

# A study of candidate binary star clusters of the Magellanic Clouds based on VISCACHA observations

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**Abstract.** This work presents an analysis of five candidate binary star clusters in the Magellanic Clouds using deep BVI photometry from the VISCACHA survey. Member stars were identified through photometric decontamination, and astrophysical parameters were derived via isochrone fitting. Cluster masses were estimated from their integrated V-band magnitudes and ages, and structural connections were investigated using density maps.

**Resumo.** Este trabalho apresenta uma análise de cinco pares de aglomerados estelares candidatos a binários nas Nuvens de Magalhães, utilizando fotometria profunda em BVI obtida pelo levantamento VISCACHA. As estrelas-membro foram identificadas por meio de descontaminação fotométrica, e os parâmetros astrofísicos foram determinados via ajuste de isócronas. As massas dos aglomerados foram estimadas a partir de suas magnitudes integradas na banda V e de suas idades, e as conexões estruturais foram investigadas por meio de mapas de densidade.

**Keywords.** Galaxies: star clusters: general - Magellanic Clouds

## 1. Introduction

Star clusters are common objects in the Magellanic Clouds (MCs), and binary clusters (gravitationally bound) appear to occur in large numbers in these galaxies, due to the low-density environment that produces a weak tidal field allowing clusters to survive for long periods.

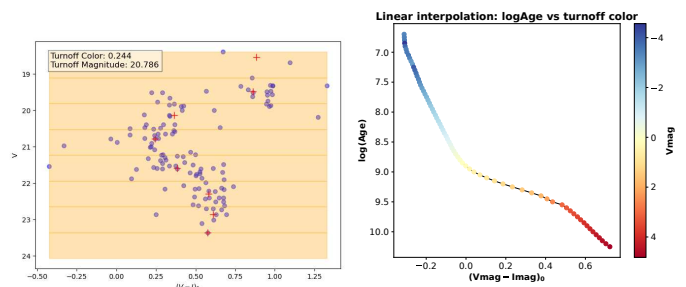
The determination of astrophysical and structural parameters of clusters belonging to the MCs using BVI photometry and their homogeneous analysis is ongoing within the scope of the VISCACHA project (Maia et al. 2019), based on deep and high-resolution observations made with adaptive optics (SAM) at the SOAR telescope. In this work we take a first step in the analysis of the population and dynamical properties of 5 binary clusters in the MCs by determining the clusters' member stars and astrophysical parameters via isochrone fitting.

## 2. Methodology

In order to verify whether the cluster pairs are real or just a chance alignment, we perform isochrone fitting on their member stars: the distances must be the same if the pair is physically interacting, and the other parameters indicate whether they share a common origin. Total cluster mass is estimated from age and integrated V-band magnitude. Density maps are constructed to investigate connection between the pairs.

### 2.1. Photometric decontamination

We first decontaminated the clusters Color-Magnitude Diagram (CMD) from field star contamination. We applied the method from Maia et al. (2010), which divides the observed region into two areas: one containing the cluster region and another with only field stars. The algorithm then assigns membership probabilities to stars based on factors such as: the stellar overdensity in the cluster region compared to the field region, and the stars' radial distances from the cluster center.

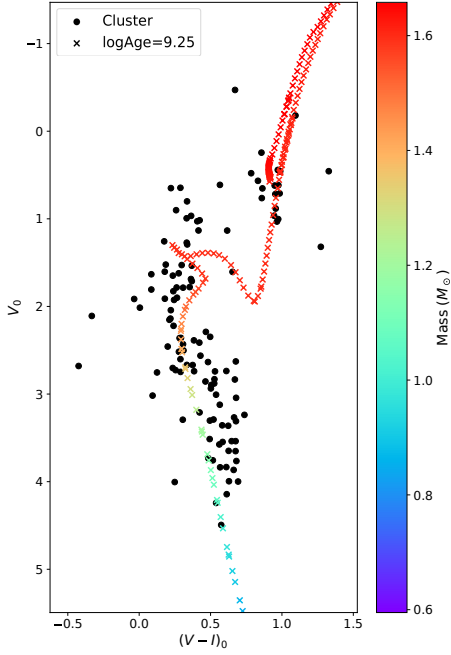


**FIGURE 1.** Left: CMD divided in magnitude bins with the main position of the stars presented as red crosses. Right: Relation between the age and turnoff color of isochrones.

### 2.2. Isochrone fitting

Using isochrones from the PARSEC database (Bressan et al. 2012) we begin by making an initial fit that requires an estimation of age, metallicity  $[M/H]$ , reddening  $E(V - I)$  and distance modulus  $(m - M)_0$ . For the metallicity and distance modulus we use the mean value of the galaxy where the cluster resides:  $[M/H] = -0.4$  and  $(m - M)_0 = 18.5$  for the Large Magellanic Cloud (LMC), and  $[M/H] = -0.9$  and  $(m - M)_0 = 18.9$  for the Small Magellanic Cloud (SMC). The initial reddening value is estimated using the reddening map for the MCs by Skowron et al. (2021), for which only the coordinates of the cluster are needed. To estimate the initial age we determine the cluster's turnoff color and match it to the turnoff color of isochrones. First, we correct the observed CMD using the  $E(V - I)$  value, then we divide the CMD into magnitude bins and compute the mean position of the stars in each bin (marked as red crosses in Fig. 1 left panel), and take the leftmost point as the turnoff color. Finally, this turnoff color is passed to a function that interpolates the relation between turnoff color and isochrone age, returning an initial estimate for the cluster (Fig. 1 right panel).

With all the four initial parameters determined we make an initial fit, illustrated in Fig. 2 for the cluster LW75.



**FIGURE 2.** Initial fit for the cluster LW75.

The final step is to optimize the initial fit. For that we vary one parameter at a time around its initial value to find the best fit. For age and metallicity, we use a set of isochrones:  $6.6 < \log[t(\text{yr})] < 10.25$  (step of 0.05) and  $-1.6 < [M/H] < 0.6$  (step of 0.1); for distance modulus and reddening, we shift the isochrone accordingly. At each step, we apply a k-nearest neighbors algorithm to compute the distance from each observed star to the isochrone (eq. 1) in the CMD. These distances are used to construct a likelihood function (eq. 2) that produces a curve (Fig. 3), where the best-fit value corresponds to the maximum likelihood (green dot). The uncertainties are indicated by red dots located at 5% below the peak. Fig. 4 shows the best fitted isochrone for the cluster LW75.

$$d_{ij}^2 = \frac{1}{N_{\text{stars}}^2} \left[ \left( \frac{(V-I)_{\text{clu}} - (V-I)_{\text{iso}}}{\sigma_{(V-I)_{\text{clu}}} \cdot e_{VI}} \right)^2 + \left( \frac{M_{V,\text{clu}} - M_{V,\text{iso}}}{\sigma_{M_{V,\text{clu}}} \cdot e_{M_V}} \right)^2 \right] \quad (1)$$

$$p_n = \frac{1}{2\pi N_{\text{stars}}} \sum \exp\left(-\frac{1}{2} \cdot d_{ij}^2\right) \quad (2)$$

### 2.3. Mass determination

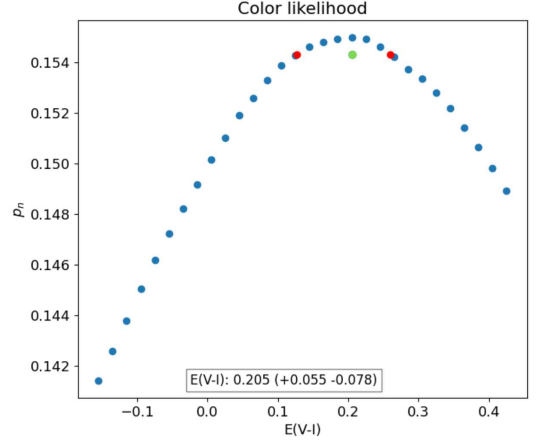
For the mass determination, we need the age and the integrated magnitude. The age ( $\log(t)$ ) comes from the isochrone fitting, and the integrated magnitude  $M_V$  is obtained by integrating the surface-brightness profile of each cluster. The total mass  $\mathcal{M}$  is calculated following Maia et al. (2014):

$$\log \mathcal{M} = a + b \log t - 0.4(M_V - M_{V,\odot}) \quad (3)$$

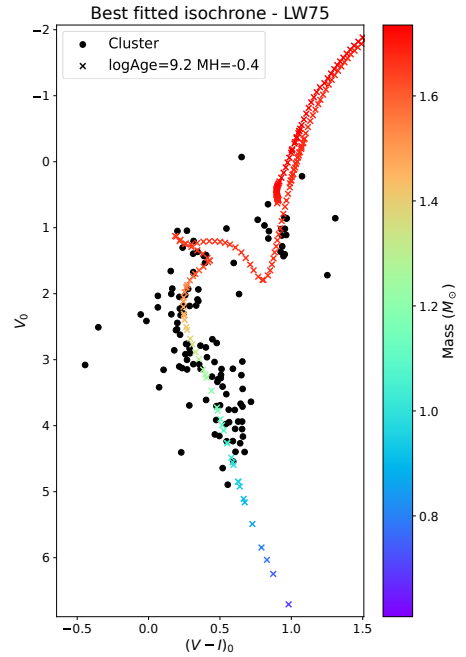
where the coefficients  $a$  and  $b$  depend on the host galaxy. For clusters in the LMC,  $a = -5.87$  and  $b = 0.608$ ; for those in the SMC,  $a = -6.14$  and  $b = 0.644$ . We adopt  $M_{V,\odot} = 4.83$  for the solar absolute  $V$ -band magnitude.

### 2.4. Density maps

We constructed density maps using an adaptive k-nearest neighbors density estimator. A grid is defined over the observed field,



**FIGURE 3.** Likelihood vs reddening, where the green dot indicates the best value of  $E(V-I)$  and the red dots indicate the uncertainties.



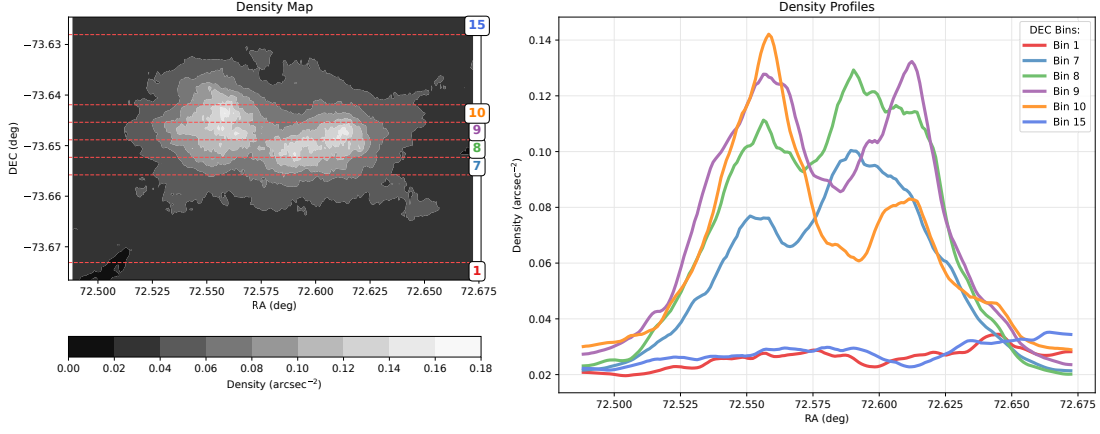
**FIGURE 4.** Best fitted isochrone for the cluster LW75.

and for each grid point the distance to the  $K$ -th nearest star is computed. This distance defines an adaptive radius  $r$  that encloses exactly  $K$  neighbors. We use  $K = \sqrt{N}$  as the number of neighbors, with  $N$  being the number of stars in the cluster. The density at each grid point is computed as

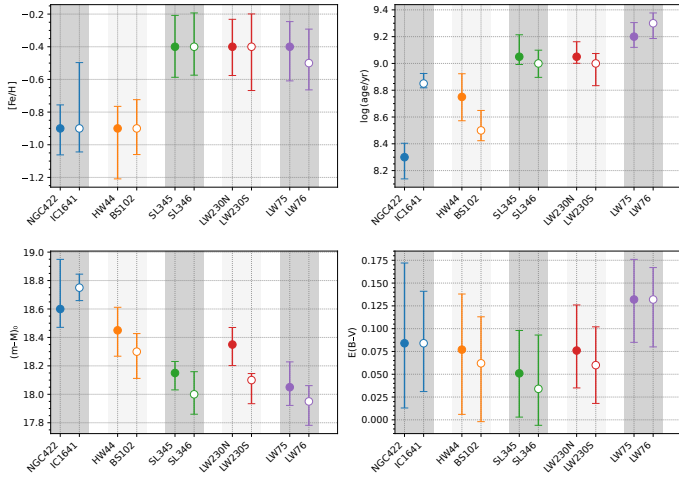
$$\rho = \frac{K}{A_{\text{corrected}}} \quad (4)$$

where  $A_{\text{corrected}}$  is the geometrically corrected area of the circle that contains the  $K$  nearest neighbors. This corrected area accounts for the portions of the circle that fall outside the observed field.

To investigate a connection between the two clusters, we divided the density map into declination bins, and for each bin we calculated a density profile. This profile is constructed by computing the mean density at each right ascension value. The entire process is illustrated in Fig. 5 for one cluster pair.



**FIGURE 5.** *Left:* Density map for the pair LW75-LW76 with red lines showing the different bins we selected. *Right:* Density profiles are shown for each selected bin, with colors identifying the corresponding bin.



**FIGURE 6.** Isochrone fitting results for the pairs.

### 3. Results

We performed the analysis for 5 cluster pairs: NGC422-IC1641, HW44-BS102, SL345-SL346, LW230N-LW230S and LW75-LW76. The parameters for the clusters obtained from the isochrone fitting are presented in Fig. 6. Each color represents a pair, with the filled circle indicating the first cluster and the open circle indicating the second. We found that the pair NGC422-IC1641 is non-coeval, but the other parameters indicate that they could form a real pair. For the pair LW230N-LW230S we found different distance moduli, indicating that they cannot form a physical pair and are likely just a chance alignment along the line of sight. Except for the pair LW230N-LW230S, all other cluster pairs show parameters consistent with being physical pairs.

Table 1 shows the masses calculated from integrated magnitude for all the clusters in the sample.

To analyze the density maps we examine the density profiles, such as the one shown in the left panel of Fig. 5. We see that the bins 1 and 15 correspond to the sky-level density, while bins 7 to 10 reveal the connection between the two clusters: there are density peaks at the positions of both clusters, but in the region between them the density does not drop to the sky level. This indicates that the clusters are connected by some form of bridge, similar to the structures described in de Oliveira et al. (2000). Following this analysis we found that the pairs NGC422-IC1641, HW44-BS102 and LW75-LW76 are connected by a bridge.

**TABLE 1.** Clusters masses.

Cluster	Mass ( $M_{\odot}$ )
LW75	$602.0 \pm 277.1$
LW76	$808.4 \pm 343.9$
NGC422	$1826.4 \pm 610.0$
IC1641	$1379.8 \pm 207.2$
HW44	$595.1 \pm 260.9$
BS102	$174.9 \pm 105.7$
SL345	$1659.6 \pm 225.0$
SL346	$1281.2 \pm 132.5$

### 4. Conclusions

In this work, we performed an analysis of five candidate binary cluster pairs in the MCs using photometric decontamination, isochrone fitting, mass determination, and density-map analysis. We identified which systems are likely to represent physical pairs. Four of the five pairs present parameters consistent with being physical pairs, while the pair LW230N-LW230S is most likely a chance alignment due to their different distances. We found one non-coeval pair, NGC422-IC1641, which suggests that one cluster may have been captured by the gravitational field of the other. Considering the uncertainties, the LW75-LW76 and NGC422-IC1641 pairs have similar masses, while in the remaining pairs one cluster is more massive than the other. Moreover, the density profiles reveal clear stellar bridges in three of the systems, supporting the scenario of physical interaction.

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