Uncertainty Quantification of Stellar Cluster Parameters Using the Method of Stellar Isochrones

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Introduction

Since the field of astronomy has existed, people have observed that certain regions in the sky are densely populated with stars all in close proximity with each other (see Figure 1). In the modern era, we know that these "star clusters" had their constituent stars birthed from a single star-forming region and that factors such as a star's mass, metallicity, and rotation speed have a discernible impact on a star's development and lifespan.

In this work, we aim to analyze the specific parameters integral to the development stellar clusters, including their age, average metallicity, and average rotation rate of their constituent stars using a database of stellar evolution models.

Figure 1: An image of the Pleiades (M45), an open star cluster. It is visible to the naked eye in low light pollution areas, and thus has been seen by humans for thousands of years. Credit: Advanced Observing Program (2014)[1]

Methods

The first step in this study is to create a stellar database using the Modules for Experimental Stellar Astrophysics (MESA) stellar evolution code.[3] This database contains a grid of computer models covering a range of stellar masses, initial metallicities, and rotation rates, which along with stellar age constitute the parameters of this problem. In the next step, we create a synthetic cluster, or a set of clusters, containing hundreds of stars, with their initial properties selected according to a prescribed initial mass function (IMF), which aims to match to the observed mass distribution of stars. Then, we use a method of stellar isochrones to estimate the average properties of our synthetic cluster's stellar population. This is done by extracting from the model stellar database information about effective temperatures and luminosities of stars that belong to the synthetic cluster. Since we assume that stars were formed at the same time, their age is identical, so we can obtain the required information by interpolating corresponding evolutionary tracks of nearby stars (in a sense of their metallicity, rotation rate, and age). A set of so-interpolated points represents theoretical positions of model stars at a given age on a so-called Hertzsprung-Russell (HR) diagram, known as an isochrone (Figure 2). Finally, we use an optimization method to estimate a set of isochrone control parameters that best fits the (synthetically generated) stellar cluster observations.

From here, two isochrones are generated in order to test the function. The first isochrone represents given synthetic observational data, where each star is given a fixed amount of Gaussian random variation in its initial metallicity, rotation rate, and age from some known mean for each of the three parameters. The second isochrone generated is the fitted isochrone, which is continuously optimized through the changing of the above-mentioned parameters to find the iteration which minimizes the difference between the data points of the observed and synthetic cluster. The fitted isochrone is perturbed in its parameters to start away from the observed isochrone. The aim is to measure differences in these perturbations with the final parameters optimizers by a fitting function. This process can be visualized in Figure 3.

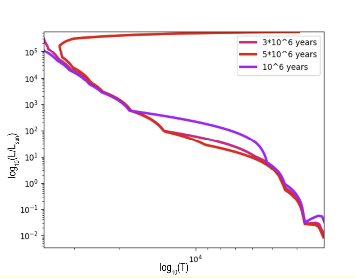

Figure 2: Stellar Isochrones on an HR diagram. Each of these was constructed from one thousand stars, with a constant metallicity and rotation rate for all constituent stars.

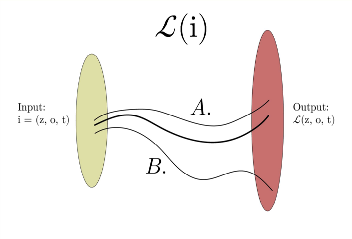

Figure 3: Visual Diagram of Procedure. The function $\mathcal{L}(\mathrm{i})$ is the isochrone fitting function, where the input is the perturbed parameters of the isochrone to be fitted. Line A represents a perturbation of unsensitive parameters, where a slight shift in the input results in minor change to the output. Line B represents either a major perturbation or a slight perturbation of a sensitive parameter, which causes a significant change in the output.

Results

Three experiments were performed, each testing how the fitting function handled a perturbation in one of the three parameters (age, metallicity, rotation rate) between the two isochrones. The perturbations were calculated using the formula $\mathrm{P} = \pm 10^{\mathrm{p}}$ where p serves as the independent variable. From there the percentage error was calculated between the optimized parameters produced by the fitting function and the original unperturbed parameters. For each of the three experiments, one and only one of the parameters was perturbed, and could be altered by the fitting function, while the other two remain static and unperturbed. In each experiment, eight different runs were recorded, with variation in the starting age of the isochrone increasing logarithmically from one million to one billion years to produce four options, and for each of these options the perturbation could either be added, or subtracted from the unpeturbed parameter. The results of each of these three experiments can be seen in Figures 4, 5, and 6.

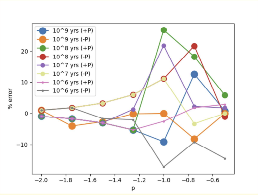

Figure 4: Amount of Perturbation in Age vs. Percentage Error in isochrone fitting function.

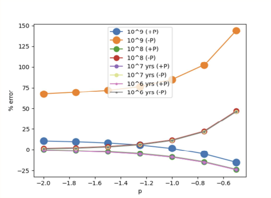

Figure 5: Amount of Perturbation in Metallicity vs. Percentage Error in isochrone fitting function.

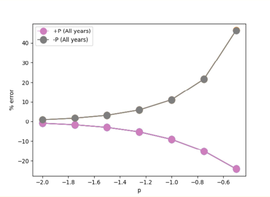

Figure 6: Amount of Perturbation in Rotation Rate vs. Percentage Error in isochrone fitting function. In this experiment, there was no variation between ages in the returned parameters of the fitting function.

Conclusions and Future Work

The experiments revealed interesting results about the sensitivity of the parameters in the fitting function. Age is the most sensitive of the three input parameters, and produces very chaotic results with a perturbation of around 10% of the original age, across all tested stellar ages. Metallicity only becomes a sensitive parameter at the age of one billion years, and rotation rate never becomes sensitive across the tested stellar ages. The many uniform results for both metallicity and rotation rate could come from how little alterations in these properties affect luminosity and temperature in the MESA models for individual stars.

The biggest one was the short timeframe of the Undergraduate Research Opportunities Program under which this research was conducted. With more time, the isochrone fitting computer program may be further developed and refined to provide more accurate estimates and at a lower computational cost. The first possible improvement is implementation of a more realistic IMF, such as those proposed by Kroupa[4] or Chabrier[2] to represent the natural variation of stellar masses in observed clusters. Another potential way to improve the method might be the broadening of range of stellar masses represented in the model stellar database. The database can also be refined by adding models of intermediate values of the model database parameters.

References

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