^{-3}$ to 4×10^4 yr for a density of 10 cm $^{-3}$. These are long compared to the formation time of the H II region. If the amount of molecular material destroyed is computed considering only the effects of OB stars, then the estimates of FST are correct. However, low mass stars are more numerous than OB stars, and their contribution to the dissociation of H_2 diminishes even more the productivity of molecular clouds. Including dust in the picture has a mitigating effect; however, the dissociation region is far more extensive than the ionized region for all the cases considered. Even in the case where the time scales for star formation are of the order of the time scale for PDR formation, assuming that the loss of coolants for the gas is as important as ionization in the cessation of star forming activity imposes more constrains on the number of O stars formed. This agrees with earlier suggestions by Elmergreen & Mathieu (1983) that low mass clouds are less likely to be sites for OB association formation.

In the near future, numerical hydrodynamics calculations of both the H II and PDR regions of different metallicities and for different density clouds will be completed, and the differences resulting from the cooling and expansion of the medium will be quantified. This will provide more accurate predictions about the production of H I envelopes around Zero Age Main Sequence Stars, correcting a historic underestimation of PDR production by low mass stars.

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