Measuring the Stellar Mass of Large Magellanic Cloud and Milky Way Sized Galaxies

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Abstract

This thesis will explore an approach to measuring the cumulative star formation history (SFH) of galaxies with sizes comparable to the Large Magellanic Cloud (LMC) and the Milky Way (MW), and their satellites. The stellar mass threshold for LMCs will be set as 1.00×10^9 - 1.00×10^{10} $M_\odot$, and 1.00×10^{10} - 1.00×10^{11} $M_\odot$ for MWs. The historic and current stellar masses that will be used to determine the cumulative SFH will be provided by the Shin-Uchuu simulation. This high-resolution simulation allows for the ultra faint dwarf (UFD) satellite galaxies to be included in the study. The Universe Machine (UM) model will be utilized in order to track the accretion of dark matter, which in turn tracks baryonic matter and leads to the SFH over lookback time. 10,000 random samples of the cumulative SFH will be taken and 1,000 will be plotted for all analogs and satellites. Satellites will be categorized into two types: classicals, which have a stellar mass of 1.00×10^5 - 1.00×10^7 $M_\odot$, and UFDs, which have a stellar mass of 1.00×10^5 $M_\odot$ and below. These results will show that star formation generally increases over lookback time for these analogs.

1 Introduction

The Large Magellanic Cloud (LMC) and the Milky Way (MW) are galaxies that have medium-sized stellar mass thresholds and host satellite and dwarf galaxies. Their satellites have quenched stars, that due to environmental processes, are made up of neutral hydrogen, and therefore do not have any recent star formation. The satellites can be separated into two classes: classicals and ultra faint dwarfs (UFDs). Classicals are more luminous with a stellar mass range of 1.00×10^5 - 1.00×10^7 $M_{\odot}$, whereas UFDs are fainter, with a stellar mass range of 1.00×10^5 $M_{\odot}$ and below. However, in isolation such as with dwarf galaxies, they maintain large gas reserves and are able to continue star formation. The satellites will have more of a dependence on their host mass than the dwarfs due to their lack of star formation. These factors make them suitable candidates for determining their star formation histories (SFHs), defined as the star formation rate (SFR) as a function of metallicity and lookback time [Weisz, 2014]. SFHs of galaxies, their satellites, and dwarf galaxies have been studied both observationally [Weisz, 2014] and theoretically [Wang, 2021]. A clearer understanding on SFHs can lead to more information on how galaxies accrue their masses as well as how they form and evolve.

On the observational side, most of the constraints are from the Hubble Space Telescope (HST) photometry, specifically MW satellites and dwarfs. One of the advantages of using the HST for observation is that it is a space-based telescope, rather than ground-based. This allows for the resolution to be set purely by optics and leads to better surface brightness visibility, due to no skyglow or atmospheric interference. However, there are also limitations to measuring SFHs observationally. For example, dwarfs are sensitive systems because of their low mass; both dark and baryonic parts can be changed from outside processes [Weisz, 2014]. Another challenge is measuring stars that are further away. Color magnitude diagrams (CMDs) can be used to extract important factors such as a star's age, metallicity, and initial mass. Of these factors, the color and luminosity can be used to measure SFRs, which as a function of metallicity and lookback time, is the SFH [Weisz, 2014]. The CMDs detect stars above a certain flux limit, so stars that are further away appear fainter, which makes them more difficult to measure.

On the theoretical side, there are several simulations that have studied SFHs. This paper will be focused on Shin Uchuu, a high resolution simulation with a large volume, and part of the larger Uchuu simulation [Ishiyama, 2021]. Shin Uchuu is a cosmological dark matter only simulation that has 262 billion particles with a particle mass of 8.97×10^5 h_{-1} $M_{\odot}$. Due to this, it can reproduce observational results with less effort and time compared to hydrodynamic models, which include both dark and baryonic matter. Its high resolution also permits directly studying stellar mass rather than halo mass. For the output of this simulation, this paper will utilize the UniverseMachine (UM) model [Behroozi, 2019]. UM is a numerical model that defines SFHs to be related to dark matter; specifically, that the maximum circular velocity is related to the halo mass and halo growth rate dependence. UM correlated the growth of the halo with the growth of SFHs, so if there is an underlying difference in the dark matter halo output, there may be environmental differences. The UM model is also unique in that it allows for more UFDs to be measured. A better understanding of UFDs can lead to a better understanding of galaxy formation in general [Wang, 2021].

In this paper, I introduce an approach to measuring the SFHs of LMC and MW-like halos and their subsequent satellite galaxies using the UM model with the Shin-Uchuu simulation. By taking 10,000 random samples of the cumulative ratio of the historic stellar mass and the current stellar mass, I aim to determine how the SFH has changed over time. I will also compare the SFHs and medians of the satellites of the LMCs and the MWs to establish if the difference between them is relevant.

This paper is organized as follows: in Section 2, I will present the methodology for calculating the

SFHs for the LMC and MW analogs and their respective satellites. In Section 3, I will analyze the results of the SFHs and their implications for satellite comparison and galaxy evolution. Finally, in Section 4, I will summarize the main findings of the paper and discuss the future outlook of how studying SFHs can provide more insight into galaxy formation, evolution, and how galaxies accumulate mass.

2 Methods

The beginning of this project involved becoming familiar with the Hierarchical Data Format version 5 (HDF5) file format, as this is how the data from the Shin-Uchuu simulations, originally from the UniverseMachine model, was released. This file format allows for metadata to be added onto the actual data and for dependent datasets to be stored together [Collette, 2013]. HDF5 is also particularly useful for larger projects because the data remains on the disk and is only loaded into memory when called upon. In terms of storage, a dataset takes up as much space as needed for the necessary data only.

This project utilized two HDF5 files from the Shin-Uchuu simulations: they shall hereafter be labeled Data1 and Data6. In order to compare star formation histories (SFH), the halos must be separated by their classes: centrals and satellites. Furthermore, the stellar mass of each halo at each point in the simulation is needed. Data1 contained the following key attributes: unique dark matter halo IDs, a method to determine if these halos are centrals or satellites, and the true stellar mass of the halos, in $M_\odot$. Data6 contained the following key attributes: all halo properties and the main progenitor galaxy's stellar mass history, used for the star formation rate.

To determine the star formation history, I first subsetted the indices for the central halos to only include the stellar mass range of the Large Magellanic Cloud (LMC), which I set between the threshold of 1.00×10^9 - 1.00×10^{10} $M_\odot$. I then selected a random sample of 10,000 from these indices. The dataset contains over 50 million data points and therefore is much too large to use all these points without cluster scale computing. A sample of 10,000 is enough so that the Poisson noise is low and the median plots are well converged. Equation 1 provides the formula for the cumulative star formation history:

$$SFH = \frac{M_*(z)}{M_*(z=0)}$$

where z is the redshift, $M_*(z)$ is the historic stellar mass of the centrals, and $M_*(z=0)$ is the current stellar mass of the centrals. Figure 1 shows 1,000 cumulative SFHs for LMC-mass centrals with lookback time in Gyr on the x-axis. This includes plotting the median line plus or minus one sigma with the 16th, 50th, and 84th percentiles.

Next, I selected the satellites for the LMC by using the 'upid' column, which was the attribute that differentiated centrals and satellites. I then distinguished the two classes of satellites used in this project: classicals and UFDs. The stellar mass threshold for classicals was set between 1.00×10^5 - 1.00×10^7 $M_\odot$. The stellar mass threshold for UFDs was set for anything below 1.00×10^5 $M_\odot$. Similar to Figure 1, Figures 2 and 3 show the cumulative SFHs for the classicals and UFDs, respectively, and use the same quantiles for the median.

I then repeated this entire process for halos and their subsequent satellites within the Milky Way (MW) stellar mass range, which was determined as 1.00×10^{10} - 1.00×10^{11} $M_\odot$. The cumulative SFH of the MW centrals can be seen in Figure 4, and the cumulative SFHs of its classical and UFDs can be seen in Figures 5 and 6 respectively.

Afterwards, I identified the isolated classicals and UFDs using the same stellar mass range as the satellites' SFHs. Figures 3 and 4 show the cumulative SFHs for the isolated satellites and again, use the same quantiles for the median as the original satellites.

Finally, in Figure 5, I compared the LMC and MW classicals and UFDs by dividing the 50th percentile of the median for the satellites from the isolated satellites. Figure 6 is a cumulative plot of all of the 50th percentiles of the median.

3 Results

In this section, I present the cumulative SFHs of all LMC and MW analogs, as well as the cumulative SFH of their respective satellites, and the cumulative plots of all analogs and all medians.

As Equation 1 shows, the cumulative SFH can be calculated by taking the stellar mass as a function of time (referred to as redshift in this paper) and normalizing it using the current stellar mass. This gives the ratio of the historic stellar mass and the current stellar mass.

Figure 1 shows all of the isolated classical satellites, for both LMC and MW. The slope of the SFH is positive, indicating that there was less star formation during the early periods of the universe, and that as time went on, star formation continued to increase. This relationship might be expected given the SFH of the LMC centrals and satellites following the same trend, with the LMC classicals matching the closest.

Figure 2 shows all of the isolated UFD satellites, again for both LMC and MW. The slope of the SFH is also positive, but not as much for Figure 1. This indicates that while star formation continued to increase over time, the rate at which it did so was not as high as with classical satellites. This could be due to how faint the UFD satellites are. Although the Shin-Uchuu simulation is high-resolution enough to pick up UFDs, the stellar mass range is still $1.00 \times 10^5\ M_\odot$ and below, so it may not be capturing all of the UFDs that are present. The morphology of Figure 2 was equally close to the UFD satellites for LMC and MW.

Figure 3 shows all of the classical satellites for MW. The slope of the SFH is positive, highly resembling the slope of Figure 1. This has the same indication of more star formation over time as Figures 1 and 2, with the morphology being similar to Figure 1 as well.

Figure 4 shows all of the UFD satellites for MW. The slope is only slightly positive, the same as Figure 2, with star formation still increasing over time. Though the morphologies of the isolated satellites and the normal satellites are similar, they do not fully match up. However, the differences between classical and UFD satellites within the same host, LMC or MW, are irrelevant because the lines of the plots are overlapping with each other.

The UM is a differential model [Wang, 2021] that uses stellar mass to track the accretion of dark matter. The dark matter brings baryonic matter with it, so the rate of changes are proportional. The low star formation at early lookback time is due to the accretion of dark matter. This increases the amount of baryonic matter over time, which in turn increases star formation over time.

Figure 5 shows all of the satellites for both LMC and MW taken over the isolated medians from Figures 1 and 2. The UFDs are extremely similar as they overlap throughout the entire lookback time. The classicals are less similar during the early lookback times, but gradually converge for more recent times. The difference in the Shin-Uchuu simulation for the classicals of LMC and MW are not significant for this paper, but statistical tests can be run to measure the exact difference in the future.

Similarly, Figure 6 shows the medians for all of the satellites for LMC and MW. Again, the UFDs overlap for the whole lookback time. The classicals began overlapped, then had some deviation early on, but eventually overlapped again. The deviation was between ∼12 Gyr - ∼8 Gyr, whereas compared to Figure 5, where the deviation was between 14 Gyr - ∼7 Gyr.

4 Conclusion

This paper covers the use of the Shin-Uchuu simulation and the UM model in order to measure the cumulative SFHs of LMC and MW analogs, as well as their satellite galaxies and isolated satellite galaxies. By taking 10,000 random samples of the ratio shown in Equation 1, I was able to determine that the SFH for all LMC and MW analogs and their satellites increased over time. However, the classical satellites had a higher star formation rate than the UFD satellites, which caused the difference in slope and morphology of the plots. Though the Shin-Uchuu simulation is high-resolution, this difference may be due to the faintness of UFD satellites, which could have lead to them being underrepresented in count. The isolated satellites followed the same patterns as the analogs and their satellite galaxies, with recent lookback times resulting in greater star formation. Finally, the cumulative analog and median plots also matched quite well, with a slight discrepancy in the overlap of the UFD satellites. Again, this could have been due to the UFD satellites having a stellar mass of $1.00 \times 10^5\ M_\odot$ and below.

5 Acknowledgements

I would like to thank Dr. Nitya Kallivayalil and Dr. Chris Garling for their kind guidance and infinite patience throughout this thesis project. I am very appreciative of the chance they took on me and the freedom I had in deciding the project and its limits. I also would like to thank my family: Nabin, Sirjana, and Niva (Sylve) Tuladhar for their continued and steadfast support, always. Finally, I want to acknowledge the entire Astronomy Department at the University of Virginia for being such an inclusive and welcoming space during my time as an undergraduate.

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A Appendix

All of the figures for the paper can be found below.

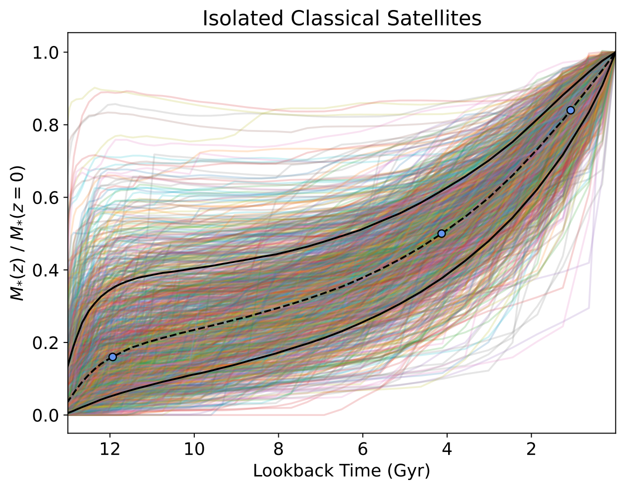

Figure 1: The SFH of the isolated classical satellites. The x-axis shows the lookback time in Gyr decreasing to the right. The y-axis shows the cumulative ratio of the historic and current stellar mass. The upper solid black line is the median line plus one sigma of error while the lower solid black line is the median line minus one sigma of error. The central dotted black line is the median itself, and the three blue dots from left to right are the 16th, 50th and 84th percentiles, respectively. It has a positive slope, indicating that the star formation increases over lookback time.

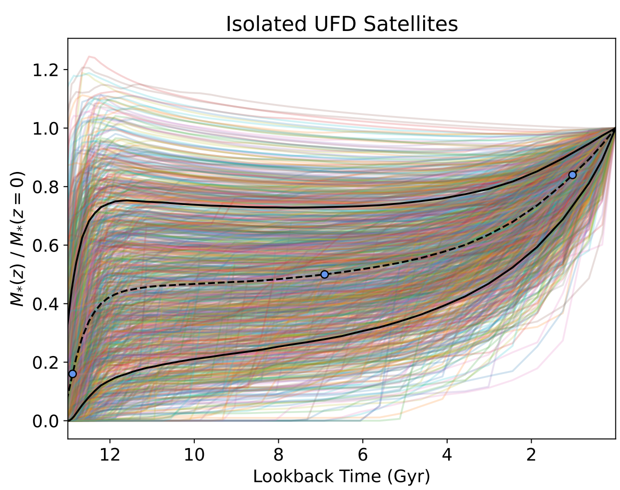

Figure 2: The SFH of the isolated UFD satellites. The features of the plot are the same as Figure 1. It also has a positive slope, but less so than Figure 1. This may be due to the faintness of UFDs. Although the Shin-Uchuu simulation is high-resolution and can identify UFDs, since the stellar mass threshold of the UFDs was set to $1.00 \times 10^5\ M_\odot$ and below, it may be under-counted by the simulation.

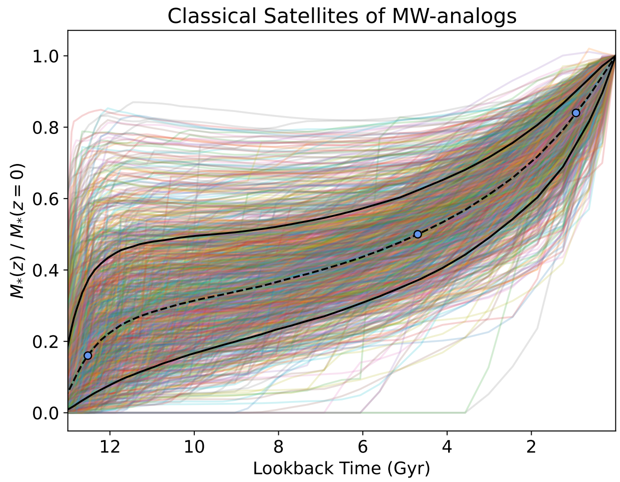

Figure 3: The SFH of the classical satellites of the MW-analogs. The features of the plot are the same as the above figures. The positive slope matches the morphology of Figure 1.

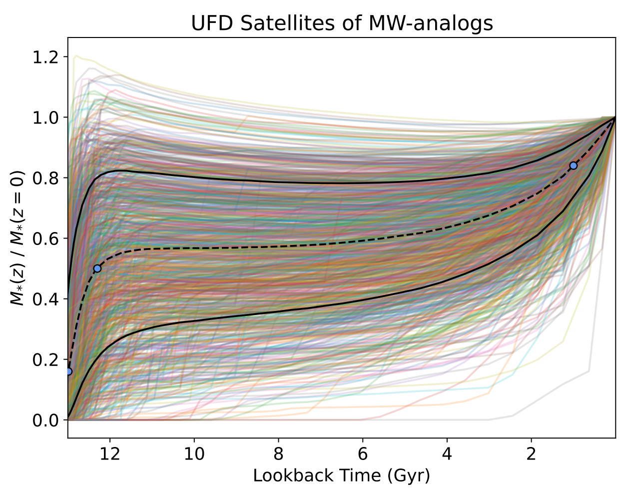

Figure 4: The SFH of the UFD satellites of the MW-analogs. The features of the plot are the same as the above figures. The positive slope matches the morphology of Figure 2.

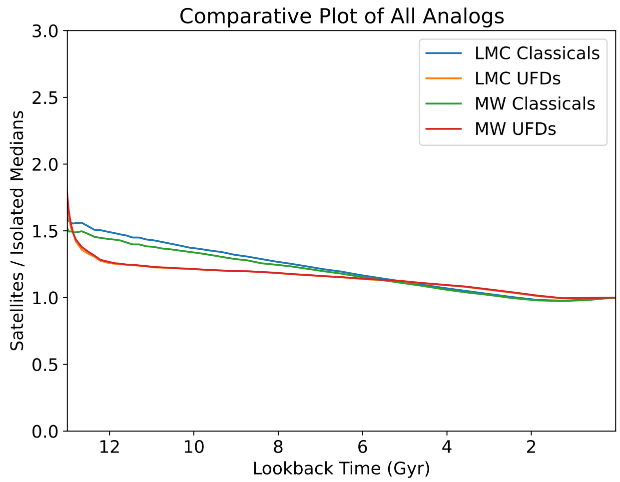

Figure 5: The comparison between the SFHs of all satellites. The x-axis shows the lookback time in Gyr decreasing to the right. The y-axis shows the medians of the satellites over the isolated satellite medians. The blue line is the LMC classicals, the orange line is the LMC UFDs, the green line is the MW classicals, and the red line is the MW UFDs. The UFDs overlap for the entirety of the lookback time, while the classicals deviate slightly during the early lookback times (∼12 Gyr - ∼8 Gyr) before converging.

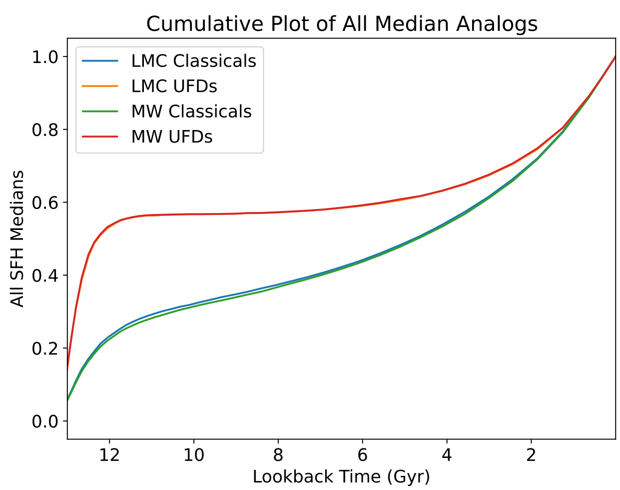

Figure 6: The comparison between the medians of the SFHs of all satellites. The features of the plot are the same as Figure 5. Similarly, the UFDs are almost the exact same for all of the lookback time, whereas the classical lines separate slightly from 14 Gyr - ∼7 Gyr.