



# Globular Cluster UVIT Legacy Survey (GlobULES) – I. FUV–optical colour–magnitude diagrams for eight globular clusters

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## ABSTRACT

We present the first results of eight globular clusters (GCs) from the *AstroSat/UVIT Legacy Survey* programme GlobULES based on the observations carried out in two far-ultraviolet (FUV) filters ( $F148W$  and  $F169M$ ). The FUV–optical and FUV–FUV colour–magnitude diagrams (CMDs) of GCs with the proper motion membership were constructed by combining the Ultraviolet Imaging Telescope (UVIT) data with *Hubble Space Telescope (HST)* UV Globular Cluster Survey data for inner regions and *Gaia* Early Data Release for regions outside the *HST*’s field. We detect sources as faint as  $F148W \sim 23.5$  mag, which are classified based on their locations in CMDs by overlaying stellar evolutionary models. The CMDs of eight GCs are combined with the previous UVIT studies of three GCs to create stacked FUV–optical CMDs to highlight the features/peculiarities found in the different evolutionary sequences. The FUV ( $F148W$ ) detected stellar populations of 11 GCs comprise 2816 horizontal branch (HB) stars [190 extreme HB (EHB) candidates], 46 post-HB (pHB), 221 blue straggler stars (BSSs), and 107 white dwarf (WD) candidates. We note that the blue HB colour extension obtained from  $F148W - G$  colour and the number of FUV detected EHB candidates are strongly correlated with the maximum internal helium (He) variation within each GC, suggesting that the FUV–optical plane is the most sensitive to He abundance variations in the HB. We discuss the potential science cases that will be addressed using these catalogues including HB morphologies, BSSs, pHB, and WD stars.

**Key words:** techniques: photometric – catalogues – blue stragglers – Hertzsprung–Russell and colour–magnitude diagrams – stars: horizontal branch – white dwarfs – globular clusters: general – ultraviolet: general.

## 1 INTRODUCTION

Globular clusters (GCs) are old roughly spherical agglomerations of stars that harbour a variety of hot and exotic stellar populations such as blue straggler stars (BSSs; Sandage 1953), helium (He) white dwarfs (WDs), cataclysmic variables (CVs; Cool et al. 1995; Cool & Bolton 2002), all of which emit substantially in ultraviolet (UV) regime. Dynamical encounters involving binary stars in the crowded environments of GCs lead to the formation of such exotic systems (Shara & Hurley 2006; Hurley, Aarseth & Shara 2007). Thus, studying them is crucial for understanding the connection between stellar evolution and dynamics (Hut et al. 1992). However, owing to their rarity compared to the total number of stars in the cluster, detecting and characterizing them is not an easy task. These populations have bluer spectral energy distributions (SEDs) than the majority of the main-sequence (MS) and red giant branch (RGB) stars. Also, since they dominantly emit in UV wavelengths,

identifying them from a crowd of MS and RGB stars becomes easier at such wavelengths than in optical (Ferraro et al. 1997, 1999).

Studies have established that far-UV (FUV) observations are crucial for identifying and probing the nature of such UV bright exotic populations in dense environments of GCs (Knigge et al. 2008). Various space missions such as the *Ultraviolet Imaging Telescope (UIT)*, *Hubble Space Telescope (HST)*, and *Galaxy Evolution Explorer (GALEX)* have highlighted the significance of FUV observations of GCs. Using deep FUV photometry and spectroscopic survey of the core of GC 47 Tuc with *HST*, Knigge et al. (2002, 2008) studied 48 blue sources leading to the discovery of exotic objects that include binary companions to WDs and a BSS. Dieball et al. (2005, 2007, 2010, 2017) detected a large number of dynamically formed stellar populations (BSSs, CVs, and WDs) in GCs NGC 2808, M15, M80, and NGC 6397 from FUV–near-UV (NUV) colour–magnitude diagrams (CMDs) using *HST* observations. Thus, FUV CMDs have proved to be a powerful tool for probing the nature of exotic objects. However, the above FUV studies with the *HST* have mostly focused on the dense cores of GCs and not their outer radii.

Several literatures (Dalessandro et al. 2013; Milone et al. 2014; Brown et al. 2016) of horizontal branch (HB) morphologies have

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**Table 1.** Observation details of GCs with the UVIT under GlobULES survey and other previous programmes (marked with \*).

Cluster	RA (h m s) <sup>1</sup>	Dec. (d m s) <sup>1</sup>	Cycle	Observation date	$t_{\text{exp}}$ (s) <sup>2</sup>	
					UVIT/F148W	UVIT/F169M
NGC 362*	01 03 14.26	-70 50 55.6	G06	2016-11-10	4614	3941
NGC 1904 (M79)*	05 24 11.09	-24 31 29.0	A02	2016-11-18	4901	3915
NGC 5272 (M3)*	13 42 11.62	+28 22 38.2	A05	2019-03-08	3000	2883
NGC 5897	15 17 24.50	-21 00 37.0	A04	2018-06-16	13715	-
NGC 6205 (M13)	16 41 41.24	+36 27 35.5	A05	2019-03-13	6657	6657
NGC 6341 (M92)	17 17 07.39	+43 08 09.4	A04	2018-06-30	13726	-
NGC 6809 (M55)	19 39 59.71	-30 57 53.1	A05	2018-10-01	6572	6630
NGC 7099 (M30)	21 40 22.12	-23 10 47.5	A06	2019-09-17	6623	7087

<sup>1</sup>Right ascension and declination (Harris 1996) (2010 edition).<sup>2</sup>Exposure time in UVIT/F148W and UVIT/F169M filters.

shown that the FUV-optical and NUV-optical CMDs are extremely useful in understanding the HB discontinuities and characterizing the He-enhanced sub-populations in GCs. FUV-NUV CMDs were also successfully used in identifying the otherwise optically faint extreme HB (EHB) and blue hook (BHk) candidates with effective temperatures ( $T_{\text{eff}}$ ) > 21 000 and 32 000 K, respectively (Momany et al. 2004). Massive GCs such as NGC 2808, M15, and M80 (Dalessandro et al. 2010; Dieball et al. 2005, 2007, 2010) host a sizeable population of EHB and BHk stars, which form well-separated clumps in FUV-NUV CMDs. However, the number of such stars identified in low-density GCs is small. Identifying and characterizing such EHB stars are important as they are one of the major contenders to explain the ‘UV upturn’ found in elliptical galaxies (Greggio & Renzini 1990; O’Connell 1999). Recent FUV studies extending to extragalactic GCs (Peacock et al. 2018), based on *HST* and *GALEX* observations, indicate that He-enhanced HB and EHB stars might be responsible for the observed excess FUV emission.

Wide-field UV observations are extremely useful for deriving a complete census of luminous and hot post-HB (pHB) stars that evolve away from the HB. They are comprised of asymptotic giant branch manqué (AGBm), post-early AGB (PeAGB), and post-AGB (PAGB) stars. Using *GALEX* observations, Schiavon et al. (2012) provided the catalogue of post-He core burning candidates (AGBm, PeAGB, PAGB) in 44 GCs classified from FUV-NUV CMDs. However, the cluster membership and evolutionary scenarios were not explored in their study. Recently, Moehler et al. (2019) studied the evolutionary phases of 19 reported PAGB stars in 17 GCs and pointed out that a complete sample of UV bright stars in a large number of GCs is required to test stellar evolution theoretical models. In all the above cases, FUV observations are necessary to efficiently detect and characterize the hot and luminous stellar populations, which otherwise suffer from crowding and have large bolometric corrections in the optical.

In the present era, a detailed analysis of UV stellar populations in a large sample of GCs covering the full cluster region in FUV is still lacking. Previous missions dedicated to FUV studies of GCs have some limitations such as (1) *HST*/WFPC2 field of view (FOV) is not large enough to cover the entire GC and its FUV filters suffer from red leak problem (Holtzman et al. 1995), (2) on the other hand, the *UIT* and *GALEX* had a large FOV (40 arcmin and 1°2). However, due to their poor resolution (3 and 5 arcsec, respectively), they are incapable of resolving the FUV sources lying just outside the *HST*’s field. The advantage of the Ultra-Violet Imaging Telescope (UVIT; Subramaniam et al. 2016; Tandon et al. 2017) onboard the Indian space observatory *AstroSat* is its larger FOV (28 arcmin) compared with the *HST*, and higher spatial resolution ( $\sim$ 1.5 arcsec) compared

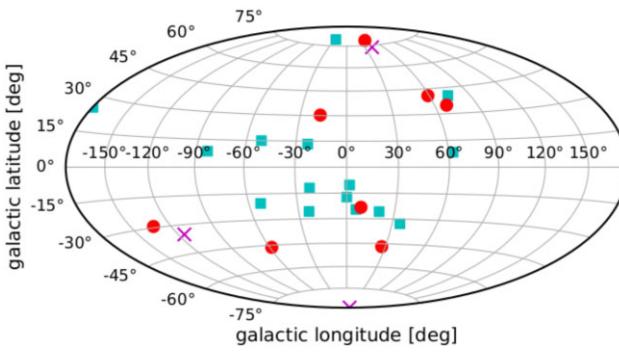
with the *GALEX* and *UIT*. In addition, multiple filters (five) in FUV can help in fine sampling the SEDs of hot stellar populations in GCs. The instrument and photometric calibration details of the UVIT are provided by Tandon et al. (2017).

Several works on GCs with UVIT/FUV filters in the past five years have contributed to our understanding of HB morphologies (Subramaniam et al. 2017; Sahu et al. 2019a; Kumar et al. 2021; Rani et al. 2021a), detection of unusual and rare populations such as pHB stars (Prabhu, Subramaniam & Sahu 2021; Rani et al. 2021b), and the identification of BSSs and EHBs with hot companions (Sahu et al. 2019b; Singh et al. 2020). To further expand our knowledge on UV bright stellar populations in GCs, we have conducted the UVIT legacy survey of GCs using two UVIT/FUV filters – *F148W* and *F169M*. This survey is designated as ‘GlobULES’, an acronym for Globular Cluster UVIT Legacy Survey. Here, we present some initial results from this survey, with the FUV-optical CMDs of eight GCs by combining UVIT/FUV observations with the *HST* UV Globular Cluster Survey (HUGS; Piotto et al. 2015; Nardiello et al. 2018) and *Gaia* Early Data Release 3 (EDR3; Gaia Collaboration et al. 2020; Riello et al. 2020) for the first time. In addition, we have created catalogues of hot stellar populations in these clusters with their membership probabilities. These catalogues will be useful for deriving the physical parameters (luminosities, effective temperatures, etc.) needed to understand the evolution of hot and exotic stellar populations.

The paper is arranged as follows. We describe the GC sample selection, along with the UVIT data reduction in Section 2. The FUV catalogue and CMDs are presented in Section 3. We highlight the important features of the stacked CMDs in Section 4. The discussion of our results and possible science cases are presented in Sections 5 and 6, respectively. We summarize and conclude our study in Section 7.

## 2 GC SAMPLE AND DATA REDUCTION

We present the FUV study of eight clusters in this work for the first time. Out of these, five are observed under the GlobULES survey and three are observed by other individual programmes using the UVIT (see Table 1 for details). The observations were carried out using the *F148W* and *F169M* filters with mean wavelengths ( $\lambda_{\text{mean}}$ ) 1481 and 1608 Å, respectively. The *F148W* is a broad-band FUV filter with  $\Delta\lambda \sim 500$  Å and *F169M* is a medium-band filter with  $\Delta\lambda \sim 290$  Å. Out of eight GCs, six have observations in two FUV filters, whereas two clusters have only *F148W* observations. We have combined this sample with previous UVIT studies of three GCs, NGC 288, NGC 1851, and NGC 5466 (Subramaniam et al. 2017; Sahu et al. 2019a,b) to analyse a total of 11 GCs in this work.



**Figure 1.** Distribution of our GC sample in the galactic plane. The red dots are eight clusters under the GlobULES survey and other individual programmes. The magenta crosses are GCs from our previous studies. The cyan square symbols are upcoming targets of the GlobULES survey.

The distribution of our GC sample in the galactic plane observed under the GlobULES survey, other programmes, and previous UVIT studies is shown in Fig. 1. There are 15 additional GCs scheduled for observations in the coming *AstroSat* cycles. Their analysis will be presented in the forthcoming papers. Overall, the sample consists of 26 GCs (20 GCs from GlobULES) with metallicities in the range  $-2.3 \leq [\text{Fe}/\text{H}] \leq -0.64$  dex and covering both the hemispheres. The sample selection was limited by various mission constraints, such as (i) avoiding observations in the Galactic plane, as the bright sources may harm the UV detectors; (ii) avoiding the GCs lying in the Dec. range  $-10$  to  $+10$  due to RAM angle constraints; and (iii) avoiding the GCs within Galactic latitude  $-30^\circ < b < +30^\circ$ , since they do not have *GALEX* observations. All the clusters in our sample have a central pointing with the UVIT, excluding NGC 1904 (M79). This cluster has an off-centred pointing due to a safe count limit in the FUV ( $\leq 300$  counts per second), set by the UVIT observations during the early observing period.

The Level 1 (L1) data of the sample were downloaded from the ISRO Science Data Archive for *AstroSat*. CCDLAB (Postma & Leahy 2017) was used to generate the science images from L1 data of the UVIT. CCDLAB corrects for the satellite drift, flat-field, distortion, fixed pattern noise, and cosmic rays. The images obtained in different orbits are aligned and combined to get the final deep exposure image of each cluster in both FUV filters. The images have sub-pixel sampling (1/8) with image dimensions  $4096 \times 4096$ . The science-ready images of the eight clusters are shown in Fig. 2. The UVIT was able to resolve most of the clusters except NGC 6341 (M92) and three core-collapsed GCs, NGC 362, NGC 1904 (M79), and NGC 7099 (M30). From the total sample of 11 GCs, the UVIT's FOV covers only six clusters out to their tidal radii.

## 2.1 Photometry

Point spread function (PSF) photometry was performed on the science-ready images using the DAOPHOT package in IRAF (Stetson 1987). PHOT task was used to perform aperture photometry. To plot the curve of growth and apply aperture correction, the magnitudes were obtained at different apertures. The photometry file generated at one aperture ( $\sim$  full width at half-maximum, FWHM) was fed to the PSTSELECT task and isolated stars in the field were chosen for generating a model PSF using the PSF task. The average PSF of the sources in the sample varies from 1.6 to 1.8 arcsec. The model PSF was fitted to all the stars in the aperture photometry file to obtain the fluxes using the ALLSTAR task.

The PSF magnitudes were converted to aperture photometry scale, and aperture correction was applied by choosing isolated bright stars in the field. Finally, the instrumental magnitudes are calibrated to the AB mag system ( $m_{\text{AB}}$ ) (Tandon et al. 2017) using the relation

$$m_{\text{AB}} = -2.5 \log(\text{CPS}) + \text{ZP}, \quad (1)$$

where CPS is the counts per second in the FUV filters and ZP is the zero-point defined as the AB magnitude corresponding to unit conversion (UC) given by

$$\text{ZP} = (-2.5 \log(\text{UC}) \times (\lambda_{\text{mean}})^2) - 2.407. \quad (2)$$

The ZPs of  $F148W$  and  $F169M$  filters are 18.003 and 17.453 mag, respectively (Tandon et al. 2017). The magnitudes obtained in the UVIT filters are corrected for saturation following the steps provided in Tandon et al. (2017). A plot of PSF fit errors (median) as a function of magnitude for eight clusters in the  $F148W$  filter and six in the  $F169M$  is shown in Fig. 3. Mostly, we detect stars up to 22 mag with fit errors less than 0.1 and 0.2 mag in  $F148W$  and  $F169M$  filters, respectively. The number of detected sources with PSF fit errors less than 0.2 along with the magnitude detection limit in the observed filters are provided in Table 2.

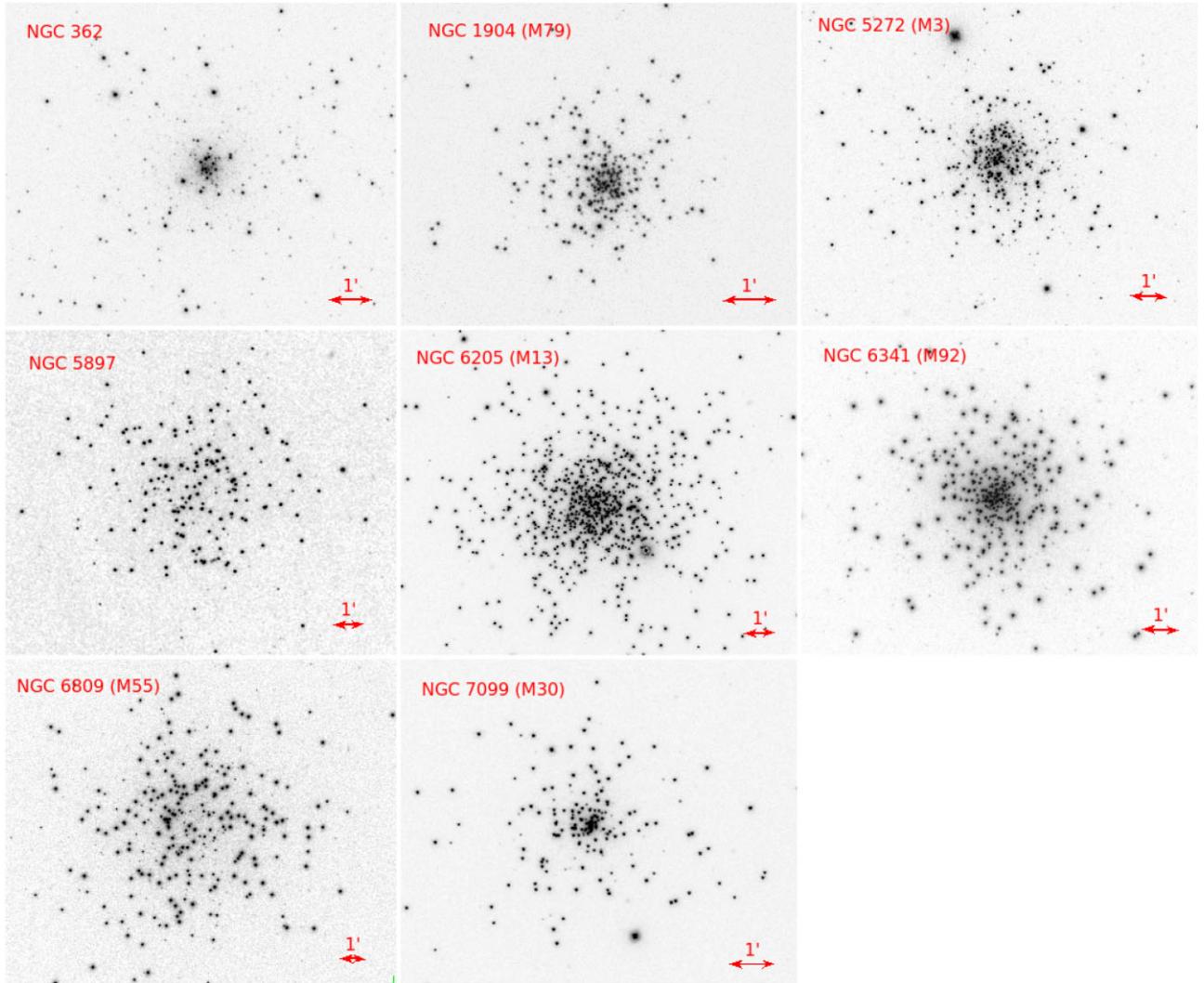
WCS registration of the UVIT images was carried out using the CCMAP task of IRAF. Typical root-mean-square errors for the astrometric calibration of images of seven clusters in  $F148W$  and  $F169M$  filters are  $\sim 0.1$ – $0.2$  arcsec both in RA and Dec. except for NGC 6341 ( $\sim 0.35$  arcsec). The X and Y positions of sources in the images were converted to RA and Dec. coordinates using the WCSCTRAN task of IRAF.

The extinction coefficients  $A_{F148W}$  and  $A_{F169M}$  in  $F148W$  and  $F169M$  filters were calculated to be  $2.64 A_V$  and  $2.56 A_V$ , respectively, using the Fitzpatrick extinction law (Fitzpatrick 1999). Here,  $A_V = R \times E(B - V)$ , where  $E(B - V)$  is the reddening of the cluster considered from Harris (1996) (Table 3). These values agree with the UVIT extinction coefficients by Chen et al. (2019).

## 2.2 Artificial star test

Since the completeness of detected sources (in the fainter magnitude end) is affected by crowding in the cores of GCs, we performed artificial star tests (AST) on the UVIT images to check the completeness of the detected sources at different magnitudes and locations. Sources ( $\leq 30$  per cent of the total detections) with a spatial density distribution similar to that of the cluster were simulated and added to the science image by keeping their magnitudes fixed using the ADDSTAR task of DAOPHOT (Stetson 1987). The model PSF constructed for performing the photometry of real stars is used in the ADDSTAR task. Once the simulated image is generated, photometry was performed adopting the same parameters and methods as used for the real stars in the science image (described in Section 2.1). We considered a star to be recovered in the test when its spatial difference is less than 1.5 arcsec from the added location and its magnitude difference is  $< 0.8$  mag. These steps were repeated by varying the XY positions of the added stars for a fixed magnitude. For checking the completeness, the AST was performed at different magnitudes with the faintest ones reaching the observational detection limit in each filter. Note that the artificial stars are added and recovered at once in the UVIT/FUV images, as crowding is less severe in FUV unlike the NUV and optical images.

To check the variation of completeness with the magnitude at increasing radii from the cluster centre, we divided the clusters into different concentric annuli and calculated the number of recovered artificial stars from photometry with the number of added stars in



**Figure 2.** The UVIT images of GCs NGC 362, NGC 1904, NGC 5272, NGC 5897, NGC 6205, NGC 6341, NGC 6809, and NGC 7099, where black dots correspond to detections in the  $F148W$  filters. North is up and east is left in the images.

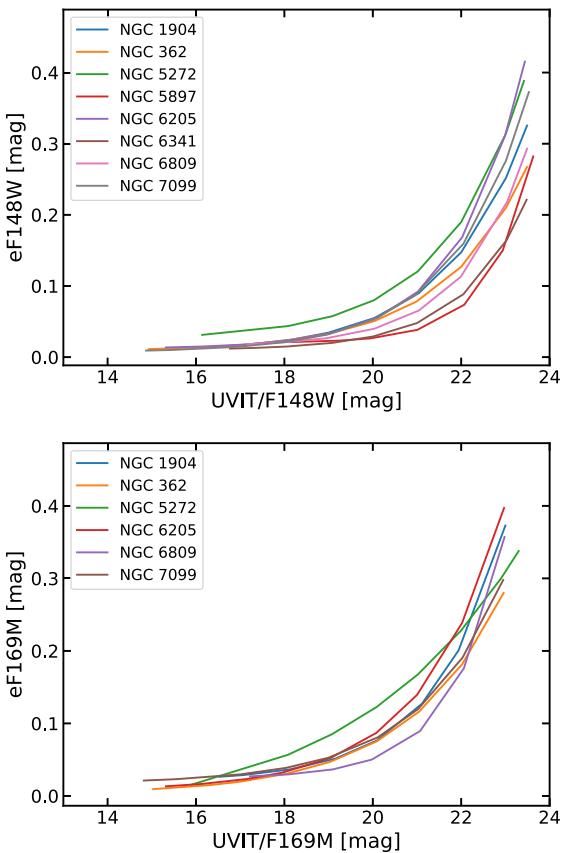
the image at each annulus. For example, the completeness plot of cluster NGC 6341 for  $F148W$  magnitude at different annuli is shown in Fig. 4. We note that the data are 100 per cent complete at 21 mag at all the radial bins. By contrast, the completeness drops to 50 per cent at 24 mag within half-light radius of the cluster ( $r_h \sim 60$  arcsec). The innermost radial bin chosen for this cluster is 20 arcsec, as this cluster is not resolved by UVIT inside that radius.

Using the above method, AST was performed for all the clusters in the sample and completeness was calculated mostly in the three annular regions,  $0 < r < r_c$ ,  $r_c < r < r_h$ , and  $r > r_h$ , where  $r_c$  and  $r_h$  are the core radius and half-light radius of the clusters, respectively (Harris 1996). The completeness plots of these clusters for sources lying inside the core radius and within the core to half-light radius are shown in Fig. A4 (online). We note that the completeness is above 90 per cent for all the sources lying in the regions outside  $r_h$ , and that are brighter than the UVIT magnitude detection limit (Table 2). For sources lying in regions  $r_c < r < r_h$ , the completeness is  $\sim 80\text{--}90$  per cent in clusters NGC 5897, NGC 6205, NGC 6809, and NGC 7099. This reduces to 60–70 per cent in case of NGC 362 and NGC 5272 with comparatively less exposure times than other GCs in the sample. Considering the core regions ( $0 < r < r_c$ )

that are majorly affected by crowding, the completeness drops down to  $\sim 70\text{--}80$  per cent in clusters NGC 5897 and NGC 6809, which further reduces to  $\sim 50$  per cent in NGC 5272 and NGC 6205. The completeness of sources lying within the core radius is not calculated for four clusters (NGC 362, NGC 1904, NGC 6341, and NGC 7099) that are not resolved by UVIT.

### 3 FUV CATALOGUE AND CMDs

To construct the FUV–optical CMDs, we cross-matched the UVIT data with the HUGS data of GCs (Nardiello et al. 2018) for the central regions covering  $202$  arcsec  $\times$   $202$  arcsec. Fig. 5 (left-hand panel) shows the area covered by the *HST* and the UVIT on top of the UVIT/ $F148W$  image of NGC 6341. We note that many UV bright stars lie outside the FOV of the *HST*. To complete the coverage of outer regions, we cross-matched the UVIT data with *Gaia* EDR3 and estimated their proper motion (PM) membership probabilities as described below. The *HST* data used in the catalogue have PM accuracy of about  $0.6$  mas yr $^{-1}$ , with a time baseline of  $7\text{--}9$  yr (Soto et al. 2017). For comparison, the PM uncertainty for *Gaia* EDR3 is around  $1.4$  mas yr $^{-1}$  at  $G = 21$  mag.



**Figure 3.** The PSF fitting errors (median) of the magnitudes obtained from PSF photometry for eight clusters in the  $F148W$  filter (top panel) and six clusters in the  $F169M$  filter (bottom panel).

**Table 2.** Photometry details of GCs observed with the UVIT under Glob-ULeS survey and other programmes.

Cluster	$r_c$ <sup>1</sup>	$r_h$ <sup>1</sup>	$N_{F148W}$ <sup>2</sup>		$N_{F169M}$ <sup>2</sup>		Magnitude limit <sup>3</sup>
			$\sigma < 0.2$	$F148W$	$\sigma < 0.2$	$F169M$	
NGC 362*	0.18	0.82	606	400	23.5	23	
NGC 1904*	0.16	0.65	280	244	22	21.5	
NGC 5272	0.37	2.31	456	366	23.5	23	
NGC 5897	1.4	2.06	213	–	22	–	
NGC 6205	0.62	1.69	882	856	22	21.5	
NGC 6341*	0.26	1.02	493	–	23.5	–	
NGC 6809	1.8	2.83	424	364	23	22	
NGC 7099*	0.06	1.03	248	240	23	22.5	

<sup>1</sup>Core radius ( $r_c$ ) and half-light radius ( $r_h$ ) in arcmin from Harris (1996) (2010 edition).

<sup>2</sup>Number of stars detected in the  $F148W$  and  $F169M$  filters with fit errors  $< 0.2$ .

<sup>3</sup>The UVIT detection limit (AB mag).

\*Cores of these GCs are not resolved by the UVIT.

We used TOPCAT (Taylor 2005) to cross-match the positions (RA and Dec.) of sources detected in the UVIT filters with the *HST* and *Gaia* EDR3 with a maximum separation of 2 arcsec, which is the typical FWHM of the PSF for the UVIT filters. However, a majority of the cross-matched sources ( $> 90$  per cent) have match radii of  $< 1$  arcsec (Fig. A3).

### 3.1 UVIT-HST data

We used the HUGS catalogues (Nardiello et al. 2018) from method-1 photometry, which gives good measurements for sources with  $F275W < 23$  mag to cross-match all the FUV stars detected with the UVIT. The catalogues also provide PM membership probabilities ( $P_\mu$ ). We have considered sources with  $P_\mu \geq 70$  per cent for analysis. However, most of the UVIT-HST cross-matched sources ( $\sim 96$  per cent) have  $P_\mu \geq 90$  per cent. Since NGC 1904 was not included in the HUGS programme, we used the data provided by Lanzoni et al. (2007) for cross-matching with the UVIT. This cluster has observations in  $F160B$ ,  $F218W$ ,  $F336W$ ,  $F439W$ , and  $F555W$  filters of *HST*-WFPC2. However, the  $P_\mu$  of this cluster is not available.

As the *HST* has a higher resolution ( $< 0.1$  arcsec) compared with the UVIT, their direct cross-matching for the cluster members may lead to incorrect matches. Since most stars bluer than MS and RGB stars are hot enough to emit in the FUV wavelengths, we have excluded MS, SGB, RGB, and AGB stars from the cross-match to reduce the crowding effects, and selected the rest of the sources from the  $F275W$  versus  $F275W - F336W$  CMD plane. In addition, we also did a visual inspection with eye to make sure that the cross-matched sources are unique. The *HST* CMD of NGC 6341 is shown in the middle panel of Fig. 5, where the UVIT-HST common detections are marked in red. The membership probabilities of WDs are unavailable in the *HST* catalogues, so we relied on the  $F275W$  versus  $F275W - F336W$  plane for their selection as they form a well-defined sequence and show FUV emission (Fig. 5).

### 3.2 UVIT-Gaia EDR3 data

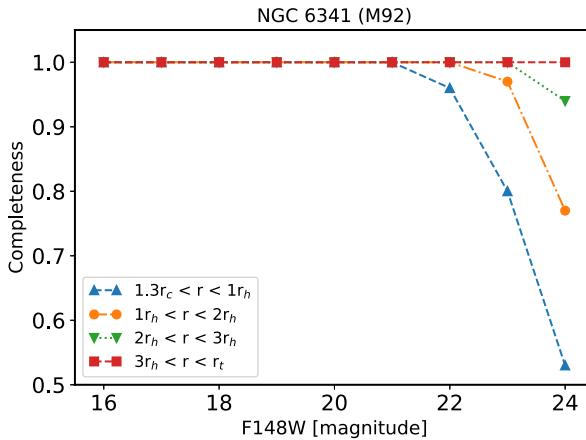
To select probable cluster members using *Gaia* PM data, we initially used the mean PMs of clusters from Gaia Collaboration et al. (2018). We considered the sources out to the tidal radius of the cluster for  $P_\mu$  determination. The vector point diagram (VPD) and the respective *Gaia* CMD of NGC 6341 are shown, as an example, in the left-hand panel of Fig. 6. The VPDs of the rest of the clusters are shown in Fig. A1 (online). The VPD selection criteria adopted for each GC show a clear separation of the probable cluster members from the field members. To find the centre of the elliptical distribution, we rotated the semimajor axis of the elliptical distribution to the normal elliptical distribution along their respective centre. Then, we obtained the mean and standard deviation of PMs for each GC from their histograms and Gaussian fits. The probable cluster members selected from the VPD show an elliptical distribution for most of the clusters. This distribution is possibly due to systematics in the PM, arising from the non-uniform sampling of the sky produced by the *Gaia* scanning law (Fabricius et al. 2021). Although *Gaia* EDR3 has significantly improved the systematics by a factor of 2.5 in comparison to *Gaia* DR2, they are still present. In order to reduce the effect of systematics, we considered stars with  $nal > 120$  and  $nper > 8$ , where  $nal$  is the total number of observations and  $nper$  is the number of visibility periods used in the astrometric solution (Kim et al. 2019).

To estimate  $P_\mu$ , we used the method of Balaguer-Núñez, Tian & Zhao (1998). We first estimate the frequency distribution of cluster stars ( $\phi_c^v$ ) and field stars ( $\phi_f^v$ ). The frequency distribution function for the  $i$ th star of a cluster and the field can be given as follows:

$$\phi_c^v = \frac{1}{2\pi\sqrt{(\sigma_{xc}^2 + \epsilon_{xi}^2)(\sigma_{yc}^2 + \epsilon_{yi}^2)}} \times \exp \left\{ -\frac{1}{2} \left[ \frac{(\mu_{xi} - \mu_{xc})^2}{\sigma_{xc}^2 + \epsilon_{xi}^2} + \frac{(\mu_{yi} - \mu_{yc})^2}{\sigma_{yc}^2 + \epsilon_{yi}^2} \right] \right\}, \quad (3)$$

**Table 3.** List of model parameters of the studied clusters.

Cluster	$E(B - V)$ <sup>1</sup>	(m-M) <sub>V</sub> <sup>2</sup>	PGPUC ([α/Fe] = 0.3) <sup>3</sup>			BaSTI ([α/Fe] = 0.4) <sup>4</sup>		
			[Fe/H]	Z	Y	[Fe/H]	Z	Y
NGC 288	0.03	14.84	-1.32	1.39E-3	0.245	-1.3	1.57E-3	0.249
NGC 362	0.05	14.83	-1.26	1.6E-3	0.245	-1.3	1.57E-3	0.249
NGC 1851	0.02	15.47	-1.18	1.92E-3	0.245	-1.2	1.97E-3	0.249
NGC 1904	0.01	15.59	-1.6	7.3E-4	0.245	-1.55	8.86E-4	0.248
NGC 5272	0.01	15.07	-1.5	9.2E-4	0.245	-1.55	8.86E-4	0.248
NGC 5466	0.00	16.02	-1.98	3.1E-4	0.245	-2.2	1.98E-4	0.247
NGC 5897	0.09	15.76	-1.9	3.7E-4	0.245	-1.9	3.97E-4	0.247
NGC 6205	0.02	14.33	-1.53	8.6E-4	0.245	-1.55	8.86E-4	0.248
NGC 6341	0.02	14.65	-2.31	1.4E-4	0.245	-2.2	1.98E-4	0.247
NGC 6809	0.08	13.89	-1.94	3.4E-4	0.245	-1.9	3.97E-4	0.247
NGC 7099	0.03	14.64	-2.27	1.6E-4	0.245	-2.2	1.98E-4	0.247

<sup>1</sup>Reddening (Harris 1996) (2010 edition)<sup>2</sup>Apparent visual distance modulus (Harris 1996) (2010 edition)<sup>3</sup>PGPUC model parameters [Fe/H], Z, and Y (Valcarce, Catelan & Sweigart 2012).<sup>4</sup>BaSTI model parameters [Fe/H], Z, and Y (Pietrinferni et al. 2020).**Figure 4.** Completeness of NGC 6341 as a function of  $F148W$  magnitude for different radial bins as marked in the figure where  $r_c$ ,  $r_h$ , and  $r_t$  are the core radius, half-light radius, and tidal radius of the cluster, respectively (Harris 1996).

$$\phi_f^v = \frac{1}{2\pi\sqrt{(1-\gamma^2)\sqrt{(\sigma_{xf}^2 + \epsilon_{xi}^2)(\sigma_{yf}^2 + \epsilon_{yi}^2)}}} \times \exp\left\{-\frac{1}{2(1-\gamma^2)}\left[\frac{(\mu_{xi} - \mu_{xf})^2}{\sigma_{xf}^2 + \epsilon_{xi}^2} + \frac{(\mu_{yi} - \mu_{yf})^2}{\sigma_{yf}^2 + \epsilon_{yi}^2}\right]\right\}, \quad (4)$$

where  $\mu_{xi}$  and  $\mu_{yi}$  denote the PMs of the  $i$ th star. The  $\mu_{xc}$  and  $\mu_{yc}$  represent the cluster's PM centre,  $\mu_{xf}$  and  $\mu_{yf}$  represent the field PM centre,  $\epsilon_{xi}$  and  $\epsilon_{yi}$  are the observed errors in PM components,  $\sigma_{xc}$  and  $\sigma_{yc}$  denote the cluster intrinsic PM dispersion, while  $\sigma_{xf}$  and  $\sigma_{yf}$  denote the field intrinsic PM dispersion, and  $\gamma$  is the correlation coefficient.

The value of  $\gamma$  can be estimated as

$$\gamma = \frac{(\mu_{xi} - \mu_{xf})(\mu_{yi} - \mu_{yf})}{\sigma_{xf}\sigma_{yf}}. \quad (5)$$

For the distribution function  $\phi_c^v$  and  $\phi_f^v$ , we considered the stars with PM error better than 1 mas yr<sup>-1</sup>.

To obtain the distribution of stars, we use

$$\phi = n_c\phi_c^v + n_f\phi_f^v, \quad (6)$$

where  $n_c$  and  $n_f$  are the normalized number of stars found for cluster and field ( $n_c + n_f = 1$ ). Hence, the membership probability for the  $i$ th star is given by

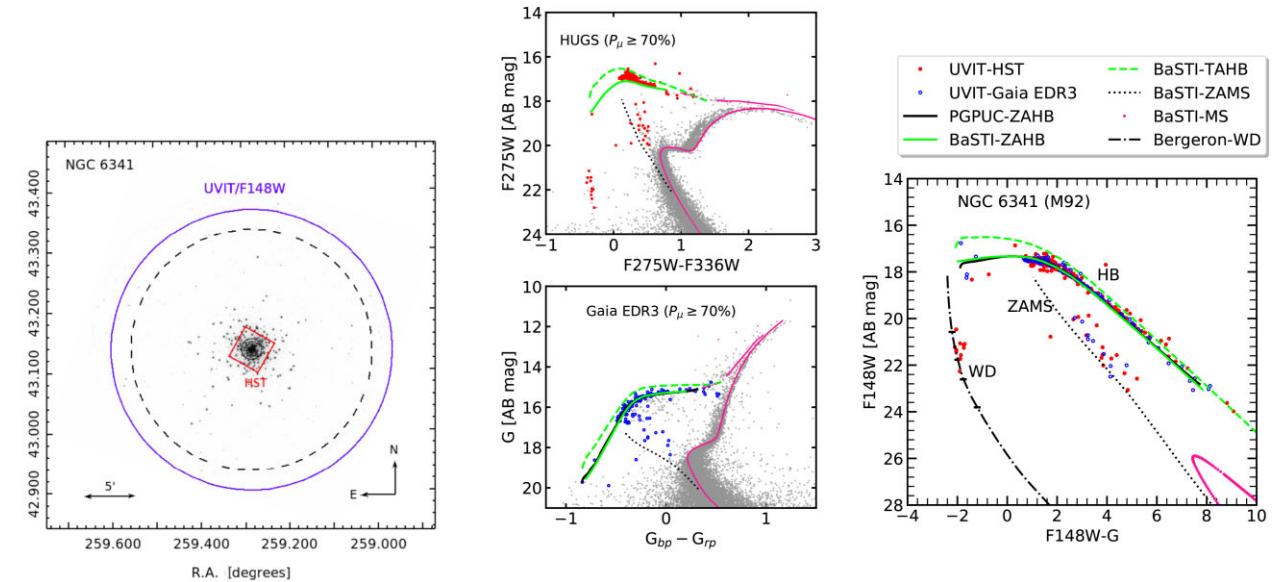
$$P^\mu(i) = \frac{\phi_c(i)}{\phi(i)}. \quad (7)$$

In the *Gaia* EDR3 catalogue, all sources have been treated like single stars, i.e. in the case of binary and multiple stellar systems, the astrometry is obtained for either component or from the photocentre of the binary/multiple systems. For a binary located at a distance,  $d \approx 500$  pc, the predicted deviation for an angular separation of 1 arcsec is of the order of μas, well below the sensitivity of *Gaia* EDR3 (El-Badry, Rix & Heintz 2021). Since GCs are located at a much farther distance, therefore, the uncertainty due to consideration of single stars would have a negligible effect on the membership determination.

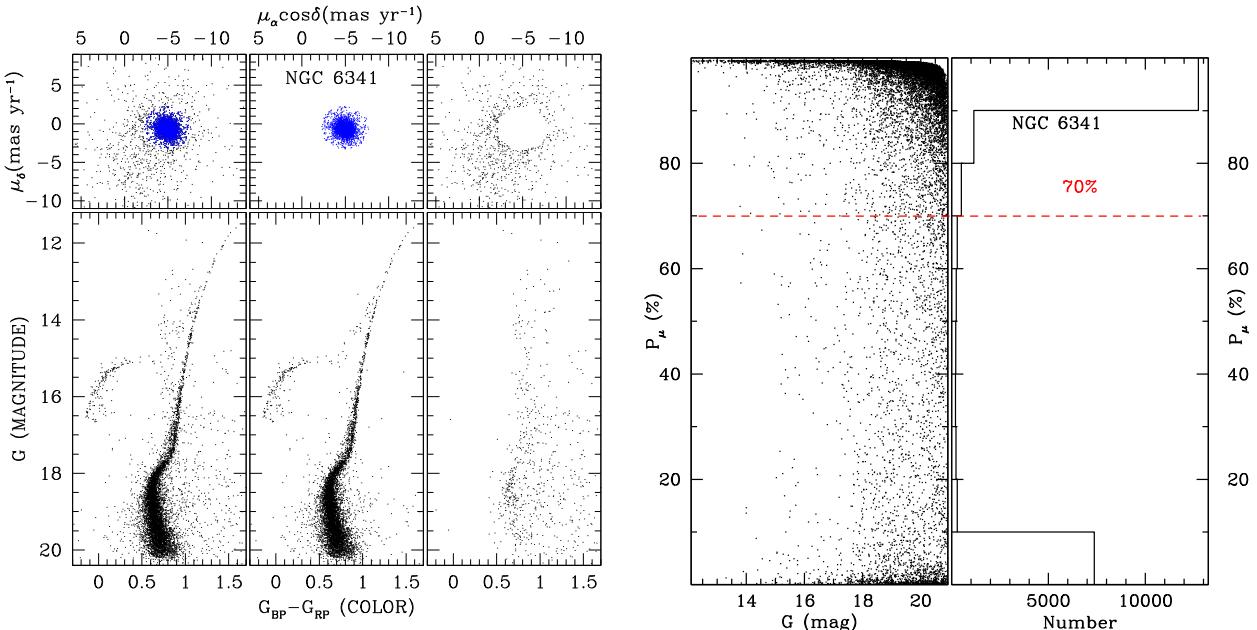
To include the fainter members of the clusters having a larger error in PM, we selected sources with a probability above 70 per cent. The right-hand panel of Fig. 6 shows the distribution of  $P_\mu$  with respect to  $G$  magnitude. From this figure, we notice that most of the stars in NGC 6341 have  $P_\mu > 70$  per cent.

We further note that almost all the UVIT-*Gaia* cross-matched sources have  $P_\mu > 70$  per cent, except in a few clusters. In six clusters, 13 stars lie in the range 30 per cent  $< P_\mu < 70$  per cent. In NGC 6205 (M13), 28 stars in the UVIT-*Gaia* EDR3 catalogue have  $P_\mu < 50$  per cent, and 7 do not have PM measurements. A comparison of this cluster data with the recently published PM catalogue of GCs from *Gaia* EDR3 (Vasiliev & Baumgardt 2021) shows that 11 of these stars have  $P_\mu > 50$  per cent but are of the lowest quality flag. Since these stars with bluer colour ( $G_{bp} - G_{rp} < 0.6$ ) are located in the high-density regions ( $< 2r_h$ ), the PM measurements might not be reliable. However, these stars mostly lying at the bluer end of the HB region (near EHB and pHB) are bright in FUV; hence, we have included them in the NGC 6205 catalogue.

We were unable to select the WD sequence as it is fainter than the magnitude limit of *Gaia* EDR3 ( $G \sim 21$  mag). We checked the expected  $G$  magnitudes for the brightest WDs in our sample from the cooling models and found that they lie at around  $G \sim 21$ –22 mag, which is near or just below the *Gaia* detection limit. In addition,



**Figure 5.** Left-hand panel: map of the UVIT (blue) and *HST* (red) FOVs plotted over the  $F148W$  filter image of NGC 6341. The cluster half-light (1.02 arcmin) and tidal radii (12.4 arcmin) are shown in black solid and dashed lines, respectively. Middle upper panel:  $F275W$ ,  $F275W - F336W$  CMD of NGC 6341 from the HUGS survey where the UVIT-*HST* common detections are shown in red dots. Middle lower panel:  $(G, G_{bp} - G_{rp})$  CMD from *Gaia* EDR3 where blue open circles are UVIT-*Gaia* common detections. Right-hand panel:  $(F148W, F148W - G/F606W)$  CMD overplotted with stellar evolutionary models.



**Figure 6.** Left-hand panel: VPD of NGC 6341 where blue dots are the sources selected for PM membership analysis, and black dots are the field stars. The stars with good astrometric measurements, i.e. with  $n_{per} > 8$  and  $n_{al} > 120$ , are used to obtain the mean and standard deviation of the cluster distribution. Right-hand panel:  $P_\mu$  with respect to the histogram of the number of stars and  $G$  magnitude in the y-axis. The red dashed line marks the stars where most of the cluster members lie with  $P_\mu > 70$  per cent.

since the WDs located in the outer regions of the clusters are affected more by background sources as compared to the core regions, their membership determination is extremely important to identify them. However, due to their fainter  $G$  magnitudes, their PM information is either unavailable or not reliable. The UVIT and *Gaia* common detections are shown in blue in the middle panel of Fig. 5.

In order to plot the FUV-optical CMD of the entire cluster region in a similar plane, we have transformed the *HST* filter

to  $G$  band of *Gaia* EDR3 by using the following relation (Fig. A2):

$$y = 0.01 + 0.05x - 0.11x^2, \quad (8)$$

where  $y = (G - F606W)$  and  $x = (F606W - F814W)$ . The stars used for deriving the relationship cover the entire HB colour range, from RHB to EHB stars, and with good astrometric measurements.

The FUV–optical CMD of NGC 6341 after transforming the *HST* to *Gaia* plane is shown in the rightmost panel of Fig. 5, where the UVIT–*HST* common detections are marked in red and the UVIT–*Gaia* in blue. Thus, the complete CMD includes HB, BSS, and WD detected from inner regions (the UVIT–*HST* cross-matched stars), and HB and BSS from the outer regions (the UVIT–*Gaia* EDR3 cross-matched stars).

### 3.3 Stellar models

The HB, BSS, WDs, etc. are most prominently observed in the FUV–optical and FUV–FUV CMDs. We used various stellar evolutionary models to identify and classify their sequences. Reddening and distance modulus of individual clusters from Harris (1996) (2010 edition) were adopted in the models to fit the observed CMDs. As an example, the rightmost panel of Fig. 5 shows an overplot of all the models described below for the FUV–optical CMD of NGC 6341.

(i) *PGPUC HB models*: We generated zero-age HB (ZAHB) loci using the Princeton-Goddard-PUC (PGPUC) stellar evolution code for the UVIT filters (Valcarce et al. 2012).<sup>1</sup> This code is an updated version of the original Princeton code by Schwarzschild & Härm (1965). The physics incorporated in the code are described in detail in Valcarce et al. (2012). The ZAHB models are created for an  $\alpha$ -element enhancement value  $[\alpha/\text{Fe}]$  of 0.3 and initial He abundance ( $Y_{\text{ini}}$ ) of 0.245 (Cassisi, Salaris & Irwin 2003) where atomic diffusion is also taken into account. This is typical  $[\alpha/\text{Fe}]$  value found in GCs (Dias et al. 2016).

(ii) *BaSTI-IAC models*: We generated the ZAHB and terminal-age HB (TAHB) evolutionary tracks for the UVIT and *Gaia* EDR3 filters from an updated BaSTI-IAC online data base (Hidalgo et al. 2018; Pietrinferni et al. 2020).<sup>2</sup> We considered  $\alpha$ -enhanced models with  $[\alpha/\text{Fe}] = 0.3$ ,  $Y_{\text{ini}} \sim 0.247$ , mass-loss parameter  $\eta = 0.3$ . Atomic diffusion is not included. The BaSTI ZAHB and TAHB models that correspond to core-He exhaustion are shown in the rightmost panel of Fig. 5.

In the case of BSSs, we used the zero-age MS (ZAMS) isochrones of 0.5 Gyr generated from BaSTI-IAC models for the UVIT and *Gaia* EDR3 filters for reference to show the extended ZAMS, by keeping the model's parameters fixed as that chosen for the HB tracks. The model parameters chosen cover the mass range from MSTO of GCs ( $\sim 0.8 M_{\odot}$ ) to twice its mass at MSTO. This range approximately corresponds to the expected locations of BSSs according to their distribution in the CMDs of several GCs (Ferraro et al. 2003; Raso et al. 2017). The 0.5 Gyr isochrone corresponding to  $[\text{Fe}/\text{H}] = -2.2$  dex and model mass range of  $0.8\text{--}1.6 M_{\odot}$  is shown in the rightmost panel of Fig. 5. The BSS sequence extends more than 4 mag in FUV–optical CMDs.

(iii) *WD cooling models*: DA spectral type WD models (Bergeron, Wesemael & Beauchamp 1995; Tremblay, Bergeron & Gianninas 2011; Bédard et al. 2020) of mass  $0.5 M_{\odot}$  (Renzini & Fusi Pecci 1988; Richer et al. 1997; Moehler et al. 2004) with pure hydrogen (H) grid and thick H layers are kindly provided and transformed into UVIT filter systems by Pierre Bergeron *Gaia* DR2.<sup>3</sup> The models are shown in black dash-dotted lines in the CMDs.

We note that the ZAHB, BSSs, and WD stars appear well matched with the locations predicted by stellar models.

The model parameters adopted for the studied clusters are given in Table 3. The metallicities in PGPUC models are interpolated to the exact values provided by Harris (1996) (2010 edition), whereas for BaSTI-IAC models, the values are chosen close to the cluster metallicities as reported by Harris (1996) (2010 edition).

### 3.4 Classification of FUV sources

For the UVIT–*HST* cross-matched data, we plotted the matched stars in the  $F275W$  versus  $F275W - F336W$  plane, whereas for the UVIT–*Gaia* cases, these were plotted in the  $G$  versus  $G_{bp} - G_{rp}$  plane. Their locations were simultaneously checked in the FUV–optical CMDs and classifications were assigned. The classified HB, BSS, and WD stars from the FUV–optical CMDs lie at locations as predicted by their respective models. The stars that lie near or above the TAHB sequence, and are bluer than  $F148W - G = 2$  mag, were classified as pHB stars..

To select EHB stars, we estimated the temperatures of the HB stars using the  $F148W - G$  versus  $T_{\text{eff}}$  relation from the PGPUC models. Those HB stars with  $T_{\text{eff}} > 23\,000$  K were classified as candidate EHB stars.

The numbers of BSSs, HBs, pHBs, and WDs detected are listed in Table 5. We compared the number of detected HB stars in the UVIT/F148W with those selected for cross-match from the *HST* and *Gaia* CMDs. We found the HB detections to be  $> 90$  per cent after cross-match for seven clusters except for NGC 5272 (M3), and three dense clusters NGC 362, NGC 1851, and NGC 1904. As M3 has a shorter exposure time compared with other clusters in our survey, we recover 73 per cent of the HB stars in the UVIT/F148W after cross-matching. To check for the variables detected in FUV, we cross-matched the UVIT data with the catalogue of variable stars in GCs by Clement et al. (2001). The numbers of FUV detected variables of 11 clusters are given in Table 5, where the classification is according to Clement et al. (2001). The probable FUV counterparts to the known X-ray sources in GCs (which includes CVs and other X-ray binaries) and their SEDs will be studied in our forthcoming work.

The final catalogue consists of cluster name, UVIT ID, RA, Dec., magnitudes, and errors in their respective  $F148W$  and  $F169M$  filters,  $G$  magnitudes from *Gaia* EDR3 data and *HST* transformed filters, membership probability, and their classification, as shown in Table 4. The full catalogues of three clusters NGC 288, NGC 1851, and NGC 5466 will be made available online through Vizier catalogue service. The catalogues of rest of the clusters will be released to the community in the future as they are being analysed for science cases discussed in Section 6.

### 3.5 FUV–optical CMDs

Here, we describe the PM cleaned FUV–optical CMDs of 11 GCs, out of which 8 are reported for the first time from the UVIT observations, whereas 3 are already studied earlier (Subramaniam et al. 2017; Sahu et al. 2019a,b). The  $F148W$  versus  $F148W - G$  CMDs of 11 GCs are shown in Fig. 7. Among our studied sample, we detect an extended HB comprising the largest number of HB and EHBs (165) in NGC 6205 with  $T_{\text{eff}}$  ranging from 22 000 to 33 000 K. We detect the second largest population of HB stars in NGC 5272 with  $T_{\text{eff}}$  between 6500 and 28 500 K. This cluster also contains the largest number of FUV bright BSSs (35), whereas NGC 6205 contains the least (10). We found the largest population of pHBs in NGC 6205 spanning 1–2 mag above the ZAHB in FUV–optical CMD. NGC 362 contains the largest population of WDs (24), with the brightest WDs

<sup>1</sup><http://www2.astro.puc.cl/pgpuc/>

<sup>2</sup><http://basti-iac.oa-abruzzo.inaf.it/hbmodels.html>

<sup>3</sup><http://www.astro.umontreal.ca/~bergeron/CoolingModels>

**Table 5.** Total number of sources detected by cross-matching the UVIT with the *HST* and *Gaia* EDR3 data along with their classification.

Cluster	UVIT/F148W - <i>HST</i>						UVIT/F148W - <i>Gaia</i> EDR3						Variables*						UVIT/F148W - UVIT/F169M	
	WD	HB	BSS	pHB	HB	BSS	pHB	HB	BSS	pHB	EHB	RRL	SX Phe	E	HST	<i>Gaia</i> EDR3				
NGC 288	12	42	17	—	90	14	—	132	31	—	3	1	5	—	—	57	97			
NGC 362	25	88	24	3	23	4	—	111	28	3	—	22	—	—	—	—	104	10		
NGC 1851	7	116	4	1	58	3	—	174	7	1	2	19	—	—	—	—	119	53		
NGC 1904	1	148	3	9	53	3	—	201	6	9	4	5	—	—	—	—	154	53		
NGC 5272	20	233	18	—	165	17	3	398	35	3*	5	147	5	—	—	209	138			
NGC 5466	5	31	14	1	56	11	—	87	25	1	—	18	2	2	2	45	63			
NGC 5897	1	71	3	1	108	6	1	179	9	2	3	9	—	—	—	—	—	—		
NGC 6205	14	368	6	10	384	4	17	752	10	27	165	7	2	—	—	385	400			
NGC 6341	11	219	15	—	136	9	—	355	24	—	5	15	2	—	—	—	—	—		
NGC 6809	4	61	13	—	190	15	—	251	28	—	2	10	16	1	1	77	202			
NGC 7099	7	104	17	—	72	1	—	176	18	—	1	4	2	1	1	119	69			

\*Total number of variables detected by cross-matching the UVIT-*HST* and the UVIT-*Gaia* EDR3 sources with Clement et al. (2001). RRL stands for RR Lyrae, SX Phe for SX Phoenicis, and E for eclipsing binaries.**Table 4.** UVIT catalogue of three clusters NGC 288, NGC 1851, and NGC 5466 where first three rows of each cluster are shown for reference. The full table will be made available online through the Vizier catalogue access tool.

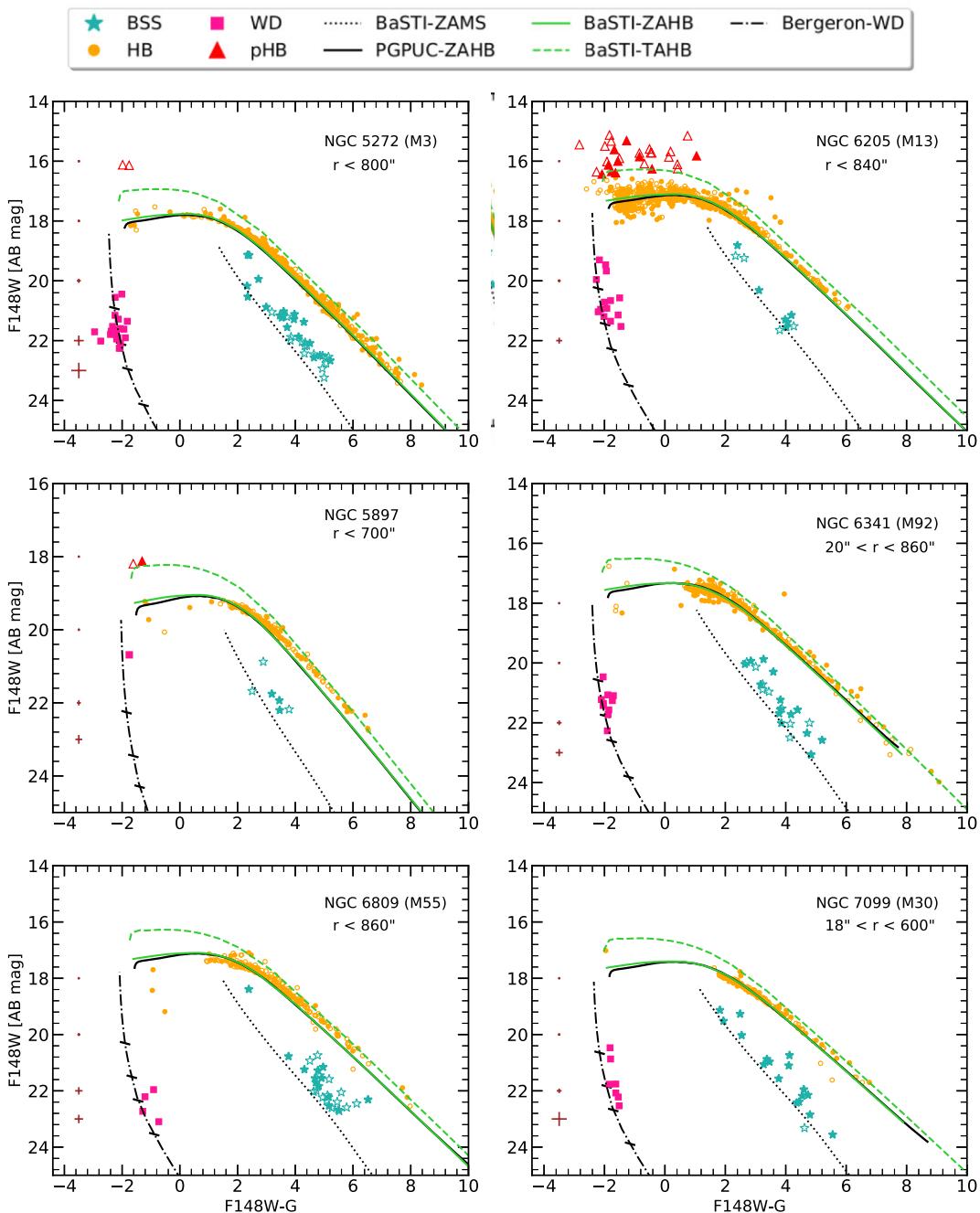
Cluster	UVIT_ID	RA (°)	Dec. (°)	F148W	eF148W	F169M	eF169M	G <sup>1</sup>	mem_prob <sup>2</sup>	unique_ID <sup>3</sup>	Classification	Cross-match data
NGC 1851	UV18510001	78.509010	-40.065076	18.472	0.025	18.359	0.035	17.095	97.9	R0000775	HB	HST
NGC 1851	UV18510002	78.501673	-40.061816	19.809	0.047	19.541	0.062	16.307	97.7	R0001235	HB	HST
NGC 1851	UV18510003	78.520213	-40.064029	21.039	0.116	—	—	16.199	96.4	R0000896	HB	HST
NGC 288	UV2880001	13.197465	-26.549876	18.1	0.019	17.915	0.028	16.063	95.3	R0001732	HB	HST
NGC 288	UV2880002	13.202455	-26.554893	17.601	0.023	17.533	0.023	17.312	96.8	R0001666	HB	HST
NGC 288	UV2880003	13.197637	-26.554042	20.191	0.061	19.719	0.057	15.42	97.3	R0001681	HB	HST
NGC 5466	UV54660001	211.3581	28.55536	20.652	0.102	20.267	0.066	16.74	96.9	R0001393	HB	HST
NGC 5466	UV54660002	211.3822	28.54057	21.376	0.154	21.43	0.114	23.534	-1.0	R0021345	WD	HST
NGC 5466	UV54660003	211.3753	28.544	22.37	0.207	22.432	0.192	18.618	96.8	R0001100	BSS	HST

<sup>1</sup> G mag in AB system from *Gaia* EDR3 data (Gaia Collaboration et al. 2020) for UVIT-*Gaia* sources, whereas transformed from *HST* filters for UVIT-*HST* sources (refer equation 8).<sup>2</sup> Membership probability from the HUGS survey (Nardiello et al. 2018) for UVIT-*HST* sources, whereas derived in this work for UVIT-*Gaia* EDR3 sources (refer Section 3.2).<sup>3</sup> Unique ID corresponding to the column name *ID\_number* from the HUGS catalogue (Nardiello et al. 2018) for UVIT-*HST* sources, and *source\_id* from *Gaia* EDR3 data for UVIT-*Gaia* sources.

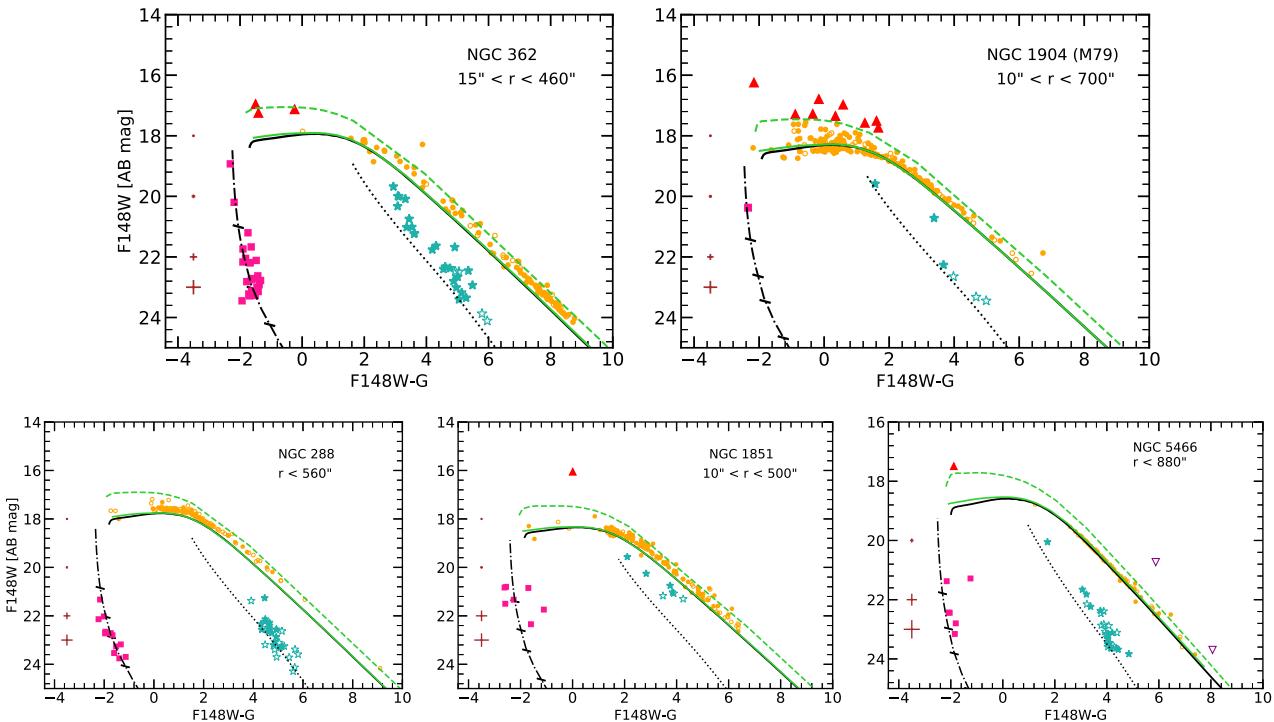
with temperatures of 90 000 K, whereas the faintest ones have  $T_{\text{eff}} \sim 30 000$  K as inferred from the WD cooling curves.

We also show the  $F148W$  versus  $F148W - F169M$  CMD of NGC 6205 as an example in Fig. 8. In only FUV CMD, the EHB stars deviate from the usual BHB distribution and turn fainter obeying the ZAHB models. We notice 1 mag dip in the  $F148W$  magnitude of HB distribution beyond  $(F148W - F169M, T_{\text{eff}}) \sim (0.02, 14 400)$  K from the ZAHB models. The models also indicate that EHBs become fainter in  $F148W$  mag at colour  $(F148W - F169M) \sim -0.05$

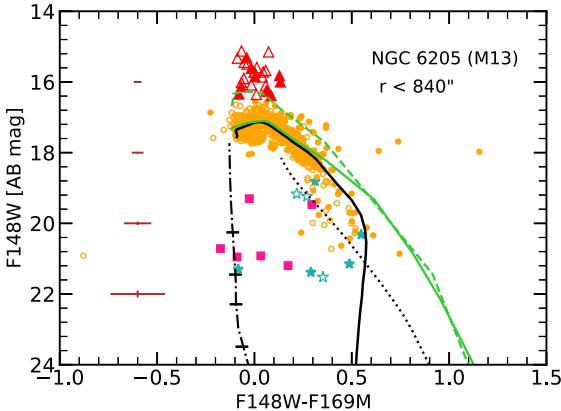
corresponding to a  $T_{\text{eff}}$  range of 30 000–34 000 K. This is roughly the region where the BHk candidates lie. We note that the ZAHB models of PGPUC and BaSTI are not in agreement for HB stars with  $F148W - F169M > 0.25$  corresponding to  $T_{\text{eff}} < 8000$  K. From the figure, it is evident that the PGPUC models agree well with the observed HB distribution (Fig. 8) as compared with the BaSTI models. However, the deviation of BaSTI models is within the  $3\sigma$  photometric errors at the fainter end of the HB distribution. For detailed description of individual cluster CMDs, we refer the readers to Appendix B (online).



**Figure 7.**  $F148W$  versus  $F148W - G$  CMDs of NGC 5272, NGC 6205, NGC 5897, NGC 6341, NGC 6809, and NGC 7099 (from top to bottom). The filled and open symbols denote the UVIT-HST and the UVIT-Gaia EDR3 cross-matched sources, respectively. The models are overplotted by considering the reddening and distance modulus of each cluster from Harris (1996). The error bars (median) are shown in brown colour on the left-hand side of each plot. The abbreviations for the type of stars and stellar evolutionary models are defined in the text.



**Figure 7 – continued.**  $F148W$  versus  $F148W - G$  CMDs of NGC 362, NGC 1904, NGC 288, NGC 362, NGC 1851, and NGC 5466.



**Figure 8.**  $F148W$  versus  $F148W - F169M$  CMDs of NGC 6205. The error bars are shown in brown colour. Refer to Fig. 7 for the description of symbols.

Detailed analysis of HB morphology and BSSs with UVIT was carried out in our previous studies for the three clusters, NGC 288 (Sahu et al. 2019a), NGC 1851 (Subramaniam et al. 2017; Singh et al. 2020), and NGC 5466 (Sahu et al. 2019b). In this work, we have updated the FUV-optical catalogues with the HUGS data and the *Gaia* EDR3 PM analysis (lower panels of Fig. 7). In addition, we have also included the WD detections from the UVIT-*HST* common fields. The hottest WDs detected in these clusters have  $T_{\text{eff}}$  varying from 50 to 70 kK. These three clusters along with the other eight have been used for the rest of the analysis below.

#### 4 STACKED FUV-OPTICAL CMDS

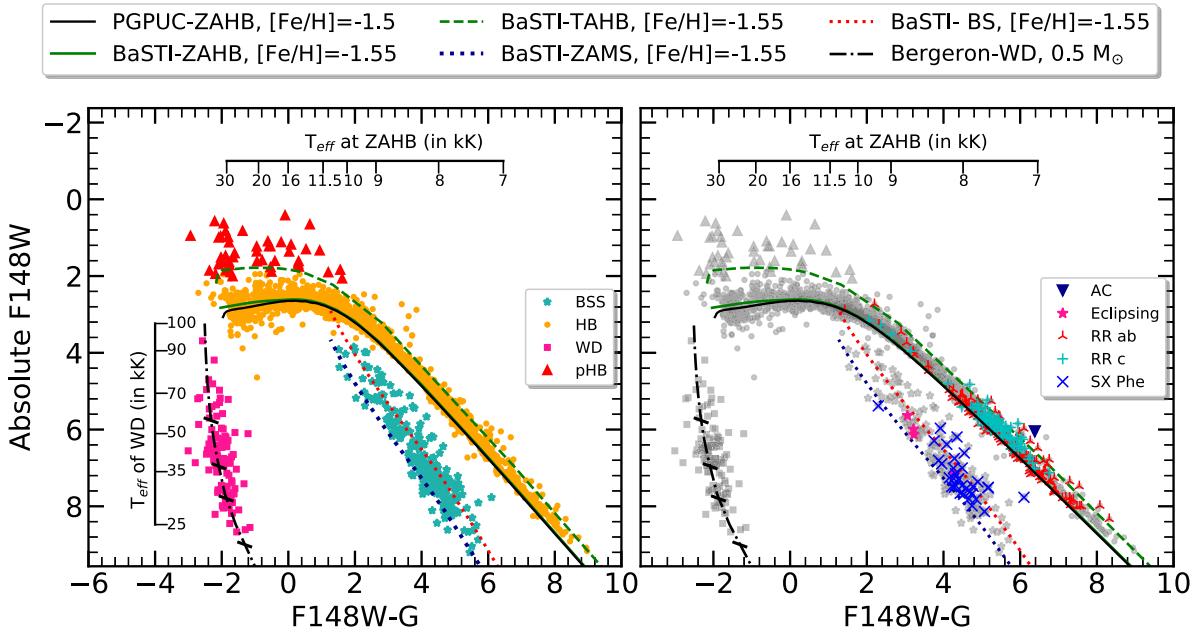
Using *GALEX* observations, Schiavon et al. (2012) generated the stacked FUV versus FUV-NUV CMDs of 23 GCs and found well-

populated HB and UV bright stars. They showed that this stacked CMD is especially useful for identifying PAGBs that are otherwise sparse in number (due to fast evolutionary time-scales), and do not form a well-defined sequence in individual UV CMDs. However, without PM information, they were unable to separate the WD and BSS sequences. These sequences were contaminated by background objects.

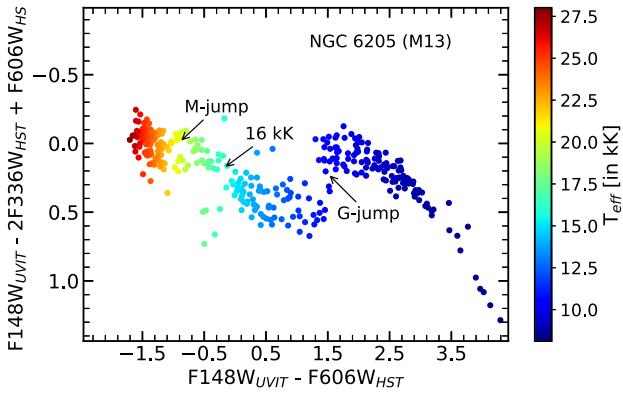
#### 4.1 HB morphology

The FUV bright population of 11 GCs comprises 2816 HB stars where 1335 are the UVIT-*Gaia* common detections. Among the HB population, 190 are EHB candidates and 257 are known RRLs. As shown in Fig. 9, the stacked HB distribution spans around 10 mag in colour and 10 mag in the  $F148W$  magnitude and 10 mag in  $F148W - G$  colour, which is mostly populated by BHB and EHB stars. The PGPUC ZAHB for  $[\text{Fe}/\text{H}] = -1.5$ , and the BaSTI ZAHB and TAHB models for  $[\text{Fe}/\text{H}] = -1.55$  dex are shown in Fig. 9. To check for peculiarities in the HB distributions, we plotted the effective temperature scale at ZAHB from PGPUC models. The HB distribution starts deviating from the usual diagonal sequence at 11 500 K, which corresponds to the well-known Grundahl jump (G-jump) where the atomic diffusion sets in (Grundahl et al. 1999).

Brown et al. (2016) used three filter combinations of the *HST* ( $F275W$ ,  $F336W$ , and  $F438W$ ) to create a pseudo-colour versus colour plot and studied the discontinuities in HB distributions for 45 GCs. Similarly, we used the multiwavelength observations by combining the UVIT/ $F148W$  with  $F336W$  and  $F606W$  filters of the *HST* from the HUGS survey to study the HB gaps/peculiarities in FUV CMDs. The filters were chosen keeping in mind their sensitivity to surface gravity,  $T_{\text{eff}}$ , and He depletion in the HB stars. The wide baseline  $F148W_{\text{UVIT}} - F606W_{\text{HST}}$  is sensitive to  $T_{\text{eff}}$  and He variations, whereas  $F336W$  is sensitive to the surface gravity of the

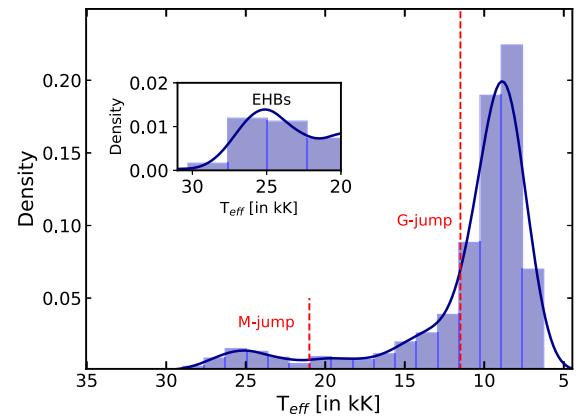


**Figure 9.** Stacked absolute  $F148W$  versus  $F148W - G$  CMD of 11 GCs after correcting for reddening and distance modulus. Both panels include the UVIT-*HST* and the UVIT-*Gaia* EDR3 common detections. For reference, ZAMS is shifted upwards by 0.75, which denotes equal-mass binary sequence (BS) (red dotted line). The effective temperatures (in  $10^3$  K) at ZAHB and WDs from the models are also marked in the figures. The horizontal marks over WD models correspond to cooling ages of 1, 5, 10, and 25 Myr, respectively (from top to bottom). Right-hand panel: all the FUV detected variables: RRLs, SX Phe, eclipsing, and Anomalous Cepheid (AC), where grey dots are the total number of detected sources from both the UVIT-*HST* and the UVIT-*Gaia* EDR3.



**Figure 10.** Pseudo-colour versus colour plot, i.e.  $(F148W - F606W)$  versus  $(F148W - 2F336W + F606W)$  for the UVIT-*HST* common HB sources of NGC 6205 (M13). The G-jump (Grundahl et al. 1999) and M-jump (Momany et al. 2004) corresponding to  $T_{\text{eff}}$  at  $\sim 11500$  and  $21000$  K, respectively, are also marked in the figure. The colour bar shows the  $T_{\text{eff}}$  (in kK) of HB stars estimated from  $F148W - G$  colour versus  $T_{\text{eff}}$  relation obtained from PGPUC models.

HB stars (Brown et al. 2016). The pseudo-colour–colour stacked plot for the UVIT-*HST* common detections of NGC 6205 with most extended HB is shown in Fig. 10 where the y-axis is the difference of two colours,  $(F148W - F336W)$  and  $(F336W - F606W)$ , and the x-axis is  $F148W - F606W$  corrected for reddening. The effective temperatures of HB stars estimated from the  $(F148W - G)$  versus  $T_{\text{eff}}$  relation are shown in the colour bar. We note that the stars in the pseudo-colour plot bend towards fainter magnitude around the G-jump at 11500 K (Grundahl et al. 1999) and show gaps at around 16 000 K and M-jump (21 000 K) (Momany et al. 2004). The pseudo-colour plot of the rest of the clusters is given in Fig. B2 (online). We found clear gaps in the HB distribution at  $(F148W - G) \sim -1.2$



**Figure 11.** Histogram of  $T_{\text{eff}}$  (in kK) for all the UVIT detected HB stars with G-jump and M-jump marked as red dashed lines. The EHB candidates are the stars that are hotter than the M-jump shown in the inset.

and  $-0.4$ . To identify the gaps more prominently, we plotted the  $T_{\text{eff}}$  histogram of the UVIT detected HB stars for all the clusters in our sample (Fig. 11). The HB distribution shows a peak at  $(F148W - G)_{\text{redd}} \sim 2.5$  corresponding to  $T_{\text{eff}} \sim 9000$  K. The histogram shows a dip at  $T_{\text{eff}} \sim 11500$  and  $21000$  K, which corresponds to G-jump and M-jump, respectively. The stars bluer than the M-jump are classified as candidate EHBs. A significant population of EHB stars (156) show a peak at  $(F148W - F606W) \sim -1.5$  corresponding to  $T_{\text{eff}} \sim 25000$  K.

We detected 46 pHB candidates in 11 GCs. The pHB candidates are 1–2 mag brighter than the ZAHB in  $F148W$  and are bluer than  $F148W - G \sim 2$  mag in the stacked CMD (Fig. 9). They include mostly the AGBm and a few P(e)AGB candidates that will evolve towards AGB or WDs depending on the envelope mass after exhaustion of core He

in the HB stars. Schiavon et al. (2012) provided a catalogue of UV bright stars using FUV versus FUV–NUV stacked CMDs of 44 GCs. By comparing the UVIT detections with their catalogue of pHB stars, we found only 9 such candidates as opposed to 19 stars for 8 GCs. The difference might be due to the membership cut-off that was not included in their studies.

## 4.2 BSSs

We detected 221 FUV BSSs in 11 GCs. As shown in Fig. 9, the BSSs occupy a  $F148W$  magnitude range ( $\sim 4\text{--}9$ ) that spans around 5 mag in brightness.

For reference, we show the ZAMS models and equal-mass binary sequence in Fig. 9. Among the total number of FUV BSSs, we noted that around 70 per cent of them lie between the ZAMS and binary sequence, whereas rest of them populate the regions on the redder side of the binary sequence that are possibly evolving away from the MS towards giant phases. A comparison with the ZAMS models shows that the BSSs located at the brightest end of their distribution have apparent masses  $\sim 1.5 M_{\odot}$ , which is twice the mass of MS turn-off (MSTO) mass ( $M_{\text{TO}}$ ) for GCs.

## 4.3 WDs

We detected 106 WDs in 11 GCs. As shown in Fig. 9, the WDs occupy a similar absolute  $F148W$  magnitude range as BSSs ( $\sim 4\text{--}9$ ) spanning around 5 mag in brightness. The WDs are 7–8 mag bluer than the BSS sequence. Bergeron WD models of DA type and mass  $0.5 M_{\odot}$  for different  $T_{\text{eff}}$  are shown in the vertical bar. We were able to detect WDs as faint as  $F148W_{\text{abs}} \sim 8.5$  mag corresponding to  $T_{\text{eff}}$  and cooling age of around 25 000 K and 17 Myr, respectively.

## 4.4 Variables

We detected 296 FUV bright variables in 11 GCs, which comprise 257 RRLs, 34 SX Phes, 4 eclipsing binaries (EBs), and 1 Anomalous Cepheid (AC), where the variables' classification is taken from Clement et al. (2001). Their distribution in  $F148W$  versus ( $F148W - G$ ) stacked CMDs is shown in the right-hand panel of Fig. 9. In the figure, most of the FUV bright variables lie in the magnitude range  $5 < F148W < 8.5$  in FUV CMDs. RRLs lying within this range cover more than 3 mag with effective temperatures varying from  $\sim 6200$  to  $8300$  K. They comprise a mixed population of RRab and RRc, where RRc stars lie on the bluer end of the distribution similar to their locations in the optical CMDs. Since RRLs are sampled at random phases, a given star is plotted at a magnitude equal to the mean of the time series of observations for that star. Thus, we found a few of them to lie at the brighter end of the HB distribution. These RRLs are from clusters NGC 5272, NGC 362, and NGC 1904, which have the shortest exposure times among our sample. The SX Phe variables cover around 2 mag in FUV with most of them lying at the fainter end of the BSS distribution in the stacked CMDs. Three EBs are lying at  $F148W = 6.5$  and one EB lying at  $F148W = 7.2$  hiding below the SX Phe. They are located near the equal-mass binary sequence as shown in the right-hand panel of Fig. 9.

**Table 6.** Parameters of clusters used for HB analysis. The fourth column denotes  $L$  extension parameter of HB and its corresponding uncertainty. See Section 5 for more details.

Cluster	$\log \rho_c$ <sup>1</sup>	$\delta Y_{\text{max}}$ <sup>2</sup>	$L_{F148W - G/F606W}$
NGC 288	1.78	$0.016 \pm 0.012$	$2.93 \pm 0.19$
NGC 362	4.74	$0.026 \pm 0.008$	$2.66 \pm 0.16$
NGC 1851	5.09	$0.025 \pm 0.006$	$2.29 \pm 0.1$
NGC 1904	4.08	–	$3.92 \pm 0.07$
NGC 5272	3.57	$0.041 \pm 0.009$	$3.85 \pm 0.05$
NGC 5466	0.84	$0.007 \pm 0.024$	$1.37 \pm 0.05$
NGC 5897	1.53	–	$3.01 \pm 0.05$
NGC 6205	3.55	$0.052 \pm 0.004$	$4.47 \pm 0.03$
NGC 6341	4.3	$0.039 \pm 0.006$	$2.89 \pm 0.05$
NGC 6809	2.22	$0.026 \pm 0.015$	$2.36 \pm 0.06$
NGC 7099	5.01	$0.022 \pm 0.01$	$1.25 \pm 0.04$

<sup>1</sup>logarithm of central luminosity density (in units of  $L_{\odot} \text{ pc}^{-3}$ ) from Harris (1996) (2010 edition).

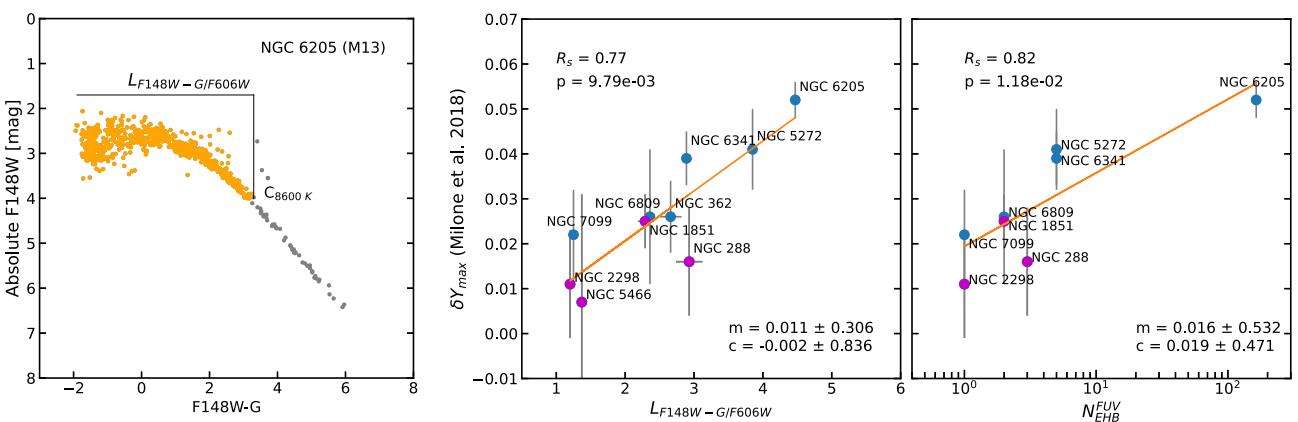
<sup>2</sup>Maximum internal He variation (Milone et al. 2018).

## 5 RESULTS

### 5.1 FUV colour extension of HB

Brown et al. (2016) studied the HB morphologies of 44 GCs and inferred that He-enhanced second-generation (2G) stars populate the bluer end of the HB region. In a recent study, using *HST* photometry, Milone et al. (2018) derived the maximum He variation ( $\delta Y_{\text{max}}$ ) between 2G and 1G stars in a sample of 57 GCs. They found that  $\delta Y_{\text{max}}$  positively correlates with the colour extension of HB derived from  $F275W - F814W$ . Recently, Tailo et al. (2020) derived the mass-loss parameters of 57 GCs and found a positive correlation of the mass-loss difference ( $\delta \mu_e$ ) between 2G and 1G stars with  $\delta Y_{\text{max}}$ . They suggested that both mass-loss and He enhancement are the main second parameters influencing the HB morphology.

We explored the effect of He enrichment in the HB morphology of 11 GCs by studying their correlation with He variations in GCs. Chung, Yoon & Lee (2017) using Yonsei Evolutionary Population Synthesis (YEPS) He-enhanced models in different passbands demonstrated that FUV –  $V$  colour is most sensitive to the variations of  $Y_{\text{ini}}$  in HB stars. Thus, for our analysis, we studied the relation using the FUV –  $G$  colour extension of HB. The  $\delta Y_{\text{max}}$  values were adopted from Milone et al. (2018) for nine clusters in our sample, which are varying from 0.007 to 0.052 (Table 6). These values were not available for NGC 1904 and NGC 5897. We chose the  $F148W - G/F606W$  plane that provides a wider colour baseline than NUV and has the maximum sensitivity to the effective temperature variations in HB stars. The HB colour extension parameter is denoted as  $L_{F148W - G/F606W}$  and their corresponding uncertainties are determined by following the method of Milone et al. (2014). Similar to their definition of  $L_{F275W - F814W}$ ,  $L_{F148W - G/F606W}$  is defined as the difference between 96th and 4th percentiles of the colour  $F148W - G/F606W$  distribution of HB stars, by excluding the stars redder than the RRL strip. We calculated the errors by performing 1000 iterations on the sample of HB stars in FUV using bootstrap statistics, where the 68.27th percentile of the bootstrap measurements was considered as the corresponding uncertainty for each cluster. For calculating the  $L$  extension parameter, we chose HB stars with  $T_{\text{eff}} \geq 8600$  K as a reference point for comparing different clusters in our sample as shown in the leftmost panel of Fig. 12, which corresponds to reddening-corrected colour  $F148W - G \sim 3.4$ . The motivation to choose this reference point is that the effects of different metallicities are not present for stars hotter than 8600 K as found from the PGPUC



**Figure 12.** Derivation of  $L$  extension parameter shown for cluster NGC 6205 as an example in the leftmost panel. HB colour extension  $L_{F148W - G/F606W}$  and number of EHB stars detected in FUV ( $N_{EHB}^{FUV}$ ) as a function of maximum He variation within each GC ( $\delta Y_{\max}$ ) (Milone et al. 2018) in the middle and right-hand panels, respectively. The blue dots are the clusters studied for the first time in this work and green dots are clusters from our previous works. The Spearman's rank correlation coefficients and  $p$ -values are provided in the figure.

and BaSTI-IAC models. This reference point was also chosen by Brown et al. (2016) for studying the HB morphologies of different clusters. The values of the  $L$  parameter and their errors are listed in Table 6.

We checked the correlation of  $L_{F148W - G/F606W}$  with  $\delta Y_{\max}$  in a sample of nine clusters with FUV observations. These clusters are mostly metal-poor ( $[Fe/H] < -1.5$  dex) and populated with only BHB stars (except NGC 362 and NGC 1851). The cluster NGC 2298 from our recent work (Rani et al. 2021b) is also included in the analysis whose  $L_{F148W - G} \sim 1.2 \pm 0.07$  and  $\Delta Y_{\max} \sim 0.011 \pm 0.012$  (Milone et al. 2018). As shown in the left-hand panel of Fig. 12, we find a strong correlation of the  $L$  parameter with  $\delta Y_{\max}$  where the Spearman's rank correlation coefficient ( $R_s$ ) is close to 0.79 with  $p$ -value  $= 6.5 \times 10^{-3}$ . From the figure, we note that the value of the  $L$  extension parameter increases with increasing  $\delta Y_{\max}$  within each GC with the clusters with higher values having more extended HB. The results are in fair agreement with Tailo et al. (2020) suggesting that the He enhancement plays an important role in shaping the bluer end of the HB morphology in GCs. The detailed HB morphologies of these clusters will be studied in the future to check the existence of multiple stellar populations (MSPs; Bastian & Lardo 2018 and the references therein).

## 5.2 FUV detected EHB stars

In the massive clusters ( $> 10^5 M_\odot$ ) that host a large number of EHB and BHk stars, such as  $\omega$  cen and NGC 2808, spectroscopic studies (Moehler et al. 2011; Brown et al. 2012) have shown that a significant population of EHBs stars are He-rich, which supports the late hot-flash scenario. On a different perspective, D'Antona et al. (2002) and Lee et al. (2005) suggested He self-enrichment scenario where EHB stars are the result of the normal evolution of He-enhanced sub-populations formed from the ejecta of massive AGB stars. This was supported by the multiple splits in the MS found in the GC CMDs from the *HST* photometry of clusters hosting EHB stars (Piotto et al. 2015). These studies were mostly biased towards clusters with uniformly populated HB extending to EHB stars. Using the FUV-optical CMDs, we were able to detect sparsely populated EHB stars in clusters mostly hosting only BHB stars (Table 5). We studied their relation with the He variation to explore the He self-enrichment scenario for the EHB formation.

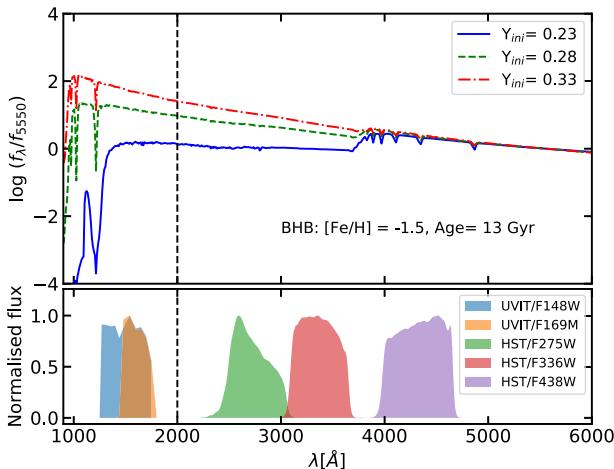
We considered seven clusters in our sample hosting EHB stars to check their correlation with  $\delta Y_{\max}$  (Milone et al. 2018). The number of FUV detected EHBs ( $N_{EHB}^{FUV}$ ) as a function of  $\delta Y_{\max}$  is shown in the right-hand panel of Fig. 12. We find a significant positive correlation of  $N_{EHB}^{FUV}$  with  $\delta Y_{\max}$  with  $R_s \sim 0.73$  and 96 per cent confidence interval denoting that the number of EHB stars increases with increasing  $\delta Y_{\max}$ . This suggests that the evolution of He-enhanced 2G MS stars would have led to the formation of EHB/BHk stars in GCs. However, we need a larger sample of GCs with EHB stars to confirm this result. Our future studies will aim at deriving the atmospheric parameters of the EHB stars using SEDs and comparing them with both the hot-flashers and He-enriched models.

## 6 SCIENCE CASES FROM GLOBULES CATALOGUE

Below, we highlight the potential science cases from the GlobULES project that we intend to pursue in the future.

### 6.1 He enrichment in HB stars

GCs host complex HB morphologies that cannot be explained by only one parameter, metallicity, that mostly contributes to the fraction of BHB and RHB stars. Additional parameters are required to explain the clusters with different HB morphologies but with no variation in metallicity or age. This is known as the ‘second parameter problem’ (refer to review papers by Catelan 2009; Gratton et al. 2010; Dotter 2013, and references therein for more details). One such important second parameter is He abundance (Sandage & Wildey 1967). Fig. 13 shows SEDs of HB stellar populations as a function of wavelength for a metallicity of  $-1.5$  dex, age = 13 Gyr, and different He abundances (Chung et al. 2017). The UVIT filter effective areas for two FUV filters ( $F148W$  and  $F169M$ ) along with the *HST* filters are also compared in the figure. We note that the flux change among the He-normal and He-rich populations is maximum in FUV wavelengths as compared with the NUV and optical. Being most sensitive to He abundance variations, Dalessandro et al. (2010, 2013) suggested that FUV-optical CMDs are optimal diagrams for studying their effect in BHB stars with  $T_{\text{eff}} > 10000$  K. Combining FUV and optical observations from the *HST*, they investigated the role of different



**Figure 13.** Top panel: synthetic SEDs of BHB stars from YEPS models (Chung et al. 2017) for  $[Fe/H] = -1.5$  dex and age 13 Gyr corresponding to three different  $Y_{\text{ini}}$  abundances 0.23, 0.28, and 0.33. The  $Y$ -axis is the logarithm of model flux normalized to the flux at 5550 Å. Bottom panel: effective area curves (normalized) for the two UVIT filters ( $F148W$  and  $F169M$ ) and three  $HST$  filters ( $F275W$ ,  $F336W$ , and  $F438W$ ) as a function of wavelength.

He abundances in the HB distribution and computed the maximum He values in various GCs (NGC 2808, NGC 6205, and NGC 1904). However, these studies covered only central regions of GCs. The GlobULES catalogue will assist in identifying the sub-populations with synthetic HB models and in comparing their spatial distributions over the cluster region extending to a 10 arcmin radius from the cluster centre. The strong correlation of HB colour extension with He variations, derived from the UVIT/FUV-optical colour for EHB stars, indicates the significance of our studies in the context of MSPs in GCs.

## 6.2 Evolutionary status of pHB stars

The most luminous and hot population among the UV bright stars are pHB stars. Schiavon et al. (2012) classified post-core-He burning stars of 44 GCs into AGBm and P(e)AGB using pHB evolutionary models of different masses. However, membership analysis was not performed. Comparing it with the GlobULES sample, we note that NGC 6205 was not included in their study.

Moehler et al. (2019) calculated the expected number of PAGB stars using stellar evolutionary models in 17 GCs and found it to be in good agreement with the observed number. However, they suggested that these comparisons are affected by low number statistics. Thus, a large sample of GCs with pHB stars is required to check their expected number from models. Our survey will help in improving the statistics. The advantage of using the UVIT to study pHBs is presented for GC NGC 2808 by Prabhu et al. (2021). From GlobULES, we have identified pHB candidates in seven GCs along with their membership using the  $HST$  and  $Gaia$  EDR3. Among the GlobULES sample, four clusters (NGC 1851, NGC 5272, NGC 6205, and NGC 7099) are in common with Moehler et al. (2019), where we detect the previously reported three PAGB stars in the clusters that are heavily saturated in the UVIT/ $F148W$  band. The FUV filter data points will be crucial for deriving the parameters of pHB stars (such as luminosity,  $T_{\text{eff}}$ ) and inferring their evolutionary status.

## 6.3 FUV bright BSSs

Using FUV observations, we have detected very bright BSSs (absolute  $F148W < 5.5$  mag) that probably have masses twice the mass of MSTO. The parameters and formation mechanism of such bright BSSs are not well understood. Sills & Bailyn (1999) compared the observed BSS distribution of NGC 5272 with theoretical CMDs generated from simulations for different assumptions and inferred that bright BSSs can be reproduced by increasing their He content resulting from mixing and rotation. Similarly, Ferraro et al. (2003) spotted very bright BSSs in NUV-optical CMDs of NGC 5272 and NGC 6341. Comparing their results with theoretical collisional models, they suggested that the presence of these BSSs could indicate a continuous BSS formation or they might belong to a different distribution involving triple collisions. Leigh, Sills & Knigge (2007) investigated the relationship of BSSs with their cluster environments and suggested that the clusters with the highest collisional rates could host the most massive BSSs due to the increased rate of three-body encounters. From the  $HST$ /FUV observations, Knigge et al. (2008) identified a supermassive BSS ( $M \sim 1.9 M_{\odot}$ ) in 47 Tuc using SED fits, pointing out that the formation of such BSSs might require the involvement of three progenitors.

From our study of BSS distribution in FUV-optical CMDs of 11 GCs, we note that the FUV bright BSSs are mostly found in high-density ( $\rho_c \geq 10^{3.6} L_{\odot} \text{ pc}^{-3}$ ) (Table 6) and dynamically more relaxed clusters, with  $N_{\text{relax}} \geq 2$ . The examples are NGC 362, NGC 6341, and NGC 7099 that are also core-collapsed. The stellar encounter rates ( $\Gamma$ ) of such clusters are high with  $\log \Gamma > 2$  (Bahramian et al. 2013). On the other hand, the presence of very bright BSSs is negligible in low-density clusters (NGC 288 and NGC 5466). These clusters have a high specific frequency of BSSs ( $N_{\text{BSS}}/N_{\text{HB}} > 0.2$ ) compared to other clusters in our sample.

It suggests that the clusters with high stellar encounter rates are hosting the FUV brightest BSSs. These bright BSSs are preferentially found in the central regions of the clusters, suggesting that the multiple collisions in the dense core regions might be responsible for their production. However, to study a specific correlation of the BSSs with cluster parameters, a complete sample of BSSs down to MSTO is required. This has been achieved using the NUV-optical CMDs from the  $HST$  observations in the recent works, but these studies were restricted to only the half-light radius of GCs. Future studies are planned in combining the  $HST$  data with the  $Swift$ /UVOT observations to cover the outer regions as well.

The GlobULES catalogue of BSSs will also be crucial to derive the properties of FUV bright BSSs and identify those showing UV excesses using SEDs. Knigge et al. (2008) and Sahu et al. (2019b) analysed this FUV excess and suggested that it is due to the presence of WD companions. The BSS-WD systems suggested by their studies are the only two such systems known to date in GCs. More discoveries of such hot companions and detailed spectroscopic diagnosis using high-spectroscopic data from large facilities (e.g. VLT/ESO), as well as theoretical modelling, will have important implications for our understanding of the binary evolution of BSS stars and the astrophysical processes involved (mass transfer, the role of metallicity, etc.).

## 6.4 Study of WDs

The WD sequence for the inner cluster region (the UVIT- $HST$ ) is prominent in the stacked FUV-optical CMD (left-hand panel of Fig. 9). We checked whether the number of WDs detected with the UVIT/ $F148W$  in FUV-optical CMDs matched the theoretical

expectations. The expected number of WDs ( $N_{\text{WD}}$ ) that are brighter than the UVIT/F148W detection limit of each GC (see Table 2) was calculated following the relation  $N_{\text{WD}}/N_{\text{HB}} = \tau_{\text{WD}}/\tau_{\text{HB}}$  (equation 3 of Knigge et al. 2002), where  $N_{\text{HB}}$  and  $\tau_{\text{HB}}$  are the number of HB stars and their corresponding lifetime, whereas  $N_{\text{WD}}$  is the number of WDs brighter than a given magnitude and  $\tau_{\text{WD}}$  is the corresponding cooling time down to that magnitude. We used HB stars as reference considering  $\tau_{\text{HB}} = 10^8$  yr as the HB lifetime (Iben 1991). We selected the number of HB stars ( $N_{\text{HB}}$ ) lying in *HST* FOV from *F275W* versus *F275W – F336W* *HST* CMDs to avoid incompleteness.

The cooling ages of WDs ( $\tau_{\text{WD}}$ ) corresponding to the UVIT magnitude detection limit were considered from Bergeron WD models of DA spectral type and mass  $0.5 M_{\odot}$ . According to the models, the WD temperatures of 11 GCs lie in the range 23 000–45 000 K with their cooling ages varying from  $\sim 4$  to 25 Myr. Comparing with the predictions, we found that 50–70 per cent of the WDs are detected with the UVIT/F148W in three GCs, > 90 per cent in three of them, while the rest of them have 30–40 per cent detections excluding NGC 1904. For the regions not covered with the *HST*, deep *UBVRI* observations of GCs (Stetson et al. 2019) will be utilized to cross-match and identify the hot WDs. Since these regions are not affected by crowding, we expect the number of WDs brighter than the detection limit to be in line with the predicted number. The WD catalogue from GlobULES will be useful to derive the atmospheric parameters and check for binarity using SEDs and models (Knigge et al. 2008).

## 7 SUMMARY AND CONCLUSION

We present the first results for eight GCs from the UV survey of GCs (GlobULES) carried out using UVIT onboard *AstroSat*. We also present some initial analysis of 11 GCs after including data of 3 more GCs previously observed using UVIT. The FUV–optical CMDs of PM members were constructed by combining *AstroSat*/UVIT observations with *HST* HUGS survey and *Gaia* EDR3 data. For the regions not covered by *HST*, the membership probabilities were derived using *Gaia* EDR3. The FUV–optical CMDs mainly consist of HBs, pHBs, BSSs, and WDs. We used several stellar evolutionary models such as PGPUC, BaSTI-IAC, and Bergeron models for HBs, BSSs, and WDs, respectively, and found it to match well with the observed CMDs. Overall, we have 1747 (1481 HBs, 134 BSSs, 107 WDs, 25 pHBs) common sources with UVIT–*HST* cross-match and 1443 (1335 HBs, 87 BSSs, 21 pHBs) from the UVIT–*Gaia* EDR3 cross-match (for the regions not observed by *HST*). A total of 190 EHB candidates in 11 GCs were identified photometrically based on the effective temperatures obtained from colour ( $F148W - G$ ) versus  $T_{\text{eff}}$  relation of HB models, with the largest population being in NGC 6205. Thus, our study highlights the importance of combining multiwavelength observations covering FUV (from UVIT) to optical for the exploration of UV bright stars.

To highlight the important features of UV CMDs, we created a stacked FUV–optical CMD of members from 11 GCs. The stacked CMD shows a dominant population of HBs spanning a  $T_{\text{eff}}$  range of 6000–32 000 K followed by the BSSs being as bright as BHs in a few clusters. The WDs span a temperature range of 25 000–90 000 K corresponding to the cooling age range of 1–25 Myr, as per the Bergeron DA WD models. We also detect 296 known variables in FUV (RRL, SX Phes) distributed mostly in the fainter end of the BHs and BSS distribution, respectively. To identify the discontinuities present in the HB distribution of the UVIT–*HST* common sources, we used three filter combinations of UVIT/F148W and *HST* (*F336W* and *F606W*) for creating pseudo-colour diagrams. The diagrams

show detectable gaps at  $T_{\text{eff}} \sim 11\,700$  and 21 000 K corresponding to the well-known G-jump and M-jump, respectively. We also found that the colour ( $F148W - G$ ) extension of HB distribution of 10 GCs for stars hotter than 8600 K is strongly correlated to the maximum internal He variation within each GC (Milone et al. 2018), thus showcasing the larger sensitivity of FUV–optical colour to the He enrichment when compared to NUV, as well as to studies that use only optical bands.

We discuss the important science cases that will be pursued in the future using the GlobULES survey products, with a particular focus on the EHB stars, pHB stars, FUV bright BSSs, and WDs. The FUV catalogues from the GlobULES survey will provide broader opportunities to reveal the nature of poorly studied hot stellar populations in GCs, which will aid in constraining the stellar evolutionary models in UV. The initial analysis of the identified UV peculiar and exotic stars from GlobULES catalogues will serve as important targets to the upcoming spectroscopic facilities in different wavebands including the UV missions that are being planned.

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## DATA AVAILABILITY

The UVIT science data underlying this work will be shared on reasonable request to the corresponding author. The raw UVIT data files of the clusters can be downloaded from the Indian Space

Research Organisation (ISRO) Science Data Archive for *AstroSat* Mission.<sup>4</sup>

## REFERENCES

- Astropy Collaboration et al., 2013, *A&A*, 558, A33
- Astropy Collaboration et al., 2018, *AJ*, 156, 123
- Bahramian A., Heinke C. O., Sivakoff G. R., Gladstone J. C., 2013, *ApJ*, 766, 136
- Balaguer-Núñez L., Tian K. P., Zhao J. L., 1998, *A&AS*, 133, 387
- Bastian N., Lardo C., 2018, *ARA&A*, 56, 83
- Bédard A., Bergeron P., Brassard P., Fontaine G., 2020, *ApJ*, 901, 93
- Bergeron P., Wesemael F., Beauchamp A., 1995, *PASP*, 107, 1047
- Bonnarel F. et al., 2000, *A&AS*, 143, 33
- Brown T. M., Lanz T., Sweigart A. V., Cracraft M., Hubeny I., Landsman W. B., 2012, *ApJ*, 748, 85
- Brown T. M. et al., 2016, *ApJ*, 822, 44
- Cassisi S., Salaris M., Irwin A. W., 2003, *ApJ*, 588, 862
- Catelan M., 2009, *Ap&SS*, 320, 261
- Chen Y. et al., 2019, *A&A*, 632, A105
- Chung C., Yoon S.-J., Lee Y.-W., 2017, *ApJ*, 842, 91
- Clement C. M. et al., 2001, *AJ*, 122, 2587
- Cool A. M., Bolton A. S., 2002, in Shara M. M., ed., ASP Conf. Ser., vol. 263, Stellar Collisions, Mergers and Their Consequences. Astron. Soc. Pac., San Francisco, p. 163
- Cool A. M., Grindlay J. E., Cohn H. N., Lugger P. M., Slavin S. D., 1995, *ApJ*, 439, 695
- Dalessandro E., Salaris M., Ferraro F. R., Cassisi S., Lanzoni B., Rood R. T., Fusi Pecci F., Sabbi E., 2010, *MNRAS*, 410, 694
- Dalessandro E., Salaris M., Ferraro F. R., Mucciarelli A., Cassisi S., 2013, *MNRAS*, 430, 459
- D'Antona F., Caloi V., Montalbán J., Ventura P., Gratton R., 2002, *A&A*, 395, 69
- Dias B., Barbuy B., Saviane I., Held E. V., Da Costa G. S., Ortolani S., Gullieuszik M., Vásquez S., 2016, *A&A*, 590, A9
- Dieball A., Knigge C., Zurek D. R., Shara M. M., Long K. S., 2005, *ApJ*, 625, 156
- Dieball A., Knigge C., Zurek D. R., Shara M. M., Long K. S., Charles P. A., Hannikainen D., 2007, *ApJ*, 670, 379
- Dieball A., Long K. S., Knigge C., Thomson G. S., Zurek D. R., 2010, *ApJ*, 710, 332
- Dieball A., Rasekh A., Knigge C., Shara M., Zurek D., 2017, *MNRAS*, 469, 267
- Dotter A., 2013, *Mem. Soc. Astron. Ital.*, 84, 97
- El-Badry K., Rix H.-W., Heintz T. M., 2021, *MNRAS*, 506, 2269
- Fabricius C. et al., 2021, *A&A*, 649, A5
- Ferraro F. R. et al., 1997, *A&A*, 324, 915
- Ferraro F. R., Paltrinieri B., Rood R. T., Dorman B., 1999, *ApJ*, 522, 983
- Ferraro F. R., Sills A., Rood R. T., Paltrinieri B., Buonanno R., 2003, *ApJ*, 588, 464
- Fitzpatrick E. L., 1999, *PASP*, 111, 63
- Gaia Collaboration et al., 2018, *A&A*, 616, A12
- Gaia Collaboration et al., 2021, *A&A*, 649, A1
- Gratton R. G., Carretta E., Bragaglia A., Lucatello S., D'Orazi V., 2010, *A&A*, 517, A81
- Greggio L., Renzini A., 1990, *ApJ*, 364, 35
- Grundahl F., Catelan M., Landsman W. B., Stetson P. B., Andersen M. I., 1999, *ApJ*, 524, 242
- Harris W. E., 1996, *AJ*, 112, 1487
- Hidalgo S. L. et al., 2018, *ApJ*, 856, 125
- Holtzman J. A., Burrows C. J., Casertano S., Hester J. J., Trauger J. T., Watson A. M., Worthey G., 1995, *PASP*, 107, 1065
- Hunter J. D., 2007, *Comput. Sci. Eng.*, 9, 90
- Hurley J. R., Aarseth S. J., Shara M. M., 2007, *ApJ*, 665, 707
- Hut P. et al., 1992, *PASP*, 104, 981
- Iben I. J., 1991, *ApJS*, 76, 55
- Kim D., Lu J. R., Konopacky Q., Chu L., Toller E., Anderson J., Theissen C. A., Morris M. R., 2019, *AJ*, 157, 109
- Knigge C., Zurek D. R., Shara M. M., Long K. S., 2002, *ApJ*, 579, 752
- Knigge C., Dieball A., Maíz Apellániz J., Long K. S., Zurek D. R., Shara M. M., 2008, *ApJ*, 683, 1006
- Kumar R., Pradhan A. C., Mohapatra A., Moharana A., Ojha D. K., Parthasarathy M., Murthy J., 2021, *MNRAS*, 502, 313
- Lanzoni B. et al., 2007, *ApJ*, 663, 1040
- Lee Y.-W. et al., 2005, *ApJ*, 621, L57
- Leigh N., Sills A., Knigge C., 2007, *ApJ*, 661, 210
- McKinney W., 2010, in van der Walt S., Millman J., eds, Proceedings of the 9th Python in Science Conference, p. 51
- Millman K. J., Avazis M., 2011, *Comput. Sci. Eng.*, 13, 9
- Milone A. P. et al., 2014, *ApJ*, 785, 21
- Milone A. P. et al., 2018, *MNRAS*, 481, 5098
- Moehler S., Koester D., Zoccali M., Ferraro F. R., Heber U., Napiwotzki R., Renzini A., 2004, *A&A*, 420, 515
- Moehler S., Dreizler S., Lanz T., Bono G., Sweigart A. V., Calamida A., Nonino M., 2011, *A&A*, 526, A136
- Moehler S., Landsman W. B., Lanz T., Miller Bertolami M. M., 2019, *A&A*, 627, A34
- Momany Y., Bedin L. R., Cassisi S., Piotto G., Ortolani S., Recio-Blanco A., De Angeli F., Castelli F., 2004, *A&A*, 420, 605
- Nardiello D. et al., 2018, *MNRAS*, 481, 3382
- O'Connell R. W., 1999, *ARA&A*, 37, 603
- Oiphant T. E., 2007, *Comput. Sci. Eng.*, 9, 10
- Peacock M. B., Zepf S. E., Maccarone T. J., Kundu A., Knigge C., Dieball A., Strader J., 2018, *MNRAS*, 481, 3313
- Pietrinferni A. et al., 2021, *ApJ*, 908, 102
- Piotto G. et al., 2015, *AJ*, 149, 91
- Postma J. E., Leahy D., 2017, *PASP*, 129, 115002
- Prabhu D. S., Subramaniam A., Sahu S., 2021, *ApJ*, 908, 66
- Rani S., Pandey G., Subramaniam A., Sahu S., Rao N. K., 2021a, *MNRAS*, 501, 2140
- Rani S., Pandey G., Subramaniam A., Chung C., Sahu S., Kameswara Rao N., 2021b, *ApJ*, 923, 162
- Raso S., Ferraro F. R., Dalessandro E., Lanzoni B., Nardiello D., Bellini A., Vesperini E., 2017, *ApJ*, 839, 64
- Renzini A., Fusi Pecci F., 1988, *ARA&A*, 26, 199
- Richer H. B. et al., 1997, *ApJ*, 484, 741
- Riello M. et al., 2021, *A&A*, 649, A3
- Sahu S., Subramaniam A., Côté P., Rao N. K., Stetson P. B., 2019a, *MNRAS*, 482, 1080
- Sahu S. et al., 2019b, *ApJ*, 876, 34
- Sandage A. R., 1953, *AJ*, 58, 61
- Sandage A., Wildey R., 1967, *ApJ*, 150, 469
- Schiavon R. P. et al., 2012, *AJ*, 143, 121
- Schwarzschild M., Härm R., 1965, *ApJ*, 142, 855
- Shara M. M., Hurley J. R., 2006, *ApJ*, 646, 464
- Sills A., Bailyn C. D., 1999, *ApJ*, 513, 428
- Singh G., Sahu S., Subramaniam A., Yadav R. K. S., 2020, *ApJ*, 905, 44
- Soto M. et al., 2017, *AJ*, 153, 19
- Stetson P. B., 1987, *PASP*, 99, 191
- Stetson P. B., Pancino E., Zocchi A., Sanna N., Monelli M., 2019, *MNRAS*, 485, 3042
- Subramaniam A. et al., 2016, in den Herder J.-W. A., Takahashi T., Bautz M., eds, Proc. SPIE Conf. Ser. vol. 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray. SPIE, Bellingham, p. 99051F
- Subramaniam A. et al., 2017, *AJ*, 154, 233
- Tailo M. et al., 2020, *MNRAS*, 498, 5745
- Tandon S. N. et al., 2017, *AJ*, 154, 128
- Taylor M. B., 2005, in Shopbell P., Britton M., Ebert R., eds, ASP Conf. Ser. vol. 347, Astronomical Data Analysis Software and Systems XIV. Astron. Soc. Pac., San Francisco, p. 29
- Tremblay P. E., Bergeron P., Gianninas A., 2011, *ApJ*, 730, 128

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- Valcarce A. A. R., Catelan M., Sweigart A. V., 2012, *A&A*, 547, A5  
 Van der Walt S., Colbert S. C., Varoquaux G., 2011, *Comput. Sci. Eng.*, 13,  
 22  
 Vasiliev E., Baumgardt H., 2021, *MNRAS*, 505, 5978

## SUPPORTING INFORMATION

Supplementary data are available at [MNRAS](#) online.

[appendix\\_GlobULES\\_survey.pdf](#)

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