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TEMPERATURE AND DENSITY GRADIENTS IN THE ORION NEBULA

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RESUMEN

Para modelizar la estructura de ionización de Orión, usamos una estratificación abrupta de la densidad, descrita por una ley de potencia ($n \propto x^{-2}$) que es función de la distancia x hacia el frente de ionización. Los gradientes de cocientes de líneas observados a lo largo de la rendija son reproducidos cualitativamente por nuestros modelos estratificados en densidad. La desexcitación colisional parece ser responsable de la mitad del gradiente del cociente sensible a la temperatura [N II] λ 5755/[N II] λ 6583.

ABSTRACT

To model the ionization structure of the Orion nebula, we adopt a steep density stratification, increasing as a power-law ($n \propto x^{-2}$) function of distance x from the ionization front. The line-ratio gradients observed along the slit are qualitatively reproduced by our density stratified models. Collisional deexcitation appears to be responsible for half of the gradient observed in the [N II] λ 5755/[N II] λ 6583 temperature sensitive ratio.

Key Words: **HII REGIONS — ISM: INDIVIDUAL (ORION NEBULA) — LINE: FORMATION**

1. INTRODUCTION

We approximate the ionization front (IF) in Orion using a power-law density distribution. We adopt a similar approach to that of Binette & Raga (1990; BR90) who studied the properties of power-law densities in photoionized slabs. In a recent paper, Binette, González-Gómez, & Mayya (2002; hereafter BGM02) showed how the observed gradient of the [S II] density and the Hβ surface brightness in Orion can be accounted for using such a simple density model. In this contribution, we adopt a similar model and focus on the spatial gradient of the temperature sensitive ratios [O III] λ 4363/[O III] λ 5007 and [N II] λ 5755/[N II] λ 6583, along the long slit.

The data presented in this contribution correspond to a long-slit spectrum of the central region of Orion taken at the Observatorio Astrofísico Guillermo Haro, Cananea, on 1998 December 21 using a 1024×1024 TEK CCD detector mounted on a Boller & Chivens spectrograph. The slit was aligned West-East and off-centered by 30″ to the south of θ^1 Ori C. Further information on the reduction of the data can be found in BGM02.

2. THE PHOTOIONIZATION MODELS

We adapted the simple slab geometry of BR90 to the more appropriate spherical geometry. The density profile (with an origin lying inside the dense cloud) is described as follows:

$$n(x) = \begin{cases} n_0 \,(L/x)^2 & x \le L, \\ 0 & x > L, \end{cases} \tag{1}$$

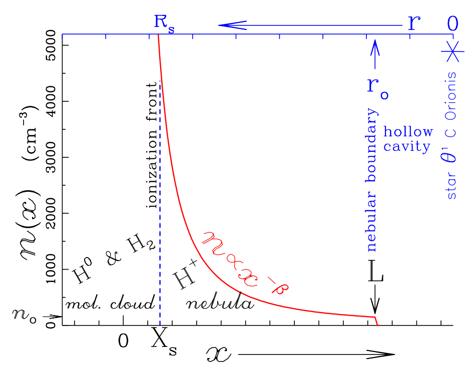

Fig. 1. Diagram qualitatively illustrating our power-law density stratification as a function of x. The origin of the spatial x-axis lies at a depth L from the nebular boundary and the density at that position (at $x = L$) is labelled n_0. The hollow gas cavity has a size r_0.

where $n(x)$ is the gas density, n_0 is the boundary density of the nebula towards the exciting star, and x is the variable representing the distance from the inner density discontinuity at $x = 0$. Note the reversal of axes relative to traditional studies: the ionizing radiation is entering at the cloud boundary $x = L$ and is absorbed inward up to the inner Strömgren boundary at X_s (see Figure 1). The steep density gradient near the origin ensures that the photons are absorbed before the density discontinuity, hence $X_s \gtrsim 0$.

In the case of Orion, the spherical geometry is necessary in order to take into account the geometrical dilution of the ionizing radiation across the radial density structure. One can define the variable, r, as the distance from the central ionizing star; that is $r = L - x + r_0$ where r_0 is the radius of the cen-

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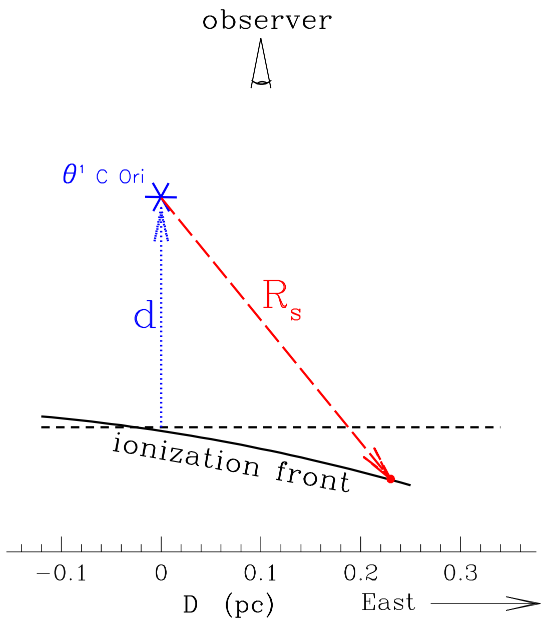

Fig. 2. Figure illustrating the sky projection of the West-East slit onto the nebular IF. The distance between θ^1 Ori C and the IF is R_s with d the substellar distance.

tral hollow cavity and n_0 is the gas density at r_0. When the ionizing photon luminosity Q_H is sufficiently high (or the density n_0 low), the Strömgren radius, $R_s = L - X_s + r_0$, is near the origin of the x-axis, at a distance $\simeq L + r_0$ from the exciting star (since X_s is negligible). This is referred to by BR90 as the "strong gradient" regime. In the converse case, for very low ionizing photon luminosities Q_H (or for high boundary densities n_0), R_s shrinks (X_s becomes non-negligible) and becomes of order r_0 plus a small fraction of L, a condition which BR90 labeled "weak gradient" because the nebula's thickness is smaller than the density gradient's scale L. All the quantities introduced above are illustrated in Fig. 1. We found no justification for having an arbitrary large region devoid of gas around θ^1 Ori C and, for definiteness, have set $r_0 = 0.007\,\mathrm{pc} \lesssim 0.05\,R_s$, a size so small that its precise value has no impact on the calculations. To account for the projection of each slit aperture element onto the calculated Strömgren spheres, we carried out in MAPPINGS Ic the integral of line emissivities over spatial limits corresponding to the appropriate aperture projection onto the calculated spheres.

Dust mixed with nebular gas, a possibility studied by Baldwin et al. (1991; BF91), can play an important role in the structure of the Orion nebula. Our models include a distribution of small grain sizes covering the range 0.005 to 0.03 μm, with a total dust mass content of $\mu_D = 0.4$, where μ_D is in units of the Solar neighborhood dust-to-gas ratio. We adopt the same gas-phase abundances as those determined by BF91 (mean metallicity of $0.7\,Z_\odot$) and the stellar atmosphere models of Hummer & Mihalas (1970) with $T_{\rm eff} = 38,000\,\mathrm{K}$. We adopted a somewhat reduced stellar photon luminosity of $Q_H = 10^{49}$ photons s^{-1} in the models (see discussion in Wen & O'Dell 1995 [WO95] and BGM02).

To relate the slit pixel position D with R_s from models, we adopted the following simple relation: $D = [R_s^2 - (0.073\,\mathrm{pc})^2]^{1/2} - d$, where 0.073 pc is the slit offset of 30″ to the south, and R_s is the true IF distance to θ^1 Ori C for a given slit position D in parsec projected on the sky (see Fig. 2). $D = 0$ corresponds to the pixel nearest to θ^1 Ori C with D increasing towards the east. The additional parameter d was obtained by iteration, using as constraint that our best model should fit as closely as possible both the observed [S II] densities and the Hβ surface brightnesses. The values favored by the study of BGM02 are $d = 0.26$ pc and a boundary gas density of $n_0 = 150\,\mathrm{cm}^{-3}$.

3. GAS TEMPERATURE AND LINE RATIOS

One important parameter is the stellar temperature, which directly affects the excitation line ratio [O III]/Hβ. We found that reproducing satisfactorily this ratio requires a stellar temperature of 38,000 K when using the stellar atmosphere models of Hummer & Mihalas (1970). This temperature is consistent with an evolved star of spectral type O7 (cf. WO95). Our line-ratio calculations of [O III]/Hβ are represented by the solid line in Figure 3*d*. We discuss below possible explanations for the solid line lying slightly below the data.

A gradient is also present in our data for the temperature indicators $R_{\rm N\,II}$ = [N II] λ 5755/[N II] λ 6583 and $R_{\rm O\,III}$ = [O III] λ 4363/[O III] λ 5007, as shown by Fig. 3*bc* (BF91 also reported a gradient of $R_{\rm N\,II}$ although for a different slit alignment). According to the models, the gradient in the ratio $R_{\rm O\,III}$ is due to a temperature gradient ($\Delta T \simeq 500\,\mathrm{K}$) alone, while in the case of nitrogen it is due to both a density gradient (via collisional deexcitation, cf. BF91) and a temperature gradient. Although the stratified models can successfully fit the observed trends in Fig. 3*b* and *c*, the predicted ratios lie somewhat lower than observed, more so for $R_{\rm O\,III}$. Lowering the metallicity would increase $R_{\rm O\,III}$ but at the expense of having the [O III]/Hβ ratio becoming larger than observed.

It is well known that photoionization models do not explain why the temperatures derived

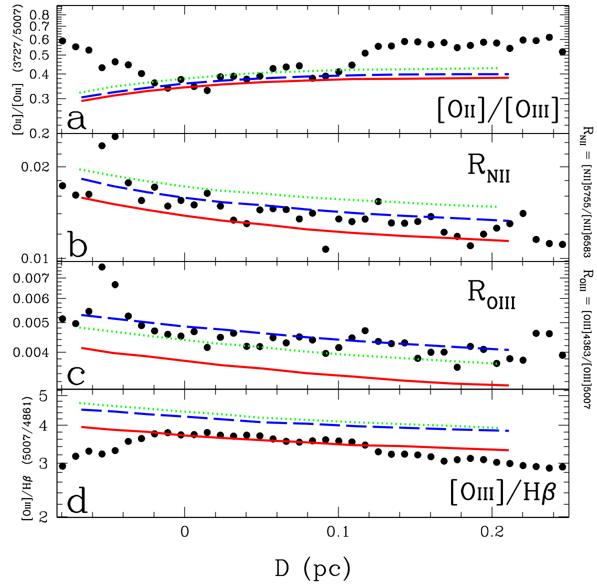

Fig. 3. The dots represent the observed line ratios. (*a*) The line ratio [O II] $\lambda\lambda$ 3727/[O III] λ 5007, which is a good indicator of the degree of ionization, (*b*) the nitrogen temperature-sensitive ratio [N II] λ 5755/[N II] λ 6583, (*c*) the oxygen temperature-sensitive ratio [O III] λ 4363/[O III] λ 5007, and (*d*) the [O III] λ 5007/Hβ λ 4861 ratio. The scale of the 3 panels (*b*), (*c*) and (*d*) is the same and extends over 0.42 dex. The models: the solid line shows the behavior of line ratios along the slit for our reference model. The long-dashed line was calculated assuming temperature fluctuations with $t^2 = 0.01$. The dotted line was calculated using half the diffuse field from the "outward-only" approximation.

from collisionally excited lines differ from that of recombination lines. This might be explained if there are high-amplitude temperature fluctuations in the nebula (Peimbert 1967) that far exceed the amplitude arising from traditional photoionization models. The mean square fluctuation amplitudes that Esteban et al. (1998) inferred lie in the range $t^2 = 0.020$ to 0.028. The effect of temperature fluctuations on line emissivities was incorporated into the code MAPPINGS Ic by the scheme described in Binette & Luridiana (2000). The long-dashed lines in Fig. 3 represent such a model calculated with $t^2 = 0.01$. As expected, $R_{\rm N\,II}$ and, more so, $R_{\rm O\,III}$ are both significantly increased and can now satisfactorily reproduce the data of Fig. 3*bc*. The calculated [O III]/Hβ ratio in Fig. 3*a*, however, now lies too high and the stellar temperature would have to be reduced in order to produce a self-consistent model in all panels. Given our current poor knowledge about the nature and cause of the postulated temperature fluctuations, we have not carried out the iterative process any further.

The diffuse ionization radiation field has a non-negligible impact on the gas temperature. In our models, we use the "outward-only" approximation to treat the transfer of the diffuse radiation. This is equivalent to assuming a single direction for the propagation of the diffuse field, a technique based on the approximation that the diffuse field is soft and does not therefore travel far from the point of emission. To test whether the integration along the direction of increasing density may cause an over-estimation of the intensity of the diffuse radiation, we have calculated models in which we reduced by half the strength of the diffuse field (keeping $t^2 = 0$). Such models are represented by the dotted line in Fig. 3. We see a significant shift, which is in the same direction as that caused by temperature fluctuations with $t^2 \sim 0.01$. The dotted line gives us a useful upper limit on the line-ratio uncertainties resulting from a possible inadequacy of the outward-only approximation.

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