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THERE'S LIFE IN H II REGIONS YET!

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RESUMEN

Hacemos una revisión de la propagación y estructura de los frentes de ionización y comentamos sobre la estructura de los frentes de recombinación. Discutimos la formación de colas cometarias por fotoionización de glóbulos, incluyendo la componente difusa del campo radiativo. Finalmente comentamos brevemente sobre la formación de estructuras pequeñas en regiones H II.

ABSTRACT

We give an overview of the literature on ionization front structure and propagation and comment on recombination front structures. We discuss the formation of cometary tails by photoionization of globules and note the importance of including the diffuse component of the ionizing radiation field. We finally briefly comment on the formation of small scale structures in H II regions.

Key Words: **HII REGIONS — HYDRODYNAMICS**

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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1. INTRODUCTION.

Ionized (H II) regions around hot stars can be bounded by neutral-ionized interfaces (Strömgren 1939). The pressure imbalance there results in H II region expansion (Oort 1954) in which a shock wave is driven into the neutral gas ahead of the expanding hot gas. Mass flows across the neutral-ionized interface, which is then described as an ionization front (IF). Kahn (1954) established the jump conditions across IFs. Fronts divide into R-types, which move supersonically into the upstream neutral gas and D-types that move subsonically. Between these classes there is a range of propagation speeds for which no physical solutions exist. At the limits of the velocity regions allowed by the jump conditions, the ionized flow out of the front takes place at the isothermal ionized sound speed and these fronts are called 'critical'. Fronts in which the gas both enters and exhausts the front supersonically are weak R-type fronts; those where the gas always moves subsonically are weak D-type fronts. Finally, in strong R-type fronts, the gas experiences a supersonic-subsonic transition, whereas in strong D-type fronts there is a subsonic-supersonic transition. The former can be effected by an internal shock but the latter has to be effected by overheating within the front to take the flow through a critical speed (Kahn 1969).

The most basic dynamical model for H II region evolution follows from Kahn's (1954) original work. If a source of ionizing radiation suddenly switches on, the IF is initially weak R-type. Once its velocity drops to about twice the sound speed in the ionized gas, a shock moves out of the IF which then becomes weak D-type. Depending on circumstances, in principle the H II region may reach pressure balance with its surroundings and they are separated by a transition region across which there is no mass flux. This evolution has been confirmed by detailed analytical (Axford 1961; Goldsworthy 1961) and numerical (Mathews 1965; Lasker 1966a) studies. The analytical studies noted that strong R-type fronts are over-determined and have no practical relevance. This dynamical sequence is in part determined by the flow pattern where the ionized gas is confined to a region bounded by a global IF. The IF incident on an isolated neutral clump can stall, and the ionized gas flows from the clump surface as a wind. The IF is strong D-type in which the gas accelerates through the isothermal sonic point inside the IF itself.

In recent years, there have been significant developments in the study of H II regions. Strong D-type fronts have acquired increased significance because of the relevance of clumps to the formation of ultra-compact H II regions (e.g., Dyson 1994; Dyson, Williams & Redman 1995; Lizano et al. 1996), as well as the direct observations of photoionized clumps and disks in H II regions such as the Orion Nebula (e.g., Johnstone, Hollenbach, & Bally 1998; Henney & O'Dell 1999), and planetary nebulae (e.g., Dyson, Hartquist, & Biro 1993). Franco et al. (2000) review recent studies of the global structure of the regions, in which the evolution of the ionizing source

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and the structure of the neutral gas surrounding it have been treated with increased accuracy. There has been recent increased interest in the study of magnetized IFs first studied by Lasker (1966b) since there is evidence (e.g., Myers & Khersonsky 1995) that the ratio of magnetic pressure to thermal pressure in diffuse clouds may be up to ten or so, and an order-of-magnitude higher still in the CO emitting clumps in the Rosette Molecular cloud. An overview of magnetized IFs is given by Williams et al. in the present volume.

2. RECOMBINATION FRONTS

Ionized gas can recombine if the ionization source is removed, for example in the gas cooling and recombining behind a supernova driven shock wave. Radiatively ionized regions recombine if the ionizing source dims sufficiently. For example, the luminosity of the central stars of planetary nebulae decrease dramatically as they evolve towards the white dwarf stage. Alternatively, mass injection into an H II region can reduce the ionizing flux available in the outer regions (e.g., Dyson at al. 1995). Usually, the regions where recombination is occurring will be extended. However, under a range of limited but interesting situations, there can be a relatively sharp ionized-neutral interface across which there is a steady flux of ionized gas. The velocity of the ionized gas through this interface defines the interface velocity (in some appropriate reference frame) and depends on circumstances. This interface is called a recombination front (RF) which is the inverse of an IF. The thicknesses of RFs are determined by the recombination of ionized gas advected through them. The typical thickness of an RF is $\sim (2/n_{\rm i})(u_{\rm i}/10{\rm km\ s^{-1}})$ pc, where $n_{\rm i}$ and $u_{\rm i}$ are respectively the density and velocity of the ionized gas into the RF, compared to a characteristic IF thickness of $(0.5/n_{\rm n})$ pc, where now $n_{\rm n}$ is the neutral density ahead of the IF. RFs can then be appreciably broader than IFs, although their thicknesses are comparable to the thermal relaxation distance behind an IF for similar densities of ionized gas. Since the ionization state in an RF is determined by recombination and that in an IF by ionization, the abundances of ionic states can be very different. For example, O^+ tracks H^+ in an IF, but O^+ recombines appreciably faster than H^+ in an RF. RFs have received less attention in the literature than have IFs, but they are likely to be important in a variety of circumstances. These include accretion flows onto stars with strong UV radiation fields (Mestel 1953); ultra-compact H II regions with continuous mass injection (Dyson et al. 1995 et seq.; Lizano et al. 1996); recombination zones in mass-loaded jets in planetary nebulae (Redman & Dyson 1999).

Newman & Axford (1968) examined the properties of RFs in the context of the ionization of winds from main-sequence stars and non-expanding planetary nebulae. They showed that there existed the analogues of the weak R, strong R and weak D IFs, but there was no strong D (i.e., subsonic to supersonic) analogue. The significance of transonic solutions is not immediately apparent when RF front structures are considered in isolation. However, such solutions can become important when initially subsonic global flows approach the sonic point as a result of geometrical divergence and/or mass loading (e.g., Williams & Dyson 1994). This will often be the case if the gas 'leaks' through the surface of an H II region. Flows that exit a region supersonically can match up to a whole range of external pressure boundary conditions simply by the insertion of a shock at some radius whereas exiting subsonic flows must match up just to the external pressure.

Williams & Dyson (1996) re-examined Newman & Axford's (1968) work and found that these latter authors had in fact inadvertently missed a small but important class of transonic solutions. The numerical integration of the flow equations between the isothermal and adiabatic sound speeds within the RF needs considerable care. Williams & Dyson (1996) also found additional supersonic to subsonic solutions generated in part by the insertion of shocks in transonic solutions. Williams (unpublished) has calculated the structures of a series of mass-loaded flows which start subsonically and fully ionized and emerge neutral and supersonically from an RF in various geometries. RFs containing magnetic fields have so far not yet been studied.

3. FORMATION OF LINEAR FEATURES ('COMETARY TAILS').

The formation of cometary features behind globules in some planetary nebulae (e.g., Meaburn et al. 1992; O'Dell & Handron 1996) has been attributed to the shadowing of gas behind the globules from the stellar sources of ionizing radiation (e.g., Cantó et al. 1998, hereinafter CRSS98). Similar explanations for the formation of tails behind globules in some regions of high-mass star formation (e.g., Bally et al. 1998) have been proposed (Richling & Yorke 1998; Störzer & Hollenbach 1999, and references therein). An alternative possibility is that a tail arises due to evaporation driven by the flow of a subsonic hot shocked stellar wind around a globule (Dyson et al. 1993).

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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The literature on the formation and development of cometary tails due to the shadowing of radiation is very large. Recent analytical and semi-analytical approaches to the problem include those of Bertoldi (1989), Bertoldi & McKee (1990), Henney et al. (1996; 1997), Johnstone et al. (1998), Mellema et al. (1998) and Störzer & Hollenbach (1999). Recent numerical simulations include those of Lefloch & Lazareff (1994, hereinafter LL94), CRSS98, Mellema et al. (1998), and Richling & Yorke (1998). Of those who have conducted numerical simulations, only CRSS98 and Richling & Yorke (1998) took account of the effects of a diffuse component of the ionizing radiation field. The first authors studied the development of tails in cylindrical symmetry without considering the variation of the ionizing radiation with distance from the source. The lifetime of the tail in the latter authors' work was extended as the angular momentum of the evaporated material prevented it from collapsing onto the axis of symmetry.

Most recently, Pavlakis et al. (2001, hereinafter PWDFH01) have performed 2D, time-dependent axisymmetric hydrodynamic simulations of the response of a non-gravitating, non-magnetic globule to the direct ionizing radiation from a star that turns on instantaneously and simultaneously with a diffuse component of the ionizing radiation field. The approach is basically that of LL94 but with the addition of the diffuse field component. A simplified treatment of the diffuse field is based on the work of CRSS98 and only the in-going part of the radiation field is considered. The initial conditions chosen are identical to those of LL98 which implies that no shadowed tail would be expected to form (CRSS98). The diffuse component of the radiation field is taken to be a constant (typically 10% or so) at a fixed radial distance from the globule. The most prominent features in the LL94 calculation are the neutral 'ears' that form quite early on in their calculations. These 'ears' converge onto the axis of symmetry producing a globule with a dense core but which is extended in the direction away from that of the direct radiation field. Eventually a continuous structure with a cometary head and a long tail is produced; this lasts for over a My before it is ionized away.

In complete contrast, the PWDFH01 calculations show that even a modest diffuse field (10% or so) results in the total suppression of 'ear' formation and so the formation of long relatively thin globules by neutral 'ear' formation no longer occurs. The globules are essentially ionized away after a time of about 1 My. Figure 1 shows a typical structure produced

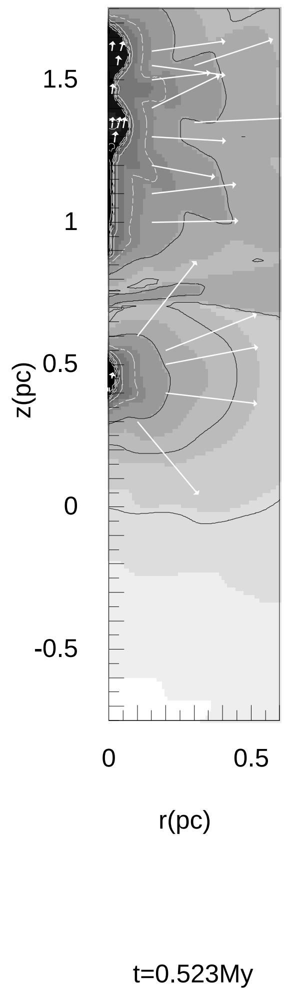

Fig. 1. Numerical simulation of the photoevaporation of a neutral globule including the effects of the diffuse ionizing field (PWDFH01).

in their simulation. They conclude that ordered cometary structures lasting for times of Myrs are not produced by globule photoionization if even a modest diffuse field component exits, at least for the parameter regime discussed. Work in progress includes studies of the photoevaporation of self-gravitating and magnetically supported globules.

4. DISCUSSION.

Over recent years, the study of H II regions has gone through a renaissance. This is in part due to the exceptional detail provided by *HST* observations of regions such as Orion and the Eagle Nebula. Radio data on ultra-compact and hyper-compact H II regions have clearly demonstrated gaps in our understanding of their structures. In attempting models for these regions, deficiencies have appeared in our understanding of some of the basic physics. For example, molecular clouds are extremely fragmented (this property was exploited in the Redman, Williams, & Dyson 1995 and Lizano et al. 1996 models of ultra-compact H II regions), yet hardly any work has been done into the propagation of IFs into clumpy media and the transition from IFs to RFs.

Another major question is the origin of small scale structures in H II regions, the key question being whether they are induced (e.g., as a result of dynamical instabilities) or primordial. The study of instabilities in connection with H II regions has a long history. Initially, Rayleigh-Taylor instabilities were invoked to account for 'elephant-trunk' structures (Spitzer 1954; Vandervoort 1962) though the predictions of such models were not in agreement with observational data (Pottasch 1958). Instabilities of ionization fronts by themselves are not very promising (e.g., Axford 1964). Instabilities of IFs coupled to other instabilities have been found (e.g., Giuliani 1979; Vishniac 1983; Franco, Tenorio-Tagle, & Bodenheimer 1990; García-Segura & Franco 1996). However even now, new instabilities can be found. For example, Williams (1999) has described a new shadowing instability of weak R-type IFs. A major area to be sorted out is that phenomena which can drive instabilities to produce structures (e.g., stellar winds) can also destroy structures (e.g., by ablation). Many of these problems will demand a better understanding of star formation for their resolution; conversely, their resolution will increase our understanding of massive star formation. There is most definitely life in H II regions yet!

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