A Novel Approach to Constraining Uncertain Stellar Evolution Models: Probabilistic CMD fitting of Magellanic Cloud Clusters

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Context

Stellar evolution models are fundamental to nearly all studies in astrophysics. They are used to interpret spectral energy distributions of galaxies, to derive the star formation histories of nearby galaxies, and as inputs to stellar population synthesis software. Despite the success in using stellar evolution models, some important aspects of stellar evolution remain poorly constrained and can impact the interpretation of observations.

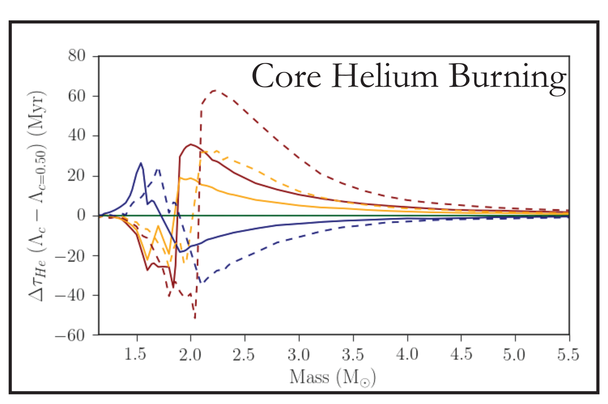
The two main uncertain process that controls a single star's evolution are the transport of convective energy and mass loss. Together, **these physical processes are too complex to be derived from first principles alone; they must be constrained by observations.**

In 1D stellar evolution codes, convective energy transport is usually approximated by mixing-length theory. However, where a convective element finally stops is highly uncertain and has dramatic consequences. If a convective element still has momentum as it passes the traditional convective zone (Schwartzchild Criterion) it will "overshoot" the boundary and deposit chemically different materials elsewhere in the star. In the stellar core, convective overshoot allows for more mixing and more material available for fusion, resulting in a larger core, and longer fusion lifetimes.

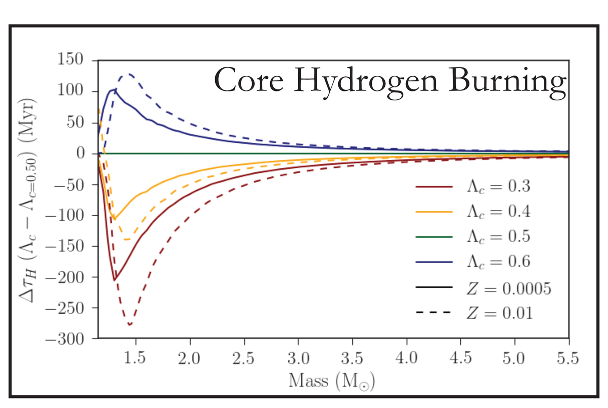
Convective overshooting, and other complications of convection are parameterized in stellar evolutionary codes, for the purpose of constraining the parameters with observations. The strength of convective core overshooting (Λ_c) is expressed in units of pressure scale heights above the Schwartzchild boundary.

Convective Core Overshooting

and Stellar Ages

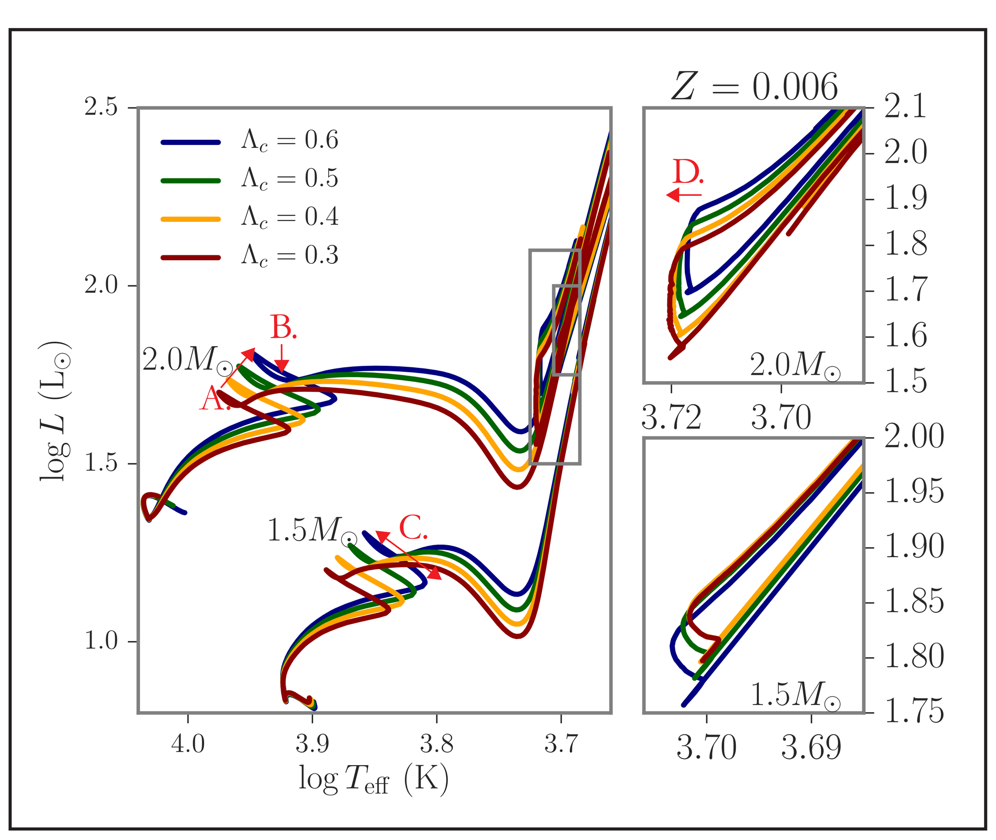


Increasing the strength of core overshooting increases stellar lifetimes at masses when the convective core is largest.



Differences in main sequence turn off (MSTO) age (bottom) or Helium burning lifetimes (top) at varying levels of core overshooting compared to the canonical PARSEC value (Λ_c=0.50) as a function of mass.

and Stellar Temperatures and Luminosities



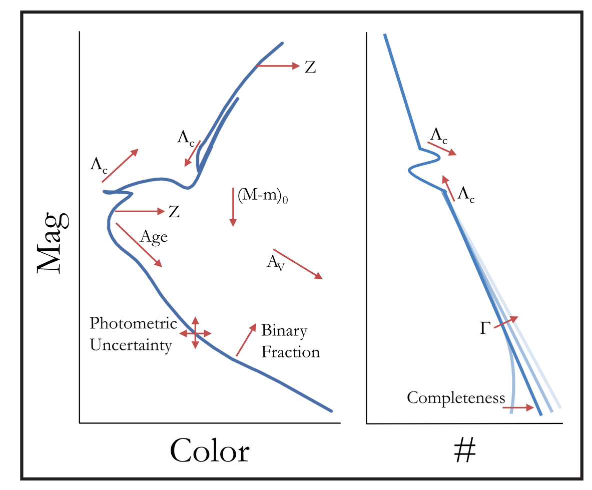
With increasing core overshooting strength:

A. MSTO is brighter & cooler
B. The luminosity dip after the MSTO is more pronounced
C. The extension between the minimum Teff on the MS and the MSTO increases.
D. The extent to hotter $T_{\rm eff}$ of the Helium burning tracks decreases

The importance of simultaneously fitting all uncertain quantities to obtain stellar model constraints

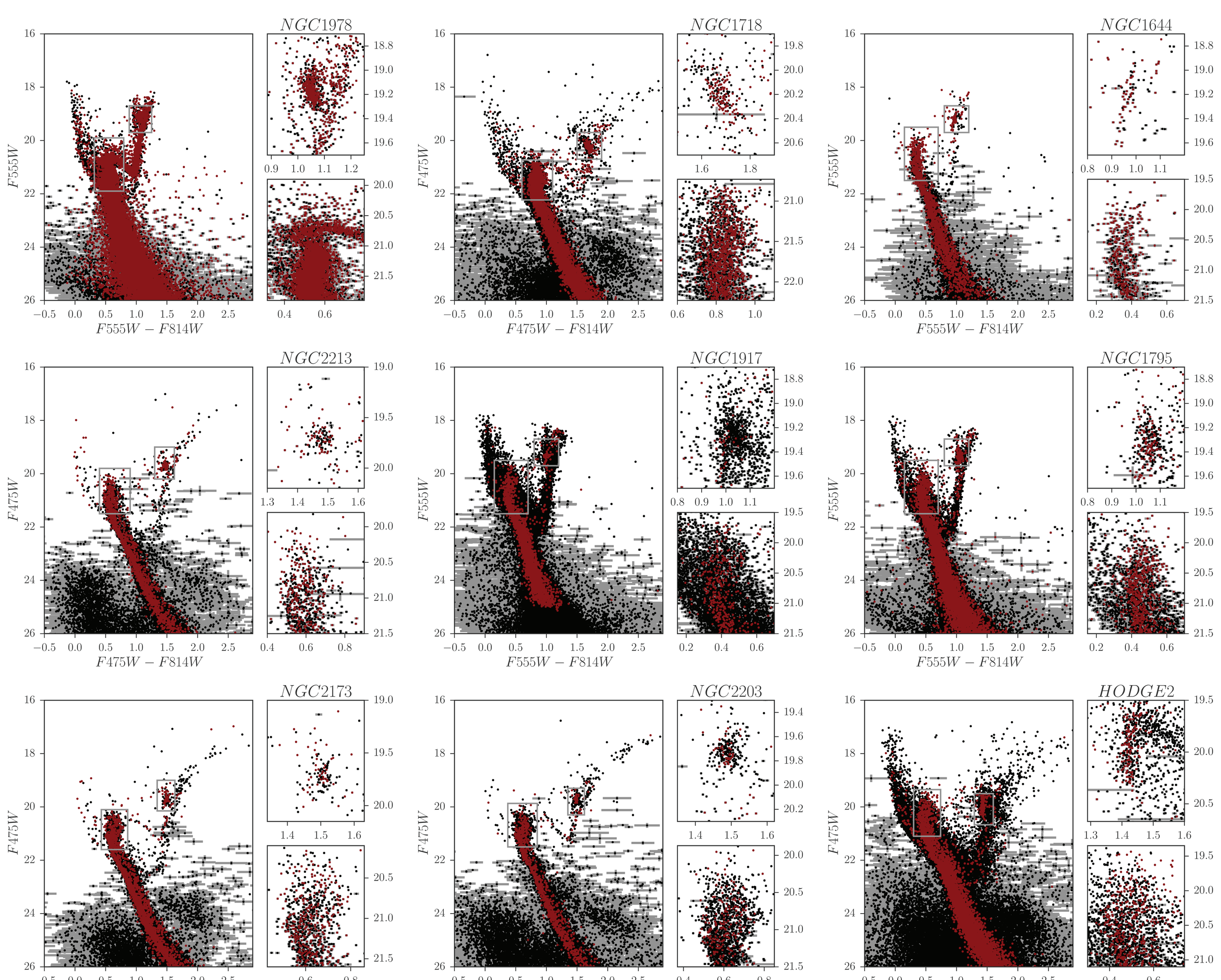
Theoretical and observational parameters can shift the morphology of an intermediate-age isochrone or synthetic stellar population. Uncertain parameters are not orthogonal.

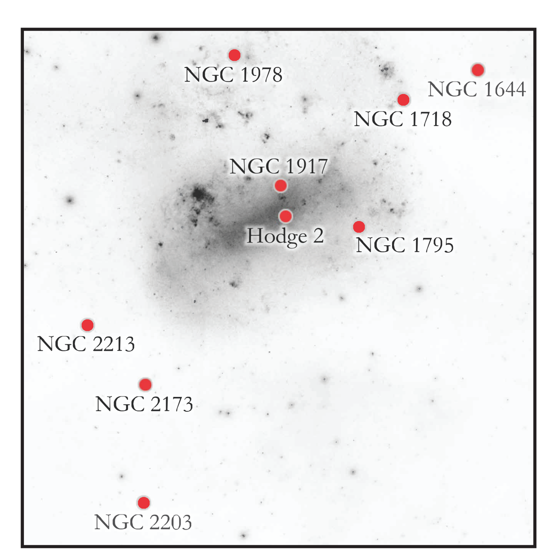
Combinations of observational uncertain parameters may mimic theoretical expectations. For example, distance and interstellar extinction, could be construed as different age and metallicity of the cluster.



Schematic optical color-magnitude diagram (CMD; left) and luminosity function (LF; right). Arrow direction denotes direction of increase.

Data





CMDs (above) of the data (black) and probable cluster members (red) with insets around the MSTO and Red Clump. Physical distribution of clusters in the LMC (below)

To test our method, we selected clusters with literature ages near 1.5 Gyr (Bica et al., 2008). MSTO stars near this age have convective cores so the strength of core overshooting will most dramatically affect the CMD morphology of the MSTOs and red clumps of these clusters.

Data were obtained as part of HST AR-13901, a program to uniformly re-reduce the Hubble Space Telescope archive of ~120 Magellanic Cloud stellar clusters and use the data to obtain constraints on stellar evolution models. Clusters shown above are from GO-9891 (PI: Gilmore) and GO-12257 (PI: Girardi).

All data were reduced and photometered using the University of Washington data reduction pipeline (e.g., Williams et al., 2014). Artificial star tests (ASTs) were conducted to assess the photometric uncertainties and completeness using ~96k artificial stars per cluster. ASTs were distributed uniformly in CMD space covering the full magnitude and color range of the data, and were distributed spatially according to a King profile, literature values for center and half-light radius, fixed concentration, covering a range in radius from 0 to four half-light radii.

Cluster centers, radii and membership tests were determined using the ASteCA code (Perren et al., 2015).

Models

The Padova-Trieste Stellar Evolution Code (PARSEC; Bressan et al., 2012) adopts the maximum core overshooting value of (Λ_c=0.5). We calculate a grid of 3,560 stellar evolution tracks using PARSEC V1.2S (Chen et al., 2014; Tang et al., 2014) with varying levels of core overshooting for both Hydrogen and Helium burning phases.

Parameter	Range	Step Size
Metallicity (Z)	0.0005, 0.001, 0.002, 0.004, 0.006, 0.008, 0.01	...
Λ_c (H_P)	0.3 – 0.6	0.1
Mass ($M_\odot$)	0.1 – 20	$0.1 \le M \le 2.4 : \Delta M \le 0.05\ M_\odot$
		$2.6 \le M \le 6.4 : \Delta M = 0.20\ M_\odot$
		$7.0 \le M < 12.0 : \Delta M = 1.0\ M_\odot$
		$12.0 < M \le 20.0 : \Delta M = 2.0\ M_\odot$

The PARSEC Convective core overshooting grid space

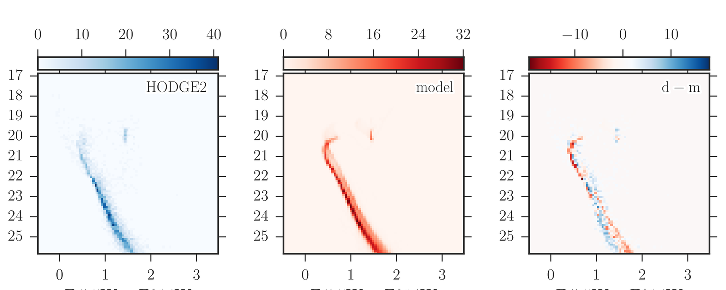
Method

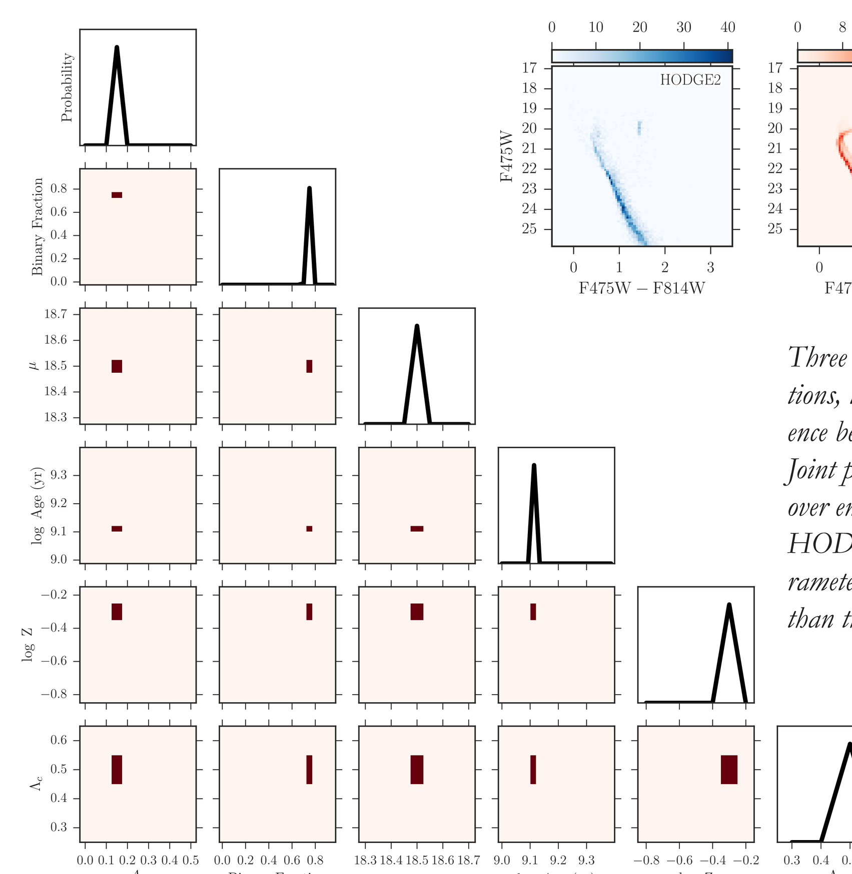
We use the CMD fitting MATCH software package (Dolphin 2002), to find the most probable model CMD determined by the minimizing the Poisson likelihood ratio (Poisson equivalent of χ^2). Model CMDs are created from a sequence of synthetic stellar populations based on input stellar models and given a range of priors.

Parameter	Range	Step Size
IMF (Γ)	1.35	(Salpeter (1955) fixed)
Binary Fraction	0.0 – 1.0	0.05
Distance ($(m-M)_0$; mag)	18.3 – 18.7	0.05
Extinction (A_V; mag)	0.0 – 0.5	0.05
Age (Gyr)	1.0 – 2.5	0.06
Metallicity ([Fe/H]; dex)	−0.85 – −0.15	0.10
Core overshooting strength (Λ_C; H_p)	0.3 – 0.6	0.1
Color (mag)	(varies by cluster)	0.05
Magnitude (mag)	(varies by cluster)	0.10

Priors and the MATCH grid search space

Results





Three CMDs (top): HODGE 2 observations, the most likely model, and the difference between observation and model. (Left) Joint probability distribution functions (pdf) over entire grid space, in the case of HODGE 2, degeneracies between the parameters and their uncertainties are less than the step size.

Most likely parameters and their uncertainties for each of the stellar clusters. NGC 1644, NGC 1718, and NGC 1978 did not converge with our automatic stellar background subtraction.

NGC 2173 and NGC1917 have extended MSTOs and multiple ages appear in their joint pdfs.

Cluster	A_V	Binary Fraction	$(m-M)_0$	Age (Gyr)	Z	Λ_C
NGC 1978	0.25±0.03	0.75±0.03	18.50±0.03	2.28±0.04	0.0048±0.0001	0.3±0.05
HODGE 2	0.15±0.03	0.75±0.03	18.50±0.03	1.30±0.03	0.0076±0.0002	0.5±0.05
NGC 1718	0.50±0.03	≥ 0.95±0.03	≥ 18.70±0.03	1.87±0.03	0.0076±0.0001	0.3±0.05
NGC 2173	0.3±0.03	0.55±0.03	18.50±0.03	1.66±0.03	0.0060±0.0001	0.4±0.05
NGC 2203	0.15±0.03	0.70±0.03	18.50±0.03	1.72±0.03	0.0072±0.0001	0.5±0.05
NGC 2213	0.15±0.03	0.75±0.03	18.55±0.03	1.60±0.03	0.0076±0.0001	0.5±0.05
NGC 1644	0.10±0.03	≥ 0.95±0.03	18.60±0.03	1.54±0.03	0.0060±0.0001	0.5±0.05
NGC 1795	0.25±0.03	0.70±0.03	18.55±0.03	1.57±0.03	0.0076±0.0002	0.5±0.05
NGC 1917	0.20±0.03	0.85±0.03	18.55±0.03	1.42±0.03	0.0076±0.0002	0.5±0.05

Conclusions

We presented a novel approach to constraining stellar evolution models using resolved stars in stellar clusters of the LMC and SMC by simultaneously fitting uncertain observational and theoretical parameters.

We chose stellar clusters near an age where the observational effects of core overshooting would be most apparent on an optical CMD.

We confirmed, given the stellar evolution models, the most probable value of core overshooting strength is Λ_c=0.5±0.05.

This method can now be extended a) to clusters at ages where core overshooting will be less apparent on a CMD; b) to more uncertain model parameters, like stellar rotation and mass loss; and c) to create a finer grid of core overshooting strength.

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