Ages, metallicities and structure of stellar clusters in the Magellanic Bridge

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1 Introduction

The Magellanic System contains the Large and Small Magellanic Clouds (LMC and SMC, the pair of satellites closest to the Milky Way), the Magellanic Bridge, Stream and Leading Arm.

- LMC: 49.6 ± 0.5 kpc[1], [Fe/H] = −0.37 ± 0.15[2], M* ~ 10^9 M⊙[3]
- SMC: 62.4 ± 0.8 kpc[4], [Fe/H] = −0.9 ± 0.2[5], M* ~ 10^8 M⊙[3]
- **Bridge:** 20 kpc extension, M* = 1.5 × 10^4 M⊙[3]

Two main models attempt to describe the formation of the LMC-SMC pair: *(i)* independent satellites until the LMC captured the SMC ~2 Gyr ago, in a bound orbit around the MW since then and with two close encounters at 1.2 Gyr and 0.25 Gyr ago[6]; or *(ii)* it is an old interacting system in a first perigalactic passage, falling into the MW potential ~2 Gyr ago[7].

In the second scenario, the Bridge formation is reproduced from a frontal collision between the Clouds around **200 Myr ago**, with an impact parameter of ~7 kpc, implying kinematic and chemical signatures along the Bridge. In this sense, a precise determination of the star formation history and chemical evolution of the stellar populations of the Bridge (~ 100 clusters and 300 associations) can contribute to a better understanding.

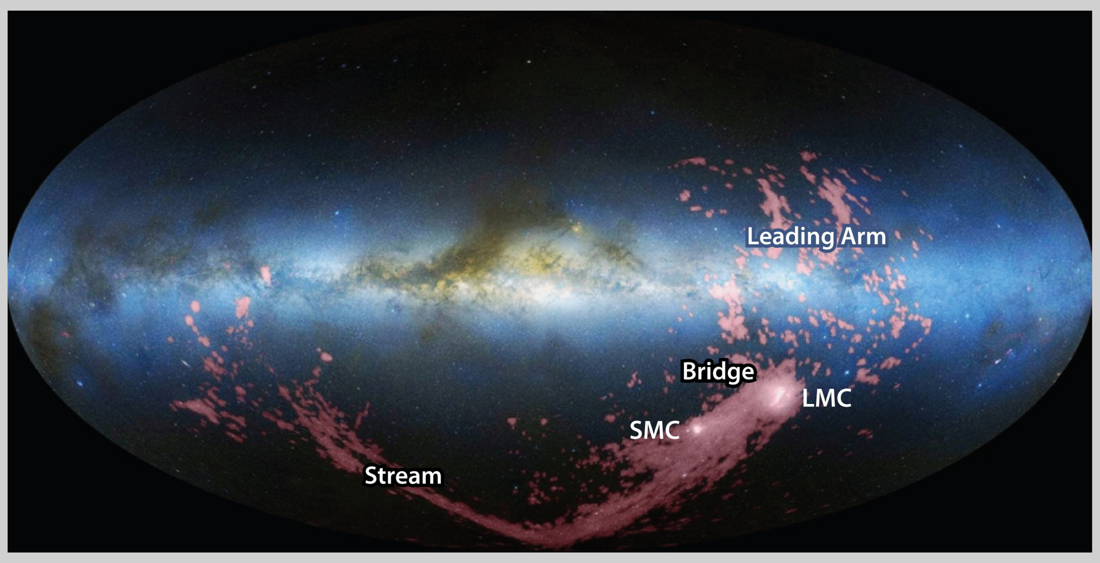


Fig. 1: Neutral hydrogen map of the Magellanic System over an optical panorama of the Milky Way. Extracted from D'Onghia & Fox (2016).

2 Data: VISCACHA[8] and SMASH[9]

Telescope	SOAR 4 m	Blanco 4 m
Filters	*BVI (Bessel)*	*ugriz (SDSS)*
FWHM	**0.6", AO**	1.0"
Field of view	3 × 3 arcmin	2.2 deg diameter
Bridge sample	33 objects	~ 100 objects
Completeness	V < 24.5 mag	g < 24.8 mag

We used this deep, high-quality photometry to homogeneously derive age, metallicity, distance, mass and structural parameters for 33 Bridge clusters, at RA < 3^h **(Oliveira et al., submitted)**. The results are being complemented with GMOS spectra in the CaT region to derive radial velocities and metallicity for clusters older than 1 Gyr (Dias et al., in preparation). New spectroscopic observations with Goodman are also being planned.

The surveys have a similar magnitude limit, but VISCACHA can resolve more central cluster stars (AO) and constrain the ages of slightly older clusters. The analysed samples are being expanded with new VISCACHA observations and DELVE data.

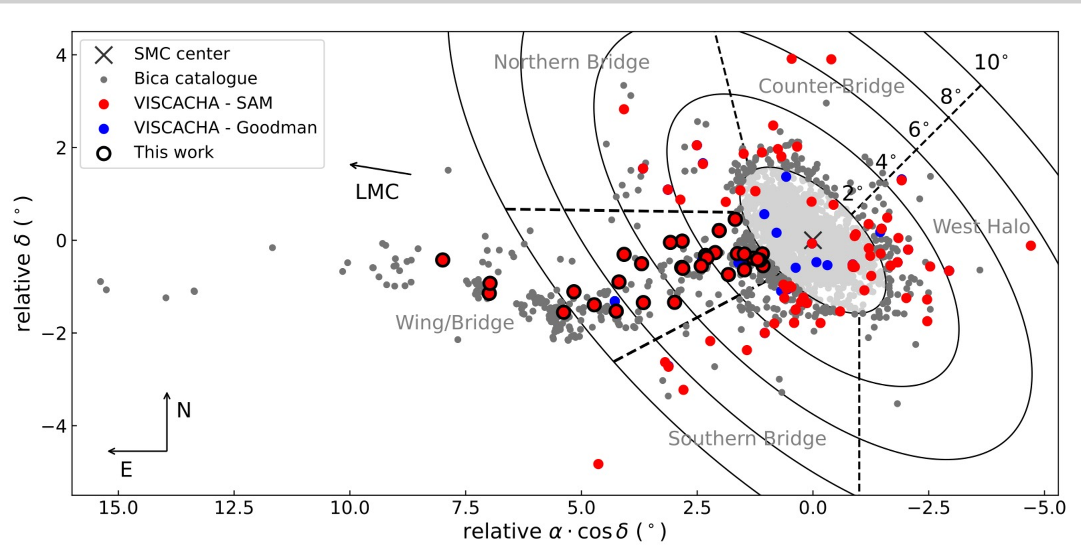


Fig. 2: Coordinates relative to the SMC centre of the SMC objects[10] and those observed in the VISCACHA survey. The 33 Wing/Bridge clusters analysed in Oliveira et al. (submitted) are marked in black.

3 Methods: Bayesian approach (likelihood + MCMC sampling)

King-profile fitting: structure

We compute the density of stars inside a circular kernel around each star, adopting a variable size to fit the function[11]:

$$\rho(r) = \rho_0 \left[\frac{1}{\sqrt{1+(r/r_c)^2}} - \frac{1}{\sqrt{1+(r_t/r_c)^2}} \right]^2 + \rho_{bg}$$

- Parameters: RA, DEC, ρ_0, r_c, r_t, ρ_{bg}
- Flat, uniform priors in all parameters

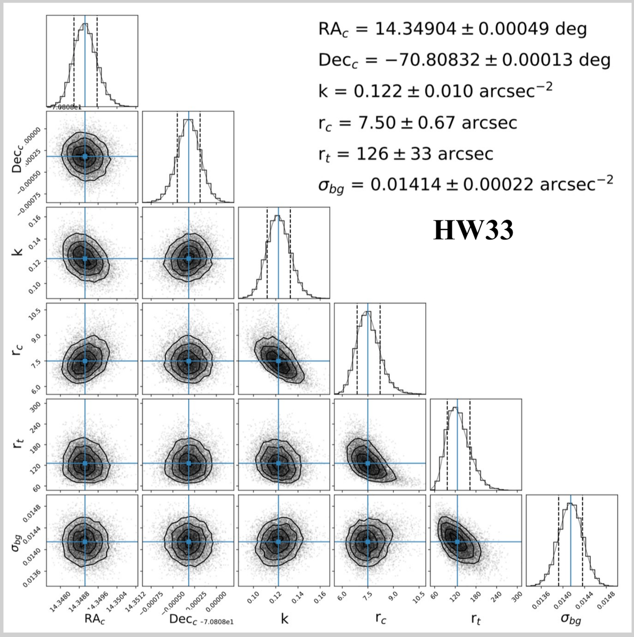


Fig. 3: Corner plots with the posterior distributions of the structural parameters derived for HW33.

Decontamination of field stars

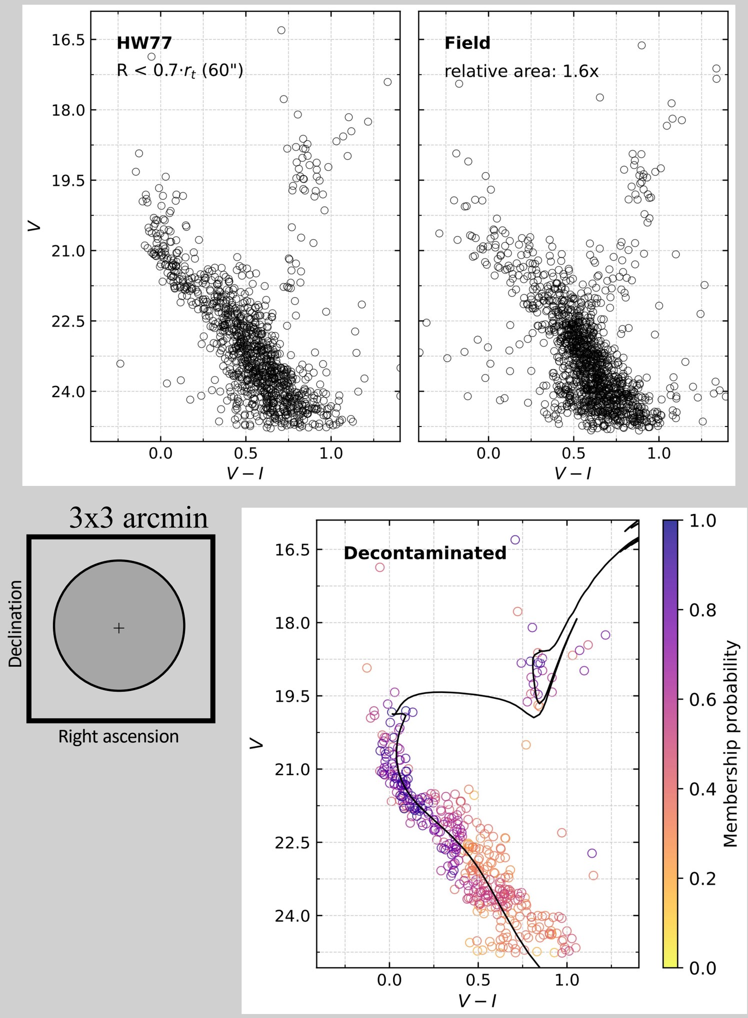


Fig. 4: Decontamination process for the 1.1 Gyr cluster HW77, involving comparison of CMD regions and machine learning methods.

Isochrone fitting: SIRIUS

The SIRIUS code[12] was updated to use *UBVRI* and *ugriz* photometric systems and PARSEC isochrones. A χ^2 is computed in magnitude and colour for each star related to each isochrone point:

$$\mathcal{L} \propto \sum_{i=1}^{N} \max \left[-\sum_{j=1}^{M} \frac{(mag_j - mag_i)^2}{\sigma^2_{mag}} + \frac{(col_j - col_i)^2}{\sigma_{col^2}} \right]$$

- Param.: age, [Fe/H], $(m-M)_0$, E(B-V)
- Conservative, gaussian prior in [Fe/H]

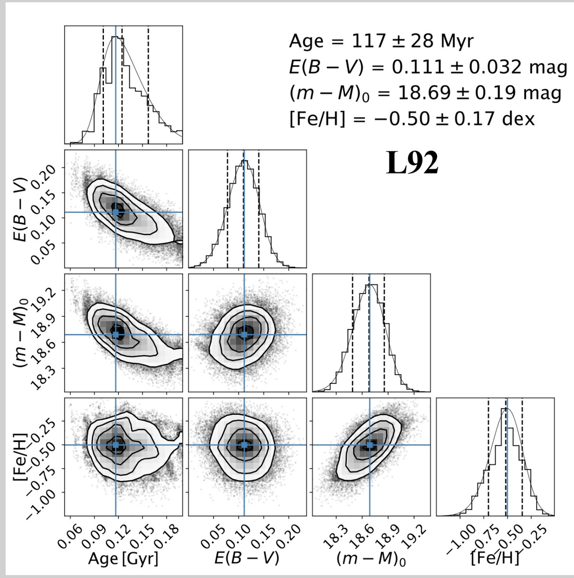


Fig. 5: Corner plots of the isochrone fitting obtained for the young cluster L92.

4 Results: cluster parameters

The structural and fundamental parameters were obtained for the 33 clusters observed in VISCACHA, spanning ages from 4 Myr (HW81) to 6.8 Gyr (HW59), distances from 50 to 69 kpc, and different radii and densities. Masses were then derived by adding up the fluxes of member stars, converting to absolute magnitude and applying age-metallicity calibrations. The masses covered from ~500 (L101, ICA45) to 1.4×10^4 M⊙ (L113, L110).

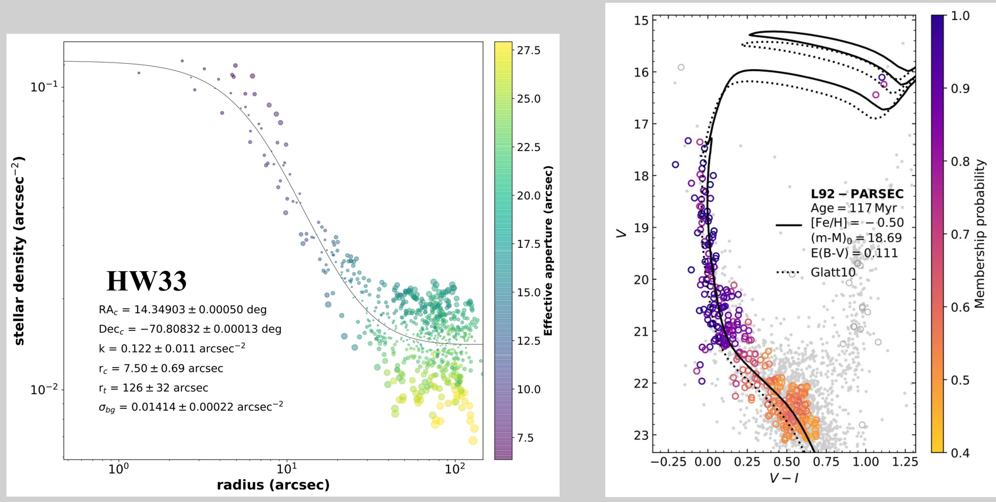
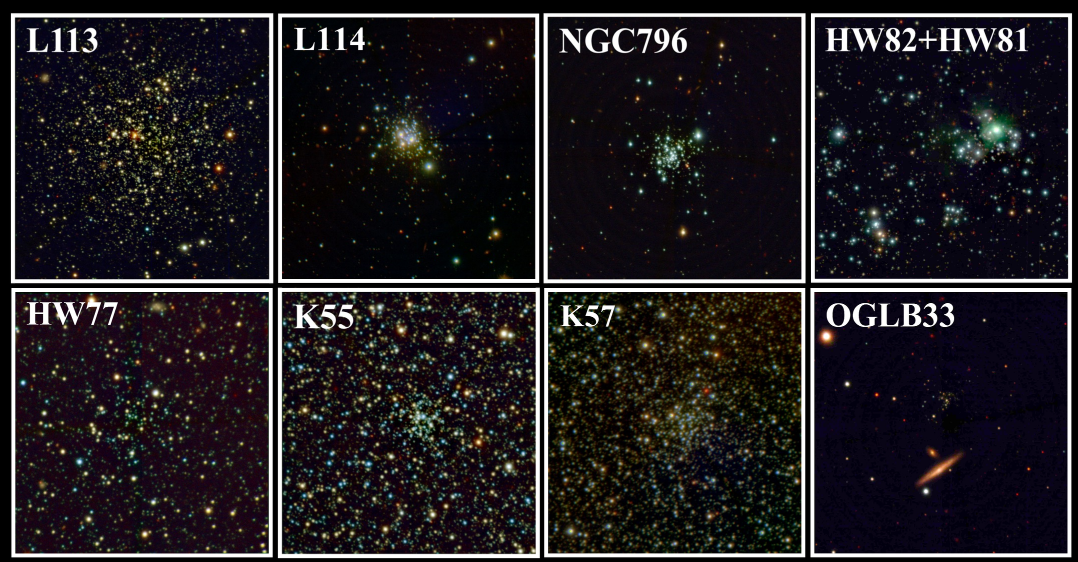


Fig. 6: Radial density profile of HW33 with the best-fitting King profile and colour-magnitude diagram of L92 with the best-fitting isochrone.



5 Results: gradients and AMR

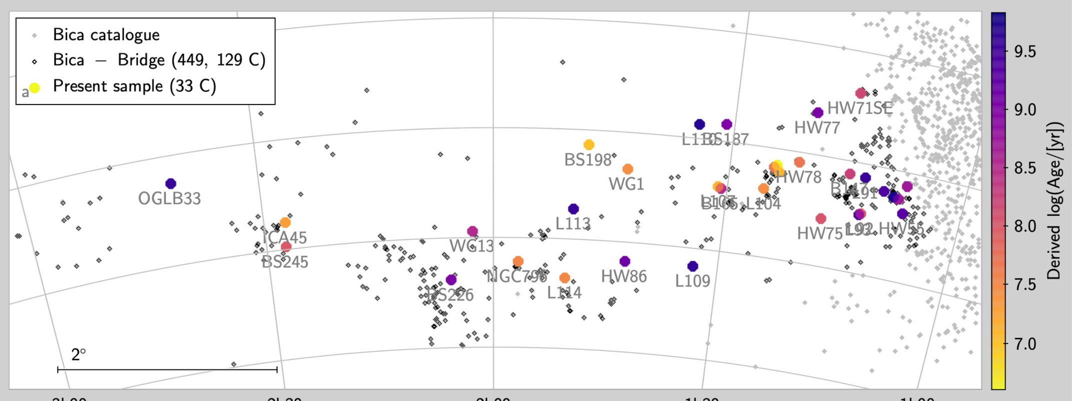


Fig. 7: Projected distribution of the 33 sample clusters, colour-coded by the derived log (Age). Most of the older clusters are located close to the SMC, whereas the younger ones are more spread out.

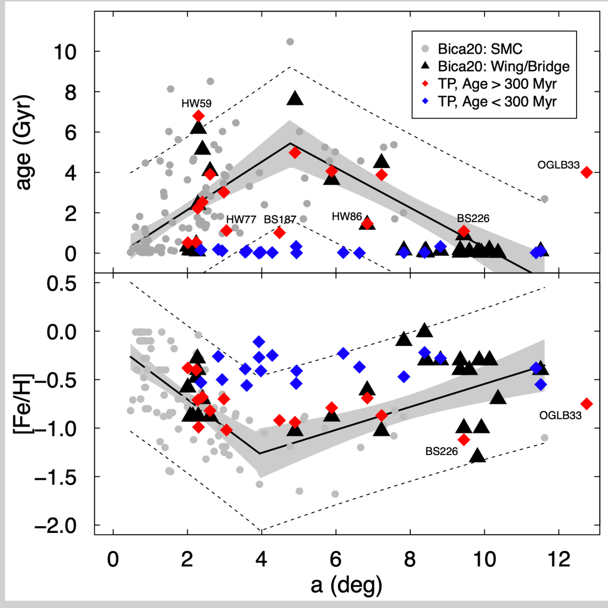


Fig. 8: Age and metallicity as a function of the projected distance to the SMC[10]. The older clusters follow the age and metallicity gradients of the SMC, whereas the younger ones have a mean [Fe/H] ~ −0.4.

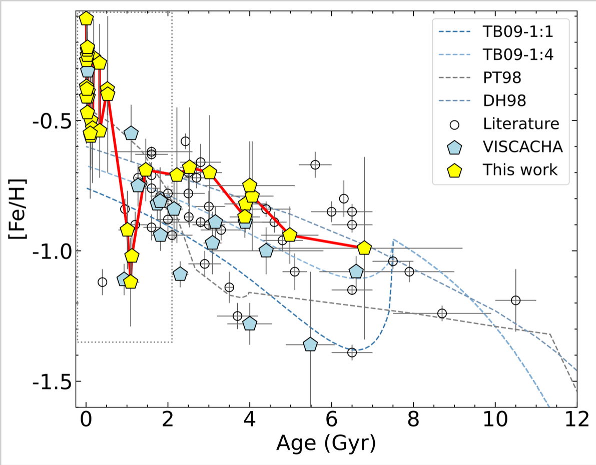


Fig. 9: Age-metallicity relation of the present results (yellow), as well as VISCACHA and literature results. Two metallicity dips (not given in the models) are observed in 1.5 Gyr and 200 Myr, possibly explained by an infall of metal-poor gas, followed by a rapid chemical enrichment.

6 Concluding remarks (Oliveira et al., submitted)

- From the cluster integrated magnitudes, we estimated a minimum stellar mass of **3 − 5 × 10^5 M⊙** for the Bridge;
- Two metallicity dips were detected in the age-metallicity relation at about **200 Myr** and **1.5 Gyr** ago, which are possible chemical signatures of the formation of the Bridge and Magellanic Stream, respectively;
- Of a total of 33 analysed clusters, the ages and metallicities were derived for **9 and 18 clusters for the first time**, respectively;
- We confirmed that the SMC Wing and Bridge at RA < 3^h are metal-rich with all young clusters with [Fe/H] ~ −0.4.

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