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Analysis of integrated magnitudes and colors of VISCACHA star clusters

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Abstract. Star clusters are often approximated as Simple Stellar Populations (SSP) in studies of galactic structure and evolution, and one way to exploit this approximation is through simulations. By simulating these populations, we can predict observational parameters — such as integrated magnitude and color — based on stellar-evolution models with specified initial mass and initial mass function. From the synthetic clusters' integrated light, we infer parameters that serve as tracers of the host galaxy's structure and evolution. Our methodology for generating synthetic stellar populations follows the Monte Carlo technique described in Santos & Frogel (1997). This study develops simple-population models that produce synthetic integrated magnitudes and colors representative of real star clusters. We compare the models with V and I photometry of Magellanic-Cloud clusters from the VISCACHA survey (SOAR/SAM) to establish robust relations between observables and cluster physical parameters.

Resumo. Aglomerados estelares são frequentemente aproximados por Populações Estelares Simples (SSP) em estudos de estrutura e evolução galáctica, e uma maneira de explorar essa aproximação é por meio de simulações. Ao simular essas populações, podemos prever parâmetros observacionais — como magnitude integrada e cor — com base em modelos de evolução estelar com massa inicial e função de massa inicial especificadas. A partir da luz integrada dos aglomerados sintéticos, inferimos parâmetros que servem como traçadores da estrutura e evolução da galáxia hospedeira. Nossa metodologia para gerar populações estelares sintéticas segue a técnica de Monte Carlo descrita em Santos & Frogel (1997). Este estudo desenvolve modelos de populações simples que produzem magnitudes e cores integradas sintéticas representativas de aglomerados estelares reais. Comparamos esses modelos a aglomerados nas Nuvens de Magalhães, usando fotometria nas bandas V e I do levantamento VISCACHA (SOAR/SAM), para estabelecer relações robustas entre observáveis e parâmetros físicos dos aglomerados.

Keywords. Galaxies: photometry – Galaxies: star clusters: general – Magellanic Clouds – Methods: numerical – Stars: evolution – Stars: luminosity function, mass function

1. Introduction

For distant galaxies, individual stars in clusters cannot be resolved. Integrated-light observations are the only way to assess their astrophysical properties and probe the characteristics of their parent galaxies. These properties can be evaluated using SSP models. In this work, we derived the total mass of Magellanic Cloud star clusters using the methodology described in Maia, Piatti, & Santos (2014). To accomplish this, we calculated integrated V and I magnitudes from images obtained by the VISCACHA project, a photometric survey specifically designed for star clusters in the Small and Large Magellanic Clouds.

The VISCACHA survey is studying the outer regions of the Magellanic Clouds using high quality data from the SOAR telescope (Maia et al. (2019)). The team provides physical parameters such as core and tidal radii, ellipticities, distances, ages, metallicities, and mass distributions. In this context, mass is an important property that cannot be directly observed and will be estimated on this work.

2. Methodology

We generate synthetic stellar populations by sampling an initial mass function (Kroupa et al. (2013)) via a Monte Carlo technique (Santos & Frogel (1997)), and placing stars along PARSEC isochrones of known age and metallicity. The mass function $\Phi(m)$ is given by a power law, which can be normalized between two mass limits, a lower-m_l, and an upper-m_u, yielding the corresponding probability distribution function. Integrating up to a mass m, we obtain a cumulative distribution function:

$$\mathcal{N}(m) = \int_{m_l}^{m} \Phi(m')\, dm'$$

Values $\mathcal{N}(m) \in (0, 1)$ map uniquely to m. For the Kroupa IMF the break at $0.5\, M_\odot$ yields two relations between $\mathcal{N}$ and m. If $\mathcal{N}'$ corresponds to $m = 0.5\, M_\odot$:

$$\begin{aligned} m &= (m_l^{-x_1} - \tfrac{x_1 \mathcal{N}}{A})^{\frac{-1}{x_1}}, \qquad && \mathcal{N} < \mathcal{N}' \\ m &= (0.5^{-x_2} - \tfrac{x_2(\mathcal{N}-\mathcal{N}')}{0.5A})^{\frac{-1}{x_2}}, && \mathcal{N} > \mathcal{N}' \end{aligned}$$

By sampling $\mathcal{N}$ in proportion to the population size, a set of masses is obtained. Each mass is then linearly interpolated along the isochrones to derive its parameters. We then compute each SSP integrated magnitude by summing the fluxes of all stars.

To obtain VISCACHA integrated magnitudes, we built surface-brightness profiles (SBP; Fig. 1) from concentric annuli and integrated them to the limiting radius where the cluster merges with the background (see Santos et al. (2020)-Paper II). The stellar background is estimated from the flux measured beyond the limiting radius.

3. Results

We carried out V− and I−band photometry for an initial sample of 10 clusters and derived results from the stellar-population simulations. Fig. 2a shows the relation between integrated (V−I) color and age for different N. The fluctuations reflect the influence of stochastic sampling of the IMF: the impact of evolved stars is stronger in the smaller population. We also see reddening with age due to the depletion of hot main-sequence stars and the emergence of red giants. Fig. 2b displays the relation between (V−I) and metallicity. It depicts the reddening with increasing metallicity, caused by enhanced stellar opacity due to a higher abundance of heavy elements.

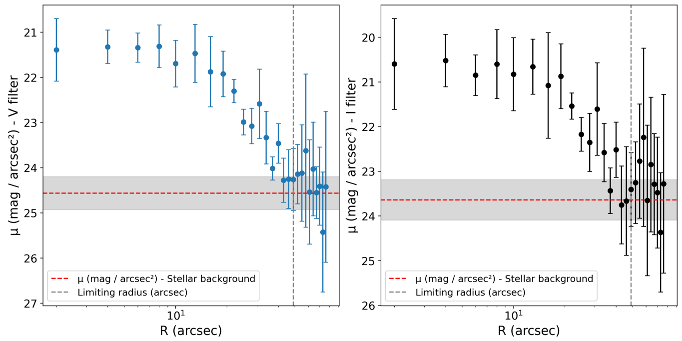

Figure 1. Surface brightness as a function of distance from the cluster center; Cluster: VIS0019.

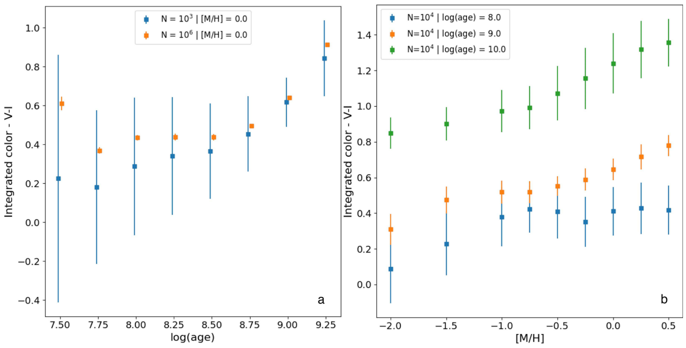

Figure 2. (a) Integrated color as a function of population age and number of stars; (b) Integrated color as a function of population metallicity.

To illustrate what can be obtained using the models, simulations were run for cluster sizes $1000 \leq N \leq 15000$, ages $6.6 \leq \log(\text{age}) \leq 10.1$, and fixed metallicity [M/H]=−0.5 (the clusters mean; Ferreira et al. (2024)). For each (N, age) pair we performed 100 Monte Carlo realizations and computed integrated magnitudes and colors. The left panel on Fig. 3 exhibits the effect of N: larger clusters are brighter and show less color dispersion. While the right panel illustrates the age gradient: older populations move progressively to redder and fainter integrated colors. Both images show how the parameter space can be explored through different combinations of population characteristics. In red we show the observed clusters. All observed values fall within the explored parameter space.

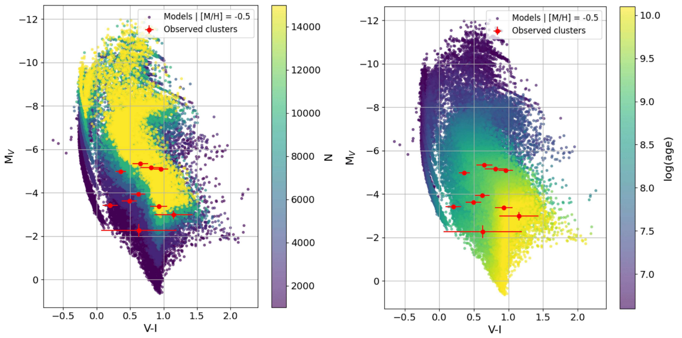

Figure 3. Distribution of synthetic populations and observed clusters in the CMD. Left panel: colored by the total number of stars; Right panel: colored by the logarithm of the population age.

4. $\mathcal{M}/\mathcal{L}$ ratio

The total mass of the cluster is derived from its integrated magnitude in a given band. We can compute the evolution of the simple stellar population mass-to-light ratio ($\mathcal{M}/\mathcal{L}$) using a total mass normalized to one and distributed according to a Kroupa IMF. This relation does not depend on the normalization constant of the IMF, since $\mathcal{M}/\mathcal{L}$ is independent of N. Fig. 4 illustrates $\mathcal{M}/\mathcal{L}$ for the B, V, and I bands for a population with solar metallicity. The idea is to generate these curves for each cluster and then interpolate its age on the plot (for more details, see Maia, Piatti, & Santos (2014)). We have:

- $log(\mathcal{M}/\mathcal{L})(M_\odot/L_\odot) = f(log(t))$;
- $log(\mathcal{M}) = f(log(t)) - 0.4(M_n - M_{n,\odot})$, where n = B, V, I and $M_{n,\odot}$ is the solar absolute magnitude in band n,
- $f(log(t))$ can be obtained by interpolating the cluster age along the curve.

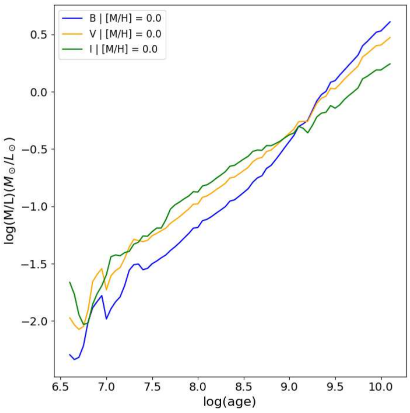

Figure 4. Mass-to-light evolution.

5. Conclusions and Perspectives

The models reproduce the expected behavior: reddening with age and metallicity, and fainter magnitudes for older or smaller populations. Fluctuations observed in smaller clusters show the impact of stochastic sampling of the IMF. Our photometric results are in good agreement with previous determinations (Paper II), and the cluster masses derived from photometry and model predictions are consistent with those reported in the literature. The parameter space in age, size, and metallicity is well explored using the models. Future work will focus on extending this analysis to a larger sample of VISCACHA clusters and investigating degeneracies in the parameter space and their implications for cluster characterization.

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