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A SIMULATION VIEW ON THE FORMATION OF ULTRA-DIFFUSE GALAXIES IN THE FIELD AND IN GALAXY GROUPS

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Abstract. Ultra-diffuse galaxies (UDGs) with dwarf stellar masses and Milky Way sizes appear to be ubiquitous in groups and clusters and are also observed in the field. We study such galaxies in cosmological zoom-in simulations, aiming at understanding their formation both in groups and in the field. We find that while field UDGs arise from dwarfs in a specific mass range from successive episodes of supernova feedback, group UDGs can also form by tidal puffing up and become quiescent by ram-pressure stripping. The host haloes of both field and group UDGs have typical spin but significant cores. Field UDGs tend to be dark-matter dominated towards their center and to be more prolate than dwarf galaxies of similar mass. In groups, satellite dwarfs can become UDGs after pericenter passage by tidal heating and simultaneously lose most of their gas by ram-pressure stripping, suppressing star formation and inducing a color gradient in agreement with observations.

Keywords: galaxies:evolution, galaxies:formation, galaxies:haloes

1 Introduction

Ultra-diffuse galaxies (UDGs) are low-surface brightness systems ($\mu_{0,\mathrm{g-band}} > 24$ mag arcsec^{-2}) with surprisingly large effective radii ($r_{1/2} > 1.5$kpc) (van Dokkum et al. 2015). They have stellar masses similar to those of dwarf galaxies and their surface density profiles show similar Sérsic indices to those of disk galaxies (e.g., Mowla et al. 2017). UDGs are ubiquitous in clusters and groups (e.g., Koda et al. 2015), where they exhibit intermediate-to-old stellar populations (e.g., Ferré-Mateu et al. 2018). UDGs are also common in the field (e.g., Martínez-Delgado et al. 2016; Román & Trujillo 2017; Leisman et al. 2017), where they are modestly rich in cold gas and forming stars. A leading scenario is that they form in the field as blue UDGs, and, when accreted by a group/cluster, get environmentally processed to become quiescent red UDGs. Our work explores UDG formation in the field and in a galaxy group using cosmological simulations (Wang et al. 2015; Dutton et al. 2015) and simple analytical modeling. We pay special attention to whether UDGs are special compared to the other dwarfs and also to Milky-Way-mass galaxies.

2 UDGs in the field – Are they special?

Fig. 1 contrasts the UDGs with the control samples regarding the distribution function of a collection of properties. We can see that the host haloes of UDGs lie in a narrow mass range of $M_{\mathrm{vir}} = 10^{10-11.2}M_{\odot}$, clearly lower than the $L^{\star}$ regime. The UDGs do not particularly occupy the high halo-spin tail – in fact, the spin parameters (Bullock et al. 2001) are distributed similarly to the other galaxies, with a median of $\langle\lambda_{\mathrm{halo}}\rangle = 0.043$. While the spin-parameter distribution of the UDGs is not special, the NFW concentrations (Navarro et al. 1997) are on average lower than those of both the low-mass sample and the $L^{\star}$ galaxies. With a median of $\langle c_{\mathrm{NFW}}\rangle = 7.3$, the concentration of UDG haloes is significantly lower than what is expected for haloes of the same mass ($M_{\mathrm{vir}} = 10^{10-11.2}M_{\odot}$) in N-body simulations, which have $\langle c_{\mathrm{NFW}}\rangle \simeq 10.5 - 13.3$ according to the concentration-mass relation of Dutton & Macciò (2014). Related, the Einasto (1965) shape parameters, α_{Ein}, of the UDGs are on the higher end, with a median of $\langle\alpha_{\mathrm{Ein}}\rangle = 0.32$. The shape parameter describes

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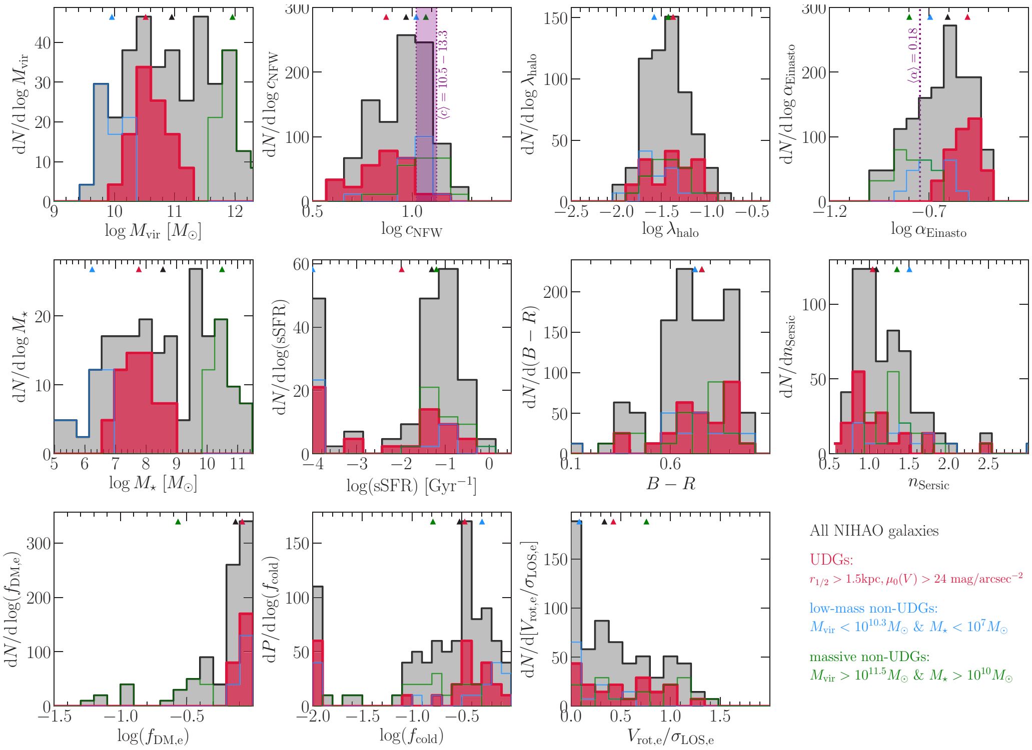

Fig. 1. Properties of field UDGs in the NIHAO simulations.

the curvature of the logarithmic density profile, with haloes that obey NFW profiles having $\alpha_{\rm Ein} \simeq 0.18$. A higher $\alpha_{\rm Ein}$ manifests a sharper transition between the inner and outer logarithmic density slopes than that of a NFW profile (e.g., Ludlow et al. 2013). The peculiarity of $c_{\rm NFW}$ and $\alpha_{\rm Ein}$ of the UDGs implies that their host haloes have responded dramatically to baryonic processes, and have dark-matter density profiles significantly different from the NFW form. Di Cintio et al. (2017) showed that the formation of the field UDGs are associated with bursty star formation histories, which result in episodic SNe outflows. The SNe outflows are believed to be responsible for the cusp-to-core transformation of dark-matter profiles (e.g., Pontzen & Governato 2012). Indeed we found that UDGs exhibit a prominent dark matter core, with logarithmic density slope $\alpha = -{\rm d}\log\rho/{\rm d}\log r$ evaluated at $r = 0.01R_{\rm v}$, $\alpha_{0.01}$, in a narrow range of $0 - 0.5$. Despite having dark-matter cores, the UDGs are among the most dark matter dominated systems: their dark-matter mass fractions within the effective radius ($f_{\rm dm,e}$) are typically over 80 per cent.

The UDGs have a median Sérsic index of $\simeq 1$, showing a mode of the $n_{\rm Sersic}$ distribution at $\simeq 0.8$, lower than that of the non-UDGs. The low Sérsic indices do not mean that UDGs are flattened, rotation-supported systems. In fact, the UDGs are not fast rotators, with the ratios of rotation speed to the radial velocity dispersion (v/σ) at $r_{1/2}$ similar to those of the full sample. We find that UDGs are mostly *not* oblate in shape. Instead, the UDGs are significantly more prolate than the $L^\star$ galaxies, and marginally more prolate than dwarf galaxies of similar and smaller masses.

The UDGs show a wide range of sSFR and colour. While the $L^\star$ analogues are mostly star-forming, with sSFR$> 0.01{\rm Gyr}^{-1}$, the UDGs seem to show a bimodality in sSFR, and are overall slightly redder. About 30 per cent of the field UDGs are not forming stars instantaneously at $z = 0$. The star-forming UDGs have modestly high cold gas fractions, with $f_{\rm cold} \equiv M_{\rm cold}/(M_\star + M_{\rm cold}) >\approx 0.4$, which is consistent with those of a few observed field UDGs (Papastergis et al. 2017).

3 Satellite UDGs – tidally puffed up or relics of field UDGs?

Since UDGs are observed both in the field and in clusters and groups, an intuitive scenario for the formation of satellite UDGs is that they were already puffed up when in the field and became quenched after falling into a dense environment, as implied by several studies (e.g., Román & Trujillo 2017, Alabi et al. 2018, Ferré-Mateu

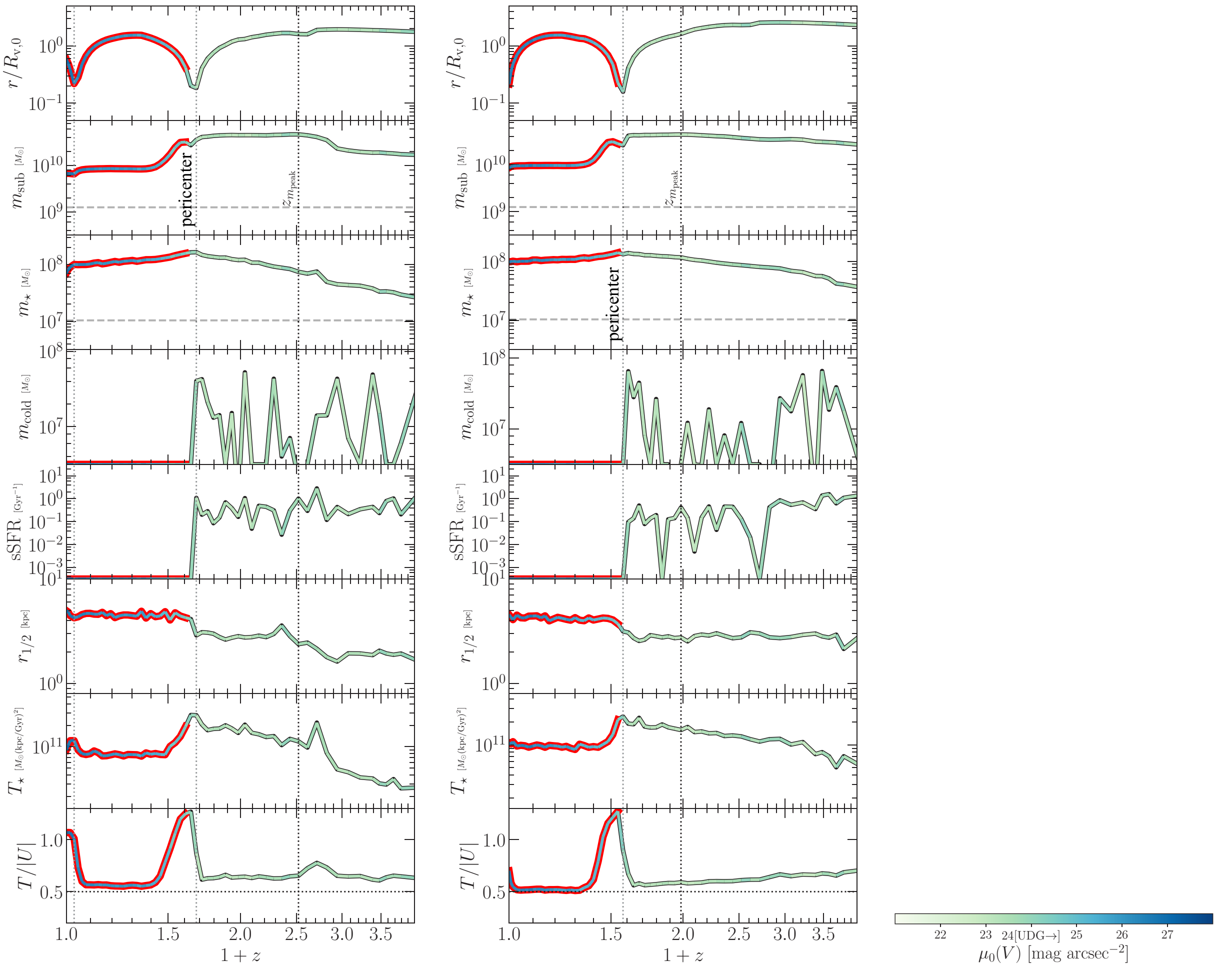

Fig. 2. Evolution of satellite galaxies that become UDGs at orbital pericentre. Two examples are presented here, showing the following quantities as functions of redshift – from the top to the bottom – group-centric distance r in units of the present-day virial radius of the host; subhalo mass (with the dashed line marking the resolution mass of $m_{\rm res} = 10^{9.1} M_{\odot}$, which corresponds to 250 dark-matter particles); stellar mass (with the dashed line marking the resolution mass of $m_{\rm res} = 10^{7} M_{\odot}$, which corresponds to $\sim$ 100 star particles); the mass of cold gas ($< 1.5 \times 10^4 K$); the specific star-formation rate (sSFR); the half stellar-mass radius $r_{1/2}$; the kinetic energy in stars $T_{\star}$; the ratio of the total kinetic energy to the binding energy $T/|U|$ (with the horizontal dotted line marking the virial-equilibrium value of 0.5). The facecolour of the lines reflects the V-band central surface brightness, as indicated by the colour bar. The UDG-phases are highlighted with red edges. The thicker vertical line marks the infall redshift, $z_{\rm peak}$, when $m_{\rm sub}$ reaches the maximum. The thin vertical lines indicate the orbital pericentres.

et al. 2018, and Chan et al. 2018). Recent observations seem to show evidence of the aforementioned scenario (Román & Trujillo 2017; Alabi et al. 2018). In this picture, what causes UDGs to lose their gas reservoir in the host system is either tidal stripping or ram pressure stripping.

We find a population of satellite galaxies that were not UDGs at infall but become UDGs inside the group. This amounts to 50 per cent of the surviving satellite-UDG population. Fig. 2 presents two examples, showing the evolution of a collection of quantities. The two satellites are both puffed up right after the first pericentre passage, becoming UDGs. The expansion at the pericentre is accompanied by a few other changes, including significant dark matter mass loss and a complete removal of cold gas. The change in stellar mass is small, implying that tidal stripping is marginal inside the baryonic range of the galaxy where stars and cold gas reside. Given that the cold gas is completely lost at the pericentre, ram pressure seems to be the main cause of the quenching of their star formation.

The increase in size also coincides with a spike in the kinetic energy of stars, and a deviation from virial equilibrium of the whole system, as can be seen from the ratio of kinetic energy and potential energy, $T/|U|$.

These phenomena together are indicative of *impulsive tidal heating* – a process describing what happens when the duration of the encounter of the system of interest (i.e., the satellite) and the perturber (i.e., the centre of the host system) is shorter than the crossing time of the constituent particles within the system of interest. During an impulsive encounter, the particles will be given a kinetic energy ΔT while retaining their potential energy instantaneously; after the satellite relaxes to a new equilibrium state (i.e., when $T/|U|$ drops back to ~ 0.5), the kinetic energy of the particles will decrease by the amount of $2\Delta T$ (if they are not stripped away); and finally, conserving the total energy, the potential energy of the affected particles increases, resulting in a size growth. This picture is manifested exemplarily in Fig. 2 – over the period of time between the initial and the new equilibrium states, the kinetic energy of the stars first rises, and then drops to a value that is lower than that before the pericentre encounter, accompanied by the increase in $r_{1/2}$. Therefore, new UDGs can be created out of normal dwarf satellites through tidal heating in a dense environment.

There are also satellite galaxies that were already UDGs at infall. Some of them survive the group environment and continue to exist at $z = 0$; others have been disrupted or merged into the central galaxy. We find in our group simulation that among the galaxies that entered the host halo as UDGs, about 20 per cent survive (as UDGs) till $z = 0$. About 20 per cent manage to coalesce with the central galaxy, while about 60 percent are disrupted before they penetrate to the inner $0.15R_{\rm v}$ radius. Along the way to their current positions, the surviving UDGs are somewhat puffed up further by tides and become quiescent due to ram-pressure stripping.

4 Conclusions

We have shown that the field UDGs that lie in a characteristic narrow halo mass range, $M_{\rm vir} = 10^{10.5\pm0.6} M_{\odot}$, tend to be triaxial and prolate, far from rotating, exponential discs, but their Sérsic indices are near unity. Their dark-matter density profile exhibits a flat density core dominating the regime within the stellar effective radius. We find a colour/sSFR gradient of group UDGs with distance from the host-halo centre, as observed. Given the mild stellar mass evolution and the significant loss of gas mass at pericentres, we infer that it is ram pressure, rather than tides, that removes the gas from group UDGs when they are near orbital pericentres and quenches star formation. We have identified two equally important origins of group UDGs. Satellite galaxies that were already UDGs at infall can survive the dense environment. In addition, more compact field galaxies can get puffed up and become UDGs near orbital pericentres. The size expansion is accompanied by energetics indicative of impulsive tidal heating. We present analytic understanding of the aforementioned formation mechanisms in Jiang et al. (2019) and Freundlich et al. (2020).

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