Spatially-Resolved Stellar Populations and Star Formation Histories Through Photometric Modeling of Semi-Resolved Galaxies

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Background: A major goal of modern astrophysics is to understand the growth and evolution of galaxies, both as a population and on an individual basis. Often, these questions can be framed in reference to the *stellar populations* of galaxies (the quantity, ages, and chemical compositions of their component stars) as well as the spatial and temporal evolution of these stellar populations. Of particular interest is the *star formation history* (SFH), or the distribution function of ages of stars in a galaxy, which traces the periods of growth and quiescence a galaxy underwent.

Two major methods are currently used to measure infer star formation histories from observations of galaxies, each with inherent strengths and limitations. The first, known as stellar population synthesis (SPS), models the observed spectral energy distribution or spectrum coming from the light of all stellar populations in the galaxy (for a review, see Conroy, 2013). The second, which we denote as resolved-star photometry (RSP), compares the color-magnitude diagram of resolved stars to stellar evolution models (eg. Dolphin, 2002). The SPS method has been used extensively to study distant galaxies, while the RSP method has been applied to nearby systems (especially dwarf galaxies) where stars can be resolved and photometered.

One limiting factor of the SPS method is that evolved stellar phases (eg. AGB stars, core He burning stars, etc.) are both poorly understood in stellar models and dominant contributors to large wavelength rages of SEDs. Therefore, the systematic differences between different stellar population models can result in significant offsets in derived galaxy properties using the SPS method. Additionally, SPS methods typically assume a fully-populated IMF, and sensitivity to Poisson fluctuations (such as for nearby galaxies) has not been extensively studied. The RSP method is limited to only the most nearby systems due to the resolving power of our best instruments: even with the Hubble Space Telescope (HST), the bulge of M31 is below the crowding limit (Williams et al., 2017).

A useful metric to use in comparing the applicability of these methods is to consider the average number of stars in a given "pixel", which we denote $N_{\rm pix}$. SPS models are typically applied to systems with $N_{\rm pix} \gg 10^6$, such that each resolution element contains a fully-populated sample of the IMF, and Poisson fluctuations of rare stars are small. The RSP method relies on resolving stars well below the crowding limit, where say $N_{\rm pix} \lesssim 10^{-2}$. Nearly all large galaxies in our local universe (from M31 out to ≈ 20 Mpc) lie in the so-called "semi-resolved" regime between these two limiting cases. They are too distant to resolve individual stars, but nearby enough for Poisson fluctuations to have a significant impact on integrated light measurements.

Method: In this thesis, I intend to extend the framework originally proposed in Conroy & van Dokkum (2016), applying stellar population models to the photometry of individual

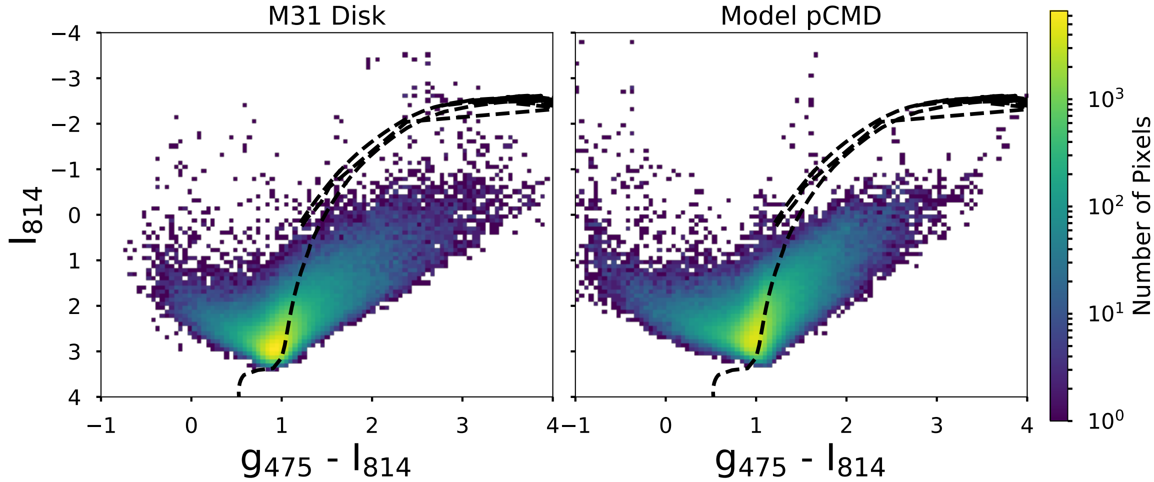

Figure 1: Example pixel Color-Magnitude Diagrams (pCMDs). *Left:* pCMD of a section of the disk of M31, as observed with HST. *Right:* modeled pCMD assuming $\log_{10} N_{\rm pix} = 1.5$, solar metallicity, no dust, and a $\tau = 4$Gyr SFH.

image pixels of galaxies in the semi-resolved regime. This method relies on constructing a forward-modeling procedure for simulating the photometric fluctuations on a pixel-by-pixel basis for a given galaxy, and comparing directly to the pixel-level photometric data. This comparison is typically done in Color-Magnitude space, and so is denoted the pixel Color-Magnitude Diagram (pCMD) method (see Fig. 1).

The underlying principle is related to SPS: the desired galaxy properties (metallicity, SFH, etc.) are used to select stellar population models (from MIST, Choi et al., 2016) which will be fed into a simulated observation. The added complication comes from loosening the assumption that the IMF is fully-populated, and instead manually populating pixels with a random number of stars from the models, based on Poisson random draws assuming the new parameter $N_{\rm pix}$. Once a simulated image has been populated with a variety of stars, their fluxes (in 2 or more filters) are convolved with an instrumental PSF appropriate to the observed data, and the resulting pixel-by-pixel fluctuations are compared to the observations. Even for relatively high values of $N_{\rm pix}$ ($\sim 10^6$) where resolved-star photometry is infeasible, Poisson fluctuations in the numbers of rare, bright stars result in significant surface-brightness fluctuations between pixels, which can be used to compare various galaxy models and infer stellar population properties (see fig. 2).

Progress Accomplished: Conroy & van Dokkum (2016) first outlined the pCMD framework, and demonstrated its application with an initial suite of mock tests and analysis of data from the M31 bulge and disk. Since joining the project, I have made significant steps towards formalizing, expanding, and improving the method. Primary among these improvements include:

1. Translated the project from Fortran to Python, which will be more widely accessible to the astronomy community once the code is released publicly.

2. Accelerated the simulation process by $\sim 16\times$ by converting the simulation steps to

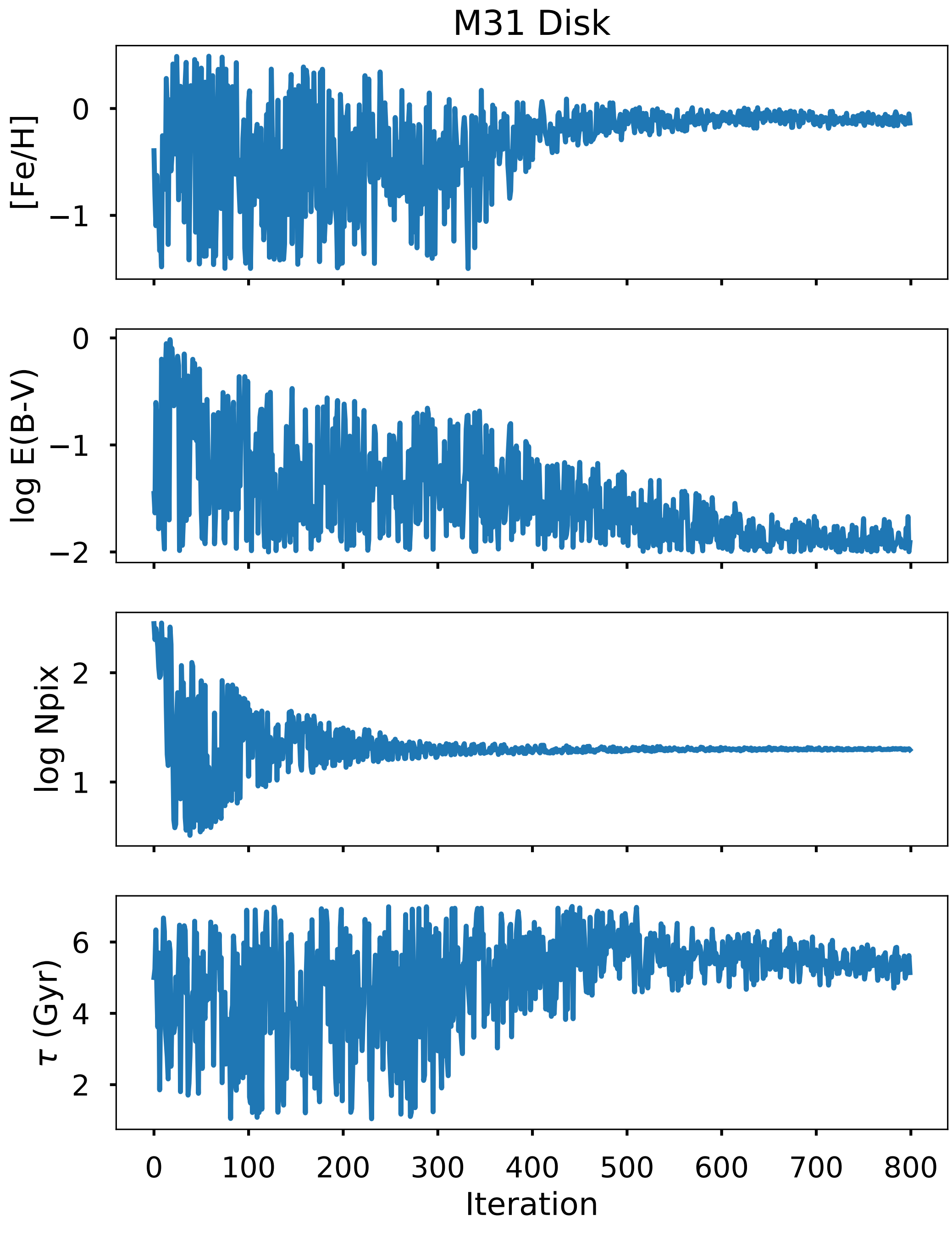

Figure 2: Results from fitting the M31 Disk pCMD from Fig. 1 using the Dynesty nested sampling algorithm. The algorithm begins with a disperse sampling of points in the prior volume, before narrowing in on the regions of prior space where likelihood is maximal.

operating on GPUs.

3. Converted from MCMC to Nested-Sampling (Dynesty), which allows more initialization-agnostic exploration of the posterior and improved model comparisons through measurement of the Bayesian evidence.

4. Significant mock testing over a wide parameter space.

Secondary goals accomplished include creating a framework for easy creation of arbitrary galaxy models, generalizing to an arbitrary number of photometric filters, incorporating the latest MIST isochrone models, and creating interactive demos of the pCMD model which run live in a browser and will eventually be expanded into an outreach resource [1]. We have also begun experimenting with running pCMD analysis on the cloud using Amazing Web Services, which we see as the way forward for running large parallel analysis of many datasets simultaneously.

Future Steps: There is a wide variety of directions that this project can continue along, from application on archival HST data to a theoretical study of the information content of pCMDs. There are a wide variety of improvements which should be made to the model, such as a more complex dust model and a distribution of metallicities. There are also outstanding questions related to the statistical properties of the model, such as the choice of likelihood function and issues of stochastic likelihood draws. Here, I propose three projects which will make up the thesis:

1. Expansion of the pCMD method to more complicated dust and metallicity models, extensive mock testing to constrain optimal model parameters, and application to archival data from M51.

2. Apply pCMD method to sample of 20 nearby galaxies to measure SFH of local universe (HST Program 14557).

3. Explore the information content of pCMDs as a function of observational campaign (angular resolution, wavelength range, number of filters), galaxy properties (distance, mass, inclination), model properties (parametric/non-parametric SFH, likelihood function) and stellar population model systematics. Compare SFH reconstruction in unresolved, semi-resolved, and fully-resolved regimes.

References

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[1] https://www.cfa.harvard.edu/~bcook/outreach.html