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DUSTY UCH II REGIONS: CLOUD PRESSURES AND DENSITY DISTRIBUTIONS

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RESUMEN

Discutimos brevemente el efecto de presión ambiental y de los gradientes de densidad en las propiedades observadas de las regiones UCH II con polvo y de la nueva clase de regiones Super-ultra-compactas. La absorción del polvo puede reducir muy eficientemente el tamaño de las regiones fotoionizadas y los gradientes de densidad pueden modificar el índice espectral de la emisión. El efecto de los gradientes también se observa en regiones H II extragalácticas.

ABSTRACT

We briefly discuss the effects of the ambient pressure and decreasing density gradients on the observed properties of dusty UCH II regions, and on the new class of Super-ultra-compact H II regions. Dust absorption can effectively reduce the size of the photoionized region, and density gradients can modify the spectral index of the emission. The effects of the density gradients seem also to be present in extragalactic H II regions.

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

1. INTRODUCTION

The initial shape and early evolution of H II regions are controlled by the density distributions of star–forming cloud cores. For uniform ambient densities, the evolution of H II regions has a well–defined evolutionary path (e.g. Kahn & Dyson 1965; Yorke 1986). The radiation field of a newly formed star creates a photoionized region with the initial Strömgren radius (Strömgren 1939) in approximately a recombination time. Then the pressure difference across the ionization front drives a shock wave into the ambient neutral medium, and the radius of the expanding H II region grows as $t^{4/7}$. For non–uniform density distributions, however, a significant departure from this simple evolution appears: depending on the density gradient, the expansion can strongly accelerate (possibly creating internal shocks) and the ionization front can grow indefinitely (Franco et al. 1989; 1990). Indeed, when the ionization front encounters a strong negative density gradient and overruns it, the expansion enters the "champagne" or "blister" phase (Tenorio–Tagle 1982; Yorke 1986).

Molecular clouds have complex morphologies and density distributions, and contain a variety of high–density condensations. Recent studies of the density structure of envelopes surrounding low–mass protostars include Chandler & Richer (2000) and Ward-Thompson, Motte & André (1999), who present detailed studies of nearby, low–mass prestellar and protostellar cores. The most salient result is density structures around pre–stellar cores that are flat in the inner regions, then dropping as ω =1.5-2 at radii of 10^3-10^4 AU. The advent of sub–mm detectors (e.g. SCUBA and SHARC) has allowed the use of warm dust as a probe of density stratifications in high–mass star–forming regions (e.g. Hatchell et al. 2000; Hunter 1998). These studies show that submillimeter continuum intensity profiles can be well–modelled with power–law density profiles. For strongly peaked sources, the addition of a constant density core appears to be necessary (Hatchell et al. 2000).

Hot molecular cores are probably the most massive and dense condensations within molecular clouds. Massive star formation seems to occur in these cores, which have densities $n_{H_2} \gtrsim 10^7$ cm^{-3} and temperatures

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Fig. 1. One of the H II regions (G35.20–1.74) studied by Franco et al. (2000).

T $\gtrsim$ 100 K (see Kurtz et al. 2000). These cores represent the conditions for the early evolution of H II regions, hence one can explore the evolution of H II regions under the density structure of these cores.

2. UCH II REGIONS AND PRESSURE EQUILIBRIUM

As discussed by Kurtz et al. (2000) the observed molecular densities and temperatures in hot cores are above 10^7 cm^{-3} and 10^2 K. Densities of $\sim 10^6$ cm^{-3} have been found for cores in several giant molecular clouds (e.g. Bergin, Snell & Goldsmith 1996). This implies large *thermal* pressures for the cores, more than four orders of magnitude above the ISM pressure in the solar neighborhood. Obviously, this is a lower limit. The existence of non–thermal "turbulent" velocities of several km s^{-1}, and strong magnetic fields, ranging from tens of μG to tens of mG, indicates that the *total* core pressures are substantially higher. Clouds can be magnetically supported (Myers & Goodman 1988; McKee & Zweibel 1995), where the non–thermal velocity field is excited by Alfvén and magnetosonic waves (see Franco & Carramiñana 1999).

Thus the cores of massive molecular clouds are highly pressurized regions. Using some of the observed parameters (e.g. $n_{H_2} \sim 5 \times 10^6$ cm^{-3}, $T \sim 10^2$ K, $v_t \sim 3$ km s^{-1}, and $B \sim 10$ mG), the resulting *total* core pressures could reach values in excess of 5×10^{-6} dyn cm^{-2}. These large values are easily provided by the self–gravity of a massive isothermal cloud core (García-Segura & Franco 1996). Here we assume that the star–forming cores have sizes of the order of tenths of a parsec. For a spherically symmetric, isothermal, self–gravitating cloud, the density structure in equilibrium is proportional to r^{-2}. Assuming, for simplicity, that the cloud has a central core with constant mass density ρ_c and radius r_c, the density structure for $r \geq r_c$ is then $\rho = \rho_c (r/r_c)^{-2}$. The pressure at the core boundary, r_c, is $P(r_c) = 10\pi G \rho_c^2 r_c^2/9$, and the total pressure at the center is

$$P(0) = P_0 = \frac{2\pi G}{3}\rho_c^2 r_c^2 + P(r_c) = \frac{8}{5}P(r_c) \simeq 2 \times 10^{-7}\ n_6^2 r_{0.1}^2 \quad \text{dyn cm}^{-2}, \tag{1}$$

where $n_6 = n_c/10^6$ cm^{-3}, and $r_{0.1} = r_c/0.1$ pc. Using $r_c = 0.1$ pc and $n_c = 5 \times 10^6$ cm^{-3}, one finds that the expected core pressure is $P_0 \simeq 5 \times 10^{-6}$ dyn cm^{-2}. This value for the central pressure is equal to the total value stated above, which shows that self–gravity is indeed capable of producing such high core pressures.

The obvious consequence of this large pressure value is that some H II regions can reach pressure equilibrium within the central uniform–density core, before the ionization front reaches the density gradient. When this occurs, the resulting pressure–confined regions will have sizes and densities

$$R_{\rm S,eq} \approx 2.9 \times 10^{-2}\ F_{48}^{1/3}\ T_{\rm HII,4}^{2/3}\ P_7^{-2/3} \quad \text{pc}, \qquad n_{i,\rm eq} = \left(\frac{P_0}{2kT_i}\right) \simeq 3.6 \times 10^4 P_7 T_{\rm HII,4}^{-1} \ \ \text{cm}^{-3}, \tag{2}$$

where $F_{48} = F_\star/10^{48}$ s^{-1}, $P_7 = P_0/10^{-7}$ dyn cm^{-2}, and $T_{\rm HII,4} = T_i/10^4$ K. These sizes and densities are typical of UCH II regions: sizes less than 0.1 pc and electron densities greater than 10^4 cm^{-3}.

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Fig. 2. Two of the H II regions (G9.62+0.19-E and G75.78+0.34) studied by Franco et al. (2000).

If one includes the attenuation of the radiation field by dust particles, the photoionized region sizes are substantially reduced. A simple but good approximation to this reduction in size is (Franco et al. 1990; Díaz-Miller et al. 1998) $R_{\rm HII,d} \approx R_{\rm HII}\, e^{-\tau/3}$, where τ is the optical depth of dust from the star to the boundary of the photoionized region. The total UV absorption cross-section per H atom is about $\sigma_d \simeq 6 \times 10^{-22}$ cm^2 (Cardelli, Clayton & Mathis 1989). For massive stars with temperatures above 35,000 K and embedded in densities above $\sim 10^6$ cm^{-3}, the sizes are reduced by more than a factor of three. Thus, the new class of Super-ultra-compact H II regions may be very young, probably nascent, H II regions embedded in dusty cores with densities $\sim 10^7$ cm^{-3}. At these large densities, the region is not only opaque to the stellar UV field but also to its own radio emission.

The motion of the exciting star can bring it near the boundaries of the constant density core and, due to the effects of the density gradient, the pressure equilibrium is broken. The external pressure decreases along the density ramp and the H II region expands, creating a shock front along this direction. For decreasing density gradients with $\omega \geq 1.5$, the ionization front eventually overtakes the shock front. The ionized gas is set into rapid motion, sometimes driving internal shocks, and instabilities in both the ionization and shock fronts generate clumps and finger–like structures (García-Segura & Franco 1996; Franco et al. 1998; Williams 1999; Freyer, Hensler & Yorke 2000). This creates an extended, low–brightness emission region that is directly connected with the ultracompact component at the core. Thus, UCH II regions with extended components might be viewed as cases in which the ionization front breaks out of the core and overruns a density ramp, creating a much larger and lower density photoionized zone.

3. DENSITY GRADIENTS IN OPTICALLY THICK H II REGIONS

For electron density distributions of power law form $n_e \propto r^{-\omega}$, the spectral index α ($S_\nu \propto \nu^\alpha$) depends on ω as $\alpha = (2\omega - 3.1)/(\omega - 0.5)$, (Olnon 1975). Thus, multi–frequency radio observations provide an effective means to probe the density structure of H II regions. Franco et al. (2000) use this technique to study three galactic UCH II regions (see Figures 1 and 2) and report density gradients steeper than ω= 1.5. G35.20–1.74 (Fig. 1), has both compact and extended emission. The original map (inset), made with sub–arcsecond resolution, was sensitive only to structures smaller than about $20''$ (Kurtz et al. 1994) and has been convolved with a $1\farcs2 \times 0\farcs9$ Gaussian. The rectangular boxes indicate the integration areas used to obtain the spectral indicies reported by Franco et al. Subsequent lower resolution observations, sensitive to structures up to $3'$ in size, show the full extent of the ionized gas in the region. G9.62+0.19-E, shown in Figure 2 (left) in a map adapted from Testi et al. (2000), has a spectral index corresponding to a density gradient of $n_3 \propto r^{-2.5}$. G75.78+0.34-H_2O, shown at right in Figure 2, in a map adapted from Carral et al. (1997) has a density gradient exponent of –4, based on the spectral index analysis of Franco et al. They suggest that a gaussian density distribution or the contribution of dust emission at high frequencies may cause this probably unrealistically large value.

If no mechanism acts to maintain density inhomogeneities within the H II region (of radius R_s and sound speed c_{II}), they will be smoothed out on the order of a sound-crossing time, R_s/c_{II} (Rodríguez–Gaspar, Tenorio–Tagle & Franco 1995). This is also true for the initial density gradients, which are smoothed over time by the expansion. Thus, the density gradients that Franco et al. report are lower limits to the original distribution. Their results are consistent with the constant-density core models suggested by Hatchell et al. (2000). Franco, García-Barreto & de la Fuente (2000) present a similar spectral index analysis for free–free emission from circumnuclear H II regions in barred galaxies and find density gradients in the range $1.5 < \omega < 2.5$.

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REFERENCES

Bergin, E., Snell, R. & Goldsmith, P. 1996, ApJ, 297, 436
Carral, P., Kurtz, S. E., Rodríguez, L. F., De Pree, C. & Hofner, P. 1997, ApJ, 486, L103
Cardelli, J. A., Clayton, G. C. & Mathis, J. S. 1989, ApJ, 345, 245
Chandler, C. & Richer, J. 2000, ApJ, 530, 851
Díaz–Miller, R. I., Franco, J. & Shore, S. N. 1998, ApJ, 501, 192
Franco, J. & Carramiñana, A. 1999, Interstellar Turbulence, (Cambridge: Cambridge Univ. Press)
Franco, J., Díaz–Miller, R. I., Freyer, T. & García-Segura, G. 1998, Astrophysics from Antarctica, ed. G. Novak & R. H. Landsberg, ASP Conf. Series, 141, 154
Franco, J., García–Barreto, J. A. & de la Fuente, E. 2000, ApJ, 544, 277
Franco, J., Kurtz, S. E., Hofner, P., Testi, L. García-Segura, G. & Martos, M. 2000, ApJ, 542, L143
Franco, J., Tenorio–Tagle, G. & Bodenheimer, P. 1989, RevMexAA, 18, 65
Franco, J., Tenorio–Tagle, G. & Bodenheimer, P. 1990, ApJ, 349, 126
Freyer, T., Hensler, G. & Yorke, H. 2000, in preparation
García–Segura, G. & Franco, J. 1996, ApJ, 469, 171
Hatchell, J., Fuller, G. A., Millar, T. J., Thompson, M. A. & Macdonald, G. H. 2000, A&A, 357, 637
Hunter, T. 1998, PASP, 110, 634
Kahn, F. D. & Dyson, J. E. 1965, ARA& A, 3, 47
Kurtz, S., Cesaroni, R., Churchwell, E., Hofner, P. & Walmsley, C. M. 2000, Protostars & Planets IV ed. V. Mannings, A. Boss, & S. Russell (Tucson: University of Arizona Press), 299
Kurtz, S. E., Churchwell, E. & Wood, D. O. S. W. 1994, ApJS, 91, 659
McKee, C. F. & Zweibel, E. 1995, ApJ, 440, 686
Myers, P. C. & Goodman, A. A. 1988, ApJ, 326, L27
Olnon, F. M. 1975, A&A, 39, 217
Rodríguez–Gaspar, J., Tenorio–Tagle, G. & Franco, J. 1995, ApJ, 451, 210
Strömgren, B. 1939, ApJ, 89, 526
Tenorio–Tagle, G. 1982, Regions of Recent Star Formation, ed. R. S. Roger & P. E. Dewdney, (Dordrecht: Reidel)
Testi, L., Hofner, P., Kurtz, S. & Rupen, M. 2000, A&A, 359, L5
Ward–Thompson, D., Motte, F. & André, P. 1999, MNRAS, 305, 143
Williams, R. J. R. 1999, MNRAS, 310, 789
Yorke, H. W. 1986, ARA& A, 24, 49

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