The UV window on counter rotating ETGs: insight from SPH simulations with chemo-photometric implementation

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Abstract The Galaxy Evolution Explorer (\textit{GALEX}) detected ultraviolet emission in about 50\% of multi-spin early-type galaxies (ETGs), suggesting the occurrence of a recent rejuvenation episode connected to the formation of these kinematical features. With the aim at investigating the complex evolutionary scenario leading to the formation of counter rotating ETGs (CR-ETGs) we use our Smooth Particle Hydrodynamic (SPH) code with chemo-photometric implementation. We discuss here the UV evolutionary path of two CR-ETGs, NGC 3593 and NGC 5173, concurrently best fitting their global observed properties, i.e., morphology, dynamics, as well as their total $B$-band absolute magnitude and spectral energy distribution (SED) extended over three orders of magnitude in wavelength. These simulations correspond to our predictions about the target evolution which we follow in the color-magnitude diagram (CMD), near-UV (NUV) versus $r$-band absolute magnitude, as a powerful diagnostic tool to emphasize rejuvenation episodes.

Keywords Galaxies: evolution, Galaxies: interactions, Galaxies individual: NGC 3593, NGC 5173

1 Introduction

The phenomenon of counter rotation, i.e. two galaxy components (gas and/or stars) rotating in opposite

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cent accretion episodes) host a rejuvenated nucleus. Similar results have been obtained by Jeong et al. (2003) for the SAURON galaxy sample (de Zeeuw et al. 2002; Jeong et al. 2009 and Marino et al. 2009) detected also UV bright outer rings. Marino et al. (2011) showed that such rings consist of young (<200 Myr old) stellar populations, accounting for up to 70% of the FUV flux but containing only few percents of the total stellar mass. In addition, the distribution of galaxies in the (NUV-r) vs r-band absolute magnitude diagram (e.g. Baldry et al. 2004; Lewis et al. 2002; Strateva et al. 2001) evidences that the red galaxy population is the result of transformations, mainly driven by the environment, of the blue, late-type galaxies via mechanisms of star formation quenching. The galaxy transition from star forming to quiescent galaxies, is captured by the presence on CMDs of an intermediate zone, the so-called Green Valley (GV) (Martin et al. 2007; Wyder et al. 2007). Investigating galaxies in the GV should shed light on the mechanisms governing the on-off state of the star formation (Mazzei et al. 2014a,b).

Here we match the global observed properties and predict the evolution of two CR-ETGs, NGC 3593 and NGC 5173, using SPH simulations with chemophotometric implementation.

The plan of the paper is as follows. In section 2 we summarize the recipes of our SPH models widely described in previous papers (Mazzei et al. 2014a,b, and references therein); in section 3 we describe the sample of CR galaxies we plan to study, and the results for two cases of interest, i.e., NGC 3593 and NGC 5173; in section 4 we drawn our conclusions.

2 The SPH simulations

We performed a large set of SPH simulations of galaxy formation starting from collapsing triaxial halos initially composed of DM and gas. We analyzed the evolution of isolated halos in previous works (Curir & Mazzei 1999; Mazzei & Curir 2003), as well as that following from a large grid of encounters of two halos with different spins, impact parameters, total masses and gas fraction, as reported in several previous papers (Mazzei et al. 2014a,b; Bettoni et al. 2012; Trinchieri et al. 2012). All the simulations include self-gravity of gas, stars and DM, radiative cooling, hydrodynamical pressure, shock heating, viscosity, SF, feedback both from evolved stars and type II supernovae, and chemical enrichment. Simulations provide the synthetic SED, based on evolutionary population synthesis (EPS) models, at each evolutionary stage. The SED extends from 0.06 to 1000 µm (Mazzei et al. 1992, 1994, 1995, 2007; Spavone et al. 2009), and references therein). From the grid of physically motivated SPH simulations, we isolate those simultaneously best fitting the global properties of selected ETGs, i.e., their absolute B-band magnitude, integrated SED, current morphology and kinematics (Mazzei et al. 2014a,b).

The selected simulation traces a viable global evolution of the galaxy by means of the star formation rate and its related tools, i.e., chemical and luminosity evolution, together with the dynamic evolution of all the galaxy components (stars, cold, warm and hot gas, and dark matter). Our simulations allow us to derive the global properties of the system, in particular the spins and relative masses of all the system components, i.e. the encounter/merger evolution.

3 The counter-rotating galaxy sample with UV emission

We aim at investigating the characteristics of the largest as possible sample of objects with CR components. To this end, we build our sample starting from the list of Galletta (1996) and Corsini & Bertola (1998) and mining the current literature (see e.g. Sil’chenko et al. (2009); Katcov et al. (2013a,b); Kannappan et al. (2001)). As a final step we checked also the SAURON (de Zeeuw et al. 2002; Emsellem et al. 2007) and ATLAS-3D (Cappellari et al. 2011; Krajinović et al. 2011) samples. The only selection criterion is the presence of both stars-gas and/or stars-stars CR. The final sample is composed of 75 galaxies with CR. In order to have an homogeneous data set, we obtained from the Lyon Meudon Extragalactic Database (LEDA Paturel et al. 2003) all the available morphological, photometrical and dynamical data for these galaxies.

Our serendipity selected sample is composed by 80% of ETGs (morphological type T ≤0) and 20% of late type galaxies. Using the homogeneous distances from LEDA, our sample spans a range of about five magnitudes in $M_B$, from -22.4 to -17.2 mag, with $M_B$= -20.04±1.21 mag in average. Moreover, we exploited the GALEX archive to obtain far-UV (FUV) and NUV magnitudes. We found that ~50% of the galaxies in this sample show the presence of a significative FUV emission, a signature of rejuvenation episodes.

We summarize below the initial conditions, i.e., the relevant characteristics, and present the results of our SPH simulations for two of our CR-ETGs, NGC 3593 and NGC 5173.
Fig. 1  The SEDs of NGC 3593 (left panel) and NGC 5173 (right panel). Blue circles are total fluxes from NED. Open circles in the FIR spectral range are from AKARI/FIS Bright Source Catalog (Yamamura et al. 2009) (black) and IRAS (red) for NGC 3593. For NGC 5173, green points are ISO data (Xilouris et al. 2004), FIR observations are from IRAS (magenta) and Temi et al. (2004) (cyan). In both panels, the error bars account for band width and 3σ uncertainties of the fluxes; solid lines are predictions from our chemo-photometric simulations at 13.1 and 13.8 Gyr, respectively. The FIR SEDs include two dust components: warm dust (HII regions) and cold dust (heated by the diffuse interstellar field) both including PAH molecules. The warm/cold energy ratio in NGC 3593 is 0.3, similar to the average for Spirals, and, in NGC 5173, double than average for Es, i.e., 1 instead of 0.5.

Fig. 2  Right: Top and bottom panels show the SDSS r-band and the GALEX (FUV blue, NUV yellow) color composite images of NGC 5173, respectively, both on the same scale, 2.7′×2.7′. Left: Top and bottom panels present, on the same spatial scale and with resolution 5″ as the GALEX image, the maps derived from our simulation, in the same bands as in the right panel, at the age of the galaxy derived from our simulation, i.e., 13.8 Gyr. Both our maps have been normalized to the total flux within each simulated image.
3.1 NGC 3593

This galaxy, classified as SA(s)0/a, is known to host two large counter-rotating stellar disks (Bertola et al. 1990) together with a gaseous disk. It shows a chaotic pattern of dust patches throughout its main body. It is very rich in both neutral (HI) and molecular (H$_2$) gas. Their total masses are 5.1×10$^8$M$_\odot$ and 2.3×10$^8$M$_\odot$, respectively (Bettoni et al. 2001). Its B-band total absolute magnitude ranges between -16.96 mag to -19.01 mag accounting for Virgo infall and 3K cosmic microwave background corrections, respectively (NED, NASA/IPAC Extragalactic Database http://ned.ipac.caltech.edu), and adopting H$_0$ = 70 km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\Lambda}$ = 0.73, and $\Omega_{\text{matter}}$ = 0.27, as in the HYPERLEDA database (http://leda.univ-lyon1.fr) Paturel et al. (2003). NGC 3593 is a very bright IR source and contains 5.6×10$^6$M$_\odot$ of dust (Bettoni et al. 2001). The galaxy hosts an inner nuclear ring (Knapen et al. 2010). Coccato et al. (2013) suggested that an accretion event occurred between 2 and 3.6 Gyr ago, i.e., 1.6 Gyr after the formation of the main galaxy disk. We found that the galaxy has a FUV − NUV color equal to 1.83, and a NUV − r = 4.5, placing it in the GV.

The global properties of this galaxy, i.e., its SED, morphology and B-band absolute magnitude, match well with a galaxy encounter between two equal halos with total mass 8×10$^{11}$M$_\odot$, semi major axis of 597.2 kpc and perpendicular spins. The initial conditions of the encounter correspond to a distance of their mass centers of 889 kpc and a velocity difference of 17 km s$^{-1}$. The galaxy is a gas-rich ETG since Kannappan et al. (2001), which discovered its gas/star CR, reported a mass of cold gas (HI) of 2.1×10$^9$M$_\odot$. In the GALEX UV image it is visible a patchy FUV inner ring.

The global properties of this galaxy match well with a galaxy encounter between two equal halos with total mass 4×10$^{12}$M$_\odot$, semi major axis 1 Mpc and parallel spins. The initial conditions of the encounter correspond to a distance of their mass centers of 889 kpc and to a relative velocity of 62 km s$^{-1}$.

From this simulation we derive that the age of the galaxy is 13.8 Gyr, and its B-band absolute magnitude -20.1 mag, to be compared with the value of -19.72±0.41 mag from HyperLeda catalog. The predicted SED is compared with observations in Fig. 1. The galaxy has a blue GALEX UV color, FUV-NUV = 0.57, and a blue UV-optical color, NUV-r = 3.73, placing also this ETG in the GV.

Fig. 2 compares both the UV composite GALEX image and the r-band SDSS one with our simulated maps. These are on the same bands and spatial scale as the observed ones. The spatial resolution of the simulated maps is 5", the same as the GALEX image (right bottom panel). The mass of cold gas, i.e., that of the gas with temperature lower than 20000 K, is 3.5×10$^8$M$_\odot$ inside the same region. This value is within a factor of two from the total gas value, (HI+H$_2$), by Corsini & Bertola (1998) and Bettoni et al. (2001). Therefore, the simulation selected is strongly constrained by the data since its best-fitting snapshot concurrently well matches the total B-band absolute magnitude, SED, morphology, cold gas amount of the galaxy and agrees with independent estimates of the average age of its stellar populations and stellar mass. Following its prediction, this galaxy stays on the blue cloud 5.7 Gyr ago.

3.2 NGC 5173

This E0 galaxy is likely paired with the SB(rs)b galaxy NGC 5169, separated by 5.5 arcmin in projection, and by a velocity difference of 17 km s$^{-1}$. The galaxy is a gas-rich ETG since Kannappan et al. (2001), which discovered its gas/star CR, reported a mass of cold gas (HI) of 2.1×10$^9$M$_\odot$. In the GALEX UV image it is visible a patchy FUV inner ring.

The stellar mass predicted inside D$_{25}$ is 1.2×10$^8$M$_\odot$. This is in good agreement with the estimate by Corsini & Bertola (1998). The average stellar population age, weighted by luminosity, ranges from 1.3 to 2.4 Gyr within $r_{eff}$ accounting for B or V-band luminosities, respectively, in agreement with the estimate made by Coccato et al. (2013). The average stellar population age within D$_{25}$ is 7 Gyr; it becomes younger, 4.4 and 5.3 Gyr, weighted by B or V-band luminosities, respectively. The mass of cold gas, i.e., the gas with temperature lower than 20000 K, is...
Fig. 3  Rest-frame $NUV - r$ versus $M_r$ CDM of the simulations which best fit of the global properties of NGC 3593 (long-dashed line) and NGC 5173 (dotted line). The red filled squares correspond to the current colors of these ETGs, both in the GV, well matched by the simulations stopped at 14 Gyr. The evolutionary path of both galaxies shows the transition from the blue toward the red sequence through the GV. Numbers are the ages in Gyr along the evolutionary traces, starting from bottom right. The red sequence (magenta) and the blue cloud (cyan) are plotted following prescriptions in Wyder et al. (2007).
4 Conclusions

We have assembled a sample of 75 CR-ETGs and studied their UV properties from GALEX archive. We found that about 50% of them show strong FUV emission. This is a percentage significantly larger than that found for a general sample of ETGs (30%, see e.g. Schawinski et al. 2007). On this basis we are performing a detailed analysis of the properties of the whole sample making use of SPH simulations with chemo-photometric implementation which give us insight into their evolution. The galaxies studied here, NGC 3593 and NGC 5173, are both ETGs. They show rather blue colors in the rest-frame $NUV - r$ versus $r$-band absolute magnitude CMD, placing them in the GV instead of on the red sequence as expected for the majority of ETGs (e.g. Mazzei et al. 2014a,b). Both galaxies are gas rich and NGC 5173 shows a patchy structure in the UV GALEX bands. Our chemo-photometric SPH simulations allow us to trace the evolutionary path of these galaxies in a fully consistent way. Their global properties, i.e., their $B$-band total absolute magnitudes, SEDs, morphologies and mass of cold gas, match well with simulations that correspond to a galaxy encounter between two equal mass halos. Their initial total masses are $8 \times 10^{11} M_\odot$ and 5 times more for NGC 3593 and NGC 1573, respectively. Their current ages are 13.1 and 13.8 Gyr, respectively. Their evolution in the rest-frame $NUV - r$ versus $r$-band absolute magnitude CMD is marked by several rejuvenation episodes, which place them, at their current age, outside the red sequence, where normal ETGs stay. Their position in the GV emphasises a quite different evolutionary path of these galaxies, as traced by our simulations. These simulations point out their origin in a galaxy encounter rather than a merger, as in the majority of ETGs analyzed with the same approach (Mazzei et al. 2014a,b). We plan to match the global properties of the whole sample of CR galaxies here presented. Our simulations with chemo-photometric implementation, will allow us to give further insight into the evolution of ETGs, in particular of those with CR. We will aim at answering to the question concerning the mechanism of their formation and the origin of CR by comparing the properties of CR galaxies in our sample with those of galaxies without CR.

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