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ENERGY IMPLICATIONS OF TEMPERATURE FLUCTUATIONS

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RESUMEN

Cuantificamos la energía radiada por todas las líneas colisionales en una nebulosa con fluctuaciones de temperatura en la forma de "zonas calientes", las cuales resultan de un proceso de calentamiento desconocido. Se encuentra que la energía de excendente radiada por estas líneas como resultado de las fluctuaciones escala de forma lineal con la amplitud de t^2. Encontramos que la luminosidad mecánica combinada de vientos estelares, flujos de champán, y *proplyds* es insuficiente para explicar las fluctuaciones en temperatura de regiones H II típicas, aunque los vientos estelares podrían explicar las fluctuaciones en nebulosas planetarias.

ABSTRACT

We quantify the energy radiated through all the collisional lines in a photoionized nebula in the presence of temperature fluctuations in the form of hot spots caused by an unknown heating process. The excess energy radiated in the lines as a result of the fluctuations is found to scale linearly with their mean-square amplitude t^2. We find that the combined mechanical luminosity of stellar winds, champagne flows and photoevaporation flows from proplyds is insufficient to account for the temperature fluctuations of typical H II regions, but that stellar winds may possibly explain the fluctuations in planetary nebulae.

Key Words: **ISM – ABUNDANCES – H II REGIONS – PLANETARY NEBULAE**

1. INTRODUCTION

Assuming that the temperature fluctuations inferred by various authors (e.g. Peimbert et al. 1995; Esteban et al. 1998; Rola & Stasińska 1994) in photoionized nebulae are caused by an additional albeit *unknown* heating agent (beside photoionization), we proceed to quantify the energy contribution which this unknown heating process must contribute to the total energy budget of the nebula in order to account for the much higher temperatures characterizing the collisionally excited lines as compared to those inferred from recombination lines (or nebular Balmer continuum).

2. THE ENERGETIC REQUIREMENTS OF NEBULAR HOT SPOTS

2.1. *Definitions of t^2 and Mean Temperature $\bar{T}_0$*

We present a few definitions followed by the procedure we adopt to implement the effect of temperature fluctuations in the code MAPPINGS IC (Ferruit et al. 1997). Following Peimbert (1967), we consider the case of a homogeneous metallicity nebula characterized by small temperature fluctuations, defining the mean nebular temperature, $\bar{T}_0$, and the rms amplitude, t, of the fluctuations as follows:

$$\bar{T}_0 \equiv \frac{\int_V n_e^2 T dV}{\int_V n_e^2 dV}\ , \qquad t^2 \equiv \frac{\int_V n_e^2 (T-\bar{T}_0)^2 dV}{\bar{T}_0^2 \int_V n_e^2 dV}\ , \tag{1}$$

where n_e is the electronic density, T the electronic temperature and V the the volume over which the integration is carried out. In this paper t^2 is considered a global property of the nebular model.

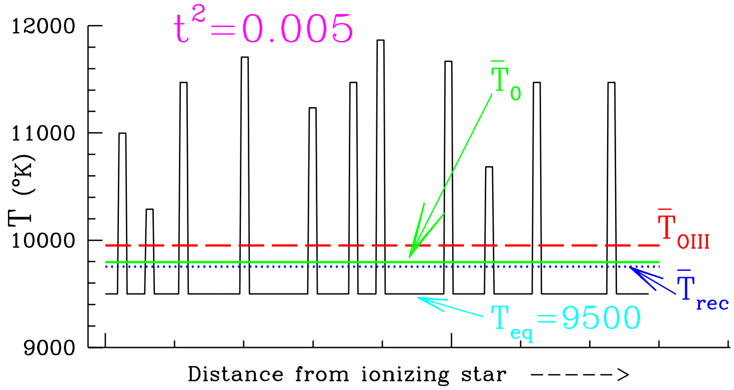

Fig. 1. A numerical simulation of temperature fluctuations consisting of hot spots characterized by an amplitude $t^2 = 0.005$ (from eq. 1). The mean temperature $\bar{T}_0$ obtained from applying eq. 1 is 9800 K (horizontal solid line). Also shown the relative position of $\bar{T}_{rec}$ and $T_{[\mathrm{OIII}]4363}$. The fluctuations' lower bound temperature (to be associated to T_{eq}) is 9500 K.

2.2. *Approximating Fluctuations as Hot Spots and the Determination of* $\bar{T}_0$

In photoionization calculations, it is customary to define and use at every point in the nebula a local equilibrium temperature, T_{eq}, which satisfies the condition that the cooling by radiative processes equals the heating due to the photoelectric effect. In our hot spots scheme, by construction, T_{eq} corresponds to the temperature floor above which take place all the fluctuations. For illustrative purposes, we show in Figure 1 a possible rendition of fluctuations (the thin, solid line) characterized by an amplitude $t^2 = 0.005$ (from eq. 1) and consisting of hot spots. Because T_{eq} is a minimum in the distribution of T fluctuations, it defines the null energy expense when calculating the extra energy emitted as result of the hot spots.

The fluctuations are taken into account by MAPPINGS Ic only in the statistical sense, that is by defining and using temperatures which are derived from $\bar{T}_0$. Given a certain amplitude of fluctuations t^2, we use everywhere a value for the mean temperature which is derived from the computed local equilibrium temperature (T_{eq}) and which takes into account that T_{eq} is a lower extremum in the distribution of T fluctuations (consisting of hot spots). To define $\bar{T}_0$, we find the following expression (motivated by the considerations of section 2.3) to be suitable

$$\bar{T}_0 \simeq T_{eq}[1 + \gamma(\gamma - 1)t^2/2]^{-1/\gamma} , \tag{2}$$

in which the optimum value of γ has been inferred using numerical simulations of the hot spots. One simulation shown in Figure 1 is characterized by $T_{eq} = 9500$ K and $t^2 = 0.005$. By fitting γ so that the value of $\bar{T}_0$ matches the numerically computed value of 9800 K, we obtain $\gamma \approx -15$. See Binette & Luridiana (2000) for more details.

2.3. *Recombination Processes*

In order to calculate the intensity, I_{rec}, of a recombination line with temperature dependence of T^α, one must use an effective recombination temperature: $\bar{T}_{rec} \equiv \langle T^\alpha \rangle^{1/\alpha} \simeq \bar{T}_0[1 + \alpha(\alpha - 1)t^2/2]^{1/\alpha}$. The second equality is valid when the temperature fluctuations are small, allowing one to discard higher order terms in the Taylor expansion about $\bar{T}_0$. Since $\alpha < 0$ in most cases, $\bar{T}_{rec}$ generally lies slightly below $\bar{T}_0$ (see Figure 1).

2.4. *Collisional Processes*

To compute the forbidden line intensities, we solve for the population of each excited state of all ions of interest assuming a system of five or more levels according to the ion. (In the case of intercombination, fine structure and resonance lines, we treat those as simple two–level systems.) More specifically, when evaluating the excitation ($\propto T^{\beta_{ij}} \exp[-\Delta E_{ij}/kT]$) and deexcitation ($\propto T^{\beta_{ji}}$) rates of a given multi–level ion, each rate ij (population) or ji (depopulation) is calculated using $\bar{T}_0$ (instead of T_{eq}) and then multiplied by a correction factor of the form $1 + At^2/2$, where

$$A^{exc}_{ij} = (\beta_{ij} - 1)(\beta_{ij} + 2x_{ij}) + x^2_{ij} \qquad \text{, or} \qquad A^{deexc}_{ji} = \beta_{ji}(\beta_{ji} - 1), \tag{3}$$

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in the case of excitation or deexcitation, respectively, and where $x_{ij} = \Delta E_{ij}/kT$. These factors result in an enhancement of the collisional excitation rates for optical and UV lines ($x_{ij} > 1$) in the presence of temperature inhomogeneities. They are adapted from the work of Peimbert et al. (1995) and were applied to all collisionally excited transitions.

2.5. *The Energy Radiated through Hot Spots*

Our aim is to quantify the excess energy generated by temperature fluctuations under the assumption that these are caused by a putative heating mechanism which operates within small regions randomly distributed across the nebula. To calculate this energy we simply integrate over the nebular volume V the luminosity of each line (or transition) ij using the statistically determined local $\bar{T}_0$ and the multiplicative correction factors of eq. 3, and then subtract the corresponding luminosity obtained by using the equilibrium temperature T_{eq} instead. This excess energy radiated in the form of collisionally excited lines can be normalized with respect to the *bolometric* stellar luminosity. This defines the quantity Γ_{bol}:

$$\Gamma_{bol} = \frac{\sum_{ij} \int_V [4\pi j_{ij}^{fluc} - 4\pi j_{ij}^{eq}]\, dV}{\int_0^\infty L_\nu^\star(T_{eff})\, d\nu} = \frac{L_{fluc} - L_{eq}}{L_{bol}^\star} , \tag{4}$$

where j_{ij}^{fluc} corresponds to the local nebular emissivity of line ij calculated using $\bar{T}_0$ and taking into account the above correction factors while j_{ij}^{eq} is the corresponding emissivity assuming equilibrium temperature everywhere. $L_{bol}^\star$ is the bolometric luminosity of the exciting star.

3. MODEL CALCULATIONS

For the photoionized H II regions, we have selected unblanketed LTE atmosphere models from Hummer & Mihalas (1970) of temperatures T_{eff} of 4×10^4 K, 4.5×10^4 K and 5×10^4 K. To represent planetary nebulae, we simply employed black bodies of 10^5 K and $10^{5.3}$ K truncated at 54.4 eV. The geometry adopted in the calculation is plane-parallel with a gas density of $n_H = 10$ cm^{-3} in all cases. The excitation of the nebula is defined by the excitation parameter U which is the ratio between the density of ionizing photons impinging on the slab (φ_H/c) and the total H density. We found no clear trends across different SEDs of how Γ_{bol} varied with U and therefore we only report results concerning a single ionization parameter of value 10^{-2}. Campbell (1988) has shown that the range of U for most H II galaxies lies in the range $10^{-2.6}$ to $10^{-1.8}$. All the calculations carried out were ionization–bounded.

3.1. *Dependence of Excess Gas Heating on Z and t^2*

In Figure 2a, we present the behaviour of Γ_{bol} of nebular models with different metallicities, covering the range 1% solar ($Z = 0.01$) to 2.5 times solar. It can be seen that a maximum in Γ_{bol} occurs within the range $Z \sim 0.2$–0.4. For the H II region models, the average values for T_{eq} across the nebulae are $\sim 15,000$ K, 9000 K, and 5000 K for $Z = 0.01$, 0.7, 2.5, respectively.

In Figs. 2b, we show the behavior of Γ_{bol} as a function of increasing t^2. Each line corresponds to a given SED and Z (either $Z = 0.2$ or $Z = 1$, labeled 'L' and 'S', respectively). We find that Γ_{bol} is comparable in magnitude to t^2 but again with a wide dispersion which result from differences in either Z or the SED.

4. DISCUSSION

Typical H II regions have $t^2 \geq 0.015$ and therefore the additional heating mechanism would have to represent more than 0.003 of the bolometric luminosity of the exciting star (see Figure 2b) in order to account for the hot spot luminosity. The exciting stars should possess strong, radiatively driven winds, whose dissipation via shocks is a possible candidate for such heating. However, although the wind momentum ($\dot{M}_{wind}V_{wind}^2$) is usually a substantial fraction of the momentum in the radiation field ($L_{bol}^\star/c$), the wind luminosity ($L_{wind} = \dot{M}_{wind}V_{wind}^3/2$) is much less than $L_{bol}^\star$ since $V_{wind} \sim 1000$ km s^{-1} $\ll c$ (with the exception of Wolf-Rayet stars,

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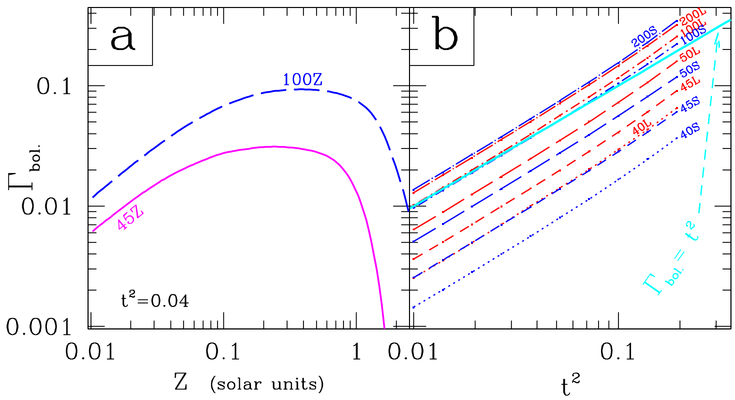

Fig. 2. Panel **a**. Behaviour of Γ_{bol} in a sequence of photoionization models which have different nebular metallicities (relative to solar $Z = 1$). The two SED used in the calculations consisted of a 4.5×10^4 K and 10^5 K star, respectively. In all models $t^2 = 0.04$ and $U = 0.01$. Panel **b**. Behaviour of Γ_{bol} with increasing t^2. Two metallicities were used: solar (label S) and 0.2 solar (label L) and 5 SED: 4×10^4 K, 4.5×10^4 K, 5×10^4 K, 10^5 K, and 2×10^5 K, labeled 40, 45, 50, 100 and 200, respectively). For comparison we show a thick line representing $\Gamma_{bol} = t^2$.

where multiple scattering can boost L_{wind}). Indeed, typical values for $\eta_{wind} \equiv L_{wind}/L^{\star}_{bol}$ are in the range 10^{-4}–10^{-3} for OB dwarfs and supergiants (Lamers & Cassinelli 1999, Table 8.1).

Further potential sources of mechanical energy in typical H II regions are photoevaporation flows from the circumstellar disks of low–mass stars (proplyds) and large–scale champagne flows induced by density gradients in the ambient medium. As an example, we consider the Orion nebula ($t^2 \gtrsim 0.02$: Esteban et al. 1998), excited by the O7V star θ^1 C Ori ($L^{\star}_{bol} \simeq 2 \times 10^5 L_{\odot}$), for which we obtain $\eta_{wind} \simeq 3 \times 10^{-4}$, $\eta_{champ} \simeq 1.5 \times 10^{-3}$, and $\eta_{prop} \simeq 6 \times 10^{-5}$. Although the champagne flow comes closest to satisfying the t^2 energy requirements, the efficiency of conversion of kinetic to thermal energy in this case is likely to be much lower than with the proplyd flows or the stellar wind. Internal shocks in the champagne flow will arise due to the convergence of streams from features such as the Orion bar, but these will tend to be oblique, hence thermalizing only a fraction of the flow's kinetic energy.

The central stars of PNe have relatively more energetic winds ($\eta_{wind} \simeq 10^{-2}$), although the higher T_{eff} ($\sim 5{\times}10^4$–10^5 K) leads to higher energetic requirements for a given t^2 (Figure 2). As a result, winds in PNe could plausibly produce $t^2 = 0.01$–0.02, which is only slightly smaller than observed values (Liu & Danziger 1993). We therefore conclude that, although dissipation of mechanical energy is incapable of explaining the observed temperature fluctuations of typical H II regions, it could possibly be responsible for the temperature fluctuations in PNe.

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