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THE ENVIRONMENT OF STAR-FORMING DWARF GALAXIES

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RESUMEN

Las propiedades espectrofotométricas de las galaxias enanas con formación estelar situadas en entornos poco densos parecen ser distintas de las que presentan estos mismos objetos pero localizados en áreas de mayor densidad de galaxias. Se hace una breve revisión de una compilación de los más recientes resultados publicados sobre efectos ambientales en galaxias con formación estelar. Algunas de las consecuencias de estos efectos pueden apreciarse en las propiedades espectrofotométricas de galaxias enanas del cúmulo de Virgo y de grupos densos. Las galaxias enanas situadas en entornos de baja densidad promedio presentan una gran actividad de formación estelar, lo que contrastaría con la hipótesis del "decaimiento" de estos objetos. Se ha analizado la posible influencia del entorno sobre el ritmo de formación estelar y la evolución de las galaxias enanas, así como sobre la forma de la relación metalicidad-luminosidad teniendo en cuenta las predicciones de los modelos evolutivos y la alta frecuencia de interacciones en los entornos ricos.

ABSTRACT

The spectrophotometric properties of star-forming dwarf galaxies located in low density environments appear different from those of similar objects populating dense areas. A compilation of recent results in the literature concerning environmental effects in star-forming galaxies is briefly reviewed. Some important consequences of these environmental effects are apparent in the spectrophotometric properties of dwarf galaxies in groups and in the Virgo cluster. Conversely, dwarf galaxies found in voids or in regions of low average density present an extreme star formation activity, in contrast with the "fading" scenario expected for galaxies in the voids. The influence of the environment on the rate of star formation and on the evolution of star-forming dwarfs, as well as on the shape of the metallicity-luminosity relation, has been analysed taking into account some of the predictions of evolutionary models and allowing for a high frequency of interactions in the more dense environments

Key words: **GALAXIES: COMPACT — GALAXIES: IRREGULAR – STARS: FORMATION**

1. INTRODUCTION

The environment in which galaxies are located is playing a very important role on their evolution. The influence of the environment on the star formation rate, or the gas content started to be studied for spirals galaxies located in clusters as compared to samples of isolated field galaxies. Radio observations have confirmed that Virgo spirals are systematically H I deficient (Haynes et al. 1984; Cayatte et al. 1990). With respect to the molecular gas content, CO observations of galaxies with high H I deficiency within the Virgo and Coma clusters (Casoli et al. 1991; Kenney & Young 1988) seem to favour relatively normal levels of their molecular gas content, and some modelling has been undertaken to interpret this fact (Valluri & Jog 1990).

At the same time, interactions between galaxies in high density environments is a very important factor that certainly affects their evolution. Although interactions among big galaxies could be catastrophic, it is clear that those galaxies with the lower masses will be the most affected by interactions and also by the action of the intergalactic medium (IGM). In this group are included systems such as star-forming dwarf galaxies, which present the lowest measured mass surface density and rotation velocities for objects supporting active star formation (Gallagher & Hunter 1989). Therefore, we are dealing with extremely fragile systems, that can be easily affected by environmental factors. This property, however, makes them ideal objects in order to test the influence of the environment on the process of star formation and galaxy evolution.

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In addition, these galaxies could be very easily suffering the effects of stripping of their gaseous component caused by the interaction with the IGM and, in some cases, also star formation bursts may be triggered by the action of ram pressure. The relatively high value of the typical density of the IGM in clusters, of the order to 10^{-3} cm^{-3}, and the high probability of encounters within rich clusters, could produce the large selective losses of material expected to occur for their gas rich dwarfs. In contrast, dwarf galaxies located in low density regions should end up as faint galactic remnants —likely dwarf ellipticals— or even fade totally away as a consequence of their evolution being strongly influenced by the action of the local IGM. This is expected under the predictions of the so called "fading" scenario that has been proposed to explain the statistics of the faint blue counts (Babul & Rees 1992). Indeed, it is well known from the observed large scale distribution of galaxies that (dwarf) ellipticals appear to be always associated to the more dense regions with a high pressure IGM (e.g., Binggeli al. 1989; Thuan et al. 1990).

In this paper, it is shown why environmental effects can be so important in order to understand the (global) evolution of star-forming galaxies. Special emphasis has been given to the study of the spectroscopic properties of galaxies from different environments. We have performed an analysis of some of the findings already obtained from our sample of dwarfs in different environments, together with several new results from observations of star-forming galaxies in Virgo and in dense groups.

2. RECENT WORK ON THE ENVIRONMENT OF STAR-FORMING GALAXIES

Two very remarkable examples of the action of the environment on the evolution of galaxies in dense environments are illustrated in the papers of Cayatte et al. (1990) and van den Berg (1994). Figure 23 of the former work presents the integrated neutral hydrogen map of the center of the Virgo cluster; it is striking how the H I diameters of the spiral galaxies suddenly decrease when going to the center of the cluster. In van den Berg (1994) it can be seen how the history of star formation of the Local Group dwarf galaxies is a function of their radial distance from the center of the Group.

The most important environmental effects that can be operating in clusters of galaxies include tidal shaking, which may alter the distribution of material within the galaxy; tidal stripping, which allows selective losses of material and which may produce the disruption of the galaxy; ram pressure sweeping and evaporation, which may give rise to different amounts of mass loss as a consequence of the action of the IGM in the cluster or dense groups.

Evidence for galaxy interactions can be found when searching for relatively close companions to the target galaxies. Although interactions have been invoked to as a possible major cause of starbursts in dwarf galaxies, however, actually few star-forming dwarfs are found to be located in the neighborhood of big galaxies, and that has been a matter of concern for some time (Campos-Aguilar et al. 1993; Telles & Terlevich 1995). Moreover, very recently it has been proposed that high speed close encounters with bright galaxies in clusters, the so called "*harassment*", may produce substantial changes in the properties of cluster galaxies, including the possibility of experiencing some degree of morphological evolution (Moore et al. 1996). In this case, the high velocity of the encounter would make highly unlikely to find an interacting companion close to the target galaxy. This is a very important feature of this kind of interaction and should be taken into account in the analysis of the results of systematic searches for companions of star-forming dwarfs. From the point of view of the *large scale environment*, the general consensus is that, though dwarf galaxies can not fill the voids, they show some degree of biasing which would imply that dwarf galaxies are less clustered than giants (e.g., Salzer et al. 1989; Rosemberg et al. 1994; Hopp et al. 1994; Popescu et al. 1995; Shull et al. 1996). A recent very interesting result related to the distribution of dwarf galaxies in voids has been the discovery of a significant number of intergalactic hydrogen clouds within low redshift voids (Stocke et al. 1995; Shull et al. 1996). These authors have detected many of these clouds making a Lyα search with the *HST* along sight lines to quasars passing through well mapped nearby voids. On the other hand, the content of star-forming galaxies in the Bootis void has been also investigated recently (Weistrop et al. 1994; Szomoru et al. 1996) including surveys in H I and in the optical. With respect to the Virgo dwarf galaxies, new work has confirmed that clear examples of extreme, blue compact galaxies do exist in the cluster (Drinkwater & Hardy 1991; Drinkwater et al. 1996). In addition, many star-forming dwarf galaxies located at different Virgo-centric distances have now been observed in broad band and Hα (Almoznino 1995; Heller et al. 1996) and spectroscopically (Vílchez 1997) and the influence of their H I content or their location in the cluster has been investigated.

With respect to the *close environment*, most of the star-forming dwarf galaxies appear to be truly isolated within a volume of 1 Mpc radius and ± 250 km s^{-1} difference in radial velocity (Campos-Aguilar et al. 1993; Telles & Terlevich 1995). However, when looking to the close environment in H I, a very interesting result

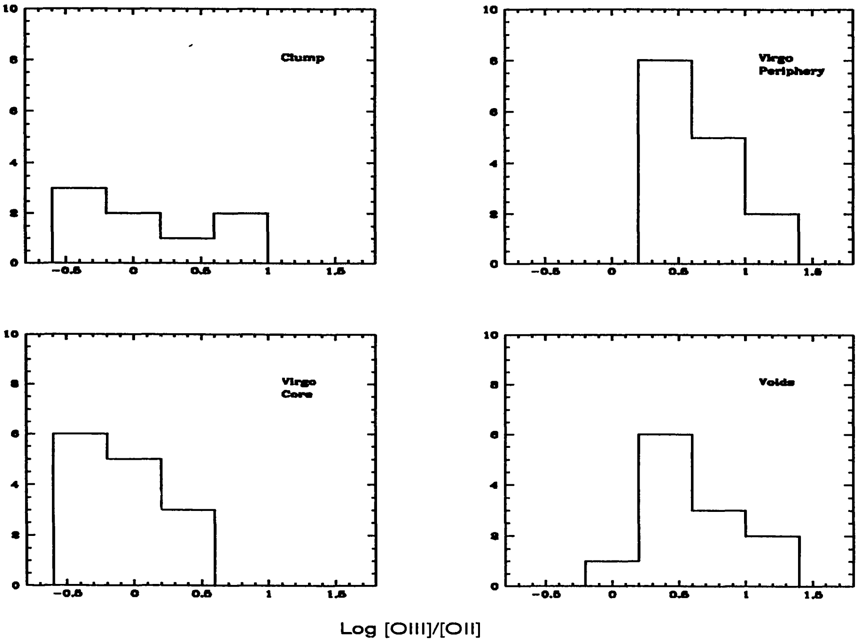

Fig. 1. The behaviour of the excitation, measured by the [O III]/[O II] ratio, for a sample of star-forming dwarf galaxies located in environments with different density, including low density objects from nearby voids and in the periphery of the Virgo cluster/Local Super-cluster, and high density objects located in the Virgo cluster and in a dense group/clump of galaxies. The higher excitation objects of the sample are found in the lower density environments.

—already suggested by Brinks (1990)— has been the detection of close H I companions in a significant fraction of star-forming dwarfs, including several cases showing multiple companions. After corrections for spurious detections and allowing for other effects related to the low surface brightness of these objects, the derived frequency of companions still remains very high (Taylor et al. 1995,1996). These H I clouds or companions may be responsible for the triggering of the bursts at least in part of the dwarf galaxy population.

The spectroscopic properties as well as the main parameters describing the history of star formation in dwarf galaxies appear well correlated with their environmental properties. Our work on the properties of star-forming dwarfs located in extreme density environments (Vílchez 1995) shows that their total luminosity of Hβ —which is a measure of the star formation rate—, excitation —which is proportional to the ionisation parameter U— and equivalent width of Hβ —which is a powerful age indicator— all appear correlated with the environment; with the higher star formation rates, higher ionisation parameters and younger ages always found for galaxies located in low density regions, see Figure 1. Overall, global trends in the $B-V$ colours and metallicities do not appear very much affected by the environment, at least in the light of the presently available data (Almoznino 1995; Telles 1995; Vílchez 1995). However, a very interesting enhancement of the oxygen abundance derived for some of the Virgo dwarfs has remained unexplained and we are currently investigating this fact with the help of new WHT observations. The prevalence of this effect for Virgo dwarfs may be fundamental for the understanding of the metallicity-luminosity relation for dwarf galaxies and its relation with the environment. Figure 2 shows the oxygen abundance versus the blue absolute magnitude for our sample of star-forming dwarfs from different environments.

The spectra of the Virgo dwarfs show evidences of substantial star formation activity previous to the present burst, with low values for the equivalent width of Hβ as well as lower excitation conditions. The high probability of encounters among cluster galaxies can be seen as the origin of the observed behaviour. The low values measured for the equivalent width and the excitation are typical signs of older starbursts; also they may indicate the presence of a significant underlying stellar component for these galaxies, in contrast to the properties of the sample objects from low density regions which are free of suffering any external triggering. For the cluster hydrogen rich dwarfs active star formation can be triggered by the environment in different ways: induced by the presence of close companions (e.g., Balkowski 92; Van driel & Van Woerden 89); during the

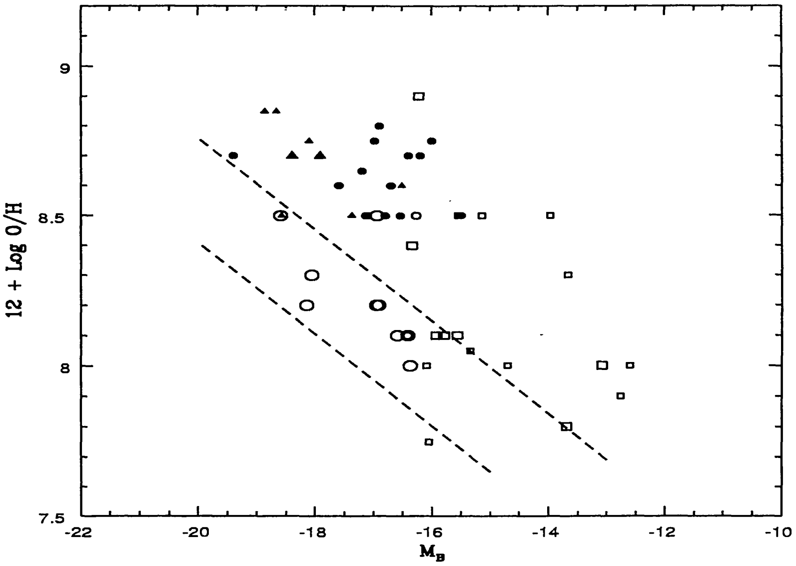

Fig. 2. The oxygen abundance, 12 + log O/H, versus the absolute magnitude M_B, for star-forming dwarf galaxies located in: nearby voids (empty circles); periphery of the Virgo cluster/Local Super-cluster (empty squares); Virgo cluster (black dots); dense group/clump of galaxies (filled triangles). Dashed lines are ± 1σ from the locus of the metallicity-luminosity relation for dwarf irregulars after Skillman et al. (1989).

process by which an H I cloud is ejected; or via the interaction of H I clouds with the intergalactic medium when falling into the cluster.

In extreme cases, one can speculate whether some of the dwarfs studied from the Virgo cluster may be originated in the "*merging*" scenario for the production of dwarf galaxies. The "*merging*" scenario has been recently extensively studied by Mirabel and coworkers (e.g., Mirabel et al. 1992; Duc & Mirabel 1994). In these mergers, in addition to the central starburst triggered by the interaction, there are new *fresh* dwarf galaxies that can be produced along the tidal tails of the merger, as it is very nicely illustrated in numerical simulations (Barnes & Hernquist 1992; Elmegreen et al. 1993). We have explored this scenario for the environment of compact groups of galaxies, which present very high densities and relatively low dispersion velocities. In these conditions galaxy interactions are expected to produce very likely luminous mergers and new dwarf galaxies, as it is shown in our observations of the Hickson compact group HCG 31 (Iglesias-Páramo & Vílchez 1996).

3. SPECTRAL CONSTRAINTS FROM EVOLUTIONARY MODELS

The behaviour of the equivalent width of Hβ has been carefully analysed, since it has revealed as a key parameter in order to know the evolutionary status of the galaxies. In Figure 3 we show the equivalent width of Hβ, W(Hβ), versus the absolute blue magnitude of our sample of galaxies: Virgo Core Dwarfs (black dots), Clump galaxies (black triangles), Voids (open circles) and galaxies in the foreground of the Virgo Periphery (open squares). W(Hβ) is a measure of the strength and the age of the burst (e.g., Terlevich 1985), being the larger values of W(Hβ) systematically present in the more recent and strong starbursts, like those observed in H II galaxies. No correlation is observed in this figure, as in the case of spiral galaxies (e.g., Kennicutt & Kent 1983), although an envelope to the sample is delineated by the straight-line fit and gives a slope of $\Delta\log W(H\beta)/\Delta M_B \approx 0.2$. This result means that galaxies with large values of W(Hβ) and high blue luminosities are not common in the sample and conversely, very low luminosity galaxies with $M_B \geq -15$ mag and showing values of W(Hβ) below 100 Å, are clearly underrepresented.

New spectroscopic observations of an extended sample of Virgo dwarfs have been performed using the WHT 4.2 m in order to study the behaviour of the equivalent width of Hβ as an indicator of their evolutionary status. Figure 4 shows the [O III]/Hβ ratio —which is a good indicator of the excitation and the abundance of the objects—, versus the equivalent width of Hβ, for the sample of galaxies in Vílchez (1995) plus some new WHT data obtained for the extended sample of Virgo dwarfs —black squares in the figure. In general terms, the new Virgo data confirm and extend the behaviour previously observed for the sample of dwarfs in different

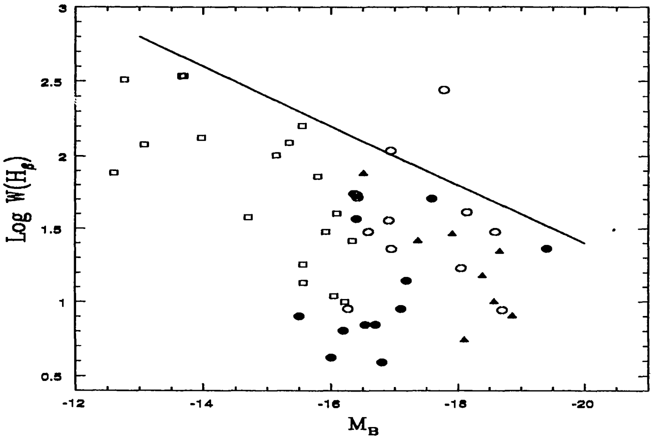

Fig. 3. Log W(Hβ) versus blue absolute magnitude for the program galaxies. Points as in Figure 2.

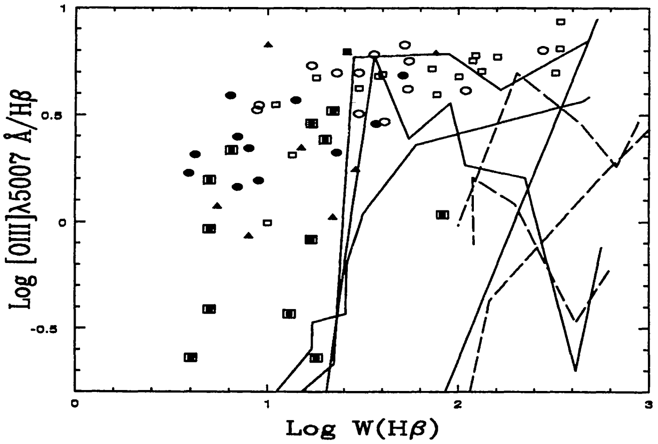

Fig. 4. The [O III]/Hβ ratio versus log W(Hβ). Points as in Figure 2. The new data for Virgo dwarfs are represented by black squares. Models by Stasińska & Leitherer (1996) and by García-Vargas et al. (1995), are shown with continuous and dashed lines, respectively.

environments. We have compared the distribution of points for the extended sample with the predictions from evolutionary photoionisation models, i.e., photoionisation models for which the evolving spectrum of the (ionising) cluster has been used as the input ionising spectrum to the photoionisation code. Two independent model predictions have been used for our comparison (García-Vargas et al. 1995; Stasińska & Leitherer 1996). They used different evolutionary tracks and stellar atmospheres, as well as different photoionisation codes. As it can be seen in the figure, the agreement is rather good for the high excitation galaxies (empty symbols), which are the ones typically found in low density environments. The problem appears when trying to reproduce the data for the dwarfs located in the high density environments; and in particular, those dwarfs from the Virgo sample. The models cannot explain their observed combination of low equivalent width and relatively high [O III]/Hβ. Of course we are dealing with single burst models, and these may be not appropriate for the case of these galaxies, in particular taking into account the effects of a high rate of interactions. In this case, a substantial amount of underlying stellar population is expected to be produced during the life of the galaxy, and therefore, this underlying population may be responsible of a significant fraction of the optical continuum which would be enough to dilute the observed value of the equivalent width of Hβ.

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