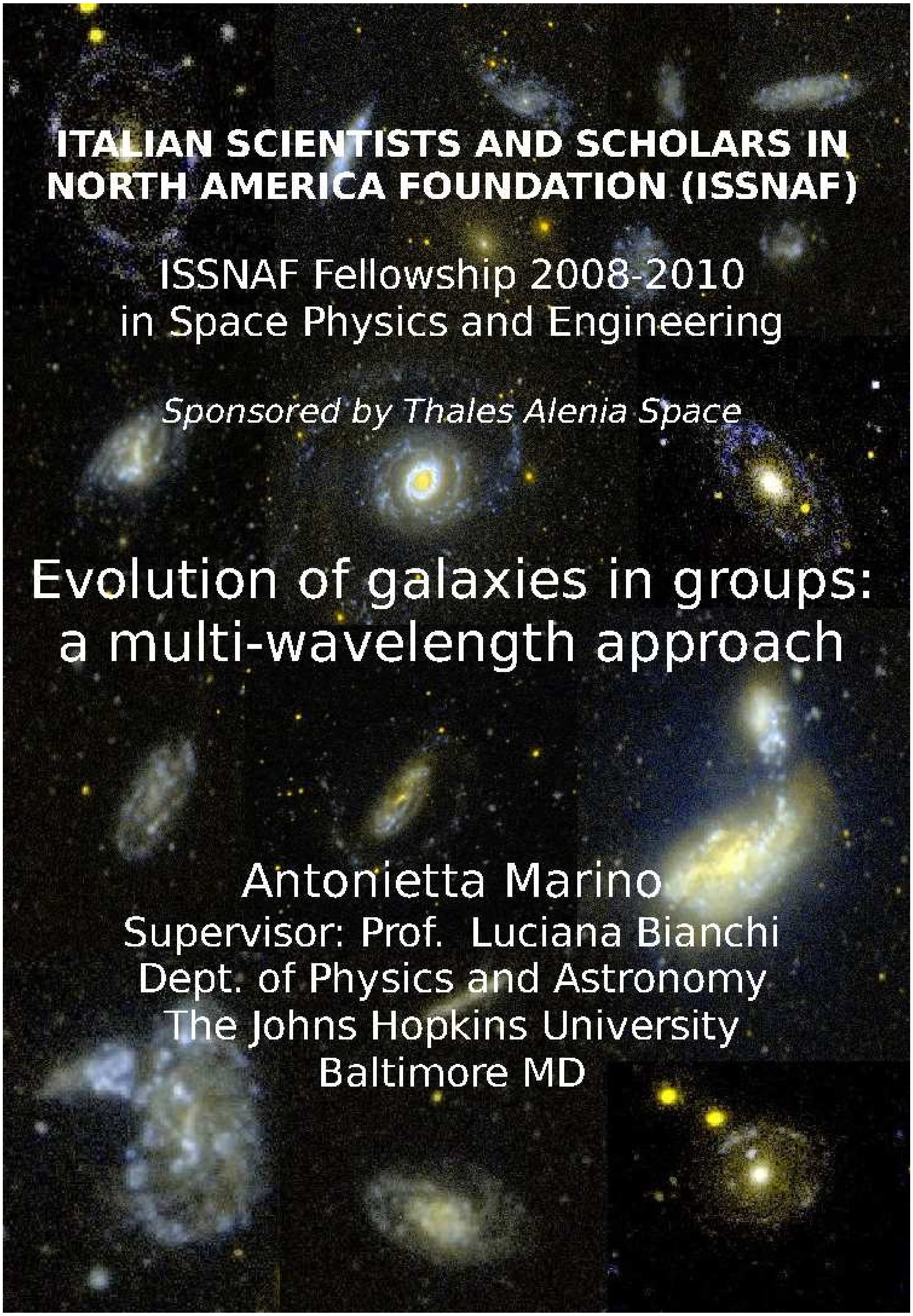

ITALIAN SCIENTISTS AND SCHOLARS IN NORTH AMERICA FOUNDATION (ISSNAF)

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Evolution of galaxies in groups: a multi-wavelength approach

Antonietta Marino
Supervisor: Prof. Luciana Bianchi
Dept. of Physics and Astronomy
The Johns Hopkins University
Baltimore MD

Summary

Aims The main goal of this program was to better understand the origin, properties and evolution of galaxies in groups. The study of galaxy groups is important because most (∼60%) of the galaxies in the local universe are in groups and most of their star-formation happens just in this environment. Despite their unique importance, groups are still poorly studied.

Data and analysis Deep imaging in two ultraviolet (UV) bands, far-UV (FUV, 1350-1780 Å) and near-UV (NUV, 1770-2730 Å), was obtained with NASA's Galaxy Evolution Explorer (GALEX) to characterize the stellar populations of a sample of galaxy groups with a wide range of properties, including analogs of our Local Group and groups with an increasing fraction of early-type galaxies (ETGs, Ellipticals and Lenticulars). We measured integrated photometry of galaxies from UV imaging and corollary optical data, and we derived ages and masses of their stellar populations by analyzing the spectral energy distribution with population synthesis models. The global properties of each host group have also been characterized through a luminosity-weighted kinematical and dynamical analysis.

Main results Some galaxies display distorted UV morphology, outer rings and arm-like structures, revealing recent intense star-formation triggered by ongoing interactions. Such outer rings account for up to 70% of the FUV flux, but contain only a small fraction of the total stellar mass of the galaxy, and are significantly younger than the overall stellar population of the galaxy. UV images also revealed young stellar populations in extreme outskirts of galaxies, undetectable in the optical images. Ages of stellar populations are a few Myrs in Irregular galaxies and up to 7 Gyr in Spiral galaxies. Our spectral energy distribution modeling of ETGs suggests that the currently accepted scenario of 'passive' evolution can be significantly modified by accretion or minor merging episodes. About 60% of the sample groups are not yet in dynamical equilibrium, and are at an early stage of their evolution.

Relevance New deep, wide-field UV imaging from GALEX allowed us to characterize star-formation in a significant galaxy group sample. The ensemble of our results contributes to the understanding of the mechanisms through which galaxies of different morphological types are actively co-evolving within groups. A multi-wavelength approach and the space UV window in particular proved to be crucial in order to place galaxy groups in an evolutionary context.

Summary of publications 4 papers published, 1 submitted and 1 in preparation in main journals; 4 conference proceedings.

The cover page background shows a mosaic of new composite-color (FUV blue and NUV yellow) GALEX images of some galaxies of the studied sample.

1 Why study galaxy groups?

Galaxy groups, such as the Local Group (LG) in which the Milky Way is located, are gravitationally bound systems with less than $\sim$ 50 galaxies, dimensions of $\lesssim$ 1-2 Mpc and velocity dispersions (the velocity scatter of the individual members within the group) of about 150 - 500 km/s. Their importance is twofold: a) $\sim$ 60% of galaxies in the nearby universe resides in groups, b) the transition between galaxy properties typical of field[1] and clusters[2] happens just at the characteristic densities of groups. Spiral galaxies, typically found in the field, are transformed into early-type galaxies, common in cluster environments, and groups evolve from an 'active' (star forming) phase, to a more 'passive' phase.

It is known that environment of a galaxy is linked to most of its properties. For example, ETGs are more likely found in denser areas while Spirals are more often found in lower density environments. Galaxies in sparse environments show a higher star-formation rate than those in denser areas. Whether the relationship between local density and the properties of a galaxy is intrinsic or a result of physical processes driven from the environment after the galaxy formation is still an open issue. Among the physical processes that play a role in galaxy transition, merging events can transform Spiral galaxies in Ellipticals (e.g., Toomre & Toomre 1972, ApJ, 178, 623) and may also quench future star-formation by ejecting the interstellar medium via starburst. Since velocity dispersions of groups are comparable to the velocity dispersion within individual galaxies, galaxy-galaxy merging and interactions are more likely in groups than in clusters or in the field.

While galaxy clusters are well studied, our knowledge of galaxy evolution within groups is still scanty, in spite of their relevance in understanding the star-formation history of the universe. In particular, whether an evolutionary link exists between groups dominated by Elliptical galaxies and groups dominated by Spiral/Irregular galaxies, i.e. whether they represent two evolutionary stages, is still unclear.

UV wide-field imaging from GALEX[3] makes it possible, for the first time, to study a significant sample of groups in the UV, and to characterize their recent star-formation activity. In this context, we have selected and analyzed a sample of galaxy groups spanning a wide range of properties, in richness of members galaxies, velocity dispersion, morphological types and spatial distribution.

We describe in the next section the selection of the group sample and the data. The analysis is described in Section 3, and main results are presented in Section 4. Future perspectives are discussed in Section 5.

[1]Isolated galaxies, typically Spirals.

[2]Systems containing hundred or thousands of galaxies where ETGs are the predominant type.

[3]GALEX is a NASA Small Explorer, providing the first comprehensive map of the sky in the ultraviolet. It performs imaging and spectroscopic observations from space in two bands, far-UV (1344-1786 Å) and near-UV (1771-2831 Å). An overview of the surveys, coverage, depth and content can be found in Bianchi (2009, Ap&SS, 320, 11)

2 UV observations of galaxy groups with GALEX

2.1 Choice of the galaxy groups

We selected our sample of galaxy groups starting from the catalog of Ramella et al. 2002, (AJ, 123, 2976) which includes 1168 groups of galaxies to a limiting magnitude $m_B \sim 15.5$. The 6846 galaxies of the catalog were cross-matched with the GALEX and Sloan Digital Sky Survey (SDSS)[4] archives. In order to make a detailed morphological and photometric analysis, we chose only groups within 40 Mpc, and composed of at least 10 galaxies, to minimize contamination by superposition of field galaxies. We selected a sample of 8 groups, having between 10 and 47 members and a fraction of ETGs varying from 20% to 70%, with UV and optical data available for most galaxy members. We obtained new GALEX imaging of the remaining galaxies thanks to a successful proposal in the 6^{th} NASA GALEX call for proposals (Principal Investigator A. Marino): the new observations are almost completed. In addition, we analyzed three nearby LG analogs and 40 ETGs belonging to environments with differing density.

2.2 UV imaging reveals star-formation

Figure 1 shows the spatial distribution and GALEX FUV (blue) and NUV (yellow) color-composite images of the galaxies in the group LGG 225. It is composed of 15 galaxies with a large number of Spirals. All galaxies but the two ETGs (NGC 3522 and NGC 3457) show evidence of tidal distortion and interactions. NGC 3447A is the bluest galaxy and it is strongly interacting with NGC 3447. NGC 3455, UGC 6035, UGC 6022, and UGC 6083 present unambiguous signatures of distortions/asymmetries in their UV morphology. Figure 2 shows GALEX UV and ground-based optical images of three galaxies representing a range of properties (see Section 4). Star-forming regions appear very prominent in UV bands[5], which reveal young stellar populations indistinguishable in the optical images. In particular, recent star-formation is seen in extreme outskirts of galaxies, extending much further out than the optical images (e.g. NGC 2962, UGC 6035 in Figure 2) as found also by Thilker et al. 2007 (ApJS, 173, 538), Bianchi, 2009 (Ap&SS, 320, 11), Thilker et al. 2010 (ApJ, 714L, 171).

2.3 Luminosity of groups' member galaxies

From UV and optical images we measured the galaxy luminosity, and light profiles in concentric ellipses. The light profile is the 2D distribution of the light as a function of the distance from the center, and is used to gain information on the 3D structure of galaxies. Figure 3 shows examples of two rather different galaxies and their light profiles. NGC

[4] This survey uses a dedicated 2.5 m optical telescope in New Mexico, to take images of the sky in five bands : u [2980-4130 Å], g [3630-5830 Å], r [5380-7230 Å], i [6430-8630 Å], and z [7730-11230 Å].

[5] Massive young stars emit most of their energy in the UV, therefore UV imaging is an excellent probe of current star-formation.

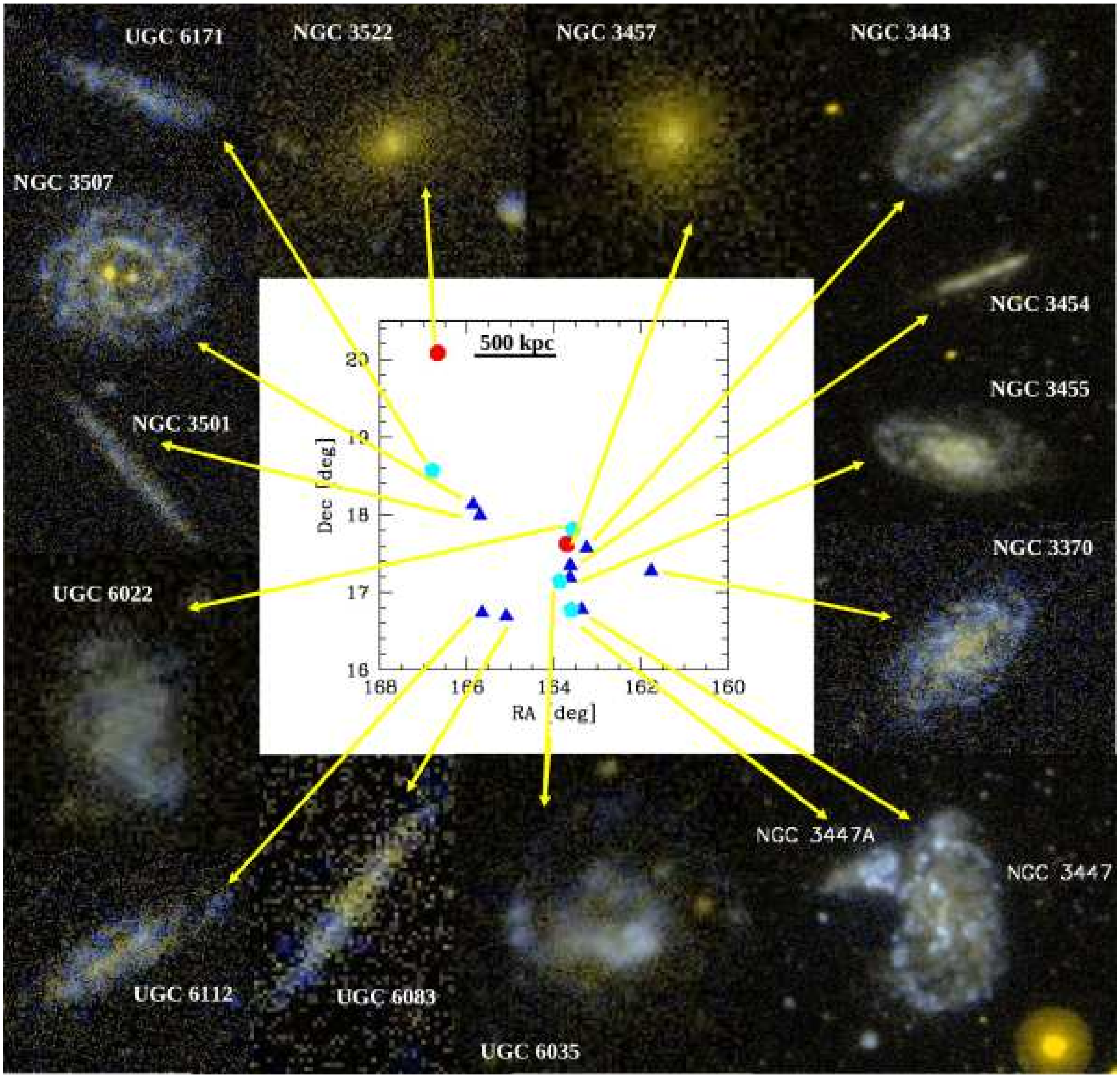

Figure 1: GALEX FUV (blue) and NUV (yellow) color-composite images of the galaxy members of LGG 225 and their spatial distribution on the sky (red circles: Ellipticals, blue triangles: Spirals and cyan pentagons: Irregulars). Note the two strongly interacting galaxies NGC 3447 and NGC 3447A. A bar is still visible in NGC 3447 while both the underlying disk and the multiple arms are tidally distorted. The sites of recent and on-going star-formation, including a knotty ring around NGC 3447, are unambiguously revealed in the UV. Most galaxies show signatures of morphological distortions and asymmetries: e.g the outer arms of NGC 3455 are possibly tidally distorted, UGC 6035 and UGC 6022 are very irregular and probably distorted by an interaction event.

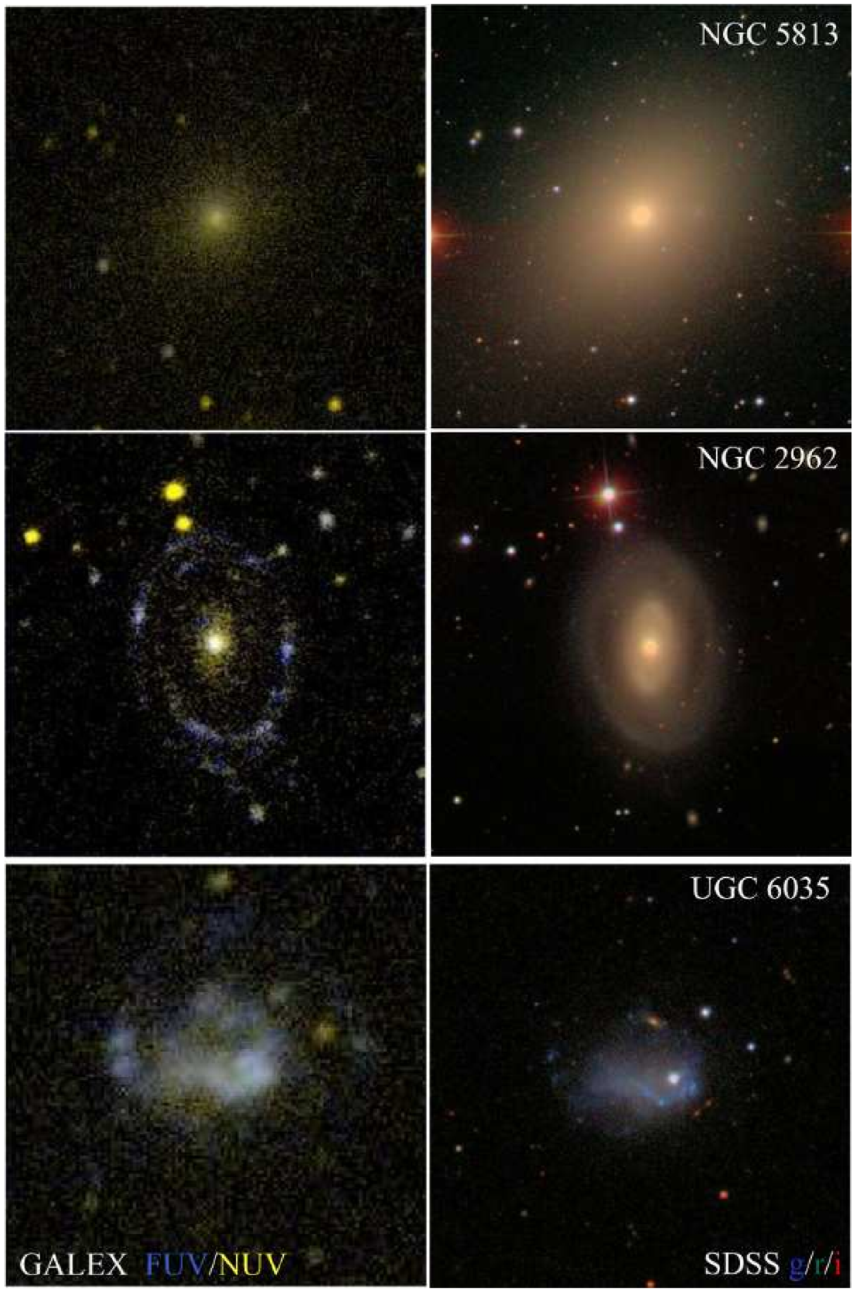

Figure 2: Color-composite UV (FUV blue, NUV yellow, left panels) and optical (SDSS, g blue, r green, i red, right panels) images of the Elliptical (passively evolving) NGC 5813 (top), of the Lenticular with a star forming ring NGC 2962 (middle) and of the Irregular UGC 6035 (bottom). Note the ring structure of NGC 2962 more prominent and defined in the UV than in optical, and bluer than the nucleus. The UV and optical images are on the same scale: the UV emission of NGC 2962 and UGC 6035 extends much further out than their respective optical images.

5636 has an outer ring quite prominent in the UV, its color is bluer than the central part of NGC 5636 and NGC 5638, indicating that its light is dominated by young stellar populations. On the contrary, NGC 5813 is an Elliptical with an old stellar population (see Section 3.5).

We also show in Figure 3 the spectral energy distribution (SED) of NGC 5636 and NGC 5638 from FUV to near infrared. The SEDs are similar at optical wavelengths but show a different slope at UV wavelengths, indicating a range of ages of the stellar populations.

3 Deriving physical properties of galaxy groups

3.1 Estimating age and stellar mass of the galaxies

In order to estimate age and stellar mass of each galaxy, and the total stellar mass of the groups, we compared the observations with synthetic stellar population models. We computed a grid of models, using the code GRASIL[6] (Silva et al. 1998, ApJ, 509, 103), which includes the effect of age-dependent interstellar extinction with young stars being more affected by dust. Typical star-formation histories (SFHs) for Spirals, Ellipticals and Irregulars were assumed. Figure 3 shows, as an example, the measured SEDs (filled points) and the best fit models (line) obtained for the ring galaxy NGC 5636 (age $\sim$ 1 Gyr, stellar mass 7.8 $\times$ 10^7 solar masses) and for the Elliptical NGC 5638 (age $\sim$ 12.5 Gyr, stellar mass 1 $\times$ 10^9 solar masses). The latter is well fitted using models of passive evolution while the FUV excess in the SED of NGC 5636 suggests a SFH different from canonical assumptions. The outer ring of NGC 5636 contains less than 10% of the total stellar mass and is younger than the main galaxy population.

3.2 Evolution of galaxy groups: from 'active' to 'passive'

We characterize the evolutionary phase of each group by performing a luminosity-weighted kinematical and dynamical analysis based on the virial method (Ferguson & Sandage, 1990, AJ, 100, 1). This approach allow us to describe in an homogeneous way the properties of the group environments. Figure 4 shows the relative positions of the galaxy members in two very different groups on a linear scale, enabling a direct comparison of group compactness. LGG 127 (left panel) is an example of loose group while USGC U677 (right panel) is compact and more evolved. The compactness of a group is quantified by the harmonic radius[7] (circle in Figure 4), typically larger in loose groups than in compact ones. We find that about 60% of the sample is still dynamically young, with galaxy

[6] GRASIL (which stands for GRAphite and SILicate), is a code to compute the spectral evolution of stellar systems taking into account the effects of dust, which absorbs and scatters optical and UV photons and emits in the Infrared region.

[7] $R_H = \frac{\Sigma_i \Sigma_{j<i} w_i w_j}{\Sigma_i \Sigma_{j<i} (w_i w_j)/(r_i - r_j)}$, r is the projected separation between galaxy i and j, and w is the NUV luminosity weight.

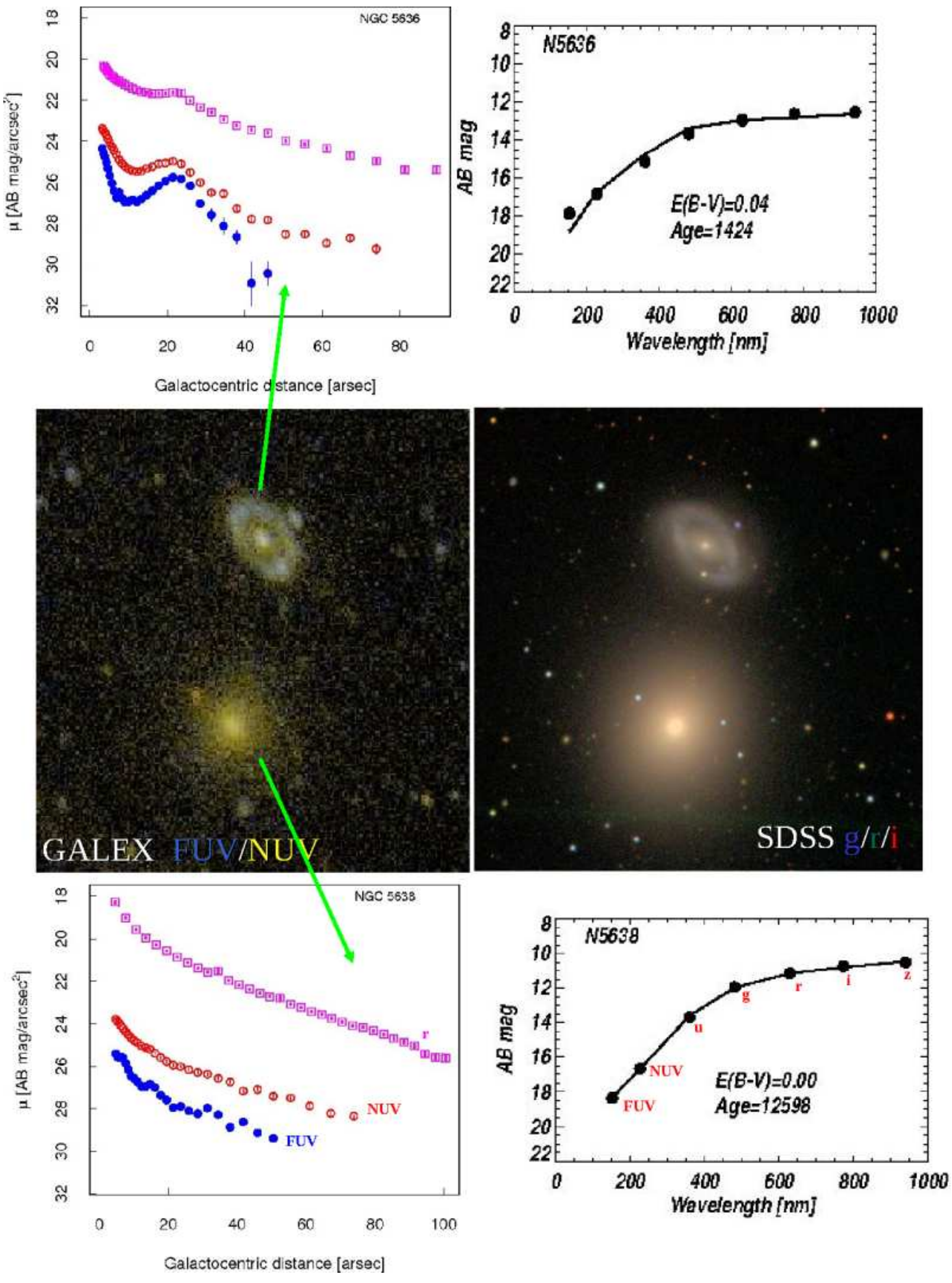

Figure 3: Top: UV and optical light profiles (left) and FUV to near-infrared SED (right filled points) with the best fits model (line) of the lenticular NGC 5636. Middle:color-composite FUV (blue) and NUV (yellow) and optical (g blue, r green, i red) images of the ring galaxy NGC 5636 and of the elliptical NGC 5638. The two companion galaxies belong to a larger group of seven galaxies. Bottom: like in the top for NGC 5638. The ring structure of NGC 5636 appears bluer than the nucleus, indicating a young component in the mix of the stellar populations. Ages are in Myr.

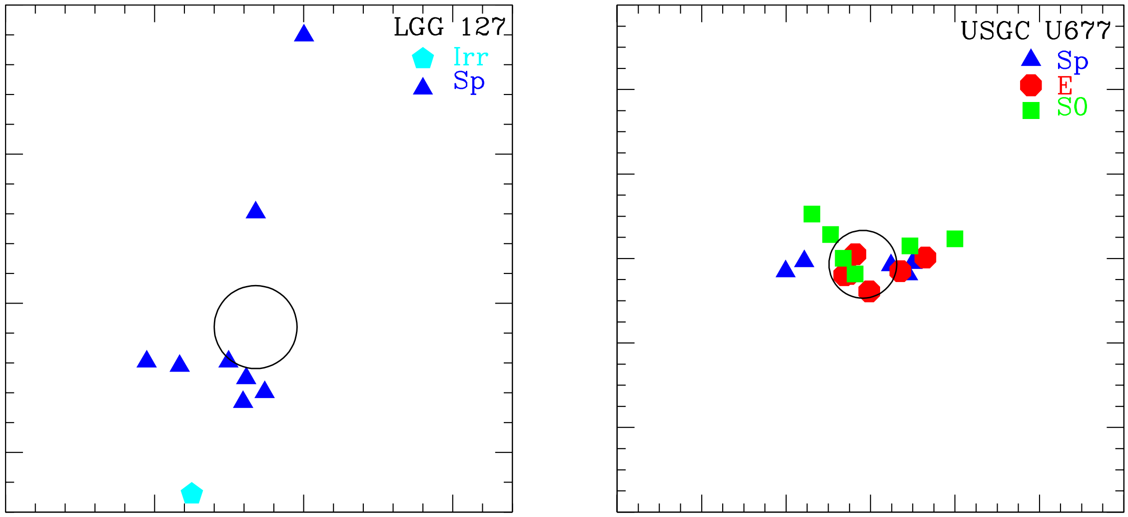

Figure 4: Position of the galaxies in a square of 4.5 $\times$ 4.5 Mpc^2 of the likely un-virialized group LGG 127 (left) and of the dynamically relaxed USGC U677. The circle represents the B luminosity-weighted harmonic radius centered on the group center of mass. Note the galaxy distribution rather irregular in the un-virialized group in comparison to the virialized one.

groups dominated by Spiral galaxies having the larger crossing time[8]. The virial mass of the groups ranges between 1 $\times$ 10^{12} and 2 $\times$ 10^{13} solar masses, and is larger than the total stellar mass of their member galaxies.

4 Understanding co-evolution of galaxies and their host groups

4.1 Local Group analogs

The analysis of three nearby groups (LGG 93, LGG 127 and LGG 225) dominated by Spiral/Irregular galaxies shows that a few member galaxies in LGG 225 have a distorted UV morphology due to ongoing interactions (Figure 1). (FUV-NUV) colors suggest that Spirals in LGG 93 and LGG 225 host stellar populations in their outskirts younger than that of M31 and M33 in the LG or with less interstellar dust. The Irregular interacting galaxy NGC 3447A (Figure 1) has a significantly younger stellar population (few Myr old) than the average of the other Irregular galaxies in LGG 225, suggesting that the encounter triggered star-formation (see Figure 1). The two early-type members of LGG 225 have stellar masses of the order of a few 10^9 $M_{\odot}$, comparable to the LG Ellipticals. For the most massive Spiral in LGG 225, we estimate a stellar mass of $\approx 4 \times 10^{10}$ $M_{\odot}$, comparable to M33 in the LG and much lower than the LG's most massive Spirals (Milky Way and M31). Ages of stellar populations range from a few to $\approx$ 7 Gyr for the galaxies in LGG 225. The kinematical and dynamical analysis indicates that LGG 127 (Figure 4 left panel) and LGG 225 (Figure 1) are in a pre-virial collapse phase, i.e. still undergoing dynamical

[8]The time a typical galaxy takes to cross the system.

relaxation, while LGG 93 is likely virialized. Both the photometric and the dynamical analysis suggest that LGG 225 is similar to the LG with many galaxies undergoing star-formation, and interactions between members, and it is in a more active evolutionary phase than both LGG 93 and LGG 127. The total stellar masses (sum of the stellar mass of all galaxies) of LGG 225, LGG 93 and LGG 127, are estimated between 5 and 35 $\times$ 10^{10}, 4 $\times$ 10^{9} and $\sim$4 $\times$ 10^{10} solar masses respectively.

Results of this work were published in the paper Marino et al. 2010, Astronomy & Astrophysics, 511, A29.

4.2 What drives ETG evolution?

Local ETGs are considered the fossil record of the process of galaxy formation. However, thanks to UV imaging from GALEX, there is growing evidence that rejuvenation episodes can occur in the star-formation history of ETGs, although it is still unclear how significant and frequent they have been during the Hubble time[9]

We analyzed 40 ETGs, members of nearby groups, to characterize their stellar populations. Most ETGs present an undisturbed UV morphology but $\approx 15\%$ of the sample shows outer rings, and shell structures very prominent in UV and indicative of recent merger/accretion events. Figure 2 shows the composite UV and optical images of two representative cases. NGC 5813 is a passively evolving galaxy, while NGC 2962 shows a blue ring which reveals recent star-formation. We find that FUV-NUV profiles become redder with increasing galacto-centric distance in most ETGs. We think that this is due, at least in part, to a metallicity[10] gradient. We characterized light profiles of the undisturbed ETGs, using a Sersic law.[11] The Sersic index n varies from 1 to 16 in the UV bands. ETGs with $n > 4$ tend to have large value of $[\alpha/\mathrm{Fe}]$[12] implying a short star-formation time scale. S0s (ETGs with $n = 3 \pm 1$,) have low values of $[\alpha/\mathrm{Fe}]$. Combined with spectroscopically derived information on metal abundance, the picture emerges that among ETGs, fast rotators having a disk, like S0s, have star-formation histories different from those of slow rotators (like Ellipticals). In the latter, episodes of rejuvenation are likely driven by small accretion events.

Results of this work were accepted for publication in Monthly Notices of the Royal Astronomical Society Journal (Marino at al. 2010 in press).

[9]The reciprocal of the Hubble constant H_0 with H0 the constant of proportionality between the distance D to a galaxy and its velocity v.

[10]In astronomy, indicates all chemical elements heavier than hydrogen and helium.

[11]A mathematical function that describes how the intensity of a galaxy varies with distance from its center: $\mu(r) \sim r^{1/n}$, μ is the surface brightness measured in magnitudes per square arcsecond; n, called the 'Sersic index', controls the degree of curvature of the profile.

[12]Abundance of the alpha elements (e.g. Mg, Si, Ne,Ca so-called since their most abundant isotopes are integer multiples of the mass of the helium nucleus) in comparison with the Fe abundance.

4.3 The transition from Spirals to Ellipticals: S0 with star-forming rings discovered with GALEX

Among the ETG sample, lenticulars (S0) galaxies show intermediate properties between Ellipticals and Spirals. They are disk galaxies, like Spirals, but are dominated by aging stars, like Ellipticals. Since S0s are typically found in dense environments, such as galaxy clusters, their properties have been interpreted as a phase in the evolution of galaxies in which Spirals are transformed into S0s as their gas is removed by ram-pressure, and on-going star formation is quenched. In our sample, five S0s show UV-bright ring structures in their outer disks, characterized by the presence of a bar. Ring structures are prominent in UV (e.g. NGC 2962 in Figure 2 and NGC 5636 in Figure 3), their luminosity account for up to 70% of the total galaxy FUV luminosity. Outer rings are bluer than the central part of the galaxy and reveal recent star-formation: their stellar populations are only a few Myrs old, i.e. younger than the overall galaxy and their stellar mass is a small fraction ($< 10\%$) of the total galaxy stellar mass.

The results of this work were presented at the 'UV Universe 2010' meeting, St. Petersburg June 2010, and a paper is also submitted to the Astrophysical Journal.

5 Future perspectives and outcome of the fellowship

The work performed during the two-year fellowship has laid the foundations for a wider program to investigate galaxy properties and evolution in different environments, and opened a number of research paths. A. Marino plans to continue this program maintaining the collaboration built between the research groups of Prof. Bianchi at JHU and Dr. Rampazzo at Padova Observatory. Using the approach and methods developed during the past two years, we will complete the analysis of the galaxy group sample, expand the model analysis, and compare the galaxy groups properties with field and cluster environments, in order to better clarify the role of the galaxy groups in the evolution of the universe.

Acknowledgments

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6 Resulting publications

- **Articles in major international journals Sept. 2008 - Sept 2010**

  - ‘*GALEX* UV properties of the polar ring galaxy MCG-05-07-001’ and the shell galaxies NGC 1210 and NGC 5329’, A. Marino, E. Iodice, R. Tantalo, L. Piovan, D. Bettoni, L.M. Buson, C. Chiosi, G. Galletta, R. Rampazzo, R.M. Rich, 2009, Astronomy and Astrophysics, 508, 1235.
  - ‘The role of the synchrotron component in the MIR spectrum of M87’, L.M.Buson, A. Bressan, P. Panuzzo, R. Rampazzo, J. R. Valdes, M. Clemens, A. Marino, M. Chavez, G.L. Granato, L. Silva, 2009, Astrophysical Journal, 705, 356.
  - ‘Galaxy Evolution in Local Group Analogs. I. A *GALEX* study of nearby groups dominated by late-type galaxies’, A. Marino, L. Bianchi, R. Rampazzo, L.M. Buson, D. Bettoni, 2010, Astronomy and Astrophysics, 511, 29.
  - ‘Nearby early-type galaxies in groups: The UV emission from *GALEX* observations’, A. Marino, R. Rampazzo, L. Bianchi F. Annibali, A. Bressan, L.M. Buson, M.S. Clemens, P. Panuzzo, W.W. Zeilinger, 2010, accepted by Monthly Notices of the Royal Astronomical Society.
  - ‘Tracing Rejuvenation events in nearby lenticular galaxies’, A. Marino, L.Bianchi, R. Rampazzo, D. Thilker, L.M. Buson, et al. 2010, ApJ, submitted.
  - ‘Nearby groups of galaxies: the ultraviolet properties’, A. Marino, L. Bianchi, R. Rampazzo, et al., 2010, in preparation.

- **Articles in conference proceedings Sept. 2008 - Sept. 2010**

  - ‘MIR properties of field Early-Type Galaxies’, R. Rampazzo, P. Panuzzo, A. Bressan, O. Vega, F. Annibali, M. Clemens, L.M. Buson, G-L. Granato, A. Marino, L.Silva, W.W. Zeilinger, in ‘Galaxy properties across cosmic ages’, Accademia Nazionale dei Lincei, April 28-29 2009, Roma, (Italy)
  - ‘Tracing rejuvenation events in nearby early-type galaxies’, R. Rampazzo, P. Panuzzo, A. Bressan, O. Vega, A. Marino, L. Bianchi, F. Annibali, L.M. Buson, M. Clemens, G-L. Granato, L.Silva, W.W. Zeilinger in ’Galaxies in isolation: exploring nature vs. nurture’, May 12-15 2009, Granada (Spain).
  - ‘Signatures of recent star formation in rings of S0 galaxies’, A. Marino, L.Bianchi, R. Rampazzo, A. bressan, D. Thilker, F. Annibali, L.M. Buson, 2010, in ‘UV Universe - 2010’, special issue of ”Astrophysics & Space Science”, editors Boris Shustov, Ana Ines Gomez de Castro and Mikhail Sachkov.
  - ‘Tracing the evolution of nearby early-type galaxies in low density environment. A view from GALEX’, R., Rampazzo, F. Annibali, A. Marino, L. Bianchi, A. Bressan, L.M. Buson, M. Clemens, P. Panuzzo, W.W. Zelinger, 2010, in ’UV

Universe - 2010', special issue of 'Astrophysics & Space Science', editors Boris Shustov, Ana Ines Gomez de Castro and Mikhail Sachkov.

- **Approved observing proposals**
  - Title: 'Tracing the transition from active to passive galaxy groups'
    Principal Investigator: A. Marino
    Co-Investigators: L. Bianchi, R. Rampazzo, L. Buson, D. Bettoni
    GALEX cycle 6.
  - Title: 'The outer atmospheres of flare stars discovered with GALEX in the near-UV'
    Principal Investigator: B. Stelzer (INAF-Ossevatorio Astronomico Palermo)
    Co-Investigators: A. Marino, G. Micela (INAF-Ossevatorio Astronomico Palermo)
    XMM AO-9.