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PHOTOIONIZATION AND STAR FORMATION

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RESUMEN

La fotoionización generada por estrellas masivas crea regiones H II cuya expansión termina evaporando la mayor parte del gas de las nubes moleculares que forman estrellas. Este es un mecanismo muy eficiente para destruir nubes moleculares y además controlar el número de estrellas formadas en una nube. La eficiencia de formación estelar resultante en regiones de baja presión es del 5%, pero puede incrementarse arriba del 50% en las regiones internas de las galaxias.

ABSTRACT

Photoionization by massive stars creates expanding H II regions, which eventually evaporate most of the gas in a star-forming molecular cloud. This is a very efficient cloud destruction mechanism that can also control the maximum number of stars that are formed within a molecular cloud. The resulting star-formation efficiency at low galactic pressures has an overall value of about 5%, but this efficiency value can increase above 50% in the inner regions of star-forming galaxies.

Key Words: **GALAXIES: ISM — H II REGIONS — STARS: FORMATION**

1. INTRODUCTION

Energy injection from massive stars, via the combined effects of supernovae and expanding H II regions, can shape the interstellar medium of gaseous galaxies and create large, expanding structures. Their mechanical energy input operates almost from birth, with strong stellar winds, to their death in a supernova explosion, and may be the agent responsible for both stimulating and suppressing the star-formation process. For instance, Franco & Shore (1984) examined how the mechanical energy from OB associations may be responsible for self-regulation of global star formation in disk galaxies, and concluded that the current star-formation rate can be maintained through stimulated star formation (see Tenorio-Tagle & Bodenheimer 1988; Shore & Ferrini 1995).

The strong UV radiation field from young massive stars, on the other hand, is highly disruptive of the cloud environment (e.g., Kahn 1954; Whitworth 1979; Tenorio-Tagle 1982; Larson 1987; Elmegreen 1993; Franco, Shore, & Tenorio-Tagle 1994), and H II region expansion is a very efficient mechanism for destroying star-forming clouds. The ultimate drivers of the formation of clouds and stars are gravitational instabilities, but the process limiting stellar production is associated with molecular cloud destruction. Cox (1983, 1985) was the first one to point out this possibility, and derived the limits imposed by photoionization in the evolution of gaseous galaxies. He noted that a quadratic dependence of the star-formation rate on the gas density can be produced in such a case. Later, Franco et al. (1994) applied these ideas to molecular clouds and found that the star-formation efficiency can be directly derived from the number of expanding H II regions that are required to ionize a cloud.

2. DESTRUCTION BY H II REGIONS

2.1. *Low Ambient Pressures*

Here we summarize the results described in Franco et al. (1994). As first described in Kahn's classic paper (1954), the pressure difference between the H II region and the ambient medium is large and an outflow occurs from the ionized region into the surrounding space. For sufficiently low ambient pressures, the outflowing gas simply reaches a terminal velocity and continues to move with this velocity for the rest of the evolution. This occurs in each H II region that is formed within the cloud and, eventually, as the number of OB stars increases, the whole cloud is finally evaporated. Thus, the limit to the number of new stars occurs when the whole cloud is completely ionized, and the star-formation process is shut off (Franco et al. 1994).

Assuming the effects of stars more massive than $10\,M_\odot$ and a molecular cloud of total mass $M_c = M_* + M_g$ (where M_* is the mass in recently formed stars and M_g is the remaining gas mass), with a gas number density of n_0, the available fraction of gas for star formation is $1-\epsilon$, where $\epsilon = M_*/M_c$ is the star-formation efficiency. For simplicity, assuming constant density clouds with Strömgren spheres formed by typical, or average, OB stars that are expanding within the cloud, the limit to the star-forming activity inside the cloud is the decrease of molecular gas by these internal H II regions. The maximum number of OB stars that the cloud can support at any time is given by the number of H II regions required to completely ionize the cloud, $N_{\rm OB} = (1-\epsilon)M_{\rm c}/M_{\rm i}$. Thus, the maximum number of massive stars that can be formed within a cloud is:

$$N_{\rm OB} \approx \frac{16 M_{\rm c,4} n_3^{3/7}}{F_{48}^{5/7}(c_{\rm s,15} t_{\rm MS,7})^{6/7}} \ , \qquad (1)$$

where $M_{\rm c,4}$ is the cloud mass in units of $10^4\,M_\odot$, n_3 is the number density in units of $10^3\,{\rm cm}^{-3}$, F_{48} is the photoionizing flux in units of $10^{48}\,{\rm s}^{-1}$, $c_{\rm s,15}$ is the isothermal sound speed in units of $15\,{\rm km\,s}^{-1}$, and $t_{\rm MS,7}$ is the mean OB star main sequence lifetime in units of 10^7 yr.

Stars formed near the cloud boundary destroy the molecular cloud via "champagne" flows, or "blisters". This is a more efficient disruption mechanism and the number of OB stars that the cloud manages to support is now

$$N_{\rm OB} \approx \frac{3 M_{\rm c,4} n_3^{1/5}}{F_{48}^{3/5}(c_{\rm s,15} t_{\rm MS,7})^{6/5}}. \qquad (2)$$

Clearly, blister erosion reduces the efficiency of star formation because the low external pressure ensures that the ionized gas expands rapidly away from the cloud and drives a fast ionization front into the dense material. One can estimate that a fraction, $f_{\rm int}$, will involve purely internal destruction processes, and a fraction $f_{\rm sur}$ will involve only surface destruction processes. The number of compact H II regions that are embedded in cloud cores (Wood & Churchwell 1989, 1991; Kurtz, Churchwell, & Wood 1994) may represent some 20% of the total H II region population (see Mezger 1985), and one can combine the internal and surface scenarios with a relative weight of $f_{\rm int} \sim 0.2$ and $f_{\rm sur} \sim 0.8$. This implies that the overall star-forming efficiency should be about 5%, irrespective of the mass of the cloud.

2.2. *High Ambient Pressures*

When the ambient pressure is high enough, the expanding photoionized gas will be eventually stopped and the H II region will reach pressure equilibrium. When this occurs, the cloud evaporation process cannot proceed with the efficiency described above because the growth of the H II region is limited by pressure and the amount of photoionized gas is now reduced. Thus, the number of massive stars required to destroy the parental cloud is increased and the corresponding star-formation efficiency is also increased.

For a given external pressure P_0, the resulting star-formation efficiency is given by

$$\epsilon \approx \frac{3}{1 + 25 F_{48}/m_{18} P_{12}}, \qquad (3)$$

where m_{18} is the mass of a typical star in units of 18 Solar masses, and P_{12} is the ambient pressure in units of the one at the Solar Circle, $10^{-12}\,{\rm dyn\,cm}^{-2}$. Thus, for pressures above 20 to 30 times that near the Sun, the star-forming efficiency can be increased to 50% or more. This would imply efficiencies similar to those found in starburst regions, and these aspects will be discussed in detail in a forthcoming paper.

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