Revista Mexicana de Astronomía y Astrofísica
Universidad Nacional Autónoma de México
rmaa@astroscu.unam.mx
ISSN (Versión impresa): 0185-1101
MÉXICO

2000
José Franco / Stan E. Kurtz / Peter Hofner / José A. García Barreto / Guillermo García Segura / Eduardo de la Fuente / Alejandro Esquivel
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Revista Mexicana de Astronomía y Astrofísica, volumen 009
Universidad Nacional Autónoma de México
Distrito Federal, México
pp. 177-180

RevMexAA (Serie de Conferencias), **9**, 177–180 (2000)

THE EFFECTS OF DUST AND DENSITY DISTRIBUTIONS IN UC H II REGIONS

José Franco,[1] Stan E. Kurtz,[1] Peter Hofner,[2] José A. García-Barreto,[1] Guillermo García-Segura,[1] Eduardo de la Fuente,[1] and Alejandro Esquivel[3]

RESUMEN

La evolución y morfología iniciales de las regiones H II están definidas por la estructura de densidad de las regiones de formación estelar. Discutimos brevemente el efecto del polvo y de los gradientes de densidad en las propiedades observadas de las regiones UC H II 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

The initial shape and early evolution of H II regions are controlled by the density distributions of star-forming cloud cores. We briefly discuss the effects of dust and decreasing density gradients on the observed properties of UC H 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 also seem to be present in extragalactic H II regions.

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

1. MOLECULAR CLOUDS

For constant ambient densities, the evolution of H II regions has some well-defined evolutionary phases (e.g., Kahn & Dyson 1965; Spitzer 1978; Yorke 1986; Osterbrock 1989). 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 $t^{4/7}$. If one changes the density distribution, however, a significant departure from this simple evolution appears: depending on the density gradient, the outflows can reach strong accelerations (they may even create internal shocks) and the ionization fronts can grow indefinitely (Franco et al. 1989, 1990). Indeed, when the ionization front encounters a strong negative density gradient and overruns it, then the expansion enters into the so-called "champagne" or blister phase (Tenorio-Tagle 1982; Yorke 1986).

Massive star formation seems to occur in hot molecular cloud cores, with densities $n_{H_2} \gtrsim 10^7$ cm^{-3} and temperatures $T \gtrsim 100$ K (see Kurtz in these proceedings), and these opaque cores represent the conditions for the early evolution of H II regions. Molecular clouds, in general, have complex morphologies and density distributions, and are composed of a wide variety of high-density condensations. Extinction studies in nearby dark clouds indicate density distributions proportional to $r^{-\omega}$, with ω ranging from 1 to 3 and having an average of $\omega \sim 2$ (e.g., Arquilla & Goldsmith 1985; Gregorio Hetem, Sanzovo, & Lepine 1988). The hot cloud cores are probably the most massive and dense high-density condensations, and one can explore the evolution

[1]Instituto de Astronomía, Universidad Nacional Autónoma de México.
[2]NAIC, University of Puerto Rico and Arecibo Observatory.
[3]Universidad Iberoamericana, México.

of H II regions under the density structure of these cores (Franco et al. 1989, 1990; García-Segura & Franco 1996).

2. CLOUD CORES, TOTAL PRESSURES, AND UC H II REGIONS

As discussed by Kurtz, the observed molecular densities and temperatures in hot cores are above 10^7 cm^{-3} and 10^2 K, respectively. This range of densities is not exclusive of regions associated with UC H II , and is similar to those derived for giant molecular cloud cores in several cloud complexes, $\sim 10^6$ cm^{-3} (e.g., Bergin, Snell, & Goldsmith 1996; see recent review by Walmsley 1995). This already translates into large *thermal* pressures for the cores, more than four orders of magnitude above the ISM pressure at the solar neighborhood. Obviously, this is a lower limit. The existence of large non-thermal "turbulent" velocities, of several km s^{-1}, and strong magnetic fields, ranging from tens of μG to tens of mG (see Myers & Goodman 1988 and references therein), indicates that the *total* core pressures are substantially higher. The nature of the turbulent velocity fields is still unclear, but recent studies indicate that the observed line widths could be due to magnetic turbulence (see proceedings of Interstellar Turbulence, Franco & Carramiñana 1999). Thus, clouds can be magnetically supported entities (Shu, Adams, & Lizano 1987; Myers & Goodman 1988; McKee & Zweibel 1995), where the non-thermal velocity field is excited by Alfvén and magnetosonic waves, and the cores of massive molecular clouds are highly pressurized regions. For instance, using some of the observed parameters (i.e., $n_{H_2} \sim 5 \times 10^6$ 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, and a central region with a constant density. For a spherically symmetric, isothermal, and 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

$$P(r_c) = \frac{10\pi G}{9} \rho_c^2 r_c^2, \tag{1}$$

and the total pressure at the center is

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

where $n_6 = n_c/10^6$ cm^{-3}, and $r_{0.1} = r_c/0.1$ pc. Using $r_{0.1} = 1$ and a conservative core density value $n_c \sim 5 \times 10^6$ cm^{-3}, one finds that the expected core pressures are

$$P_0 \simeq 5 \times 10^{-6} \quad \text{dyn cm}^{-2}. \tag{3}$$

This value for the central pressure is similar to the total value stated above, 5×10^{-6} dyn cm^{-2}, and 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 core boundaries, before the ionization front reaches the density gradient. When this occurs, the resulting pressure-confined regions will have sizes

$$R_{\rm S,eq} \approx 2.9 \times 10^{-2}\ F_{48}^{1/3}\ T_{\rm HII,4}^{2/3}\ P_7^{-2/3} \quad \text{pc}, \tag{4}$$

and densities

$$n_{i,\rm eq} = \left(\frac{P_0}{2kT_i}\right) \simeq 3.6 \times 10^4 P_7 T_{\rm HII,4}^{-1} \ \text{cm}^{-3}, \tag{5}$$

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. For hot cloud cores, these values are within the range of observed properties of UC H II regions: sizes less than 0.1 pc and electron densities greater than 10^4 cm^{-3} (see Kurtz these proceedings).

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; Diaz-Miller, Franco, & Shore 1998)

$$\mathrm{R_{HII,d}} \approx \mathrm{R_{HII}}\ \mathrm{e}^{-\tau/3}, \tag{6}$$

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where

$$\tau = \int_0^{\mathrm{R_{HII,d}}} \sigma_{\mathrm{d}} \mathrm{n_{tot}} \mathrm{d}l$$

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 3.5×10^4 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 can be understood as very young, probably nascent, H II regions embedded in dusty cores with densities of about 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 (Franco, Kurtz, & Hofner 2000).

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. At this location, the external pressure drops down 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 and a large cone centered at the core becomes ionized. 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, UC H II regions with extended components can be viewed as those 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. OPTICALLY THICK EXTRAGALACTIC H II REGIONS

Giant complexes of extragalactic H II regions represent the largest scale size for H II regions, and here, too, evidence is seen for density gradients. Franco, García-Barreto, & de la Fuente (2000) report the spectral index analysis of radio emission from the circumnuclear regions of three barred galaxies and find evidence for density gradients. The flux density distributions they report are shown in Figure 1, with data at 1.5, 5, and 15 GHz. The negative spectral indices from 1.5 to 5 GHz are indicative of non-thermal (synchrotron) emission present in the circumnuclear regions. The shift to positive spectral indices from 5 to 15 GHz is indicative of free-free emission dominating at these wavelengths. For a power law of the form $n_e \propto r^{-\omega}$, the spectral index $\alpha, S_\nu \propto \nu^\alpha$ depends on ω as $\alpha = (2\omega - 3.1)/(\omega - 0.5)$, (Olnon 1975). The spectral indices reported by Franco et al. (2000) indicate that the density gradients of these H II regions could be approximated by power-laws of the form $n_e \propto r^{-\omega}$, with exponents in the range $1.5 < \omega < 2.5$.

It is a pleasure to thank Jane Arthur for her infinite patience. JF acknowledges partial support by DGAPA-UNAM grant IN130698, and by a R&D CRAY Research grant. E. de la F. wishes to acknowledge financial support from CONACYT-México grant 124449 and DGEP-UNAM through graduate scholarships.

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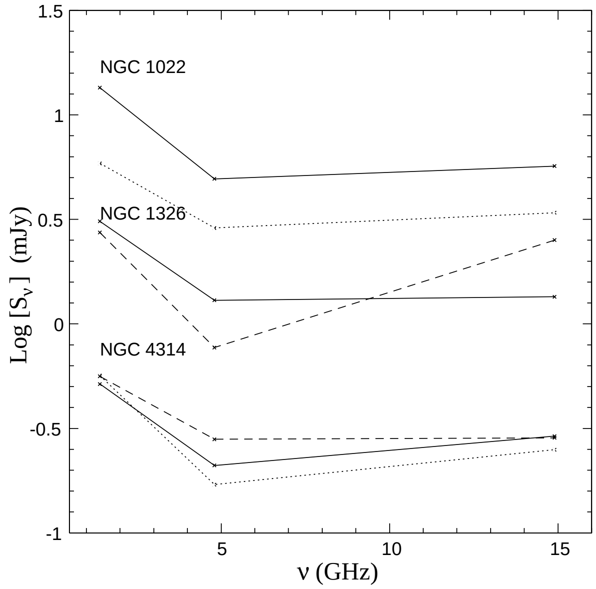

Fig. 1. Radio continuum flux density versus frequency, for the galaxies NGC 1022, 1326, and 4314. Three distinct regions are plotted for NGC 1022 and 4314 (solid, source 1; dotted, source 2; dashed, source 3) while one component is plotted for NGC 1326 (solid, source 1). The transition from a non-thermal to a thermal spectral index occurs at ∼5 GHz; the positive spectral index between 5 and 15 GHz provides a means to determine the density gradient.

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J. Franco, J. A. García-Barreto, and E. de la Fuente: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D. F., México (pepe, tony, edfuente@astroscu.unam.mx).
S. E. Kurtz: Instituto de Astronomía, UNAM, Campus Morelia, Apartado Postal 3-72, C. P. 58089 Xangari, Morelia, Michoacán, México (kurtz@astrosmo.unam.mx).
P. Hofner: University of Puerto Rico and Arecibo Observatory, HC3 Box 53995 Arecibo PR 00612, USA (hofner@naic.edu).
G. García-Segura: Instituto de Astronomía-UNAM, Apartado Postal 877, 22800 Ensenada, B. C., México (ggs@astrosen.unam.mx).
A. Esquivel: Universidad Iberoamericana, México D. F., México (esquivel@grace.dci.uia.mx).

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
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