TIDAL INTERACTION AS THE ORIGIN OF EARLY-TYPE DWARF GALAXIES IN GROUP ENVIRONMENTS

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ABSTRACT

We present a sample of dwarf galaxies that suffer ongoing disruption by the tidal forces of nearby massive galaxies. By analyzing structural and stellar population properties using the archival imaging and spectroscopic data from the Sloan Digital Sky Survey (SDSS), we find that they are likely a “smoking gun” example of the formation through tidal stirring of early-type dwarf galaxies (dEs) in the galaxy group environment. The inner cores of these galaxies are fairly intact and the observed light profiles are well fit by the Sérsic functions while the tidally stretched stellar halos are prominent in the outer parts. They are all located within a sky-projected distance of 50 kpc from the centers of the host galaxies and no dwarf galaxies have relative line-of-sight velocities larger than 205 km s$^{-1}$ to their hosts. We derive the Composite Stellar Population properties of these galaxies by fitting the SDSS optical spectra to a multiple-burst composite stellar population model. We find that these galaxies accumulate a significant fraction of stellar mass within the last 1 Gyr and contain a majority stellar population with an intermediate age of 2 to 4 Gyr. Based on this evidence, we argue that tidal stirring, particularly through the galaxy-galaxy interaction, might have an important role in the formation and evolution of dEs in the group environment where the influence of other gas stripping mechanism might be limited.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: stellar content – galaxies: structure

Online-only material: color figure

1. INTRODUCTION

The extreme morphology-density relations found in low-mass galaxies are considered to be the result of the effective role environment plays in the evolution of these galaxies. In particular, a class of low-mass non-star-forming galaxies, i.e., early-type dwarf galaxies (dEs), is mostly found in cluster environments, and so their origin is usually connected to the environmental effects of where they reside (Binggeli et al. 1988; Boselli & Gavazzi 2006; Lisker et al. 2007).

Although a variety of different mechanisms, such as ram pressure stripping (RPS; Gunn & Gott 1977), tidal harassment (Moore et al. 1996), and galaxy starvation ( Larson et al. 1980), have been proposed to describe how the environment may act, their relative effectiveness for producing the observed stellar population and structural properties of dEs have yet to be understood (Boselli & Gavazzi 2006; Mayer et al. 2001; Smith et al. 2010). RPS is expected to be more efficient in cluster environments and evidence of ongoing RPS in the cluster environment, explicitly in the Virgo cluster, has been frequently presented in recent literature (Kenney et al. 2004, 2014; Vollmer et al. 2001).

However, the observed diversity in the stellar population and structural properties of dEs indicates that RPS alone cannot explain their origin (Janz et al. 2014; Paudel et al. 2010). Although some features (e.g., the presence of faint spiral arms/bars or significant rotation) may be explained by an RPS scenario relating these features to a progenitor disk spiral galaxy, a significant fraction of dEs show no rotation and not all dEs possess structural features that can be linked to disk spiral galaxies (Lisker et al. 2007; Ryš et al. 2013).

On the other hand, the hierarchical framework of structural growth predicts that virtually every small galaxy in group or cluster environments is accreted from the field (White & Rees 1978). Such a process, however, does not happen smoothly and low-mass infalling galaxies can experience a strong tidal force produced by differential gravitational acceleration that first affects the dynamics of satellite galaxies orbiting the central host potential (Mayer et al. 2001; Sawala et al. 2012). Known as tidal stirring/threshing or galaxy harassment1, this process not only alters the internal kinematics and structural properties of affected galaxies, but also removes a significant fraction of both stellar and gas mass (Mastropietro et al. 2005; Moore et al. 1996).

The role of tidal forces in shaping the morphological and kinematical properties of small satellite galaxies around giant galaxies like the Milky Way has been extensively studied in recent literature. In fact, compact galaxies, such as M32, the compact early-type galaxy (cE) around M31, are considered to be the survivors of these events (Bekki 2008; Chilingarian 2009). Furthermore, state-of-art numerical simulations suggest that in both group and cluster environments, despite the influence of lethal tidal forces, a low-mass satellite can survive in the form of present-day dwarf-spheroidal (dSph) galaxies or dEs (Kazantzidis et al. 2011; Mastropietro et al. 2005; Sawala et al. 2012).

In this work, using the Sloan Digital Sky Survey (SDSS) imaging and spectroscopic database (Ahn et al. 2012; York et al. 2000), we present some of the best examples of tidal stirring where dwarf galaxies are disrupted by the tidal force of massive companion galaxies. Examples are particularly found in group environments and may provide a clue when searching for the origin of the formation and evolution of dEs in group environments through tidal interactions.

1 Generally, galaxy harassment is known for the cluster environment. In the group, tidal interaction between dwarf satellite and massive host galaxies is better known as tidal stirring (Mayer et al. 2001). Some might call it galaxy threshing (Forbes et al. 2003; Koch et al. 2012; Sasaki et al. 2007).
### 2. DATA ANALYSIS

#### 2.1. Sample Identification

Since our main objective is to search for tidal features around dwarf galaxies in the local universe \((z < 0.02)\), we carry out an extensive search for these objects in SDSS color images. By inspecting the SDSS color image cut-outs, we compile a catalog of all of the observed features, e.g., stellar tail, stream, bridge, shell, and filament, around dwarf galaxies. These features might originate from tidal interactions with nearby massive galaxies or they may be the remnant of past merger activity. A complete analysis of these features with a categorization of their possible origin will be presented in a subsequent publication. Of particular interest are the dEs\(^2\) that are located near giant galaxies and prominently display tidal features. They possess stretched outer stellar halos while the inner cores remain undisturbed; these cores are visual analogs to typical dEs. Given the availability of imaging and spectroscopic data in SDSS-III (Ahn et al. 2012), we choose to study in detail the structural and stellar population properties of six candidate galaxies.

A list of basic global properties, such as position, host galaxy name, sky-projected separation from the host, and relative line-of-sight radial velocity, is presented in Table 1. To convert the angular separation to the physical separation, we assume that the dwarf galaxies are at the same distance as their hosts, which is taken from the NED\(^3\) database. Interestingly, all of the tidally disrupted galaxies are found within a 100 kpc sky-projected distance from their hosts and no dwarf galaxies have a relative line-of-sight velocity larger than 205 km s\(^{-1}\) to their hosts.

A complete schematic view of dEs with their tidal features is shown in Figure 1. All of the dEs prominently show stretching of their outer stellar bodies while the central cores remain somewhat round. S-shape stretching is apparent among HdE1, HdE2, and HdE4, and the rest show elongated stellar streams on both sides of the central body of dwarf galaxies.

#### 2.2. Image Analysis

To perform surface photometry on the optical images, we retrieve archival images from the SDSS-III database (Ahn et al. 2012). We make extensive use of \(r\)-band images, since they provide a higher signal-to-noise ratio (S/N) than the other bands. Although the SDSS-III database provides sky-subtracted fits images that are much improved from previous releases, we again subtract the sky-backgrounds using an approach similar to that in Paudel et al. (2014).

The IRAF ellipse task has been used to extract the galaxy’s major-axis light profile. Before running the ellipse task, we manually masked all of the non-related background and foreground objects, including the host galaxies. Since all of the candidates are well separated from the hosts, we did not subtract the host galaxy light, but instead we simply mask them with a sufficiently large aperture. During the ellipse fit, the center and the position angle are held fixed and the ellipticity is allowed to vary. The centers of the galaxies are calculated using the IRAF task imcent and the position angles are determined with several iterative runs of ellipse before the final run.

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2. It is worth noting that we classify galaxies as dEs based on visual inspection of their color image and SDSS spectroscopy, which appear smooth in the sense that no star-forming clumps are present and they have no visible Balmer emission lines in the optical spectrum.

3. http://ned.ipac.caltech.edu

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Table 1

| Name | R.A. (h:m:s) | Decl. (d:m:s) | Host | \(m_r\) | \(v_1\) | D |
|------|-------------|--------------|------|--------|------|---|
| HdE1 | 00:14:37.29 | +18:34:22.67 | N0052 | 13.14(73) | ... | 18 |
| HdE2 | 00:39:15.48 | +00:56:33.67 | N0196 | 13.00(66) | 179 | 34 |
| HdE3 | 09:43:31.05 | +21:32:31.29 | N2968 | 11.47(15) | 205 | 24 |
| HdE4 | 10:22:26.03 | +21:32:31.29 | N3221 | 12.69(55) | 028 | 35 |
| HdE5 | 12:15:38.99 | +33:09:35.26 | N4203 | 11.07(16) | 024 | 37 |
| HdE6 | 22:37:12.42 | +34:37:12.64 | N7331 | 10.63(14) | ... | 49 |

Notes. For simplicity, we rename our candidate dwarf galaxies in the first column, and their positions on the sky are given in the second (R.A.) and third (Decl.) columns. The names of the host galaxies and their total luminosities (with distances from the Sun in megaparsecs) are given in the fourth and fifth columns, respectively. The sixth column represents the difference in radial velocity between dwarf and giant companions and the sky-projected separations between them are given in the last column.
The derived one-dimensional light profile along the major axis is shown in Figure 2.

Using the χ² minimization scheme, we fit the observed galaxy light profile to a Sérsic function. To avoid complexity due to the extended low surface brightness tail when modeling the galaxy light profile, we only include the inner region during the fit. This is accomplished by applying a cut-off to the surface brightness at 24.5 mag sec⁻². The results of the best-fit Sérsic parameters are presented in Table 2, and the observed and modeled one-dimensional light profiles are shown in Figure 2. We find that some cases have relatively high Sérsic indices for them to be considered dEs, these are particularly the farthest ones. We suspect that this is due to the inclusion of points from the stretched stellar body in the fitting, where a simple cut-off limit of 24.5 mag sec⁻² might not be sufficient to define the inner core of the galaxy properly.

We measure the total light in the residual images after model galaxy subtraction to assess the light fraction in the stretched tidal tail. However, we warn that the derived values are not free from large uncertainties. One obvious reason for this is that the SDSS images are not deep enough for accurate surface photometry. The Sérsic index n and Re(model) are from the best-fit Sérsic model parameters. In the last column, the light fractions of the leftover are presented after the best-fit model galaxy is subtracted from the image.

Table 2

| Name  | M_r (mag) | Re (kpc) | ⟨μ⟩ (mag arc⁻²) | n | Re(model) (kpc) | Fr (%) |
|-------|----------|----------|-----------------|---|----------------|-------|
| HdE1  | −19.10   | 0.832    | 19.22           | 3.5| 0.91           | 30    |
| HdE2  | −17.06   | 0.753    | 20.98           | 3.7| 0.66           | 45    |
| HdE3  | −16.44   | 0.793    | 21.34           | 2.9| 0.68           | 45    |
| HdE4  | −18.83   | 1.002    | 19.83           | 4.3| 1.41           | 15    |
| HdE5  | −16.03   | 0.909    | 22.32           | 1.5| 0.64           | 60    |
| HdE6  | −16.09   | 0.954    | 22.58           | 1.1| 1.12           | 40    |

Notes. The values in the Columns 2, 3, and 4 are derived from a non-parametric method. i.e., Petrosian photometry (see the text). The Sérsic index n and Re(model) are from the best-fit Sérsic model parameters. In the last column, the light fractions of the leftover are presented after the best-fit model galaxy is subtracted from the image.

The total flux is computed within an aperture of twice the Petrosian radius (Petrosian 1976). Since we use the ellipse output to derive the Petrosian radius, and hence the total flux, the derived half-light radius is the half-light semi-major axis. We then convert it to the circularized half-light radius by multiplying by a scaling factor (b/a)⁰.₅. Note that we do not attempt to correct for the missing flux outside the distance of twice the Petrosian radius as suggested by Graham & Driver (2005). We find that the measured half-light radius (Re) varies from 0.7 to 1.1 kpc. Although the statistics is small, this range agrees fairly well with the study of Janz et al. (2014). They measured the sizes of a large sample of early-type galaxies in the Virgo cluster using a similar method (see their Figure 9).

2.3. Spectroscopy

Four of our galaxies (HdE2, HdE3, HdE4, and HdE5) are targeted for spectroscopic observation in the SDSS survey. Having retrieved the optical spectra of these galaxies from the SDSS data archive, they seem to have a reasonable signal-to-noise ratio. They are observed with the spectrograph fed with 3″ fibers, and since the sample galaxies cover a wide range of distances, the central 3″ represents a 200 pc to 900 pc central region of the galaxies depending on the distance to these galaxies. The optical spectra of these galaxies do not show strong emission lines and resemble a typical spectrum of a non-star-forming galaxy. While zoomed in on this region, we find that only HdE3 contains a minute emission line of Hα. Not surprisingly, the center of this galaxy is relatively bluer than the outskirts, similar to the blue-centered dEs in the Virgo cluster (Lisker et al. 2006).

By exploiting the large wavelength coverage of the SDSS optical spectroscopy, we derive Composite stellar population (CSP) properties of the galaxies using a full-spectrum fitting method. For this purpose, we have used a publicly available code UlySS⁴ from Koleva et al. (2008). We follow the procedure implemented in Koleva et al. (2013) to study the CSP from a similar kind of spectroscopic data set. We fit the observed galaxy spectra with a combination of three Single Stellar Population (SSP) models, see Koleva et al. (2013) for detail. The main idea is to decompose the available information in the observed spectrum into three different epochs of star-formation. Although this may seem more reasonable than assuming a single burst of stellar population, we should keep in mind that the degeneracy between age and metallicity becomes even more complex.

⁴ http://ulyss.univ-lyon1.fr
We use the SSP model from Vazdekis et al. (2010). The two (young and intermediate) ages lie in the ranges 0.1 to 0.8 and 0.8 to 5 Gyr. We fix the old population at an age of 12 Gyr while the metallicities in all three episodes of star-formation are allowed to vary. Emission lines are not included in the fitted model, but instead we permit the code to mask emission lines automatically using the internally imbedded clipping procedure. No corrections for Galactic extinction have been applied to the SDSS spectra.

The results from our full spectrum fitting to derive the CSPs that we decompose into the three episodes of star-formation are listed in Table 3. We find that two galaxies, Hde3 and Hde5, possess a significant young component of age less than 0.5 Gyr, while the others, Hde2 and Hde4, contain no such young stellar population. It seems, however, that all of the galaxies in this sample accumulated a considerable fraction of stellar mass within the last Gyr. Nevertheless, the dominant populations are from intermediate ages, i.e., 2 to 5 Gyr, and they show a significant chemical enrichment during that period of star formation. We detect a similar trend of ages and metallicities for all galaxies, i.e., an increase of metallicity with time. Note that, to some extent, this trend is not free from the so-called age-metallicity degeneracy (Worthy 1999).

### 3. SUMMARY AND DISCUSSION

We presented a caught-in-the-act view of the tidal disruption of dwarf galaxies around massive galaxies. Given the large luminosity range of the dE/dSph class ($M_r \sim -4$ to $-19$ mag), our candidate galaxies represent the bright end of the luminosity function of dEs in any environment (i.e., group or cluster). However, dEs with a magnitude of $M_r \sim -16$ are not uncommon and this luminosity range traces those which are extensively studied beyond the Local group. This usually happens due to the extremely low surface brightness of these galaxies and they require extensive telescope time to obtain good SNR data. Our study also suffers, by design, from a similar limitation as we have used the shallow SDSS imaging data. Indeed, deep imaging like NGVS and MALTAS will allow us to explore fainter regimes (Paudel et al. 2013). We therefore limit our discussion to the possible formation and evolutionary scenarios for dEs, not for their faint cousins dSphs.

We find that the difference in total luminosity between the host and disrupted dwarf galaxies is always larger than 2 mag for this sample. Interestingly, the host galaxies are disk galaxies in all cases. Three of them, N0196, N2968, and N4203, can be classified as S0s, and the others are typical spiral galaxies. We find that most of them are members of well-defined groups, listed in the group catalogs of Giuricin et al. (2000) and Makarov & Karachentsev (2011). N0196 is a member of a compact group (Hickson et al. 1989) and N3221 hosts many dwarf satellites around it. Our search in NED provides at least eight dwarf satellites around N3221 within 500 kpc and ±300 km s$^{-1}$ of sky-projected distance and radial velocity range, respectively, which well satisfies the group selection criteria of Makarov & Karachentsev (2011).

For those dwarf galaxies with optical spectroscopic data in the SDSS archive, we perform a detailed study of their stellar population properties. We derived CSP properties of these galaxies which can be used as a proxy for the history of stellar population build-up at three different epochs. This reveals that these galaxies contain a significant fraction of young (~1 Gyr) stellar population, and in two of our sample galaxies even younger (~0.2 Gyr) stellar populations are also detected. Nevertheless, all four galaxies seem to have achieved their majority of stellar mass in the intermediate age, i.e., 2 to 5 Gyr. Since the stellar population model used for CSP study is scaled at a fixed $\alpha$ abundant ratio ([α/Fe]) equal to the solar value, the derived CSPs do not vary in [α/Fe]. Using the method of LICK-indices, similar to Paudel et al. (2010), we derive the SSP [α/Fe]. We find that these galaxies possess slightly subsolar values of [α/Fe] with an average of $-0.05 \pm 0.1$ dex. This is consistent with the study of Paudel et al. (2010) and indicates that these galaxies might have experienced relatively less intense star-formation activity in the past.

#### 3.1. Tidal Interaction and Formation of dEs

Tidal disruption of dwarf galaxies plays an important role in many astrophysical phenomenon. For example, the outer stellar halos of giant galaxies and intra-cluster light in cluster cores are thought to be built by the stellar population of dwarf galaxies that are disrupted during accretion onto larger systems such as galaxy groups and clusters (Gregg & West 1998; Koch 2009). Indeed, recent deep imaging of nearby giant galaxies have discovered that fine structures in the form of stellar shells, filaments, and streams are ubiquitous around such galaxies which primarily emerge from the disruption of dwarf galaxies through the action of tidal forces from host galaxies (Martinez-Delgado et al. 2010; Miskolczi et al. 2011).

On the other hand, how such a fundamental process shapes the properties of dwarf galaxies themselves is also a crucial issue to understand the evolution of the low-mass satellite population in group and cluster environments. Under what conditions these tidally perturbed dwarf galaxies can survive and when they cannot is critical even to solve some fundamental

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Table 3

| Name  | Young Light | Intermediate Light | Old Light | SSP |
|-------|-------------|--------------------|-----------|-----|
|       | Age (Gyr)   | [Fe/Z] (dex) (%)   | Age (Gyr) | [Fe/Z] (dex) (%) | Age (Gyr) | [Fe/Z] (dex) (%) |
| Hde2  | 1.32 ± 0.04 | 0.20 ± 0.02 53    | 3.59 ± 0.39 –0.06 ± 0.04 40 | 12.00(Fixed) –1.60 ± 0.29 07 | 1.8 ± 0.2 0.11 ± 0.06 |
| Hde3  | 0.32 ± 0.02 | 0.21 ± 0.02 11    | 1.46 ± 0.02 0.02 ± 0.02 79 | 12.00(Fixed) –1.06 ± 0.17 10 | 1.2 ± 0.1 0.01 ± 0.05 |
| Hde4  | 1.29 ± 0.15 | 0.00 ± 0.15 14    | 3.95 ± 0.29 –0.09 ± 0.03 72 | 12.00(Fixed) –1.29 ± 0.27 14 | 3.1 ± 0.2 –0.19 ± 0.04 |
| Hde5  | 0.18 ± 0.02 | –0.16 ± 0.09 18   | 2.85 ± 0.13 –0.25 ± 0.04 51 | 12.00(Fixed) –1.38 ± 0.11 30 | 2.5 ± 0.2 –0.44 ± 0.05 |

Notes. CSPs that we decompose into the three epochs of star-formation. Young, intermediate, and old populations are presented in the second, third, and fourth panels, respectively. The ages, metallicities, and observed light fractions are listed in the first, second, and third columns in each panel, respectively. SSPs parameters are presented in the fifth panel.

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5 Note, however, that this is only for primary guesses. If we do not find any young component (i.e., < 0.8 Gyr), then we use slightly older age boundaries of 1 to 2 and 2 to 8 Gyr. Therefore, the final CSPs are obtained with iterations applying different age boundaries.
problems of current cosmology, such as the missing satellite problem (Henriques et al. 2008; Klypin et al. 1999). Early speculation concerning the formation of compact satellite, such as M32-type galaxies, by tidal stripping (Faber 1973) has been nearly well-established by recent observations of unequivocal evidence (Huxor et al. 2011). However, how the same tidal force influences the evolution of a majority of satellite galaxies that are of the dEs/dSphs class is still under debate.

As these iconic examples suggest, galaxy stirring might be more important to form dEs, particularly in the group environment, than other gas-stripping mechanisms. Based on a detailed study of a sample of dEs using two-dimensional kinematic information, Ryš et al. (2014) claim that even in the Virgo cluster, tidal harassment might be more responsible for producing the present-day kinematic and structural properties of dEs.

A comparison between the observed stellar population ages and some form of dynamical timescale of interaction might provide us with a better understanding of how the interactions unfolded and how they evolved in the past. Simple speculation concerning the ages of the interactions is not trivial compared to the nature of the problem (see Łokas et al. 2013). However, since Łokas et al. (2013) predicts that the detection probability of tidal debris around the satellite dwarf is at maximum near pericenter passage, we expect that our dwarf galaxies are located not far from the pericenters of their orbits.

While the work presented here certainly does not provide a conclusive understanding of the formation and evolution of dEs in the group environment, we have provided “smoking-gun” examples of the tidal stirring phenomenon that may help not only in our understanding of the formation and evolution of dEs, but also when deciphering the process of the interaction of galaxies itself. Further detailed studies of the internal kinematics of these galaxies might scrutinize our findings.

This study is entirely based on SDSS archival data (http://www.sdss.org/) and has made use of NASA Astrophysics Data System Bibliographic Services and the NASA/IPAC Extragalactic Database (NED).

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