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THE INFLUENCE OF THE ENVIRONMENT IN COMPACT GALAXY GROUPS: AN INFRARED PERSPECTIVE

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Abstract. We present a comprehensive study on the influence of the environment of compact galaxy groups to the evolution of their members using a multi-wavelength analysis, from the UV to the far-IR, on a sample of 32 Hickson Compact Groups (HCGs) containing 135 galaxies. Fitting the SEDs of all galaxies with the state-of-the-art model of da Cunha et al. (2008) we can accurately calculate their mass, SFR, and extinction, as well as estimate their infrared luminosity and dust content. We contrast our findings with control samples of field galaxies, early-stage interacting pairs, and galaxies in clusters.

We find that classifying the evolutionary state of HCGs as dynamically "old" or "young" depending on whether or not they contain more than 25% or early-type galaxies is physical and consistent with past classifications based on their gas content. Late-type galaxies in dynamically "young" groups have sSFR, as well as NUV-r and mid-infrared colors, which are similar to those of field and early stage interacting pairs. However, late-type galaxies in dynamically "old" groups have redder NUV-r colors, as they have likely experienced several tidal encounters in the past and built up their stellar mass, and they display lower sSFRs. Finally our model suggests that in 13 groups, 10 of which are dynamically "old", there is diffuse dust in the intragroup medium.

All these evidence point to an evolutionary scenario in which it takes time for the group environment to visibly affect the properties of its members. Early on the influence of close companions to group galaxies is similar to the one of galaxy pairs in the field. However, as the time progresses, the effects of tidal torques and minor merging shape the morphology and star formation history of the group galaxies, leading to an increase of the fraction of early type members and a rapid built up of the stellar mass in the remaining late type galaxies.

Keywords: Infrared: galaxies, Galaxies: evolution, Galaxies: interactions, Galaxies: star formation

1 Introduction

It has become increasingly evident that interactions and merging of galaxies have contributed substantially to their evolution, both in terms of their stellar population as well as their morphological appearance. Compact galaxy groups, with their high galaxy density and signs of tidal interactions among their members, are ideal systems to study the impact on environment to the evolution of galaxies. The Hickson Compact Groups (HCGs) are 100 systems of typically 4 or more galaxies in a compact configuration on the sky (Hickson 1982) They contain a total of 451 galaxies and are mostly found in relatively isolated regions where no excess of surrounding galaxies can be seen, reflecting a strong local density enhancement. The HCGs occupy a unique position in the framework of galaxy evolution, bridging the range of galaxy environments, from field and loose groups to cores of rich galaxy clusters. The fact that the original selection of the HCG members did not include redshift information, led to the inclusion of interlopers among them, the most famous being NGC 7320 in Stephan's Quintet (HCG 92). This led to a debate as to whether compact groups are line-of-sight alignments of galaxy pairs within loose groups, or filaments seen end-on (Mamon 1986; Hernquist et al. 1995). However, the detection of hot X-ray gas in ∼75% of the HCGs by Ponman et al. (1996) implies that they reside in a massive dark matter halo and thus are indeed physically dense structures. Numerical simulations indicate that in the absence

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of velocity information, raising the minimum surface brightness criterion for the group used by Hickson would help eliminate interlopers (see McConnachie et al. 2008).

Because of the nature of these groups, the high density enhancements in addition to the low velocity dispersions (~250 km s^{-1}), make them ideal to study the effects of galaxy interactions. Hickson (1982) found that the majority of HCGs display an excess of elliptical galaxies, ~31% of all members compared to the field, while the fraction of spiral galaxies and irregular is only 43%, nearly a factor of two less of what is observed in the field. Optical imaging by Mendes de Oliveira & Hickson (1994) showed that 43% of all HCG galaxies display morphological features of interactions and mergers, such as bridges, tails and other distortions. Similar indications of interactions are seen in maps of the atomic hydrogen distribution in selected groups by Verdes-Montenegro et al. (2001). Moreover, Hickson (1989) found that the fractional distribution of the ratio of far-infrared (far-IR) to optical luminosity in HCG spiral galaxies is significantly larger than that of isolated galaxies, suggesting that for a given optical luminosity, spiral galaxies in groups have higher infrared luminosities. Comparison of HCG spirals with those in clusters of galaxies from Bicay & Giovanelli (1987) reveals that the distributions of the IR to optical luminosity, as well as the 60 to 100μm far-IR color are similar. Finally, nuclear optical spectroscopy studies indicate that almost 40% of the galaxies within these groups display evidence of an active galactic nucleus (AGN, Martinez et al. 2010; Shimada et al. 2000). All these clues are consistent with an evolutionary pattern where tidal encounters and the accretion of small companions by the group members, redistribute the gas content of the groups and affect the morphology of their members.

Verdes-Montenegro et al. (2001) and Borthakur et al. (2010) have proposed an evolutionary sequence for the HCGs based on the amount and spatial distribution of their neutral atomic gas. Using HI maps they classified the groups into three phases based on the ratio of the gas content within the galaxies over the total observed in the group. However, a necessary step to determine the evolutionary state of HCGs, is the analysis of not just the morphology of the group members, but of their stellar population and star formation history. In the present paper we summarize the work of Bitsakis et al. (2010) and Bitsakis et al. (2010) who presented a complete multiwavelentgh analysis and theoretical modeling of the spectral energy distribution (SED) of a compact group sample and we refer the reader to these papers for more details. The sample was constructed from the original Hickson (1982) catalogue of 100 groups, using as criterion the availability of high spatial resolution 3.6 to 24μm mid-infrared imagery from the Spitzer Space Telescope archive, as well as UV imaging from GALEX. The infrared data are essential to probe the properties of the energy production in nuclei of galaxies, some of which may be enshrouded by dust, while the UV is necessary to properly estimate the effects of extinction and accurately account for the global energy balance when we model their SED. These constrains resulted in a sample of 32 compact groups containing 135 galaxies, 62 (46%) of which are early-type (E's & S0's) and 73 (54%) are late-type (S/SB's & Irr's). We collected a wealth of NUV/FUV (GALEX), optical (SDSS), near-IR (J,H,Ks), mid-IR (Spitzer), and far-IR (IRAS/Akari) for our sample, fitted their SED using the model of da Cunha et al. (2008), and derived their physical properties, such as: the stellar mass, star formation rate (SFR), specific SFR (sSFR), L_{IR}, and extinction (A_V). We compared our findings with a number of control samples including the well known SINGS, and LVL Spitzer samples, isolated galaxies, early-stage interacting systems (Smith et al. 2007), as well as galaxies in clusters (Haines et al. 2008).

2 HCG late-type galaxies

In order to study the star formation properties of HCGs groups, (Bitsakis et al. 2010) separated them into dynamically "young" and dynamically "old". We classified a group as dynamically "young" if at least 75% of its galaxies are late-type. Conversely, a group is dynamically "old" if more than 25% of its galaxies are early-type. The fact that the group environment has played an important role in the evolution of its member galaxies, is evident since the fraction of early-type systems in groups is higher that what is found in the field. So one would expect that because of their proximity, the late-type galaxies in groups would display different star formation properties from the ones in the field. It is known that the sSFR, is a tracer of the star formation history of a galaxy, and galaxies in compact groups do experience multiple encounters with the various group members. We display in Fig. 1a (left) a histogram of the sSFR of the late type galaxies in our sample and compare it with late-type galaxies in the field, as well as early-stage interacting systems. Galaxies in dynamically "young" groups have a median sSFR of $8.51^{+4.07}_{-2.75} \times 10^{-11}\mathrm{yr}^{-1}$, while for galaxies in the dynamically "old" groups sSFR=$2.75^{+2.03}_{-1.16} \times 10^{-11}\mathrm{yr}^{-1}$. Similarly, galaxies in interacting pairs have a sSFR=$11.20^{+3.67}_{-2.70}\times 10^{-11}\mathrm{yr}^{-1}$ and in field galaxies sSFR=$15.30^{+5.65}_{-4.29} \times 10^{-11}$ yr^{-1}. An analysis using two sided KS test indicates that there is no statistical difference between the samples of late-type galaxies in dynamically "young" HCGs and those of the

SINGs and interacting pair samples (P_{KS}>0.80). However, the same KS test reveals that the late-type galaxies in dynamically "old" groups, having a median sSFR which is more than three times lower, can not be drawn from same parent distribution as the other three samples ($P_{KS}\sim10^{-3}$). Investigating in more detail the reason for this disparity, we find that it cannot be attributed to depressed SFR but instead it is due to a substantially more massive stellar content ($\sim3\times10^{10}M_{\odot}$), similar to what is found early-type systems.

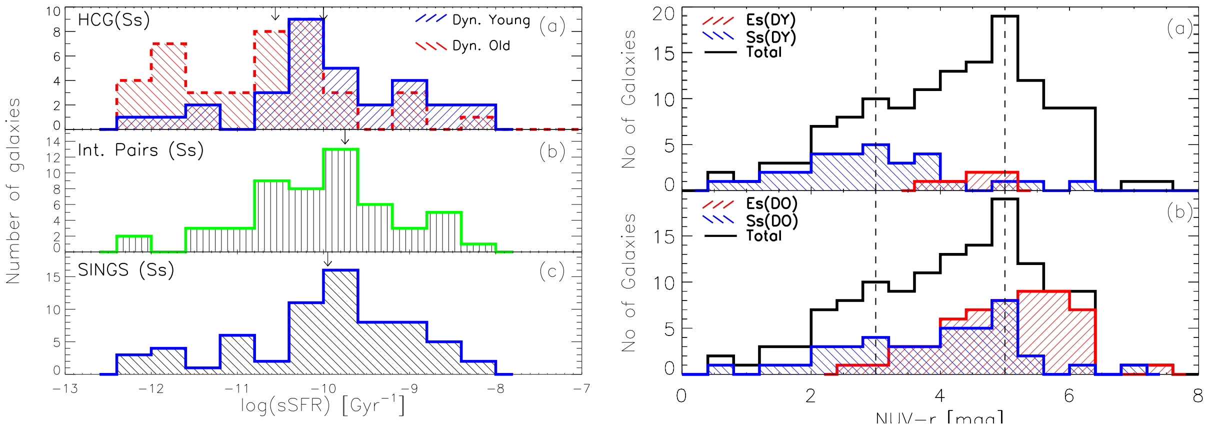

Fig. 1. Left: Histograms of the specific star formation, sSFR, of the late-type galaxies our three samples, estimated by modelling their SED. The top plot displays in blue the histogram of the sSFR of the 31 late-type galaxies found in dynamically-young, spiral-dominated groups. Over-plotted in red is the corresponding histogram of the 42 galaxies in dynamically-old elliptically dominated groups. The middle and bottom plots present the histograms of the 52 late-type galaxies in the Smith et al. (2007) interacting galaxy pairs, as well as the 71 SINGS late-type galaxies. The arrows indicate the median sSFR value of each distribution. **Right:** a) NUV-r histogram of our HCG galaxy sample shown in black solid line. The corresponding histograms of the early- and late-type galaxies found in dynamically "young" groups are shown with the red and blue shaded areas respectively. b) Same as in a), but for the galaxies in dynamically "old" groups. The region of 3<NUV-r<5, identified as "green valley", is marked with the vertical dashed lines.

3 Bimodality in HCG galaxy colors

In order to explore the color variations as a function of the evolution state of the groups, we plot in Fig. 1 (right) the histograms of the early- and late-type galaxies found in the dynamically "young" and "old" groups respectively. Observing the top right panel we find that almost 60% the late-type galaxies in dynamically "young" groups are located within the "blue cloud" and 43% of them, for which nuclear spectra were available, host an AGN in their nucleus. There are also three outlier galaxies which have red NUV-r colors (>5mag). It is possible, that these systems have built up their stellar mass in the past and their UV/optical colors are currently dominated by emission from old stars. In addition, past tidal interactions probably stripped some of their gas in the intragroup medium decreasing the fuel necessary for current star formation. In dynamically "old" groups the late-type galaxies are redder and as we can see in Fig. 1 (bottom-right panel) most of them (>63%) are located within the "green valley". As in dynamically "young" groups there are also four galaxies in these groups which are found in the "red sequence". Since dust appears to affect the UV colors of HCG galaxies, we used our SED models and produced an extinction corrected NUV-r histogram similar to Fig. 1 (right). Furthermore, one could suggest the use of their mid-IR colors, because they trace the light which was originally absorbed by the dust grains in the UV-optical. In Fig. 12 of Bitsakis et al. (2011) we present an IRAC $f_{8.0\mu m}/f_{4.5\mu m}$ vs $f_{5.8\mu m}/f_{3.6\mu m}$ diagram and note that most of the late-type galaxies are located in the upper right quadrant of the plot (also displaying NUV-r<2.5), while most of the early-types (which have NUV-r>3.5) are in the lower left. This suggest that the color bimodality observed in the extinction corrected UV/optical colors, is also observed in the mid-IR and emerges from the same physical properties of the galaxies.

4 Conclusions

Based on the analysis of 135 galaxies residing in 32 Hickson Compact Groups Bitsakis et al. (2011) conclude the following:

- The classification of the evolutionary state of HCGs according to the fraction of their early-type members appears to be physical and is in general agreement with previous classifications. The study of their properties suggest that dynamically "old" groups are more compact and have higher velocity dispersions. They also display higher stellar masses than the "young" ones, while both have similar HI mass distributions. However, "old" groups have nearly an order of magnitude larger dynamical masses than "young" groups.

- The late-type galaxies in dynamically "old" groups display lower sSFRs since the multiple past interactions have already converted a fraction of their gas into stars increasing their stellar masses. This is also the main reason why these galaxies show redder NUV/optical colors than field spirals. However, there are few spiral galaxies in these groups which display even redder colors. They all have very small SFRs, similar to early-type systems. We speculate that tidal interactions must have stripped the gas out of their disk suppressing their star formation activity.

- Most early-type galaxies in dynamically "old" groups, seem to migrate from the star-forming to the quiescent galaxy colors, even though a fraction of them ($\sim$25%) display bluer colors and higher star formation activity than normal field ellipticals possibly due to gas accretion from other group members as well as merging of dwarf companions.

- Late-type galaxies in dynamically "young" groups have similar star formation properties to field spirals, as well as in early-stage interacting pairs.

- Even though nearly 46% of the HCG members have an optically identified AGN, we find no evidence of enhanced AGN activity at any stage of the group evolution, or the optical/mid-IR colors of the galaxies.

- Our analysis suggests that the reported lower density of galaxies in the IRAC color-color diagram is caused by the morphological natural bimodality of galaxies and it is similar to what is also observed in the UV-optical colors.

- Our SED model suggests that in 13 groups, 10 of which are dynamically "old", there is diffuse cold dust in the intragroup medium.

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