Characterization of NGC6705 (M11) open cluster

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Abstract: The main purpose of this work is to derive the physical properties of NGC6705 open cluster using Strömgren photometry; such as distance, average colour excess, metallicity and age. Besides, this method provides individual temperatures, gravities and metallicities that are compared to the spectroscopic independent results from Gaia-ESO survey. 12137 stars with all Strömgren indices are obtained out of 63437 stars that have partial data on *m1*, *c1* and H_β indices, with V reaching a limiting magnitude of $\sim21^{\rm m}$. The physical parameters obtained from an automatic algorithm lead to the evidence of differential reddening with a mean value of $E(b-y) = 0^{\rm m}.30 \pm 0^{\rm m}.02$, metallicity of $[Fe/H] = -0.3 \pm 0.3$ dex and absolute distance modulus of $V_0 - M_V = 12^{\rm m}.0 \pm 0^{\rm m}.3$. From PARSEC and Dartmouth isochrones' best fit, we retrieve that NGC6705 is a 250-316 Myr open cluster that has a turn off mass of $3.3 \pm 0.2 {\rm M}_\odot$, $E(b-y) = 0^{\rm m}.30 \pm 0^{\rm m}.01$, $V_0 - M_V = 11^{\rm m}.5 \pm 0^{\rm m}.1$ and $[Fe/H] = -0.1 \pm 0.1$ dex.

I. INTRODUCTION

NGC6705 (RA=$18^{\rm h}$ $51^{\rm m}$ $05^{\rm s}$, DEC= -06º 16' 12") is a massive, packed and relatively young open cluster laying towards the central part of the Galactic disk. Chemical inhomogeneous populations are seen in globular clusters with masses over $\sim 4 \times 10^4 {\rm M}_\odot$. NGC6705's mass is well below this limit (see [3]), so it is believed to host only one population, as commonly seen in open clusters. It has been studied several times with wide-passband photometry [3, 7, 15]. However, there is only one existing Strömgren photometry of NGC6705 [1], which covers an area limited to the cluster's core. The presence of both evolved and young stars and the low interstellar extinction makes this cluster an important asset to test models of stellar evolution. Accordingly, it has been surveyed by Gaia-ESO Survey (GES) [6] and been proposed to validate Gaia results.

Strömgren photometry was designed to provide more precise information about intrinsic stellar parameters than other wide-passband photometric systems such as Johnson UBV system and give results as good as those of low resolution spectroscopy. In fact, it is possible to obtain a spectral classification for O-K stars given their position in colour-colour diagrams. Indices derived from $uvbyH_\beta$ photometry allow us to measure apparent and absolute brightness and consequently, the distance modulus. Moreover, one can derive colour excess and $[Fe/H]$ abundances. Stellar isochrones' fitting with PARSEC [2] and Dartmouth [5] stellar evolutionary models allows us to estimate the age of the cluster. Besides, isochrones' fit provides another method to obtain physical parameters such as $V_0 - M_V$, $E(b-y)$ and metallicity.

II. PHOTOMETRY

$uvbyH_\beta$ Strömgren photometry was undertaken using 2.54 m Isaac Newton Telescope (INT) at Roque de los Muchachos, La Palma. The observations were done on May 30 2015 with the Wide Field Camera (WFC). On that night, the seeing was variable (0".8-1".4 with half an hour reaching 1".7) and it was nearly full moon. The WFC is a 4 chip optical mosaic with 2048 x 4100 pixels^2 area of useful imaging with 0".333 per pixel, which consequently covers 34'.2 field from edge to edge of the mosaic. Data from another survey on NGC6705 from our group of one exposure for each Strömgren filter (reaching a limiting magnitude of $\sim21^{\rm m}$) was already taken with WFC in an observing campaign on July 3-5 of 2010. However, stars brighter than $12^{\rm m}$ were saturated and thus suffer from non-linearity. The new photometry aims to cover the lost range adding completeness to the final catalogue with 6 more observing runs of short, middle and long exposures that reach a limiting magnitude of $\sim18^{\rm m}.5$. 198 images for each CCD were reduced and the resulting catalogue was crossed with the previous observing run.

The reduction of the data is done with IRAF [17], a on purpose software released for reduction and analysis of astronomical data. In the first steps, overscan zones have to be trimmed out and bias and flats are corrected for each CCD's image. In addition to masking the vignetting on chip 3, bad pixels are corrected. Next, CCD non-linearity corrections proposed by CASU INT WF-Survey are applied. *Daofind* subroutine conducts a search of stars with a local density maxima that has a peak amplitude greater than a given threshold and then yields pixel coordinates for each of them. Given this star list, subroutine *daophot* computes sky flux and initial magnitudes. A curve of growth for each star with a 12 concentric apertures is done with *mkapfile* routine, which makes use of *daogrow* algorithm (see [13]). Aperture correction is a particularly useful tool in this cluster due to its crowded centre. Improved astrometry is computed

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with *WCSTools* package running *xy2sky* routine, which works out right ascension and declination from pixels positions using *USNO-B1.0* catalogue, *GSC-II* catalogue and image header's information. An astrometric correction is done for all CCD's chips, accounting for a curvature distortion at the focal plane of INT's. Positions are compared to those of *USNO-B1.0* catalogue and thus, they are corrected using *geomap* routine from *IRAF*. Atmospheric extinction coefficients must be obtained per night and filter. They are computed through six different pointings of standard stars (with known photometry) at different airmasses and then applied to the whole sample. Instrumental photometry (prime indices) is converted to standard using cluster NGC6633 known photometry and Eqs.(1a)-(1e):

$$y' - V = A_1 + B_1 \cdot (b - y) \quad (1a)$$

$$(b - y)' = A_2 + B_2 \cdot (b - y) \quad (1b)$$

$$c_1' = A_3 + B_3 \cdot (b - y) + C_3 \cdot c_1 \quad (1c)$$

$$m_1' = A_4 + B_4 \cdot (b - y) + C_4 \cdot m_1 \quad (1d)$$

$$H_\beta' = H_{\beta_w}' - H_{\beta_n}' = A_5 + B_5 \cdot H_\beta \quad (1e)$$

$$c_1 = (u - v) - (v - b) \ , \ m_1 = (v - b) - (b - y) \quad (1f)$$

NGC6633 cluster was chosen as standard due to the existing Strömgren photometry by [12] and by our own group. The transformation to standard photometry has to be done per night, and each CCD has to be treated indepently because they have different responses. Coefficients are computed and therefore applied to the whole photometry (prime indices) to obtain standard indices. The final catalogue is formed by 63437 stars: 12848 have c_1, 26304 have m_1 and 38800 have H_β index. Furthermore, we are able to derive physical parameters from 12137 stars with complete $uvbyH_\beta$ photometry.

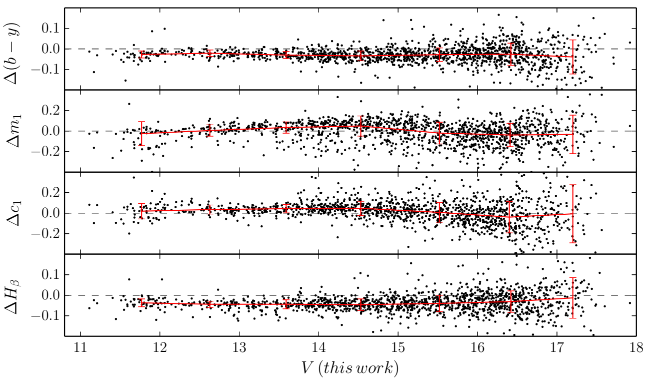

FIG. 1: Differences in colours((b - y), m_1, c_1, H_β), in the sense this work minus [1]. In red, the median and standard deviation with a 3σ clipping.

Our survey is in rather good agreement in all indices with [1] (see Figs.(1)-(2)). There are small offsets in (b - y) of $\sim 0^{\rm m}.03$ and in H_β of $\sim 0^{\rm m}.04$ and a trend with V in indices c_1 and m_1 (see Fig.(1)). In [1] comparison, there is a group of bright stars fainter in our photometry that we have identified as belonging to the red clump. This may be due to how coefficients are standardized with colour (b - y). We are in good agreement with V photometry from [3], [7] and [15] (see Fig.(2)). In [1] catalogue, V is brighter by an offset of $0^{\rm m}.02$ that increases slightly with V (see Fig.(2)). For [3] photometry, differences increase slightly with magnitude in such a manner that our stars become relatively fainter. [3] photometry is dependent on [15] catalogue, but in both cases we have a different trend.

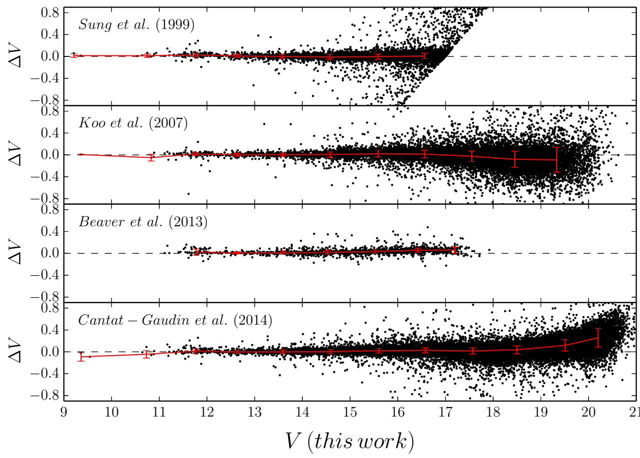

FIG. 2: Differences in V, in the sense this work minus others, with [15], [7], [1] and [3]. In red, the median and standard deviation with a 3σ clipping.

III. PHYSICAL PROPERTIES

This intermediate-passband photometry, which was conceived by Bengt Strömgren (see [14]), allow us to easily obtain spectral classifications and physical parameters. It was semi-empirically calibrated by authors such as Strömgren or Crawford, and it is thanks to Kurucz [8] theoretical stellar atmospheres models that, given $uvbyH_\beta$ photometry, effective temperatures ($T_{\rm eff}$) and surface gravities (log$g$) can be derived. These models provide synthetic colours for each $T_{\rm eff}$ and log$g$. Therefore, our observed colours are interpolated in grids that relate $T_{\rm eff}$ and log$g$ to photometric indices. Furthermore, with index m_1 and suitable spectroscopic calibrations for each spectral type, it is possible to obtain $[Fe/H]$ abundances. Based on empirical calibrations and stellar atmospheres models studied in [9], E. Masana built up a fully automatic algorithm (*pf.f*) to classify and derive the physical parameters of stars.

In Strömgren photometric system, each index is chosen carefully to provide information about certain star features. (b - y) measures the slope of Paschen continuum, like B-V from Johnson system. As b and y are equally sensitive to *blanketing*, they give information on the $T_{\rm eff}$.

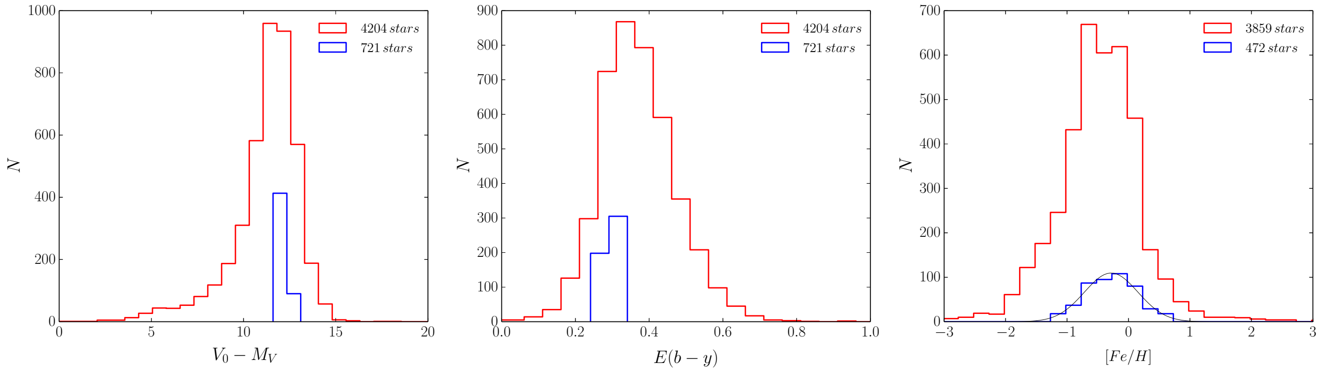

FIG. 3: From left to right, $V_0 - M_v$, $E(b-y)$ and $[Fe/H]$ histograms with bins of $0^{\rm m}.75$, $0^{\rm m}.05$ and 0.25 dex respectively. In red, A-G main sequence stars. In blue, stars that belong to the cluster. $[Fe/H]$ distribution for members can be approximated by a Gaussian fitting with a mean of -0.28 dex and standard deviation of 0.44 dex.

m_1 (metallicity index) measures the depression due to metal line absorption (*blocking*) and how this energy is redistributed along the spectrum, which in turn increases $T_{\rm eff}$ (*backwarming*). For a given $T_{\rm eff}$, line *blanketing* (sum of *backwarming* and *blocking*) depends only on the star chemical composition. c_1 (colour difference) is rather clean of metallicity effects (v is half affected by *blanketing* when compared to u) and measures the height of Balmer discontinuity. c_1 is a good temperature indicator for O-A stars and of luminosity for A-F stars. H_β measures the strength of the H_β line that provides $T_{\rm eff}$ for A-G stars and it is a luminosity index for O-A stars.

Region	1	2	3	4	5
Spec. class	O,B,A1	A0-A4	A2-F2	A8-G4	G0→
N stars	2524	344	871	2145	844

TABLE I: Spectral classification done by algorithm *pf.f* for 6728 stars (out of 8617), belonging to the main sequence (V) and to giants (VI-III) luminosity classes.

8617 out of 12137 stars are within the calibration range of *pf.f* algorithm (Table I). In order to segregate cluster members and field stars, we use membership probabilities derived by [3] from radial velocity data. We accept as members those stars with probability greater than 0.5. From this selection, we calculate the median and MAD values. With a σ clipping, we derive the following cuts: $11^{\rm m}.4 > V_0 - M_V > 12^{\rm m}.6$ and $0^{\rm m}.24 > E(b-y) > 0^{\rm m}34$. Where V_0 is $V - A_V$ and $V_0 - M_V$ is the absolute distance modulus. The cuts are applied to the whole sample (8617 stars), which results in 721 stars that belong to the cluster (see Fig.(3)). As seen in Fig.(4), the cluster is projected on a dense starfield background. However, the main sequence is rich enough to be unveiled in the colour-magnitude diagram. Therefore, median and MAD values for the physical parameters of cluster's members are:

$$V_0 - M_{V\ members} = 12^{\rm m}.0 \pm 0^{\rm m}.3 \quad (2)$$

$$E(b-y)_{members} = 0^{\rm m}.30 \pm 0^{\rm m}.02 \quad (3)$$

$$[Fe/H]_{members} = -0.3 \pm 0.3 \text{ dex} \quad (4)$$

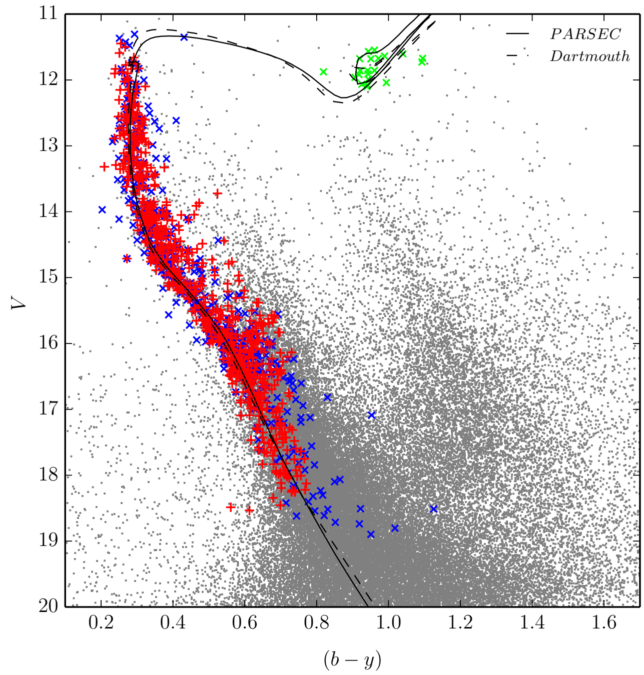

FIG. 4: Colour-magnitude diagram of NGC6705 open cluster with isochrones' best fit from PARSEC and Dartmouth models. In green, UVES red clump cluster members. In blue, Cantat-Gaudin et al. (2014) selected stars with a membership probability greater than 0.5. In red, main sequence members identified in our work. In grey, all available photometry of our survey.

For age determination, theoretical stellar isochrones are needed. For Strömgren photometric system, PARSEC [2] and Dartmouth [5] models are available. 21

UVES red clump stars that are members of the cluster by $[Fe/H]$ and radial velocity determination [3] are also part of our sample. This helps in choosing the isochrones that best reproduces the position of the red clump. 514 main sequence stars from the same authors with a membership probability greater than 0.5 are also part of our sample. PARSEC models best fit leads to a 316 Myr cluster at a distance of $V_0 - M_V = 11^{m}.47$ (1968 pc), $Z = 0.016$ ($[Fe/H] = -0.01$ dex), $E(b-y) = 0^{m}.29$ and a turn off mass of $3.2 \pm 0.1 M_\odot$. We choose a solar metallicity of $Z_\odot = 0.02$ for the relation between $[Fe/H]$ and Z ($[Fe/H] = log_{10}(Z/Z_\odot)$). Dartmouth models best fit leads to a 250 Myr cluster at a distance of $V_0 - M_V = 11^{m}.50$ (1995 pc), $Z = 0.02$ ($[Fe/H] = 0$ dex), $E(b-y) = 0^{m}.31$ and a turn off mass of $3.4 \pm 0.1 M_\odot$. The latter models take into account the relative abundance of α-elements as a variable, with $[\alpha/Fe] = 0$ dex as the best fit for this cluster. As also seen in [3], an older PARSEC isochrones is needed to fit the red clump position due to the fact that its position in PARSEC isochrones is brighter than in Dartmouth.

The resulting age and reddening agree with those found in [3]: 250-316 Myr old cluster with $E(B-V) = 0^{m}.4$ or equivalently $E(b-y) = 0^{m}.3$. Such consistency also appears in [1] results: 250 Myr old cluster with $E(b-y) = 0^{m}.33 \pm^{m}.03$. Isochrones' fitting derives slightly subsolar metallicities whilst *pf.f* algorithm provide distributions with metallicity: $[Fe/H] = -0.3 \pm 0.3$ dex. Isochrones' result does not take into account neither which estimated error the stellar evolutionary model may carry, nor the degeneracy associated on the isochrones' fit. Besides, published metallicities range from wideband results of [16] catalogue, which uses *blanketing* lines: $[Fe/H] = -0.39$ dex, to the moderate resolution spectroscopic results of [18]: $[Fe/H] = 0.14 \pm 0.09$ dex. In determining the absolute distance modulus, isochrones determine: $11^{m}.5$, and the median of algorithm distribution: $12^{m}.0 \pm 0^{m}.3$. The dispersion in $V_0 - M_V$ distribution (seen in Figs.(3)) does not constrain the result as much as fitting an isochrones, yet it does not have its degeneracy. [3] finds an absolute distance modulus of $11^{m}.45 \pm 0^{m}.2$ and [15] of $11^{m}.55 \pm 0^{m}.1$, from which we are in agreement.

Indices *(b - y)*, c_1 and m_1 are affected by interstellar reddening or selective absorption of light. [4] studied how absorption A_V is dependent on colour excess for the Strömgren system: $A_V \simeq 4.23\ E_{b-y}$, and thus it can be compared to other authors using: $E_{B-V} \simeq 1.34\ E_{b-y}$. In Fig.(5), one can see through both reddening maps that NGC6705 cluster area suffers from differential reddening from mostly dust and gas at less than 11.5 kpc. Emission line maps indicate that the fractal nature of dust is seen only on small scales (see [10]), so discretized data can be interpolated with Gaussians in order to have a continuous distribution. The results are in good agreement with [11] and [3] with the fact that for RA $< 282.8^{o}$ and DEC$> -6.1^{o}$ the cluster is much more reddened ($E(b-y) \approx 0^{m}.5$). It is also consistent with the $E(b-y)$ value found in isochrones' fitting due to the centre of the cluster being mainly affected by $E(b-y) \approx 0^{m}.3$.

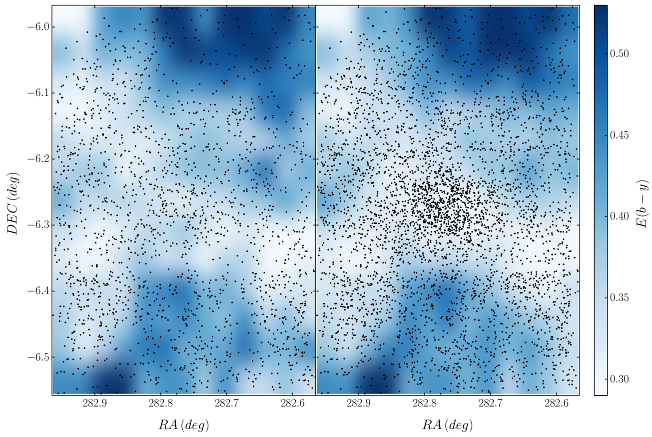

FIG. 5: Reddening maps for cluster NGC6705 with 13x13 bins and a Gaussian interpolator. Each bin has the median colour excess of the stars that fall in it. On the left, the density map for stars closer than the cluster (< 11.5 kpc). On the right, reddening is integrated for all the stars in the line of sight.

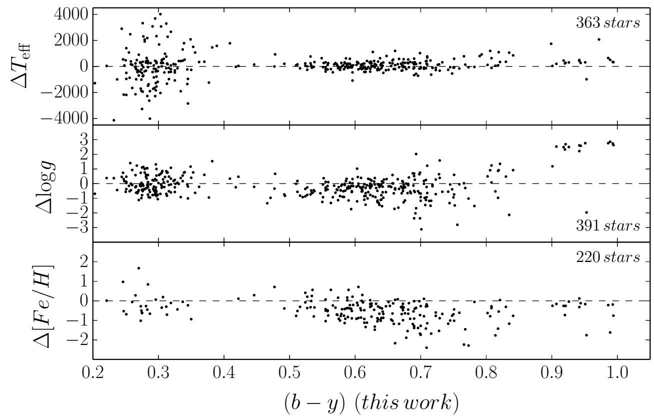

FIG. 6: Differences, in the sense of this work minus GES [6], of $T_{\rm eff}$, log$g$ and $[Fe/H]$.

GES [6] is a spectroscopy survey that uses the FLAMES instrument on VLT (Very Large Telescope, Chile), which provides additional information to Gaia mission about kinematics and chemical abundances of the Milky Way. From its Data Release 2, we obtain the differences represented in Fig.(6). The differences for $T_{\rm eff}$ have a median of approximately 30 K in the sense that GES' temperatures are higher than those from this work. Mean uncertainties for $(b-y) < 0^{m}.4$ are of 270 K for *pf.f* algorithm and 760 K for GES' stars, whilst for $(b-y) > 0^{m}.4$, internal errors are respectively 320 K and 100 K. For $(b-y) < 0^{m}.4$, there is a high dispersion that it is partially understood by large internal errors in GES' sample. log$g$ differences have a median of approximately 0.4 in the sense that GES' log$g$ are higher than those from this work. There is high discrepancy for red giants with a median of 2.5. Mean uncertainties for $(b-y) < 0^{\rm m}.4$ are of 0.18 for *pf.f* algorithm and 0.51 for GES' stars, whilst for $(b-y) > 0^{\rm m}.4$, internal errors are respectively 0.20 and 0.15. As seen with $T_{\rm eff}$, there is high dispersion for $(b-y) < 0^{\rm m}.4$, but GES' uncertainties are large in this range. $[Fe/H]$ differences present a trend with colour in such a manner that our A8-G4 main sequence stars (region 4, see Table I) have less $[Fe/H]$ abundance the more redder they are. This suggest that a revision of $m_1 - [Fe/H]$ calibration is needed.

IV. CONCLUSIONS

Standard Strömgren photometry was obtained for 198 images of our WFC (INT) $uvbyH_\beta$ instrumental photometry. This new photometry adds completeness to the previous survey on NGC6705 and provides a total sample of 63437 stars from which 12137 have all photometric indices. Besides, it is in general agreement with the only Strömgren photometry done on NGC6705 open cluster by [1]. 8617 stars are inside the calibration range of *pf.f* algorithm. These stars provide individual distances and atmospheric parameters that give information about the physical structure and evolutionary state of each star. After a membership study, we obtain 721 stars that are cluster's members and provide the following median values: $V_0 - M = 12^{\rm m}.0 \pm 0^{\rm m}.3$, $E(b-y) = 0^{\rm m}.30 \pm 0^{\rm m}.02$ and $[Fe/H] = -0.3 \pm 0.3$ dex. This method allow us to characterize members that are not only from the clusters' core but also from its extended halo. From PARSEC [2] and Dartmouth [5] isochrones' best fit, average reddening would be $0^{\rm m}.30 \pm 0^{\rm m}.01$, distance modulus $11^{\rm m}.5 \pm 0^{\rm m}.1$ and metallicity -0.1 ± 0.1 dex. Considering both stellar models, cluster's estimated age is of 250-316 Myr with a turn off mass of $3.3 \pm 0.2 {\rm M}_\odot$. With individual $E(b-y)$ values provided by *pf.f* algorithm, we see that NGC6705 suffers from differential reddening that covers part of its halo, but leaves the nucleus of the cluster with a mean value of $E(b-y) = 0^{\rm m}.30 \pm 0^{\rm m}.02$. This cluster has little extinction given its low galactic latitude and location in the inner Galaxy, however the $E(b-y)$ mean value found in this work is in perfect agreement with other authors such as [3] or [1]. The results are also compared with GES to evaluate the quality of $T_{\rm eff}$, log$g$ and $[Fe/H]$ photometric determinations. $[Fe/H]$ disagreement suggests that a revision of $m_1 - [Fe/H]$ calibration is needed.

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