Investigation of the Globular Cluster NGC 2808 with the Ultra-Violet Imaging Telescope

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ABSTRACT
Globular clusters represent stellar laboratories where observations can be used to validate models of stellar evolution. In this study, we put forth new ultraviolet (UV) photometric results of stars in the Galactic globular cluster NGC 2808. NGC 2808 is known to host multiple stellar populations that include at least four distinct groups of horizontal Branch (HB) stars. We have observed this cluster with the AstroSat-UltraViolet Imaging Telescope in two far-UV (FUV) and five near-UV (NUV) filters, respectively. These UV filters enable the identification of HB populations of stars. The results from four NUV filters exhibit bimodal distributions in magnitude histograms. The nature of bimodality has been investigated on the basis of distinct stellar types contributing to those bands. The color-magnitude diagrams constructed using FUV and NUV filters enable the location of hot stellar populations, viz. stars belonging to Red HB (RHB), Blue HB, Extreme HB, Blue Hook branch and post-Asymptotic Giant Branch. Prominent gaps are observed in the UV color-magnitude diagrams. We report for the first time, a photometric gap in a NUV color-magnitude diagram, that segregates the RHB population of this cluster into two groups, that are likely to be associated with distinct generations of stars. We also investigate the spatial density distributions of various groups of stars in the cluster and comment on the proposed formation models of multiple populations.

Key words: (Galaxy:) globular cluster: individual: NGC 2808 – stars: horizontal branch – (stars:) Hertzsprung-Russell and color-magnitude diagrams – techniques: photometric

1 INTRODUCTION
Stars in Globular Clusters (GCs), being the oldest population in the Galaxy, form an ideal test bed for stellar evolution theories owing to their sheer numbers, metallicities, assorted stellar populations, and visibility due to negligible interstellar medium in the halo. In addition, having a statistical advantage of millions of stars as members, most of the stars are well resolved for a detailed scrutiny leading to a sampling of even the short-lived populations (van den Bergh 1993). Although significant advances have been made in our understanding regarding the evolution of stars, ambiguities and gaps remain (Moehler 2001). Unlike the optical wavebands where a large body of work on GCs has been carried out, ultraviolet (UV) studies of globular clusters have been relatively sparse (Dalessandro et al. 2012; Dieball et al. 2005). Certain evolved populations are brighter in UV as compared to optical, due to various effects that include significant mass loss and metallicity. The main UV contributors in GCs are the horizontal branch (HB) stars, the Asymptotic Giant Branch (AGB) population, the blue stragglers, and the white dwarf stars (Zinn et al. 1972; Harris et al. 1983).

The HB stars are central core helium burning low mass stars whose effective temperatures are expected to reach up to \( \sim 45,000 \) K (Castellani et al. 1995). They produce copious amounts of UV flux during this core He burning (CHeB) stage. The horizontal branch itself is not comprised of a simple stellar population and it is an aggregate of groups of stars separated by gaps in the color-magnitude diagrams, i.e the red horizontal branch, blue horizontal branch and extreme horizontal branch (Dalessandro et al. 2011; Catelan et al. 1998; Ferraro et al. 1998). Among the HB group of stars, the red horizontal branch (RHB) stars are the cooler stars which lie towards the red end of the HB. Their effective temperatures are expected to be in the range \( \sim 5,000 - 6,200 \) K (Afsar et al. 2013). These have also

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been referred to as Red Clump stars (e.g. Brown et al. 2016; D’Antona & Caloi 2008). In accordance with the definition of Catelan (2009) and following Marino et al. (2014), we address these stars as RHB in the present work. These stars are cooler than the RR Lyrae instability strip. The blue HB (BHB) stars lie on the hotter bank of the instability strip. In addition, there is a group of stars which are very luminous in far-UV, and these are believed to be in their post core helium burning stage or post AGB (PAGB) phase.

It is still not understood how various parameters affect the HB morphology. One of the parameters is the mass loss during the RGB phase. The HB stars have a core mass of $\sim 0.5 M_\odot$ surrounded by a hydrogen rich envelope (Iben & Rood 1970; Moehler 2010). The mass of hydrogen envelope that surrounds the core could be related to the spread of stars along the blue HB, and those with thinner envelopes are expected to reside towards farther end of the blue HB. If the mass of H rich envelope exceeds 0.02 $M_\odot$, the H shell burning is expected to remain active during the HB lifetime and later as it evolves towards the AGB phase, subsequent to the exhaustion of helium in its core. These represent the blue horizontal branch (BHB) stars. On the other hand, if the mass of H envelope is less than 0.02 $M_\odot$, the H shell burning cannot be sustained and the star directly evolves towards the white dwarf sequence. These hot but faint stars which are lower in mass are called extreme horizontal branch (EHB) stars. They do not ascend along AGB but proceed towards becoming white dwarfs. They do not ascend along the red giant branch (RHB) stars, which have a core mass of $\sim 1 M_\odot$. The BHB stars were corre- lated to models with high helium content, $Y=0.3$ (progeny of metal-poor clusters) and unusually high mass-loss ($\geq 0.5 M_\odot$) (Bedin et al. 2004; Piotto et al. 2002; Moehler et al. 1997). The BHB stars were correlated to models with high helium content, $Y=0.3$ (progeny of normal-MS population), while RHB stars were matched by models with $Y=0.24$ (Red-MS) and EHB stars were mapped to Blue-MS ($Y=0.4$) by D’Antona & Caloi (2008). It is now established that NGC 2808 hosts at least five populations of stars (Milone et al. 2015; Carretta 2015). An elaborate study has been carried out by Moni Bidin et al. (2011) to identify HB stars in NGC 2808 using spectroscopy. In addition, Gratton et al. (2011) spectroscopically classified HB stars of NGC 2808 using Na-O anticorrelation. The UV wavebands provide a singular platform to testify the origin of a clumpy distribution of hot stars. Using GALEX, Schiavon et al. (2012) investigated a number of GCs including NGC 2808 and distinguished Post-AGB and Post (early) AGB stars in these clusters using CMDs. The GALEX field of NGC 2808 in FUV is shown in Fig. 1. In the current study, we investigate the hot population of the cluster in the ultraviolet realm of UVIT.

In Sect. 2, we present the UV observations and procedures adopted for data reduction and analysis. The results are described in Sect. 3 and discussed in Sect. 4. The article concludes with a brief summary in Sect. 5.
Investigation of NGC 2808 with the UVIT

2 OBSERVATIONS AND DATA REDUCTION

2.1 AstroSat - UVIT Observations and pipeline reduction

The UVIT on-board the AstroSat has been used to image the globular cluster NGC 2808. AstroSat is India’s first space based multiwavelength mission (Agrawal 2004) that observes simultaneously in UV, visible and X-rays. UVIT has a twin telescope system with a diameter of 38 cm, in Ritchey-Chretien configuration. One of the telescopes is dedicated for observations in FUV and the second telescope observes in NUV and visible channels. UVIT is primarily an imaging instrument and covers a circular field of view of \( \sim 2\arcmin \). The spatial resolution achieved by UVIT in FUV and NUV is \( < 1.5\arcsec \), while it is \( < 2.2\arcsec \) in the visible channel. Each channel (FUV, NUV and visible) constitutes of a number of selectable filters with smaller passbands. Further details about the UVIT and the instrument performance can be found in Tandon et al. (2017b).

NGC 2808 was observed by UVIT on April 4, 2017, in two FUV, and five NUV filters. The data from simultaneous imaging in a neutral density visible filter were used for aspect reconstruction during the post-observation data processing stage. The filters used during the observations were F154W and F169M in FUV, and N242W, N219M, N245M, N263M and N279N in NUV. The details of the filters are listed in Table 1. The exposure times of observations through various filters are also listed in the table. The Level-1 data products made available by the Indian Space Science Data Center (ISSDC/ISRO) were processed using the UVIT Level-2 Pipeline (UL2P) version V5.6. The final products generated by the UL2P include FITS images of the sky. The images cover the field of view with a pixel size of \( 0.41\arcsec \times 0.41\arcsec \). These images have been used for the present study. The pipeline corrects for various instrumental effects such as spacecraft drifts, jitters, thermal effects and other corrections required for astronomical imaging. The final output comprises of an image through each (NUV/FUV) filter along with the corresponding uncertainty image. The intensity unit of the images are in counts/second. The angular resolution achieved in the images is \( \sim 1.2\arcsec \), superior to that of GALEX (\( \sim 6\arcsec \)).

2.2 Additional Data Reduction and GALEX

Long (> 2000 sec) on-target observations of UVIT are generally split into exposures in multiple orbits (as UVIT can operate only during the ‘dark’ part of each orbit when the spacecraft is in earth’s shadow). The UL2P processes datasets from individual orbits to generate sky images from each of them as well as combined products from all orbits contributing to the on-target integration. The UL2P pipeline includes an Astrometry block at the very end of the processing sequence, which uses a set of brightest stars detected in the UV image and their coordinates are correlated with entries in the optical catalogue USNO-A2.0. In our case, the Astrometry block of UL2P was unable to refine the absolute aspect of the sky images due to the crowded field of NGC 2808. Accordingly, an additional reduction scheme was employed to improve the aspect. This scheme used IRAF task ‘CCMAP’ by considering 10 bright stars from the USNO-A2.0 catalog distributed across the field-of-view. The positions of the sources are found to be uncertain up to \( \sim 1.0\arcsec \) after the corrections were applied.

The images of NGC 2808 through the FUV filter F154W and NUV filter N242W are displayed in Fig. 1. A comparison between the images shows that NUV is substantially crowded across the field whereas FUV is relatively sparse, as expected. Thus, the stars in the inner central region were resolved in FUV, whereas in NUV the field is considerably crowded near the cluster core.

2.2.1 Photometry

We performed photometry on the images in order to extract the magnitudes of stars in all the UV filters. For this, we used a combination of DAOPHOT and SExtractor (SE). We employed the DAOPHOT subroutine, DAOFIND, to locate the stars in the field and PHOT for the initial level aperture photometry. The results from PHOT are used to construct a PSF model using bright stars in the field and then the subroutine ALLSTAR was used to perform the PSF photometry.

The central circular region (radius \( < 20\arcsec \)) in the NUV images is deliberately omitted from photometric analysis because of the inability of the software to resolve stars in this region. A number of faint stars were observed in the field in NUV, that were not detected by DAOPHOT. SE, on the other hand, performed better and was able to detect and carry out photometry on these stars. The integrated counts/sec corresponding to the brightness of a star through a filter was converted to the AB magnitude system after removing the sky background appropriately (which is minimal), taken from the neighbourhood. The AB magnitudes have been calculated using the following expression:

\[
m_{\text{AB}} = m_{\text{ZP}} - 2.5 \times \log(\text{CPS})
\]

Here, \( m_{\text{ZP}} \) represents the Zero-Point magnitude of the filter, taken from Tandon et al. (2017a), and CPS is the...
Table 1. Details of UVIT filters and observations of the globular cluster NGC 2808.

| Band | Filter  | Alternate Name | \(\lambda_{\text{mean}}\) (\(\text{Å}\)) | \(\Delta\lambda\) (\(\text{Å}\)) | ZP mag | Exposure Time (sec) | Sensitivity Limit (AB mag for SNR=3.5) | Number of stars | Number of Saturated stars |
|------|---------|----------------|----------------|----------------|--------|---------------------|---------------------------------------|----------------|--------------------------|
| FUV  | F154W   | BaF2           | 1541           | 380            | 17.77±0.01 | 4172               | 24.034                               | 905            | 1                        |
| FUV  | F169M   | Sapphire       | 1608           | 290            | 17.45±0.01 | 3553               | 23.548                               | 855            | 1                        |
| NUV  | N242W   | Silica         | 2196           | 785            | 19.810±0.002 | 403          | 23.542                               | 1556           | 21                       |
| NUV  | N219M   | NUVB15         | 2447           | 280            | 18.50±0.07  | 477             | 22.415                               | 905            | 2                        |
| NUV  | N245M   | NUVB13         | 2632           | 275            | 18.18±0.01  | 348             | 21.752                               | 1275           | 10                       |
| NUV  | N279N   | NUVN4          | 2792           | 90             | 16.50±0.01  | 2639           | 22.155                               | 1810           | 1                        |

Figure 2. The UVIT images of the globular cluster NGC 2808. The far-UV F154W image is shown on the left panel, while the near-UV N242W image is displayed in the right panel.

integrated counts/sec due to the star. The ZP magnitudes as well as their uncertainties are listed in Table 1. The error in AB magnitude for each UV filter has been estimated considering: (i) the uncertainties in CPS arising from Poisson noise of the photon-counting detector, and (ii) the error in the ZP magnitude from calibration uncertainties. A plot showing the variation of errors as a function of magnitude is displayed in the Fig. 3, each line representing one UV filter.

The bright stars in the field are likely to be affected by saturation. In particular, stars that are brighter than the Zero-point magnitude by 1.95 magnitude or more (in a given filter) are likely to be severely affected. We have corrected for saturation using the procedure described by Tandon et al. (2017a). The number of stars saturated in each filter is listed in Table 1. We find that the brightest star is heavily saturated in all the UV filters. This star is located at \((\alpha, \delta)_{\text{J2000}} = 9^\text{h} 11^\text{m} 33.32^\text{s}, -64^\circ 51’ 03”\), which is 3.25’ from the cluster centre. It was not possible to correct for saturation for this star and therefore, the given magnitudes of this stars represent lower limits to its brightness.

In addition to the above procedures, the field of NGC 2808 was also visually scrutinised through each filter in order to separate out closely stars that were identified as a single star by DAOPHOT and SE. The magnitudes of these stars were estimated manually through aperture photometry. Aperture photometry was also carried out for few faint stars that were not picked by either of the softwares. Finally, the stars detected through each filter was compiled to construct a catalogue of UV stars. It is to be noted that the number of stars detected through a given filter depends on the exposure time and effective area of the filter. In order to have a magnitude limited sample through each filter,
we considered those stars in the present study that were brighter than the magnitude corresponding to a signal-to-noise ratio of 3.5. The AB magnitudes corresponding to this sensitivity limit are given in Table 1. Note that these values represent native limits that have not been corrected for extinction. The total number of UV stars detected is 2253, of which 484 are common to all the UV filters. The number of stars detected through each UVIT filter is listed in Table 1. In the FUV, we detected more than 900 stars. Nearly double the number of stars were detected in few NUV filters.

2.2.2 Extinction Correction
Extinction correction of stellar magnitudes is important for ultraviolet wavebands. An accurate analysis requires the knowledge of foreground extinction of the cluster. The integrated color and spectral type of the cluster gives the value of selective extinction $(E_{B-V})$ to be 0.18 towards this cluster (Bedin et al. 2000). Adopting the ratio of total-to-selective extinction as $R_V = 3.1$ (Whitford 1958) for Milky Way, the extinction co-efficient in visible is $A_V = 0.54$. The $A_V$ is used to determine extinction co-efficients $A_\lambda$ for all passbands using the reddening relation of Cardelli et al. (1989). Table 2 summarizes the values of $A_\lambda$ estimated by interpolation.

### Table 2. Extinction values through the UVIT filters corresponding to $A_v=0.54$ based on the extinction law given by Cardelli et al. (1989).

| Filter  | $\lambda_{\text{mean}}$ (\AA) | $A_\lambda$ (mag) |
|---------|-----------------------------|-------------------|
| F154W   | 1541                        | 1.46              |
| F160M   | 1608                        | 1.43              |
| N242W   | 2418                        | 1.40              |
| N219M   | 2196                        | 1.77              |
| N245M   | 2447                        | 1.36              |
| N263M   | 2632                        | 1.18              |
| N279N   | 2792                        | 1.09              |

3 RESULTS
Having carried out photometry on the images of NGC 2808 and constructed a catalog of UV stars, we proceed towards the understanding of hot stellar populations that contribute to UV. We begin with understanding the magnitude distribution of stars through various filters.

3.1 UV Magnitude Distribution
The magnitude distribution of the UV stars of NGC 2808 through the various filters of AstroSat are displayed in Fig. 4. We observe that the distributions through both the FUV filters are unimodal and quite similar. Most of the stars lie in the magnitude range 16 – 19 mag, and the peak of the distribution is $\sim 18$ mag. The magnitude distributions display a sharp decline from the peak towards the brighter magnitudes whereas the drop is more gradual towards the fainter side. We expect the FUV field to be dominated by the hottest sub-populations of HB stars which is likely to explain the lack of bimodality in the distribution of the FUV magnitudes. The similarity in the magnitude distributions is attributed to the fact that the cut-off wavelengths of the two FUV filters are quite similar (1340 Å for F154W, and 1420 Å for F160M). This implies that the presence of any absorption lines in the cut-off interval, 1340 – 1420 Å is unlikely to play an important role in the hot stellar populations sampled by FUV. The FUV spectroscopy of hot stars in this cluster by Brown et al. (2012) confirms this view.

The NUV filters, on the other hand, exhibit unimodal and bimodal distributions. The filter N219M shows a single broad peak unlike the other NUV filters that display bimodality in their magnitude distributions. The presence of bimodal peaks primarily points towards the segregation of hot stellar populations in the respective filter, albeit in a complex way. The wide band NUV filter N242W displays two peaks, wherein the brighter (primary) distribution peaks at $\sim 18.5$ mag, has a larger number of stars, and is broad. The bimodal separation is observed at 20 mag in this filter. We note that sensitivity prevents the detection of cluster members beyond 22 mag, hence we refrain on commenting on the width of the secondary peak. The medium bandwidth filters include N219M, N245M and N263M. Among them, N219M which is the shortest waveband filter in NUV, displays a single peaked distribution centered around 17.5 mag. Moreover, the distribution is perceived to be skewed with a gradual decline towards the fainter side of the peak, unlike the lowering towards the brighter side. The other two medium band filters, N245M and N263M both display bimodality with the former showing a narrower secondary peak compared to the latter. N279N, the narrow band filter at the longest NUV waveband reveals a narrow primary distribution and broad secondary distribution. In the three NUV narrow and medium waveband filters displaying bimodality, we observe that the magnitude bin separating the primary and secondary distributions shifts towards the brighter side as the wavelength increases. This is likely to be related to the stellar population distribution and we discuss this in later sections.

3.2 Identification of hot stellar populations
NGC 2808 has been very well-studied at a multitude of wavelengths, spanning UV to near-infrared. Imaging as well as spectroscopy have led to an understanding of various stellar populations of this globular cluster. In this subsection, we elaborate on the identification of various hot stellar populations in our UV catalog from other works in literature. The purpose of the cross-identification is to understand and interpret the location of these populations in the color-magnitude space of the UV filters of AstroSat-UVIT.

- **Red Horizontal Branch and Blue Horizontal Branch stars:** Gratton et al. (2011) spectroscopically identified 49 RHB stars and 36 BHB stars in NGC 2808. The identification is based on the anti-correlation between Na and O discerned in HB stars of globular clusters. The RHBs stars are characterised by Na poor and O rich content while the BHB stars have Na rich and O poor composition (Gratton et al. 2011; Carretta et al. 2009). We find a match of 34 RHB and 35 BHB stars in the cluster as the rest are from the central region excluded from our analysis.
- **Extreme Horizontal Branch stars:** Moni Bidin et al. (2011) identified 8 EHB stars from the catalogue published.
Figure 4. The magnitude distribution of the cluster members of NGC 2808 through various AstroSat-UVIT filters. The total number of stars in each magnitude bin for NUV filters have been decomposed into various sub-groups of stars based on the classification from the CMD of N242W-N279N versus N242W (see Section 3.3.2). Note that ∼60% of total stars are detected in these two filters. The numbers of stars corresponding to each of the 4 sub-groups have been overplotted for each NUV filter. The histogram in the panel (a) shows the magnitude distribution of both the FUV filters, while panels (b), (c), (d), (e) and (f) exhibit the magnitude distributions through the NUV filters N242W, N219M, N245M, N263M, and N279N, respectively.

by Momany et al. (2003). They employed a temperature criterion of the zero age HB model in their optical color-magnitude diagram to identify the association. We have identified all the eight EHB sources in our catalogue.

- Blue-hook stars: Moehler et al. (2004) performed ground based spectroscopy for stars in NGC 2808 which were identified as BHk Stars. All these stars are located beyond 2′ from center of cluster. All the 19 BHk stars from their sample have been matched in our catalogue.

- Post-AGB, Post-Early AGB and AGB-manque stars: Schiavon et al. (2012) have studied several GCs in UV using GALEX, and published a list of PAGB, Post-early AGB and AGB-manque stars in these clusters. Towards NGC 2808, their list comprises 22 stars belonging to this UV-bright category. All these UV-bright stars have been identified in our catalogue.

We observe that there are overlaps between classifications among our cross-matched samples: 5 BHB stars are also classified as BHk stars, 2 stars are classified as BHB and PAGB, and 1 star is common in the catalogs of BHk and PAGB.

3.3 UVIT Color-Magnitude Diagrams

In this section, we discuss the UV color-magnitude diagrams and analyse them based on the known stars of different stellar populations. We continue to refer to the term ‘color’ inspite of the fact that responses of some filters overlap in wavelength. In other words, the ‘color’ derived from overlapping filters cannot be directly used as a proxy of effective temperature, although they are expected to be related in an intricate way. In certain cases, where the filter responses are completely non-overlapping (e.g. colours corresponding to FUV - NUV and N245M - N279N), they can directly probe the effective temperatures.

3.3.1 FUV - NUV Color-Magnitude diagram

Considering that we have 2 FUV filters and 5 NUV filters, a large number of color - magnitude diagrams (CMDs) are feasible. However, in the present work, we consider only those diagrams where we discern a notable segregation of stars. Among the two FUV filters, we can select any one, as the number of stars and magnitude distributions are similar. We consider F154W for the present case. Among the NUV filters, we use N279N as we find that the colors associated with this filter exhibit a bimodal distribution unlike the other filters. The CMD of F154W - N279N versus N279N is displayed in Fig. 5. Also overplotted on this CMD are the BHB, EHB, BHk and PAGB stars identified from literature (Sect. 3.2). The known RHB stars were not detected in FUV and hence they are not present among the sample. We observe that the various stellar groups appear well separated.

The BHB group of stars occupy the region associated within the color range -0.7 – 1 in the FUV - NUV color-magnitude plane. A majority of the stars detected in these two filters belong to the BHB group, evident from the color histogram. The stars hotter then BHB stars occupy a re-
region within the color range -2.5 - 0.5 on the color axis. This group of hotter HB stars comprises of EHB and BHk stars of the cluster. The BHB group is separated from the group of EHB and BHk stars by a jump, which is reported to be a ubiquitous feature of the GCs hosting BHB and EHB stars (Brown et al. 2001). This jump, also known as Momany jump (M-jump, Momany et al. 2004) corresponds to a temperature ~ 20,000K. In our filters, we associate this jump with a color corresponding to -0.7 mag. The BHks occupy the hotter end of the CMD while the EHB group is intermediate, between the BHk and BHB stars. There is a superluminous sub-population that occupies the magnitude range 17 - 14 in the FUV. These stars belong to the PAGB and Post-early AGB stages. The number of stars belonging to this group is smaller than the HB population, and they are sparsely distributed towards the brighter side of the magnitude range. There are a few stars that are subluminous in FUV and are very red in the CMD, encircled within a dashed ellipse in Fig. 5. It is possible that few of these belong to the blue straggler (BS) category (Brown et al. 2001). BS stars are more massive than the main sequence turn-off stars, and their presence is ascribed to mass transfer or collision (Mapelli et al. 2006; Carney et al. 2001). The blue square symbols in the figure represent stars classified as blue-tail stars, defined later in Sect. 3.3.2.

3.3.2 NUV - NUV Color-Magnitude Diagrams

In the NUV - NUV plane, we present two color-magnitude diagrams. We first select two NUV filters that probe distinct wavelength ranges with each filter exhibiting a bimodal distribution in magnitude, viz. N245M and N279N. The CMD of N245M - N279N versus N245M, constructed using these filters is shown in Fig. 6. The CMD reveals three prominent groups and the cluster members identified from literature help in ascertaining the nature of stars in each group. A clear gap is observed to run diagonally across the CMD that segregates one group of stars from the other two. The distinct gap can be characterised by a straight line in the CMD plane, given by the following expression:

\[ N245M = 1.2 \times (N245M - N279N) + 18.0 \]  

The filter names in the equations refer to magnitudes associated with the respective filter. To the upper right of the gap associated with Eqn. (1) lie the BHBs. The BHB group of stars are relatively bright in NUV and occupy the region on the brighter end of the magnitude axis but span a wide range on the color axis, -0.5 to 3. The sparse distribution of stars that are luminous represent the Post-AGB and Post-Early AGB stars. To the lower left of the gap are seen groups of stars belonging to the RHB, EHB and BHk stages. These sets of stars are divided into two groups with a gap that is not very broad. This gap can be represented by a straight line represented by the following equation:

\[ N245M = 2.5 \times (N279N - N245M) + 20.5 \]  

The RHB group occupies a region within the color range 0 to 2.5 while lying on the fainter end of the magnitude distribution in N245M filter. It is to be noted that this combination of filters helps in the identification of the RHB stars, which were not detected in FUV. The RHB stars are cooler and fainter as compared to hot BHB stars. As a result, they are very faint in FUV while they are relatively bright in NUV, enabling their detection. The second group of stars to the left of the gap occupying regions of brighter magnitude are the EHB and BHk stars. This group appears segregated with respect to the RHB group although the gap is not very broad.

An alternate combination of NUV filters that segregates the UV cluster members into four groups is the conjunction of N242W and N279N. These two NUV filters are not exclusive and the wavelength range of N279N filter lies within the broad band of N242W towards the red extremity. Both the filters show bimodal magnitude distributions, but the resultant color shows a unimodal distribution. This is apparent from the CMD constructed using N242W - N279N versus N242W, shown in Fig. 7. In this CMD arena, the filter combination enables a separation of cluster members
into four groups. The four stellar groups are designated as G1, G2, G3 and G4. The gaps separating the four groups are represented by lines, given by the following equations:

\[
N242W = 1.5 \times (N242W - N279N) + 18.1
\]  

\[
N242W = 2.0 \times (M279N - M242W) + 18.1
\]  

\[
M242W = 0.3 \times (N279N - M242W) + 20.1
\]  

As earlier, based on the identification of cluster members from previous studies, we attempt the recognition of different stellar groups. G1 comprises of BHB, Post-AGB and Post-early AGB stars. The BHB stars occupy the fainter end of this group and the UV super-luminous stars appear as the brighter extension of this group. G2 consists of EHB and BHk stars. Unlike the other two groups, G3 and G4 show unique features in the sense that RHB stars are present in both the groups. Most of the known RHB stars are present in G4, while few are brighter and present in G3. These two groups are distinguished by a gap suggesting the segregation of RHB stars into two groups.

In order to validate this segregation, we located the positions of these groups of RHB stars in the NUV-NUV CMD, which is shown in Fig. 6. The various groups of stars in the CMD are distinguished by different colors in Fig. 8. The two groups of RHB stars are clearly differentiated in this CMD, although no gap is present between the two groups. The G4 stars are bluer than the RHB stars of G3 in the N245M - N279N color and the merging of the two classes appears gradual. This visually demonstrates the presence of two groups of RHB stars in this cluster. We notice that few G4 stars also belong to the EHB - BHk categories of stars. We speculated on the nature of these stars and found that these stars are FUV bright. This group of stars is unlikely to be affiliated to the RHB group since they are hot enough to be observed in FUV filters. Their distribution in CMD constructed using filters F154W and N279N indicates that these belong to the hot HB group. We term these stars as blue tail stars, as their behaviour is different from the RHB stars of G3 in the N245M - N279N color and NUV-NUV CMD considered earlier, i.e. N245M - N279N versus N245M (Fig. 6). The various Groups of stars in the CMD are distinguished by different colors in Fig. 8. The two groups of RHB stars are clearly differentiated in this CMD, although no gap is present between the two groups. The G4 stars are bluer than the RHB stars of G3 in the N245M - N279N color and the merging of the two classes appears gradual. This visually demonstrates the presence of two groups of RHB stars in this cluster. We notice that few G4 stars also belong to the EHB - BHk categories of stars. We speculated on the nature of these stars and found that these stars are FUV bright. This group of stars is unlikely to be affiliated to the RHB group since they are hot enough to be observed in FUV filters. Their distribution in CMD constructed using filters F154W and N279N indicates that these belong to the hot HB group. We term these stars as blue tail stars, as their nature (EHB/BHk member) is not certain.

We distinguish between the two RHB groups (excluding the blue tail members), by naming the RHB stars in G3 as RHBI and those in G4 as RHBII. We note that few RHB members detected in the N242W and N279N filters are not detected above the considered sensitivity limits of N245M. However, they are faint and have been detected, albeit with a lower signal-to-noise ratio (SNR), \( 2.5 \lesssim \text{SNR} \lesssim 3.5 \). These have also been plotted with their respective error bars in Fig. 8 to increase the sample size of these RHB groups in the CMD. We find that the broad progression of RHBI and RHBII towards red color continues to hold. Our Group classification based on detection in filters N242W and N279N leads to identification of 621 stars in G1, 143 stars in G2, 247 stars in G3 (24 Blue tail stars and 223 RHBI stars), and 267 stars in G4.

### 3.4 GAIA Color-Magnitude Diagram of UVIT Counterparts

We plot the hot UVIT stars in an optical colour-magnitude diagram to distinguish their location. We use the GAIA-DR2 catalog (Gaia Collaboration et al. 2018) to identify and cross-match the UVIT sources. For a search radius of 1", we find that 1267 UVIT stars have GAIA counterparts. The photometric magnitudes of these stars through the GAIA Blue-Photometer (BP: 330 - 680 nm) and Red-Photometer (RP: 640 - 1000 nm) passbands (Gaia Collaboration et al. 2016) have been used to create a colour-magnitude diagram (BP - RP versus BP) as the wavelength overlap is minimal. The GAIA colour-magnitude diagram is shown in Fig. 9. A gap is evident in the BP - RP colour corresponding to \( \sim 7.5 \) mag. The counterparts of UVIT stars belonging to various groups: G1, G2, G3 and G4 are marked with different symbols. We notice a conspicuous trend among the UVIT groups. Most of the G1 stars are concentrated towards the blue bank of the gap and there are few which lie on the brighter side of the BP magnitude range. This is in accordance with expectation as G1 comprises of BHB as well as the bright Post AGB and Post-early AGB stars. G2, comprising of EHB and BHk stars lie towards the fainter end of the blue branch. G3 and G4, that comprise of RHB stars are congregated towards the redder precints of the CMD. G3 and G4 stars occupy distinct regions in the CMD although the transition from G3 to G4 is progressive in terms of brightness. They occupy the same range in colour: 0.8 -
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Figure 7. The color-magnitude diagram constructed using N242W - N279N versus N242W. The green filled circles represent stars common to N242W and N279N filters which have not been identified in earlier studies. The other symbols are the same as those shown in figure 5. The solid lines are used to demarcate the gaps (discussed in the text) and are represented by Eqs. 3, 4 and 5.

Figure 8. The color-magnitude diagram constructed using N245M - N279N versus N245M. The colours represent different groups of stars identified from Fig. 7. The open symbols with errorbars (shown in grey) represent stars below the sensitivity limit considered, i.e. stars identified in these two filters (N245W and N79N) whose $2.5 \leq SNR \leq 3.5$.

Figure 9. The color-magnitude diagram constructed using BP - RP versus BP passbands of GAIA showing stars detected with UVIT. The stars identified as G1, G2, G3 and G4 represent different groups of stars identified from Fig. 7. The black filled circles represent the other stars detected with the UVIT.

1.2. As the overlap between the BP and RP filters is small ($\sim 40$ nm), the colour can be used as an approximate temperature proxy. The notion that the two RHB groups have similar temperature ranges corroborates well with our findings from the UVIT colour-magnitude diagram of N245M - N279N versus N245M (Fig. 8).

3.5 Radial Density Distribution of UVIT cluster members

Having discerned the hot cluster members based on their location in the CMDs, we proceed towards inspecting the relative distributions of various stellar groups across the cluster. In order to accomplish this, we ascertain the radial distance of each star from the cluster centre, taken as $(\alpha, \delta)_{2000} = 9^h12^m03.10^s, -64^\circ51'48.6''$ and estimate the surface density of stars in annular regions about the centre. The histogram displaying the radial surface density distribution of all stars in the cluster is shown in the top panel of Fig. 10. Stars have been detected up to an outer radius of 17'16. Since the pointing of UVIT during our observations of NGC 2808 was not centered at the cluster centre, we consider a symmetric region about the centre, which corresponds to a radius of 10'82. We note that the tidal radius of the cluster is 15'55 (Bedin et al. 2000). The radial region within the two vertical dashed lines (corresponding to 60'' and 10'82, respectively) represents the region where the stars extracted are believed to be largely complete. We have tested the completeness of our sample by adding artificial stars of varying intensity to the images and extracted them using the methods described earlier. For instance, we find that the extraction is 100% complete in N242W for stars up to extinction corrected magnitude of 20.2 mag from the central 60'' outwards. We find that this completeness magnitude represents the brighter edge of G4 group of stars (see Fig. 7). It is to be noted that 100% completeness is achieved at fainter magnitudes in the outer regions as the cluster spatial density decreases. The radial profile plot of G4 is therefore for a sample that is incomplete in the inner regions.
We observe a bimodality in the magnitude distributions of stars detected in most of the NUV filters. We investigate the nature of the bimodality observed in different filters based on our classification of the cluster members into distinct groups. It is to be noted that the group classification is applicable to the subpopulation (~60%) that have been detected in both the filters N242W and N279N. Fig. 4 displays the contributions of G1 (BHB and PAGB), G2 (EHB and BHk), G3 (RHBI and blue tail) and G4 (RHBII) populations to the total number of stars in the magnitude distribution. For all the NUV filters, we find that the BHB or G1 stars always lie on the brighter end of magnitude range whereas the RHB stars from G4 and G3 constitute the red edge of the histograms.

We perceive that the contributions of various group of stars giving rise to bimodality is different in the UV wavebands (filters) under consideration. In the broad band N242W filter, the bimodality essentially arises due to differences in luminosities of RHBI and RHBII, leading to a gap that defines the bimodality. The blue tail population of G3 has an overlap with the G2 population. The luminosities of EHB and BHk stars (G2 population) is intermediate to the RHB and BHB stars. The latter constitute the brighter extremity of the primary peak. In N245M and N263M, we notice that the bimodality appears to be due to the contrast in luminosities between the RHB and hot HB populations. In N279N, the narrow primary peak is composed of hot BHB stars (i.e. G1), while the broad secondary peak has contributions from the remaining populations. Another striking feature is the shift of magnitude distribution of G2 stars from N219M to N279N filters. The median of G2 magnitude distribution becomes fainter (by ~0.8 mag) from N219M to N279N filter, i.e. as wavelength increases. Considering that they represent the hottest HB populations, this is in accordance with expectation. The RHB group of stars are barely detected in N219M filter. This particular waveband effectively probes the shortest of the NUV wavelengths. Hence we attribute the relative lack of detection of RHB stars to their lower photospheric temperatures.

The magnitude corresponding to the minimum between the peaks of the bimodal distribution also shifts with wavelength: 19.8 mag in N245M, 19.1 mag in N263M and 18.3 mag in N279N. In other words, the specific flux density establishing the bimodality becomes larger with increasing wavelength. As the flux contribution by specific groups to a given filter is a reflection of the underlying stellar atmospheric processes, detailed stellar evolution modeling is vital for understanding the nature of the bimodality and the specific flux density defining the bimodality. The evolution of bimodality with wavelength observed for NGC 2808 demonstrates the power of UVIT’s multiple filters to advance our understanding of stellar atmospheric processes of the RHB group.

4.2 Gaps in UVIT CMDs

The UV magnitude distributions also manifest as gaps and accumulations of stars in specific regions of CMDs. In F154W - N279N CMD, the gap that separates the BHB

Figure 10. Histogram representing the radial distribution of the stellar surface density in steps of 20″. The regions in the top panel window displays the surface density distribution of all the stars that are detected through UVIT. The other panels represent the distribution of stars belonging to G1, G2, G3 and G4 respectively. In the window displaying G3, red indicates all the G3 stars while the black line outlines distribution of stars that belong to G3 but are also observed in FUV filters. The distribution plot of the detected G4 stars is shown in grey as the sample is incomplete towards the central regions.

The surface radial density distributions of the total number of stars as well as various groups of stars is displayed in Fig. 10. The radial density distribution of total number of stars is seen to decline with distance from the cluster centre. We observe that G1 or the number of post-AGB as well as BHB stars falls off with radial distance monotonically. The stars belonging to G2 category, i.e. EHB and BHk display a flattened distribution till ~100″ and the number declines thereafter. This is in contrast to the radial distributions of G3 and G4 that appear to be nearly uniformly distributed across the cluster. G3 comprises RHBI stars as well as blue tail stars, while G4 consists of RHBII stars. We observe that in G3, the blue-tail stars group close to the centre. Both RHBI and RHBII stars are found to extend to outer radial regions till the cluster tidal radius.

4 DISCUSSION

Gaps and jumps have been demonstrated to be ubiquitous features in the CMDs and color-index diagrams (CID) of HB populations in globular clusters. These are believed to be intricately linked to inherent processes in stellar interiors and atmospheres (Brown et al. 2016). We have observed this cluster anew in the near and far-ultraviolet space using UVIT filters spanning across the wavelength range 130 – 300 nm.
from the EHB and BHk stars can be attributed to the bi-modality in the magnitude distribution of N279N filter. This specific FUV - NUV CMD can be compared to that constructed by Brown et al. (2001) for the same cluster using filters similar to the ones used in the current work: HST STIS FUV/F25QTZ and NUV/F25CN270 filters for the same cluster. It is to be noted that a direct comparison of CMDs is difficult in the absence of colour equations connecting the two photometric systems with different filter characteristics. Consequently, the gap separating the BHB stars from the EHB and BHks are perceived at different values of color and magnitude.

The BHB population provides a tighter clustering unlike the EHB and BHk populations of stars (see Fig 7). We note that the blue tail stars appear to belong to the group of EHBs and lie close to the gap. However, they are different from EHBs and BHks, as is evident from the N242W - N279N CMD. In addition, we observe from the FUV - NUV CMD that there are a group of objects located in the region where ZAMS track is expected. These are encircled in Fig. 5 and we suspect them to be BS candidates. These stars are expected to lie at the fainter end of the extension of zero age HB loci, as demonstrated by Brown et al. (2001).

The gap separating the BHB from the EHBs is the M - jump (Momany et al. 2004), corresponding to T ∼20,000 K. This gap is prevalent in numerous globular clusters (Brown et al. 2016). This M - jump appears between G1 and G2 stars in the N245M - N279N CMD (Fig 6). This CMD shows a broad starless gap separating the BHBs (G1) from other groups of stars that includes EHBs, BHks and RHBs. The progression from RHBs (G3 and G4) to G2 is gradual and a tentative paucity of stars is seen between the RHB group and G2. The same M - jump that separates BHBs from EHBs and BHks, also extends further and segregates the BHBs and RHBs. This would suggest a similar underlying mechanism for separation between both the groups. Thus, the UV CMDs enable us to analyse the gaps as a common feature unlike the optical and UV-optical CMDs (Ferraro et al. 1998) and CIDs which divulge the gaps as discrete, i.e. in distinct locations.

The two RHB groups of stars are set apart by a marginal gap (described by Eqn. 5) in the N242W - N279N CMD. This gap is not apparent in CID of this cluster described by Brown et al. (2016). It is likely that this is analogous to the two RHB groups observed in other metal-rich globular clusters such as NGC 6637, NGC 6352, NGC 5927. While there is a large body of work on the extended HB morphology of NGC 2808, we could not find any work that substantiates the presence of two RHB groups of stars in this cluster. There is, however, the tantalising spectroscopic evidence provided by Marino et al. (2014) based on Na abundances of 96 HB stars that indicated that there could be two groups of RHB stars. Based on the Na content, they observed a bimodality which is not consistent with a single RHB population. They also observed a gradient in colors of these RHB stars but the uncertainties did not allow the confirmation about the nature of star-formation histories. With our N242W - N279N diagram, we distinctly perceive two groups of RHB stars. It is difficult to gauge their temperatures as the progression is gradual and both groups occupy similar temperature ranges evident from the colour-magnitude diagrams of N245M - N279W and BP - RP. It is likely that this is responsible for the lack of distinct bimodality in Na-abundance. We also observe that the G3 stars are brighter compared to the G4 stars. Thus, our photometric method enables the segregation of 490 RHB stars into the two groups.

### 4.3 Multiple UV populations in view of evolutionary scenarios

We next speculate on the origin of the RHB groups of stars. The distinct RHB groups in UV CMDs appear to point towards distinct star formation histories. The main-sequence (MS) of this GC is comprised of quintuplet stellar populations, labeled A, B, C, D and E by Milone et al. (2015). The mid-blue and extreme-blue MS (D and E, respectively), associated with higher helium enrichments, are believed to give rise to the BHB and EHB stars. The red MS (rMS) comprises of three branches (A, B and C) and we anticipate that the two RHB groups are plausibly related to the rMS branches discerned. The rMS branches are likely to have evolved to distinct RHB populations. However, which rMS groups and/or their combinations are responsible for RHB and RHBII is not known with the information available and detailed investigation is required to ascertain this.

In case of NGC 2808, different stellar populations show distinct spatial distributions. While the hotter G1 and G2 are concentrated in the core, the cooler RHB stars (G3 and G4) have a distribution extending outwards. Earlier studies investigating the radial distribution of HB stars (Iannicola et al. 2009; Bedin et al. 2000) did not find any significant radial trend from centre to outward regions. However at 1.5σ level, Iannicola et al. (2009) did find a trend, i.e. a deficiency in RHB stars towards the centre (radius < 35′′). An alternate study by Simioni et al. (2016) compares the radial distributions of the multiple populations of MS stars (i.e. A, B, C, D, E). These authors find that the D and E stars are concentrated towards the centre while the A+B+C stars extend outwards with a progressive scarcity towards the central region (they investigated annular regions between 45′′ and 9′′). As the D and E are believed to be the pre-cursors of G1 and G2 helium enhanced second generation of stars, these results are in agreement with our observations. This is because according to multiple population formation models (D’Antona & Caloi 2008), intermediate and blue MS would give rise to BHB and EHB stars. The scarcity of A+B+C stars towards the centre observed by Simioni et al. (2016) is difficult to directly corroborate with the spatial distribution of RHB stars from this work. However, the fact these groups of stars are extended to large radial distance suggests that the RHB groups of stars could represent the evolved populations of the rMS.

The spatial distribution of cluster members from the present study can be used to comment on the evolutionary scenarios proposed for the formation of multiple populations. We consider the AGB ejecta scenario where the formation of multiple generations of stars in globular clusters has been investigated through simulations (D’Ercole et al. 2008; D’Antona & Caloi 2008). In this framework, the gas near the centre is cleared by the supernova explosions of first generation stars. A cooling flow develops as a result of which the CNO processed winds from massive AGBs are retained by the cluster potential as they are slow. This provides the gas necessary for the formation of second generation stars.
The first generation stars, associated with RHB, have normal helium abundance while the later generation BHB, EHB and BHk stars have enhanced helium abundances as they are formed from processed gas. Thus, it is expected that the later generation stars would be concentrated within the inner core of a more extended first generation population.

More recently, D’Antona et al. (2016) have attempted to explain the five generations of stars using the same model. In addition to AGB ejecta, they also invoke the accretion of pristine gas to explain the multiple populations. They arrive at the BEDCA scenario for the main sequences A, B, C, D and E. According to this scenario, the rMS type B corresponds to the first generation, while C and A types of rMS correspond to the last generation. The mid- and extreme-blue MS (D and E) correspond to the stars of the second and third generations, respectively. From our spatial distribution, we find that the hot HB population (G1 and G2) are abundant near the centre which is consistent with the premise that they are related to the D and E types. The G1 population which corresponds to MS type D is more centrally concentrated than G2, associated with EHBs and BHks (MS type E). The normalised spatial density distribution is shown in Fig. 11 for comparison. This is in excellent agreement with the suggestion that G1 stars which are more centrally concentrated formed later than G2 with a broader distribution.

The spatial distribution of the RHB classes are similar and show broad radial distributions compared to G1 and G2. If the RHB groups of stars correspond to evolution associated with the A and/or C rMS, then it is expected that few of these stars would be more concentrated towards the centre than G1 and G2, rather than distributed in the outer radial regions. It is possible that G3 RHBII stars are related to B rMS. Whether G4 type RHBII stars are associated with earliest B rMS or later AC rMS is difficult to authenticate due to lack of detected stars near the central region. The spatial density of RHBII and RHBII stars in the outer radial regions are higher compared to G1 and G2 stars. If the rMS are believed to be the precursors to the RHB (as suggested from similar spatial distributions of rMS and RHB stars), then it would appear that all groups of rMS formed within short times of each other, unlike what has been proposed in the BEDCA model. With the current RHB identification, it should be possible to carry out detailed spectroscopic studies and ascertain abundances that will shed light on the formation scenario in greater detail.

5 CONCLUSIONS

The photometric results for the Galactic globular cluster NGC 2808 from an ultraviolet study using multiple filter of UVIT, shows that the cluster is an abode to exotic stellar population that includes EHB and BHk stars apart from the classic HB stars (BHB and RHB). We have identified for the first time the split in RHB population photometrically. This is another supporting evidence for multiple stellar population that resides in the GC. Based on CMDs constructed using multiple FUV and NUV filters, we conclude that:

(i) There is a bimodal distribution of stars on FUV-NUV CMD, which divides the group of stars into BHB and hot blue stars such as EHB and BHk stars.
(ii) A third group of stars is also seen in N245M - N279N CMD which comprises of relatively cooler RHB stars.
(iii) In N242W - N279N CMD, the RHB of the cluster segregates into two subgroups (RHBII and RHBIII).
(iv) Based on the gaps seen in N242W - N279N CMD, the RHB of the cluster is divided into four groups, G1 are the BHB and PAGB, G2 comprises the EHB and BHk stars, G3 has mixed population of blue tail stars and RHBII stars, and G4 consists of cool RHBII stars.

The presence of stellar groups that may belong to various generations of stellar population is backed by the spatial extent of various group of stars and conforms broadly with the suggested evolutionary scenarios. The hotter stars are concentrated towards the center of the cluster, while the cool stars are spread uniformly across the field of view away from the cluster center. There is a need to understand the formation as well as spatial distribution of the RHB groups of stars in the cluster as it does not comply with the current AGB ejecta models of formation of RHBs. The current study provides new information and insights regarding NGC 2808, which can be useful to understand the genesis of globular clusters.

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