Deriving physical parameters of unresolved star clusters

VI. Adaptive aperture photometry of the M31 PHAT star clusters[★]

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ABSTRACT

Context. This study is the sixth of a series that investigates degeneracy and stochasticity problems present in the determination of the age, mass, extinction, and metallicity of partially resolved or unresolved star clusters in external galaxies when using *Hubble* Space Telescope broadband photometry. In the fifth publication, it was noticed that inconsistencies in cluster colour indices, which arise due to projected foreground and background stars on the apertures, enhance age-metallicity-extinction degeneracies.

Aims. In this work we aim to present new aperture photometry results for a sample of star clusters from the M31 Panchromatic *Hubble* Andromeda Treasury (PHAT) survey.

Methods. We employed two methods of aperture photometry. The first method is ordinary aperture photometry to measure total cluster fluxes. The second method was introduced to avoid the brightest foreground and background stars that project onto large apertures. This method employs smaller apertures, adapted to cover a central part of clusters, and applies an aperture correction, derived for the *F475W* passband, to other passbands. We note that this procedure is valid only for clusters without prominent systematic gradients of colour indices beyond half-light radii.

Results. We present two catalogues of star cluster aperture photometry (produced by applying ordinary aperture photometry and adaptive aperture photometry methods) with estimated uncertainties for a sample of 1181 star clusters from the M31 PHAT survey. Compared to the M31 PHAT fundamental star cluster aperture photometry catalogue published by Johnson et al., there are changes made in the following: cluster centre coordinates, aperture sizes, and sky background estimates.

Key words. galaxies: individual: M31 – galaxies: star clusters: general

1. Introduction

Recently, the Panchromatic *Hubble* Andromeda Treasury (PHAT; Dalcanton et al. 2012) survey used the *Hubble* Space Telescope (HST) to observe a third of Andromeda's (M31) star-forming disk and published a large sample of star clusters (Johnson et al. 2012, 2015). These clusters are subject to a variety of environments, spanning from dense central parts of M31 to more sparsely populated outskirts, and can thus provide important information about their evolution.

Star clusters can be characterised well by the main parameters – age, mass, metallicity, and interstellar extinction – which can be determined using various methods. In recent studies of M31 star clusters using PHAT data (Johnson et al. 2016, 2017), parameters of young clusters were derived using colour-magnitude diagrams (CMDs) constructed from individual stars and measured in clusters' regions. However, the CMD fitting method, in order to obtain reasonably accurate results, is limited by a necessity to resolve and measure stars down to the main-sequence turnoff point.

Other methods used to derive star cluster parameters fit stochastic theoretical cluster models to the observed integrated cluster magnitudes (Fouesneau & Lançon 2010; Fouesneau et al. 2014; de Meulenaer et al. 2013, 2014, 2015) or

employ a more sophisticated approach, as in the publicly available code SLUG (Krumholz et al. 2015). These methods enable us to investigate unresolved and semi-resolved star clusters of various ages and masses. However, the accuracy of the derived cluster parameters strongly depends on uncertainties of aperture photometry and the proper account for projecting background and foreground stars (hereinafter field stars) and the brightest evolved cluster members.

In the study by de Meulenaer et al. (2017), we noticed strong age-extinction degeneracies in the cases of clusters containing bright field (likely) stars within applied apertures. Moreover, an extensive study of the effects of the bright post-main-sequence stars on the accuracy of cluster parameter determination was performed by Beerman et al. (2012). They demonstrated that cluster parameters can be derived more precisely by excluding bright evolved stars in the cases of low-mass star cluster aperture photometry.

In this paper we present an adaptive aperture photometry method developed to mitigate problems arising due to the bright field stars projecting onto star clusters and the stochasticity of the brightest evolved cluster members. Beerman et al. (2012) suggested a careful account of the bright evolved cluster stars in cases where they are excluded from aperture photometry. The adaptive aperture method, which is primarily targeted to exclude bright field stars, could also exclude from measurements some evolved cluster members residing away from the central part of clusters. Therefore, users of the adaptive photometry results should take care to propagate this effect into models that are used

[★] Full Tables 2 and 3 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/654/A6>

to fit these data or take into account uncertainties that this censoring could introduce.

We present star cluster photometry results by using two approaches: (i) ordinary aperture photometry to measure ‘total’ (T) fluxes and magnitudes; and (ii) adaptive aperture photometry to measure less contaminated fluxes from the central parts of clusters with the further use of an aperture correction (AC; derived for the *F475W* passband) to all other passbands – ‘colour’ (C) fluxes and magnitudes. We carefully selected C apertures and, in most cases, we succeeded in avoiding some of the brightest field or cluster stars that fall within T apertures. This procedure ensures the consistency of colour indices for the majority of star clusters from our sample. However, it is accurate for the clusters without strong systematic gradients of colour indices beyond the clusters’ half-light radii. By ‘systematic gradients’ we mean (here and throughout the paper) only those gradual radial changes in colour indices that arise due to the variation in cluster stellar populations – not those due to one or a few of the brightest field or cluster stars that fall within the T aperture.

The structure of the paper is the following: In Sect. 2 we present the description of observation data and the selected cluster sample; in Sect. 3 we discuss details of the applied photometry procedure; in Sect. 4 we compare the multi-colour photometry results obtained with ordinary and adaptive aperture methods; and in Sect. 5 we present brief conclusions.

2. Observations and cluster sample

2.1. Observation data

Our research is based on the HST PHAT survey (Dalcanton et al. 2012) data obtained from the *Hubble* Legacy Archive (HLA)¹. The full extent of the PHAT survey covers an area from the centre to the outermost north-eastern side of the M31 disk. The whole survey area is divided into 23 regions called ‘bricks’, with increasing numbering the farther away they are from the galaxy’s centre.

We used the so-called ‘Level 2’ products that have been processed by the automated HLA pipeline. This means that bias and dark frames are already subtracted, flat fielding is applied, and all available exposures are combined. The dataset consists of six passbands from three different HST channels: the *F275W* and *F336W* passbands from the Wide Field Camera 3 UVIS channel (WFC3/UVIS), the *F475W* and *F814W* passbands from the Advanced Camera for Surveys (ACS/WFC), and the *F110W* and *F160W* passbands from the Wide Field Camera 3 IR channel (WFC3/IR). Various passbands have a different number of exposures combined to produce the resulting frames: the *F475W* frames are combined from five exposures, the *F814W* and *F160W* frames from four exposures, the *F275W* and *F336W* frames from two exposures, and the *F110W* frames from a single exposure.

We performed a spatial alignment of all frames with the *tweakreg* task, which is a part of the *drizzlepac* package². Initially, astrometrically correct *F475W* passband frames from the Mikulski Archive for Space Telescopes and the PHAT archive³ were used as a reference for the *F475W* frames obtained from HLA. Subsequently, remaining passbands were aligned with their closest aligned counterpart in wavelength, namely, the *F336W* and *F814W* frames were aligned to the

F475W frames, then the *F275W* frames were aligned to the *F336W* frames, and finally the *F110W* and *F160W* frames were all aligned to the *F814W* frames.

The *F275W* and *F336W* passband frames contain a large number of cosmic-ray artefacts because they have only two repeated exposures available, which makes it difficult to reliably clean them in an automated manner. To remove the artefacts in these ultraviolet (UV) frames, we used colour images constructed from the *F275W* + *F336W* + *F475W* passbands to identify and manually clean them using the *imedit* task from PyRAF⁴. This allowed us to remove the most obvious defects that fall inside or close to the cluster’s aperture as defined in Johnson et al. (2015). However, there are some cases where clusters fall inside the gap area between two WFC3/UVIS sensors. Therefore, they have significantly increased artefact and noise counts due to only a single exposure being available at that location. Ultraviolet measurements were discarded where artefacts overlap with clusters, thus making them un-cleanable. Even though the obvious artefacts were removed, there is a possibility that some were not noticed during the visual inspection.

Additionally, some frames contained empty pixels with values equal to zero. This was an especially considerable problem for the *F110W* passband, which has only one exposure available for each field. We replaced empty pixels with an average of eight surrounding non-zero-valued pixels (a required minimum for averaging was set to four non-empty pixels). However, if any uncorrected empty pixel remained inside the aperture, we omitted measurements in this passband.

As noted by Williams et al. (2014), the *F110W* passband in field 8 of brick 22 has elevated sky background levels, likely due to the 10830 Å He I airglow emission line. Two clusters from our sample are located in the aforementioned field (AP0461 and AP0800) and have higher-than-usual sky background noise levels; however, we provide their measurements.

2.2. Cluster sample

For the present study, we used a sample of 1363 clusters analysed in de Meulenaer et al. (2017). Their selection criteria and details are provided in the cited paper. Based on an interactive analysis, we determined that clusters closest to the M31 centre are too contaminated by projecting stars. Therefore, we omitted the bricks numbered 1, 3, 5, and 7. This left us with 1184 clusters.

We found that clusters AP0147 and AP3779 are missing in both WFC3 channels, while cluster AP4132 has a lot of corrupted pixels in the *F475W* passband. Therefore, these three clusters were also omitted from further analysis. Locations of the remaining 1181 star clusters are shown in Fig. 1; they cover a wide range of galactic environments, from dense central regions to the relatively empty outermost areas.

We performed an interactive cluster profile and image analysis by using DS9 software (Joye & Mandel 2003) to inspect and, if needed, to adjust centres of clusters based on *F336W*, *F475W*, and *F814W* passband frames. The original coordinates of the majority of the clusters as provided by Johnson et al. (2015) were kept or only slightly adjusted (median difference of 0′.15). However, in some cases of large stellar associations, we significantly readjusted centres and aperture sizes to cover only the most concentrated parts that could likely be considered as young clusters.

¹ <http://hla.stsci.edu>

² <https://drizzlepac.readthedocs.io>

³ <https://archive.stsci.edu/prepds/phat/datalist.html>

⁴ http://www.stsci.edu/institute/software_hardware/pyraf – PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

Fig. 1. Locations of the 1181 clusters analysed in this paper overlaid on the Multi-Band Imaging Photometer for *Spitzer* (*Spitzer*/MIPS) 70 μ m M31 map.

Table 1. Photometric zero points.

<i>F</i> 275W	<i>F</i> 336W	<i>F</i> 475W	<i>F</i> 814W	<i>F</i> 110W	<i>F</i> 160W
22.67	23.52	26.15	25.52	26.06	24.70

3. Aperture photometry

We performed photometry by using circular apertures from the *photutils*⁵ package. The exact measurement method, which determines the exact fraction of pixels located inside the aperture, was selected. We produced the magnitude growth curves for each cluster in all six passbands in steps of 0''.01 up to two times the aperture radius of a cluster set by Johnson et al. (2015). However, in cases of smaller apertures, a minimum radius of 5'' was set in order to get sufficient sky background coverage. The area beyond the cluster's aperture was used to determine the sky background level interactively (see the description in Sect. 3.1), while a small incremental step for growth curves was chosen to have cluster measurements with any aperture size needed during the analysis.

Photometric zero points for the ACS camera are taken from the ACS zero point calculator⁶, while the ones for both WFC3 channels are taken from the Space Telescope Science Institute (STScI) website⁷. They are listed in Table 1. We assumed a distance modulus of the M31 galaxy of $m - M = 24.47$ (McConnachie et al. 2005).

Figures 2 and 3 give an example of a set of images used for the analysis of clusters. Figure 2 includes three coloured images of the star cluster AP0094 constructed from the following

passband combinations: $F275W + F336W + F475W$, $F336W + F475W + F814W$, and $F475W + F110W + F160W$. Individual frames of all passbands are shown in grey scale in the bottom row. A blue circle indicates a large aperture used to measure the T magnitudes of the cluster. A red circle indicates a smaller aperture (covering the cluster's central part, which is least contaminated by the brightest resolved field or cluster stars) was used to measure C magnitudes, which are appropriate for producing consistent colour indices (unbiased by projecting field stars). Figure 3 shows the measured growth curves (top) and their differential flux profiles (bottom) in each passband for the star cluster AP0094. The T aperture magnitudes of the cluster are indicated by the horizontal blue lines, while the red lines mark the magnitudes derived from the fluxes measured through the C aperture. Vertical blue and red lines indicate the sizes of applied T and C apertures, respectively. Differential flux profiles show the sky-background-subtracted flux (in arbitrary units) of the cluster, contained in rings of 0''.05 width. Negative values correspond to the areas that, on average, have smaller fluxes than the subtracted sky background level. Various peaks represent resolved luminous stars and demonstrate the complicated nature of surrounding sky backgrounds.

Appearances of clusters and surrounding sky backgrounds vary significantly among objects, which makes it difficult to determine whether any particular star belongs to the cluster or if it is a field object. However, in most cases, 10'' $\times$ 10'' size images centred on the cluster were large enough to estimate the probabilities of field stars, which, not being cluster members, fall within T and C apertures. The multi-colour images of clusters (Fig. 2) together with their growth curves (Fig. 3) were used to determine optimal sizes of the T and C apertures.

3.1. Sky background

The accuracy of sky background determination in the cluster aperture photometry is the main issue, and various automated methods have been proposed (Barmby & Huchra 2001; Krienke & Hodge 2007; Johnson et al. 2012). However, in especially complicated situations, which are encountered in crowded fields such as the M31 disk, their reliability is lower.

Sky background areas around clusters usually comprise a statistically small number of well-resolved bright stars. Being irregularly distributed, they greatly complicate the determination of sky background levels in different passbands. It is apparent that fluxes in different passbands are dominated by stars that differ significantly in colour (Fig. 2). Since the majority of bright field stars are red giants located in M31, they predominantly affect the infrared (IR) passbands and complicate cluster parameter derivation by imitating effects of extinction and/or older ages (de Meulenaer et al. 2017). A number of IR bright field stars strongly vary with the distance from the M31 centre and especially dominate in the *F*110W and *F*160W passbands.

We performed extensive tests of the automatic sky background level determination methods and found that the accuracy of the local sky background (under the cluster) strongly depends on the presence of bright stars, dusty lanes, and other unevenness or crowdedness within the regions surrounding the clusters. Moreover, we noticed that sky background levels, determined using automatic methods, are inconsistent among various passbands for the majority of clusters from our sample.

For these reasons, we plotted growth curves and differential flux profiles in all passbands (Fig. 3) for each cluster and derived consistent sky background levels interactively. We developed a custom user interface to adjust sky background levels

⁵ <https://doi.org/10.5281/zenodo.596036>

⁶ <https://www.stsci.edu/hst/instrumentation/acs/data-analysis/zeropoints>

⁷ <https://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/photometric-calibration>

Fig. 2. Cluster AP0094 shown in colour panels (*top*), produced by combining three passbands, and grey-scale panels (*bottom*), produced from individual passband frames (the passbands are labelled inside the panels). Blue and red circles represent applied T and C apertures, respectively. The size of each panel is $10'' \times 10''$; north is up, and east is to the left. An insert at the top-right corner indicates the location of the cluster in M31.

Fig. 3. Growth curves (*top*, in magnitudes) and differential flux profiles (*bottom*, in arbitrary units) for the cluster AP0094. Solid vertical blue and red lines show applied T and C aperture radii, respectively. Blue and red horizontal lines indicate magnitudes derived from the T and C fluxes.

interactively and to visually control the changes of growth curves and differential flux profiles. The main objective of the interactive procedure is to accurately determine the unresolved sky background value and to estimate the impact of resolved stars. For this purpose, we heavily employed differential flux profiles

(the lower graphs in each panel of Fig. 3) that clearly show fluctuations arising due to the resolved stars. Special care was taken to correctly account for the presence of the brightest field stars (mainly in the IR passbands) and image defects, as well as cosmic-ray artefacts (abundant in the UV passbands).

As an initial step, we calculated mean and median sky background values in the ring-shaped areas extending from $1.2R_T$ to $3.4R_T$ (where R_T is the radius of the cluster's T aperture), following Johnson et al. (2015). Both sky background values are used to draw the first iteration of star cluster growth curves and differential flux profiles. Then sky background levels were adjusted interactively in each passband to flatten growth curves and make differential flux profiles close to zero in the sky background determination region. In most cases, the interactively determined sky background values are somewhat lower than the calculated mean, but they are higher than median values. This is understandable since the mean sky background values are strongly influenced by bright resolved stars located in the sky background area, while median values are not sensitive to the presence of bright resolved stars.

The method of visual analysis of cluster images together with their growth curves and differential flux profiles enables us to determine sky background levels accurately and consistently across all six passbands. However, there is a disadvantage of this sky background determination method – it is a highly time-consuming process.

3.2. Apertures

Aside from the accurate sky background determination problems, strong contributors to the uncertainties in photometry are bright resolved field stars projecting onto T apertures. To minimise the impact of these stars, we used two co-centred apertures: a large one to determine T magnitudes and a smaller one (selected to avoid the brightest stars) to determine C magnitudes. Such a procedure enabled us to derive more consistent cluster colour indices (less contaminated by bright stars), which are of the highest importance for determining cluster parameters from integrated photometry results (de Meulenaer et al. 2017).

The T magnitudes of clusters in the majority of cases were measured by applying apertures equal to or slightly smaller than those used by Johnson et al. (2015), to avoid bright field stars at the edges of apertures. In some cases, we used larger apertures to include more of the clusters' outskirts. There are also a few cases where we reduced T apertures that would otherwise fall outside of the frame area in at least one of the passbands. In a few instances, some parts of the clusters fall outside of frames in one or two UV or IR passbands; therefore, we discarded measurements in those passbands. However, the requirement to derive magnitudes in at least four passbands (including $F336W$, $F475W$, and $F814W$) is fulfilled for all star clusters in our sample.

We chose the $F475W$ passband as a base to derive colour-consistent magnitudes. Observations in the $F475W$ passband, compared to the $F336W$ passband, are of a much higher signal-to-noise ratio; frames in the $F475W$ passband, compared to the $F814W$ passband, are less contaminated by the light of resolved field stars from old M31 populations. The C apertures in most cases include the central (and possibly larger) parts of clusters. Radii of C apertures (R_C) typically range from $0''.4$ to $1''.4$, depending on the clusters' size and the location of resolved probable field stars. We followed a rule (with a few exceptions) that radii, R_C , have to be equal to or larger than the half-light radii, R_h , of corresponding clusters. It should be noted, however, that even the smallest applied C apertures, $R_C = 0''.4$ (eight pixels in ACS/WFC), engulf a number of pixels large enough to guarantee accurate photometry.

Finally, we derived colour-consistent cluster magnitudes by applying an AC, determined for the cluster in the $F475W$ passband, to the magnitudes calculated from the fluxes measured in individual passbands through the C aperture: $F?W_C = F?W_{CA} + F475W_{AC}$, where $F?W_C$ are the final C magnitudes in corresponding passbands ($F?W$ represents six individual passbands, and '?' marks a three-digit code of the passband), $F?W_{CA}$ are the magnitudes derived from the fluxes measured through the C aperture, and $F475W_{AC}$ is the AC derived for the cluster in the $F475W$ passband ($F475W_{AC} = F475W_T - F475W_{CA}$).

We note, however, that in order to apply this transformation safely, it is necessary to check for the absence of strong systematic radial gradients of colour indices beyond the half-light radius of the cluster, R_h (i.e., beyond R_C). Objects in the studied cluster sample, in general, have flat profiles of colour indices at large radii, except for a few dozen clusters that suffer from partly projecting bright field stars or the brightest cluster members on the C aperture edge. Also, we note that in some extreme cases a failure of the $F475W$ -based AC method could occur due to numerous bright field or evolved cluster stars (especially of differing colours from the dominating cluster's stellar population) residing within the T aperture.

Here we explain in more detail the aperture issues based on the case of the cluster AP0094 (Fig. 2). This cluster is young, rather massive, and prominent; therefore, photometry should be performed easily with high precision. However, it resides within a stellar association in the dense background of bright blue and red stars. The cluster's environment seriously complicates colour-consistent aperture photometry. Moreover, a 'dead zone' to the south of the cluster, where data in the $F110W$ and $F160W$ passbands are missing, limits the T aperture size. Two bright red stars located to the west and to the south of the cluster are most probably field stars (based on the CMDs of the stars residing within the field of $10'' \times 10''$ surrounding the cluster) and should be avoided by selecting the C aperture. A relatively bright star (in all passbands), located to the south-east of the cluster, is probably a real member of this cluster. However, following Beerman et al. (2012), cluster parameters would be determined more accurately if we could avoid this star in aperture photometry. Therefore, to obtain consistent colour indices of this cluster, it is difficult to choose an optimal combination of T and C apertures (Fig. 2).

Unfortunately, there are even more complicated cases in the studied cluster sample. The accuracy of the photometry results suffers from these effects, especially in the cases of fainter clusters and in more crowded star fields. However, the adaptive aperture photometry method in most cases helps to obtain colour-consistent cluster photometry results that fit well with the models (see Sect. 4).

3.3. Photometric accuracy

Determining correct statistical photometric errors when performing aperture photometry on mosaicked frames and having fluxes reduced to one-second exposures is virtually impossible. Therefore, in order to roughly estimate photometric errors in this study, we took into account two main sources that contribute to the uncertainties of cluster magnitudes.

Since the mean sky background level has been subtracted in the HLA frames, it is impossible to determine a realistic signal-to-noise ratio directly. Therefore, we estimated an amplitude of sky background variation by fitting the Gaussian profile to the histogram of pixel values. In general, the sky background pixel

Fig. 4. Uncertainties of star cluster T magnitudes (σ_T) in all six passbands versus their T magnitudes.

value histogram is rather asymmetric due to pixels from bright resolved stars, which do not represent the sky background but strongly skew the histogram nevertheless. Therefore, to improve the accuracy of the Gaussian profile fitting, we discarded the highest-value pixels (30% of the total pixels) and derived the sky background flux variation per pixel as a Gaussian σ_{sb} . The ring-shaped area chosen for the sky background analysis was similar to that in [Johnson et al. \(2015\)](#) and extends from $1.2R_T$ to $3.4R_T$.

The first part of magnitude uncertainty in each passband, arising due to sky background variations, was calculated as:

$$\sigma_1 = 2.5 \log_{10} \left(1 + \frac{\sigma_{sb} \sqrt{A_{ap}}}{F_{cl}} \right), \quad (1)$$

where F_{cl} is the integrated cluster flux inside the T or C aperture and A_{ap} is the area of aperture in pixels.

The second part of the magnitude uncertainty in each passband could arise because of a possible aperture position bias (with respect to the cluster) and different sizes of stellar images in various passbands. We estimated these effects by performing photometry at eight additional positions shifted symmetrically by $0''.05$ around the cluster's centre (one pixel in ACS/WFC) in the cases of C magnitude and by $0''.1$ (two pixels in ACS/WFC) in the cases of T magnitude. Finally, the resulting standard deviation (σ_2) was derived out of those nine independent cluster measurements in each passband. The final uncertainty (σ) of the cluster photometry in each passband was calculated as:

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}.$$

Figures 4 and 5 show the estimated T and C magnitude uncertainties versus corresponding magnitudes for all clusters. Uncertainties in the UV passbands are mainly dominated by sky background variations (σ_1) and correlate well with magnitude. On the other hand, uncertainties in the IR passbands are much more scattered due to the presence of irregularly distributed bright stars; therefore, uncertainties are more sensitive to the clusters' position bias within apertures (σ_2).

It is difficult to quantify uncertainties caused by the interactive sky background level determination procedure. However, they are of systematic nature and correlate well in neighbouring passbands; therefore, they only marginally affect cluster colour indices. Based on the individual sky background level determination by the team members, we conclude that these systematic errors can reach up to 0.05 mag for the faintest clusters.

4. Multi-colour photometry results

The T aperture photometry results with uncertainties (σ_T) in each passband and the half-light radii derived from growth curves in the $F475W$ passband (R_h) are provided in Table 2 for all (1181) studied clusters. The C aperture photometry results with uncertainties (σ_C) are provided in Table 3.

We show star cluster photometry results by plotting the differences between the T and C magnitudes versus corresponding C magnitudes (Fig. 6). We note that panel c shows the aperture corrections, $F475W_{AC}$, determined for the $F475W$ passband. Additionally, we show the differences between some colour indices derived from the T and C magnitudes versus C magnitudes (Fig. 7).

Figures 6 and 7 show large differences of magnitudes and colour indices determined by the two methods. It should be noted, however, that these differences are due to the effects of smaller apertures (selected in order to avoid the brightest field and cluster stars) used to derive C magnitudes. Other photometry-affecting parameters (positions of clusters within apertures, T aperture sizes, and sky background levels) are the same in both methods. Therefore, Figs. 6 and 7 show clearly the importance of the problems addressed in this paper. Also, it is noteworthy that there are no significant differences in bright object photometry compared with the [Johnson et al. \(2015\)](#) results when cluster centre positions and applied T aperture sizes coincide. This suggests that our dataset is unbiased and well calibrated.

Fig. 5. Uncertainties of star cluster C magnitudes (σ_C) in all six passbands versus their C magnitudes.

Table 2. M 31 star cluster T aperture photometry results.

AP	RA(2000)	Dec(2000)	$R_T^{(a)}$	$R_h^{(b)}$	$F275W_T$	$F336W_T$	$F475W_T$	$F814W_T$	$F110W_T$	$F160W_T$
0001	11.435516	41.698562	2.0	0.6	20.057	19.283	18.811	17.645	17.040	16.424
					0.034	0.011	0.006	0.005	0.012	0.010 ^(c)
0002	11.366514	41.701013	1.4	0.6	21.341	20.522	20.019	18.913	18.292	17.623
					0.073	0.018	0.009	0.011	0.028	0.028

Notes. The table shows an excerpt from data presented in the catalogue. The full table is available at the CDS. ^(a)The T aperture radius in arcseconds. ^(b)The half-light radius in the $F475W$ passband in arcseconds. ^(c)The uncertainties of T magnitudes (σ_T) in corresponding passbands.

Table 3. M 31 star cluster C aperture photometry results.

AP	RA(2000)	Dec(2000)	$R_T^{(a)}$	$R_C^{(b)}$	$F275W_C$	$F336W_C$	$F475W_C$	$F814W_C$	$F110W_C$	$F160W_C$
0001	11.435516	41.698562	2.0	0.6	20.198	19.330	18.811	17.599	17.081	16.497
					0.024	0.011	0.006	0.008	0.011	0.010 ^(c)
0002	11.366514	41.701013	1.4	0.7	21.276	20.561	20.019	19.075	18.794	18.450
					0.058	0.018	0.009	0.014	0.038	0.049

Notes. The table shows an excerpt from data presented in the catalogue. The full table is available at the CDS. ^(a)The T aperture radius in arcseconds. ^(b)The C aperture radius in arcseconds. ^(c)The uncertainties of C magnitudes (σ_C) in corresponding passbands.

To test the quality of new photometry data, we employed stochastic star cluster models in the age range of $\log_{10}(t/\text{yr}) = 6.6\text{--}10.1$ and with masses from $10^2 M_\odot$ to $10^5 M_\odot$. These models are based on the PAdova and tRieste Stellar Evolutionary Code (PARSEC)-COLIBRI isochrones⁸ (Marigo et al. 2017) and were calculated using the same method as described in de Meulenaer et al. (2017). The models are plotted in the extinction-free form in the background of Figs. 8 and 9.

In Fig. 8 we show colour-colour diagrams constructed from T aperture photometry (panels a–c) and C aperture photometry results (panels d–f) compared to the synthetic models (grey density contours in the background). Masses of model clusters are from 10^2 to $10^5 M_\odot$, and their density distribution is emphasised by grey contour plots. The C aperture photometry results of star clusters, especially taking into account the non-zero interstellar extinction within the M 31 galaxy, follow the distribution of the models more closely in all panels.

The largest adaptive aperture photometry effects are seen in the IR passbands where the field star contamination is heaviest. The youngest star clusters are especially sensitive to the C

⁸ <http://stev.oapd.inaf.it/cgi-bin/cmd>

Fig. 6. Differences between T and C magnitudes. Panel c shows the ACs, $F_{475W_{AC}}$, determined for the F_{475W} passband.

Fig. 7. Differences between colour indices derived from the T and C magnitudes (colour index made from T magnitudes minus colour index made from C magnitudes).

Fig. 8. Colour-colour diagrams showing star cluster photometry results. *Panels a–c:* T aperture photometry (blue dots). *Panels d–f:* C aperture photometry (red dots). Distributions of star cluster models with masses from 10^2 to 10^5 M_⊙ are plotted in the background (grey density contours). Colour indices indicated on the X axis are constructed from T magnitudes in *panels a–c* and C magnitudes in *panels d–f*. Arrows in the lower-left corners of the panels indicate the extinction vectors of $A_V = 1$, assuming the standard Milky Way extinction law.

Fig. 9. CMDs of various passband combinations showing star clusters over-plotted on the distributions of models; colours code cluster masses of: 10^2 M_⊙ (blue), 10^3 M_⊙ (green), and 10^4 M_⊙ (red). Arrows in the upper-right corners of the panels indicate the extinction vectors of $A_V = 1$, assuming the standard Milky Way extinction law.

Fig. 10. $F475W_C$ magnitudes versus half-light radii, R_h , determined in the $F475W$ passband, plotted for all clusters from our sample. Dashed red and blue lines indicate the limits of the constant surface brightness (within apertures of R_h radii) of $21.5 \text{ mag/arcsec}^2$ and $22.5 \text{ mag/arcsec}^2$, respectively.

aperture method because they are very faint in the IR passbands (Figs. 8c,f). On the other hand, the accuracy of UV colour indices (Figs. 8a,d) is limited by the low signal-to-noise ratio rather than other biases. Outlying star clusters in Figs. 8d–f usually have very complicated surrounding sky backgrounds, which are difficult to take into account correctly, or have bright contaminating field stars, which fall within the C aperture. Some of them are strongly affected by interstellar extinction; especially noticeable effects could arise due to the peculiar extinction law. There is a clear systematic shift due to the extinction between modelled and observed clusters (the extinction vectors, assuming the standard Milky Way extinction law, are shown at the bottom-left corners of panels).

The distribution of star cluster models in CMDs strongly depends on their mass. This effect is shown in Fig. 9. A bimodal distribution of the modelled and observed clusters is seen clearly in Figs. 9a,b. The decrease in stochasticity with increasing cluster mass is also apparent. It is worth noting that the majority of star clusters from our sample fit well with models of $10^3 M_\odot$ mass, except for the most massive (brightest) globular-like clusters (located at $(F475W - F814W)_C \sim 1.5 \text{ mag}$). Therefore, we conclude that the new photometry data are compatible with the stochastic cluster models calculated according to de Meulenaer et al. (2017).

Figure 10 shows $F475W_C$ magnitudes of star clusters versus their half-light radii determined in the $F475W$ passband. The majority of clusters from our sample are faint ($F475W_C > 20$) and compact ($R_h \sim 0''.5$). The largest objects, with $R_h \gtrsim 1''.4$, are mostly stellar associations. Taking into account a detection limit as a constant surface brightness of $22.5 \text{ mag/arcsec}^2$ (the blue line in Fig. 10) and an approximate detection completeness of a $\sim 50\%$ limit of $\sim 21.5 \text{ mag/arcsec}^2$ (the red line in Fig. 10), there is no clear correlation between star cluster luminosity and size.

5. Conclusions

We performed multi-colour aperture photometry of a sample of 1181 star clusters from the M31 galaxy PHAT survey (Dalcanton et al. 2012; Johnson et al. 2012, 2015). We used two methods of photometry: ordinary aperture photometry (T) and a new adaptive aperture photometry (C). As the main product of this study, we provide T and C aperture photometry catalogues of star clusters in six passbands (Tables 2 and 3).

The results of the present study are summarised in Figs. 6 and 7. We have demonstrated that the proposed method of photometry with C apertures gives more robust results in the sense of consistent colour indices compared to the T aperture photometry (Fig. 8). We also show that the new photometry results fit well within a space of stochastic star cluster models (Fig. 9).

There are two main issues limiting the accuracy of cluster aperture photometry in crowded fields: sky background determination problems and field stars projecting onto apertures. We carefully took both of these effects into account. However, for some clusters ($\sim 10\%$), bright field stars reside near the centres, within R_h .

The most promising further accuracy improvement of the aperture photometry of semi-resolved star clusters would be the subtraction of individual resolved field stars. However, to solve this problem, it is necessary to perform accurate stellar photometry in extremely crowded fields (on clusters), which is a challenging task even for semi-resolved clusters.

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