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PHOTOEVAPORATED GLOBULES IN HII REGIONS

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RESUMEN

Presentamos un resumen de modelos de la dinámica de un viento estelar ionizado de una estrella masiva cargado de masa por la fotoevaporación de glóbulos dentro de la región ionizada. El efecto de la inyección de masa es el de modificar el perfil de densidad, de manera que el frente de ionización puede ser atrapado durante 10^5 años, dependiendo de las características de los glóbulos neutros. Para glóbulos con tamaños ~ 0.01 pc, masas $M_g \sim 1 M_\odot$ y densidad numérica $n_g \sim 2 \times 10^4$ pc^{-3}, que se observan en regiones de formación de estrellas masivas, la densidad media y los diámetros de las regiones ionizadas cargadas de masa son $\bar{n} \sim 10^4$ cm^{-3} y $D \sim 0.1 - 0.2$ pc, similares a los de las regiones HII compactas observadas. Estos modelos tienen flujos ionizados con velocidades en el radio de Strömgrem $v_i(R_S) \sim 15$ km s^{-1} y ritmos de pérdida de masa $\dot{M}(R_S) \sim 10^{-4} M_\odot$ año^{-1}. Además, delante de la región HII se recombina el flujo,‘ acelerándose adiabáticamente hasta velocidades terminales $v_{HI} \sim 60$ km s^{-1}.

ABSTRACT

We present a summary of models of the dynamics of a fast isothermal ionized stellar wind from a massive star loaded with mass injection from photoevaporated globules inside the ionized region. The effect of the mass injection is to produce a density profile such that the ionization front can be trapped for 10^5 yrs, depending on the characteristics of the neutral globules inside the HII region. For neutral globules with sizes $r_g \sim 0.01$ pc, masses of $M_g \sim 1 M_\odot$, and number densities $n_g \sim 2 \times 10^4$ pc^{-3}, observed in regions of massive star formation, the mean density and diameters of the mass loaded regions of ionized gas are $\bar{n} \sim 10^4$ cm^{-3} and $D \sim 0.1 - 0.2$ pc, respectively, similar to those of observed compact HII regions. These models have ionized flows with velocities at the Strömgrem radius $v_i(R_S) \sim$ 15 km s^{-1} and mass loss rates $\dot{M}(R_S) \sim 10^{-4}$ M$_\odot$ yr^{-1}. Furthermore, beyond the HII region, a neutral flow should be observed since the ionize flow will recombine and adiabatically accelerate to a terminal velocity of $v_{HI} \sim 60$ km s^{-1}.

Key words: **ISM : HII REGIONS – – STARS: FORMATION**

1. INTRODUCTION

Since Wood & Churchwell (1989) presented the apparent paradox of the excess number of observed compact and ultracompact HII regions, different theoretical models have been proposed to lengthen this compact phase of evolution in order to reconcile the number of observed HII regions with the star formation rate of O and B stars determined by other means.

In these models the dynamical time R/c_i of the HII region is not related to its age as in the standard model of evolution by overpressure of the ionized gas with respect to the ambient cloud (Spitzer 1978). The associated dynamical age of the compact and ultracompact regions is $\sim 10^4$ yr, while the models can lengthen this phase to 10^5 yr.

There is for example, the bow shock model of Van Buren et al. (1990) and MacLow et al. (1991) for cometary HII regions. In this model a star moves in a dense cloud core and the ram pressure of the molecular gas flowing into a bow shock balances the pressure the stellar wind exerts on the post-shock gas producing the characteristic parabolic shape of the bow shock. The HII region is trapped in the post-shock gas. While the star traverses a region of dense gas, this bow shock structure is stationary. Another model for spherical or unresolved UC HII regions is that of the photoevaporated disks of Hollenbach et al. (1994). In this model the ionized gas in the HII region expands but is replaced by material photoevaporated from a circumstelar disk around the massive star producing a core halo emission as observed in a fraction of the UC HII regions.

Recently, De Pree et al. (1995) have proposed that in fact the UC HII regions follow the standard evolution but that they are born inside very dense cloud cores ($n_{H2} > 10^8$ cm^{-3}) and have therefore reached their final Strömgren radius, i. e. they are not expanding any more.

Here we present a summary of models that consider the effect of mass injection due to the photoevaporation of neutral globules inside the HII region to lengthen the compact phase. This models are discussed in detail in Lizano et al. (1995). In particular, since OB stars are known to have very powerful winds, we model a fast isothermal stellar wind loaded with mass from these globules. We assume that due to the high densities, the wind does not go through an adiabatic phase. The evolution of these globules have been studied by several authors (e.g. Oort & Spitzer 1965; Dyson 1969, 1973; Kahn 1969; Tenorio-Tagle 1977; Bertoldi 1989; Bertoldi & McKee 1990). In this work we are interested in the neutral globules only as a source of mass.

2. MODEL

In this section we present a summary of the modeling an isothermal ionized fast stellar wind that is loaded with mass due to the photoevaporation of neutral globules. We have solved for the velocity and density structure of a spherically symmetric mass loaded wind and for the rate of ionizing photons as a function of distance to the central star. We have assume that the wind density is sufficiently high that it does not have an adiabatic phase. Under these assumptions, the steady state equations in spherical coordinates for the gas are:

(i) the equation of continuity

$$\frac{1}{r^2}\frac{d(r^2\rho v)}{dr} = \dot{q}, \tag{1}$$

where r is the distance to the central star, v is the gas velocity, ρ is the ionized gas density, and $\dot{q}$ is a mass source term (g cm^{-3} s^{-1}), which will be discussed below;

(ii) the momentum equation

$$\rho v\frac{dv}{dr} = -c_i^2\frac{d\rho}{dr} - v\dot{q}, \tag{2}$$

where c_i is the isothermal sound speed of the ionized gas; and

(iii) the ionizing photon rate equation

$$\frac{dS}{dr} = -4\pi r^2 J A_g n_g - 4\pi r^2 \alpha_R \left(\frac{\rho}{m_H}\right)^2, \tag{3}$$

where S is the rate of ionizing photons ($h\nu > 13.6ev$) and $J = S/4\pi r^2$ is the flux of ionizing photons, A_g and n_g are the area and number density of the globules respectively, and α_R is the recombination rate to the energy level $n = 2$. The first term of the right hand side corresponds to the ionizing photons absorbed by evaporation of the globules. The second term corresponds to the photons absorbed by the recombinations.

The flux of ionizing photons that arrives to the surface of a photoevaporated globule, J_g, is given by $J_g = n_{i0}c_i - \int_{r_g}^{\infty} \alpha_R n_i^2 dr$, where we take the density profile of the atmosphere of the photoevaporating globule as $n_i = n_{i0}(r/r_g)^{-2}$ (see Dyson [1968] for an exact solution). Here n_{i0} is the density at the D-critical ionization front moving slowly into the globule. Then the above equation becomes a quadratic equation for n_{i0} (Spitzer 1978). Since recombinations in the dense atmosphere of the photoevaporating globule dominate we take

$$n_{i0} = \left(\frac{3S}{4\pi\alpha_R r_g r^2}\right)^{1/2} \tag{4}$$

The mass source term,

$$\dot{q} = n_{i0} c_i A_g n_g m_H, \tag{5}$$

depends then on the square root of the ionizing photon flux.

Furthermore, we take into account the effect of the photoevaporation of the globules in the process of mass injection, by setting $A_g = A_{g0}\, g(r,t)$, where

$$g(r,t) = \frac{1}{\left[1+(r_d/r)\right]^4}. \tag{6}$$

Here $r_d \equiv \frac{t}{M_{g0}}\left(\frac{3S_*}{4\pi\alpha_R}\right)^{1/2} c_i \pi r_{g0}^{3/2} m_H$ is the radius inside which the globules have been destroyed. A_{g0}, M_{g0}, and r_{g0} are the initial area, mass and radius of the neutral globules.

Equations (1 - 3) are solved given the boundary conditions at the star: the stellar rate of ionizing photons S_*, the stellar mass loss rate $\dot{M}_w$, and the wind velocity v_w.

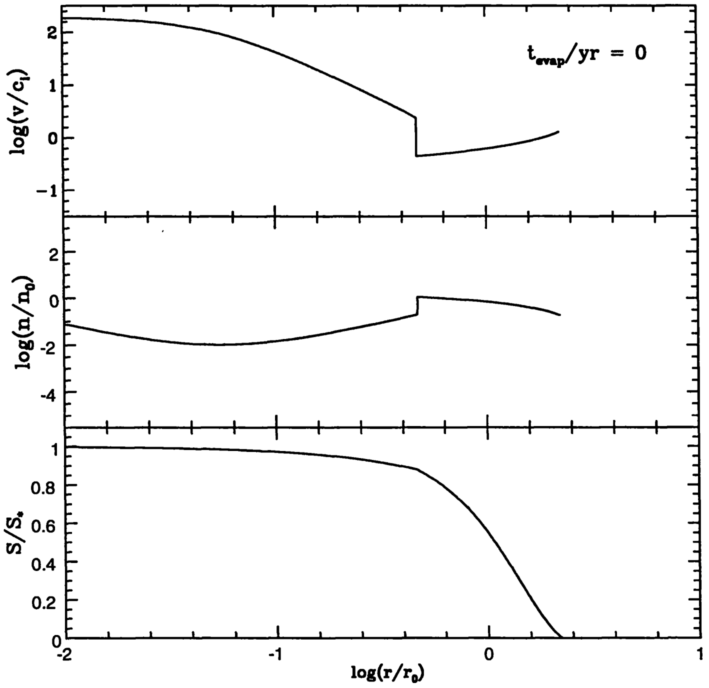

Fig. 1.— Normalized velocity, number density, and ionizing photon rate as a function of normalized distance to the central star at a time $t_{\rm evap} = 0$ yrs. This model has an isothermal shock at a radius $r/r_0 = 0.47$ and a sonic point at a radius $r/r_0 = 1.85$.

3. RESULTS

In Figure 1 we present a model of a wind loaded with mass from the evaporation of neutral globules with $r_{g0} = 0.01$ pc, $n_g = 2 \times 10^4$ pc^{-3}, and a mass of $M_{g0} = 1 M_\odot$. This type of neutral globules, called partially ionized globules (PIGS), are observed in regions of massive star formation (e.g Lacques & Vidal 1979; Churchwell et al. 1987; Garay 1987). The model has an O9 central star with $S_* = 10^{48} s^{-1}, \dot{M} = 1 \times 10^{-7} M_\odot\,{\rm yr}^{-1}, v_w = 2500\,{\rm km\,s}^{-1}$. This figure shows the normalized velocity, number density, and ionizing photon rate as a function of the logarithm of the normalized distance to the central star, at an evaporation time $t_{\rm evap} = 0$ yr. The latter is the time since the evaporation of the globules began, inmediately after the initial Strömgren radius is established. Up to $t_{\rm evap} \sim 1 \times 10^3$ yr the solutions are almost identical because the destruction radius in equation (6) is small and the mass loading is efficient. This model has an isothermal shock at $r/r_0 = 0.47$ and a sonic point at $r/r_0 = 1.85$. The normalized distance is

$$\left(\frac{r_0}{\mathrm{pc}}\right) = 4.39 \times 10^{-2} \left(\frac{r_{g0}}{0.01\,\mathrm{pc}}\right)^{-1} \left(\frac{n_g}{2 \times 10^4\,\mathrm{pc}^{-3}}\right)^{-2/3},$$

and the normalized density is

$$\left(\frac{n_0}{\mathrm{cm}^{-3}}\right) = 3.96 \times 10^4 \left(\frac{r_{g0}}{0.01\,\mathrm{pc}}\right)^{3/2} \left(\frac{n_g}{2 \times 10^4\,\mathrm{pc}^{-3}}\right) \left(\frac{S_*}{10^{49} s^{-1}}\right)^{1/2}$$

The velocity is measured in units of c_i and the rate of ionizing photons in units of S_*.

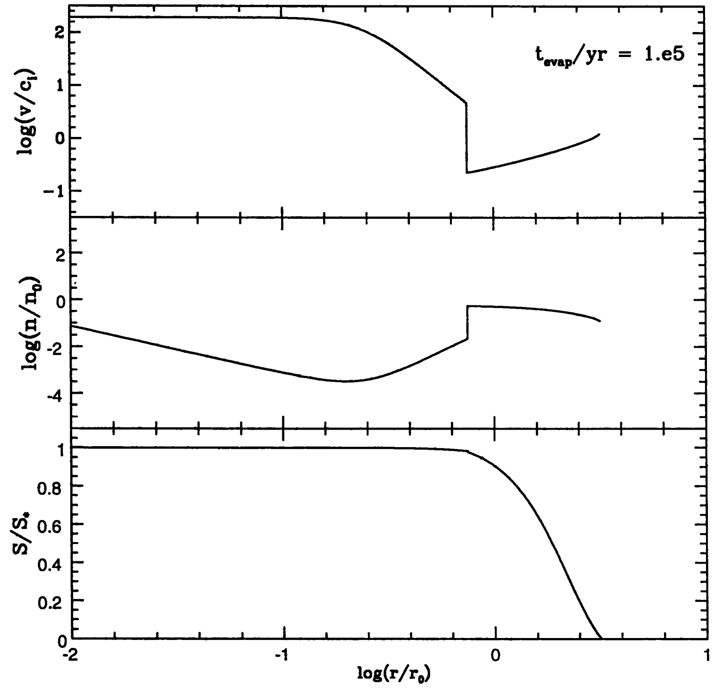

Fig. 2.— The same as Figure 1 but for a time $t_{\mathrm{evap}} = 10^5$ yrs. This model has an isothermal shock at a radius $r/r_0 = 0.75$ and a sonic point at a radius $r/r_0 = 2.92$.

Figure 2 shows the same model at $t_{\mathrm{evap}} = 10^5$ yr. At this time the model has an isothermal shock at a radius $r/r_0 = 0.75$ and a sonic point at a radius $r/r_0 = 2.92$. Because the globules have been evaporated in the center as described by the function $g(r,t)$, the density profile goes like $n \propto r^{-2}$ in the center, until the mass loading starts and flattens the profile, trapping the ionization front of the HII region. As the globules are evaporated, the HII regions becomes more extended with a smaller mean density.

The two solutions shown in Figures 1 and 2 are representative of all the solutions in the parameter space explored: the Strömgren radius of mass loaded HII region increases with time as the globules are evaporated in the center and the mean density decreases. Also the shock radius and the sonic radius increase as the loading of mass decreases in the center.

We find that models with central stars with ionizing photon rates $S_* > 10^{47}$ s^1, in dimensional units have densities and sizes which correspond to those observed in compact HII regions: electron densities $n_e \sim 10^4$ cm^{-3} and diameters $D \sim 0.1 - 0.2$ pc. (e.g. Wood & Churchwell 1989; Garay et al. 1993). Therefore, the ionized regions will survive in the compact phase while the neutral globules last. An interesting point is that Garay et al. (1993) have suggested that several of the UC H II regions catalogued by Wood & Churchwell (1989) are not internally excited but correspond to dense neutral structures embedded within more extended ionized regions excited by a single luminous stars. In our model, these structures would "feed" the compact HII region, trapping the ionization front for timescales $\sim 10^5$ yr. One way of determining the true nature of these UC HII regions is by searching for the internal energy source (the star) with the new IR cameras.

Note that a change in the properties of the globules will result in models with different mean densities and radii. For example, if the number density of the globules n_g increases, the mean densities of the HII regions increase and the sizes decrease with respect to the models presented.

Finally, the velocity of the ionized gas at the Strömgren radius is $v(R_S) \sim 1.3c_i$. The mass loss rate of the ionized flow has increased from $\dot{M}_w$, at the stellar surface, to $\dot{M}_S \sim 10^{-4} M_\odot\,\mathrm{yr}^{-1}$, at the Strömgren radius. This ionized flow could be studied in radio recombination lines, looking for weak extended wings. After this point, this flow should recombine and accelerate, as the flow adiabatically expands, to a terminal velocity $v_{HI} \sim 2.5 \times v(R_S)$. This implies that massive neutral outflows will be the output of this compact regions produced by the mass loading of the ionized stellar wind. This neutral flow could be observed in absorption against the continuum of the HII region.

4. CONCLUSIONS

We have modeled the dynamics of a fast isothermal ionized stellar wind from a massive star loaded with mass injection from photoevaporated globules. The mass injection considered is proportional to the square root of the ionizing photon flux. The effect of the mass injection is to produce a density profile such that the ionization front can be trapped for 10^5 yr, depending on the physical characteristics (mass and radius) of the neutral globules inside the HII region.

We find that in the case of neutral globules of the charactheristic sizes and observed number densities of the so-called PIGS, the mean densities and sizes of the ionized regions of this mass loaded winds correspond to those observed in compact regions: electron densities $n_e \sim 10^4$ cm^{-3} and diameters $D \sim 0.1 - 0.2$ pc.

Finally, the effect of dust in the above calculations is discussed in Lizano et al. (1995).

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REFERENCES

Bertoldi, F. 1989, ApJ, 346,735

Bertoldi, F., & McKee, C. F. 1990, ApJ, 354, 529

Churchwell, E., Felli, M, Wood, D. O. S., & Massi, M. 1987, ApJ, 321, 516

De Pree, C., Rodríguez, L. F. & Goss, M. 1995, RevMexAA , in press

Dyson, J. E. 1968, Ap&SS, 1, 338

Dyson, J. E. 1973, A&A, 27, 459

Dyson, J. E. 1993, in Lecture Notes in Physics 43: "Star Formation Technnques in Infrared and mm-wave Astronomy", ed. T. P. Ray & S. V. W. Beckwith, in press

Garay, G. 1987, RevMexAA, 14, 489

Garay, G., Moran, J. M., Rodríguez, L. F., & Churchwell, E. 1993, ApJ, 418, 368

Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. H. 1994, ApJ, 428, 654

Kahn, F. D. 1969, Physica, 41, 172

Lacques, P., & Vidal 1979, A&A, 73, 97

Lizano, S., Cantó, J., Garay, G., & Hollenbach, D. 1995, ApJ, submitted

Oort, J. H., & Spitzer, L. 1955, ApJ, 121, 6

Spitzer, L. 1978; in Physical Processes in the Interstellar Medium (John Wiley & Sons, New York)

Tenorio-Tagle, G. 1977, A&A, 54, 517

Wood, D. O. S. W., & Churchwell, E. 1989, ApJS, 69, 831

Van Buren, D. 1985, ApJ, 294, 567