

RECONSTRUCTION OF THE EVOLUTION OF GALAXIES USING THE EXTENDED-PRESS-SCHECHTER MODEL WITH GLOBULAR CLUSTERS

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ABSTRACT

Galaxies are large gravitationally bound systems that consist mainly of stars, interstellar gas and dust, and dark matter. The Milky Way, our own galaxy and home to Earth, has evolved from its infantile stage billions of years ago to what we see today. A question one may pose is how did the Milky Way form and is its evolution different to those of its neighboring galaxies. In the general case galaxy evolution can be depicted through collision and cannibalization, but to observe a galaxy and know its history has proven to be a difficult task. In this research a solution to the withstanding problem via a new method will be discussed. By using an advanced semi-analytical model known as the extended-Press-Schechter method and globular clusters we have obtained Monte Carlo data that resembles observed galaxies, whose implications are discussed in the paper.

1. INTRODUCTION

Among the problems that still persist in astronomy, the origin and evolution of galaxies remain elusive. Since the time that Edwin Hubble discovered galaxies nearly a century ago, tracing the evolutionary path of these objects has proven to be an ambitious venture. The primary questions concerning galaxy origins are the following

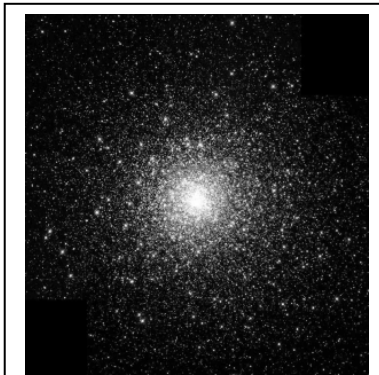


Fig. 1. Globular cluster M80 observed on the Hubble Telescope. Image Credit: The Hubble Heritage Team (AURA/STScI/NASA)

- "1) From a homogeneous universe how did the inhomogeneous one we see today come about?
- 2) How did galaxies form in the early stages of the Universe?
- 3) How do galaxies change over time?"¹

While all these questions have been thoroughly researched, a new method has been brought forth that applies particularly to the third question by using properties of globular clusters to determine galaxy histories. Globular clusters are dense gravitationally bound objects that contain anywhere between 10^4 to 10^6 stars which orbit around galaxies. An example of a globular cluster is shown in Figure 1. An interesting and potentially useful property of globular clusters is the bimodality of its metallicity distribution.

¹ http://en.wikipedia.org/wiki/Galaxy_formation_and_evolution

Why would one use the bimodal property of globular clusters to describe galaxy histories? Let us note some well-known facts of globular clusters to answer the question. First, globular clusters are of ancient origin dating back to 10 to 15 billion years ago (West et al. 2004). This means that the globular clusters were companions of the birthing galaxies and have remained unscathed through galaxy evolution because of the relatively large gravitational attraction between the stars. Second, the number of globular clusters per galaxy correlates with the luminosity of their parenting galaxies (West et al. 2004). As galaxies undergo evolution we have found compelling evidence of numerous events of galaxy mergers or larger galaxies "cannibalizing" smaller galaxies. With the large perturbations that are involved in galaxy evolution the initial galactic structures will have undergone change. What may be initially a spiral galaxy could turn into an elliptical galaxy after merging with its neighboring galaxies. The globular clusters of the galaxies during these merging and cannibalizing events remain unperturbed. Hence, it may be possible to use these globular clusters as 'fossils' (West et al. 2004) to determine the unique histories of galaxies. In this paper we will study only the history of elliptical galaxies. To test the idea that has been put forth by Cote, West, and Marzke (1993) Monte Carlo simulations are used. There are two ways to undertake this problem: (1) N-body model or (2) the Press-Schechter model. Here we focus on the Press-Schechter formalism because of its advantages that are described in the next section. An astronomer from the Astronomical Observatory of Rome, Dr. Nicola Menci, has collaborated and provided a program² utilizing the extended-Press-Schechter method (EPS), which produce galaxy histories. To test the EPS program this thesis extends Menci's simulations by adding the globular clusters, which allows us to study detailed components of galaxy evolution. With direction provided by Dr. West and Dr. Marianne Takamiya I have written a program that allows us to study globular cluster population in the galaxies simulated by Dr. Menci's EPS program.

2. MONTE CARLO MODELS

Recently there have been large advancements in simulations of galaxy evolution. There are two primary tracks that one can embark to create Monte Carlo simulations. The first, N-body model, is the most widely-used and popular method where sets of differential equations are solved to track motions of bodies that interact with one another over a set period of time. The other method known as the Press-Schechter model was created by two Caltech graduate students in 1974 to bypass the computational difficulties that come along with the N-body model (Press et al.). Brief descriptions of the two types of simulations are presented next, to understand the reason why the Press-Schechter model is implemented in this research.

2.1 N-BODY METHOD

The N-body method is a flexible and modifiable system. Ranging from particle physicists to astronomers, they use the model to solve a diverse number of problems encompassing the atomic to the cosmological scale. In each of these domains different assumptions have to be made to allow the N-body simulations to work properly. For example an astronomer studying stellar interactions will devote their research to the interactions between the particles in terms of collisions. On the other hand, an astronomer working on galaxy evolution prefers collision-less interactions because collisions between stars are negligible (Binney, 1987). Due to the intensive computations of N-body simulations at the galactic scale, the stars are clustered into

² <http://lbc.mporzio.astro.it/menci/>

superparticles (Bertin, 2000). In one case of galaxy evolution simulations, 100 million particles are used to represent the Milky Way. Using the N-body model allows the user to obtain comprehensive and accurate data for galaxy evolution simulations, but at the cost of intensive supercomputer usage with extended periods of time. For example, a simulation representing the Milky Way and Andromeda galaxies colliding took a period of around four³ days to complete.

Another problem that N-body simulations pose is the particle resolution. At galactic scales in these simulations the superparticles represent a large collection of stars that contain 100 times more particles than globular clusters. This means that in a typical N-body model at the galactic scale one would not be able to track the dynamics of the globular clusters. The study of globular cluster systems as proxies for galaxy evolution is cumbersome using N-body simulations because higher mass resolution demands unrealistically large supercomputer power and time.

2.2 EXTENDED-PRESS-SCHECHTER METHOD

The original Press-Schechter model has been used since its inception in 1974 in numerous studies. Over the span of the last 30 years the model has been modified to provide increasingly accurate solutions. Two of the currently modified forms are the extended-Press-Schechter (Lacey et al. 1993) and modified-Press-Schechter (Salvador-Sole et al. 1998) models. The milestone of the Press-Schechter model in general is its ability to bypass the non-linearity of the N-body model by making statistical assumptions. The upshot of employing the EPS model is its ability to be executed on a personal computer and requiring relatively minimal computer time. Having the ability to run galaxy simulations many times on a regular computer allows us to re-parameterize the system for optimal performance. EPS supersedes high-resolution N-body simulation models. Therefore, the EPS simulation method is efficiently the best choice in terms of time, computing power, and flexibility for this research.

3. MENCI'S PROGRAM

The EPS program from Menci's research provides the merging trees of several galaxies. We studied the merging histories of 1100 galaxies. Menci's program (hereafter MP) output consists of redshift, total dark matter mass, total stellar mass, and final absolute visual magnitude of the galaxies involved. The typical format of the output is an X by 5 matrix where X is determined by the number of galaxies and interactions that are present in the output file, which we can refer to as the merger tree. In the research the current output contains roughly 1,100 unique merger trees for final galaxies.

4. GLOBULAR CLUSTER PROGRAM

With MP's output being a record of multiple galaxy merger trees we require a program that assigns globular clusters to galaxies that appears for the first time in the merger trees. Since there was no program of this sort readily available in the public domain I wrote a program in IDL⁴ to do the required task. We can refer to the globular cluster program as GCP. The GCP algorithm is as follows:

³ <http://www.newsandevents.utoronto.ca/bin/000414b.asp>

⁴ Interactive Data Language - <http://rsinc.com/idl/>

1. Search for young galaxies and assign globular clusters accordingly. The globular clusters' mean metallicity values are determined by

$$[Fe/H] = a_0 + a_1 M_V^i + a_2 M_V^{i2}$$

where a_0 , a_1 , and a_2 are constants and M_V^i is the absolute visual magnitude of the corresponding galaxy (Cote et al. 1993).

2. Determine the number of globular clusters per galaxy from the specific frequency. The specific frequency (S_N) is defined as the number of globular clusters per galaxy luminosity. Based on McLaughlin's equations (McLaughlin, 1999) we ascertain the specific frequency, which is dependent on the galaxies' absolute visual luminosity, denoted as L_V . For galaxies with $L_V < 3.5 \times 10^9 L_{solar}$, where L_{solar} is the total luminosity unit of the Sun, we have

$$S_N = 5 \left(\frac{L_V}{2 \times 10^8 L_{solar}} \right)^{-0.4}$$

For galaxies with $L_V > 3.5 \times 10^9 L_{solar}$ we use

$$S_N = 5 \left(\frac{L_V}{3 \times 10^{10} L_{solar}} \right)^{0.75}$$

With the specific frequencies defined for the galaxies we use the following equation and solve for N_T :

$$S_N = N_T \times 10^{0.4(M_V + 15)}$$

By solving for N_T we obtain the number of globular clusters per galaxy as a function of their galaxies' luminosities.

3. Sum up the number of globular clusters in each final galaxy.

To test the validity of the results of the simulation we compare metallicity distribution of the galaxies for simulations vs. observations. A sample of simulation data vs. observation is provided in a histogram format, which can be seen in Figure 2.

5. KMM TESTING

The data from the globular cluster program is best analyzed in histogram format. In these histograms we look for bimodality. In some cases the mean values of the curves are indeterminate from one another visually. Hence, using a statistical algorithm software known KMM⁵ (Ashman, Bird & Zepf 1994) allows us to test the difficult data sets for bimodality.

⁵ <http://cas.umkc.edu/physics/ashman/blake.html>

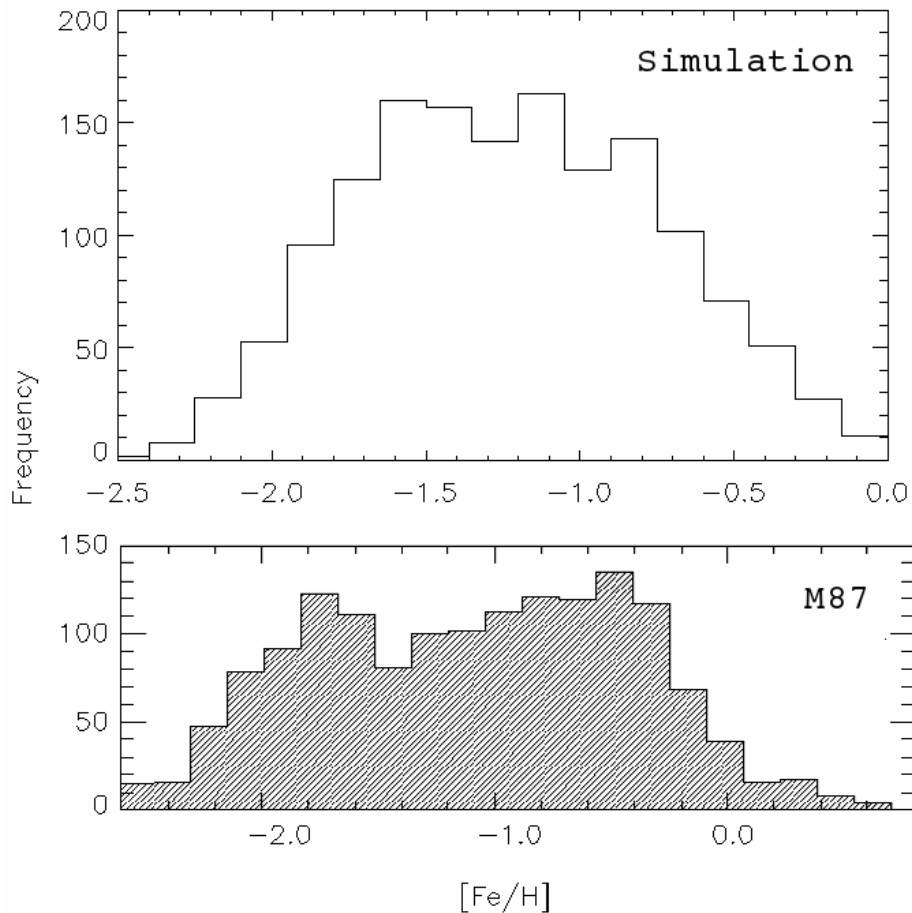


Fig. 2. The simulated galaxy, on top, which has $M_V = -22.25$ is a plot that represents a simulated Monte Carlo globular cluster set that is comparable to M87's globular cluster set. The number of globular clusters for the simulated galaxy and M87 are approximately the same at ~ 1500 . KMM testing of the simulation data gives strong indication that it is bimodal with its mean peak values at -1.52 and -0.80 .

6. RESULTS

GCP has various options for computing the luminosity of the galaxies based on the stellar matter mass provided in MP through the mass-luminosity ratio. Since we are dealing with multiple different galaxies in sequential time the mass-luminosity ratio contains a large range of values. Hence, we use mass-luminosity ratios that best fit the galaxies in the merger trees. The results from the simulations provide globular cluster populations of similar characteristics to observed data. In addition, we apply the KMM test to the simulated results to obtain verification of bimodality and the mean values of the peaks. An example of this can be seen in Figure 2.

7. FUTURE

As the Monte Carlo simulations are tested and more results are produced we will use one more statistical method to test for the validity of the data; the Kolmogorow-Smirnov method. This method is used to test goodness-of-fit between the simulated and observed data of galaxies

and their respective globular cluster population characteristics. In the GCP there are placeholders for more parameters to be added for more complex assumptions concerning globular cluster formation. These placeholders will most likely be used for events such as galaxy mergers where stellar gases are exposed to density perturbations from the collisions and new globular clusters are formed. Another possible assumption that will be appended is the globular clusters' mean metallicity as a function of redshift. By working from the simplest assumptions we can append the more complex parameters for better precision in the simulations. Last but not least, MP is being configured to compute precise values of absolute visual magnitudes of galaxies in the merger tree outputs. This will provide GCP the ability to produce more accurate Monte Carlo results of globular clusters populations.

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REFERENCES

- Ashman, K.M., Bird, K.A., Zepf, S.E. (1994) Detecting bimodality in astronomical datasets. *AJ* 108, 2348.
- Bertin, G. (2000) *Dynamics of Galaxies*, Cambridge University Press, Cambridge, UK. □ □
- Binney, J., Tremaine, S. (1987) *Galactic Dynamics*, Princeton University Press Princeton. Cambridge, UK. □ □
- Cote, P., Marzke, R.O. & West, M.J. (1998) The formation of giant elliptical galaxies and their globular cluster systems. *AJ* 501, 554-570. □ □
- Harris, W. E., & van den Bergh, S. (1981) Globular clusters in galaxies beyond the local group. I - New cluster systems in selected northern ellipticals. *AJ* 86, 1627. □ □
- Lacey, C., Cole, S. (1993) Merger rates in hierarchal models of galaxy formation. *MNRAS* 262, 627. □ □
- McLaughlin D. (1999) The efficiency of globular cluster formation. *AJ* 117, 2398.
- Press, W. H., & Schechter, P. (1974) Formation of galaxies and clusters of galaxies by selfsimilar gravitational condensation. *ApJ* 187, 425 □ □
- Salvador-Sole E., Solanes J. M., Manrique A. (1998) Merger vs. accretion and the structure of dark matter halos. *ApJ* 499, 542.
- West, M.J., Cote, P., Marske, R.O., & Jordan, A. (2004) Reconstructing galaxy histories from globular clusters. *Nature* 427, 31.