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GRAIN HEATING IN HII REGIONS

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RESUMO. O aquecimento de regiões HII por elétrons ejetados por grãos após a absorção de fótons estelares e do campo de radiação difuso é considerado. Este mecanismo é comparado com o aquecimento proveniente da fotoionização, levando-se em conta estrelas centrais em diferentes posições no diagrama HR. A contribuição dos grãos para a temperatura eletrônica é examinada. Os resultados indicam a posição no diagrama HR onde a contribuição dos grãos tende a ser mais importante.

ABSTRACT. The heating of HII regions by electrons ejected from grains after absorption of stellar and diffuse photons is considered. This mechanism is compared with photoionization heating, taking into account central stars in different positions on the HR diagram. The grain contribution to electron temperature is also examined, and the results indicate the position on the HR diagram where grain contribution is likely to be important.

Key words; HII regions - grains

I. INTRODUCTION

The presence of solid grains in HII regions is indicated by the observed excess in IR emission and by scattered radiation (Savage and Mathis 1979, Wynn-Williams and Becklin, 1974). The physical properties of such regions can be influenced by the presence of the grains, particularly the thermal and ionization structure.

The thermal structure can be especially affected by changes in the heating rate and in the cooling rate due to modifications in the radiation spectrum and in the ionization structure of heavy elements, respectively (see for example Sarazin 1977, Balick 1975).

The gas heating by photoelectrons ejected by dust grains is another mechanism that can possibly influence the thermal structure of HII regions. This mechanism was recently taken into account by Maciel and Pottasch (1982), who have shown that the electron temperature between 20% and 60% of Strömgren radius can be increased by up to 10% relative to pure photoionization heating.

In the present paper, the mechanism proposed by Maciel and Pottasch (1982) is generalized, and several models are calculated with central stars in different positions on the HR diagram.

The model is described in section II. In section III we study the grain influence on the heating function, and a comparison with a heating function of dust-free models is made. The influence of helium in this process is also considered. Finally, in section IV an estimate of the grain influence on the electron temperature is made.

II. THE MODEL

We consider a spherical dusty HII region, photoionized by a unique central star with a Planckian radiation field, using the "on the spot" approximation.

First we considered a pure hydrogen HII region with O, N, Ne 80% singly ionized and 20% doubly ionized with normal abundances ($O/H = 6\ 10^{-4}$, $N/H = 5\ 10^{-5}$, $Ne/H = 6\ 10^{-5}$). Later on, He was included with an assumed abundance of 0.15 by number.

With input parameters like radii, effective temperatures of central stars and electron density, the model gives the heating rate Γ (erg cm^{-3} s^{-1}) taking into account the photoionization and photoelectric process ; the cooling rate Λ (erg cm^{-3} s^{-1}) involves recombination process, collisional excitation of heavy elements and free-free radiation. The electron-grain recombination losses is negligible (Maciel and Pottasch 1982). A grid of models was obtained from the catalogue of Stasińska(1982).

The electron density was taken as $n_e = 100$ cm^{-3}, and effective temperatures of central stars are in the range 30000 - 55000 K (Table 1).

The heating due to the grains is given by $\Gamma(gr) \simeq \Gamma_{L\alpha} + \Gamma_*$, where $\Gamma_{L\alpha}$ is the heating produced after the absorption of a Lα photon from recombination of hydrogen, and Γ_* is the corresponding quantity caused by the direct absorption of stellar photons. The latter can still be divided into two components , Γ_* ($h\nu < 13.6$ eV) and Γ_* ($h\nu \geq 13.6$ eV), depending on the photon energy. For the detailed equations the reader is referred to the paper by Maciel and Pottasch (1982). It should be mentioned that the grains are assumed to be neutral on average, and that the adopted grain parameters (photoelectric yield, absorption cross section) are characteristic of metallic and silicate grains.

TABLE 1.

model	T_{eff}(K)	log($L/L_\odot$)	R_*(cm)
01	55000	5.76	5.89(11)
02	50000	5.76	2.16(11)
03	45000	5.76	8.80(11)
04	50000	5.30	4.16(11)
05	45000	5.30	5.18(11)
06	40000	5.30	6.47(11)
07	55000	4.80	1.94(11)
08	50000	4.80	2.34(11)
09	45000	4.80	2.89(11)
10	40000	4.80	3.66(11)
11	35000	4.80	4.78(11)
12	50000	4.25	1.25(11)
13	45000	4.25	1.55(11)
14	40000	4.25	1.96(11)
15	35000	4.25	2.53(11)
16	30000	4.25	3.48(11)
17	50000	3.62	5.54(10)
18	45000	3.62	6.84(10)
19	40000	3.62	8.65(10)
20	35000	3.62	1.13(11)
21	30000	3.62	1.54(11)
22	40000	2.48	2.55(10)
23	35000	2.48	3.33(10)
24	30000	2.48	4.54(10)

Note - Numbers in parentheses are powers of 10

III. THE GRAIN HEATING FUNCTION

In order to evaluate the importance of the grain contribution to the heating process, it is interesting to investigate the behaviour of the ratio Γ(gr)/Γ(gas) in the nebula, which is shown in Figure 1. Models having the same luminosity are represented approximately by the same curves, since the ratio Γ(gr)/Γ(gas) does not depend strongly on the effective temperature. Therefore, Figure 1 shows 6 of the models, enclosing within parentheses the models having the same luminosities.

In agreement with the previous results by Maciel and Pottasch (1982), the grain heating is more important in intermediate parts of the nebula. Close to the star the grains can no longer be assumed to be neutral, as shown in figure 2. The grain potential can be determined at every point in the nebula assuming electrical equilibrium between photoelectric emission and electron-grain recombination. According to Figure 2, the grains are electrically neutral (V ≃ 0 ± 1 eV) away from the central stars, implying that the grain heating

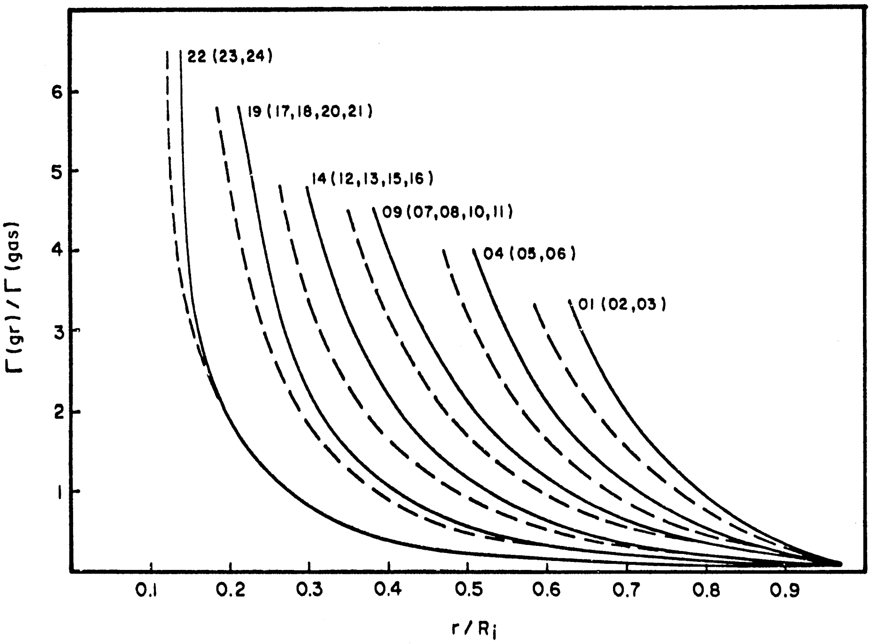

FIGURE 1. The ratio Γ(gr)/Γ(gas) as a function of the position r/R_i relative to the ionized radius R_i.The numbers refer to the models defined in Table 1. Other models having the same luminosities are given within parentheses.

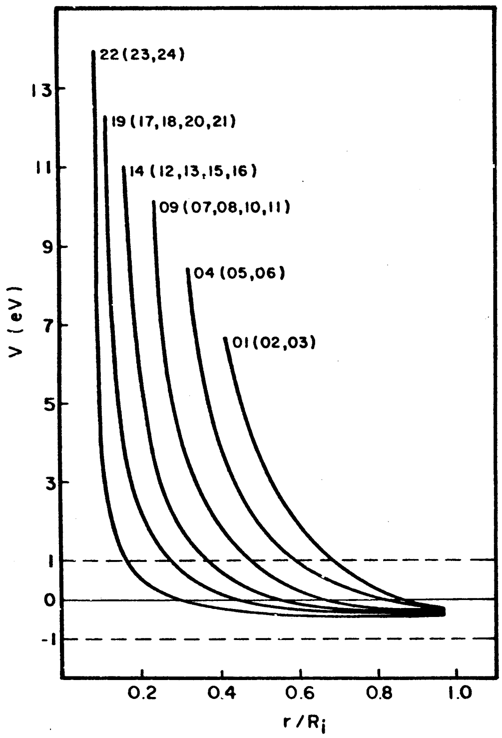

FIGURE 2. Crain potential V as a function of the position r/R_i (see Figure 1).

mechanism cannot operate efficiently in inner portions of the nebula. Analogously, calculations of the grain temperature including photoabsorption and infrared emission indicate that high temperatures ($T_{gr} >> 120$ K) are attained in the inner parts of the nebula, so that grain survival is critical in that region.

On the other hand, as shown in Figure 1, the ratio $\Gamma(gr)/\Gamma(gas)$ strongly decreases as the nebular outer boundary is approached. The solid lines shown in Figure 1 refer to H photoionization only. When He is included, the general effect is a reduction of the $\Gamma(gr)/\Gamma(gas)$ ratio, since the gas heating function increases with the He addition, which is shown by the broken lines in Figure 1. The mean decrease of $\Gamma(gr)/\Gamma(gas)$ when He is included is about 30% for the hotter models (models 01,02,03, etc.; $T_{eff} > 40000$ K) and about 8% for models with $T_{eff} \leq 40000$ K (models 06,10,11, etc.). In the cooler models the ionized He region is smaller, decreasing the effect of He heating.

IV. GRAINS AND THE ELECTRON TEMPERATURE

In order to estimate the importance of grain heating, it is interesting to compute an average electron temperature representative of the whole nebula. Assuming that the thermal structure can be determined from the condition $\Lambda = \Gamma(gas)$, the mean temperature $\overline{T}(gas)$ is computed. Alternatively, the condition $\Lambda = \Gamma(gas+grains)$ would imply the average temperature $\overline{T}(gas+grains)$. A comparison of $\overline{T}(gas)$ and $\overline{T}(gas+grains)$ would indicate the importance of the grain contribution in each case. The grain contribution to nebular heating can be calculed as $C(\%) = 100\{ \overline{T}(gas+grains) - \overline{T}(gas) \}/\overline{T}(gas)$. The mean temperatures calculated and the corresponding grain contribution for each model are given in Table 2. The grain contribution C shows a weak dependence on the effective temperature of the central star, as a consequence of the weak dependence of $\Gamma(gr)$ on T_{eff}. Figure 3 shows the average grain contribution as function of the luminosity for the models having the effective temperatures shown.

The maximum contribution is about 9% at $\log (L/L_{\odot}) \simeq 4$ decreasing at both lower and higher luminosities. Such behaviour is explained by the fact that very luminous central stars produce large regions having grain potential $V >> 0$, where the mechanism is not very efficient. Note however that locally the contribution from the high-luminosity models can be very large, due to the large rate of ionizing photons. On the other hand, in models having low luminosity stars, the contribution is limited by the stellar radiation field.

The inclusion of helium would further reduce the grain contribution shown in Table 2 and Figure 3, since $\overline{T}(gas)$ would increase more rapidly than $\overline{T}(gas + grains)$. For the hotter models, C reduces to about 80-85% of the values given in Table 2. Analogously to the discussion in section 3, such effect is small in the cool models where the He^+ zone is smaller. In this case, the contribution is reduced by only 2-5%.

TABLE 2.

model	$\overline{T}$(gas) (K)	$\overline{T}$(gas+grains) (K)	C(%)
01	8588	9130	6.3
02	8354	8878	6.3
03	8056	8581	6.5
04	8343	8960	7.4
05	8063	8684	7.7
06	7813	8438	8.0
07	8540	9269	8.5
08	8357	9069	8.5
09	8114	8786	8.3
10	7864	8528	8.4
11	7493	8151	8.8
12	8354	9143	9.5
13	8097	8861	9.4
14	7902	8591	8.7
15	7552	8218	8.8
16	7145	7825	9.5
17	8344	9125	9.4
18	8116	8837	8.9
19	7884	8555	8.5
20	7538	8209	8.9
21	7158	7828	9.4
22	7871	8473	7.7
23	7531	8137	8.1
24	7158	7770	8.6

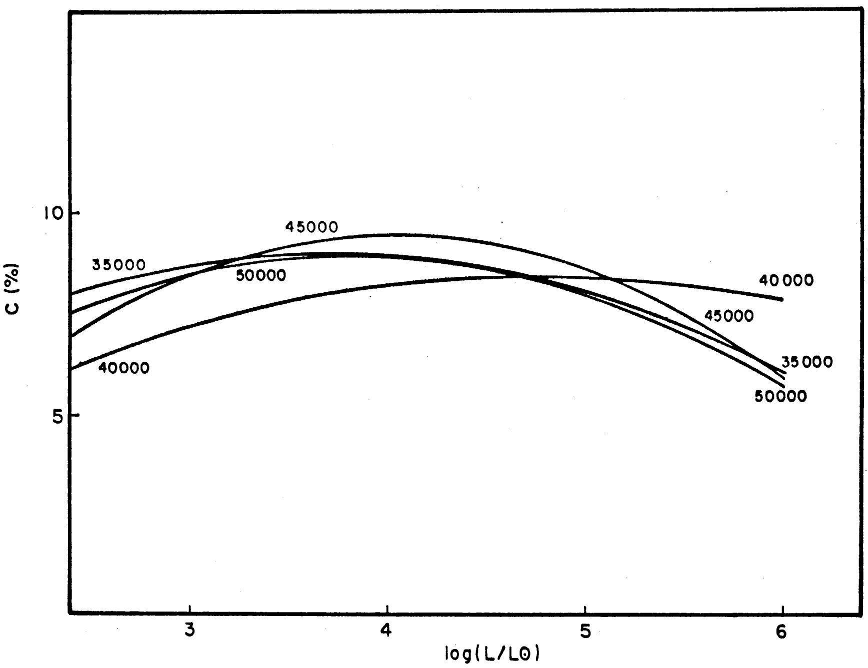

FIGURE 3. The grain contribution to the average electron temperature given as a function of the central star luminosity. Each curve is labeled according to the effective temperature of the models.

In conclusion, the maximum increase in electron temperature due to photoelectric heating is about 10%, in agreement with the previous calculations by Maciel and Pottasch (1982). As shown in Figure 3, the region on the HR diagram where the mechanism is more likely to operate is characterized by $4.4 \geq \log(L/L_\odot) \geq 3.6$ and $55000 \geq T_{eff} \geq 30000$. In order to make these results more general, further calculations would be useful, including a better treatment of the diffuse radiation field and considering the grain properties in more detail.

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