Dwarf Galaxies: From the Deep Universe to the Present
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Diffuse post-starburst galaxies: a smoking gun of formation of ultra-diffuse galaxies via ram pressure stripping

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Abstract. Ultra-diffuse galaxies (UDGs) have sizes comparable to the Milky Way and stellar masses of about 1/1000 of it. They attracted a lot of attention as possible "dark galaxies" heavily dominated by dark matter, however, no reliable dynamical mass estimates were done because of their extremely low surface brightness. We have recently found 13 gas free diffuse young (300–500 Myr) post-starburst galaxies (PSGs) without ongoing star formation in Coma and Abell 2147, which, should they continue to evolve passively, will become UDGs in 5 Gyr. We obtained deep spectroscopic observations for 11 diffuse PSGs and derived their internal kinematics and stellar population properties. All of them possess disk-like kinematics (substantial rotation, low stellar velocity dispersion) and likely experienced starburst episodes prior to the star formation quenching by ram pressure stripping. Our results suggest that at least some UDGs were "normal" intermediate to large-sized disk galaxies in the past, which were later quenched by dense environment.

Keywords. galaxies: dwarf, galaxies: evolution

1. Introduction

Ultra-diffuse galaxies (UDG; van Dokkum *et al.* 2015a) were identified from deep ground-based observations performed with the Dragonfly telescope array as extended ($r_e > 1.5$ kpc) low surface brightness ($\mu_{0,g} > 24$ mag arcsec^{-2}) galaxies populating the Coma cluster. With the sizes comparable or sometimes exceeding the Milky Way size, these galaxies have stellar masses of 0.1%−1% that of the Galaxy. The initial sample of 47 Coma UDGs grew to 854 (Koda *et al.* 2015; Yagi *et al.* 2016) found in deep Subaru Suprime-Cam images, 271 of which turned to be larger than the Milky Way.

Low surface brightness in UDGs prevent their efficient studies using ground based spectroscopy. Only a few UDGs have spectroscopic measurements of their radial velocities confirming their Coma cluster membership (van Dokkum *et al.* 2015b; Kadowaki *et al.* 2017), and only two integrated stellar velocity dispersion measurements have been carried out so far. UDGs are hypothesized to be heavily (98%-99%; van Dokkum *et al.* 2015a, Koda *et al.* 2015) dark matter dominated and sometimes even called "dark galaxies". The formation mechanisms for UDGs remain purely speculative because no observational

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data can confirm/refute any particular scenario, e.g. slow star formation in a shallow primordial dark matter potential well quenched by environment, interstellar medium (ISM) stripping from disky progenitors by SN feedback and/or ram pressure, star formation quenching by tidal stirring in a cluster, etc. (van Dokkum *et al.* 2016; Zaritsky 2017; Yozin & Bekki 2015; Di Cintio *et al.* 2017).

2. Diffuse Post-Starburst Galaxies

The only "easy" option to study origin and evolution of UDGs is to find them in the early stage of evolution when their stars are still young and, therefore, the surface brightness is comparable to that in normal galaxies.

We have identified a sample of 13 very unusual extended diffuse post-starburst (PSG) galaxies in the Sloan Digital Sky Survey DR7 (Abazajian *et al.* 2009) using our stellar population analysis presented in the Reference Catalog of Spectral Energy Distributions (RCSED, Chilingarian *et al.* 2017). This sample includes all galaxies in the SDSS primary sample with Hα emission not exceeding the 10σ detection in order to exclude star forming objects, simple stellar population ages younger than 2 Gyr and the k-corrected color $g - r < 0.55$ mag. 10 of 13 galaxies turned to be Coma cluster members, two others are hosted by the double galaxy cluster Abell 2147, and one is in the compact galaxy group SDSSCGA 01018.

We retrieved archival optical images from the Canada-France-Hawaiian Telescope and Subaru for 12 cluster galaxies and near-infrared Spitzer Space Telescope images at 3.6, 4.5, 5.8, and 8μm for 10 Coma galaxies. All of them have effective radii between 1.8 and 4.0 kpc and quite regular morphologies, mean stellar ages between 300 and 750 Myr and central surface brightness levels about μ_0, g=20.5–22.0 mag arcsec$^-$2. If these objects continue to evolve passively, in 5–7 Gyr they will all end up as UDGs because their surface brightness will decrease by 2–4 mag/arcsec$^-$2. Three galaxies in Coma exhibit prominent straight tails up-to 250 kpc long (see Fig.1) supposedly formed by material stripped by the ram pressure. We analyzed SDSS spectra and multi-wavelength SEDs using the NBursts+phot spectrophotometric fitting technique (Chilingarian & Katkov 2012). Our result show that none of the galaxies is consistent with simple stellar populations and requires at least two starburst to adequately describe observational data.

3. Spectroscopic Observations and Data Analysis

We observed one galaxy in June/2017 using the GMOS-N spectrograph at the 8-m Gemini-North telescope in the long-slit mode with intermediate spectral resolution (0.75" slit; $R = 2500$; $3800 < \lambda < 5400$ Å; exposure time of 3.2h) along the galaxy major axis. Then we collected data for 10 PSGs in the Coma and Abell 2147 clusters using the new multi-object spectrograph Binospec at the 6.5-m converted MMT telescope. We used multi-object slit masks and oriented slitlets along major axes. The MMT data have higher spectral resolution despite a wider slit used (1.0" slitlets; $R = 4200$; exposure times from 2.0 to 2.33h per each of 4 MOS masks). All data were reduced using custom data reduction pipelines specifically optimized for low surface brightness targets.

We analyzed long-slit spectra using the NBursts full spectrum fitting technique (Chilingarian *et al.* 2007ab) applying adaptive binning along the slit in order to reach a minimal signal-to-noise ratio of 10 per spectral pixel per bin. We were able to measure internal kinematics out to 1.5–2 half-light radii. Preliminary results of the data analysis for three Coma cluster galaxies are shown in Fig. 2.

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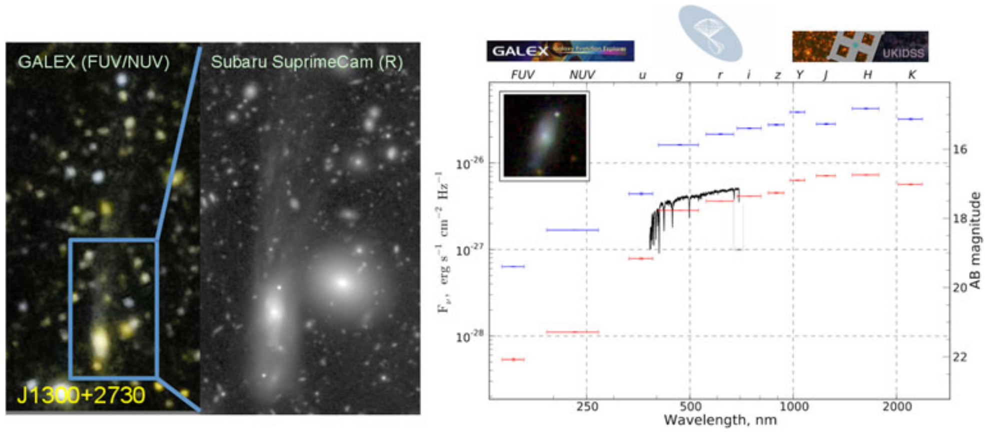

Figure 1. One of the Coma cluster PSGs with a prominent tail of material formed by ram pressure stripping (two left panels). A spectrum lacking emission lines and low ultraviolet luminosity of the galaxy suggest that the star formation is still going on in the tail while the galaxy itself is completely quiescent.

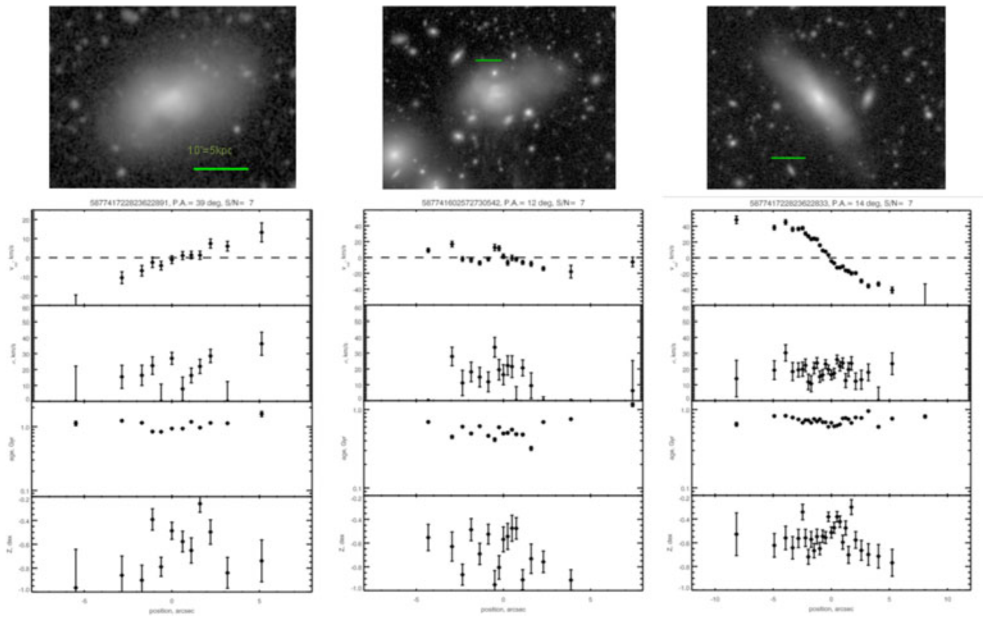

Figure 2. Stellar kinematics and parameters of stellar populations (SSP-equivalent ages and metallicities) of three diffuse PSGs in the Coma cluster derived from the analysis of Binospec data. The top panels display Subaru Suprimecam R-band stamp images of galaxies and a scale-bar corresponding to 5 kpc. The image scale is 0.5 kpc/arcsec at the distance of Coma cluster.

4. Results and Discussion

Our data show that 9 of 11 galaxies show regular rotation and low stellar velocity dispersions. They also exhibit young stellar SSP ages and intermediate metallicities. 5 galaxies show complex multi-component kinematics, the central region appears to be rotating more rapidly than the outer parts where the rotation curves flatten. 4 galaxies exhibit clear signs of recent ram pressure stripping: straight tails with a comet-like

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morphology; in the youngest object we even detect asymmetric stellar ages across the disk. The observed kinematics is consistent with moderate amounts of dark matter (50–80%) if we assume stellar mass-to-light ratios that correspond to SSP models. Real stellar M/L ratios are likely much higher, hence, suggesting even lower dark matter contents within 2 half-light radii.

What can we tell about formation scenarios of diffuse PSGs looking at our results? If a "normal" disk (size of Messier33 or smaller) in a sparse dark matter halo slowly forming stars enters the dense region of the Coma cluster, the ram pressure will first induce a burst of star formation then becomes too high finally stripping the disk, which can still contain substantial gas mass. Then the gravitational potential lowers, stellar disk starts to expand and oscillate, surface brightness declines, stellar orbital anisotropy parameter $\beta = 1 - \sigma_Z^2/\sigma_R^2$ increases because σ_R goes up while σ_z stays the same. We observe all these phenomena in our PSGs.

The future evolution of diffuse PSGs is relatively easy to predict. Because they have no gas left and no ongoing star formation, and the amount of underlying old stellar population derived from deep Spitzer IRAC photometry is very low, they will age and drop the V-band surface brightness by a factor of 20-50 in about 5 Gyr. Then they will become legit UDGs explaining the UDG formation without involving exotic scenarios (e.g. "failed galaxies", "dark galaxies" etc.) The only concern regarding this particular scenario is their location in dense cluster environment. Some of them might not survive long enough to become UDG and be destroyed by tidal interactions with massive cluster members.

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