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Abstract. Hubble Space Telescope observations of NGC 2004, a cluster located in the Large Magellanic Cloud, have been used to derive an improved age estimate of the stellar population by means of isochrones fitting and synthetic cluster comparison. The cluster's structural parameters have been calculated from a model based on number-density profiles, giving radius of the core 2.85 ± 0.46 parsecs.

INTRODUCTION

Star clusters are the fundamental building blocks of a galaxy. Their physical characteristics bring valuable information not only on the processes of their own formation, but also on the history of the evolution of the galaxies they reside in. NGC 2004 is a populous star cluster from the Large Magellanic Cloud (LMC) located at $RA = 82.670208$ and $DEC = -67.288055$ degrees (J2000).

In this study we provide cluster structural parameters from density profile fitting and an accurate age estimate using the latest PARSEC and SYCLIST theoretical models of evolution.

OBSERVATIONS AND PHOTOMETRY

For the purpose of stellar photometry performed in this study we used archive observations of NGC 2004 taken with the filters F555W and F814W of Wide Field Camera and Planetary Camera 2 (WFPC2) onboard Hubble Space Telescope (HST proposal 5904, PI Fischer). The three Wide Field Chanel (WFC) images cover 4.9 square arcminutes of cluster NGC2004 with a resolution of 0.1 arcsec/pixel. The Planetary Camera (PC) image covers the cluster core, the most crowded region, with a superb resolution of 0.0455 arcsec/pixel.

The HST pipeline processed images have been calibrated for bias, dark, flat-field using the final procedures before WFPC2 decommissioning [1]. The photometrical zeropoints and charge-transfer efficiency corrections applied during photometry are taken from Dolphin 2000 [2]. Calibrated science data and corresponding data quality masks were downloaded from the Space Telescope Science Institute (http://archive.stsci.edu/). Table 1 presents used observations. The choice of images taken with different exposures was aimed to ensure better detection and reliable photometry for both bright and faint stars in the crowded cluster field. The dithering pattern of observations shifted by 11 PC pixels greatly improves the bad pixels removal and provides a higher signal-to-noise ratio.

The photometry was done using *HSTphot* [2] - a package designed especially for simultaneous PSF photometry of multiple WFPC2 images.

The calibrated images obtained from the STScI, were first masked by data-quality mask to reject bad pixels with already known defects. Each individual image was masked with its data quality mask constructed during calibration. Pixels with data quality values of 1 (decoding error), 2 (calibration file defect), 4 (permanent camera defect), 16 (missing data), 32 (bad pixel), 256 (questionable pixel), or 512 (unrepaired warm pixel), as well as saturated pixels, are rejected using the *HSTphot* routine *mask* and subsequently ignored.

The photometric solutions were done by the *hstphot* routine. In essence, this routine locates iteratively brightness peaks on the image with a sub-pixel accuracy and finds its PSF solution in a grid of 5x5 pixels. During the photometry the sky background is recomputed, as recommended in the *HSTphot* manual [2]. The PSF solution that returns the

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TABLE 1. The observations used.

Filter name	Exposure time	Dataset name	Filter name	Exposure time	Dataset name
F555W	300	u2y80201t	F814W	300	u2y80208t
F555W	300	u2y80202t	F555W	300	u2y80209t
F555W	300	u2y80203t	F555W	300	u2y8020at
F814W	300	u2y80204t	F555W	10	u2y8020bt
F814W	300	u2y80205t	F555W	10	u2y8020ct
F814W	300	u2y80206t	F814W	10	u2y8020dt
F814W	300	u2y80207t			

smallest χ / S/N is selected as a star's centre. The *hstphot* routine does the photometric solutions with detection threshold of 5 σ.

To account for the geometric distortions of the cameras Holtzman corrections [3] were applied additionally using *distort* routine. At this step all individual frame coordinates were translated to a global coordinate system with respect to the PC pixel coordinates. The resulting coordinates have the orientation and scale of the PC frame, as shown in Figure 1 Left panel.

For each detected object *HSTphot* provides position, χ of the fit, signal-to-noise, sharpness, roundness, major axis, crowding and object type, which are useful for distinguishing between stars and other objects. Final quality selection was performed to objects presenting the output photometry list with V and I stellar magnitudes. Only objects classified as a star (type ≤ 3) with a non-zero signal-to-noise ratio and sharpness between -0.3 and 0.3 were selected. This way a list containing 8984 entries was prepared and used for further exploration.

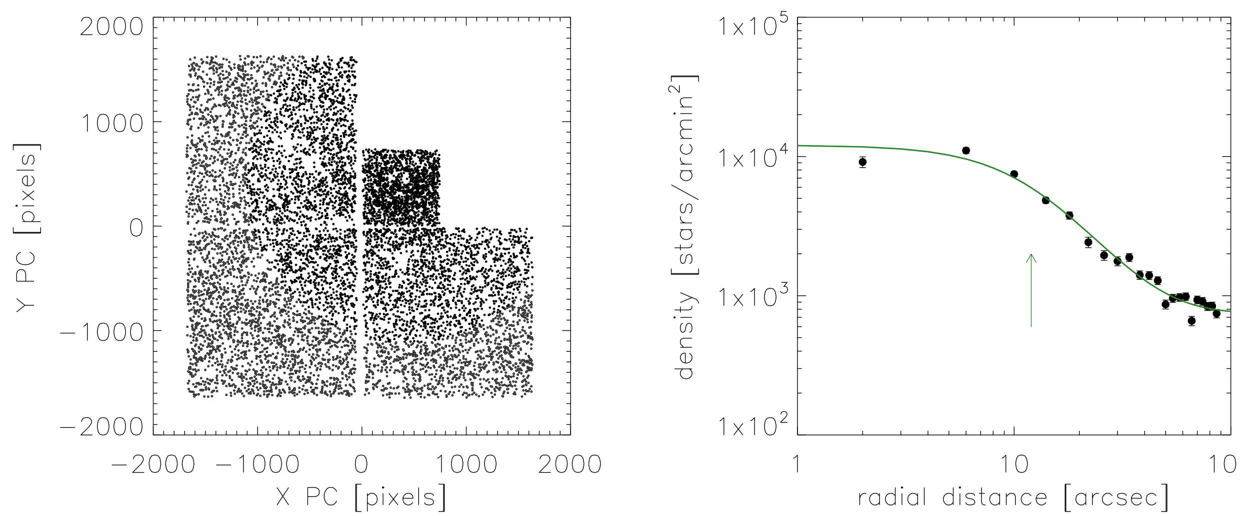

FIGURE 1. Left panel: Stars of NGC 2004. In grey are objects considered to be field contamination from the LMC. In black are stars of the inner region, centered on the cluster core. Right panel: Number density profile King model fit in logarithmic scale. Best-fitting model is plotted with a solid line, its core-radius indicated by an arrow at r_c = 11.99 arcsec.

SURFACE DENSITY PROFILE

The radial profile of a cluster provides structural parameters, such as core-radius, radius of tidal stripping from the host galaxy, concentration of the cluster. These parameters are linked to the dynamical state of the cluster (see [4, 5]) and can be used to assess mass segregation, core-collapse, expansion [6, 7].

A surface-number radial density profile has been constructed to determine structural parameters of the cluster NGC 2004. An empirical King model [8] is fitted to the density profile, incorporating the background stellar density level f_b in the following form:

$$f = f_0 \left\{ \frac{1}{\sqrt{1 + (r/r_c)^2}} - \frac{1}{\sqrt{1 + (r_t/r_c)^2}} \right\}^2 + f_b, \tag{1}$$

where the r_c is the core-radius corresponding to half-number radius, r_t is the tidal-radius, and f_0 represents the central density. Fitting is done in *IDL* with *MPFIT* fitting package [9], which does a non-linear least squares fitting of the model to the data. In Figure 1 Right panel, the Y error bars represent Poisson uncertainties, while the radial step on X axis is 4 arcseconds, which after experimentation provided both profile resolution and enough stars in each ring. The best-fit to the observed cluster's stellar density profile (Figure 1 Right panel, continuous curve) was achieved using King's model with a core radius of $r_c = 11.99 \pm 1.88$ arcsec, which at the adopted distance modulus to the cluster $m - M = 18.45$ translates to a radius of 2.85 ± 0.46 parsecs. The estimated tidal radius is $r_t = 134 \pm 93$ arcsec, the central maximum density $f_0 = 13618 \pm 1827$ and background density $f_b = 760 \pm 120$ stars per square arcminute.

COLOR-MAGNITUDE DIAGRAM AND FIELD DECONTAMINATION

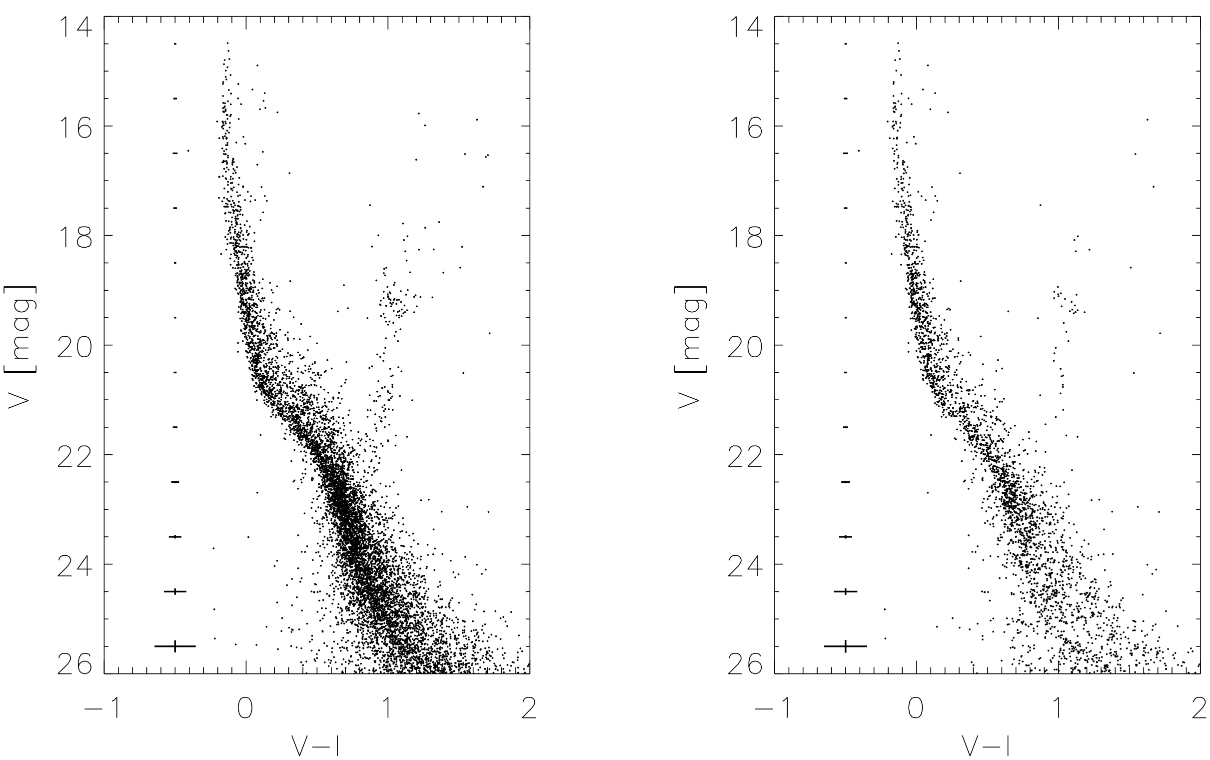

FIGURE 2. CMD of the cluster NGC 2004. Left panel: all objects from the photometry list. Right panel: Stars of the cluster population, after the field decontamination.

The observed $(V, V - I)$ colour-magnitude diagram (CMD) is presented in Figure 2, Left panel. Representative error bars along the two axes are shown to the left of the diagram. As expected, the observed CMD is affected by field stars from the host LMC galaxy. In order to account for the contamination of the LMC field stars on the NGC 2004 CMD stars from two different cluster fields was used to construct the CMD. The procedure is described in Bastian et al. 2016 [10] and discussed in detail in Cabrera-Ziri et al. 2016 [11]. In this approach two different regions, one in the central part and another representing the sparse outer regions of the cluster are chosen to build the observational CMD. The radius of the area centered on the cluster core was adopted in accordance with the core radius derived in the previous section being 6 times larger than r_c (72 arcsec). The central region contains 5530 stars. As a second step a reference field covering approximately the same area, but not larger, as the first one was chosen. The reference region presents stellar density as far from the cluster center as possible. In our case the reference region contains 3454 stars. As a final step for every star in the CMD of the reference field, star in the cluster CMD that is closest to the reference field star in colour-magnitude space was rejected. This way stars of the field area were matched on the $(V, V-I)$ plane with stars of the inner area, the latter being flagged and removed from the photometry list. Matching is performed in *topcat* [12] by finding the closest match on the colour-magnitude diagram with tolerance 1 magnitude in both color $V-I$ and V magnitudes. This way one reduced photometry list was derived. It contains 3201 stars all located in the inner area. These stars are considered to be cluster stars objects most probably belonging to the cluster population (Figure 2, Right panel).

ISOCHRONES FITTING AND SYNTHETIC CLUSTER

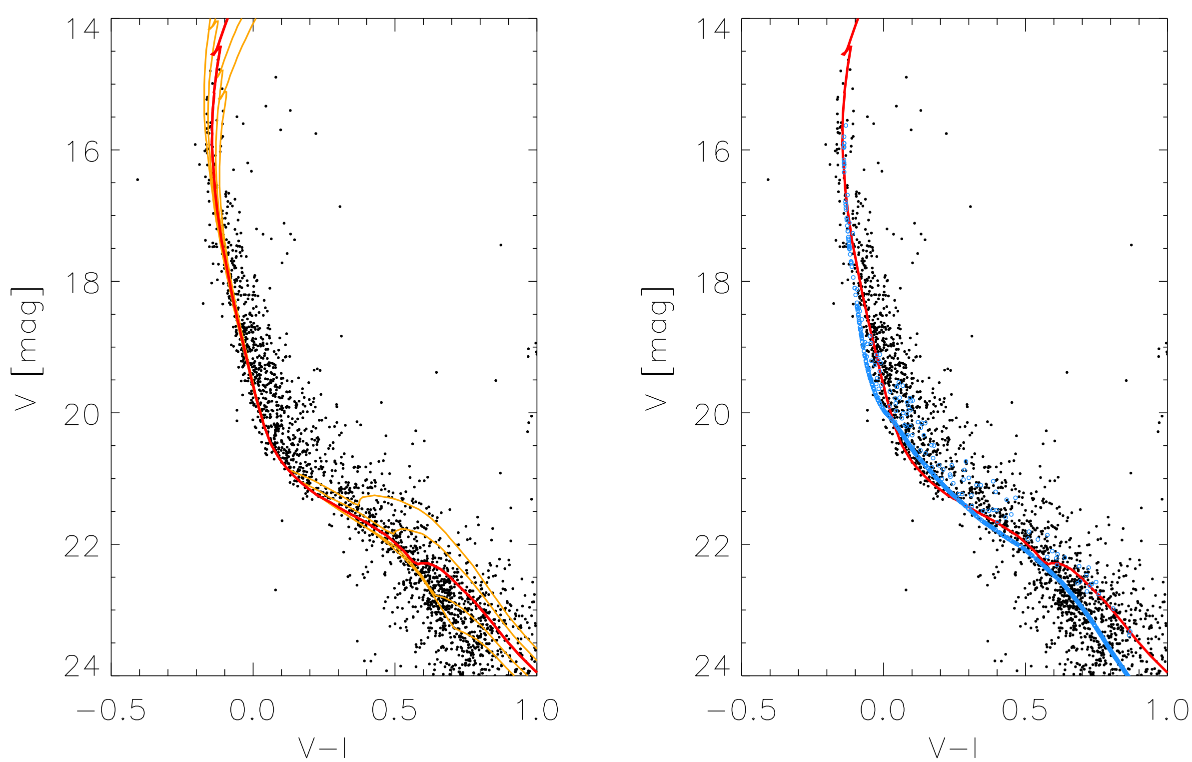

FIGURE 3. Final CMD of the cluster NGC 2004 cleaned for field stars contamination. Left panel: PARSEC isochrones of *logage* = 7.0, 7.1, 7.2, 7.3, 7.4 drawn, the one corresponding to an age of 16 Myr is shown with red line. Right panel: Best-fitting PARSEC isochrone of age 16 Myr is shown with red line, synthetic clusters simulated from SYCLIST are shown with blue and green circles.

To estimate the age of NGC 2004 the latest PARSEC (http://stev.oapd.inaf.it/cmd) isochrones from the Astronomical Observatory of Padova [13] were used. Fitting is done on the cleaned decontaminated cluster population, by finding the isochrone that best represents the Main Sequence (MS) until the turn-off point. The isochrone itself represents population of single stars forming the MS. This is the reason we fit the isochrone to this part of the observed CMD, ignoring unresolved binaries that lie above and to the red of the MS. In Figure 3, Left panel, the isochrones with logarithm of the age *logage* = 7.0, 7.1, 7.2, 7.3, 7.4 are shown with yellow lines.

The metallicity $z = 0.008$ and reddening $E(V - I) = 0.3$ of NGC 2004 are accepted with accordance to other studies of LMC clusters [14, 15]. Taking into account these values and following the best-fitting isochrone from the used set of models (Figure 3) we accept the age of NGC 2004 to be 16 Myr. For the completeness of the study we have to point that the Niederhofer et al. (2015) [15] found that the position of helium burning stars on their $(V, B - V)$ diagram is best reproduced by an isochrone corresponding to 20 Myr which resembles the value declared by Elson (1991) [16]. The CMD in our work reaches considerably deeper limit in magnitudes, compared to other published studies of NGC 2004 [14, 15].

For validation of the results from isochrones fitting, we requested a simulation of a synthetic cluster by the SYCLIST tool (https://www.astro.unige.ch/syclist/index/) from the Geneva stellar models. Such approach is presented in Ref. [17] on the galactic cluster NGC 663.

In our work the number of simulated stars is 1000, a representative number comparable to the number of cluster stars. Using the age found by isochrones fitting in the previous section and the accepted LMC metalicity, a synthetic cluster model was simulated from the available grids with two rotation rates and stellar masses covering a mass range from 0.8 to 120 solar masses (large grids). A typical binarity fraction of 30% [18] and a noise of 0.1 magnitudes on the simulated stars were accepted as simulation parameters. The CMD of the synthetic clusters is presented in Figure 3, Right panel with blue circles. We found that the observed and synthetic CMDs are in a good agreement. The observed discrepancies could be explained by the inherent differences between PARSEC and SYCLIST models and the lower metallicity (Z=0.002) of the available best-fitting isochrone found in PARSEC models. The unresolved binaries both synthetic and observed are located above the Main Sequence population, while at magnitudes fainter than 22 magnitude a residue of field LMC stars can be identified.

SUMMARY

In this work we present precise two band (V,I) photometry of more than 3000 stars members of stellar cluster NGC 2004 (LMC). Age estimation of 16 Myr was obtained using isochrone fitting and single stellar population models. A good agreement of the observed color-magnitude diagram with the one derived on the base of simulated synthetic cluster (Geneva SYCLIST tool) adopting 16 Myr cluster age with 30% binarity fraction is demonstrated.

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