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DIAGNOSTICS OF THE IONIZED ISM: THE IMPORTANCE OF DENSITY FLUCTUATIONS

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RESUMEN

Es bien conocido que al medir densidades electrónicas en regiones H II de forma local utilizando razones entre líneas de emisión, los valores que se obtienen son $\approx 100\mathrm{cm}^{-3}$, pero cuando se utiliza la medida de emisión, con el brillo superficial como parámetro observable, los valores globales son de $1\mathrm{cm}^{-3}$. Esta diferencia se puede atribuir a fluctuaciones en la densidad, en donde el modelo tradicional es el modelo de "factor de llenado (FF)" de Osterbrock y Flather. Implicito en este modelo está el grosor óptico de la fluctuación. Aquí mostramos que si estas fluctuaciones son ópticamente gruesas los diagramas de diagnóstico, que se utilizan para encontrar parámetros como la abundancia, van a estar significativamente afectados. Presentamos argumentos apoyándo estos modelos "de grumos" y señalamos brevemente algunos resultados iniciales de su uso.

ABSTRACT

It is well known that when measuring electron densities in H II regions locally via emission line ratios the values observed are 100 cm^{-3}, but gobal values obtained via emission measure using surface brightness as the observed parameter are $\sim$1 cm^{-3}. This difference is attributable to density fluctuations,and traditional models for these is the "Filling factor (FF)" model, of Osterbrock and Flather. Implicit in this model is the optical thinness of the fluctuations. We show here that if these fluctuations are optically thick the diagnostic diagrams which are used to find parameters, notably abundances, will be significantly affected. We present observational arguments supporting these "clumpy" models, and outline some initial results of their use.

Key Words: **H II REGIONS**

1. THE DICHOTOMY BETWEEN IN SITU AND GLOBAL ELECTRON DENSITIES.

Direct measurements of the electron densities in the H II regions of typical spiral galaxies presented in Zaritsky, Kennicutt & Huchra (1994) give values of order a few hundreds cm^{-3}. These are known to be strongly biased towards the densest zones, as the intensities of the lines depend on the square of the electron density. To find average values one can derive the emission measure from e.g. Hα surface brightness measurements, and this yields values in the range a few cm^{-3} (see e.g. Rozas, Knapen & Beckman 1996; Rozas, Zurita, Beckman 2000). The difference is explained by assuming that the densities within H II regions show strong fluctuations, with the densest zones dominating the line emission, and this is the basis of all model treatment of photoionization within the regions, embodied in the "filling factor" (FF) models first treated in Osterbrock and Flather (1959), in which the structure is simplified in terms of a volume ratio ϕ occupied by dense clumps, with the rest of the region empty. An implicit assumption is that each clump is optically thin, and thus fully ionized. From previous studies of the H II region centred on the OB associations in the spiral arm of the Galaxy near the Sun (Trapero, Beckam, Genova & McKeith 1992) it seemed to us more probable that many if not all of the clumps of dense gas in an H II region should be large enough to be optically thick to ionizing radiation, and this presentation outlines some of the consequences of this assumption, in a series of "clumpy" models.

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2. THE IONIZATION STRUCTURE OF THE CLUMPY MODELS:PREDICTION V. OBSERVATION.

The "clumpy" models have their gas in clumps, spherical for simplicity, (but this condition is easily relaxed during calculations, and has no real effect on the qualitative results) with hydrogen density 100 cm^{-3} and radii of order 1 pc. In Fig. 1 we show how the ionization structure within a clump as a function of its distance from an intense ionizing source (10^{42} erg s^{-1}). We can see that beyond, say 20 pc the clump is largely neutral. Thus our hypothesis of optically dense clumps predicts that most of the gas mass in an H II region of radius 100 pc or more will be

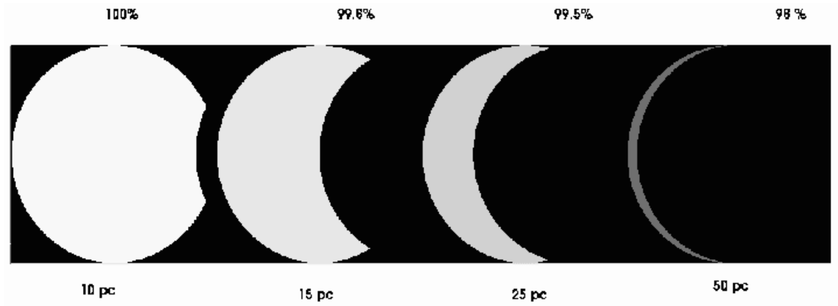

Fig. 1. Ionization structure within individual representative clumps in a clumpy model of an H II region, over a range of distances from the central source. White implies complete photoionization, grey partial ionization, and black shows neutral gas. Clumps have radii 1 pc and density 100 cm^{-3}, and the ionizing source is conservatively intense: 10^{42} erg s^{-1}. These results imply that ∼90 % of the gas in a large region of radius 100 pc will be neutral.

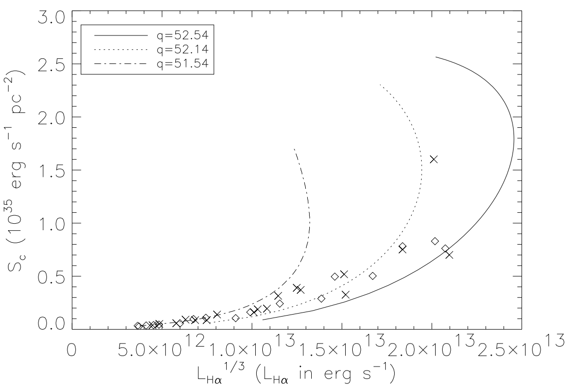

Fig. 2. Central surface brightnesses in Hα plotted against the cube root of the total Hα luminosity for selected H II regions measured in three nearby galaxies, compared with curves predicted from clumpy models with different central ionizing source luminosities, indicated in photons s^{-1} and corresponding to 3, 10 and 30 O3 stars in order of increasing luminosity.

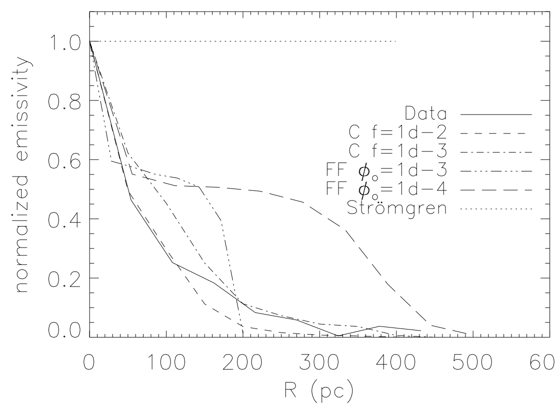

Fig. 3. Radial surface brightness profile, converted into radial contribution per unit (spherical) shell thickness, derived from observations in Hα of a large isolated, circulary close to symmetric, H II region. Comparisons are with a Strömgren sphere of uniform density, two traditional filling factor (FF) models, (values for the filling factor ϕ are shown) and two "clumpy" models (values for the geometrical filling factor of the clumps are shown). For more details see Giammanco et al. (2004).

neutral, and calculations for typical large regions in NGC 1530 based on Hα observations (Relaño, Beckman, Zurita et al. 2004), show that the total gas mass of large regions will be an order of magnitude greater than the ionized gas mass. This prediction is supported by the few direct measurements of this ratio in local galaxies of which we quote here the result of Yang, Chu, Skillman & Terlevich (1996) on NGC 604 in M33.

Figs. 2 and 3 show two types of predictions of clumpy models confronted with observational results. In Fig. 2 we have plotted observations of the central surface brightness in Hα of a set of H II regions from 3 external galaxies, against the cube root of the total Hα luminosity of the regions. These variables were chosen because in a homogeneous Strömgren sphere model or its "filling factor" equivalent they would show a linear dependence. The three curves are predictions of clumpy models, and differ only in the ionizing luminosities of their central sources. The models give global qualitative agreement, though we would not want to use this as anything more than a demonstration.

In Fig. 3 we have plotted the radial surface brightness profile in Hα of a well resolved isolated H II region in NGC 1530, and compared this with the predictions of three different types of models: the idealized homogeneous Strömgren sphere, two traditional FF models, and two clumpy models. It is clear that while the clumpy models bracket the

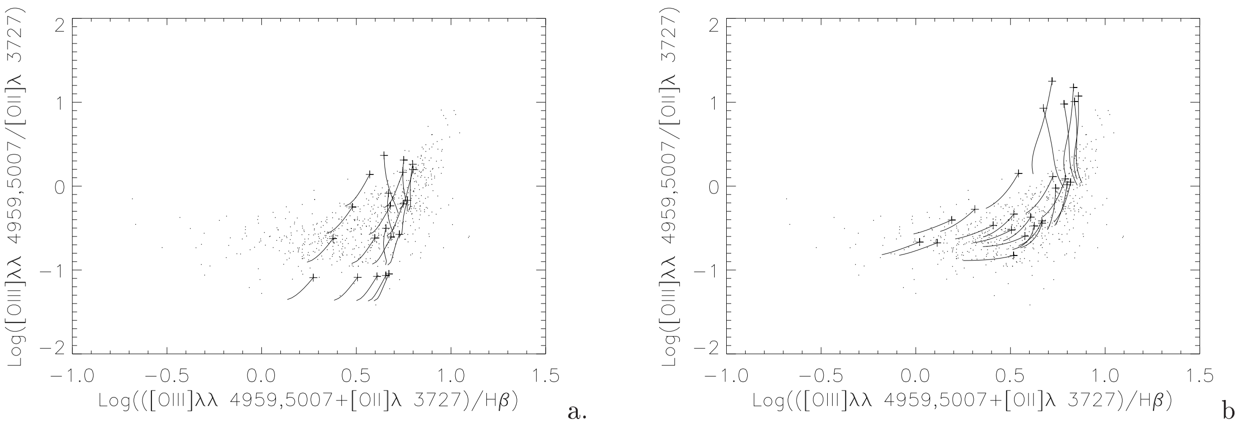

Fig. 4. Diagnostic diagram combining [O III], [O II] and Hβ emission line intensities first used by McCall et al. (1985) to test for photon escape from H II regions. Points are observations from a number of workers (see Giammanco et al. 2004), while lines represent FF model (Fig. 4a) and "clumpy" model (Fig. 4b) predictions. Each line corresponds to given values of ionizing source luminosity and metallicity, and lines trace variation in H II region radius, i.e. photon escape fraction (maximum escape fraction the cross at the top of each trace).

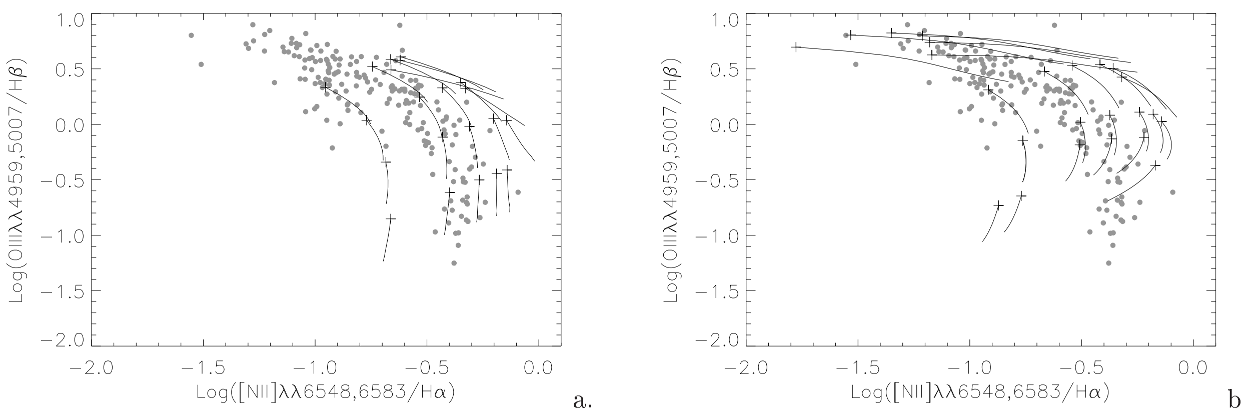

Fig. 5. Diagnostic diagram combining [O III], [N II], Hα and Hβ line intensities. Data points from a number of observers (see Giammanco et al. 2004 for details). Model fits are for FF models (Fig. 5a) and for "clumpy" models, (Fig. 5b). As in Fig. 4 the clumpy models give a better global fit to the whole data set, but more significant, clumpy models with the same parameters fit the points corresponding to the same H II regions in the two figures, while this is not the case for the FF models. Significance of different model traces as in Fig. 4.

observed curve, the FF models show convex profiles while the data give a concave profile; the homogeneous Strömgren sphere prediction is even further from the data than the FF models. Thus we have significant observational support for the validity of our optically dense clumpy models.

3. DIAGNOSTIC DIAGRAMS AND IMPLICATIONS.

In this section we show how the predictions of clumpy and FF models differ when confronted with data presented in the form of two diagnostic diagrams in which emission line intensity ratios are used. In Fig. 4 the diagram shown is made up of an [O III]/[O II] line intensity ratio plotted against the sum of [O III] and [O II] line intensities ratio against Hβİn Fig. 4a we compare observational points in this diagram obtained by a number of authors (for the details see Giammanco et al 2004), with the predictions of FF models, and in Fig. 4b with the predictions of clumpy models, in both cases using the CLOUDY suite of programmes (Ferland, Korista, Verner et al. 1998) to compute the line ratios for the appropriate ionization conditions. We can see that the clumpy models cover the parameter space marked out by the observations better than the FF models, but the argument in favour of the clumpy models is stronger than this as we will see below. In Fig. 5 we show another diagnostic diagram: [O III]/Hβ vs. [N II]/Hα again compared with the models predictions for the clumpy and FF models respectively in Figs. 5a and 5b. Here again the clumpy models cover the observational parameter space better than the FF models. However a key point with these diagrams is not obvious, and needs stating. A specific datum in Fig. 4 is well fitted by a specific clumpy model (same ionizing luminosity and photon escape factor) and the datum for the same H II region in Fig. 5 is fitted by exactly the same clumpy model. On the contrary, for the FF models although the gobal predictions do overlap with the data points, a given datum in Fig. 4 and its corresponding point in Fig. 5 are fitted with models having differing stellar sources and escape factors. The clumpy models are clearly superior.

In a short presentation we cannot do justice to all the implications of this modelling study. However we will bring out one single result as an illustration only. We used the diagnostic diagrams as a step in the inference of the O abundance for a specific H II region from the data points in Figs. 4 and 5. We did this for the best fitting FF model and clumpy model, obtaining a difference in the O abundance of 0.6 dex! This single trial need not be taken as characteristic, and we need to go further into the details and the self consistency of our work. Nevertheless it is clear that when H II region diagnostics are revised to take optically thick density fluctuations correctly into account, some significant effects on abundance determinations will be found, as significant as the effects predicted by Peimbert (1967) when he introduced the careful treatment of temperature fluctuations.

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