Modeling the Milky-Way Satellite galaxies

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Abstract. We revisit the Milky Way satellite problem using a semi-analytical model of galaxy formation and compare the predicted luminosity function to recent result from the SDSS. With cosmic photoionization, the luminosity function can be brought into broad agreement with the data between $-15 < M_V < -2$. This improvement over previous semi-analytical model results (e.g., Benson et al. 2002) is from our adoption of improved models for galaxy merger history and galaxy merging time-scales. The very faint satellites ($M_V > -5$) formed in halos with virial temperature over $10^4K$ (mass around $10^9M_\odot$ before accretion), but their baryon content are strongly suppressed by photoionization. We model the mass evolution of the subhalos, and compare the predicted mass-to-light ratio with the data. We find that the measured total mass inside the luminous radii of satellites are about 5% of their present total dark matter mass.

Keywords. Galaxy: formation, galaxies: luminosity function

1. Introduction

One of the most mysterious of our Milky-Way Galaxy is the “missing satellite problem” that cold dark matter scenario predicts its number of satellite galaxies to be around hundred, but only dozens are observed (e.g. Moore et al. 1999). A few solutions have been proposed for this contradictory. One instant question is if we are comparing the right things, i.e. how to relate the observed stellar velocity dispersion to the measured circular velocity from N-body simulation (Hayashi et al. 1999). Another possible solution is that photoionization suppress the gas accretion in small halos, and only halos formed before reionization can form stars. (e.g. Gnedin 2000). Also there is worry about the incompleteness of observation as very faint satellites have too low surface brightness to be observed. In recent years, more faint satellites are observed along with their kinematics and mass measurements, and the satellite luminosity function is also well determined from the SDSS (Koposov et al. 2008). One the other hand, theoretical modelling of dark matter halo formation history (Cole et al. 2008) and galaxy merging time-scales (Jiang et al. 2008, Boylan-Kolchin et al. 2008) are also improved. Given these progress, it is deserved to revisit the “missing satellite problem” and there have been a few papers to address this (e.g. Simon & Geha 2007).

Here we use the semi-analytical model of galaxy formation (Kang et al. 2005) to predict the luminosity function, mass-to-light ratios for satellite galaxies and compare them with the data.

2. Model

One of the main ingredients to model the satellite galaxy population is to produce their formation and assembly history. Here we use the Monte-Carlo merger tree code from Parkinson et al. (2008) to obtain the formation history of a Milk-Way type galaxy with mass around $10^{12}M_\odot$. This new Monte-Carlo algorithm is still based on the EPS formula, but revised to match the Millennium Simulation (Springel et al. 2005) results at different
mass scales. Cole et al. (2008) have shown that for halo with mass around $10^{12} M_\odot$, the merger tree from the previous Monte-Carlo algorithm (Cole et al. 2000) produces too strong evolution and too many major mergers at lower redshift. We produce 1000 realizations of the merger trees using the new Monte-Carlo algorithm, and in Fig.1 we show their formation history with comparisons to the N-body simulation results (Stewart et al. 2008, Giocoli et al. 2008). It can be seen that both the evolution of the main progenitors and the mass function of accreted subhalos agree well with the simulation results.

We then use the semi-analytical model of Kang et al. (2005) to model the formation of satellite galaxies along the merger trees. The semi-analytical model includes a few important physical processes governing galaxy formation: hot gas cooling in halos, star formation from cold gas, supernova feedback to reheat the inter-stellar medium, stellar evolution, galaxy merger. We update the model of Kang et al. (2005) by using an improved fitting formula for the galaxy merging time-scales from Jiang et al. (2008), who have shown that for massive mergers, the survival time of satellite galaxies in SPH simulation is longer than the prediction from Lacey & Cole (1993).

Here we also include a simple model for photoionization from Kravtsov et al. (2004). In case of heating from ionized photons, the gas content in halos formed after reionization are suppressed and can be simply described by a filter mass which increases with redshift. The filter mass increase from $10^8 M_\odot$ at $z=8$ to $4 \times 10^{10} M_\odot$ at $z=0$ (Okamoto et al. 2008) recently argue that the filter mass should be smaller). The gas fraction in a filter mass halo is about half of the universal fraction. With photoionization the amount of gas available for star formation is decreased significantly in less massive halos formed after reionization. In this paper, we take the reionization redshift as $z=7$. 

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**Figure 1.** The formation history of halos with mass of $10^{12} M_\odot$ at $z=0$. Left panel: the mass evolution of the main progenitors. Right panel: the mass function of accreted subhalos by the main progenitors. Good match are found with N-body simulations (Stewart et al. 2008, Giocoli et al. 2008).
3. Result

3.1. Luminosity function of satellites

In Fig. 2 we show the model luminosity function (LF) of satellites with comparison to the recent results of Koposov et al. (2008) from SDSS DR5. Koposov et al measured the LF up to \( M_V = -2 \), and found that LF can be described by a power law with slope of 0.1. At the very faint end \( (M_V > -5) \) the solid circle points in Fig. 2 are extrapolated assuming the satellite galaxies following a NFW density distribution, and empty circles are assumed with an isothermal distribution (See Koposov et al. 2008). It can be seen that if there is only supernova feedback (dashed line), the predicted total number of satellites are more than observed by a factor of 3. With the suppression of gas accretion by photoionization, the LF (solid line) can be brought into a broad agreement with the data. This is expected that the decrease of gas content produce less stellar mass. Compared to the model prediction of Benson et al. (2002), our model produces more luminous satellites with \( M_V < -15 \). This success is credited to the combination of improved models for halo merger tree and galaxy merging time-scales. The merger tree used by Benson et al. (2002) is based on Cole et al. (2000), which produces too many recent major mergers. As the galaxy merging time is shorter for major merger, so less is the number of survived massive satellites. Also we use the new fitting formula from Jiang et al. (2008) for galaxy merging time-scales, which is longer than the often used dynamical friction time scale from Lacey & Cole (1993).

As we can see that without photoionization, there are only a few satellites fainter than \( M_V = -5 \). This is because hot gas can not cool via hydrogen line emission in halos with virial temperature below \( 10^4 K \) (\( \sim 10^9 M_\odot \)) and \( H_2 \) cooling is very inefficient. The solid line shows that those faint satellites formed in halos with virial temperature just over \( 10^4 K \), but have their gas content strongly suppressed by photoionization (Similar conclusion was also obtained by Kravtsov et al. 2004). In our model, it is difficult to produce satellite \( (M_V \approx -3) \) with number around 30, and this favors the satellites to have an isothermal density distribution.

Figure 2. The luminosity function of satellite galaxies in a Milky-Way type halo. Data points (circles) are from Koposov et al. (2008). Dashed line is model result with supernova feedback only, and solid line (with Poisson error) is model with photo ionization included.

Figure 3. The mass-to-light ratio of satellite galaxies. Data points are from compilation of Simon & Geha (2007). Solid line is the model prediction with 20th and 80th percentiles of the distribution (dashed lines). Here we assume that measured total mass (inside luminous radii) of satellites are 5% of their present dark matter mass.
Figure 4. The mass of faint satellites \( (M_V > -5) \). Dashed line is their mass distribution before accretion, and solid line is the distribution of their present mass after evolution. The distribution has a sharp peak at \( 10^9 M_\odot \) before accretion, where hydrogen line emission cooling is efficient. The present mass has a broad distribution around \( 3 \times 10^7 M_\odot \), and the wide spread is from the dispersion of accretion times.

3.2. Mass-to-light ratio of satellites

With the advent of accurate measurements of satellites kinematics, it is possible to obtain the total mass of satellite galaxies inside their luminous radii. It is found that most satellites are dominated by dark matter inside their luminous radii. Here we show the mass-to-light ratio of satellites in Fig.3, where the data points are from compilation by Simon & Geha (2007). We model the dark matter mass evolution of satellite galaxies using the model of Giocoli et al. (2008), and we further assume that about 5% of the total dark matter mass are inside their luminous radii. The model prediction (solid line) along with 20th and 80th percentiles of the distribution (dashed lines) are shown in Fig.3. We can find good agreement with the data from \( M_V = -3 \) up to \( M_V = -15 \).

The above results of LF and mass-to-light ratio are encouraging as they indicates that we can model the luminosity and mass of satellites simultaneously. Now we make prediction for the dark matter mass of satellites faint than \( M_V = -5 \). In Fig.4, we show their host halo mass before accretion (dashed line) and the present dark matter mass after evolution (solid line). As we can see that the faint satellites \( (M_V > -5) \) formed in halos with mass peak at \( 10^9 M_\odot \), and they have a broad distribution for their present mass with peak at about \( 3 \times 10^7 M_\odot \). The broad distribution is from the spread of their accretion times.

4. Conclusion

we revisit the “missing satellite problem” using a semi-analytical model of galaxy formation combined with a high-resolution merger tree from Monte-Carlo algorithm (Parkinson et al. 2008). we model the luminosity function and mass-to-light ratio for the satellites. The model luminosity function agrees well with the recent results of Koposov et al. (2008) from the SDSS DR5 only if the photoionization effect is included to suppress the gas fraction in less massive halos. Our ability to produce more luminous satellite galaxies than previous semi-analytical models (e.g., Benson et al. 2002) is from
the improvement on modelling of halo merger tree and galaxy merging time-scales. Very faint satellites \((M_V > -5)\) form in halos with virial temperature above \(10^4 K\), but their gas content are strongly suppressed by photoionization. In addition their number density favors an isothermal density distribution in the Milky-Way. We model the mass evolution of subhalos using the model of Giocoli et al. (2008), and find that the measured total kinematic mass inside the luminous radii of satellite galaxies are about 5% of their present dark matter mass.

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