Dynamical Masses of Local Group Galaxies
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Dwarf Properties and Satellite Planes Beyond the Local Volume

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Abstract. Dwarf satellite galaxies in our Milky Way and different galaxy systems in the Local Volume appear to be arranged in thin, vast planes. It has been argued that these phase-space correlations cannot be explained to a satisfactory degree by the ΛCDM paradigm but it is unclear whether these planes in our neighborhood are statistical outliers, or if they are perhaps a common phenomenon in the Universe. Recent deep imaging surveys have significantly increased the number of known dwarf galaxies and allow us to advance such small-scale tensions beyond the Local Volume. We present our study analyzing the spatial distribution of 2210 dwarf galaxies identified in the MATLAS survey as well as results from follow-up observations with the MUSE instrument on the VLT. Spectral information for 56 of these dwarf galaxies allow for a deeper dive into their properties and for a comparison to the Local Volume dwarfs.

Keywords. Cosmology: dark matter, Cosmology: observation, Galaxies: dwarf

1. Introduction

Dwarf galaxies are thought to be the fundamental building blocks of more massive galaxies in a ΛCDM context (Frenk & White 2012). As such they are ideal test beds for the study of formation and evolution of galaxies. Furthermore, they are not only the most dark matter dominated type of galaxy but also the most abundant one in the Universe (e.g., Mateo et al. 1991). Even though dwarfs are numerous, they are also on average small and faint, with magnitudes > -17 (Tammann 1994). These properties make them difficult to observe, in particular at larger distances. Therefore, until recently instrumental limits have constrained the highly detailed study of dwarf galaxies mostly to the Local Group (LG) (Mateo 1998; McConnachie 2012; Drlica-Wagner et al. 2020), a few nearby groups (e.g., Chiboucas et al. 2013; Danieli et al. 2017; Carlsten et al. 2019; Byun et al. 2020; Müller et al. 2021) and a hand-full of galaxy clusters (e.g., Ferrarese et al. 2012; Eigenthaler et al. 2018; Venhola et al. 2019). Thisraises the important question of whether we have been able to paint a complete picture of dwarf galaxies via the investigation of these mostly nearby environments. It is plausible that dwarfs show a range of different properties in various environments and in more distant regions of the Universe.

Recently there have been great efforts to push observations of dwarf galaxies beyond the Local Volume (D $\leq$ 10 Mpc). A number of surveys have been conducted and are currently underway (e.g., Duc et al. 2015; Geha et al. 2017; La Marca et al. 2022). These new observations will enable us to further address the so-called small-scale challenges of ΛCDM which arise on dwarf galaxy scales and have been discussed for decades (see e.g., Bullock & Boylan-Kolchin 2017, for a review). The so-called planes-of-satellites problem is interesting in particular, as it cannot be solved by the careful treatment of baryonic physics in cosmological simulations and is dominated by gravity (e.g., Müller et al. 2018). In several nearby galaxy systems dwarf satellites are orbiting their host galaxy in thin, co-rotating structures (e.g., Kunkel & Demers 1976; Pawlowski et al. 2012; Ibata et al. 2013; Müller et al. 2018). This is unexpected in a ΛCDM Universe, since the model of hierarchical structure formation predicts that satellites should be distributed in close to isotropic fashion and to move with random motions (Kroupa et al. 2005).

Another avenue to further improve our understanding of dwarf galaxies are the so-called scaling relations. Much can be learned by investigating if they persist in different environments or if there are deviations. Although galaxy formation and evolution is thought to depend on the complex interplay of various factors, galaxies have shown some remarkably tight correlations or scaling relations between their basic dynamical and stellar properties (see e.g., D'Onofrio et al. 2021, for a recent review). One such relation is the stellar mass-metallicity relation which shows a tight correlation for the dwarf galaxies in the LG (Kirby et al. 2013). In this work we report on our studies investigating the spatial distribution, the radial velocities and stellar population properties of dwarfs in the MATLAS survey beyond the Local Volume. In particular, we study the dwarfs in light of the planes-of-satellites problem as well as the universal stellar mass-metallicity relation for dwarf galaxies.

2. Flattened structures of dwarf satellites in the MATLAS survey

2.1. *MATLAS: data*

The "Mass Assembly of early-Type GaLAxies with their fine Structures "(MATLAS)" survey (Duc et al. 2015) is a deep optical imaging survey which was conducted using the MegaCam on the Canada-France-Hawaii Telescope (CFHT) from 2010 until 2015. The survey is an extension of the larger ATLAS^{3D} project (Cappellari et al. 2011) which has the scientific goal of characterizing the morphology and kinematics of 260 early-type galaxies in distances between 10 and 45 Mpc. In Habas et al. (2020) 2210 dwarf galaxies were identified in the 1 deg^2 fields around the targeted ETGs and their structural and morphological parameters extracted and discussed in Poulain et al. (2021). Around 3% of this sample were classified as Ultra-Diffuse Galaxies (UDGs) which were discussed in Marleau et al. (2021). In Heesters et al. (2021) we present the 2D spatial distribution of the dwarf galaxies identified in the MATLAS fields in the context of the planes-of-satellites problem. We summarize the methods and results of this work in the following.

2.2. *MATLAS: methods*

In order to characterize the spatial distribution of the dwarfs, we utilize the so-called Hough transform (Hough 1959, 1962). This mathematical technique was originally developed to find lines and other simple shapes in digital image processing. The principle of this approach is that every pixel is transformed into a parameter space and all possible slopes and intercepts for a given pixel or data point are calculated. In this 'Hough space' a voting procedure determines the best fit that is suitable for the majority of data points. The Hough method allows for an educated guess on whether or not a dwarf is part of a given flattened structure. The use of this method is also motivated by the fact that only about half of the dwarf population of M31 appear to lie in a thin co-rotating plane, the Great Plane of Andromeda (GPoA; Ibata et al. 2013).

2.3. *MATLAS: results*

We identify 31 (26%) statistically significant (p-value ≤ 0.05) flattened dwarf structures in 119 MATLAS fields. Due to the absence of distance estimates, we are only able to observe these structures edge-on and are missing all flattened face-on dwarf configurations. The number of flattened structures we observe should therefore be considered a lower limit. The majority of these structures show physical dimensions between the LG planes (VPOS & GPoA) and the Centaurus A satellite plane (CASP). We find no correlation between the presence of a statistically significant flattened dwarf structure and the properties of the assumed host such as stellar mass or photometric and kinematic position angle. In fields featuring multiple massive host galaxies we perform a simple total least square fit to the massive galaxies and use it as a proxy estimation to the larger scale structure. We find a preference (50%) for flattened structures to be aligned with the orientation of these massive hosts. Furthermore, we find a small excess of flattened structures around slow rotators (40%) when compared to fast rotators (16%). Such a correlation is expected if these planes-of-satellites candidates originate from galaxy mergers, since slow rotators have been shown to host more tidal features and other signs of recent mergers (Duc 2019; Bílek et al. 2020).

3. Spectroscopic follow-up of 56 dwarf galaxies with MUSE

3.1. *MUSE follow-up: data*

We followed up 56 dwarf galaxies which were idenitfied in the MATLAS fields with the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010, 2012) at the Very Large Telescope (VLT) of the European Southern Observatory (ESO). The observations were part of different filler programmes (PI Marleau, F.) which were conducted with the aim to generate a reference sample of dwarf galaxies with spectroscopic data beyond the LV. Due to the nature of the filler programmes, the dwarf galaxies are located in different galaxy systems and do not form complete systems. For this reason we cannot study potential co-rotational trends in the identified flattened dwarf structures to further investigate phase-space correlations in light of the planes-of-satellites problem. Instead we use the data to confirm the dwarf and satellite nature of these dwarfs through line-of-sight velocity measurements and study their stellar population properties through full spectrum fitting with single stellar population models.

3.2. *MUSE follow-up: methods*

We use full spectrum fitting with the Penalized Pixel-Fitting algorithm (pPXF; Cappellari & Emsellem 2004; Cappellari 2017) in order to extract the radial velocities, ages and metallicities of the dwarfs in our sample. We fit the spectra using linear combinations of SSP models from the E-MILES library (Vazdekis et al. 2016) ranging from 14 Gyr - 70 Myr in age and from solar to -2.27 dex in metallicity. By varying the

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aperture around the dwarf from which the spectra are extracted we find the aperture which maximizes the signal-to-noise ratio (SNR) in the resulting spectrum.

We estimate the errors in the measured parameters by first calculating the residuals between the input galaxy spectrum and the best fit at every wavelength. The signs of the residuals are randomized at each wavelength, added back to the best fit and re-fitted giving slightly different values than the best fit parameters. This procedure is repeated 400 times for every galaxy. The standard deviation of the resulting MC distribution of parameter values around the best fit values gives the errors.

3.3. *MUSE follow-up: results*

Using the recessional velocities returned by pPXF we match them with the velocities of the massive galaxies observed in the ATLAS^{3D} survey and can determine their satellite nature. In this way we find that 42/56 (75%) dwarfs are consistent with being satellites of nearby massive ATLAS^{3D} galaxies. Almost a third (30%) of these matched dwarfs show star formation activity. 10 dwarfs (18%) are located further in the background based on their radial velocities. 70% of these are star forming which can be explained by the specific semi-automatic approach used to identify the dwarf galaxies (see Habas et al. 2020). We cannot detect any spectral lines for 4 (7%) of the dwarfs due to low SNR.

We find that the dwarfs in our sample are systematically offset towards lower metallicities when compared to the universal stellar mass-metallicity relation presented in Kirby et al. (2013). This discrepancy might be attributed to the difference in methodologies for measuring the metallicity. Kirby et al. (2013) analyze and average spectra from resolved individual red giant branch (RGB) stars in the MW dwarfs and present their results in the form of iron metallicities [Fe/H]. This work and other studies used to compare our results to use full spectrum fitting and thus report total metallicities [M/H]. We note that the environment the dwarfs reside in, an insufficient SNR or the inclusion or exclusion of the nucleus in nucleated dwarfs in our sample are unlikely to cause the observed systematic offset.

3.4. *Conclusions*

- We find 31 (26%) flattened dwarf structures around massive ETGs in 119 MATLAS fields beyond the Local Volume.
- These planes-of-satellites candidates are based on a 2D analysis and co-rotation and thus phase-space correlation remains to be investigated via follow-up spectroscopic observations.
- We followed up 56 MATLAS dwarf galaxies with the MUSE integral field spectrograph on the VLT.
- We confirm their dwarf nature and find that 75% of the dwarfs are satellites of nearby massive hosts in the ATLAS^{3D} survey volume. 10% are background dwarfs and 7% show no spectral lines due to insufficient SNR.
- We find that our dwarf metallicities are offset towards lower metallicities when compared to the LG dwarfs on the universal stellar mass-metallicity relation. This shift might be attributed to the different methodologies used to extract the metallicity in this work (full spectrum fitting) vs Kirby et al. (2013) (resolved RGB stars).

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Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1743921323001539

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