The abundance of satellite galaxies in the inner region of ΛCDM Milky Way sized haloes

Ming Li1,*, Liang Gao1,2, Jie Wang1

1 Key Laboratory for Computational Astrophysics, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, China.
2 Institute of Computational Cosmology, Department of Physics, University of Durham, Science Laboratories, South Road, Durham DH1 3LE.

ABSTRACT

The concordance ΛCDM Cosmology predicts tens of satellite galaxies distributed in the inner region (< 40 kpc) of the Milky Way (MW), yet only 7 were discovered at present day, including 3 discovered recently by Dark Energy Survey (DES). We use 5 ultra-high resolution simulations of MW sized dark matter haloes from the Aquarius project, combined with GALFORM semi-analytical galaxy formation model, to investigate properties of the model satellite galaxy population inside 40 kpc of MW sized haloes. On average, in each halo this model predicts about 20 inner satellite galaxies, among them 5 are comparable to the classic satellites in the luminosity, these are in stark contrast to the corresponding numbers in observations. We further investigate the survivability of these model inner satellites in the presence of a central stellar disk with a set of ideal simulations. These are done by re-evolving a quarter (30) of the whole Aquarius inner satellite galaxies (121) by including a static disk potential in addition to the MW halo. Our finding is that, while the additional disk can completely disrupt some satellites with very close percentiles, 60 percent of them could still survive to the present day. This results in 14 satellite galaxies within the 40 kpc of each Aquarius when taking into account of the MW disk, still a factor of 2 more abundant than the observed number. Therefore, unless half a dozen satellite galaxies could be discovered within 40 kpc of the MW by future surveys, the deficiency in the inner satellite galaxy population may post a serious challenge to the standard ΛCDM theory.

Key words: method: numerical – cosmology: theory – galaxies: haloes – galaxies: dwarf – dark matter.

1 INTRODUCTION

The Λ Cold Dark Matter model (dubbed ΛCDM) has been extremely successful to predict various observational properties and the evolution of the large-scale structure of the Universe. However it is not equally well to predict the galaxy properties on galactic scale and below. For instance, there has been long debate on whether the ΛCDM theory can accommodate the observed abundance and internal structure of satellite galaxies in our Milky Way, namely the so called “missing satellite” (Klypin et al. 1999; Moore et al. 1999), “core and cusp” (Simon et al. 2005; de Blok 2010; Strigari et al. 2010; Walker & Peñarrubia 2011; Martinez 2015) and “too big to fail” (Boylan-Kolchin et al. 2011, 2012) problems.

Gao et al. (2010) (hereafter G10) put forward a related problem on this regard. In G10, the authors use a set of ultra-high resolution dark matter only simulations of Milky Way (MW) sized haloes, and find there are quite abundant dark matter subhaloes residing in the inner 40 kpc of their host haloes, among these about 20 – 30 should be relics of the first galaxies shining light at present day because they were massive enough to cool by atomic hydrogen cooling before reionization. On the contrary, among the observed MW satellite galaxies from SDSS and DES survey combined, only 7 are within the same distance at present time. Hence, the results may point out a discrepancy in the abundance of satellites in the inner region of the MW between observation and theory.

The galaxy formation model used in G10 is robust yet simple by using atomic cooling argument to judge whether or not a halo can form stars, but make no prediction on
properties of the satellite galaxies. In this short paper, we compensate G10 by taking advantage of the power of a sophisticated galaxy formation model GalForm (Bower et al. 2006; Font et al. 2011), to make more detailed predictions of properties of inner satellite galaxies in the MW sized dark matter haloes, and compare with observations to investigate whether or not the abundance of inner satellite galaxy is a problem of ΛCDM Cosmology. Moreover, we will take into account the impact of a stellar disk in the centre of MW halo on the survivability of these inner satellite galaxies. Hydrodynamic simulations from previous studies on this subject often have much poorer resolution, we compensate these studies by performing a sequence of ideal simulations of varying resolution in order to carry out numerical convergence study.

The organization of this paper is as follows. In Section 2, we briefly introduce the numerical simulations and galaxy formation model used in this study. In Section 3, we use GalForm to predict the satellite population within 40 kpc of MW and compare them with observations. In Section 4, we present ideal simulations in order to assess the impact of a stellar disk on the survivability of the model inner satellite galaxies. In Section 5, we summarize our results and draw conclusions.

2 THE COSMOLOGICAL SIMULATIONS

Numerical simulations used in this work comprise high resolution re-simulations of 5 individual MW sized dark matter haloes and their surroundings from the AQUARIUS Project (Springel et al. 2008). Each AQUARIUS halo has been simulated at different resolutions to carry out numerical convergence studies. Here we use the simulations with level 2 resolution which contains about $10^8$ particles inside the virial radius of each halo. The AQUARIUS simulation suits assume cosmological parameters as $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\sigma_8 = 0.9$, $n_s = 1$ and $h = 0.73$. These values deviate from the latest Planck results (Planck Collaboration et al. 2014, 2016) but this small offset has negligible effect on our main results.

At each recorded snapshot, dark matter haloes are identified with the friends-of-friends (FoF) algorithm by linking particles separated by 0.2 times the mean inter-particle separation (Davis et al. 1985). Based upon the FoF group catalogue, the SUBFIND (Springel et al. 2001) is applied to identify local over-dense and self-bound dark matter sub-haloes; merger trees were constructed by linking each sub-halo at successive snapshots to its unique descendant using the algorithm described in Helly et al. (2003). We follow the baryonic evolution using the semi-analytic model GalForm developed by Font et al. (2011). The model explicitly follows the evolution of the dark matter halo within which a galaxy forms, and after the halo is accreted to a larger object and becomes a satellite galaxy. Font et al. (2011) have shown that the model matches a large body of observational data.

3 THE INNER SATELLITE GALAXIES IN SIMULATIONS AND OBSERVATIONS

In Figure 1 we present cumulative $V$–band luminosity function (top panel) and spatial distribution (bottom panel) of the model satellite galaxies within 40 kpc of the AQUARIUS haloes. The thick black lines show the averaged value of five AQUARIUS haloes, while gray region displays the halo-to-halo variation. The thick orange lines show result for the observed MW satellites. The vertical spanned region indicates the $V$–band detection limit at 40 kpc from the MW centre, computed with eq. 2 in Tollerud et al. (2008).

Figure 1. $V$–band luminosity function (top panel) and spatial distribution (bottom panel) of the model satellite galaxies within 40 kpc of the AQUARIUS haloes. The thick black lines show the averaged value of five AQUARIUS haloes, while gray region displays the halo-to-halo variation. The thick orange lines show result for the observed MW satellites. The vertical spanned region indicates the $V$–band detection limit at 40 kpc from the MW centre, computed with eq. 2 in Tollerud et al. (2008).

In Figure 1 we present cumulative $V$–band luminosity function and spatial distribution of the model and satellite galaxies within 40 kpc of five AQUARIUS haloes. The dark solid line shows the averaged count and the light shaded area displays the whole scatter of five haloes. We also show results for the known satellite galaxies within the same distance in the same figure with orange lines. These known satellite galaxies are collected from McConnachie (2012, Table1-3), Drlica-Wagner et al. (2015) and Koposov et al. (2015). They are listed in Table 1. The vertical yellow shaded area indicates the observational detect limits of satellite galaxy of the SDSS survey (Koposov et al. 2008, 2009; Tollerud et al. 2008).
Table 1. Known MW satellite galaxies distributed within $D_{GC} \leq 40$ kpc of the galactic centre. The first section of satellites were discovered from SDSS survey (McConnachie 2012). The second section of satellites were detected by DES (Drlica-Wagner et al. 2015; Koposov et al. 2015). In the table, the distance of each satellite galaxy from the MW centre (the sun) $D_{GC}$ ($D_{C}$), $V$-band magnitude $M_V$, stellar mass $M_\star$, and dynamical mass within half light radius $M_{dyn}(\leq r_h)$ (if available) are listed.

| Name                  | $D_{GC}/D_{C}$ (kpc) | $M_V$ (mag) | $M_\star$ ($M_\odot$) | $M_{dyn}(\leq r_h)$ ($M_\odot$) |
|-----------------------|----------------------|-------------|------------------------|----------------------------------|
| Sagittarius dSph      | 18.0 / 26.0          | -13.5       | 2.1 x 10^7            | 1.9 x 10^8                       |
| Segue I               | 28.0 / 23.0          | -1.5        | 3.4 x 10^2            | 2.6 x 10^5                       |
| Ursa Major II         | 38.0 / 32.0          | -4.2        | 4.1 x 10^3            | 3.9 x 10^6                       |
| Bootes II             | 40.0 / 42.0          | -2.7        | 1.0 x 10^3            | 3.3 x 10^6                       |
| Tucana III (DES J2356-5935) | 23.0 / 25.0       | -2.4        | 8.0 x 10^2            | —                                |
| Ret II (DES J03356-5403)  | 32.0 / 32.0      | -3.6        | 2.6 x 10^3            | 2.4 x 10^5                       |
| Cetus II (DES J0117-1725)  | 32.0 / 30.0        | 0.0         | 1.0 x 10^3            | —                                |

4 THE IMPACT OF A STELLAR DISK ON THE ABUNDANCE OF INNER SATELLITE GALAXIES

4.1 Models and numerical experiments

Model of the MW. The MW comprises a dark matter halo and a disk as well as a bulge. For simplicity, we neglect the bulge component and treat the dark matter halo and disk components as rigid background potentials and thus neglect the effect of dynamical friction. We assume that dark matter distribution of the MW follows a NFW (Navarro et al. 1996) distribution. The potential corresponding to the NFW halo reads

$$\Phi_{NFW}(r) = - \frac{G M_{\text{vir}}}{r} \ln \left( 1 + \frac{r}{r_{\text{vir}}} \right).$$

4 Defined as the radius within which the mean density is 200 times the critical density at the time of infall.
Figure 2. Cumulative distribution function of orbital energy parameter $R_{\text{circ}}(E)/R_{\text{vir}}$ at infall (left) and the first pericentric radius $R_{\text{per}}$ since infall (right) of the Aquarius inner satellites. The blue solid lines are for the full sample, and the orange solid lines are for the random selected 30 satellites.

We model the disk as an embedded potential which follows an axisymmetric disk model (Miyamoto & Nagai 1975):

$$\Phi_d(R,z) = -\frac{GM_d}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}$$

with radial and vertical scale lengths $a = 6.5$ kpc and $b = 0.25$ kpc, and mass $M_d = 0.1M_{\text{vir}}$.

Model of satellite galaxy. The orbiting satellite galaxy is discretized with N-body model by generating an equilibrium particle realisation, the density distribution follows a truncated NFW profile (Kazantzidis et al. 2004b)

$$\rho(r) = \begin{cases} \rho_0 & (r \leq r_{\text{vir}}), \\ \frac{\rho_0}{\left(1 + \frac{r}{r_{\text{vir}}}\right)^{\frac{1}{\alpha}} - \frac{c_{\text{vir}}}{\epsilon}} & (r > r_{\text{vir}}) \end{cases}$$

$\rho_0$ and $c_{\text{vir}}$ are the characteristic density and the concentration of the satellite respectively, $r_{\text{dec}}$ is a parameter that controls the sharpness of the slope transition towards an exponential cutoff and is set to 0.3 times of satellite’s virial radius $r_{\text{vir}}$. To obtain a continuous logarithmic slope, $\varepsilon$ is defined as

$$\varepsilon = -\gamma - \beta c_{\text{vir}} + \frac{r_{\text{vir}}}{r_{\text{dec}}}.$$ 

Throughout this work we adopt a cuspy NFW density profile with $(\alpha, \beta, \gamma) = (1, 3, 1)$.

The coordinate system is centred on the MW halo. The disk potential is fixed on the $X-Y$ plane. The N-body simulations presented in this study were carried out with the P-GADGET3 code (Springel 2005) under isolated boundary conditions.

Table 2. Overview of the detailed properties of the satellite galaxies used in our ideal experiments. Columns (2–4) show the virial mass, radius and concentration (calculated with the halo mass-concentration relation from Duffy et al. (2008)) respectively. Column (5–6) are particle numbers and the corresponding softening lengths used for the resolution test and ordinary simulations.

| Run   | $m_{\text{vir}}$ (M$_{\odot}$) | $r_{\text{vir}}$ (kpc) | $c_{\text{vir}}$ | $N_{\text{part}}$ (part) | $\epsilon$ (kpc) |
|-------|------------------|----------------|------------|-----------------|-------------|
| halo.m1e8 | $10^8$ | 7.548 | 13.127 | $10^4$ | 0.34 |
|       | $10^5$ | 106 | 0.03 |

Table 3. The collection of parameters of different orbit setups with initial orbital energy characterised by $R_{\text{circ}}(E)/R_{\text{vir}}$, the pericentric distance and the initial velocity expressed in circular velocity at virial radius of the host halo.

| Run   | $R_{\text{circ}}(E)/R_{\text{vir}}$ | $R_{\text{per}}$ | $(v_{x0},v_{y0},v_{z0})$ (V$_{\text{vir}}$) |
|-------|------------------|-------------|-----------------|
| Orbit I | 1.34 | 16.26 | (-1.19,0.04) |
| Orbit II | 3.25 | (-1.18,0.14) |

4.2 Resolution Test

It is important to firstly identify the required numerical resolution to reliably resolve the dynamics of satellite galaxies. To this end, we evolve a satellite galaxy at varying numerical resolutions and assuming two sets of orbital parameters. The mass and orbit energy parameter of the satellite is assumed to be $M = 10^8$ M$_{\odot}$ and $R_{\text{circ}}(E)/R_{\text{vir}} = 1.34$, respectively. These parameters are chosen to closely match the typical values of the satellite galaxies in the Aquarius simulation.
Satellites in the inner region of MW

suit These acts. We adopt two pericentres for the tests by choosing values of $R_{\text{per}}$ to be 10 and 50 percentiles of the distribution function shown in the right panel of Figure 2, representing an extreme and a typical case to examine the impact of the disk on the tidal disruption of the galaxy.

We assume the total mass profile of the galaxy following a NFW profile with concentration parameter $c = 13.1$, corresponding to the value estimated by the halo mass-concentration relation given by Duffy et al. (2008). The model galaxies are starting from the virial radius of the MW halo with the coordinates $(x, y, z) = (1, 0, 0) R_{\text{vir}}$, and are evolved for 10 Gyr which corresponds to the typical infall redshift $z = 2$ of satellite galaxies in the AQUARIUS simulation suits.

We carried out numerical experiments with different particle numbers, $N_{\text{part}} = 10^4, 10^5, 10^6$ and $10^7$. For the galaxy we follow its evolution in the MW halo model with and without a disk component under two set of orbital parameters. SUBFIND (Springel et al. 2001) is applied to calculate the residual bound mass of each galaxy.

In Figure 3, we present the evolution of the bound mass fraction of the satellite galaxy with different resolutions and different orbital parameters. Upper panels show results for the extreme orbit case Orbit I and bottom panels are for the typical one, Orbit II. Simulations excluding and including the disk are shown in the left-hand and right-hand panels, respectively. In both cases, numerical resolution has a large effect on the tidal distribution of the satellite galaxy. Using a number of particles like $10^4$, as similar to the most up-to-date highest resolution hydrodynamic simulations, severely underestimate the survivability of the galaxy, in particular in the cases including the disk. For the extreme orbital parameter, our numerical experiments converge at a particle number $10^6$. The particle number for the convergence is less for the typical case of Orbit II, which is about $10^5$. From a conservative consideration, in the follows, we will perform all our experiments with a particle number $10^6$ for each satellite galaxy. This number is compatible to that used in previous works (Chang et al. 2013; Errani et al. 2017; Frings et al. 2017) and is much larger than the highest resolution hydrodynamic simulation in the community. This should partially

Figure 3. The evolution of the bound mass fraction of a satellite galaxy with an initial mass $10^8 M_\odot$ in the MW model without (left) and with (right) a disk component. The top and bottom rows show the results for Orbit I and Orbit II, respectively. Lines with different colours distinguish simulations with different resolutions.
account for the fact that these simulations nearly have no any satellite galaxies near the centre.

4.3 The impact of the MW disk on the abundance of the inner satellite galaxies

To explore the impact of the disk on the tidal disruption of the model inner satellite galaxies, we randomly select 30 galaxies from our full 121 inner satellite galaxy sample. The orange lines in the Figure 2 display distributions of orbital parameters of this sub-sample. As can be seen, they agree very well with the whole sample, suggesting that they are a fair representative sample of the Aquarius inner satellite galaxies. For each galaxy in the random selected sample, we follow its evolution from its infall time with $10^5$ particles in the MW model with the disk we described in previous section. The mass distribution of each galaxy is assume to follow NFW profile, it’s mass, orbital parameters, concentration parameter and position are set to be the corresponding values at infall given by the Aquarius simulation suits. The disk is fixed on $X–Y$ plane. We also re-run 10 of these galaxies by varying the disk plane to be $X–Z$ and $Y–Z$, and find the results hardly change. In the final outcome of our 30 simulations, 12 (40%) galaxies are completely disrupted due to the presence of the disk. Here we define a galaxy completely disrupted when Subfind is not able to find more than 32 bound particles. Apply the result to the whole Aquarius inner galaxy sample, 73 out of 121 model inner satellite galaxies should survive to the present day. Namely, on average, each Aquarius halo contains 14 inner satellite galaxies after taking into account the effect of the disk. We present the the corrected cumulative $V$–band luminosity function of the model satellite galaxy in Figure 4. Apparently, the impact of the disk on the abundance of the inner satellite galaxy is only moderate, the model predicts 2 times more inner satellite galaxies than observations.

5 CONCLUSIONS

In this work we make use of the Aquarius project—a set of ultra-high resolution simulations of MW sized dark matter haloes, combined with a sophisticated semi-analytical galaxy formation model–Galform, to investigate the abundance of satellite galaxies residing within 40 kpc of halo centre. Using a simple atomic cooling argument, G10 suggested that the abundance of MW inner satellite galaxies may be incompatible with observations. We use Galform to predict properties of these $\Lambda$CDM model inner satellite galaxies. On average, about 20 satellite galaxies reside within 40 kpc of each Aquarius halo, about a factor of 3 times exceeding the observed number. Most of these model inner satellite galaxies are brighter than the detection limit of SDSS survey, 5 of them are as bright as classic satellite galaxies.

Given the apparent inconsistency between the $\Lambda$CDM prediction and observations, we perform a series of numerical experiments to examine the impact of the disk on the abundance of the inner model satellite galaxies. To this end, we randomly select a quarter of the Aquarius inner satellite galaxies. For each of them, we follow its evolution from the infall time to the present day, with the orbital parameters and positions taken from the original Aquarius simulation suits. Our finding is that, the MW disk only has strong effect to disrupt satellite galaxies with very close pericentric parameters. As a result, in the presence of the disk, the number of the model inner satellite galaxies can only be reduced by 40 percent when comparing with the case without the disk. For each Aquarius halo, the model still predicts 14 satellite galaxies within 40 kpc, a factor of 2 more abundant than observations. Note, when we evolve each galaxy in the simulation, we assume static potentials for the MW halo and disk with present day values during its entire evolution. This neglects facts that the MW only acquires a fraction of its present day mass by then and the MW disk may grow significantly after the infall of the satellite galaxy. Hence, our results may overestimate the impact of the disk on the disruption of the inner satellite galaxies. Therefore, unless at least half a dozen satellite galaxies could be discovered in future surveys, the deficiency in the inner satellite galaxy population in the MW may poses a serious challenge to the current concordance $\Lambda$CDM model.

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