Highlights on Spanish Astrophysics X, Proceedings of the XIII Scientific Meeting of the Spanish Astronomical Society held on July 16 – 20, 2018, in Salamanca, Spain. B. Montesinos, A. Asensio Ramos, F. Buitrago, R. Schödel, E. Villaver, S. Pérez-Hoyos, I. Ordóñez-Etxeberria (eds.), 2019

Ultra-Diffuse Galaxies: a formation scenario.

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Abstract

A large number of Ultra-Diffuse Galaxies (UDGs) has been detected over the past few years, both in clusters and in isolation. UDGs have stellar masses typical of dwarf galaxies but effective radii of Milky Way-sized objects, and their origin remains puzzling. Using hydrodynamical zoom-in simulations from the NIHAO project we show that UDGs form naturally in dwarf-mass haloes, as a result of episodic gas outflows associated with star formation. The simulated UDGs live in isolated haloes of masses $10^{10-11}\mathrm{M}_\odot$, have stellar masses of $10^{7-8.5}\mathrm{M}_\odot$, effective radii larger than 1 kpc and dark matter cores. Remarkably, they have a non-negligible HI gas mass of $10^{7-9}\mathrm{M}_\odot$, which correlates with the extent of the galaxy. Gas availability is crucial to the internal processes that form UDGs: feedback driven gas outflows, and subsequent dark matter and stellar expansion, are the key to reproduce faint, yet unusually extended, galaxies. This scenario implies that UDGs represent a dwarf population of low surface brightness galaxies and that they should exist in the field. Several predictions and comparisons with stat-of-the-art observational data will be presented. Amongst other, we will show that the largest isolated UDGs sistematically contain more HI gas than less extended dwarfs of similar $\mathrm{M}^\star$, corroborating our proposed formation scenario.

1 Introduction

Recently, a substantial number of faint - yet extended - galaxies have been discovered in deep imaging surveys of several clusters of galaxies, including Coma [20, 9], Virgo [11], Fornax and eight low redshift clusters [19], as well as in the field and groups [18, 10]. These objects have the stellar mass and magnitudes typical of dwarf galaxies ($\mathrm{M}^\star \sim 10^{7-8.5}\mathrm{M}_\odot$) but the extent of Milky Way-like spirals. A small number of stars and a large effective radius of r_e>1 kpc implies that these objects have a very low surface brightness, between 24 and

28 mag/arcsec^2: they have been named Ultra-Diffuse Galaxies (UDGs). UDGs differ from regular low surface brightness galaxies (LSBs) mostly in color, being redder than LSBs, and in the stellar content which is typical of dwarf galaxies, unlike LSBs that also include large spiral galaxies. More recently, however, it appeared clear that blue UDGs exist in the field. UDGs could either be giant Milky Way galaxies that stopped forming stars ('failed L*' galaxies) or genuine dwarf galaxies with an unusually extended size. Understanding the properties and formation of UDGs is challenging: a key question is whether such diffuse galaxies can arise within the current ΛCDM model of galaxy formation. An appealing possibility is that the formation of UDGs is not connected to the cluster environment, but rather to internal processes. Simulation work extensively showed that feedback driven gas outflows are able to cause expansion not only of the central DM distribution in galaxies, but also of the stellar one [8, 7]: the mass range where we expect maximum efficiency in core formation overlaps nicely with that of UDGs, i.e. galaxies with $M^\star \sim 10^{7-9} M_\odot$ should form large DM and stellar cores, while at higher and lower masses energy from stellar feedback alone becomes less efficient at creating cores [5, 17]. We explore feedback driven expansion as viable mechanism for the formation of UDGs, by using numerical simulations from the NIHAO project. We refer the interested reader to the main manuscript in which a detail analysis is presented [6].

2 Hydrodynamical simulations

The simulated galaxies are taken from the Numerical Investigation of a Hundred Astrophysical Objects (NIHAO) project [22], evolved using the SPH code Gasoline [21]. Star formation and feedback follows the model used in the MaGICC simulations, that for the first time reproduced several galaxy scaling relations over a wide mass range, adopting a threshold for star formation of $n_{\rm th}$>10.3cm^{-3} [3]. Stars feed energy back into the ISM via blast-wave supernova feedback and early stellar feedback from massive stars [16]. Particle masses and force softenings are chosen to resolve the mass profile to below 1% of the virial radius at all masses, ensuring that galaxy half-light radii are well resolved. The NIHAO galaxies cover a broad mass range, from dwarfs to Milky Way mass. The galaxies are all centrals and isolated, and lie on abundance matching predictions, having the expected $M^\star$ for each $M_{\rm halo}$. Within the NIHAO simulations, we identified those galaxies that match the UDG definition, by following the criteria: i) their 2D effective radius, r_e, is larger than 1 kpc, ii) their absolute magnitude in R band is $-16.5 \lesssim M_{\rm R} \lesssim -12$, corresponding to a stellar mass of $10^7 \lesssim M^\star/M_\odot \lesssim 10^{8.5}$, iii) their effective surface brightness is low, with μ_e>23.5 mag/arcsec^2. We found a total of 21 simulated galaxies that meet these requirements. We then explore how these UDG-like objects arise in our simulations.

3 UDG formation scenario

In the left panel of Fig. 1 we summarize the properties of simulated UDGs: from top to bottom we specify stellar mass, halo mass, HI gas mass ($M_{\rm HI}$), 2D effective radius, effective surface brightness, R-band absolute magnitude, B-R color, Sérsic index, DM halo inner slope, spin parameter and concentration. Specifically, the Sérsic index n_{Sersic} is computed by fitting the 2D surface brightness profile in R-band out to $2\times r_e$ with a Sérsic profile, the inner slope γ of the DM halo is found by fitting its density profile with a power law between 1 and 2% of the virial radius, in a region where all our galaxies are well resolved. All the currently observed structural properties of UDGs (M_{HI}, $M^{\star}$, n_{Sersic}, color, M_R, r_e and μ_e) are in excellent agreement with the ones of the simulated sample. The mean value of the spin parameter is close to the peak of the distribution of spin parameters for DM haloes (log($\lambda \sim$-1.45), indicating that our simulated UDGs do not live in particularly high-spin objects as suggested by [1]. The range of DM inner slopes, -0.78<γ<-0.01, shows that UDGs live in expanded DM haloes, whose logarithmic inner slope is shallower than the universal NFW value of γ=-1. This is closely linked to the formation of UDGs. Indeed, the formation of DM density cores is related to rapid oscillations of the central potential driven by gas outflows following bursty star formation [12]: this purely gravitational mechanism affects as well the stellar distribution [7, 4]. In the right panel of Fig. 1 we show the evolution of the 3D stellar density as a function of redshift for all stars (solid lines) and old stars (tform<5 Gyrs, dashed lines). As the DM halo expands and forms a central core due to episodic and powerful gas outflows driven by star formation, the stellar distribution expands as well: r_e increases and μ_e decreases bringing the dwarf onto the UDG regime. We confirm that r_e increases due to expansion of the stellar distribution, by separating the contribution of all stars and old stars: we observe that even the oldest stellar population expands as a response to core creation.

X	$\overline{X} \pm \sigma$	$X_{min,max}$
log($M^{\star}$[$M_{\odot}$])	7.66±0.42	6.83 , 8.40
log(M_{halo}[$M_{\odot}$])	10.53±0.18	10.22 , 10.85
r_e[kpc]	1.87±0.53	1.07 , 3.06
μ_e[mag/arcsec^2]	25.23±0.94	23.69 , 26.84
M_R	-14.61±1.07	-16.25 , -12.57
B-R	0.77±0.12	0.54 , 0.97
n_{Sersic}	0.83±0.27	0.31 , 1.46
γ(1-2%R_{vir})	0.37±0.18	0.01 , 0.78
log(λ)	-1.48±0.25	-2.04 , -1.17

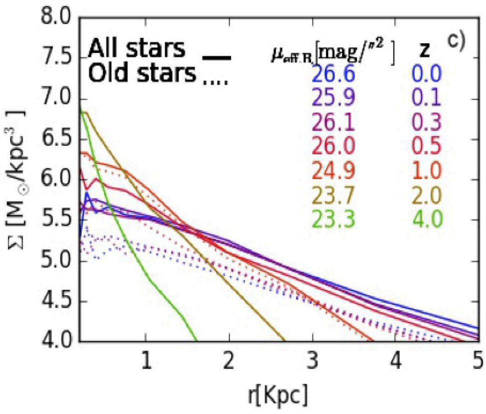

Figure 1: Left panel: Average properties of simulated UDG sample. Concentrations and spin parameters were computed in the original DM-only run. Right panel: formation of UDGs, the contribution of all stars and old stars formed within the first 5 Gyrs of the galaxy's life is indicated as solid and dashed line, respectively, with the μ_e evolution also shown.

4 Observational prediction

In Fig. 2 we show the SFH of galaxies whose effective radii are the largest (right column) and smallest (left column) in their respective mass bin. From top to bottom, we pair galaxies with

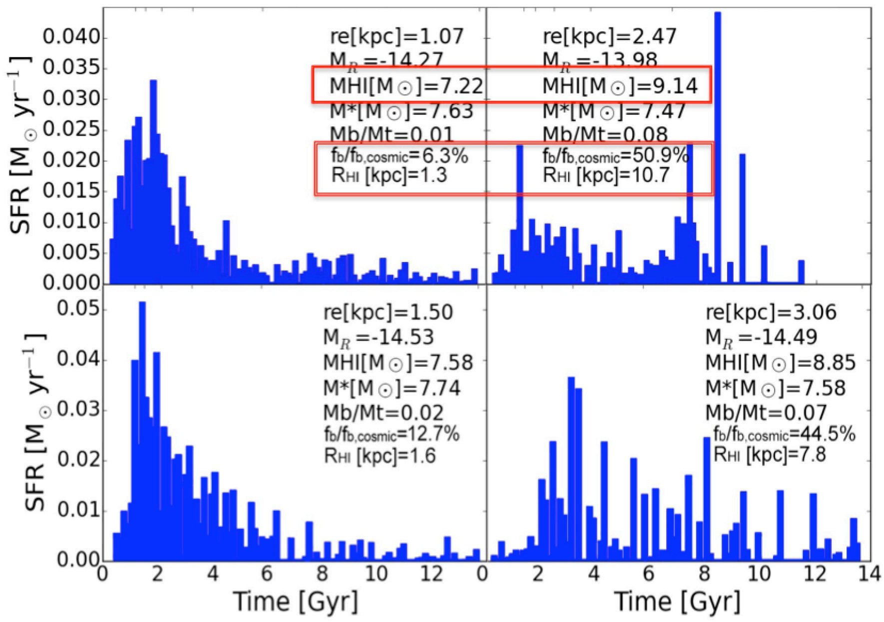

Figure 2: SFHs of galaxies with the largest (right column) and smallest (left column) effective radius in their mass bin. From top to bottom, each row shows galaxies with similar halo mass and magnitude, $\log_{10}(\mathrm{M_{halo}}/\mathrm{M_\odot})$∼10.45,10.50 and M_R∼-14.0,-14.5. In each panel r_e, M_R, $\mathrm{M_{HI}}$, $\mathrm{M}^\star$, f_b and HI radius are indicated. The largest isolated UDGs contain more HI gas, have a larger baryon fraction and a more extended and bursty SFH than less extended dwarfs of similar $\mathrm{M}^\star$.

similar halo and stellar masses, quoting in each panel the r_e, M_R, $\mathrm{M_{HI}}$, $\mathrm{M}^\star$, HI radius (the radius at which the HI surface density reaches 1 $\mathrm{M/pc^2}$) and baryon fraction relative to the cosmic one, f_b . The difference in properties between the most extreme UDGs (right panels) and the less extreme, more compact dwarfs (left panels) are striking: galaxies with large r_e also have a larger $\mathrm{M_{HI}}$, baryon fraction and HI radius, and more prolonged and persistently bursty SFH, including a larger fraction of young stellar population, compared to galaxies with a smaller r_e. This is because when most of star formation happens in the first 3-4 Gyrs, feedback can eject significant amounts of gas from relatively shallow potential wells at early times, resulting in low baryon fractions by z=0. Since gas is expelled at early stages, there is less gas for ongoing star formation and crucially there is less gas to be expelled from the inner regions when star formation occurs, being this the key aspect of the mechanism for core creation. Conversely, galaxies with star bursts occurring after the rapid halo growth phase has finished are the ones that can keep their gas, which can not escape the deeper potential well: they have enough gas available at all time to drive DM cores and a spatially extended stellar distribution, retaining about 50%f_b and up to $10^9\mathrm{M_\odot}$ in HI gas by z=0. This prediction has been recently confirmed. Using the ALFALFA survey, ∼ 115 isolated HI sources bearing UDGs have been identified: they are bluer than in clusters, supporting the scenario in which UDGs form in isolation and then accrete into clusters, and, most importantly, they all have large HI radii and are HI-rich relative to their stellar masses [10].

5 Conclusions

State-of-the-art cosmological simulations of isolated galaxies from the NIHAO project, which include feedback from SNe and massive stars, reproduce a population of Ultra-Diffuse Galaxies (UDGs): feedback driven gas outflows give rise to a spatially extended stellar component, while simultaneously expanding the dark matter halo, leading to the emergence of low surface brightness dwarf galaxies, or UDGs. Our findings imply that UDGs: i) are dwarf galaxies, with $M_{\rm halo}{\sim}10^{10-11}M_{\odot}$, in agreement with recent estimates in clusters and field [2, 15], ii) are expected to be found in the field, where they should be extremely gas rich, with HI gas mass $\sim10^{7-9}M_{\odot}$, as later on demonstrated using the HI ALFALFA survey [10] iii) have typical distributions of halo spin and concentration, an average Sérsic index of less than one and dark-matter cores, and iv) the largest UDGs should retain the highest baryon fraction, largest amount and extent of HI gas, and, interestingly, they should have an high fraction of young stars. The latter point has recently been demonstrated to be valid for Local Group dwarfs [13], such that galaxies that stopped forming stars over 6 Gyrs ago favour high central densities (and small, <1kpc, r_e), while those with more extended star formation favour dark matter cores and larger, >1 kpc, r_e. Nevertheless, the field of deriving reliable SFHs for UDGs is still in its initial stage. Significant progress has been recently made, using deep optical spectroscopic data from the OSIRIS instrument, in characterising the stellar component of a sample of UDGs [14]: the recovered SFHs are compatible with both bursty star forming episodes declining with time as well as with a more gradual decrease in the SFH, making impossible, at the present stage, to further validate our prediction. In the future, better data and sophisticated analysis will be necessary to verify the correlation between sizes and extent of HI gas, SFHs and retained baryon fraction, further supporting our proposed formation scenario.

Acknowledgments

ADC acknowledges financial support from a Marie-Skłodowska-Curie Individual Fellowship grant, H2020-MSCA-IF-2016, Grant agreement 748213 DIGESTIVO. Computational resources were provided by the High Performance Computing at NYUAD, the THEO cluster at MPIA and the HYDRA clusters at Rechenzentrum in Garching.

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