THE NUMBER OF TIDAL DWARF SATELLITE GALAXIES IN DEPENDENCE OF BULGE INDEX

MARTÍN LÓPEZ-CORREDOIRA1,2 AND PAVEL KROUPA3
1 Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain; martinlc@iac.es
2 Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
3 Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, Nussallee 14-16, D-53115 Bonn, Germany; pavel@astro.uni-bonn.de

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ABSTRACT

We show that a significant correlation (up to 5σ) emerges between the bulge index, defined to be larger for a larger bulge/disk ratio, in spiral galaxies with similar luminosities in the Galaxy Zoo 2 of the Sloan Digital Sky Survey and the number of tidal-dwarf galaxies in the catalog by Kaviraj et al. In the standard cold or warm dark matter cosmological models, the number of satellite galaxies correlates with the circular velocity of the dark matter host halo. In generalized gravity models without cold or warm dark matter, such a correlation does not exist, because host galaxies cannot capture infalling dwarf galaxies due to the absence of dark-matter-induced dynamical friction. However, in such models, a correlation is expected to exist between the bulge mass and the number of satellite galaxies because bulges and tidal-dwarf satellite galaxies form in encounters between host galaxies. This is not predicted by dark matter models in which bulge mass and the number of satellites are a priori uncorrelated because higher bulge/disk ratios do not imply higher dark/luminous ratios. Hence, our correlation reproduces the prediction of scenarios without dark matter, whereas an explanation is not found readily from the a priori predictions of the standard scenario with dark matter. Further research is needed to explore whether some application of the standard theory may explain this correlation.

Key words: dark matter – galaxies: bulges – galaxies: dwarf – galaxies: formation – galaxies: interactions

1. INTRODUCTION

According to the cold- or warm-dark-matter-based standard model of cosmology (SMoC), dark matter halos merge to form more massive host halos. This occurs because initially hyperbolic relative encounters between halos, some carrying galaxies, are dissipative due to the dark matter halos becoming partially unbound and due to dynamical friction. Each major galaxy (with stellar mass $M_\star \gtrsim 5 \times 10^9 M_\odot$) is therefore at the center of a major dark matter host halo (dark matter mass within the virial radius $M_{\text{DM}} \gtrsim 10^{11} M_\odot$, either isolated or as part of a cluster of galaxies; see Figure 4 in Wu & Kroupa 2015) and ought to have many hundreds of dark matter sub-halo satellites of which a certain fraction contain dwarf galaxies (Klypin et al. 1999; Moore et al. 1999), at least in field galaxies and Local Group equivalents. The fraction of satellite galaxies depends on how baryonic processes interplay in early structure formation (e.g., Cooper et al. 2010; Kroupa et al. 2010; Guo et al. 2015, and references therein). In this model and at any time, a dark matter host halo contains many sub-halos, many of which are constantly decaying toward the center through dynamical friction while new sub-halos enter, and this process slows down with cosmological time and is punctuated by a few major merger events. The expected distribution of satellite galaxies is spheroidal and approximately isotropic around the major galaxies, as detailed and mathematically thorough analysis of the distribution of sub-halos has shown (Metz et al. 2007; Pawlowski et al. 2014). Particularly important in this context is the demonstration by Pawlowski et al. (2015a), that when baryonic physics is taken into account then the spatial distribution of dark-matter-dominated satellite galaxies is not affected and remains indistinguishable from being isotropic. The satellite galaxies have high dynamical mass-to-light ratios because their potentials are dominated by dark matter in their inner regions (e.g., Simon & Geha 2007). The number of satellite galaxies is predicted to increase monotonically with the mass, i.e., the circular velocity, of the host dark matter halo (Moore et al. 1999; Kroupa et al. 2010, and references therein; Klypin et al. 2011; Ishiyama et al. 2013).

A different model has been formulated according to which gravitation is generalized such that it is scale-invariant in the regime when the gravitational acceleration is smaller than Milgrom’s constant $a_0 \approx 3.8 \text{ pc/Myr}^2$ (Milgrom 2009; Famaey & McGaugh 2012; see also Kroupa 2015; for another approach to generalized gravitation, see Moffat 2006). This model is consistent with the observation that most galaxies are simple dynamical objects lacking scars from major and minor mergers (Disney et al. 2008). It implies that galaxies evolve largely in isolation, whereas some experience interactions and rarely mergers (Kroupa 2015). Dwarf galaxies, which condensed from the expanding universe after the Big Bang, grow through gas accretion to become the present-day star-forming galaxies. This model is largely unexplored\(^4\), but even if structure formation would proceed similarly to that of the dark-matter-based models, the incoming dwarf or major galaxy would move past the primary galaxy on a hyperbolic orbit because dynamical friction on the non-existing dark matter halos would not dissipate relative orbital energy. Only in rare near head-on collisions would galaxies be captured (Toomre 1977), Some would interact strongly and would merge after many orbits due to the lack of dark-matter-particle-driven dynamical friction (Combes & Tirut 2010). This Milgromian model would therefore predict few satellite galaxies, as there is no significant mechanism to capture a dwarf galaxy within a few hundred kiloparsecs from a major galaxy unless the dwarf is initially on a radial orbit, in which case it is likely to be destroyed due to the external field effect.

\(^4\) However, this can now be alleviated since the publication of the publicly available Phantom of Rameses code for galaxy evolution and cosmological structure formation by Kroupa (2015).
(Famaey & McGaugh 2012; Kroupa 2015; Wu & Kroupa 2015). However, the encounters between galaxies draw out long tidal arms which, when gas-rich, fragment forming populations of star clusters and dwarf galaxies which are strongly correlated in phase-space (Tiret & Combes 2008; Pawlowski et al. 2011; Yang et al. 2014). Although such tidal-dwarf galaxies (TDGs) are dark-matter-free (Bournaud 2010), they feign dark matter domination if their internal motions are interpreted for virialised systems with Newtonian dynamics (Kroupa 1997; McGaugh & Milgrom 2013; Yang et al. 2014; Pawlowski et al. 2015b). The number of TDGs is expected to statistically scale with a parameter which is a measure of the degree of encounters a given host has experienced. Classical and pseudo-bulges typically form in a galaxy after it experiences a tidal perturbation. Therefore, a convenient parameter as a measure of how much the host galaxy was perturbed in the past would be the relative bulge mass or bulge index B (see Section 2 below).

Two implications thus arise from the above.

1. Dark matter models:
   - The satellite galaxies are spheroidally distributed around their hosts.
   - The number of satellite galaxies scales with the rotation velocity of the host galaxy, which is a measure for the mass of the dark matter halo.
2. Milgromian and generalized (non-dark-matter) gravitation models:
   - The satellite galaxies stemming from one encounter are phase-space correlated TDGs. The existence of planes or disks of satellites are a necessary consequence of this model.
   - The number of TDGs scales with the bulge index.

According to point 1.2, the relevant measure of the number of satellite galaxies, $N_s$, is the rotational velocity $V_C$ of the host galaxy, while according to point 2.2, the bulge index, $B$, is the relevant measure. Thus, an observational assessment of which model is relevant for describing reality is possible by investigating correlations of $N_s$ with $V_C$ or with $B$. By selecting galaxies with a comparable $V_C$ and thus comparable baryonic mass, because galaxies follow the baryonic Tully–Fisher relation (McGaugh & Schombert 2015), $N_s$ should correlate with $B$ in model 2 and not in model 1 (Kroupa 2015).

The observational data situation is such that major galaxies have few satellites (the missing satellite problem of the SMoC; Klypin et al. 1999; Moore et al. 1999), and for those for which sufficiently good three-dimensional (3D) spatial data exist anisotropic, phase-space-correlated satellite galaxy distributions are ubiquitous. Indeed, the Milky Way (MW) has an extremely pronounced, highly significant rotating disk of satellite (DoS) or vast polar structure (VPOS) which includes all material (satellite galaxies, globular clusters and gas, and stellar streams) beyond about 20 kpc distance (Kroupa et al. 2005; Metz et al. 2007, 2008, 2009; Pawlowski et al. 2012, 2014, 2015b). Andromeda has a very thin great plane of Andromeda (GPOA) made up of half of all its satellite galaxies (Metz et al. 2007, 2009; Ibata et al. 2013, 2014b). Both the DoS/VPOS and the GPOA are rotational structures. Furthermore (Pawlowski et al. 2013): (i) Not only are the VPOS and the GPOA extremely pronounced and incompatible with the dark matter models, they are also mutually correlated in that the GPOA points precisely at the MW and both the VPOS and the GPOA have spin vectors which point to a similar direction. (ii) The entire Local Group has a highly symmetrical structure around the MW–Andromeda axis which is, by all counts of probability and by virtue of the thinness of the non-satellite vast planar structures, impossible to obtain in structure formation within the SMoC, in which the dwarf galaxies in the Local Group have largely independent formation and infall histories. The nearest other galaxy group (M81) also has a significantly anisotropic satellite galaxy distribution (Chiboucas et al. 2013), and a significant number of bright host galaxies have rotational satellite populations (Ibata et al. 2014a, 2015). The disagreement of these anisotropic satellite distributions with the dark-matter-based models has, for the first time, been pointed out by Kroupa et al. (2005), a problem or failure of the dark matter models which, to date, has not been solved within the dark matter models.

The interested reader is referred to several rebuttals (Metz et al. 2007, 2009; Ibata et al. 2014b, 2015; Pawlowski et al. 2014, 2015a) to obtain more details on the numerous but incorrect claims by the standard-dark-matter teams that the observed satellite galaxy anisotropies are consistent with the satellite distributions with the SMoC. A unifying problem with these is that simplified and often inadequate plane finding and characterization algorithms are used, thereby ignoring the sophisticated standardized mathematical tools developed for rigorous statistical assessment of phase-space correlations of data by the work of Metz et al. and Pawlowski et al. (see Section 5.1.3 in Kroupa 2015 for elaboration on this point). This discussion need not be repeated here, but along similar lines, recently Cautun et al. (2015: “Planets of satellite galaxies: when exceptions are the rule”) appear to suggest that the VPOS and GPOA are as unlikely in the models and therefore they are normally unlikely and thus not a problem for the SMoC. We can point out some of the shortcomings already: Cautun et al. merely seek 11 or fewer satellites in their models which are as correlated as the observed satellites, while the VPOS contains more than 20, and Cautun et al. add the Sculptor satellite without taking into account that it is on a counter-rotating orbit within the VPOS. The Cautun et al. analysis does not specify the PAndAS footprint they applied, which may introduce biases, and they compare model GPOA 3D velocities with the observed (i.e., projected) two-dimensional (2D) GPOA structure, thereby introducing unaccounted for biases. Cautun et al. neither take into account that the VPOS contains much more than only 11 or fewer satellites, nor that the GPOA is heavily lop sided toward the MW, and their choice of the MW obscuring region (±19.5°, i.e., 33% of the sky) is too restrictive for a region that is not backed up by data. Finally, even if their analysis were to be assumed to be correct, it implies that the MW system would be in the 5% and the Andromeda system would be in the 9% tails of their distributions, such that the Local Group would constitute a 0.45% outlier. Thus, without even taking into account the mutual correlation of the GPOA and of the VPOS, their result leads to very significant disagreement with the SMoC, which they essentially appear to interpret to mean that the Local Group properties are consistent with the SMoC. Another claim based on simplified plane searching strategies that the planar satellite distributions are readily compatible with the dark-matter model, has been
made by Buck (2015: “The Plane Truth: Andromeda analog thin Planes of Satellites are not kinematical coherent structures”): they use newly discovered “satellites” of Andromeda which are, however, beyond its virial radius. Buck et al. misrepresent the literature (Lynden-Bell 1976 only knew of 6 satellite galaxies rather than the claimed 11; they ignore that Kroupa et al. 2005 were the first to demonstrate that the distribution of the 11 classical satellites are inconsistent with the SMoC), and it is unclear what “perfectly describes the collapse of dark matter halos” (their introduction) means. The analysis of the orbital pole directions is flawed in that they are mirrored onto one hemisphere, and by the authors preselecting those satellites from 30 models with Andromeda-like orbital poles, to then argue that this selected ensemble is similar to the MW. Buck et al. argue that the planar satellite arrangements of Andromeda and of the MW are both chance occurrences which exist only for a few hundred million years, but they neither elaborate why we would be observing them at this special epoch simultaneously and mutually correlated, nor how their “solution” compares with the other solutions proposed by the dark matter community. There can be only one physical solution to the real Local Group rather than many partially mutually excluding ones.

With this contribution, we address the avenues other than anisotropy for testing the fundamental models of physics concerning cosmology, namely the number of satellites ($N_s$) versus host galaxy property. Kroupa et al. (2010) found that for the Local Group a tight correlation exists between $N_s$ and bulge mass. Here we revisit this issue, which is necessary given that the Local Group argument rests on only three such data points. Thus, with this contribution, we pursue extending this correlation to galaxies with redshifts $z < 0.1$ and absolute r-band magnitudes $M_r < -20$. Section 2 gives information about a pair of catalogs used for this propose, containing respectively a list of TDGs and morphological characterization of Sloan Digital Sky Survey (SDSS) galaxies. Section 3 shows the correlation of the number of satellites as a function of the bulge index, and we discuss its interpretation in Section 4.

2. DATA

To test whether the above correlation between the bulge index or mass and the number of satellite galaxies exists in systems other than the Local Group, we seek to cross correlate a catalog of major disk galaxies with a catalog of TDGs. We thus use the following two catalogs.

Kaviraj et al. (2012, hereafter K12): a statistical observational study of the TDG population in the nearby universe performed by exploiting a large, homogeneous catalog of galaxy interactions compiled from SDSS Data Release 6. Of all TDG-producing interactions, 95% involve two spiral progenitors, while most remaining systems have at least one spiral progenitor. Here we explore how the ratio between the number of satellites and the total number of host or parent galaxies depends on the prominence of the bulge of the host galaxy. The redshifts of these TDGs (and of their parent galaxies) are $z \leq 0.10$; their absolute magnitudes in the r band, $M_r$, are between $-12$ and $-20$; their stellar masses are between $10^8$ and $10^{10} M_\odot$. We have selected the TDGs with a high (rather than “unsure” or “low”) confidence and flag = 1 (we reject those with flag = 2, which would require further visual inspection of the object for it to be verified as a TDG): a total of 508 TDGs associated with 298 different parent galaxies are obtained, and many of these galaxies have another galaxy associated with the interaction, producing the given TDGs.

Galaxy Zoo 2 (Willett et al. 2013): a citizen science project with more than 16 million morphological classifications of 304,122 galaxies drawn from the SDSS Data Release 7, with apparent r-band magnitude $m_r < 17$, in addition to deeper images from SDSS-Stripe 82. Among the features described in this catalog, for spiral galaxies, there is a classification of the bulge intensity in contrast with the disk, which we associate with a “bulge index”: 0—no bulge; 1—just noticeable bulge; 2—obvious bulge; 3—dominant bulge. Indeed, for each galaxy there are several votes for each classification from the different participants, and we use its average and root mean square dispersion defined, respectively, as

$$B = \frac{\sum_i i \times f_i}{\sum_i f_i},$$

$$\text{rms}_B = \sqrt{\frac{\sum_i (B - i)^2 \times f_i}{\sum_i f_i}},$$

where $f_i$ is the debiased$^6$ vote fraction associated with a bulge index equal to $i$. Note that with this definition, our bulge indices do not constitute ordered cardinal data, and they can be treated with the statistical tools of real variables. From this catalog, we select only the sources with redshift $0 < z < 0.10$, with clean flags(=1) for the classification as disk galaxy. Moreover, we restrict our sample to galaxies with $\geq 4$ votes, $\text{rms}_B < 0.5$ (i.e., we avoid those galaxies in which there is a high dispersion of opinions about its classification) and $-20 \leq M_r \leq -23$ (absolute magnitudes corrected for Galactic extinction). This gives a total of 14,878 galaxies.

Note that this range of absolute magnitudes is related through the Tully–Fisher relation ($\log_{10} v_{80} = 2.210 - 0.135(M_r + 21.107)$, where $v_{80}$ is the rotation velocity at the radius containing 80% of the i-band light; Pizagno et al. 2007) with the range of circular velocities $115 \text{ km s}^{-1} < v_{80} < 295 \text{ km s}^{-1}$. This corresponds to $(1.2 - 26.3) \times 10^9 M_\odot$ of baryonic mass (using the orthogonal fit between maximum velocity and baryonic mass of Avila-Reese et al. 2008, and assuming $v_{80}$ to be the maximum velocity).

3. NUMBER OF SATELLITES AS A FUNCTION OF THE BULGE INDEX

We cross correlate the parent galaxies of TDGs with our selected sample of Galaxy Zoo 2, allowing a maximum angular distance of 1° in the astrometry (either with the first parent galaxy or with the second, not with both) and a maximum difference of redshifts of 0.002. We find 26 TDGs around 16 galaxies, all of them with $z$ between 0.04 and 0.10, an average of $1.7 \times 10^{-3}$ TDGs per galaxy in the here used sample. The distribution of the ratio between total number of TDGs and the total number of galaxies according to the bulge index $B$ and absolute magnitudes is shown in Figures 1 and 3. In Figure 2 we see the variation of the average absolute magnitude as a function of $B$. These plots represent average ratios for bins with

$^6$ The overall effect of this bias is a change in observed morphology fractions as a function of redshift independent of any true evolution in galaxy properties; this is corrected for here: see Willett et al. (2013, their Section 3.3).
the same number of galaxies. For any absolute magnitude range, the same trend of an increasing number of satellites with bulge index is evident, and we note that the variation of the average absolute magnitude is not large in our sample. Table 1 gives the data of the 16 galaxies with TDGs.

The correlation of the ratio,

$$r(B) = \frac{\text{Nr. of TDGs associated to galaxies with bulge index } B}{\text{Nr. of galaxies with bulge index } B}$$

with the bulge index \( B \) is \((r(B)) - 1 = 0.27 \pm 0.09\). A linear fit of the type \( r = a + b \times B \) gives \( a = (-2.7 \pm 1.4) \times 10^{-3}, \ b = (3.2 \pm 1.0) \times 10^{-3} \). Therefore, \( r \) being independent of \( B \) is excluded at around 3\( \sigma \). Note that this statistic is evaluated with the entire set of galaxies, not only within the bins plotted in Figure 1.

### 3.1. Selection Effects

We now consider whether and how the specific parameters used in the selection of our catalogs and their correlation affect the results. The following issues may be considered.

1. Dropping the constraints on the flags in the K12 catalog, we obtain 1644 TDGs but with lower confidence to be true TDGs, instead of the 508 TDGs above. Performing the analysis with these 1644 TDGs, 83 are associated with a galaxy in the Galaxy Zoo 2 catalog. This results in a more significant correlation: \((r(B)) - 1 = 0.29 \pm 0.06\), i.e., an almost 5\( \sigma \) signal. This is shown in Figure 4.

2. Dropping the constraint/flag of the clean disk galaxy in the Galaxy Zoo 2 catalog, we obtain 39,682 galaxies instead of 14,878 galaxies. This analysis gives 40 TDGs associated with these galaxies and \((r(B)) - 1 = 0.11 \pm 0.07\). This is a more diluted correlation than previously, which is due to introducing noise in the host galaxy sample without a clear classification that they are disk galaxies.

3. Requiring a different amount of minimum votes, instead of four, for the classification of a galaxy in the Zoo 2 catalog, we would have a value of the correlation \((r(B)) - 1 = 0.32 \pm 0.12\) for \( \geq 1 \) votes (18,972 galaxies); 0.29 \( \pm 0.10 \) for \( \geq 2 \) votes (16,903 galaxies); 0.25 \( \pm 0.09 \) for \( \geq 8 \) votes (12,519 galaxies); 0.22 \( \pm 0.10 \) for \( \geq 16 \) votes (8912 galaxies); 0.18 \( \pm 0.16 \) for \( \geq 32 \) votes (3688 galaxies). All these results in the same trend but with a slightly lower correlation for galaxies with more votes, although being compatible with the result of \( \geq 4 \) votes within the uncertainties.

4. Changing the constraint on rms\(_B\), away from the above applied constraint \(<0.5\), we find \((r(B)) - 1 = 0.46 \pm 0.24\) for \(<0.4\) (3425 galaxies); 0.15 \( \pm 0.05 \) for \(<0.6\) (28,057 galaxies); 0.01 \( \pm 0.03 \) for \(<0.8\) (44,339 galaxies); \(-0.02 \pm 0.03\) for \(<1.0\) (48,690 galaxies). Here a clear decrease of the signal becomes evident with increasing rms. This may be attributed to a misclassification of the galaxies with rms\(_B\) \( \geq 0.5\); this large rms indeed reflects that the participants of the Galaxy Zoo 2 catalog were more in disagreement among themselves in the classification in the included more doubtful cases. Anyway, if we explore further the origin of the low correlation, we see that it is mainly due to an excess of the ratio \( r \) for galaxies with a \( B \leq 1 \) galaxies with no bulge or just a noticeable bulge. If we explore only the region of galaxies with obvious or dominant bulges, \( B > 1.0\), the results of the correlations are (note that these numbers are not directly comparable to the previous ones because \( B \) is larger; pay only attention to the signal-to-noise ratio): we get 0.22 \( \pm 0.17 \) for rms \(<0.4\); 0.21 \( \pm 0.07 \) for \(<0.5\); 0.11 \( \pm 0.04 \) for \(<0.6\); 0.06 \( \pm 0.03 \) for \(<0.8\); 0.07 \( \pm 0.02 \) for \(<1.0\).

5. The faintest galaxies in our sample are the most difficult to categorize in terms of them having a bulge. Using the range of absolute magnitude \( M_B > -20\), we get 1702 galaxies with correlation \((r(B)) - 1 = -0.12 \pm 0.23\). There is a high ratio of galaxies without a bulge (classified with \( B < 1 \)) but with TDGs. We attribute this result again to a misclassification of faint objects, all of them being near the limit of \( m_I \approx 17 \) where visual inspection is more likely to fail and it is difficult to observe a bulge if it were present. For the objects with \( B > 1 \), \((r(B)) - 1 = 0.09 \pm 0.17\), which is inconclusive due to the large error bars given the small number
statistics. For $M_2 < -23$, there are only 32 galaxies, and none of them have TDGs in the K12 catalog, so a statistical assessment of a possible correlation is not possible.

6. The results of the correlation do not change if we vary slightly the angular separation since we are using the same original source (SDSS) with almost the same coordinates. The variation of the range of redshift to $\Delta z = 0.001, 0.003, \text{ or } 0.004$ instead of 0.002 changes none of the results: the same pairs of galaxy-TDG are detected.

Summing up, our result is robust against the change of parameters used to estimate the relationship between the ratio of TDGs and the bulge index, giving a correlation with a significance of up to $5\sigma$ in the best of the cases. Five sigma is a very improbable configuration (probability lower than one in a million) so we do not believe this is by chance due to a posteriori statistics. We do not have a continuous variable (the number of TDGs) from which we have taken the most convenient value in order to improve the signal-to-noise to our advantage, but instead we have a discrete variable (the flag) by which either we take the entire sample or we exclude those TDGs with flag = 2; there are only these two options. If, just including flag = 2 TDGs, we get a significance several orders of magnitude higher, this cannot be due to fine tuning, but is due to the detection of a real signal which is amplified by the increase of the number of TDGs. In any case, the result with the most conservative sample of secure TDGs gives a correlation between the number of TDGs and the bulge index which has a significance of $3\sigma$. The above discussed departures from this significance when the criteria are varied are due to a high contamination of galaxies with possible incorrect classifications.

4. DISCUSSION AND CONCLUSIONS

As discussed in the Introduction, two competing cosmological frameworks exist for the emergence of galaxies, the dark-matter-based standard models and the generalized gravity models without cold or warm dark matter. They differ by dynamical friction on the expansive and massive dark matter halos not acting in the generalized gravity models, such that the formation and growth of galaxies differs significantly. In the dark-matter-based models, each major galaxy has many dark-matter-dominated satellite galaxies, which have independent infall histories and are captured around the host galaxy through dynamical friction. In the generalized gravity models,
companion galaxies are either on hyperbolic flybys or are TDGs which form, together with populations of star clusters, phase-space correlated populations around the major hosts. The observational evidence strongly favors the latter models, given the small number of satellite galaxies observed around major galaxies and given their ubiquitous phase-space correlations. Another implication of the generalized gravity models is that galaxies rarely merge, but they nevertheless interact. Interactions form bulges and TDGs. A strong correlation between the bulge mass and the number of faint satellite galaxies has been noted to exist for Local Group galaxies. Here we revisit this issue by considering a large ensemble of host galaxies which we cross correlate with catalogs of typically bright and thus very rare TDGs. The results suggest a strong correlation exists between the bulge index and the number of TDG companions. This supports the result obtained for the Local Group and therefore also the generalized gravity models.

Can the SMoC explain in some way this correlation of the number of satellites with the bulge index? In principle, we see only one possibility: that the bulge/disk ratio is correlated with the halo mass, i.e., that the formation of a classical bulge or pseudo-bulge/bar depends on the halo mass. The bulge may be a classical bulge, i.e., with a stellar orbit distribution typical of elliptical galaxies and formed at the early stages of the host galaxy’s life, or it may be a pseudo-bulge, or a long bar, or a misaligned triaxial bulge and a long bar may both be present in spiral galaxies (Compère et al. 2014). In any of the cases, the situation is similar.

Later galaxy types (higher Hubble stage) have an observed smaller bulge index (Simien & de Vaucouleurs 1986) and have lower luminosities on average (Graham & Worley 2008). Therefore, one may suspect that the average mass of the host galaxies in our sample increases with the bulge index. However, there is an anticorrelation of the fraction of satellites with the luminosity or with the stellar mass (Velander et al. 2014), so a higher luminosity or stellar mass of galaxies with prominent bulges would give fewer satellites. This is the opposite of what we see. Nonetheless, the variation of the average absolute magnitude in our sample is not large (see Figure 2) and, even if we subdivide the sample into smaller ranges of absolute magnitude, the trend of more satellites with higher bulge index is retained (see Figure 3). Moreover, the ratio of the dark-to-luminous mass in galaxies is either higher with higher Hubble stage (Tinsley 1981) or it is uniform (Jablonka & Arimoto 1992). However, the Snyder et al. (2015) results obtained using the “illustrious” simulations to represent the SMoC point out that bulge-dominated galaxies should have a higher ratio of dark-to-stellar mass, so one may thus note that stellar mass and luminosity are not proportional. Therefore, assuming an approximate constant luminosity, the total dynamical mass is either lower or roughly the same with larger bulge index. This is the opposite of what would be needed to explain the correlation discovered here within the dark matter scenario. With respect to the existence of long bars, data on rotation curves do not show a clear trend toward higher halo masses for barred galaxies (López-Corredoira 2007). Hence, given the above, we do not see how the SMoC can explain our results. Further research is needed to explore the possibility that the bulge index in the SMoC might correlate with other quantities that also influence the number of TDGs (e.g., measures of the assembly history of the halo). What is evident from our analysis is that the available data favor the Milgromian model, which gives a simple and direct explanation of the data, over the SMoC, within which one needs to explore complex ad hoc modifications of the application of the theory in order to explain something that was not predicted a priori.

To put this finding on a more secure footing, a dedicated observational survey is required as follows (Kroupa 2015): a catalog of disk galaxies with similar circular velocities but different bulge masses are needed. Each of these disk galaxies needs to be surveyed over regions with radii of 150–250 kpc to seek faint dSph-like satellite galaxies. Such a survey will allow a quantification of a possible bulge mass versus number of satellite galaxy correlation to seek confirmation or rejection of the correlation found in the Local Group and with this study. The implications of the existence or absence of such a correlation would pose important empirical constraints on fundamental physics because it is directly related to the question of whether dark matter particles exist, or whether the standard model of particle physics remains the best current description of all existing particles.

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