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Density Bounding of Giant HII Regions and the Ionisation of the Diffuse Interstellar Medium

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Abstract: Three different types of evidence are presented in favour of the hypothesis that the HII regions in disk galaxies with Hα luminosities greater than a critical value of $10^{38\cdot 6}$ erg s^{-1} are density-bounded, and that the escaping Lyman continuum photons from these are the principal ionising agents for the diffuse ISM in disk galaxies. This has important implications for the ionisation of the intergalactic medium, and for computed star formation rates in spirals.

Keywords: galaxies: ISM — galaxies: spiral — galaxies: intergalactic medium — ISM: HII regions

1 Introduction

The question of the cause of the ionisation of the diffuse medium in disk galaxies can be separated into two aspects: the origin of the ionising photons, and the transparency of the medium between their site of origin and the diffuse medium which they ionise. Here we address essentially the former question, although the two are interlinked, as we will see. There is little doubt that the collective OB star population of a disk galaxy puts out ionising photons at a rate commensurate with the ionisation of its diffuse medium. Typical integrated values of order a few times 10^{41} erg s^{-1} ($\sim 10^{53}$ photons s^{-1}) have been measured for the total Hα flux from spirals (Ferguson et al. 1996), of which some 20% to 30% comes from the diffuse gas between HII regions. Thus in order to support the hypothesis that no ionising source other than OB stars is needed, we need to show that sufficient Lyman continuum (Lyc) is leaking out of the HII regions, which is the topic of the present paper.

2 Evidence for Density Bounding in the Most Luminous Regions

2.1 Hα Luminosity Functions

The first clue to the presence of density bounding in the most luminous HII regions of spirals comes from their Hα luminosity functions (LFs). Following the early work by Kennicutt, Edgar & Hodge (1989) using pre-CCD images, we showed with high-resolution, high-quality CCD frames (Rozas, Beckman & Knapen 1996) that there is a break in the LF slope, accompanied by a jump in the function, at a luminosity which varies rather little from one galaxy to another (see Figure 1). Our tentative hypothesis for this (see Beckman, Rozas & Knapen 1998) is that the relation between cumulative stellar mass and cloud mass in OB star-producing clouds causes the Lyc flux from OB associations to be a more than linearly rising function of the cloud mass. Thus at a critical mass the HII region just ionises its cloud; clouds of higher mass will have a larger flux per unit mass and will therefore be density-bounded. Although a model by McKee & Williams (1997), based on the transition from ionisation by one star to more, gives rise to a change in LF slope, this occurs at a luminosity in Hα lower by a factor 10 than our observed 'glitch', and would not explain the jump in value which accompanies the break.

2.2 Internal Surface Brightness Gradients of HII Regions

When we measure the radial gradients in the Hα surface brightnesses of individual HII regions, and plot these against their integrated luminosities, we find constant values up to a critical luminosity, followed by a steady rise with increasing luminosity to much steeper gradients at higher luminosities. This behaviour is shown in Figure 2, which summarises the results from a number of spirals. The value of the critical luminosity is just that at the jump observed in the Hα LFs (Figure 1). The hypothesis that the HII regions are ionisation-bounded below the critical value and density-bounded above it gives a model which explains this behaviour. It cannot be explained by assuming a jump, at this luminosity, in the number of stars ionising the region, since the brightness gradient is independent of this number, as was in fact shown in Strömgren's

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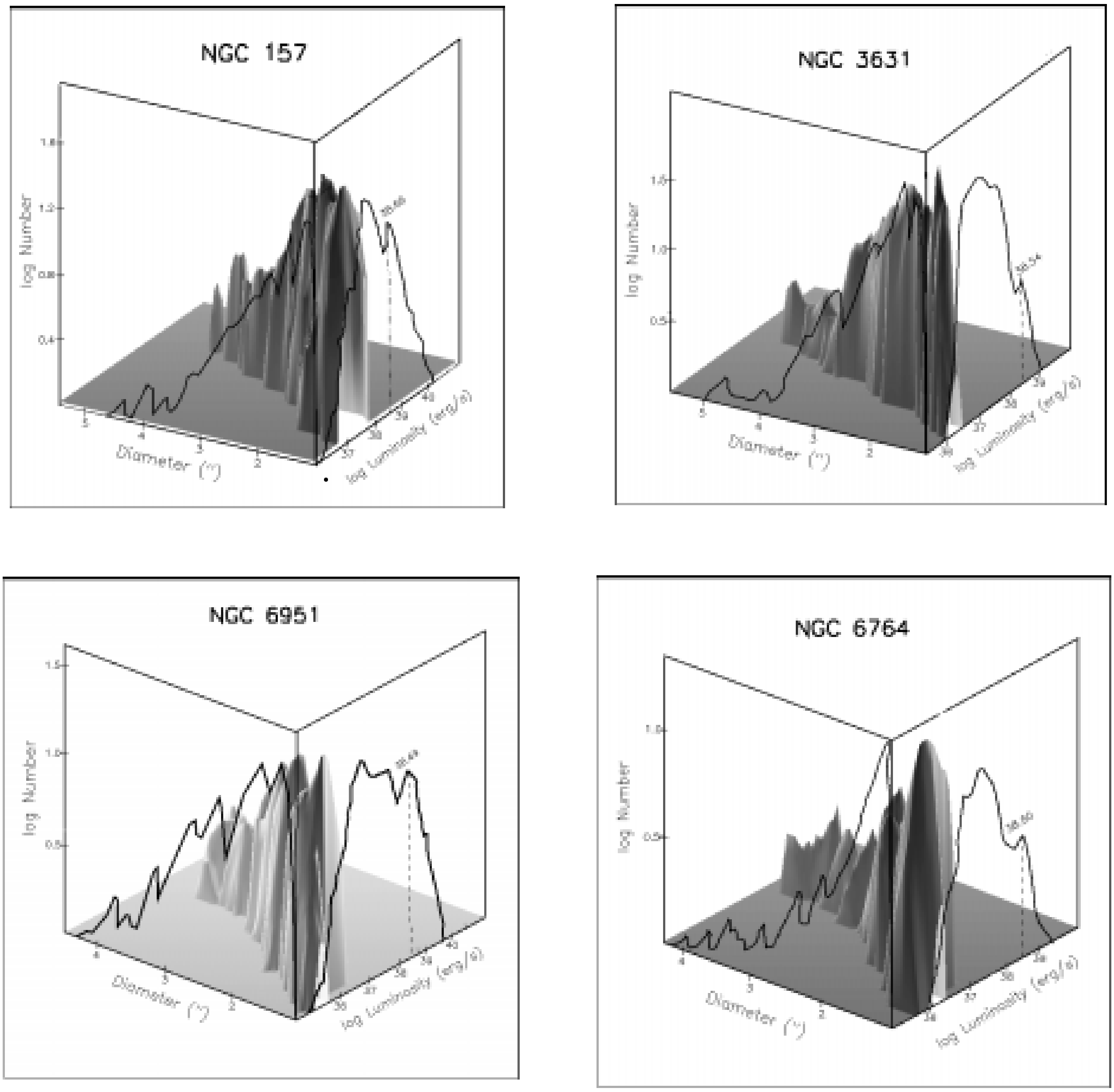

Figure 1—Hα luminosity of the HII regions in four late-type spiral galaxies. The sample is complete to well below 10^{38} erg s^{-1}. The LF is obtained by projecting the number–diameter–luminosity surface into the $\log N - \log L$ plane. Note the ‘glitch’ (change in gradient accompanied by peaks) in the LF near $L = 10^{38\cdot 6}$ erg s^{-1} (see text for details).

(1939) original article. Only a geometrical property of the surrounding gas cloud can account for our observations. A simple corollary of our hypothesis is that the brightest HII regions, those above the critical luminosity, should also be those with highest surface brightnesses, and this is clearly observed. This would not be caused by a change in the number of stars ionising the regions, in the absence of the geometrical effect due to density bounding.

In the paper by Sabalisck, Rozas & Beckman (1998, present issue p. 161), we measure the internal velocity dispersions of the 200 most luminous regions in the grand-design spiral M100, via their Hα emission, using a Fabry–Perot mapping technique. Plotting these dispersions against luminosity we find an upper envelope which we attribute to virialised regions. We find a similar result, with an envelope having the same slope of $2\cdot 6$ in the $\log\sigma - \log L$ plane for M101. This slope is predicted to take a value of 4 (Terlevich & Melnick 1981), but this value would be for ionisation-bounded regions. It is easy to show that if a fraction of the ionising photons escape, the observed slope should be reduced. The value of $2\cdot 6$ falls well within the predictions of a straightforward density-bounded model for the regions lying on the envelope, and offers further evidence for our hypothesis.

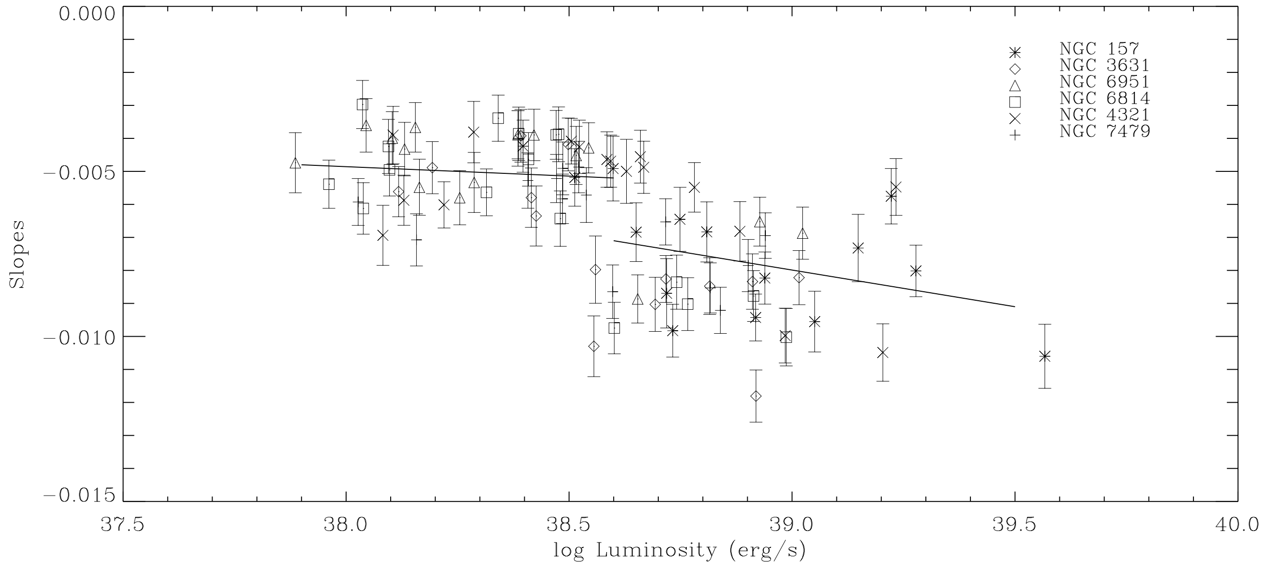

Figure 2—Observed internal surface brightness gradients of individual HII regions in the galaxies indicated, as a function of their luminosities. The break in this graph at $L = 10^{38\cdot 6}$ erg s^{-1} is as predicted for a change in regime from ionisation bounding to density bounding. The gradients steepen and the change occurs over a restricted luminosity range.

3 Available Flux for Ionising the Diffuse Medium

In Rozas, Zurita & Beckman (1998, this issue p. 159), we apply our hypothesis of density bounding to estimate numerically the flux of ionising photons which leak from the luminous HII regions and are available to ionise the diffuse gas in the disk and the halo. This is done by extrapolating the luminosity function below the break to values above the luminosity of the break, and subtracting off the observed LF above the break. As a clear example, we can estimate that an HII region with observed Hα luminosity of $5{\times}10^{39}$ erg s^{-1} should be emitting a few times 10^{40} erg s^{-1} in escaping Lyc photons. Just half a dozen of these per galaxy (and generally there are a few tens of regions with luminosities above the critical value) would, at least in energy terms, give the ionising luminosity required to ionise the diffuse medium. Regions of this luminosity have diameters of a couple of hundred parsecs, at least, which implies that a good fraction of the escaping photons are emitted at a sufficient distance from the galactic plane to escape readily from their immediate surroundings, both into the halo and across the disk. There is a number of further, rather direct observational tests which can be carried out in order to check the overall picture, which include a geometrical correlation between the positions of the density-bounded regions and the isophotes of the observed diffuse Hα, and these are in progress.

4 Implications for the Intergalactic Medium

The density-bounding hypothesis, and our measurements, separately, of the Hα luminosities from the full set of HII regions in a disk, and from the diffuse component, allow us to estimate the fraction of the ionising continuum that escapes into the intergalactic medium. The difference between the flux escaping from the ionisation-bounded regions and the observed diffuse Hα flux gives us this estimate. It turns out to be around one-third of the total ionising flux from a galaxy, i.e. of order 10^{41} erg s^{-1} per galaxy in those observed. This fraction depends on the photons escaping from the HII regions, and the amount of diffuse gas available to soak them up. Of the four galaxies observed by Rozas et al. (1998), three emit over one-third of their ionising photons into the IGM, while the fourth, NGC3631, emits only some 15%. As well as offering a potential quantification of the ionisation equilibrium in the IGM, these losses imply major corrections when using observed integrated Hα fluxes to compute overall star formation rates in disk galaxies.

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