A correlation between the number of satellites and the baryonic bulge-to-total ratio extending beyond the Local Group

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ABSTRACT

Recent observations of the fields surrounding a few Milky-Way-like galaxies in the local Universe have become deep enough to enable investigations of the predictions of the standard $\Lambda$CDM cosmological model down to small scales outside the Local Group. Motivated by an observed correlation between the number of dwarf satellites ($N_{\text{sat}}$) and the bulge-to-total baryonic mass ratios ($B/T$) of the three main galaxies in the Local Group, i.e. the Milky Way, Andromeda, and Triangulum (M33), we use published data of three well-studied galaxies outside the Local Group, namely M81, Centaurus A, and M101, and their confirmed satellites, and we find a strong and significant correlation between $N_{\text{sat}}$ and $B/T$. This presents itself in contradiction with the hitherto published results from cosmological simulations reporting an absence of a correlation between $N_{\text{sat}}$ and $B/T$ in the $\Lambda$CDM model. We conclude that, based on the current data, the $N_{\text{sat}}$ vs. $B/T$ correlation is no longer a property confined to only the Local Group.

Key words: galaxies: bulges – galaxies: dwarf – Local Group – methods: data analysis – cosmology: observations – dark matter

1 INTRODUCTION

Until recently, the halos of only the Milky Way (MW) and Andromeda (M31) galaxies have been observed deep enough to enable studying different properties of their dwarf satellites (e.g. Grebel 1997; McConnachie 2012; Collins et al. 2015) and to test the expectations of galaxy formation and evolution scenarios down to small scales. The observations of these two galaxies, and the Local Group (LG) in general, has led to some of the long lasting challenges for the standard Lambda-Cold-Dark-Matter ($\Lambda$CDM) cosmological model, viz: the missing satellites (Klypin et al. 1999), the too-big-to-fail (Boylan-Kolchin et al. 2011), and the disk of satellites (Kroupa et al. 2005; Pawlowski & Kroupa 2013) problems. The numerous observational, theoretical, and computational studies aiming at solving these issues have not reached a consensus so far (see e.g. Bullock & Boylan-Kolchin 2017, for a review). These problems required systematic and deep surveys for finding more dwarf satellites outside the LG. In the recent years, and thanks to various dedicated deep observations (e.g. Geha et al. 2017; Greco et al. 2018), other galaxy groups are also turning into very useful laboratories for investigating the small scale predictions$^1$ of the $\Lambda$CDM model, and for learning about galaxy formation and evolution in general.

Another interesting feature of the LG that motivated dedicated studies (such as Javanmardi et al. 2016; López-Corredoira & Kroupa 2016; Henkel et al. 2017) is an observed correlation between the number of dwarf satellites, $N_{\text{sat}}$, and bulge mass ($M_{\text{bulge}}$) of M33, MW, and M31 (Kroupa et al. 2010). This correlation appeared to be a puzzling one due to the following two reasons: i) in the $\Lambda$CDM model, $N_{\text{sat}}$ is expected to correlate with only the mass of the dark matter halo, hence with the rotation velocity, of the disk galaxy, and ii) galaxies with similar rotation velocities (e.g. M31 and M101, Faber & Gallagher 1979) but with very different $M_{\text{bulge}}$ are observed in the Universe. Therefore, unlike the expected correlation between $N_{\text{sat}}$ and rotation velocity, a correlation between $N_{\text{sat}}$ and $M_{\text{bulge}}$ was not expected.

To quantify the expectations from the $\Lambda$CDM model for this correlation, Javanmardi et al. (2019) used data from the Millennium-II simulation (Boylan-Kolchin et al. 2009) with the semi-analytic galaxy formation model of Guo et al. $^1$

$^1$ We note though that the disk-of-satellites problem is not a small scale problem as it refers to the distribution of baryonic matter on scales of hundreds of kpc about major host galaxies.
(2011) and reported three main results: i) for a sample of disk galaxies with a wide mass range, a weak correlation (with a large scatter) between \( N_{\text{sat}} \) and \( M_{\text{bulge}} \) emerges which reflects the seemingly independent correlations between these two quantities and the mass of the disk galaxy; ii) for disk galaxies with similar masses or rotation velocities, no correlation between \( N_{\text{sat}} \) and \( M_{\text{bulge}} \) is found, and iii) when normalizing \( M_{\text{bulge}} \) with the mass of the disk galaxy, i.e. when considering \( B/T \) ratios, no correlation is found between \( N_{\text{sat}} \) and \( B/T \) of disk galaxies with stellar mass \( M_*=10^{10}-10^{11} M_\odot \) in the \( \Lambda \)CDM model.

Recently, observations of the galaxies M81, Centaurus A (Cen A), M94, and M101 (at distances of about 3.7, 3.8, 4.2, and 7 Mpc, respectively) have become deep enough to enable studying their satellite properties and their relation to their hosts (Chiboucas et al. 2013; Crnojević et al. 2019; Müller et al. 2019; Smercina et al. 2018; Carlsten et al. 2019b; Bennet et al. 2019). In this contribution, we use the published data from these galaxy groups, together with the available data from M33, MW, and M31, to investigate the \( N_{\text{sat}} \) vs. \( B/T \) correlation.

2 DATA AND ANALYSIS

In this section, we first introduce the data we use in our analysis from different studies published in the literature. See Table 1 for a summary. We then apply a simple correlation analysis and present the results.

2.1 Number of dwarf satellites

The information about the satellite populations of the galaxies in our study are as follows:

- The LG galaxies: we refer to McConnachie (2012) and McConnachie et al. (2018), for the information about MW and M31 satellites, respectively.
- M81: using the Canada-France-Hawaii Telescope (CFHT) and Hubble Space Telescope (HST) observations, Chiboucas et al. (2009) and Chiboucas et al. (2013) have discovered and confirmed 14 new dwarf galaxies in the M81 group. Their survey covers at least \( \leq 300 \) kpc projected distance around M81 (and in some directions more than twice that, see figure 27 of Chiboucas et al. 2013). They increased the number of known members of this group to 36 with its faintest dwarf having an r-band absolute magnitude of \( M_r=-6.8 \) (Chiboucas et al. 2013). See their Table 4 for a full list of information.

The latter galaxy group imposes a magnitude limit on our analysis and to be able to compare the satellite populations of all galaxies, we only count the satellites with \( M_V \leq -8.2 \) mag. In addition, we will perform our correlation analysis (Section 2.3) with two projected distance limits; first considering only the satellites within 200 kpc projected distance to their hosts, and second increasing the projected distance limit to 250 kpc by assuming that the satellite population of Cen A is complete-enough out to that distance, see the last columns of Table 1 where \( N_{\text{sat}}^{200} \) and \( N_{\text{sat}}^{250} \) represent the number of satellites within 200 and 250 kpc of each galaxy, respectively.

2.2 Bulge-to-total mass ratios

The information about the \( B/T \) ratios of the galaxies in our study are as follows:

- For MW, M31, M81, Cen A, and M101, stellar mass and \( B/T \) values are directly adopted from Bell et al. (2017). See their table 1 for a list of references and other measurements.
- For M33, using \( M_{\text{bulge}}=1.14(\pm0.14)\times10^9 M_\odot \) reported by Seigar (2011), and adopting a total mass of \( \approx 10^{11} M_\odot \) reported by Corbelli (2003), we obtain \( B/T=0.01\pm0.001 \). being nearly isolated, and therefore we consider it as a separate galaxy and not as a satellite of Andromeda.
Section 2. Table 1. The data used in this study and their references. See Section 2.

| Galaxy | $M_*(10^{10}M_\odot)$ | $B/T$ | $N_{sat}^{200}$ | $N_{sat}^{250}$ |
|--------|-----------------|------|-------------|-------------|
| MW     | 6.1 (a)         | 0.2±0.075 (a) | 10 (b) | 12 (b)   |
| M31    | 10.3 (a)        | 0.32±0.11 (a) | 17 (c) | 18 (c)   |
| M33    | 1 (d)           | 0.01±0.001 (d,e) | 0  | 0        |
| M81    | 5.6 (a)         | 0.46±0.15 (a) | 16 (f) | 19 (f)   |
| Cen A  | 11.2 (a)        | 1.0±0.1 (a)   | 27 (g,h) | 29 (g,h) |
| M94    | 4 (i)           | 0.1±0.02 (j,k) | 2^2 (i) | 2^2 (i)  |
| M101   | 5.9 (a)         | 0.05±0.03 (a) | 8 (1,m) | 8 (1,m)  |

(a) Bell et al. (2017); (b) McCookachie (2012); (c) McCookachie et al. (2018); (d) Corbelli (2003); (e) Seigar (2011); (f) Chiboucas et al. (2013); (g) Crnojević et al. (2019); (h) Müller et al. (2019); (i) Smercina et al. (2018); (j) Moellenhoff et al. (1995); (k) Jałocha et al. (2010); (l) Carlen et al. (2019b); (m) Benet et al. (2019).

† Note that the field of M94 is surveyed only out to 150 kpc projected distance, and while we show it in Figure 1, we do not include it in our correlation analysis.

For M94, we adopt the mean (and its standard error) of the $M_{\text{bulge}}$ values reported in Moellenhoff et al. (1995) and Jałocha et al. (2010); $M_{\text{bulge}} = 4.54\pm0.86 \times 10^{9}M_\odot$. Considering a stellar mass of $4 \times 10^{10}M_\odot$ (Smercina et al. 2018), we obtain a $B/T = 0.1 \pm 0.002$ for M94.

See the second and third columns of Table 1 for a summary.

Figure 1. Number of satellites, $N_{sat}$ (with $M_V \leq -8.2$) vs. bulge-to-total baryonic mass ratio, $B/T$. The left and right panels correspond to considering satellites within 200 and 250 kpc of their host galaxies, respectively. The color code is $M_*$, the solid grey lines are the results of linear fits taking into account uncertainties on both axes, and the shaded regions are the $1\sigma$ uncertainty of the fitted results. For both of the analyses, the probability that the correlation arises by chance is only 0.5 percent. Since the current surveys cover only 150 kpc projected distance of M94 (shown by a diamond in this figure), this galaxy is excluded from both the fitting and the correlation analyses. Adding M94 would increase the significance of the correlation.

2.3 The correlation

The data listed in Table 1 are visualized in Figure 1 by plotting $N_{sat}$ vs. $B/T$. Each galaxy is labeled on this figure and the color code represents the $M_*$. The uncertainties on $B/T$ are values from Table 1, and we consider an uncertainty of $\pm \sqrt{N_{sat}}$ for the number of satellites. The left and right panels correspond to considering satellites within 200 and 250 kpc of their host galaxies, respectively. The solid grey lines are the result of linear least squared fits to the data: $N_{sat}^{200} = 30.2(\pm6.2)B/T + 1.7(\pm1.3)$, and $N_{sat}^{250} = 33.6(\pm6.5)B/T + 1.7(\pm1.3)$. In the fitting procedure, we take both $N_{sat}$ and $B/T$ uncertainties into account. The shaded regions reflect the $1\sigma$ uncertainty of the fitting results. However, we note that we do not aim to present a formula for $N_{sat}$ vs. $B/T$ and the purpose of the fitting is to better see the trend presented by these data.

Our main finding is that using these data we measure the linear correlation coefficient for $N_{sat}$ vs. $B/T$ to be $r = 0.94$ and the probability that this correlation arises by chance to have a $p = 0.005$, for both of the projected distance conditions\(^4\). In other words, the data yield a 99.5 percent (around $3\sigma$) significant correlation between $N_{sat}$ and $B/T$. We note that M94 is excluded from both the linear fitting and the correlation measurement.

\(^4\) The $r$ and the $p$ values for the two projected distance conditions differ only after the third decimal places, not reported here.
3 DISCUSSION AND CONCLUDING REMARKS

Figure 1 can be compared with the right panel of figure 4 in Javanmardi et al. (2019) which shows $N_{\text{sat}}$ vs. $B/T$ for a sample of more than 6000 disk galaxies with stellar masses between 1.2 and $26.3 \times 10^{10} M_\odot$ from the Millennium-II simulation (Boylan-Kolchin et al. 2009). This mass range almost encompasses that of the spiral galaxies in our study. Javanmardi et al. (2019) measure a linear correlation coefficient of only $r = 0.13$ for $N_{\text{sat}}$ vs. $B/T$, being consistent with no correlation between these two quantities in the $\Lambda$CDM model.

This can be understood also qualitatively by noting that in the $\Lambda$CDM model, $N_{\text{sat}}$ is directly related to dark matter halo mass; the heavier the halo, the larger the number of accreted subhalos (top left panel of figure 3 in Javanmardi et al. 2019), and heavier halos accrete also more baryonic mass forming galaxies with statistically larger stellar masses. In addition, in this model, galaxies with larger stellar masses are found to be more likely to grow heavier bulges (figure 2 in Javanmardi et al. 2019). Therefore, in the $\Lambda$CDM model, $N_{\text{sat}}$ weakly correlated with $M_{\text{bulge}}$, but not with $B/T$. This certainly requires further detailed studies of bulge formation and its possible connection with large-scale environment in this model (Romano-Díaz et al. 2017, Tavasoli et al. in prep.).

An interesting point in the current data is that while M81, M101, and the MW have very similar stellar masses, they have different $N_{\text{sat}}$ and very different $B/T$ ratios, implying a lack of correlation between these two quantities and stellar mass.

We note that Cen A has a few features which makes it distinct with respect to the other galaxies in our analysis. It is not a disk-galaxy (with $B/T = 1.0$), it has an active nucleus, and it has a perturbed structure. Assuming that these have a significant impact on its population satellite, remeasuring the $N_{\text{sat}}$ vs. $B/T$ correlation without Cen A gives $r = 0.93$ and $p = \text{value} = 0.02$, not changing our main result.

In addition, it should be emphasised that as mentioned earlier, M94 is not included in our correlation analysis because its field is surveyed out to only 150 kpc projected distance. Assuming that future surveys do not change the number of satellites of M94 significantly, adding it to the analysis would increase the significant of the correlation to well above the $3\sigma$ confidence level. Actually, even if future surveys increase the number of confirmed satellites of M94 by a factor of 3 or 4, the significance of the $N_{\text{sat}}$ vs. $B/T$ correlation would increase even further. It is therefore very important to conduct deeper and wider surveys in the field of this particular galaxy.

In a very recent study, Carlsten et al. (2019a) have reported the detection of satellite galaxy candidates around 10 galaxies including M104 (a.k.a. the Sombrero galaxy, at a distance of around 9.5 Mpc). They report in total 27 satellite candidates within 150 kpc projected distance of this galaxy\(^5\). With $B/T > 0.7$ (Gadotti & Sánchez-Janssen 2012), this galaxy can add another point to the large $B/T$ values of the $N_{\text{sat}}$ vs. $B/T$ relation. Carlsten et al. (2019a) also report in total 21 satellite candidates for NGC 4565 that has a $B/T = 0.25$ (Bell et al. 2017). However, follow up distance measurements for their satellite candidates are essential before including these two galaxies in the analysis.

As a final remark, it is also worth noting other reported interesting properties of the non-LG galaxies in our study. Chiboucas et al. (2013) found that M81 has a disk of satellites similar to those of MW (Kroupa et al. 2005; Pawlowski & Kroupa 2013) and M31 (Metz et al. 2007; Hammer et al. 2013; Ibata et al. 2014). In addition, Müller et al. (2018) reported a similar structure around the Cen A galaxy. Smércina et al. (2018) and Bennet et al. (2019) conclude that M94 and M101 have sparse satellite populations, not fulfilling the expectations from the $\Lambda$CDM model. Bennet et al. (2019) suggests a link between the properties of these galaxy groups and their environments reporting that galaxies in more tidally active environments tend to have a larger $N_{\text{sat}}$ (see their figure 8).

The latter point is in line with an alternative scenario by Kroupa (2015) arguing that if most of the observed satellites are ancient tidal dwarf galaxies, then a correlation between $N_{\text{sat}}$ and $B/T$ can emerge because bulge growth is enhanced significantly in galaxy-galaxy encounters. This would also explain the observed preferred distribution of satellites in rotating disks (Pawlowski et al. 2013; Kroupa 2012). This scenario also requires further detailed and quantitative studies (see e.g. Combes 2016; Biflek et al. 2018; Banik et al. 2018).

Whatever the correct underlying theory will turn out to be, and while further observational studies of these and other galaxy groups are necessary, the main finding of our study is that the current data show a strong and significant correlation between $N_{\text{sat}}$ and $B/T$ in the most well-studied galaxy groups in the Local Volume.

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REFERENCES

Banik I., O’Ryan D., Zhao H., 2018, MNRAS, 477, 4768
Bell E. F., Monachesi A., Harmens B., de Jong R. S., Bailin J., Raddburn-Smith D. J., D’Souza R., Holwerda B. W., 2017, ApJ, 837, L8
Bennet P., Sand D. J., Crnojević D., Spekkens K., Zaritzky D., Karunakaran A., 2017, ApJ, 850, 109
Bennet P., Sand D. J., Crnojević D., Spekkens K., Karunakaran A., Zaritzky D., Mutlu-Pakdil B., 2019, arXiv e-prints, p. arXiv:1906.03230
Biflek M., Thies I., Kroupa P., Famaey B., 2018, A&A, 614, A59
Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., Lemoine G., 2009, MNRAS, 398, 1150
Boylan-Kolchin M., Bullock J. S., Kaplinghat M., 2011, MNRAS, 415, L40
Bullock J. S., Boylan-Kolchin M., 2017, ARA&A, 55, 343
Carlsten S. G., Greco J. P., Beaton R. L., Greene J. E., 2019a, arXiv e-prints, p. arXiv:1909.07389

\(^5\) Also confirming the low surface brightness galaxies found by the Dwarf Galaxy Survey with Amateur Telescopes (DGSAT, Javanmardi et al. 2016) within 80 kpc projected distance of M104.
