PRESSURE AND DENSITY GRADIENTS IN H II REGIONS

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Abstract. Here we discuss the effects of large ambient pressures and decreasing density gradients on the observed properties of dusty UCH 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 to be present in both galactic and extragalactic H II regions.

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1. Molecular Clouds

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 some well-defined evolutionary phases (*e.g.,* Kahn and Dyson, 1965; Yorke, 1986). The radiation field of a newly formed star creates a photoionized region with the initial Strömgren radius 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, significant departures from this simple evolution appear: depending on the density gradient, the expansion can strongly accelerate and the ionization front can grow indefinitively (Franco *et al.*, 1989, 1990). 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. Extinction studies in nearby dark clouds indicate density distributions proportional to $r^{-\omega}$, with ω ranging from 1 to 3 (*e.g.,* Gregorio Hetem, Sanzovo and Lepine, 1988). 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 *et al.*, 2000). These cores represent the conditions for the

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early evolution of H II regions, and one can explore the evolution of H II regions under their density structure (Garcia-Segura and Franco, 1996).

2. Cloud Pressure and UCH II regions

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. This range of densities is not exclusive of regions associated with UCH II , and is similar to those derived for giant molecular cloud cores in several cloud complexes, $\sim$ 10^6 cm^{-3} (*e.g.,* Bergin *et al.*, 1996). 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 indicates that the *total* core pressures are substantially higher. Clouds can be magnetically supported (Myers and Goodman, 1988; McKee and Zweibel, 1995), where the non-thermal velocity field is excited by Alfvén and magnetosonic waves (see the book edited by Franco and Carramiñana, 1999).

Thus the cores of massive molecular clouds are highly pressurized regions. For instance, using some of the observed parameters (*i.e.,* $n_{H_2} \sim 5\times10^6$ 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 (Garcia-Segura and 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 total pressure at the center is

$$P(0) = \frac{2\pi G}{3}\rho_c^2 r_c^2 + \frac{10\pi G}{9}\rho_c^2 r_c^2 \ \simeq\ 2 \times 10^{-7}\ n_6^2 r_{0.1}^2 \quad \text{dyn cm}^{-2}, \tag{1}$$

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 $n_c = 5\times10^6$ 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 similar to the total value stated above, 5×10^{-6} dyn cm^{-2}, showing that self-gravity can indeed produce such high core pressures.

The attenuation of the radiation field by dust substantially reduces H II region sizes. A simple but good approximation to the reduced size is (Franco *et al.*, 1990; Díaz-Miller *et al.*, 1998)

$$\mathrm{R}_{\mathrm{HII,d}} \ \approx\ \mathrm{R}_{\mathrm{HII}}\ \mathrm{e}^{-\tau/3}, \tag{2}$$

where τ is the optical depth of dust from the star to the boundary of the photoionized region. 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.

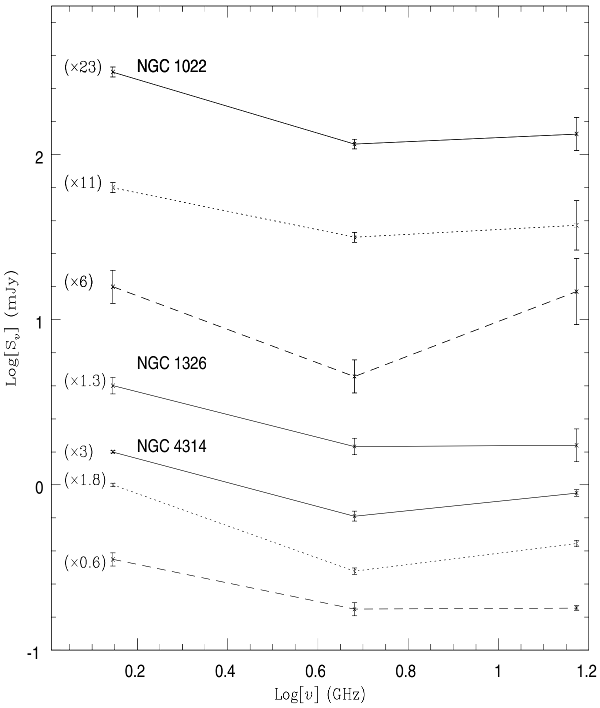

Figure 1. Radio Continuum Flux Density vs. Frequency, for the galaxies NGC 1022, 1326, and 4314. Three distinct regions are plotted for NGC 1022 and 4314 (solid, source 1; dotted, source 2; dashed, source 3) while one component is plotted for NGC 1326 (solid, source 1) The transition from a non-thermal to a thermal spectral index occurs at 6 cm; the positive spectral index between 6 and 2 cm provides a means to determine the density gradient.

3. The Density Gradients in H II Regions

Giant complexes of extragalactic H II regions represent the largest scale size for H II regions, and they show evidence for density gradients. Franco, García-Barreto and de la Fuente (2000) report a 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 20, 6, and 2 cm. The negative spectral indices from 20 to 6 cm are indicative of synchrotron emission present in the circumnuclear regions. The shift to positive spectral indicies from 6 to 2 cm is indicative of free-free emission dominating at these wavelengths. The spectral indices reported by Franco *et al.*indicate that the density gradients of these H II regions can be approximated by power-laws of the form $n_e \propto r^{-\omega}$, with ω in the range $1.5 < \omega < 2.5$ (Olnon, 1975). Franco *et al.*(2000) made a similar analysis for three galactic H II regions, and find density gradients $\gtrsim -1.5$.

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