Properties of the satellite population of a Milky Way galaxy in the $\Lambda$CDM Universe

Abstract

We combine a series of high-resolution cosmological simulations with semi-analytic galaxy formation recipes to follow the evolution of a system resembling the Milky Way and its satellites. The semi-analytic model is based on that developed for the Millennium Simulation which successfully reproduces the properties of galaxies on large scales and as well as those of the Milky Way. In this model, we are able to reproduce the luminosity function of the satellites around the Milky Way by preventing cooling in haloes with $V_{\text{vir}} < 16.7\,\text{km}\,\text{s}^{-1}$ (i.e. the atomic hydrogen cooling limit) and including the impact of the reionization of the Universe. Our model satellites show good agreement with the observations. In particular, the mean metallicities, half-light radii, stellar populations and mass-to-light ratios are well matched in our models. We have also investigated how these properties depend on feedback. In particular we do not find a very strong dependence upon the particular implementation of feedback except that a recipe which is more efficient in galaxies embedded in smaller haloes, i.e. shallower potential wells, gives better agreement with the properties of the ultra-faint satellites.

Key words: cosmology: theory – galaxies: Local Group – galaxies: formation – galaxies: dwarf – dark matter

* paper in preparation
3.1 Introduction

The satellites of the Milky Way (MW) are powerful touchstones for galaxy formation and evolution theories. Their proximity facilitates detailed observations and characterisation of their properties and hence constrains ‘near-field’ cosmology. On the other hand, their shallow potential wells make them more sensitive to some important astrophysical processes such as supernova (SN) feedback (Larson 1974; Dekel & Silk 1986) or to the presence of a photoinization background (Babul & Rees 1992).

Deep images have allowed the construction of colour-magnitude diagrams (CMD) of the MW satellites, from which the star formation histories have been deduced. These studies indicate that there is a large variety in the star formation histories of these objects (Mateo 1998; Dolphin et al. 2005). The two gas-rich dwarf irregular (dIrr) Magellanic Clouds show on-going star formation while the other dwarf spheroidal galaxies (dSphs) are gas-deficient and show generally little evidence for recent star formation. Modern studies have revealed that all satellites contain an old stellar population (> 10 Gyr). With the prevalence of the old stellar populations, the MW satellites are likely to have kept the imprints of the young Universe.

In recent years, the number of known satellites around the MW has doubled thanks to the discovery of very low surface brightness dwarf galaxies in the Sloan Digital Sky Survey (SDSS) (Willman et al. 2005a,b; Zucker et al. 2006b; Belokurov et al. 2006b; Zucker et al. 2006a; Belokurov et al. 2007; Irwin et al. 2007; Walsh et al. 2007; Belokurov et al. 2008). These new satellites have lower surface brightness ($\mu > 27$ mag arcsec$^{-2}$) compared to the classical satellites and have similar extents. On the other hand, they have comparable luminosities to some Galactic globular clusters, but are significantly bigger (Belokurov et al. 2007). The nature of these newly discovered satellites is unclear. They could be the prolongation towards the faint luminosity end of the classical MW satellites, tidal features or a brand new class of objects.

Kinematic modelling based on the line-of-sight velocity dispersions have demonstrated that the classical MW satellites are likely embedded in dark matter haloes (Mateo 1998). It has also been shown that the ultra-faint satellites have the mass-to-light ratios as high as $\sim 100$ – 1000 under the assumption of virial equilibrium. This could imply that these are the most dark matter dominated objects known (e.g. Muñoz et al. 2006; Simon & Geha 2007). The constraint on the total mass inferred by the velocity dispersions is still uncertain also because of the mass-velocity anisotropy degeneracy and the small number of tracers employed in these studies. Recent analyses suggest that the MW satellites (including the SDSS satellites) have a common mass scale in their innermost regions (600 or 300 pc) (Strigari et al. 2007, 2008).

The cold dark matter (CDM) hierarchical paradigm successfully explains the large scale structures of the Universe (Spergel et al. 2007). Semi-analytic (hereafter SA) galaxy formation models coupled with merger trees derived within the CDM paradigm are a good technique to diagnose the complex physics involved in the assembly of galaxies with modest computational costs. SA models have suc-
cessfully reproduced properties of galaxies on large scales, e.g. spatial and colour-
magnitude distributions, for galaxies seen in the local Universe (Croton et al. 2006
Bower et al. 2006) and at higher redshifts (Kitzbichler & White 2006). This implies
that galaxy formation and evolution may be understood in detail from first princi-
ples. In spite of the encouraging progress on the large scale, CDM faces its most
severe challenges on the galaxy-scale and below. An example is the ‘missing satel-
lites problem’: namely that the substructures resolved in a galaxy-size DM halo in
high resolution $N$-body simulations significantly outnumber the satellites observed
around the MW (Klypin et al. 1999; Moore et al. 1999).

Earlier studies using SA models already predicted an excess of faint satellite
galaxies around galaxies like the MW (Kauffmann et al. 1993). This as well as later
works have suggested astrophysical processes such as the presence of a photoion-
ization background to reconcile this discrepancy without invoking modifications on
the nature of the CDM particles (e.g. Bullock et al. 2000; Benson et al. 2002
Somerville 2002).

Several groups have more recently attempted to model the properties of the
MW and its satellites in a (semi-)cosmological setting. For example, satellites in SA
models have been shown to reproduce some of the properties of those around the
MW and Andromeda at present-day (Kravtsov, Gnedin & Klypin 2004) and some of
those accreted very early on could have contributed to the MW stellar halo (Font
et al. 2006). However, these studies adopt simple phenomenological recipes of the
star formation and feedback, whose parameters are tuned to reproduce some of
the properties of the satellites in the Local Group. It is therefore less clear how
strong their predictive power is, or whether these models could also account for
observations of galaxies on larger scales.

Benson et al. (2002) use a SA model which successfully reproduces the present-
day field galaxy luminosity function in the local Universe to study the properties of
dwarf satellite galaxies. Their model calculates the influence of reionization self-
consistently based on the production of ionizing photons from stars and quasars
and the reheating of the intergalactic medium. Using this same model, they show
that their satellites have properties which are in good agreement with those around the
MW and M31, such as their luminosity distribution, size, gas content and metal-
llicity. They suggest that the surviving satellites are those which formed while the
Universe was still neutral. The formation of galaxies with small mass that would col-
lapse later is inhibited through a photoinization. They also predict a large number
of faint satellites. However, since their galaxy formation models are coupled with
mergers trees from the extended Press-Schechter formalism (rather than based on
$N$-body simulations), they have to trace the evolution of the dark matter haloes
which host satellites analytically, which prevents them from following the dynami-
cal histories of these objects self-consistently.

Kravtsov et al. (2004) coupled a SA model with merger trees extracted from $N$-
body simulations of MW-like haloes. They followed the dynamical evolution of the
dark matter haloes in the potential well of three MW-like haloes. They found that a
significant fraction of present-day satellites had considerably higher masses when
they formed and therefore could host stars. Though their galaxy formation model successfully reproduce many of the satellites’ properties, it is calibrated using the properties of Local Group galaxies, and hence has less predictive power.

In this Chapter, we diagnose the impact of various astrophysical processes on (sub)galactic scales and gain new insights onto the formation and evolution of satellites around the Milky Way. We combine high-resolution simulations of a MW-like halo with semi-analytic galaxy formation recipes in a full cosmological context to follow the evolution of baryons in the host galaxy and its satellites. We find that by preventing cooling in haloes with $T_{\text{vir}} < 10^4$ K (the atomic hydrogen cooling limit) and including the impact of the reionization of the Universe we are able to reproduce the latest estimation of the luminosity function of the satellites around the Milky Way by Koposov et al. (2008). We are also able to reproduce the metallicity distribution function (MDF) of the MW satellites by including a route to recycle metals produced in newly formed stars through the hot phase. Moreover, our model satellites follow several scaling relations similar to the MW satellites, such as the metallicity-luminosity and the luminosity-size relations. Some other properties including their stellar populations and mass-to-light ratios are also well reproduced in our models while preserving the properties of the central host galaxy (which resembles the MW). We have also investigated how the baryonic properties depend on the SN feedback recipe. In general we do not find a very strong dependence on the particular implementation used except for the newly discovered ultra-faint SDSS satellites. As shown in Chapter [4], we find that the common mass scale of a few times $10^7 \, M_\odot$ seen recently in the MW satellites is a natural outcome of the CDM galaxy formation and evolution model (Li et al., 2008). We also predict that the surviving satellites are associated with haloes whose total mass exceeded a few $10^6 \, M_\odot$ at $z \sim 10 - 20$ and which acquired their maximum dark matter mass, well above the cooling threshold, after $z \sim 6$.

This Chapter is organised as follows. Section [3.2.1] gives a brief summary of the cosmological simulations that we use in this study, and in Section [3.2.2] we summarise our semi-analytical galaxy formation models emphasising the new features added to the sibling model from De Lucia & Helmi (2008). In Section [3.3] we present our main results and in Section [3.4] we discuss the implications of our work. We conclude in Section [3.5].

### 3.2 The hybrid method of galaxy formation and evolution

#### 3.2.1 $\Lambda$CDM Simulations of a Milky Way-like halo

We have utilised a series of high resolution simulations of a MW-like halo (Stoehr et al., 2002; Stoehr, 2006). We note that this is the exact GAnew series used in the previous studies by Li & Helmi (2008) (Chapter 2), De Lucia & Helmi (2008) and Li et al. (2008) (Chapter 4). We therefore only recapitulate the basic properties of the simulations here and refer the reader to the first two above mentioned papers.
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for more details. The simulations were carried out with GADGET (Springel et al., 2001b) in a full cosmological context with $\Omega_0 = 0.3, \Omega_\Lambda = 0.7, h = 0.7$, and Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$. The MW-like halo was simulated four successive times with the mass resolution increased by a factor 9.33 each time. In the highest mass resolution simulation (GA3new), there are approximately $10^7$ particles with mass $m_p = 2.063 \times 10^5 M_\odot h^{-1}$ within the virial radius. Each of these re-simulations produced 108 outputs. These outputs are equally spaced logarithmically in time between $z = 37.6$ and $z = 2.3$ and are nearly linearly spaced from $z = 2.3$ to the present time.

Virialised structures were identified using the standard friends-of-friends (FOF) algorithm linking particles separated by less than $0.2$ of the mean interparticle separation. The SUBFIND algorithm (Springel et al., 2001a) was then applied to each FOF group to find the gravitationally self-bound subhaloes. Following Navarro et al. (1997), we define $R_{200}$ of a sphere enclosing a mass, $M_{200}$, whose average density is 200 times the critical density of the Universe at redshift, $z$, i.e.:

$$M_{200} = \frac{4\pi R_{200}^3}{3} \cdot 200\delta_{\text{crit}}(z) = \frac{100H(z)^2 R_{200}^3}{G}.$$  

The velocity, $V_{200}$, is defined as the circular velocity of the halo at $R_{200}$ and $V_{200} = \sqrt{GM_{200}/R_{200}}$. $M_{200}$ is directly measured from the simulations and used to calculate $R_{200}$ and $V_{200}$. In our models, we approximate the virial properties of dark matter haloes, e.g. virial radius ($R_{\text{vir}}$), virial mass ($M_{\text{vir}}$) and virial velocity ($V_{\text{vir}}$) by $R_{200}, M_{200}$ and $V_{200}$ respectively unless otherwise explicitly stated.

As in De Lucia & Helmi (2008), we scaled down the original outputs by a factor of $1.42^3$ for the mass and $1.42$ for the positions and velocities in order to have a MW-like halo with $V_{200} \sim 150$ km s$^{-1}$ (Battaglia et al., 2005; Smith et al., 2007; Xue et al., 2008). Therefore, after scaling, the smallest resolved subhaloes containing 20 particles have dark matter mass $M_{DM} \sim 2 \times 10^6 M_\odot$ in GA3new. Here $M_{DM}$ is the total mass at $z = 0$ given by the number of bound particles as determined by SUBFIND. The present-day virial mass and the virial radius for the MW-like halo is $M_{200} \sim 10^{12} M_\odot$ and $R_{200} = 209$ kpc respectively.

3.2.2 Semi-analytic modelling

We use a semi-analytical galaxy formation model to study the baryonic properties of a MW-like galaxy and its satellites at $z = 0$. This model has been developed mainly at the Max–Planck–Institut für Astrophysik and we refer to it as the Munich model later in the text. The essential ideas of the Munich model can be traced back to the works by White & Rees (1978) and White & Frenk (1991), and include physical processes such as the cooling of gas, star formation and feedback due to stars. Over the years, other important ‘ingredients’ have been incorporated, e.g. the growth of supermassive black holes (Kauffmann & Haehnelt, 2000), the inclusion of dark matter substructures resolved in the simulations (Springel et al., 2001a), chemical enrichment (De Lucia et al., 2004b) and AGN feedback (Croton et al., 2006). The model we use in this study is based on the recent version summarised in Croton...
but we assume a Chabrier IMF plus some updates on the galaxy mergers and the dust attenuation as described in De Lucia & Blaizot (2007). Thus our SA model is essentially the same used by De Lucia & Helmi (2008) to study the properties of the MW and its stellar halo. However, we have made a few modifications to account for the properties of the satellites. From now on, we refer to the model used by De Lucia & Helmi (2008) as the MW-model and that used in this work as the satellite-model. Here we give a brief summary of the physical processes implemented in our models which are crucial to the properties of the satellites.

**Reionization**

As in Croton et al. (2006), we make use of the results of Gnedin (2000) who simulated the impact of reionization caused by stellar sources. Gnedin finds that reionization reduces the baryon content in haloes whose mass are smaller than a particular ‘filtering mass’ scale at each redshift. The fraction of the baryons in a halo, \( f_{\text{halo}}(z) \), is decreased compared to the universal baryon fraction \( f_b = 0.17 \) from WMAP 3-year data, Spergel et al. (2007) according to the ratio of the halo mass and the ‘filtering mass’, \( M_F(z) \):

\[
f_{\text{halo}}(z, M_{\text{vir}}) = \frac{f_b}{[1 + 0.26 M_F(z)/M_{\text{vir}}]^3}.
\] (3.1)

In practise, we have implemented the analytic formulae of \( M_F(z) \) given by Kravtsov et al. (2004) based on Gnedin’s results. In the fiducial satellite-model, the two reionization parameters which we use are \( z_0 = 15 \) and \( z_r = 11.5 \). This choice translates to a reionization which starts at \( z_0 \) and is complete by \( z_r \) while in the MW-model it was \( z_0 = 8 \) and \( z_r = 7 \) (equivalent to a duration of 0.12 Gyr). For simplicity, we refer to the reionization epoch, \( z_{\text{reio}} \), as \( z_0 \) hereafter.

**Cooling**

In both MW and satellite models, the cooling of the shock-heated gas is treated as a classical cooling flow (e.g. Springel et al. 2001a). The cooling rate is a function of temperature and metallicity of the hot gas given by Sutherland & Dopita (1993). For primordial (or low-metallicity) composition gas, in the high temperature regime \( (T \gtrsim 10^6 \text{ K}) \), the cooling is dominated by bremsstrahlung (free-free) emission. The cooling is efficient at \( T \sim 10^5 \text{ K} \) and \( \sim 1.5 \times 10^4 \text{ K} \) and driven by the atomic hydrogen H and He\(^+\) respectively. For \( T < 10^4 \text{ K} \), i.e. below the atomic hydrogen cooling limit, the dominant coolant is molecular hydrogen (\( \text{H}_2 \)). The virial temperature of a halo is related to its virial velocity as:

\[
T_{\text{vir}}(z) = 35.9 \left( \frac{V_{\text{vir}}(z)}{\text{km s}^{-1}} \right)^2.
\] (3.2)

Therefore, for a halo with \( T_{\text{vir}} = 10^4 \text{ K} \), the correspondent virial velocity is \( V_{\text{vir}} = 16.7 \text{ km s}^{-1} \) which is equivalent to \( M_{\text{vir}} \sim 3 \times 10^7 \text{ M}_\odot \) when \( z = 15 \) and \( M_{\text{vir}} \sim 2 \times 10^9 \text{ M}_\odot \) when \( z = 0 \).
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In the MW-model, haloes with \( T_{\text{vir}} \) smaller than \( 10^4 \) K, are able to cool as much gas as a \( 10^4 \) K halo with the same metallicity. However, in the satellite-model, we simply forbid cooling in small haloes with \( T_{\text{vir}} < 10^4 \) K at all times. This is a reasonable approximation since molecular hydrogen is subject to the photo-dissociation caused by UV photons from (first) stellar objects \( \text{(Haiman et al., 2000)} \). This treatment is also implemented in some previous SA models, e.g. \( \text{Kravtsov et al., 2004} \).

**Star formation and supernova feedback**

The star formation model used in both the MW-model and the satellite-model is described in detail in \( \text{De Lucia & Helmi (2008)} \) and the supernova feedback in \( \text{Croton et al. (2006)} \). We briefly depict the central ideas here. The star formation rate is modelled in proportion to the available cold gas, assumed to be distributed in an exponential disk, that is above a certain surface density threshold,

\[
\psi = \alpha_{\text{SF}} M_{\text{sf}} / t_{\text{dyn}}, \tag{3.3}
\]

where \( \alpha_{\text{SF}} \) is a free parameter which controls the star formation efficiency, and \( t_{\text{dyn}} \) is the disk dynamical time. We fix \( \alpha_{\text{SF}} \) at 0.03 for a Chabrier IMF \( \text{(De Lucia & Blaizot, 2007)} \) throughout our modelling. The surface density threshold takes a constant value throughout the disk and is calculated using the disk size and the disk circular velocity (in practise approximated with the \( V_{200} \) of the halo). At each time step, \( \Delta t \), we calculate the amount of newly formed stars,

\[
\Delta M_* = \psi \Delta t. \tag{3.4}
\]

Massive stars explode as SNe and inject energy in the form of feedback. In our modelling, we do not consider the delay between the formation of these stars and their corresponding SN feedback, i.e. the lifetime of such stars is assumed to be zero. The energy injection by SNe per solar mass is described as \( V_{\text{SN}}^2 = \eta_{\text{SN}} \cdot E_{\text{SN}} \), where \( \eta_{\text{SN}} = 8.0 \times 10^{-3} \text{ M}_\odot^{-1} \) is the number of SNe per unit solar mass expected from a Chabrier IMF, and \( E_{\text{SN}} = 1.0 \times 10^{51} \) erg is the energy per SN. The energy of SNe available in the time step is approximated as \( 0.5 \Delta V_{\text{SN}}^2 M_* \) and only a fraction of it, \( \epsilon_{\text{halo}} \), is used for feedback:

\[
\Delta E_{\text{SN}} = \epsilon_{\text{halo}} \cdot 0.5 \Delta V_{\text{SN}}^2 M_* \tag{3.5}
\]

The amount of cold gas heated by SNe is proportional to the newly formed stars,

\[
\Delta M_{\text{reheat}} = \epsilon_{\text{disk}} \Delta M_* \tag{3.6}
\]

We assume the heated gas is added back to the hot phase and carries the energy

\[
\Delta E_{\text{hot}} = 0.5 \Delta M_{\text{reheat}} V_{\text{vir}}^2. \tag{3.7}
\]

It is possible that SN feedback is energetic enough to eject some hot gas out of the halo. The energy available for ejecting is \( \Delta E_{\text{SN}} - \Delta E_{\text{hot}} \) if this difference is positive.
The energy carried away by the ejecta is assumed to be \(0.5 \Delta M_{\text{eject}} v^2_{\text{vir}}\). If there is energy present for ejection, the amount of ejected hot gas is

\[
\Delta M_{\text{eject}} = \Delta E_{\text{SN}} - \Delta E_{\text{hot}} \over 0.5v^2_{\text{vir}} = \left( \epsilon_{\text{halo}} \frac{V^2_{\text{SN}}}{v^2_{\text{vir}}} - \epsilon_{\text{disk}} \right) \Delta M_*.
\]  (3.8)

We assume the ejected gas can fall back and be reincorporated into the cooling cycle as the halo keeps growing by accreting material from the surroundings \(\text{(Springel et al., 2001a; De Lucia et al., 2004b; Croton et al., 2006)}\). The two parameters which regulate the feedback, \(\epsilon_{\text{halo}}\) and \(\epsilon_{\text{disk}}\), are adopted as 0.35 and 3.5 respectively from \(\text{Croton et al., (2006)}\).

**An alternative supernova feedback prescription**

Since the dwarf galaxies have shallow potential wells, their properties may be quite sensitive to SN feedback. This is why it is important to explore different implementations of SN feedback in the models. We have therefore also tried an alternative SN feedback recipe in addition to the ‘standard’ recipe mentioned above. This alternative feedback recipe was implemented in some previous versions of the Munich model and is known as the *ejection* model described in \(\text{De Lucia et al., (2004b)}\). In the *ejection* model, the gas reheated by SNe is related to the amount of newly formed stars as:

\[
\Delta M_{\text{reheat}} = \frac{4}{3} \epsilon \frac{V^2_{\text{SN}}}{v^2_{\text{vir}}} \Delta M_*.
\]  (3.9)

This implies, together with our choices of the feedback efficiency \(\epsilon = 0.05\) and \(V_{\text{SN}} \sim 634 \text{ km s}^{-1}\) parameters, that haloes with \(V_{\text{vir}} < 87 \text{ km s}^{-1}\) would have more heated mass per unit newly formed stellar mass compared to the standard recipe (Eq. 3.6). The other feature of the *ejection* model is all the reheated gas is assumed to always leave the halo and is directly deposited to the ejecta component and can be reincorporated into the hot halo at later time.

We will show later our results for the baryonic properties of the satellites with both the standard and alternative SN feedback recipes.

**Metal recycling through the hot phase**

At each time step, the masses exchanged among the four phases: \(M_{\text{hot}}, M_{\text{cold}}, M_*, M_{\text{eject}},\) (i.e. hot gas, cold gas, stars and ejecta) are updated as described in Section 4.7 and Fig. 1 in \(\text{De Lucia et al., (2004b)}\). The metallicity in each phase is denoted as \(Z_x\) and is defined as the ratio between the mass in metals in one component \((M^Z_x)\) and the corresponding mass \((M_x)\) where the suffix \(x\) is hot, cold, star or eject. In the satellite-model, we include a route to recycle metals made in newly formed stars through the hot phase of a galaxy. This is done by assigning a fraction of the metals, \(F_{\text{shot}}\), released from the newly formed stars to the hot component at each time step while keeping the rest in the cold phase. The equations specifying the metal route including the recycling metals through hot phase using the
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standard SN feedback recipe are:

\[ \dot{M}_* = +(1 - R) \cdot \psi \cdot Z_{\text{cold}} \]

\[ \dot{M}_{\text{hot}} = - \dot{M}_{\text{cool}} \cdot Z_{\text{hot}} + \dot{M}_{\text{back}} \cdot Z_{\text{eject}} + \sum_{\text{sat}} (\dot{M}_{\text{reheat}} \cdot Z_{\text{cold}}) + F_{\text{zhot}} \cdot Y \cdot \psi \]

\[ \dot{M}_{\text{cold}} = + \dot{M}_{\text{cool}} \cdot Z_{\text{hot}} - (1 - R) \cdot \psi \cdot Z_{\text{cold}} + (1 - F_{\text{zhot}}) \cdot Y \cdot \psi - \dot{M}_{\text{reheat}} \cdot Z_{\text{cold}} \]

\[ \dot{M}_{\text{eject}} = + \dot{M}_{\text{eject}} \cdot Z_{\text{hot}} - \dot{M}_{\text{back}} \cdot Z_{\text{eject}}. \]

A yield \( Y \) of heavy elements produces in newly formed stars per solar mass is assumed. A fraction of \( R = 0.43 \) of the mass in stars is also assumed to return into the cold phase to account for the mass loss during the lifetimes of stars. The cooling rate of gas in the hot halo is \( \dot{M}_{\text{cool}} \); the reincorporation rate for the ejecta back to the hot halo is \( \dot{M}_{\text{back}} \); the mass reheated by the SNe per unit time is \( \dot{M}_{\text{reheat}} \); and the rate of mass ejected out of the halo is \( \dot{M}_{\text{eject}} \).

For the alternative SN feedback recipe, since the reheated gas is assumed to be ejected from the cold phase directly, the metallicity in the ejecta is updated as:

\[ \dot{M}_{\text{eject}} = + \dot{M}_{\text{reheat}} \cdot Z_{\text{cold}} - \dot{M}_{\text{back}} \cdot Z_{\text{eject}}. \]

In the MW-model, the metals made are assumed to return to the cold phase immediately in all galaxies, i.e. \( F_{\text{zhot}} = 0 \). However, Mac Low & Ferrara (1999) using hydrodynamical simulations to study the fate of metals ejected by SNe in dwarf galaxies, find that metals can be blown out completely from small galaxies with gas mass below \( 10^7 M_\odot \) (corresponding to a halo of \( M_{\text{vir}} = 3.5 \times 10^8 M_\odot \) in their modelling). We then assume a simple two-state value for \( F_{\text{zhot}} \) to account for the mass dependence:

\[ F_{\text{zhot}} = \begin{cases} 
0.0 & \text{if } M_{\text{vir}} \geq 5 \times 10^{10} M_\odot \\
0.95 & \text{otherwise.} \end{cases} \]

This means that for galaxies with a dark matter halo with virial mass less than \( 5 \times 10^{10} M_\odot \), 95% of newly produced metals are deposited into the hot phase.

3.2.3 What happens to the satellites in the modelling?

We follow the convention established along the development of the Munich model to classify galaxies according to their association with a subhalo. The galaxy associated to the most massive subhalo in a FOF group is a Type 0 galaxy and is sometimes referred to as the central galaxy. Other galaxies in a FOF group are
usually referred to as satellites and are further differentiated into Type 1 galaxies if their dark matter subhalo is still present or Type 2 when their subhalo has fallen below the resolution limit of the simulation. When a galaxy becomes a satellite, its $M_{200}$ is approximated using the number of bound dark matter particles given by SUBFIND instead of the conventional value as described in Section 3.2.1. The disk size is fixed at the value it had just before accretion. In our SA modelling, only Type 0 central galaxies are allowed to accrete mass from the ambient medium. Satellite galaxies do not have hot and ejected components and the cooling is also forbidden, i.e. $M_{\text{hot}} = M_{\text{eject}} = \dot{M}_{\text{cool}} = 0$. When a galaxy becomes a satellite, its hot and ejected components are transferred to the corresponding components of the central galaxy. As a consequence once matter leaves the cold phase of a satellite, it does not rejoin the (Type 1 or Type 2) satellite at a later time.

3.2.4 On the modelled central MW-like galaxy

The values of the parameters that enter in the SA model are chosen so as to reproduce several observations of galaxies on large scales, such as, the $I$-band Tully-Fisher relation for Sb/c galaxies. Since the number of parameters is significantly smaller than possible observables, this implies that the predicting power is not hindered. This same set of values for the parameters was used by De Lucia & Helmi (2008) to model the MW after coupling to the merger tree of a MW-like halo and resulted in agreeable properties without any fine-tuning. It is important to emphasise that the prescriptions and parameters that describe well galaxy properties on large scales will not necessarily lead to satisfactory properties of a single MW-size galaxy and its satellites, particularly because of the simplified treatments of the various physical processes in the models.

To fix the values of the parameters in the satellite-model, we simply adopt those from De Lucia & Helmi (2008) except the reionization epoch, $z_{\text{reio}}$, and the metal fraction to the hot gas, $F_{zh\text{ot}}$. Below we briefly discuss the dependence on our changes on $z_{\text{reio}}$, cooling in small haloes and metal recycling through hot phase of the MW-like galaxy properties. We will focus on the baryonic properties of the central galaxies in different models and discuss the number of satellites in Section 3.3.1 where we show our results for the luminosity functions of the satellites. Table 3.1 summarises the properties of the MW-like galaxies in different SA models at $z = 0$.

The results using the MW-model are given in the first row (see also Fig. 2 of De Lucia & Helmi, 2008). We remind the reader that in the MW-model, haloes with $T_{\text{vir}} < 10^4$ km s$^{-1}$ are allowed to cool at the rate of a $10^4$K halo, the reionization epoch is $z_{\text{reio}} = 8$ and the fraction of metals recycled through hot phase is $F_{zh\text{ot}} = 0$. We refer to the fiducial model which gives best results for the satellites as the ‘satellite-model’. This is the fourth row with $z_{\text{reio}} = 15$ and a fraction of 95% for the recycling of metals through the hot component for galaxies with $M_{\text{vir}} < 5 \times 10^{10}$ M$_\odot$. In all the models with the name with ‘satellite’, we forbid the cooling in haloes with $T_{\text{vir}} < 10^4$ K. The last two rows in Table 3.1 show results with the alternative SN feedback recipe and will be discussed in Section 3.3.1 and 3.3.2.
The only difference between the MW-model and the satellite-model A is in the cooling of small systems. Comparing the results of these two models, we find no significant changes in the properties of the present-day MW-like galaxy. In satellite-model B, we also change $z_{\text{reio}}$ to 15 and keep $F_{\text{shot}} = 0$. We note that the only significant impact of an early reionization is to bring down the black hole mass by $\sim 15\%$ compared to that of the MW-model. The early reionization results in an increase of the stellar mass but this is still within the observational uncertainties. We note the black hole mass $M_{\text{BH}} = 6.9 \times 10^6 M_\odot$ from the satellite-model is still only in marginal agreement with the latest measurement of the MW black hole mass $M_{\text{BH}} = (4.5 \pm 0.4) \times 10^6 M_\odot$ (Ghez et al., 2008). By comparing the satellite-model B and the satellite-model, it is clear that (our simple implementation of) the recycling of a fraction of the just formed metals through the hot phase for haloes with $M_{\text{vir}} < 5 \times 10^{10} M_\odot$ only makes the bulge slightly more metal-poor ($\sim 0.06$ dex).

Our fiducial satellite-model gives similar total stellar mass for the central host as the MW-model, and both models are consistent with the current observational constraints $M_* \sim 5 - 8 \times 10^{10} M_\odot$. The results of these two models also agree well with each other in terms of the mass of the bulge and the cold gas content, albeit they are slightly higher compared to the MW values. We therefore conclude that the changes which we have made in the satellite-model only have significant impact on the properties of dwarf galaxies and are very likely to preserve the properties of MW-like galaxies.

### 3.3 Results

We define as SA model satellites of the MW-like galaxy those that satisfy the following conditions at $z = 0$: i) a satellite has to be in the same FOF group where
the MW-like galaxy is; ii) the distance to the MW-like galaxy is < 280 kpc; iii) the
galaxy is associated to a dark matter subhalo (Type 1 galaxies in the previous dis-
cussion with \( N > 20 \) i.e. \( M_{DM} \sim 2 \times 10^6 \, M_\odot \)). The distance cut corresponds to the
current observational limits, except it excludes the very distant recently discovered
satellite Leo T at ~ 420 kpc.

### 3.3.1 The luminosity function

Our fiducial satellite-model predicts 51 satellites within 280 kpc. This is in good
agreement with the estimated ‘all sky’ number of satellites (\( \sim 45 \)) brighter than
\( M_V = -5.0 \) by Koposov et al. (2008). If we remove the above-mentioned distance
constraint, the number of satellites is only increased from 51 to 52 and the number
of subhaloes from 1865 to 1869. We therefore keep the distance cut to make our
results easily comparable with the observations.

The mass functions of model satellites and of surviving subhaloes within 280 kpc
are shown in Fig. 3.1. The mass plotted here is the total associated dark matter
mass at \( z = 0 \) determined by SUBFIND. All subhaloes with present-day \( M_{DM} >
10^9 \, M_\odot \) are populated with galaxies. The mass function of the subhaloes which
host galaxies deviates from the power-law shape mass function of the full subhalo
population and is fairly flat below \( M_{DM} = 10^9 \, M_\odot \) down to the resolution limit of
\( M_{DM} \sim 10^{6.5} \, M_\odot \). We also show the mass function of surviving subhaloes within
the same distant range from the central galaxy in the lower resolution simulation
(GA2new) as the dotted histogram in Fig. 3.1. The smallest subhalo which could
be resolved in GA2new has \( \sim 2 \times 10^7 \, M_\odot \). The mass functions for the subhaloes
agree well in the two simulations with different resolutions down to \( 10^8 \, M_\odot \), below
which numerical effects start to become important in GA2new. However, note that
number of satellites with \( M_{DM} < 10^9 \, M_\odot \) is still much less than that of the sub-
haloes resolved in GA2new. This result implies that the decline in the luminosity
function around \( M_V = -5 \) seen in our highest resolution simulation is not due to
the possibility that GA3new fails to resolve the low mass subhaloes which host the
MW satellites but is more likely a result of how we model the baryonic physics, e.g.
SN feedback, as we will see later.

In Table 3.2, we compare the difference in the number of satellites in the SA
models discussed in Table 3.1. For reference, in the MW-model the number of sur-
viving satellites is 285. The drastic difference between the MW- and the satellite-
model is mostly at the faint end of the luminosity function, and it is due to the
combined effect of an early reionization and no cooling in small haloes. When
applying the cooling threshold alone and keeping \( z_{reio} = 8 \), the number of satellites is
reduced from 285 to 88 (see the MW-model and satellite-model A) and affects mostly
the faint end, i.e. \( M_V > -7 \) mag. The number of satellites is further reduced to 51
when applying \( z_{reio} = 15 \) and mostly affects \( M_V \in [-7, -10] \) mag (compare satellite-
model A and satellite-model B). It is known that an earlier reionization helps to
reconcile the ‘missing satellites problem’ because it suppresses the baryon con-
tent of a given halo beforehand (e.g. Somerville [2002]). We note that an even
earlier reionization, e.g. \( z_{reio} = 20 \), can give a comparable total number of surviv-
Figure 3.1: The solid histogram shows the present-day mass function of the model satellites for the highest resolution simulation. Error bars denote the 1-σ Poisson uncertainties. The dashed histogram shows the subhalo mass function for the highest resolution simulation, which steeply rises up to the resolution limit. The dotted histogram is the subhalo mass function for a lower resolution simulation (i.e. GA2new).

Table 3.2: Number of satellites around Milky Way-like galaxy for various SA models in the GA3new simulation

<table>
<thead>
<tr>
<th>Model Name</th>
<th>$N_{\text{sat}}$</th>
<th>$z_0, z_{\text{reio}}$</th>
<th>$F_{\text{shot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-model</td>
<td>285</td>
<td>(8, 7)</td>
<td>0.0</td>
</tr>
<tr>
<td>satellite-model A</td>
<td>88</td>
<td>(8, 7)</td>
<td>0.0</td>
</tr>
<tr>
<td>satellite-model B</td>
<td>51</td>
<td>(15, 11.5)</td>
<td>0.0</td>
</tr>
<tr>
<td>satellite-model</td>
<td>51</td>
<td>(15, 11.5)</td>
<td>0.95, 0.0</td>
</tr>
<tr>
<td>satellite-model ejection</td>
<td>51</td>
<td>(15, 11.5)</td>
<td>0.95, 0.0</td>
</tr>
<tr>
<td>satellite-model combined</td>
<td>51</td>
<td>(15, 11.5)</td>
<td>0.95, 0.0</td>
</tr>
</tbody>
</table>

The descriptions for each column are: (1) the model names; (2) number of satellites; (3) reionization epoch; (4) fraction of metals recycled through the hot component.

...ing satellites even without applying the threshold for cooling. This is because the reionization starts to reduce the accretion of baryons in small haloes in the first place and consequently leaves little room for changes in the cooling to have an effect. However, the shape of the luminosity function for $z_{\text{reio}} = 20$ is not in good agreement with the data. Note that besides the cooling, the epoch of reionization is the only parameter which has an impact on whether a subhalo would host stars; changes in the metal recycling through the hot component of a galaxy or the SN feedback implementation are not relevant for the missing satellites problem.

The left panel in Fig. 3.2 shows the luminosity function of the satellites in our
Figure 3.2: Luminosity function for the MW satellites and for the semi-analytically modelled satellites around a MW-like galaxy. The left panel compares the MW satellites with satellites from our fiducial model and the right panel from the model with a more efficient SN feedback for dwarf galaxies (see Section 3.2.2). The integrated \( V \)-band luminosities of MW satellites (dots) are taken from various sources. The classical dSphs are from Mateo (1998); most of the ultra-faint dwarfs are adopted from Martin et al. (2008) except Leo T (Ryan-Weber et al., 2008) and Leo V (Belokurov et al., 2008).

The fiducial satellite-model (solid histograms) compared with the ‘all sky SDSS’ power-law luminosity function of satellites within 280 kpc estimated by Koposov et al. (2008) in dashed. The error bars on the model luminosity function denote the 1-\( \sigma \) Poisson noise. We have also overplotted the data points of the 22 known satellites in the MW including the latest ultra-faint satellite Leo V (Belokurov et al., 2008). The model luminosity function covers a similar luminosity range as the 22 MW satellites though the model does not predict as many faint satellites with \( M_V > -5 \) mag when compared to the expected ‘all sky’ luminosity function. Furthermore, the satellite-model does not have any satellites fainter than \( M_V = -4 \) mag. On the other hand, it shows an excess around \( M_V = -10 \) of 10 - 15 satellites compared to the data. It also seems that there are fewer very bright satellites in the model, however, it is the regime where both the data and the simulations suffer from small number statistics.

We rerun the satellite-model with the alternative SN feedback recipe while keeping all other physical prescriptions and the values of the parameters intact. The results for the MW-like galaxy and the number of the surviving satellites are given as the ‘satellite-model ejection’ entry in Table 3.2. It is reassuring that the same set of 51 subhaloes are populated with galaxies in the SA with the standard and the alternative SN feedback recipes. This, on the one hand, implies that the SN feedback alone cannot solve the ‘missing satellites problem’ as has been suggested in some previous work (Somerville, 2002); on the other hand, it ensures that the differences in the properties of the satellites are entirely caused by how the feed-
back is implemented. It also implies that the model is robust and that the issue of which haloes can host stars must be driven by their mass assembly history and dynamics.

The luminosity function of surviving satellites resulting from the alternative feedback recipe is shown in the right panel of Fig. 3.2 where we also plotted the Koposov et al. 'all sky' luminosity function and the data for the MW satellites. This model luminosity function agrees well with the observations. When compared with that of the standard feedback, the alternative luminosity function extends more to the faint end reaching $M_V \sim -3$ mag. The bump at $M_V \sim -10$ which we saw in the standard feedback recipe is not present either.

The differences in the results of these two models can be understood from the fact that the amount of heated gas scales as $1/V_{\text{vir}}^2$ in the ejection model, and for a galaxy with $V_{\text{vir}} < 87$ km s$^{-1}$, more gas is heated with the alternative recipe than with the standard recipe. In contrast, in the standard feedback recipe, the amount of gas heated by SNe is only proportional to the newly formed mass in stars. Therefore, in this case, for galaxies with low star formation rates (always the case for galaxies that live in small subhaloes), only very little gas is heated. This is most likely the reason why we see an excess of satellites around $M_V \sim -10$ mag in the luminosity function of our fiducial model. In contrast, in the alternative feedback model, when star formation occurs in a central galaxy, the ejected gas has to wait several dynamical timescales to be reincorporated into the hot halo, which therefore delays the subsequent star formation. Furthermore, the impact on the star formation of a satellite associated to a subhalo with $V_{\text{vir}} < 87$ km s$^{-1}$ is more drastic also in this model since satellites have neither a hot halo nor ejecta, which implies that once the gas is heated/ejected by the SN feedback, it is lost completely from these satellites. Small satellites therefore run out of fuel for star formation due to the SN feedback much more rapidly.

Let us now focus on what happens to the central host galaxy with the alternative feedback recipe. Since the amount of reheated gas (or ejecta) is proportional to $1/V_{\text{vir}}^2$, massive systems like the MW counterpart in our model are much less effected by the alternative SN feedback for a given amount of newly formed stars compared to the standard feedback recipe. This is why the MW-like galaxy now has a much higher stellar mass, bulge mass and is more metal-rich (see Table 3.1).

### 3.3.2 The metallicity distribution

We compare the metallicity distribution of the model satellites in the fiducial satellite-model with that observed in the left panel of Fig. 3.3. The metallicity in our model is mass-weighted and is defined as the ratio between the mass of metals in stars and total stellar mass:

$$Z_* = M^Z_* / M_* .$$

Since we do not distinguish in the modelling the long-lived main iron contributors (SNIa) from the short-lived $\alpha$-elements enrichers (SNI), a direct comparison of $Z$ to $[\text{Fe}/\text{H}]$ might not be completely valid. Nevertheless, here we assume that the
Figure 3.3: Histogram of the mean iron abundance $[\text{Fe}/\text{H}]$ determined for red giant branch stars in the MW satellites. For the semi-analytically modelled satellites we plot $\log(Z^*/Z_\odot)$. The left panel compares the MW satellites with model satellites from our fiducial model and the right panel from the model with a more efficient SN feedback for dwarf galaxies (see Section 3.2.2). Data for the MW satellites are taken from various sources: LMC and SMC from Westerlund (1997); Sgr from Cole (2001); Ursa Minor and Draco from Harbeck et al. (2001); Sextans, Sculptors, Carina and Fornax from the DART survey (Helmi et al., 2006a); Leo II from Koch et al. (2007a); Leo I from Koch et al. (2007b). For the newly discovered SDSS ultra-faint dwarfs, Leo V does not have a published measurement. For the rest of the ultra-faint satellites, we take the measurements from Kirby et al. (2008) except for Böotes I for which we use Muñoz et al. (2006) and Böotes II from Koch et al. (2008).

The logarithmic value of the mass-weighted metallicity normalised to the solar value ($Z_\odot = 0.02$) can be compared qualitatively with the $[\text{Fe}/\text{H}]$ derived from spectra of Red Giant Branch stars in the MW satellites.

Among the 51 surviving satellites in the satellite-model, four of them are free of metals since they have only made stars once from pristine gas. Those four metal-free satellites all have present-day $M_{\text{DM}} \lesssim 10^8 M_\odot$ and $M_* < 10^4 - 10^5 M_\odot$. We do not include these 'metal-free' satellites in the left panel of Fig. 3.3 and related discussions. The distribution of the mean $[\text{Fe}/\text{H}]$ of stars in the 11 classical MW satellites is the dotted-dashed histogram while that including also 10 ultra-faint satellites is the dashed histogram. The metallicity distributions of the model satellites and those in the MW cover similar ranges. However, the metallicity distribution for the 21 MW satellites is more uniform compared to that in the satellite-model. The excess of model satellites in the range of $-2 < \log(Z^*/Z_\odot) < -0.5$ corresponds to the bump of $M_V = -10$ seen in the luminosity function as we will show in the metallicity-luminosity relation in the following section. If we set $F_{\text{zhot}} = 0$, the predicted metallicity distribution would be shifted towards higher metallicity with 37 of them more metal-rich than $\log(Z^*/Z_\odot) = -1$ and only 10 of them having $\log(Z^*/Z_\odot) < -1$. Note that in our fiducial model satellites with $M_{\text{vir}} < 5 \times 10^{10} M_\odot$...
3.3. RESULTS

deposit 95% of newly made metals into their hot components, but since these systems do not have associated hot haloes according to the SA recipe, most of the metals therefore leave the satellites and do not enrich their cold gas reservoir.

In the right panel of Fig. 3.3 we plot the metallicity function of 38 satellites in the satellite-model *ejection* using the alternative SN feedback. This metallicity distribution also shows good agreement with the observations and has a more even distribution compared to that of the standard recipe. As we discussed in Section 3.3.1, satellites with $V_{\text{vir}} < 87 \text{ km s}^{-1}$ loose more of their cold gas reservoir, and more importantly since most of the cold gas including the metals are mostly heated and join the ejecta of the central galaxy, a much higher fraction of the metals leaves the satellites in the *ejection* model. This explains why in this model satellites have a lower metallicity on average.

The above analysis suggests that a SN feedback recipe which reduces cold gas more efficiently yields better agreement with observations of the satellites around the MW. This leads us therefore to propose a combination of these two feedback recipes in the hope to reproduce most properties for both MW and the satellites. This new ‘combined’ SN feedback recipe works as follows:

$$M_{\text{reheat}} = \begin{cases} \frac{4}{3} \epsilon \frac{V_{\text{SN}}^2}{V_{\text{vir}}^2} \Delta M_\ast & \text{if } V_{\text{vir}}^2 < \frac{4}{3} \frac{\epsilon}{\epsilon_{\text{disk}}} V_{\text{SN}}^2 \\ \epsilon_{\text{disk}} \Delta M_\ast & \text{otherwise.} \end{cases}$$

The reheated gas is treated as in the *ejection* model and is to be added to the ejecta component of a central galaxy and lost for a satellite. The ‘satellite-model combined’ entry in Table 3.1 lists the properties of the MW-like galaxy with this recipe. As expected, the stellar mass, the metallicity for the entire galaxy and for the bulge, as well as the total luminosity are now very similar to what we get with the standard feedback recipe, albeit the bulge (and the black hole) are now more massive. We have also checked the properties of the satellites, and find that again the combined feedback recipe populates the same set of 51 subhaloes with stars, and that the luminosity function and the metallicity distribution are almost identical with those obtained using the ejection model.

3.3.3 Star formation histories

In Fig. 3.4 we present the evolution of the stellar mass and the SUBFIND dark matter mass predicted in our satellite-model. The satellites are sorted by their present-day luminosity into three bins, i.e. high: $-16 < M_V < -13$, similar to Sagittarius and Fornax, intermediate: $-12 < M_V < -10$ (Leo I and Sculptor) and low: $-10 < M_V < -8$ (Leo II, Sextans, Carina, UMi and Draco) from the top to the bottom panels. Note that in the current model, we do not model the tidal stripping of stars while the dark matter mass is traced explicitly with $N$-body simulations. We therefore do not include the two model satellites (one in the high and one in the intermediate luminosity bin) which have more stellar mass than dark matter mass at $z = 0$ due to significant tidal interactions with the central galaxy. The loss of the

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1 i.e. 13 satellites are ‘metal-free’ in this case.
cold gas reservoir is not modelled either so we also refrain from considering systems which form > 50% of stars after becoming satellites of the MW-like halo. The later criterion reduces the number of satellites from 16 to 13 in the intermediate bin and from 14 to 7 in the low luminosity bin.

The Local Group satellites all possess old stellar populations with age > 10 Gyr (Dolphin et al., 2005; Orban et al., 2008). It is encouraging that the model satellites also present such a feature regardless of their luminosity. When we examine the evolution of stellar mass sorted by the luminosity, we find that the most luminous satellites build up their stellar content over a longer period compared to the faintest ones as also seen in the Local Group satellites (Dolphin et al., 2005). These most luminous satellites are also associated with massive dark matter subhaloes with $M_{\text{DM}} > 10^9 M_\odot$. We plot the fraction of the old stars as a function of the present-day total luminosity in Fig. 3.5. Although the scatter in the fraction of old stars in the two brightest luminosity bins is big, there is a trend that the faintest satellites have a larger fraction of old stellar populations. The five systems that are accreted the earliest (> 9 Gyr), are also associated with fainter satellites and have a significant fraction of old stars. This indicates that these satellites stopped forming stars soon after the accretion. Note as well that the faint satellites do not show significant young stellar populations (of 1 – 2 Gyr age). It is also discernible that all the bright satellites consist of less than 1% of stars made by the end of the reionization while a few of the faint ones have > 50% of such very old stars.

We should bear in mind that the star formation history is coupled with the dark matter mass assembly history and the dynamics in our model. Subhaloes which fell in early have experienced a greater mass loss than those fell in later due to the interaction with the MW-like halo. A dark matter halo is also prevented from accreting mass from the ambient medium and from further cooling after it has become a satellite. It is then reasonable to see that none of the currently bright (and also massive) satellites fell in before $z \sim 1$, that they are also the most massive and that they show extended star formation histories.

### 3.3.4 Other properties of the satellites

#### Radial distribution

Fig. 3.6 shows the cumulative radial distribution of the MW satellites as the dashed line and of the model satellites with the solid line. Note that the median distances of the two distributions agree well. For comparison, we also plot the distribution of all the surviving dark matter subhaloes (with or without stars) as the dotted line. It is clear that the radial distribution of all the subhaloes is much less concentrated compared to that of the MW satellites and to the model ones. The reason why our model satellites show a similar cumulative radial distribution to the MW satellites can be understood from Fig. 3.7. This figure shows the present-day $M_{\text{DM}}$ as a function of the accretion time. The small grey circles are for the dark satellites, and the bigger black ones are for those which host galaxies. It is clear that the bulk of dark satellites (i.e. subhaloes without stars) in the mass range of $10^6 M_\odot <
Figure 3.4: Evolution of the stellar mass (solid lines) and dark matter mass (dashed lines) for satellites in the fiducial satellite-model. Satellites are sorted by $M_V(z = 0)$ into three panels: $-16 < M_V < -13$ (top); $-12 < M_V < -10$ (middle); $-10 < M_V < -8$ (bottom). $t = 0$ represents the present time. Stellar masses are normalised by the present-day values, $M_*(z = 0)$. Different colours correspond to different satellites, and the arrows indicate the accretion time defined as when a satellite was identified as a central galaxy for the last time. The same colour is used to plot the stellar and the dark matter mass for a given satellite in a panel. The vertical dashed lines mark the end of the reionization $z_r = 11.5$. 
CHAPTER 3. MODELLING SATELLITES OF A MW-LIKE GALAXY

Figure 3.5: The mass fraction of old (> 10 Gyr) stellar population for the model satellites discussed in Fig. 3.4. Triangles are satellites accreted earlier than 9 Gyr ago.

Figure 3.6: Normalised cumulative radial distributions of the MW satellites (dashed lines) compared with that for the model satellites (solid lines) and the dark matter subhaloes (dotted lines) at $z = 0$. 
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Figure 3.7: Present-day bound dark matter mass as a function of the time since accretion. Black symbols are the surviving model satellites, and the grey ones denote dark matter subhaloes which failed to form stars.

\[ M_{\text{DM}}(z=0) \leq 10^7 M_\odot \] has been accreted in the last two Gyr, which implies that they are preferentially found in the outskirts (for this mass scale, dynamical friction is not important, Ghigna et al. 2000; De Lucia et al. 2004a; Gao et al. 2004a). Since these small dark satellites dominate by number, this leads to a much more even distribution with radius than for the luminous satellites. Note that in contrast, half of the satellites were accreted more than 7 Gyr ago, and the most massive ones \((e.g. M_{\text{DM}} > 10^9 M_\odot)\) at \(z = 0\) are all accreted after \(z \sim 1\) (see also Fig. 3.4). There is also a clear bias for the least massive subhaloes hosting stars to have fallen in the earliest as mentioned in Section 3.3.3.

Luminosity-size relation

Here we compare the size of the model satellites with the observed distribution as a function of the total \(V\)-band absolute magnitude. The left panel in Fig. 3.8 is for the standard SN feedback recipe and right for the alternative recipe. The size of a satellite in our models is obtained assuming the stars are distributed in an exponential disk and, is roughly proportional to the virial radius of the associated dark matter subhalo, i.e. \(r_{1/2} \approx 1.2 \lambda R_{\text{vir}}\), where \(\lambda\) is its spin parameter. In Fig. 3.8 we distinguish the classical dSphs and the ultra-faint satellites with asterisks and diamonds respectively, and the circles are the model satellites. The half-light radii of the ultra-faint satellites are from the recent systematic study by Martin et al. with \(r_{1/2} \approx 1.68 \ r_D\) for an exponential disk and \(r_D\) is approximated to be \(r_D = \frac{\lambda}{\sqrt{2}} R_{\text{vir}}\) to first order.
Figure 3.8: The luminosity-half-light radius distributions for the MW semi-analytically modelled satellites around a MW-like galaxy. The half-light radii for MW satellites are taken from various sources: For the classical dSphs, data are from the compilation of van den Bergh (2000). For the ultra-faint dwarfs, from Martin et al. (2008) except for Leo V, which is taken from Belokurov et al. (2008). See the caption of Fig. 3.2 for the sources of the total V-band luminosity. (2008) while the classical ones are drawn from van den Bergh (2000). The model satellites with either feedback recipe have sizes between $\sim 30$ to 2000 pc, generally in a good agreement with the MW satellites especially with the classical ones. But the lack of faint satellites beyond $M_V = -5$ in the satellite-model makes the comparison with the ultra-faint satellites inconclusive. The compact satellites in the satellite-model with $r_{1/2} < 100$ pc are a few magnitudes brighter than the ultra-faint MW satellites of similar size. The satellite sizes obtained with the alternative feedback recipe are a bit larger than those observed and also than in the standard feedback model. This is expected as in the alternative feedback recipe, more gas is ejected by SNe in small galaxies which is only reincorporated later after the halo has grown in mass and in size. Since the alternative feedback recipe pushes the luminosity function towards the fainter end, the comparison with the ultra-faint satellites is in better agreement than in the standard recipe.

Metallicity-luminosity relation

The classical satellites in the MW are known to follow a metallicity-luminosity relation: the faint satellites are metal-poor and luminous ones are metal-rich (Mateo, 1998). Fig. 3.9 shows the distribution of the model satellites (circles) in the metallicity-luminosity plane. The satellites in the satellite-model are in black, and the grey ones correspond to the ejection model. Here again, we compare $Z_*/Z_\odot$ for the model satellites with the averaged $[\text{Fe}/\text{H}]$ for stars in the MW satellites. The error bars on the $[\text{Fe}/\text{H}]$ values indicate the spread of the distributions rather than measurement uncertainties. The model satellites in the fiducial model follow a similar trend as the classical MW satellites. It is not possible to compare the
model satellites to the ultra-faint satellites since the satellite-model does not predict galaxies with luminosity less than $L_V \sim 10^4 L_\odot$ (see also Fig. 3.2). Note however the large spread in the metallicity around $L_V \sim 10^5 L_\odot$. The excess of model satellites seen in the luminosity function (Fig. 3.2 left panel) around $M_V \sim -10$ mag corresponds to objects with $\log(Z_*/Z_\odot)$ in $[-1.5, -1.0]$ dex, and hence are also responsible for the bump in the metallicity distribution mentioned earlier.

With the alternative SN feedback recipe, the model satellites also follow the relation of the classical satellites but with a hint that when $L_V > 10^6 L_\odot$, the model satellites are a bit more metal-rich compared to the observations. At the faint luminosity end there is better agreement with the ultra-faint satellites, since the alternative feedback recipe predicts fainter and metal-poor satellites below $L_V = 10^5 L_\odot$.

**Cold gas content**

The majority of the dSph satellites of the MW are gas deficient. In Fig. 3.10, we compare the cold gas content as a function of the luminosity for our model satellites with the observations.

It is clear that the modelled satellites from either feedback model are much more gas-rich than the observed counterparts by factors of a few hundred except at the brightest end. The satellites from the alternative feedback recipe populate
Figure 3.10: Cold gas content as a function of $V$-band absolute magnitude. Black circles are for the standard feedback and grey for the alternative feedback. The HI masses for the classical dSphs are taken from Mateo (1998) and for the Magellanic Clouds are from Bruns et al. (2005). Apart from the gas rich Magellanic Clouds, most of classical dSphs are only constrained with upper limits (indicated by the downward pointing arrows) except Sculptor. The distant Leo T is the only one with a clear detection of $M_{\text{HI}} = 2.6 \times 10^5 M_\odot$ among the newly discovered ultra-faint satellites (Ryan-Weber et al., 2008).

We note again that we do not model the loss of the satellites’ cold gas component due to the interaction with the host galaxy. It has been known that Local Group galaxies show a morphological segregation in the sense that gas-deficient dSphs are closer to the giant spirals while the gas-rich dIrrs are more evenly distributed (Mateo, 1998). This morphological segregation is a hint that the environment plays a role in the evolution of the satellites. From a theoretical point of view, the gas content of a satellite is very likely to be largely affected through the ram-pressure stripping caused by the presence of a hot gas component in the host. (See Grebel et al. (2003) for a discussion of possible gas removal mechanisms including the internal, e.g. star formation, and external, e.g. ram-pressure and tidal stripping by Mayer et al. (2006).)
3.3.5 Dark matter halo mass and the dynamical properties

The M/L ratio and the distribution of dark matter mass

Recent work by Strigari et al. (2007) suggests that mass within 0.6 kpc, $M_{0.6}$, for a satellite is robustly measured via analyses of the velocity dispersions using Jeans equation.

For each satellite in our model, two methods can be applied to measure the $M_{0.6}$: 1) to directly sum up bound dark matter particles within 0.6 kpc from the centre of mass determined with the 10% most bound particles in each associated subhalo; 2) to assume the inner density profiles are fit by Einasto profiles. As in Li et al. (2008), we trace the evolution of $V_{\text{max}}$, $M_{DM}$ and the directly measured $M_{0.6}$ in the last 2 Gyr for each satellite and identify satellites which are more tidally disturbed. We assign $M_{0.6}$ with the second method for satellites which show signatures of tidal perturbation and use the directly summation of bound particles within 0.6 kpc for the rest. Before we start to address the dark matter content of our model satellites, we note that we exclude the two model satellites which have experienced severe tidal stripping from the analyses here as their $M_*>M_{DM}$. The mass-to-light ratio using $M_{0.6}$ and the integrated $V$-band absolute magnitudes as a function of absolute magnitude is shown in Fig. 3.11 for our model satellites. The data points for the eight classical MW dSph measured by Strigari et al. (2007) are overplotted in this Figure with (blue) asterisk symbols. The lower and middle dashed lines correspond to constant mass values of $M_{0.6} = 6 \times 10^6 \, M_\odot$ and $M_{0.6} = 7 \times 10^7 \, M_\odot$ and indicate the upper and lower limits for the observed $M_{0.6}$ by Strigari et al. (2007).

Fig. 3.11 shows that $M_{0.6}/L_V$ for the model satellites is in agreement with what is observed. Our model predicts that the faint satellites are the most dark matter dominated objects in the satellite population as $M_{0.6}/L_V$ increases as their luminosity decreases. It is also encouraging that the data points and the model satellites follow a similar trend and the spread in the mass-to-light ratio is also comparable. This result favours the idea that the MW satellites are embedded in dark haloes whose mass is $\sim 10^7 \, M_\odot$ within the optical extent as proposed by Mateo (1998), despite the fact that their luminosities span nearly five orders of magnitude (Strigari et al. 2008).

Datasets which cover large radius as well as internal proper motions for stars in these systems are crucial for drawing further conclusions on the total mass content of the MW satellites. But we should note that from our modelling of the baryonic physics, we expect a minimum dark matter halo mass of galaxies before accretion onto a MW-like host (with a equivalent $V_{\text{vir}} = 16.7 \, \text{km} \, \text{s}^{-1}$) which is introduced by the atomic hydrogen cooling limit (see also the discussion in Section 3.4.2).

The distance to the central galaxy at emergence

It is interesting to ask where the satellites nowadays in the MW-halo typically were formed. For each of the model satellites, we have traced the associated main subhalo back in time until its mass is smaller than $2 \times 10^6 \, M_\odot$, i.e. it falls below the resolution limit. We then mark its distance and denote this time as the time of
CHAPTER 3. MODELLING SATELLITES OF A MW-LIKE GALAXY

Figure 3.11: Mass-to-light ratio of 8 Milky Way classical dSphs and model satellites as a function of luminosity. The mass corresponds to the dark matter mass within 0.6 kpc. For the MW dSphs, data are taken from Strigari et al. (2007) and plotted with asterisks. The lower and middle dashed lines correspond to constant values of $M_{0.6} = 6 \times 10^6 \, M_\odot$ and $7 \times 10^7 \, M_\odot$ indicating the upper and lower limits of the measured $M_{0.6}$ for the MW dSphs.

‘emergence’. Fig. 3.12 shows the distance as a function of the emergence/detection redshift. The curve represents $R_{200}(z)$ of the central galaxy. The surviving satellites are all detected early around the epoch of reionization ($z_{\text{reio}} = 15$ in the satellite-model) and most emerged before the end of reionization. The distance of the model satellites to the MW-like galaxy at emergence is typically around $\sim 100$ kpc.

3.4 Discussions and Implications

3.4.1 Number of satellites

Spectra of distant quasars constrain the reionization to be completed by $z = 6$ (Fan et al., 2002), yet the exact duration and processes by which the Universe was reionized are not well understood. Our choice of $z_{\text{reio}} = 15$ is consistent with the current observational constraints and gives a number of surviving satellites within 280 kpc down to $M_V = -5$ that is comparable to the latest estimates of the luminosity function of the MW satellites. Recent hydrodynamical simulations of reionization have suggested that the value of the ‘filtering mass’ $M_F$ given by Gnedin (2000) may be too large (Hoefy et al., 2006; Okamoto et al., 2008). This could imply that our results may underestimate the number of surviving satellites, especially at low or intermediate luminosities.
Figure 3.12: ‘Emergence’ distance to the central galaxy as a function of the ‘emergence’ redshift. The ‘emergence’ epoch is defined when the subhalo of a surviving model satellite exceeded the resolution limit. The curve represents $R_{200}(z)$ of the central galaxy.

It is worthwhile mentioning here that we do not include the loss of stellar components due to tidal stripping in our modelling, which could lead to an overestimation of the present-day luminosity of satellites as well as to the number of surviving satellites down to a certain luminosity level. However, we have carefully checked the evolution of the bound dark matter mass ($M_{DM}$) and $M_{0.6}$ for the model satellites and find that only $\sim 10$ of them show significant evolution in both these quantities in the last 2 Gyr. We therefore suspect that the total number of surviving model satellites, but especially their luminosity, should not change much if we include the tidal stripping of stars.

Another process that we have not included, and which is potentially important is ram pressure stripping. We plan to do so in the near-future. A more careful modelling that includes how baryons are affected by the interactions with the MW-like galaxy is clearly needed.

3.4.2 What dark matter substructures can form stars?

In this Section we shall refer to the subhaloes with stars as the luminous satellites and those without as the dark satellites. Apart from how we model the baryonic physics, there is also a hint that the difference between the luminous and dark satellites depends on the properties of the associated dark matter haloes themselves. We have seen in Fig. 3.12 that all the surviving luminous satellites emerged before $z = 11$ (roughly at the end of reionization) while the dark ones have emerged
Interestingly, in Fig. 3.1, the mass range of $10^8 - 10^9 \, M_\odot$ is populated with subhaloes both with and without stars. The question upon us now is why some massive subhaloes have failed to form stars. To address this we trace the evolution of the dark matter mass for all satellites and mark the maximum mass and epoch when this is reached. Fig. 3.13 shows the maximum mass against the present-day mass $M_{DM}$, where the luminous satellites are in black and the dark ones in grey. It is clear that most of the subhaloes associated with the luminous satellites were once much more massive (see also Fig. 3.4). On the other hand, the dark satellites (in this mass range) have present-day masses similar to their peak values (see also Kravtsov et al., 2004).

We plot the maximum mass as a function of the redshift when a galaxy reached its maximum mass, $t_m$, in Fig. 3.14. The minimum mass defined by the cooling via atomic hydrogen as a function of redshift is indicated by the solid curve. Notice that most of the dark satellites were below the threshold and not able to cool gas even when they reached their peak mass. In contrast, the luminous satellites live in subhaloes which have been massive enough and managed to have sufficient cold gas to fuel star formation. We also notice that no luminous satellites achieved their maximum mass before $z = 6$.

Font et al. (2006) suggest that surviving satellites were accreted up to 9 Gyr ago and therefore have been through a different chemical enrichment history compared to those accreted very early on and which contributed to the stellar halo. However, in our model there are a few objects that became satellites more than 10 Gyr ago and which have survived the tidal interactions with the MW-halo (see Fig. 3.4 and Fig. 3.7). Typically, however, their peak masses are smaller than those throughout the Hubble time.

**Figure 3.13:** Maximum (virial) mass against present-day bound dark matter mass for luminous (black) and dark (grey) satellites in the modelling.
3.5 Conclusions

We use a hybrid model of galaxy formation and evolution to study the satellites of the Milky Way in a cosmological context. Our method combines high resolution $N$-body simulations which allow us to trace the evolution and the dynamics of dark matter haloes directly, and phenomenological prescriptions to follow the evolution of baryons. Our adopted semi-analytical recipes and values for the relevant parameters result in models that reproduce the properties of galaxies on large scales as well as those of the MW. We have however, made a few modifications to the model to accommodate properties of dwarf galaxies.

With the presence of a reionization background that reduces the baryon content of subhaloes around $z = 15$ and the suppression of cooling for haloes with $V_{\text{vir}} < 16.7 \text{ km s}^{-1}$, our model can reproduce the total number and the luminosity function observed for the satellites of the MW. Our fiducial SA model also shows good agreement with the metallicity distribution and the metallicity-luminosity relation thanks to the improvement on the recycling of metals from newly formed stars through the hot component of a galaxy. It also shows good agreement with other properties shared by the MW satellites, e.g. the radial distribution, luminosity-size relation and the star formation histories. It also reproduces many properties of the central host galaxy as compared to those of the MW. However, our fiducial model

**Figure 3.14:** Maximum (virial) mass as a function of the redshift when the maximum mass occurred for luminous (black) and dark (grey) satellites in the modelling. The minimum mass of cooling via atomic hydrogen as a function of redshift is indicated as the curve.

of the objects that contributed significantly to the build up of the stellar halo (De Lucia & Helmi 2008).
produces an excess of satellites with $M_V \sim -10$ mag and $\log(Z_*/Z_{\odot}) \sim -1$ and does not predict ultra-faint satellites with the total luminosity below $L_V \sim 10^5 L_{\odot}$.

We have also tested an alternative SN feedback recipe which is stronger for galaxies with $V_{\text{vir}} \lesssim 90 \text{ km s}^{-1}$ compared to the standard feedback recipe. With this alternative feedback recipe, our model predicts the same number of surviving satellites (which populate the same set of subhaloes as the standard feedback model). The alternative feedback model predicts satellites with $M_V < -5$ which also follow the metallicity-luminosity relation traced by the classical and the ultra-faint SDSS MW satellites [Kirby et al., 2008] down to $[\text{Fe/H}] \sim -2.5$ and $L_V \sim 10^3 L_{\odot}$.

In addition to the baryonic properties, our hybrid model also gives us insights into the characteristics of the present-day dark matter haloes of the satellites. Our model satellites are embedded in haloes with innermost masses between $6 \times 10^6 M_{\odot}$ and $7 \times 10^7 M_{\odot}$, in very good agreement with the estimates for the classical MW dSphs derived by [Strigari et al., 2007]. This demonstrates that the existence of a common scale for the innermost mass is a natural outcome of the CDM galaxy formation and evolution model (see also Chapter 4 and Macciò et al., 2008). The mass-to-light ratio using $M_{0.6}$ and total integrated $V$-band luminosity for the model satellites is similar to those observed in the dSphs in the MW. It shows that these satellites are dark matter dominated even within the optical extent, and that the faint satellites are the most dark matter dominated objects amongst all satellites. Our surviving model satellites are associated with ancient haloes which by $z \sim 10 - 20$ already had masses of a few $10^6 M_{\odot}$ and acquired their maximum dark matter mass after $z \sim 6$.

Although our model satellites are in very good agreement with the latest observations in terms of luminosity, metallicity and the innermost dark matter content, the agreement with the ultra-faint galaxies is less conclusive. Note that the alternative feedback recipe seems to give a better fit to the properties of ultra-faint satellites. This could imply that the ultra-faint satellites of the MW are associated with dark matter haloes with lower $V_{\text{vir}}$ compared to the classical ones (i.e. they are more sensitive to SN feedback). However, until we model the loss of baryons due to tidal stripping and ram pressure in these small systems, and until we obtain more observational constraints on these objects, their nature will probably remain unclear.

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