The gap of stellar mass in galaxy groups: another perspective of the Too-big-To-Fail problem in the Milky Way

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ABSTRACT

The Milky Way presents the too-big-to-fail (TBTF) problem that there are two observed satellite galaxies with maximum circular velocity larger than 55 km/s, and others have velocity less than 25 km/s, but the cold dark matter model predicts there should be more than 10 subhaloes with velocity larger than 25 km/s. Those massive subhaloes with \(25 \text{ km/s} < V_{\text{max}} < 55 \text{ km/s}\) should not have failed to form stars. The TBTF problem severely challenges the CDM model. Most efforts are seeking the effects of baryonic feedback, decreasing the mass of the Milky Way, changing the properties of dark matter, so as to assign the observed low-velocity satellites into the massive subhaloes found in simulations. However, the TBTF problem can be avoided if the MW have not accreted subhaloes with velocity between \(25 \text{ km/s} < V_{\text{max}} < 55 \text{ km/s}\) although the probability of such a gap is lower as \(\sim 1\%\) and can not be tested against observations. In this work we study the gap in stellar mass of satellite galaxies using the SDSS group catalogue and a semi-analytical model. We find that there are 1-2\% of galaxy groups with a large gap in the stellar mass of their satellites. These ‘big gap’ groups have accreted less massive subhaloes in their formation history and naturally display a gap between their satellite galaxies. If extrapolating our results to the Milky Way is appropriate, we conclude that it is very likely that our Milky Way has not accreted enough massive subhaloes to host those low-velocity satellites, and the TBTF problem is naturally avoided.

Key words: methods: numerical – methods: statistical – galaxies: haloes – Galaxy: halo – cosmology: dark matter

1 INTRODUCTION

In the last two decades there are three prominent problems concerning the satellite galaxies in the Milky Way (MW). The first is the ‘missing satellite problem’ that cold dark matter (CDM) model predicts hundred of subhaloes but only a dozen classical satellite galaxies are observed (Klypin et al. 1999; Moore et al. 1999). With more faint satellites being found and development of more realistic modeling of galaxy formation, the tension in this problem is greatly alleviated (e.g., Gendin 2000; Benson et al. 2002; Koposov et al. 2008; Macciò et al. 2010; Font et al. 2011). The second is the thin planar distribution of the classical satellites (Kroupa et al. 2005). Analysis using simulation found that the probability of such a thin disk ranges from a few percent to 30\% (e.g., Kang et al. 2005; Zentner et al. 2005; Libeskind et al. 2009; Wang et al. 2013), but the chance is much lower considering the co-rotation of the majority of the satellites in the plane (e.g., Pawlowski & Kroupa 2013). The third is the too-big-to-fail problem (TBTF; Boylan-Kolchin et al. 2011; 2012) that only two (LMC, SMC) of the dozen satellites have \(V_{\text{max}} > 55 \text{ km/s}\) and others have \(V_{\text{max}} < 25 \text{ km/s}\), but CDM predicts more than 10 subhaloes with \(V_{\text{max}} > 25 \text{ km/s}\) in the Milky Way-size halo and they should not have failed to form stars. The TBTF problem is also seen in the local group (Garrison-Kimmel et al. 2014; Sawala et al. 2015; Brooks & Di Cintio 2015).

The TBTF problem severely challenges the CDM model. The most straightforward solution is to lower the circular velocity or central density of the massive subhaloes in simulations so as to host those observed satellite galaxies. Most efforts are invoked to include the baryonic feedback to decrease the central density of subhalo in simulations (e.g., Governato et al. 2012; Zolotov et al. 2012; Brooks et al. 2013; Brooks & Zolotov 2014; Aaron et al. 2016). However, the baryonic effects are still debated (e.g., Boylan-Kolchin et al. 2012; Garrison-Kimmel et al. 2013; Pawlowski et al. 2015). Alternative solution to lower the subhalo central density is to change the dark matter property, such as using a warm dark matter (e.g., Lovell et al. 2012; Maccio et al. 2013), or the self-interacting dark matter (e.g., Vogelsberger et al. 2012; Rocha et al. 2013).

On the other hand, the TBTF problem can be alleviated if there is only a few massive subhaloes in the MW mass halo. Wang et al. (2012) have shown that the number of subhalo with \(V_{\text{max}} > 25 \text{ km/s}\) decreases quickly with halo mass, and if requiring the MW has at most three subhaloes with \(V_{\text{max}} > 25 \text{ km/s}\),
the halo mass of the MW would be lower than $1.4 \times 10^{12} M_\odot$. However, a lower MW mass is difficult to reconcile with the occurrence of the two observed massive satellites (LMC, SMC) with $V_{\text{max}} > 55\text{km/s}$. Boylan-Kolchin et al. (2010) have shown that a MW halo with mass of $10^{12} M_\odot$ will have less than 10% chance to host two satellites as bright as the Magellanic Clouds. Such a lower chance is also observationally supported (Liu et al. 2011). Thus the occurrence of the Magellanic Clouds and avoidance of more than three subhaloes with $V_{\text{max}} > 25\text{km/s}$ together can put a strong constraints on the MW mass (Cautun et al. 2014).

A more accurate description of the MW satellite velocity distribution is that there are no satellite galaxies with $25\text{km/s} < V_{\text{max}} < 55\text{km/s}$ (e.g., Jiang & van den Bosch 2016). Cautun et al. (2014) found that the probability of having such a wide gap in velocity space is about 1% in the CDM model. Jiang & van den Bosch (2016) find the probability is even lower as 0.1% using a Monte-Carlo method. If the subhalo population of the MW happens to has such a gap or distribution, the TBTF problem is naturally avoided. However, due to lack of large data sample analog to the MW mass/luminosity (along with measurement of their satellites velocity) from observations, such a statistical probability can not be tested.

To find the occurrence of systems alike the MW in terms of a big gap in the distribution of its satellites, one need large sample of galaxies with well determined satellite galaxy population. Using galaxies from the Sloan Digital Sky Survey (SDSS), Yang et al. (2012) constructed a large sample of galaxy groups with member galaxies are well determined. However, the SDSS lacks velocity dispersion measurement of the main galaxy sample, we thus describe the gap using the stellar mass of satellite galaxies in the group. We ask one related question: are there any galaxy groups which display similar gap in the stellar mass of their satellites as in the MW? We term those groups with a big gap in the stellar mass of their satellites as ‘big gap’ groups. We first identify ‘big gap’ groups from the Yang et al. (2012) group catalogue and compare their properties to the predictions from a semi-analytical model (Kang et al. 2012). For those ‘big gap’ groups in our model, we look into their formation history and investigate the origin of the gap in the stellar mass of their satellites. We believe that although we are looking at massive counterparts of the MW, the formation of those ‘big gap’ groups can also shed light on the formation of the MW, even on the nature of the TBTF problem.

The paper is organized as: in Section.2 we broadly introduce the used group catalogue, model galaxies and how we identify the ‘big gap’ groups. In section.3 we compare the data to the model predictions and use the model galaxies to identify the origin of the ‘big gap’ groups. We finally summarize and discuss in Section.4.

2 GROUP CATALOGUE AND MODEL GALAXIES

We use the group catalogue constructed by Yang et al. (2012) which is now publicly available. The group catalogue is based on the data from the SDSS Data Release 7 (Abazajian et al. 2009) which contains both photometric and spectroscopic of about 1 million galaxies with Petrosian magnitude $r < 17.77$. For each galaxy the stellar mass is estimated using the model of Bell et al. (2003). Using the stellar mass and position of each galaxy, the group catalogue is constructed using the halo-based group finder of Yang et al. (2005). For detail of constructing the group catalogue, we refer the reader to Yang et al. (2012). For each group, the most massive member galaxy is called as the central galaxy and others are satellites. In our work, we select group with virial mass $(M_{\text{vir}})$ larger than $10^{12} M_\odot$ and with redshift $z < 0.1$. Groups selected in the way is more robust and contains more member galaxies (on average with 8 satellite galaxies per group), and we have 9610 groups in total.

The model galaxies used are from the semi-analytical model of Kang et al. (2012) combined with a cosmological N-body simulation with the WMAP seventh-year cosmological parameters (Komatsu et al. 2011). The simulation is run using the Gadget-2 code (Springel 2005) with $10^{24}$ dark matter particle in a cubic of $200\text{Mpc/h}$ on each side. The semi-analytical model includes key physics governing galaxy formation, such as gas cooling, star formation, supernova and AGN feedback. By grafting the model onto the merger trees from the N-body simulation, the model provides good match to the observed stellar mass function of SDSS and the galaxy two-point correlation function simultaneously (Kang 2014). Also the model fits the stellar mass functions of satellite galaxies in different halo mass obtained by Yang et al. (2012) using the SDSS DR7. The success of the model lay down the basis for comparison with the data in this work.

As said before the MW displays a gap between the two massive satellites (LMC, SMC, $V_{\text{max}} > 55\text{km/s}$) and the third massive one Sagittarius ($V_{\text{max}} \sim 25\text{km/s}$, see Tab.1 in Jiang & van den Bosch 2016) and references therein). In the SDSS DR7, there is no velocity dispersion measurement for the main galaxies, we have to translate this velocity gap into the stellar mass gap. The observed gap in stellar mass between SMC ($4.6 \times 10^{9} M_\odot$) and Sagittarius ($2.1 \times 10^{9} M_\odot$), see Tab.4 in McConnachie et al. 2012 for compilation of local dwarfs) is about $\Delta \log M_* \sim 1.3$. Is this gap in stellar mass expected for the two satellites based on their $V_{\text{max}}$ or is there any significant contribution from the stochastic star formation in them? Rodriguez-Puebla et al. (2013) have shown that the SMC, Sagittarius well stand on the extrapolated stellar mass-$V_{\text{max}}$ relation (stellar Tully-Fisher relation, Avila-Reese et al. 2008) with a slope of $\sim 0.3$. The expected gap in stellar mass between the two satellites from the $M_* - V_{\text{max}}$ relation is thus $\Delta \log M_* \sim \Delta \log(V_{\text{max,SMC}}/V_{\text{max,Sag}})/0.3 \approx 1.1$, which is close to the observed one. It indicates that the stochasticity of star formation in SMC and Sagittarius is equal or not important, so the gap of $\Delta \log M_* \sim 1$ is more physically related to the difference in mass/$V_{\text{max}}$ of the two satellites.

For the following analysis, we describe the gap in stellar mass between the satellite galaxies in a group as $\Delta_{i,j} = \log M_{*,i} - \log M_{*,j}$, where $M_{*,i}$ is the stellar mass of the $i^{th}$ massive satellite galaxy. The gap in the MW is then described as $\Delta_{23} > 1$. To be exactly analogous to the MW, we should look into groups with $\Delta_{23} > 1$. In our simulation, we have 2831 groups with $M_{\text{vir}} > 10^{13} M_\odot$, and only 13 of them have $\Delta_{23} > 1$. To increase the sample for statistical significance, here we use $\Delta_{12}$ and label those groups with $\Delta_{12} > 1$ as ‘big gap’ groups. In this way we then have 40 groups with $\Delta_{12} > 1$ from our simulation, and it enable us to derive reliable formation history of them and study the origin of these ‘big gap’ groups.
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3 RESULTS

In this part we present the gap distribution in the data and in the simulation, and check if the model galaxies reproduce the gap distribution seen in the group catalogue from the SDSS. Only in the case the model is able to describe the gap distribution or gap-halo properties correlation, we are able to use the simulated galaxies to investigate the origin of the ‘big gap’ groups.

Fig. 1 shows the scatter between $\Delta_{12}$ and the halo properties. The upper panels are from the group catalogue of Yang et al. (2012), and the lower panels are results from our semi-analytical model. The left panel show the distribution between $\Delta_{12}$ and the virial mass of the group. It is seen that the distribution from the data and the model is very similar: the gap distribution is dependent on group mass. In massive groups the gap is much narrow and lower, that the difference in stellar mass of the first, second massive satellite galaxies is smaller. In low-mass groups, the distribution of $\Delta_{12}$ is wider, with a tail up to 1.5. The vertical dashed line in the upper left panel show the gap in the MW, and the groups to the right of the line are called as ‘big gap’ groups. As the distribution of $\Delta_{12}$ is a function of halo mass, we select a narrow mass bin with $\log M_{\text{vir}} = [13, 13.5] M_\odot$, and plot the cumulative distribution of $\Delta_{12}$ in these haloes in the inserted panel in the left lower panel, where the solid line is for the SDSS data and dotted line is our model. It is seen that the distribution is very similar. There are 1% ‘big gap’ groups in the data (solid line with Poisson error bar) and 2% in the model.

The right panels further test if the gap distribution is similar in the data and the model by showing the scatter between $\Delta_{12}$ and $\Delta_{01}$, where $\Delta_{01}$ is the gap in stellar mass between the central galaxy and the most massive satellite. Usually $\Delta_{01} > 1.0$ is an indication of a fossil group (Ponman et al. 1994) and a fossil group is believed to has formed early and being relaxed for a longer time, so most massive satellite galaxies have merged with the central galaxy (e.g., Jone et al. 2003; D’Onghia et al. 2005; von Benda-Beckmann et al. 2008; Kundert et al. 2015). Firstly seen is that the scatter distribution between the data and the model is again very similar, indicating the model well reproduce the properties of observed galaxies. It is also seen that in either fossil groups ($\Delta_{01} > 1$) or ‘big gap’ groups ($\Delta_{12} > 1$), the distributions of $\Delta_{01}$ and $\Delta_{12}$ are not strongly correlated, indicating that the formation of fossil groups and ‘big gap’ groups are not related. The formation of a fossil group is not due to the selective mergers of satellite galaxies, ie, those satellite with mass between the first and second massive satellites.

The above comparison shows that our model is able to reproduce the distribution of the gap seen in the data, and now we use the model galaxies to investigate the origin of the ‘big gap’ groups in...
we show the stellar mass versus the accretion halo mass. The data have similar distributions on the gap in stellar mass between the most and second massive satellite galaxies. We conclude that these 'big gap' groups are purely due to their formation history.

In Fig. 3 we show the distribution of the accretion halo mass (normalized by the group virial mass) of the most massive satellite galaxies (solid lines) and the second massive satellites (dashed lines). It is found that in normal groups the accretion mass between the first and second massive satellites are closer, with the peak mass differ by about 0.4 dex. But for the 'big gap' groups, the second massive satellites have a peak accretion mass at about 1% of the group virial mass. The peak accretion mass of the first massive satellites in 'big gap' groups is slightly higher than that in the normal groups. The right panel of Fig. 3 shows the halo mass function of accreted satellite galaxies per group. The black solid line shows that in normal groups, the number of accreted low-mass haloes increases with decreasing mass, consistent with the expectation from the CDM model. However, in the 'big gap' groups, there is a dip at around $M_{acc}/M_{vir} \sim 0.1$ (seen in the left panel), which happens to be between the first and second massive satellites. The lack of accreted haloes with $M_{acc}/M_{vir} \sim 0.1$ well explains why there is a big gap in the stellar mass of satellites in the 'big gap' groups.

4 CONCLUSION AND DISCUSSION

Using the group catalogue from the SDSS DR7 and the galaxies from a semi-analytical model, we study the gap in stellar mass between the most massive and the second massive satellite galaxies in groups. We have obtained the following results,

- The data and the model have similar distributions on the gap in stellar mass between the most and second massive satellite galaxies in groups. The gap in stellar mass is dependent on group mass and being wider in low-mass groups. For groups with virial mass $M_{vir} = [13, 13.5]M_\odot$, there are 1% of groups with a larger gap with $\Delta_{12} > 1$ (a factor of 10) in the data, and it is about 2% in the model.
- Using model galaxies from the simulation, it is found that there is a good correlation between stellar mass and accretion halo mass, and the lower stellar mass in the second massive satellite is from their lower halo mass at accretion. The gap in the 'big gap' groups is from the lack of accreted haloes with $M_{acc}/M_{vir} \sim 0.1$ compared to other normal groups. The formation of 'big gap' groups is purely due to their formation history.

We note that in our analysis we use the gap in stellar mass as an analog of the TBTF problem in the MW. The often termed TBTF in the Milky Way is expressed using the maximum circular velocity which is a more reliable estimator of the halo mass at accretion. However, on groups scales it is expected that stellar mass is more strongly correlated with the accretion mass as the stochasticity in star formation is only expected in low-mass haloes. If the extrapolation of our results to the Milky Way is appropriate, it implies that the TBTF problem in the Milky Way could be a very nature consequence of its formation history although the probability is only around 1%.

The lack of accreted massive subhaloes in the Milky Way is also consistent with other expectations. The appearance of two massive satellites (LMC, SMC) in MW-size halo is actually in low probability, and the accretion of too many massive subhaloes will also challenge the observed stable disk in the Milky Way (e.g., Boylan-Kolchin et al. 2010). However, along with other facts on the rarity of MW satellite distribution (e.g., Boylan-Kolchin et al. 2010). However, along with other facts on the rareness of MW satellite distribution (great thinner disc and core of the Milky Way), it is very likely that the formation of MW is quite different from the typical MW-size halo in the CDM model. Future surveys, such as GAIA, could put more strong constraints on the formation history of the Milky Way.

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Figure 3. The distribution of the accretion halo mass for satellite galaxies. Left pane: the accretion mass distribution for the first, second massive satellite galaxies using solid and dashed lines. Right panel: the number of accreted haloes as a function as the accretion mass. In both panel, red color is for the ‘big gap’ groups and black for other groups. A lack of accreted galaxies with accretion mass $M_{\text{acc}}/M_{\text{vir}} \sim 0.1$ is clearly seen in the ‘big gap’ groups.

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