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Simulation of old open clusters for UVIT on ASTROSAT

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Abstract The Ultra Violet Imaging Telescope (UVIT) is one of the payloads on the first Indian multiwavelength satellite ASTROSAT, which is expected to be launched by the Indian Space Research Organisation (ISRO) in the year 2015. We have performed simulations of UV studies of old open clusters for the UVIT. The colour magnitude diagrams (CMDs) and spatial appearances have been created using 10 filters associated with the FUV channel (130–180 nm) and NUV channel (200–300 nm) that are available for observations on the UVIT, for the three old open clusters M67, NGC 188 and NGC 6791. The CMDs are simulated for different filter combinations, and they are used to identify the loci of various evolutionary sequences, white dwarfs, blue stragglers, red giants, subgiants, turn off stars and the main sequence of the clusters. The present work helps in identifying a potential area of study in the case of these three old open clusters by considering the availability of filters and the detection limits of the instrument. We also recommend filter combinations, which can be used to detect and study the above mentioned evolutionary stages. The simulations and the results presented here are essential for the optimal use of the UVIT for studies of old open clusters.

Key words: (stars:) blue stragglers — (stars:) Hertzsprung-Russell and C-M diagrams — (stars:) white dwarfs — (Galaxy:) open clusters and associations: individual (M67, NGC 188, NGC 6791) — ultraviolet: stars

1 INTRODUCTION

Ultraviolet (UV) studies have a vital role in the understanding of stellar evolutionary stages such as blue stragglers, white dwarfs (WDs), hot subdwarfs and other exotic populations of hot stars. Previous studies in the UV region have shown spectacular results and have added vital information to studies of stellar evolution. The UV images of older clusters provide one of the best means to study low mass hot stars, subdwarfs, WDs, blue stragglers and horizontal branch stars. In the UV range, most cool stars appear very faint, resulting in less crowding of stars in the cluster region. Hence one can easily identify peculiar stars that emit in the UV and study their properties. With the need to study celestial objects in the UV band, many missions have been previously launched and UVIT will add to the list with its unique characteristics of having a wide field of view of $0.5°$, high spatial resolution of $1.8''$ and a large set of filters that will allow the scientific community to pursue

major scientific research in the UV region, both new as well as follow-ups of recent discoveries. Siegel et al. (2014), in their table 1, list previous UV missions and their associated characteristics.

UVIT has a twin 38 cm telescope with three channels: far-ultraviolet (FUV:130–180 nm), near-ultraviolet (NUV:200–300 nm) and visible (350–550 nm). One of the telescopes carries the FUV channel and the other telescope can record in both the NUV and visible channels. The incoming beam is divided by a dichroic beam splitter, where the visible beam is transmitted and the NUV beam is reflected. The visible channel will primarily provide information about the pointing. All three channels use Micro Channel Plate (MCP) based intensified Star250 CMOS imaging detectors to record frames at the rate of 29 frames sec^{-1}. UVIT aims to provide flux calibrated images. The images on the detector are recorded in either photon counting mode (high gain) or integrating mode (low gain).

The UVIT carries a set of filters mounted on the filter wheel located close to the focal plane between the primary mirror and the detector, for selection of the spectral band within each of the three channels (viz., FUV, NUV and VIS). Five filters and two gratings for the FUV channel, six filters and a grating for the NUV channel and five filters for the visible channel are placed on the filter wheels that have a diameter of 50 mm. The wheel also carries a blind that can block any radiation from directly reaching the detector. The filter wheels have an independent drive mechanism to bring the desired filter into the optical path of the telescope. The wavelength range of the five FUV filters are BaF2 (137 – 175 nm), Sapphire (146 – 175 nm), Silica (166 – 178 nm), CaF2-1 (130 – 175 nm) and CaF2-2 (130 – 175 nm). The wavelength range of the five NUV filters are Silica (200 – 280 nm), NUVB13 (230 – 260 nm), NUVB15 (206 – 233 nm), NUVB4 (250 – 278 nm) and NUVN2 (275 – 284 nm). The passband wavelength of all the filters as well as the effective area is given in Subramaniam (2012).

For the present study, we have selected three well known old open clusters: M67, NGC 188 and NGC 6791. This study presents estimations of the flux from various stars in these clusters in the UVIT filters and creates the fundamental colour magnitude diagram (CMD) in various filter combinations. The simulated CMDs developed and presented in this study will be used as diagnostic tools when the actual data are obtained from the mission. We have summarised the previous studies of the three open clusters below and the basic parameters are tabulated in Table 1.

Table 1 Basic Parameters Describing the Three Old Open Clusters

Parameter	M67	NGC 188	NGC 6791
R.A. (2000)	$8^h 51^m 18^s$	$00^h 47^m 28^s$	$19^h 20^m 53^s$
Dec. (2000)	$+11°48'00''$	$+85°15'18''$	$+37°46'18''$
Gal. longitude	215.696	122.843	69.959
Gal. latitude	31.896	22.384	10.904
log age	9.409	9.632	9.643
$E(B-V)$ (mag)	0.059	0.082	0.117
Distance (pc)	908	2047	4100
Metallicity	Solar	–0.02	0.15

1.1 M67

M67 is an old open cluster, located at a distance of 908 pc in the constellation Cancer. The age of the cluster is found to be 4 Gyr (VandenBerg & Stetson 2004). This old cluster has evolved phases of single as well as binary star evolution, such as blue stragglers, WDs, cataclysmic variables, a yellow giant with a WD companion, etc. Landsman et al. (1998) reported the analysis of images obtained with the Ultraviolet Imaging Telescope (UIT) of the old open clusters M67, NGC 188 and NGC 6791. The UIT detected 20 stars in cluster M67, which include 11 blue stragglers, seven WDs

and a yellow giant WD binary. A hot luminous companion for two blue stragglers (S975 and S1082) has been suggested by ultraviolet photometry. The study also shows the dominance of blue stragglers in the integrated spectrum at wavelengths shorter than 2600 Å. Siegel et al. (2014) presented the Swift Ultraviolet/Optical Telescope (UVOT) observations of this cluster in the optical and NUV region, and their CMDs. Montgomery et al. (1993) investigated the central one half degree of the old open cluster M67 using U, B, V and I photometric data to a limiting magnitude of $V = 20$. We use this photometry for our simulations. They have determined the possibility of 38% of the stars in the cluster being binary systems.

1.2 NGC 188

NGC 188 is one of the older clusters in our Galaxy, which has been widely studied due to its richness in stars and also heavy elements, age and its location in the Galactic plane. The cluster is located at a distance of 2047 pc. The age of the cluster is determined to be 6.0 Gyr (Caputo et al. 1990) and was more recently found to be 6.8 Gyr (VandenBerg & Stetson 2004). The metallicity of the cluster is found to be [Fe/H] = 0.075±0.045 from the analysis of low resolution spectra of K giants (Worthey & Jowett 2003). This cluster is also one of the important clusters chosen by the WIYN Open Cluster Study (Mathieu 2000). The cluster has been studied to understand the origin of blue stragglers and the existence of contact binaries (Leonard & Linnell 1992). The central concentration of blue stragglers is greater than that of giants and 15 blue stragglers have been observed in cluster NGC 188 (McClure & Twarog 1977). In our study, we used the photometric data of 1514 stars from (Sarajedini et al. 1999). Recently, Siegel et al. (2014) presented the Swift UVOT observations of this cluster, in the optical and NUV region and their CMDs.

1.3 NGC 6791

NGC 6791 is one of the oldest open cluster candidates with an age of 8 Gyr (Chaboyer et al. 1999). It has been studied because it is metal-rich, and has a large population of stars, especially evolved hot stars (Liebert et al. 1994). A photometric study of the cluster field in V and B led to the discovery of 17 variable stars (Kaluzny & Rucinski 1993) with the majority being in the turn off region, of which eight are contact binaries and nine others are variables. Two of the contact binaries which exhibited various evolutionary stages were observed to be blue stragglers. They suspect one of the variables to be a binary composed of a red dwarf and hot subdwarf. Montgomery et al. (1994) used photoelectric and charge-coupled device (CCD) photometry to study this cluster and we have used these data for our simulations. The cluster has also been studied in the UV region by Buzzoni et al. (2012), which shows the phenomenon of UV upturn that is similar to what is observed in the most active cases of UV-upturn in elliptical galaxies. This phenomenon is primarily observed due to the hot stellar component with $T_{\text{eff}} \geq 10\,000$ K, which contributes UV luminosity of the cluster shortward of 2500 Å. The cluster also has a dozen hot stars along the extreme horizontal branch.

The paper is arranged as follows. Section 2 deals with the methods used for the estimation of FUV and NUV magnitudes and simulations of CMDs. Section 3 presents and discusses the FUV CMDs, NUV CMDs and NUV-Visual CMDs. Section 4 discusses the colour-colour diagrams. Section 5 presents the simulated spatial appearance of the clusters in a few of the FUV and NUV filters. Section 6 provides a comparison with Galaxy Evolution Explorer (GALEX) and the Swift UVOT. The discussion and conclusions are presented in Section 7.

2 SIMULATION OF MAGNITUDES AND CMDS

We first estimate the expected flux for stars in all the UVIT filters in each of the open clusters, using the optical data mentioned in the previous section. We have used the V magnitude and $(B-V)$ colour of stars to estimate the flux. In order to achieve this, we first estimate the expected count rate using the
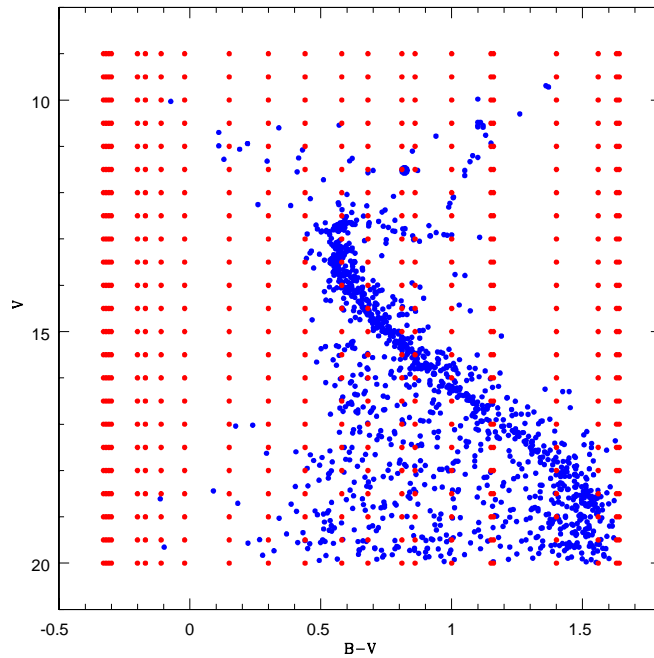
Fig. 1 Parameter grid to obtain the count rate and magnitude for the old open cluster M67.

UVIT exposure time calculator (ETC) developed by the Indian Institute of Astrophysics, available in the web site *http://uvit.iiap.res.in/*. This tool predicts the count rates for stars with specific spectral type and magnitude, by convolving the effective area curve of the filters with the Kurucz model for spectral type. The web site also gives the effective area curves of the filters used in this study. The tool estimates the count rates for one star at a time for a given magnitude and spectral type. As the star clusters have a large number of stars, with a range of magnitude and spectral type, it is not efficient to use this tool directly. Hence, we created a grid of count rates for a range of magnitudes (e.g., $V = 10, 11, 12, 13, 14$, etc.) and spectral types or their equivalent $(B - V)$ (e.g., $(B - V) =$ –0.5, –0.3, –0.1, 0, ...), such that the cluster stars have magnitudes and colours within this range. As the ETC does not accept the colour index $(B - V)$ as input, the data are taken from Zombeck (1990) for all the spectral types. That is, we generated count rates for all filters for these fixed values of V and $(B - V)$ and created a grid as shown in Figure 1, where we have also overplotted the CMD of M67. For each point on the grid, the count rates in all 10 UVIT filters are obtained using the ETC. As stars in the cluster can have any value of V and $(B - V)$ (in between the grid points, as shown in Fig. 1), we created a two dimensional interpolation method to estimate the count rate for any value of V and $(B - V)$ within the grid. The interpolation should be able to handle multiple stars at a time, as the clusters have several hundred to a few thousand stars. Thus the tool we have developed helps to compute the expected counts of a large number of stars with known V and $(B - V)$ values in one go. The tool needs the grid values, in the form of a table, as input to the program. This tool will be made available to the community in a web based form.

The present work utilizes the V and $(B - V)$ data of 1271 stars of the old open cluster M67 from Montgomery et al. (1993) and similar data of two blue stragglers and four WD stars in the cluster from Landsman et al. (1998). For the cluster NGC 188, similar data of 1514 stars are taken from Sarajedini et al. (1999), and for NGC 6791 the data of 1654 stars are from Montgomery et al.

(1994). The above mentioned tool is used to estimate the count rates of all these stars in the 10 UVIT filters. The next task is to estimate the magnitudes based on the count rates. The FUV and NUV magnitudes are calculated using the formulae given below:

$$FUVmag = -2.5 \times \log(\text{count rate}) + 15 \,, \tag{1}$$

$$NUVmag = -2.5 \times \log(\text{count rate}) + 16 \,. \tag{2}$$

The FUV and NUV magnitudes are derived by assuming the above zero point. This zero point is assumed based on the expected count rates for known sources. This number will be refined after the launch and is expected to change. Thus, the magnitudes and colours estimated and shown in the CMD are only indicative. As we do not use these for any quantitative estimates, but only as guidance to plan our observations, these estimations are considered for further analysis. We expect to obtain an AB magnitude of 20 mag in the FUV for an integration time of 200 s. We also expect to detect sources up to 20 mag in all filters, and perhaps a bit fainter in the broadband filters.

The magnitudes estimated above are used to plot the cluster CMDs in various filter combinations and the spatial appearance of the cluster in various filters. The filter combinations are selected based on their wavelength coverage. The cluster evolutionary sequences look different in the FUV and NUV filter combinations with respect to the optical CMD. The following section presents the UV CMDs, and identification and discussion of various evolutionary sequences.

3 RESULTS: SIMULATED UV CMDS OF M67, NGC 188 AND NGC 6791

One of the main aims of this study is to identify the locations of various evolutionary sequences in the UV CMD with the help of known clusters and their population. In order to achieve this, we need to mark stars in various sequences in the optical CMD. Thus, a CMD is plotted with V on the vertical axis and $B - V$ on the horizontal axis (Fig. 2) using the above mentioned data. We have selected stars with magnitude $V < 20$. In Figure 2, blue stragglers, WDs and red giants have been identified, along with the subgiants, turn off and main sequence stars for the old open clusters M67, NGC 188 and NGC 6791. The different coloured symbols are used in the plot to cross identify them in the FUV and NUV plots. These symbols have the same meaning in all the FUV and NUV CMDs.

The region between $V < 12.4$ and $(B - V) < 0.6$ is identified as the location of blue stragglers for M67, $V \leq 14.5$ and $(B - V) \leq 0.6$ for the cluster NGC 188 and $V < 17$ and $(B - V) < 0.7$ for the cluster NGC 6791 as seen in Figure 2. Blue stragglers are located within a magnitude range of 3 mag. In Figure 2 the subgiant branch is identified within the region $0.7 < (B - V) < 1.2$ and $12.5 < V < 13.5$ for M67, $0.73 < (B - V) < 1.4$ and $14.8 < V < 15.2$ for NGC 188 and $1 < (B - V) < 1.2$ and $17.2 < V < 17.5$ for NGC 6791. The location of the red giant branch is in the region demarcated by $(B - V) > 0.9$ and $V < 12.5$ for the cluster M67, $(B - V) \geq 0.9$ and $V \leq 14.5$ for cluster NGC 188 and $(B - V) \geq 1.2$ and V< 17 for cluster NGC 6791. The WDs are in the hotter and fainter part of the CMD. The yellow giant WD binary is located at a $V = 11.52$ and $(B - V) = 0.82$ in the M67 cluster.

3.1 FUV CMDs

The FUV channel has five filters: BaF2, CaF2-1, CaF2-2, Sapphire and Silica. The FUV filter wavelength range lies between 130 and 180 nm. As the two CaF2 filters are similar, we only use CaF2-1 for our analysis. We plotted CMDs for various combinations of these filters. For this study, we present the CMD up to 23 mag. We estimated the expected error to be ~ 0.2 mag at FUV 20 mag, based on the error in the corresponding V and $(B - V)$ values. We do not show the errors as this makes it difficult to interpret the CMD. In all the FUV CMDs, we could detect blue stragglers, WDs and the tip of the turn off stars for the cluster M67. The tip of the turn off stars are not observed in NGC 188 and only the blue stragglers are observed in the cluster NGC 6791. In M67, we identify
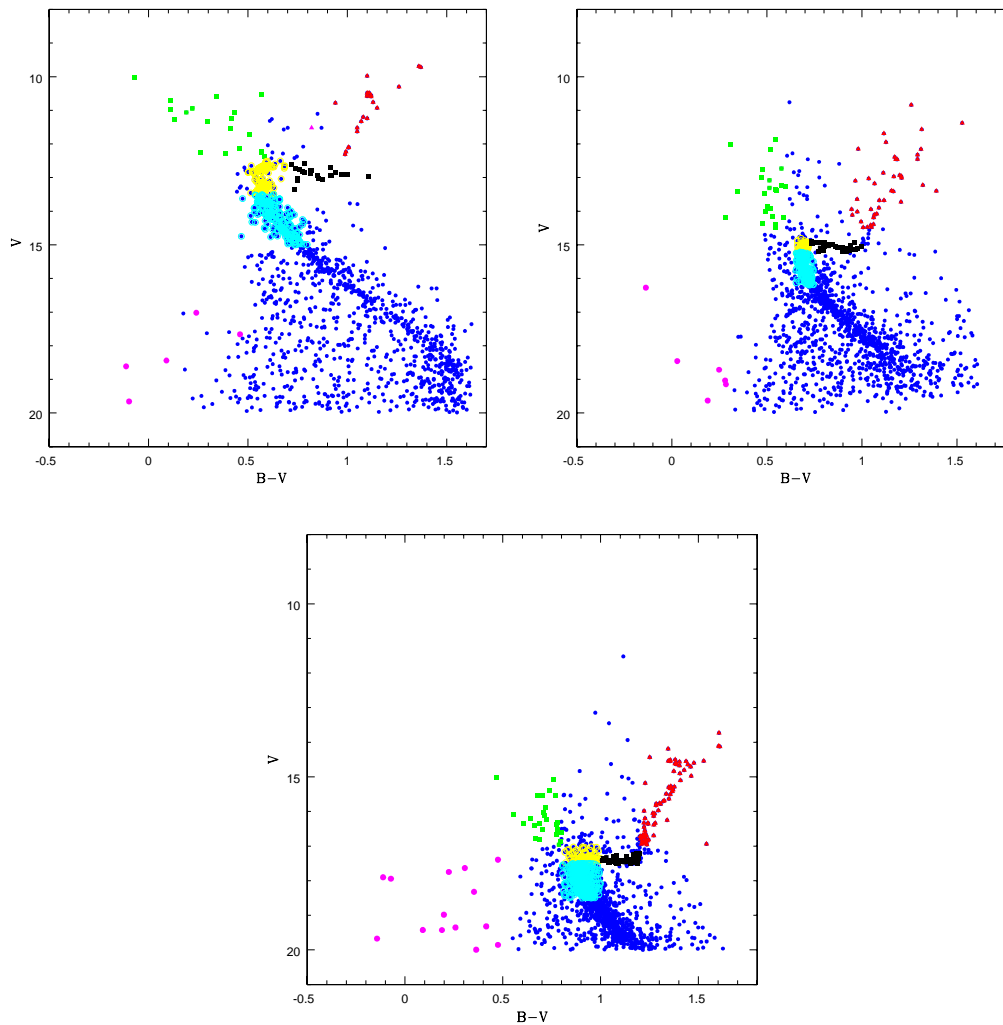
Fig. 2 The optical CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*). Stars selected for the study are blue stragglers (*green filled squares*), white dwarfs (*magenta filled circles*), red giants (*red filled triangles*), subgiants (*black filled squares*), turn off (*yellow open circles*) and the top part of the main sequence (*cyan open circles*).

stars near the turn off (yellow points) and those below the turn off (cyan points) located in a very similar area of the CMD. We also notice that these stars are located either very close together or are mixed up, making it difficult to identify a distinct location for these evolutionary phases.

3.1.1 CMDs using the BaF2 filter

We created three CMDs using BaF2 magnitudes and three colours estimated using CaF2-1, Sapphire and Silica. The three CMDs for each cluster are shown in Figure 3. We observe that the magnitude range occupied by the blue stragglers gets stretched from ≈ 3 magnitudes in the optical CMD to about 13 magnitudes in M67 and 7 magnitudes in NGC 188. We only detect one blue straggler in the
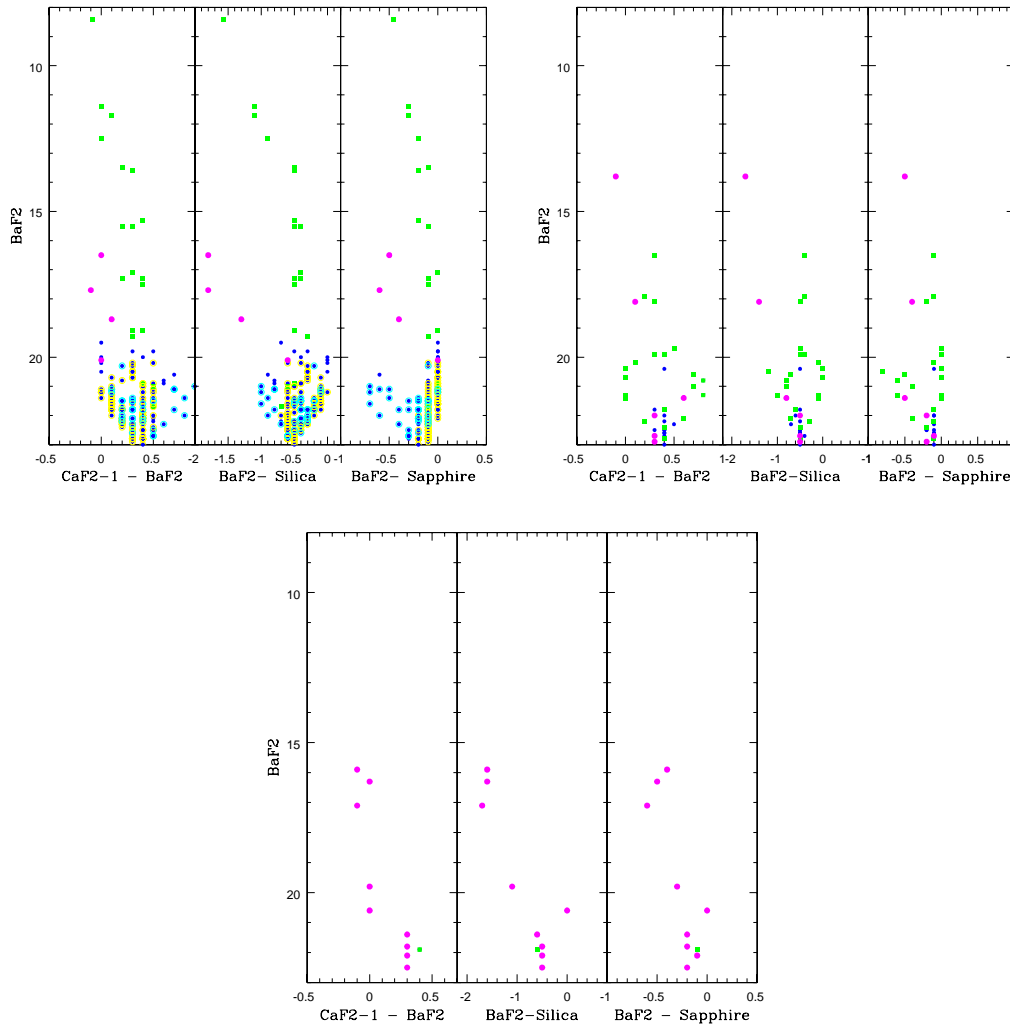
Fig. 3 FUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

cluster NGC 6791. It must be noted that the blue stragglers are treated as normal main sequence (MS) stars, when the count rates are estimated. The WDs and blue stragglers are seen to be well separated when the BaF2-Silica colour is used, as illustrated in the middle CMD of M67 and NGC 188. This filter combination also provides a large colour range for the WDs (≈ 1.5 magnitude). In these CMDs, only the tip of the turn off stars are observed in M67, whereas only the blue stragglers and WDs are observed in NGC 188 and NGC 6791.

3.1.2 CMDs using the CaF2 filter

In these CMDs, the CaF2-1 filter is taken as the magnitude in the vertical axis and plotted in combination with the other three FUV filters as the colour (Fig. 4). We observe that the number of blue stragglers and WDs does not change for different FUV filter combinations though there is a slight increase in the magnitude range for blue stragglers and WDs in all CaF2-1 filter combinations. The
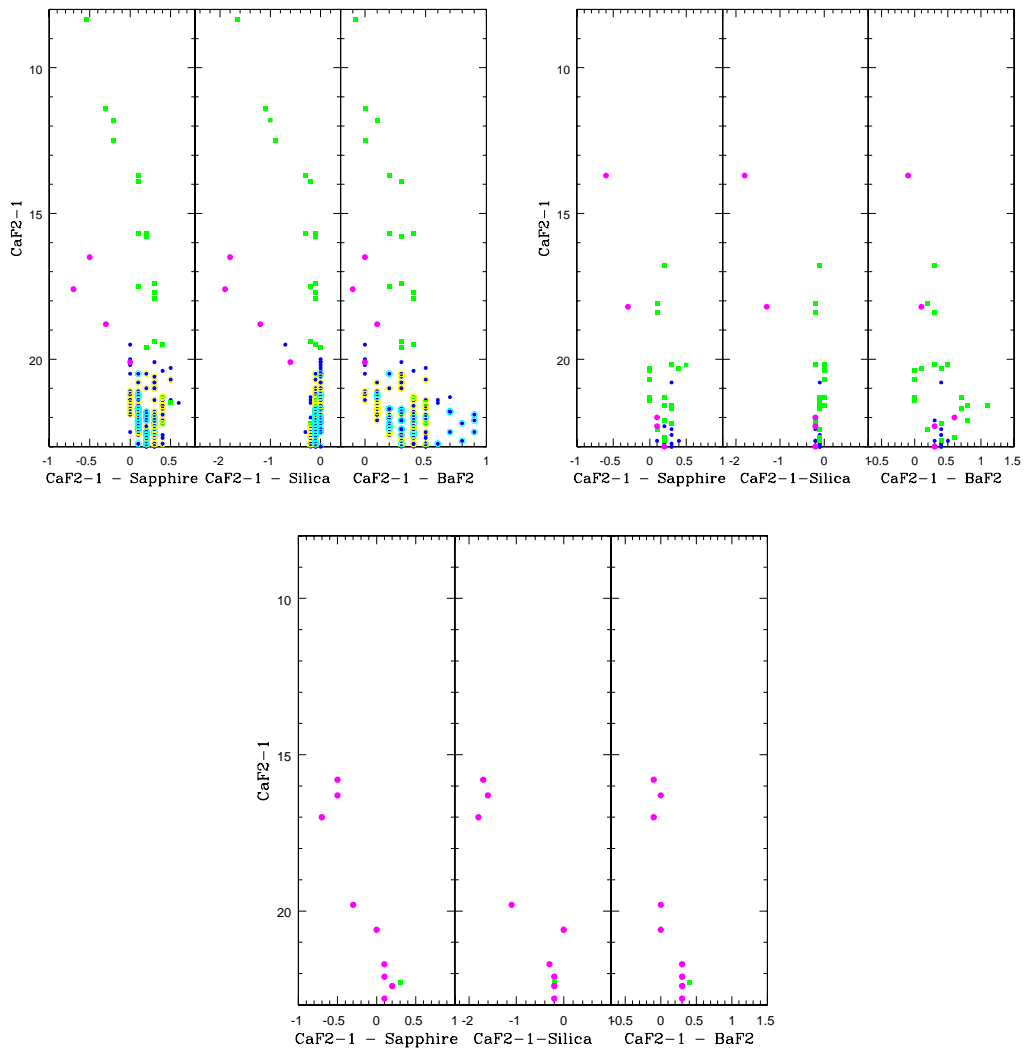
Fig. 4 FUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

turn off region of M67 is just fainter than ~ 20 mag. It is interesting to note that the turn off region has a wider colour range ($\sim$1 mag) in the CaF2$-$BaF2 filter combination, with a decreasing colour range in CaF2$-$Sapphire and CaF2$-$Silica combinations. Hence we suggest that the CaF2$-$BaF2 colour combination is best suited to study the turn off region of similar clusters. The CaF2$-$Silica combination has the maximum colour range and thus helps to separate WDs from blue stragglers, as suggested in the M67 CMD. Thus, this combination is likely to help in identifying new WDs.

3.1.3 CMDs using Sapphire and Silica filters

The CMDs with Sapphire and Silica magnitudes are presented in Figures 5 and 6 respectively. These CMDs appear similar to the CMDs created with BaF2 and CaF2 filters. In the case of Sapphire filter CMDs, we observe that the turn off stars and the tip of the main sequence in all the FUV CMDs are
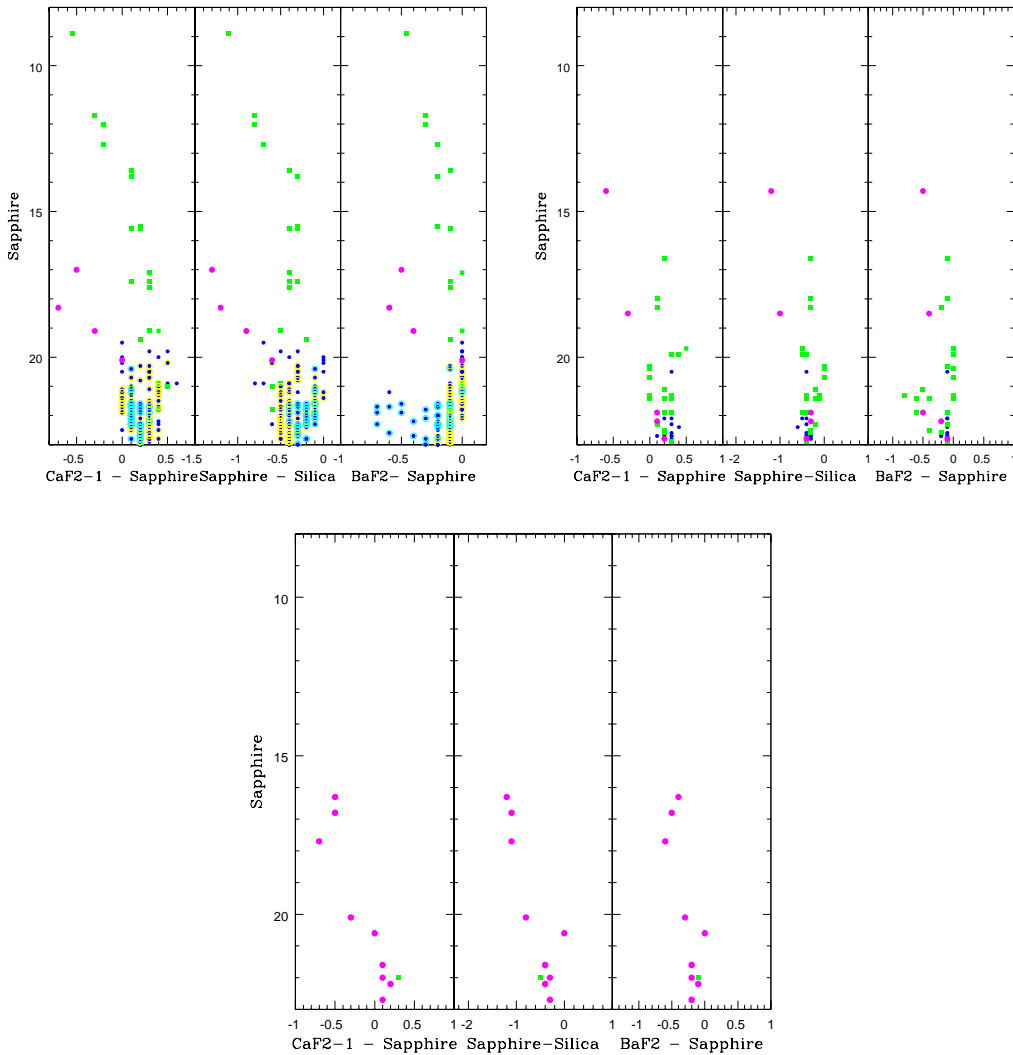
Fig. 5 FUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

bluer, due to the wavelength coverage of the Sapphire filter with respect to other filters. The Silica filter CMDs once again suggest that the CaF2−Silica colour combination has a large colour range, which helps to separate WDs. We do not notice any other specific advantage in these CMDs.

3.2 NUV CMDs

The NUV channel has five filters: NUVB13, NUVN2, NUVB4, NUVB15 and NUV Silica. We derived the magnitudes of stars in the three open clusters and these are used to create the CMDs with various combinations of these filters. For this study, we have shown the CMD up to 23 mag, such that we could consider detectable characteristics. We estimated the expected error to be 0.2 mag at 20 mag in NUV, based on the error in the corresponding V and $(B - V)$ values. We do not show the errors as they make it difficult to interpret the CMD. The NUV filter wavelength range is from
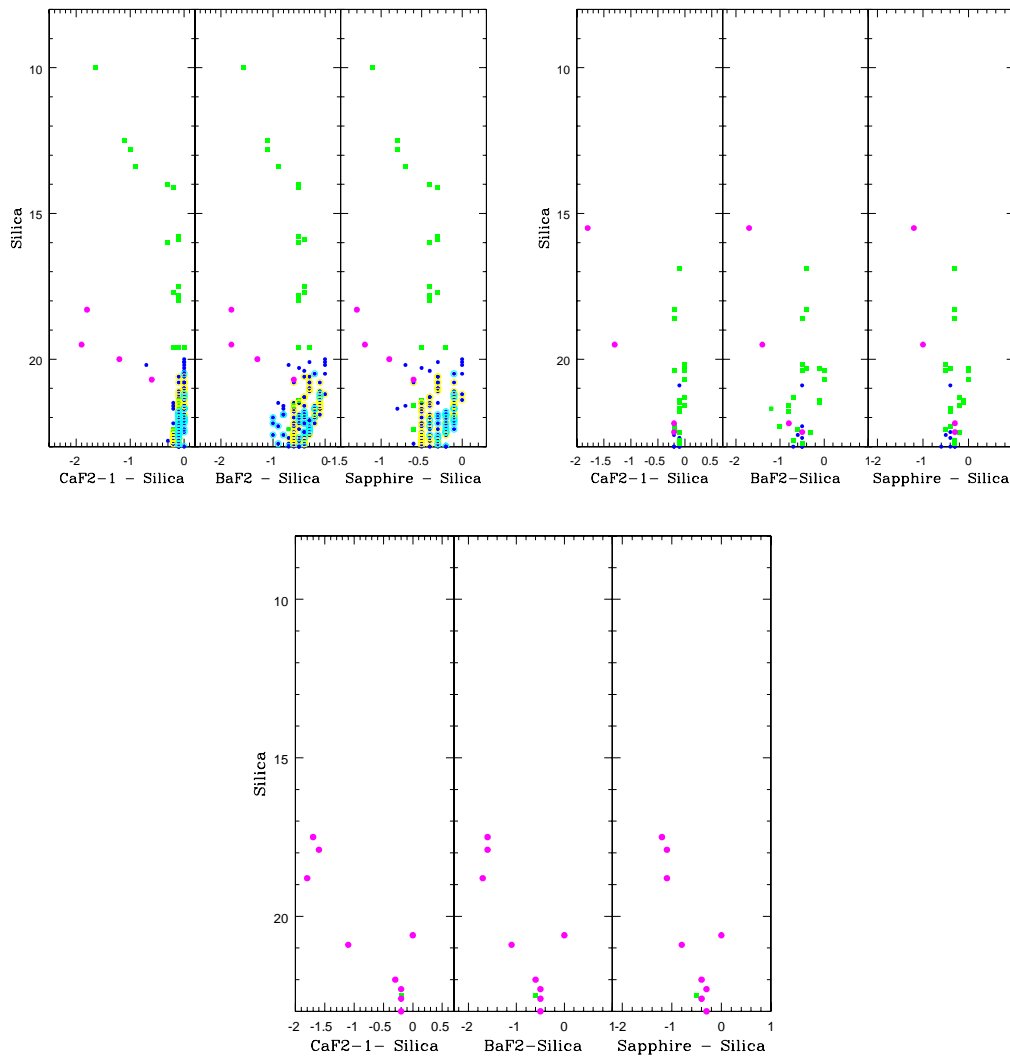
Fig. 6 FUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

200 to 300 nm. We observe blue stragglers, red giants, WDs, subgiants, turn off and main sequence stars. For simplicity, the following notations are used for the filters: B13 (NUVB13), N2 (NUVN2), B4 (NUVB4), B15 (NUVB15) and Silica (NUV Silica). Among these filters, B15 has a relatively poor efficiency.

In the optical CMD of M67, 20 blue stragglers, five WDs, a yellow giant-WD binary, 22 red giants, the subgiant branch, and turn off stars were identified. We identify the same number of stars in all the NUV CMDs, though with variations in their brightness and colour.

In Figure 7, we have plotted simulations from the B13 filter as magnitude on the vertical axis and combined it with different NUV filters to get the colour on the horizontal axis. Various evolutionary phases can be easily identified with the help of the colour code. The MS just below the turn off (cyan points) is stretched up to 5 magnitudes, whereas it is stretched to ∼1.5 magnitude in the V filter. Thus, this stretching of the MS near the turn off region can help in estimating the ages more
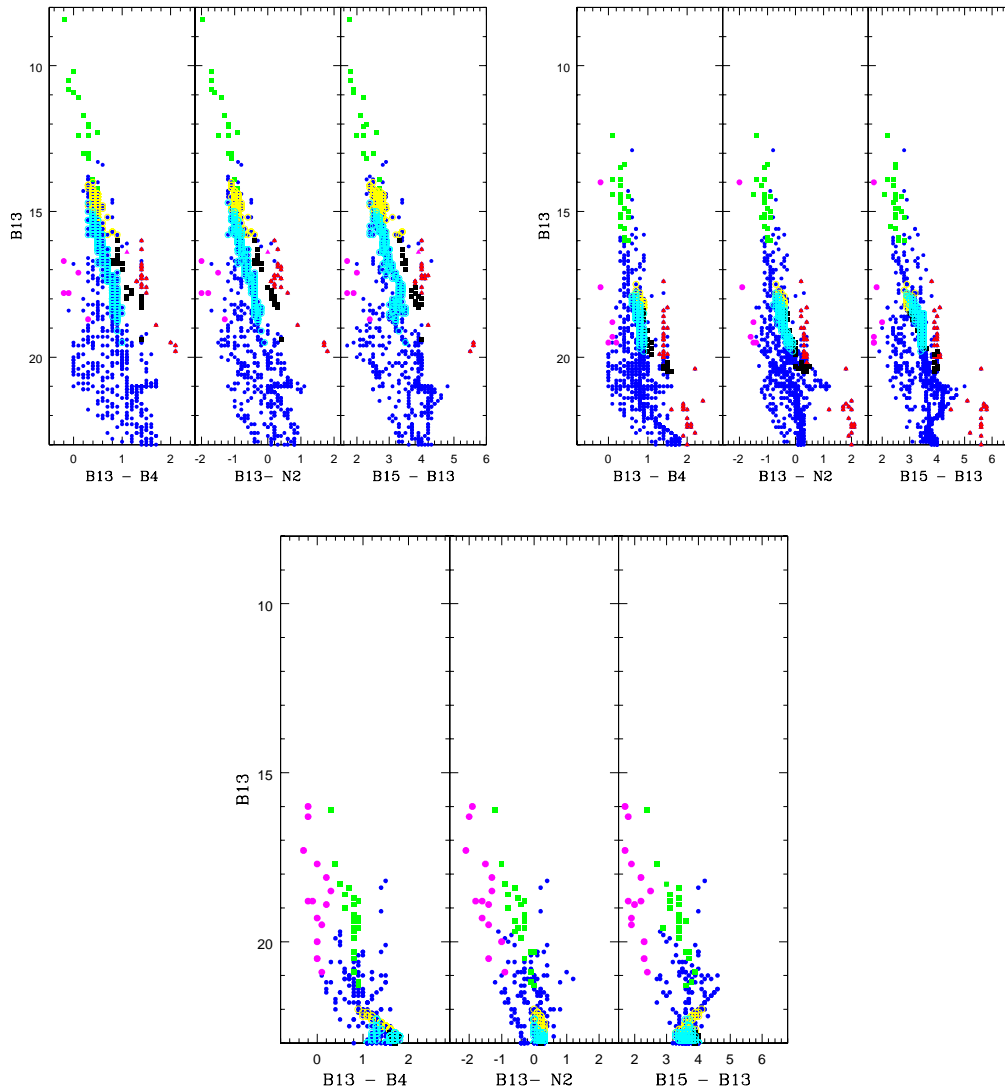
Fig. 7 NUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

accurately. The turn off stars can be identified as located parallel and close to cyan points, followed by the subgiant stars (black points). This suggests that the subgiant branch appears almost vertical and parallel to the MS in the NUV CMDs. The giant branch starts at the faintest end of the subgiant branch and appears as a vertical distribution. Thus, unless they are previously known or identified, it will not be possible to separate the MS stars from subgiants.

3.2.1 CMDs using the B13 filter

In Figure 7, we have shown the CMDs with values from the B13 filter. As expected, M67 has the brightest turn off and hence a good portion of the MS can be detected. In the case of NGC 188, the MS near the turn off is clearly seen. On the other hand, only the blue stragglers above the turn off can
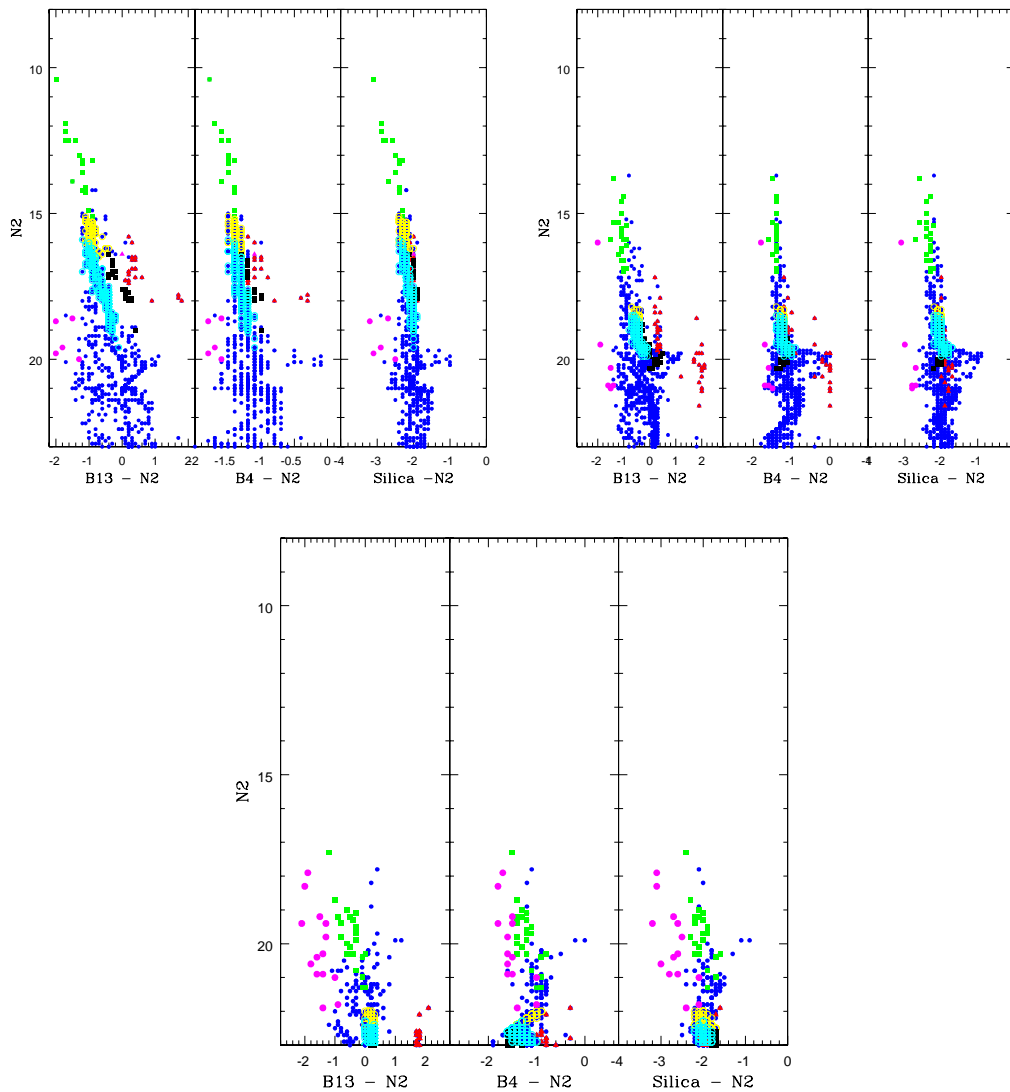
Fig. 8 NUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

be detected in the case of NGC 6791. The colour range which can be observed for the combinations shown suggest that the filter B13 with N2 has a better colour separation to study blue stragglers. Also, from Figure 7 (B13-N2 vs. B13) we observe that these stars appear bluer in this NUV CMD. However from Figure 7 (B15-B13 vs. B13), which has a good colour separation, the B15 filter may not be able to detect stars that appear red. The NUV CMD of B13-N2 vs. B13 is better for studies of subgiant branch stars, as they have better colour separation.

3.2.2 *CMDs using the N2 filter*

The NUV CMD for the cluster M67, with B13−N2 vs. N2 (Fig. 8), also supports the above inferences. In Figure 8, we can also notice that the upper MS, turn off, subgiant branch and the giants get
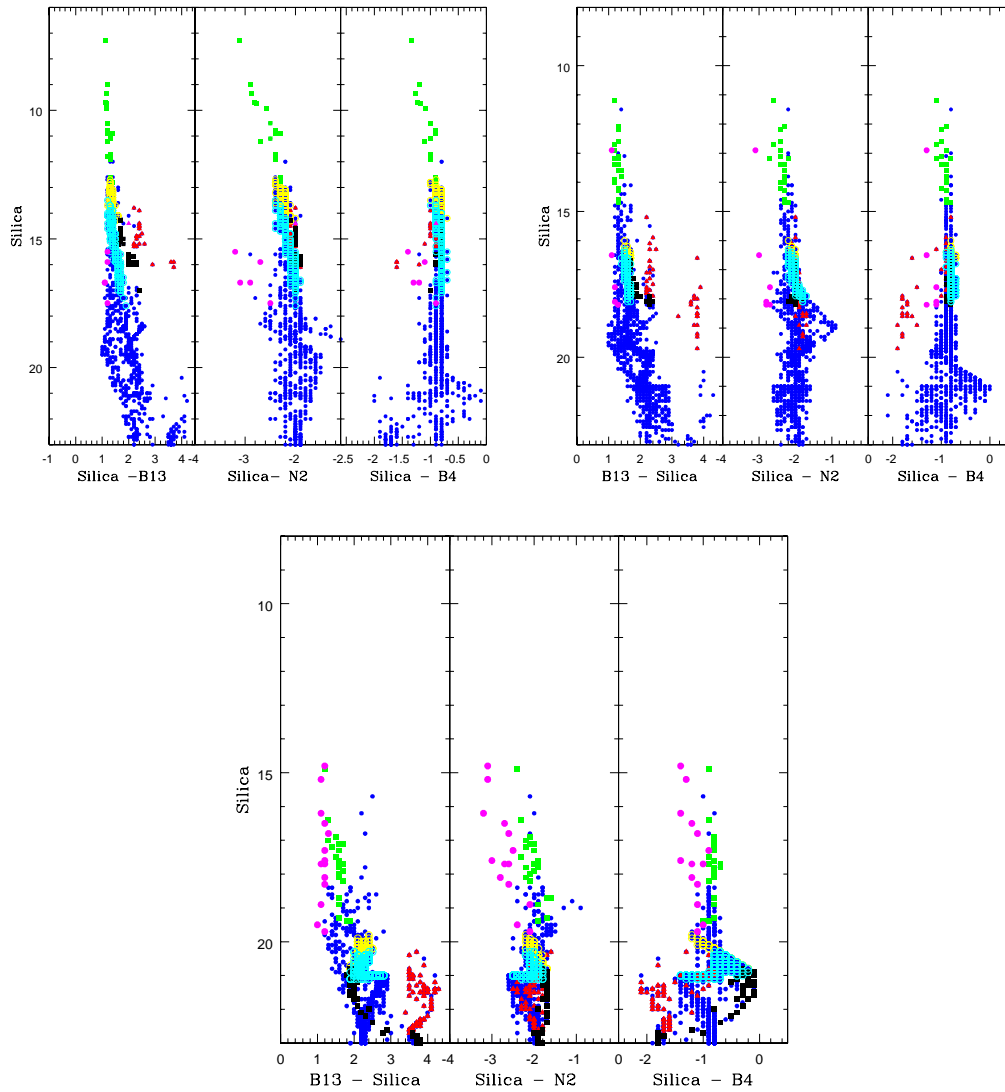
Fig. 9 NUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

narrowed down to a small range in colour. In the case of Silica−N2 colour, the WDs appear bluer, along with a larger range of colour for the entire stellar sequence.

3.2.3 CMDs using the Silica filter

In the Silica CMDs, shown in Figure 9, we observe a large colour range for the Silica−N2 colour. The CMD using B13−Silica colour separates the subgiant stars from the upper MS and red giants, but the WDs do not get separated from the MS. Also, the red giants are found to have very red colour, separating them from subgiants. The CMD with Silica−N2 colour separates the WDs, but the MS, subgiants and red giants do not get separated. The Silica−B4 colour makes the red giants bluer than

the MS, which is incorrect. This may be due to the combination of input spectra and the coverage. We plan to further investigate this problem in the future.

3.2.4 CMDs using the B4 filter

The B4 CMDs are shown in Figure 10. It can be seen that the CMD using the B13−B4 colour separates most of the sequences. On the other hand, the B4−N2 has a larger colour range. The colour derived using the silica filter has the same issues as mentioned above.

We do not present the CMDs using the B15 filter due to the poor efficiency of the filter, even though we have simulated them. We have presented the simulated CMDs in the FUV filters and NUV filters separately. It will not be a good idea to combine FUV with NUV, as only the blue stragglers and WDs are detected in the FUV. Hence, in order to study or distinguish between blue stragglers or WDs, it may be useful to combine any one of the FUV filters with the NUV filters. It will be a good idea to combine the NUV filter magnitudes with the V magnitude to create CMDs, as it is possible to detect a good fraction of the upper MS in the NUV filters. We present the CMD using the NUV silica filter and V magnitude in the next section.

3.3 NUV Silica vs. V CMD

For the NUV-V CMD, we chose the Silica filter in NUV as it has the largest wavelength coverage. We have shown the Silica vs. (Silica-V) CMD in Figure 11 for the three clusters studied here. We obtain a better and broader colour separation when compared to the FUV, NUV and optical CMDs. We observe the complete stellar sequence that is observed in the optical, but in this CMD, they have a wider colour separation.

The WDs and the blue stragglers have shifted to a bluer colour index. They also appear brighter in this filter combination and hence studying them in this filter combination is most appropriate. The upper MS, turn off, subgiants and the red giants can be separated due to the large colour range. These figures suggest that the NUV-V CMDs will be quite useful in separating stars that follow various evolutionary sequences, which can then be used in the analysis of the FUV and NUV CMDs. It is thus important to have V observations of the clusters which can then be combined with the UVIT observations.

4 COLOUR - COLOUR DIAGRAMS OF M67

As the UVIT has a large number of filters, it will be a good idea to check whether the colour-colour diagrams can be used as a diagnostic to identify any specific evolutional phase, or separate stars at various evolutionary phases.

In Figures 12, 13 and 14, we have shown various UV colours as a function of $(B - V)$ colour for the cluster M67. We see that many of the diagrams separate WDs and blue stragglers from the MS stars and red giants. On the other hand, the blue stragglers and WDs occupy a similar location, and MS and red giants also occupy a similar location in most of the colour-colour diagrams. In combination with the optical CMD, the colour-colour diagrams may be used to effectively separate hot stars in the cluster. We also plot similar diagrams for the other two clusters studied here, which also have similar characteristics. As M67 has a larger number of stars, we have only shown colour-colour diagrams for M67.

5 SPATIAL APPEARANCE OF M67, NGC 188 AND NGC 6791 IN THE FUV AND NUV FILTERS

It is important to have a finding chart for the object to be studied using UVIT. A finding chart will thus provide immediate confidence that the field observed is correct. The finding charts for the three
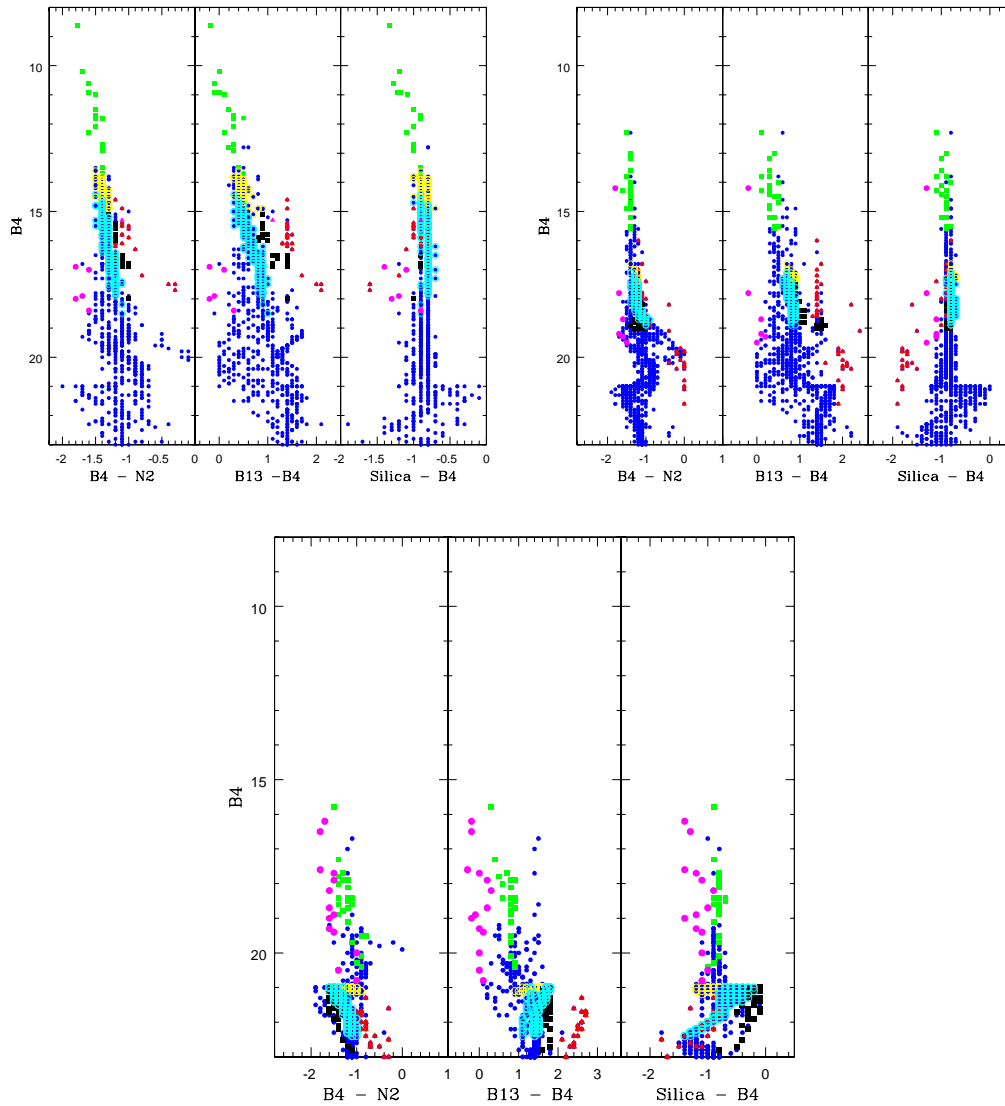
Fig. 10 NUV CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*).

clusters studied here are prepared using the magnitudes estimated in the CaF2-1 filter for FUV, and the Silica and B15 filters for NUV. The plots are made such that the sizes of the stars are scaled according to the magnitude in a way that brighter stars appear bigger. The spatial appearance of all three clusters is shown in Figures 15, 16 and 17.

We observe that there is relatively less crowding of stars in the FUV filters. Each point in the plot indicates a star, and only stars which are brighter appear in the diagram. Therefore, in the FUV, as suggested by the CMDs, all those we detect will be WDs and blue stragglers. Thus, Figures 15, 16 and 17 primarily show the location of these stars and will be useful when doing the actual observations.
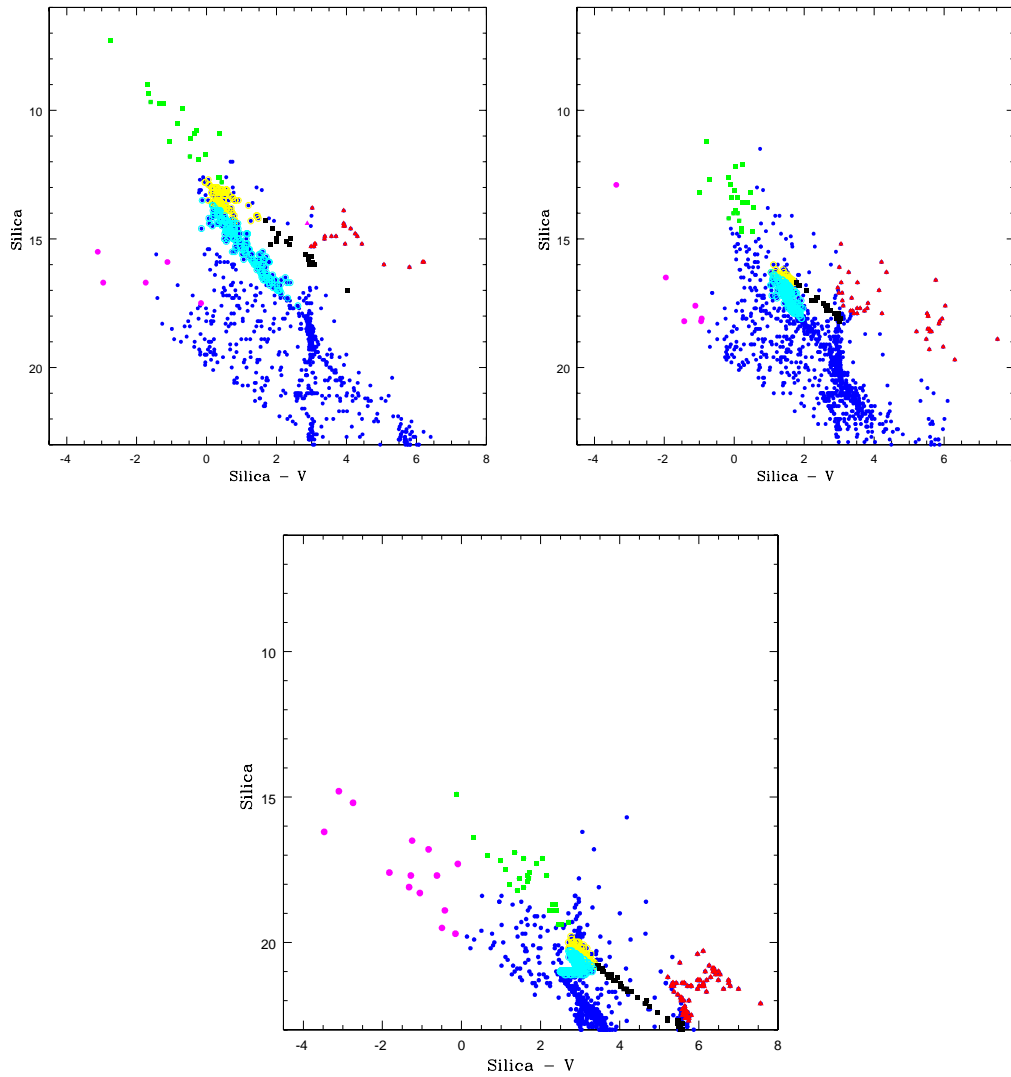
Fig. 11 NUV-*V* CMD of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*) of Silica-*V* vs. Silica.

We have presented the distribution in two NUV filters, Silica and B15. The spatial appearance of the cluster in these filters appears similar, but Silica will be more efficient due to its larger wavelength coverage. The appearance in NUV is very similar to that in optical, except that there is a variation in the relative brightness. Thus, the NUV field connects the optical and FUV field, such that the WDs and blue stragglers get progressively brighter. We expect that these finding charts will be helpful during actual observations. Siegel et al. (2014) presented the observed field of NGC 188 in their figure 1. As the field of view of UVOT is much smaller, they only presented the central region of the cluster. We are unable to perform a one-to-one comparison of our simulations with these observations, as the filter systems are different and the UVOT filters have high red leaks.
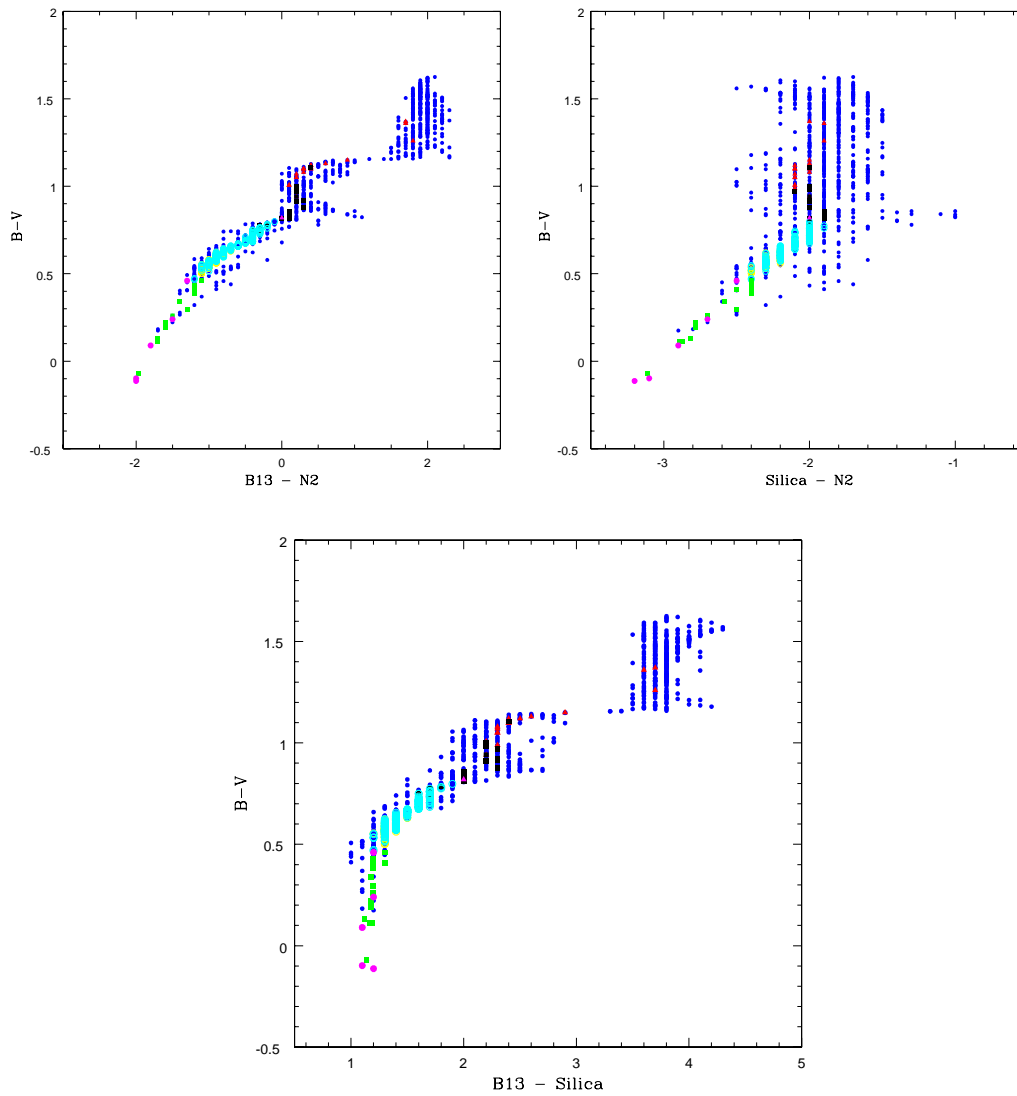
Fig. 12 Colour−Colour diagram of M67 with NUV filters and $B - V$ colours B13−N2 (*top left*), Silica−N2 (*top right*) and B13−Silica (*bottom*) vs. $B - V$.

6 COMPARISON WITH GALEX AND SWIFT UVOT

We compared our simulations with observations of M67 with GALEX, and two clusters with SWIFT UVOT. GALEX has two channels, NUV and FUV. The wavelength coverage of the GALEX NUV matches that of the NUV Silica filter in the UVIT. Similarly, the wavelength coverage of GALEX FUV matches that of the CaF2 filters in UVIT. As there are only a very small number of stars detected in the FUV region, we compare the NUV magnitudes of GALEX with simulated data for the filter NUV Silica, for the cluster M67. We have shown the simulated CMD and observed CMD for M67 from GALEX, side-by-side, in Figure 18. The locations of the MS, blue stragglers, subgiants and giants are very similar. This gives us confidence that the patterns and relative locations of various
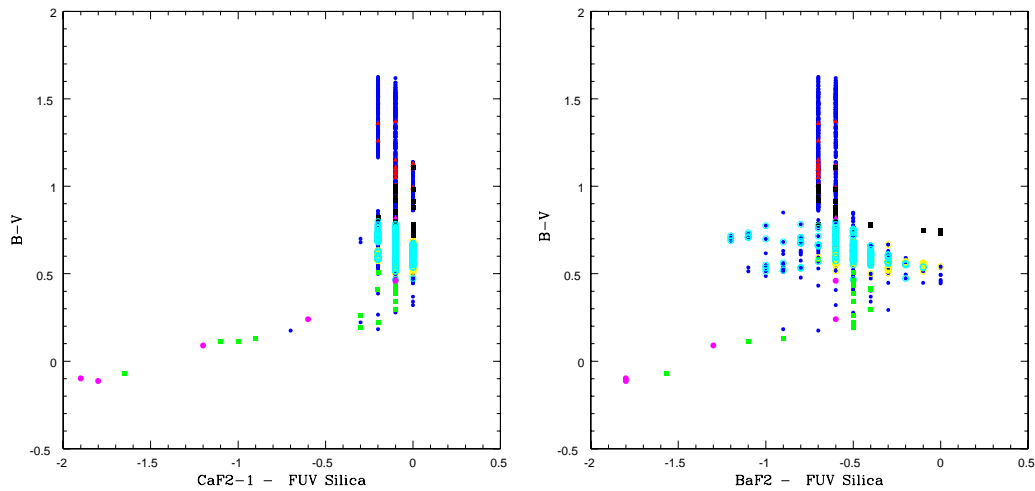
Fig. 13 Colour - Colour diagram of M67 with FUV filters and $B - V$ colour. *Left*: CaF2−FUV Silica vs. $B - V$. *Right*: BaF2- FUV Silica vs. $B - V$.
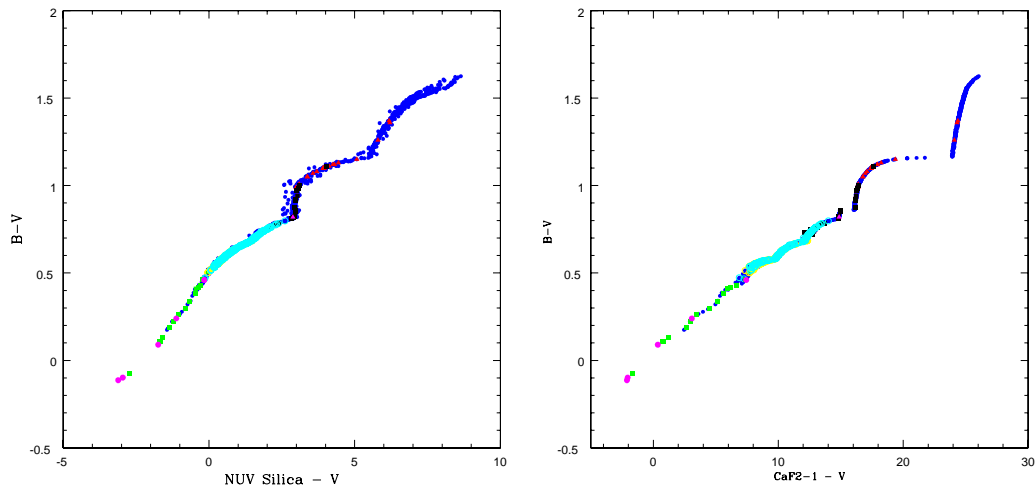

Fig. 14 Colour-Colour diagram of M67 using FUV and NUV filters $- V$ colour with $B - V$ colour *Left*: NUV Silica-V vs. $B - V$. *Right*: FUV CaF2-V vs. $B - V$.

stars presented in the simulated CMD are likely to be correct. The main difference between the two plots in Figure 18 is the difference in NUV magnitude and hence the colour, such that the simulated magnitudes are brighter. This is due to the adopted zero point. We computed the difference between the GALEX NUV and simulated magnitude (NUV Silica) as 4.1±0.4 mag for 59 common stars. This difference is the same as the difference in the adopted zero point for UVIT (16 mag) and that of GALEX (20.06 mag). Hence we believe that the shift in the magnitudes can be corrected with the correct estimation of the zero point, which will be done after the launch during the initial calibration phase. We also computed the difference between the GALEX FUV and the simulated FUV CaF2-1
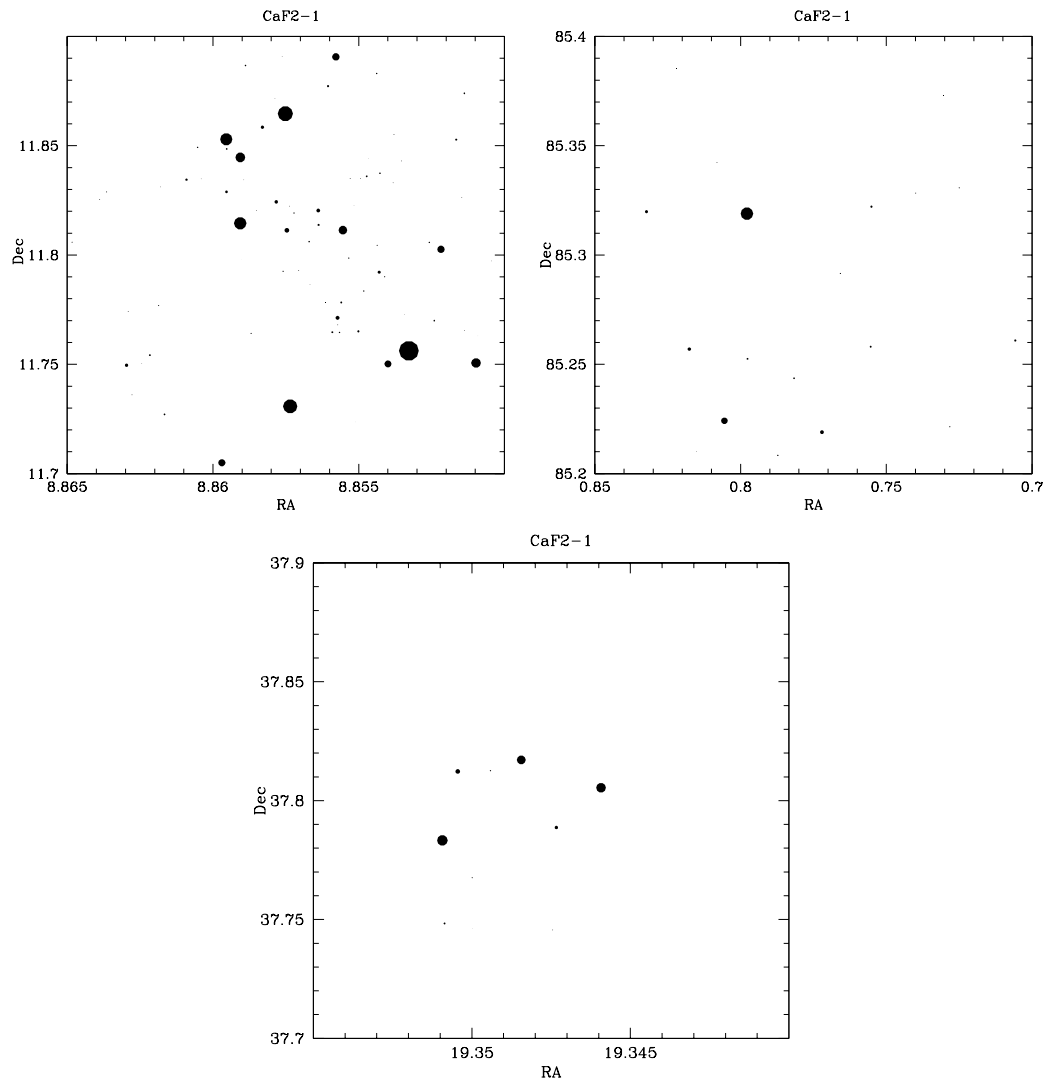
Fig. 15 Spatial distribution of M67 (*top left*), NGC 188 (*top right*) and NGC 6791(*bottom*) in the FUV CaF2-1 filter.

magnitude, for eight common stars, which is found to be 2.7±1.2 mag. Again, the scatter is found to be large, mainly due to the filter mismatch. The zero point for the GALEX FUV filter is 18.82, which is similar within error, when we add the above difference to our zero point.

Siegel et al. (2014) presented the CMDs of M67 and NGC 188 using UVOT observations. The features identified in our study and those in their CMDs are similar. For example, in the CMD using the NUV colour, the blue stragglers are bright and have a larger range of magnitude. Also, the MS and the subgiant branch occupy the same space, making it difficult to separate the two sequences in the CMDs, similar to what was suggested by our simulations. The other NUV CMD shows the subgiant branch being almost parallel to the MS. The CMDs also show a wider colour separation for the WDs. Hence, we find that our simulations are comparable to the CMDs presented by Siegel et al. (2014), which once again gives confidence about the simulations presented in this study. The large
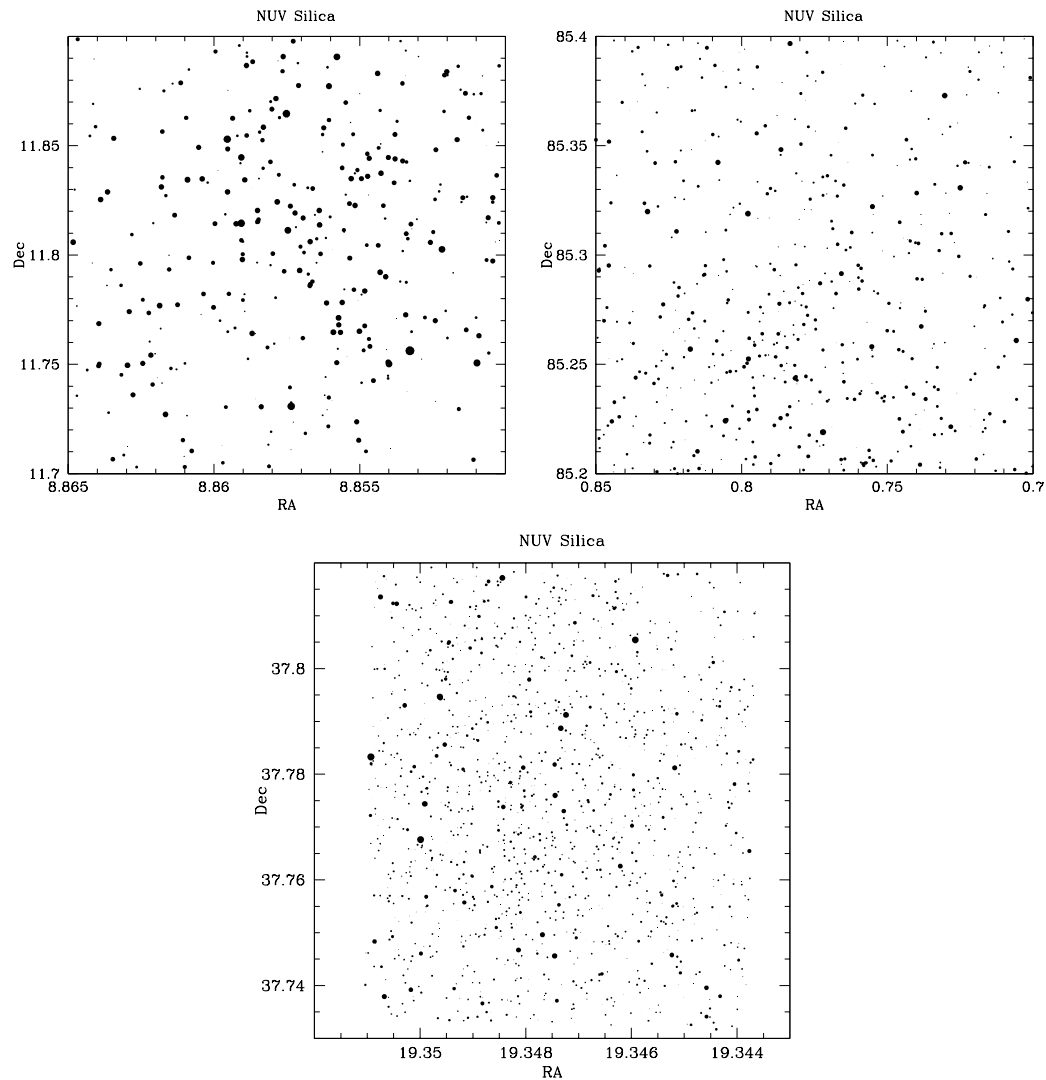
Fig. 16 Spatial appearance of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*) in the NUV Silica filter.

scatter is due to the mismatch between the two filters and its effect on the hotter (WDs) and cooler (giants) stars, as shown in Figure 19.

7 DISCUSSION AND CONCLUSIONS

UVIT is one of the state of the art telescopes that will be flown in the multi-wavelength ASTROSAT mission. This telescope has an angular resolution much better than previous missions and it also carries a set of very useful filters. Simulations to predict the expected output from the UVIT payload for various science topics of interest are highly essential, particularly because it has filters within the FUV and NUV channels for the first time. The results presented in this paper are part of a preparatory exercise to understand and efficiently utilise the telescope and filter capability to maximise its science
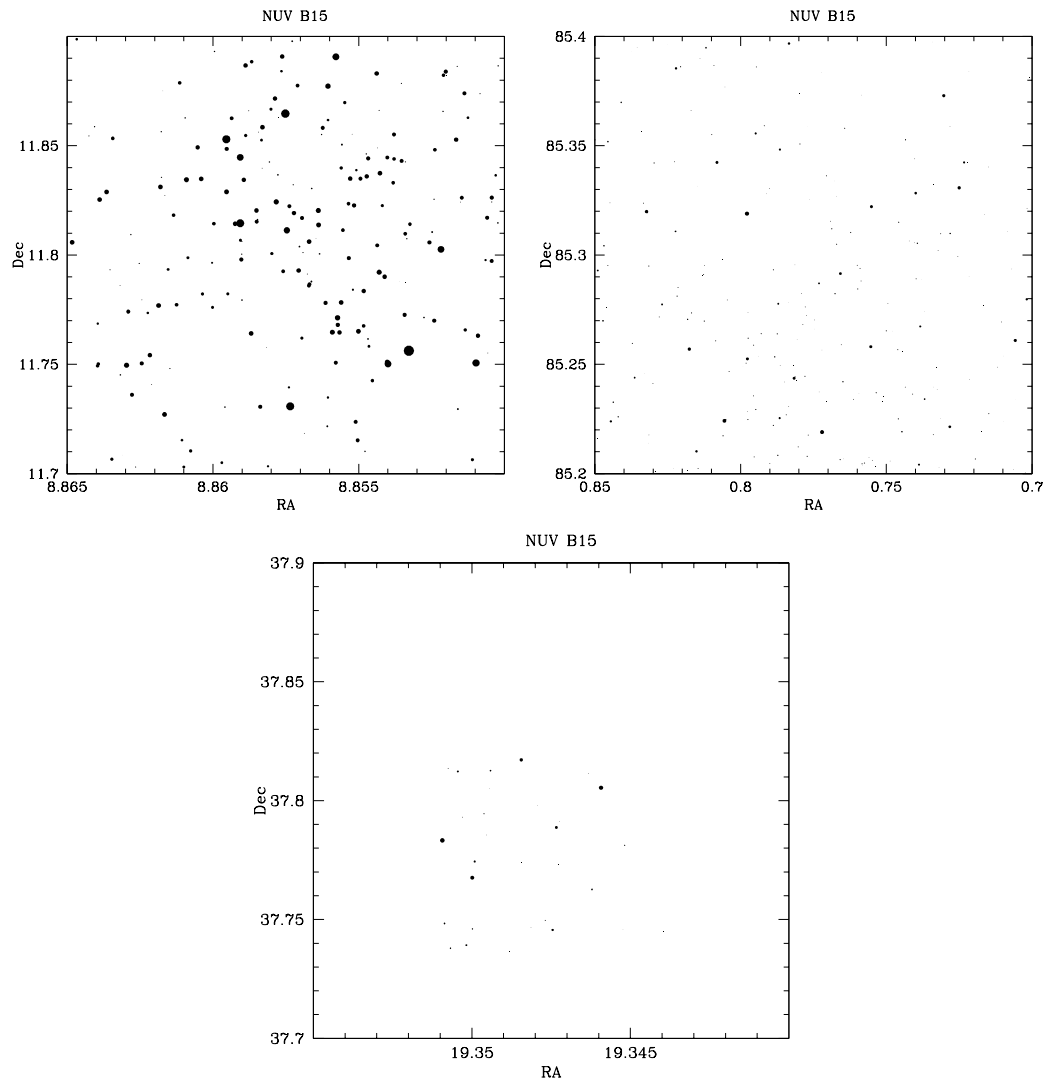
Fig. 17 Spatial appearance of M67 (*top left*), NGC 188 (*top right*) and NGC 6791 (*bottom*) in the NUV B15 filter.

output. In this study we have presented simulated CMDs of three open clusters and their spatial appearance in the UVIT filters. We have used the ETC as well as stand alone software to estimate count rates of a large number of stars in three clusters. We have assumed a zero point to convert the count rates to magnitudes, which is compared with the GALEX zero points. The CMDs are plotted using all the filter combinations of FUV and NUV. We are able to identify the location of various evolutionary sequences in the cluster CMD of M67, NGC 188 and NGC 6791. Stars and evolutionary sequences that are identified here are those which were previously known in the optical CMD. The identification of the expected location for stars with known type will help in identifying new candidates in studied and unstudied clusters. The present study recommends the most suitable filter combination to study various stellar sequences that are identified.
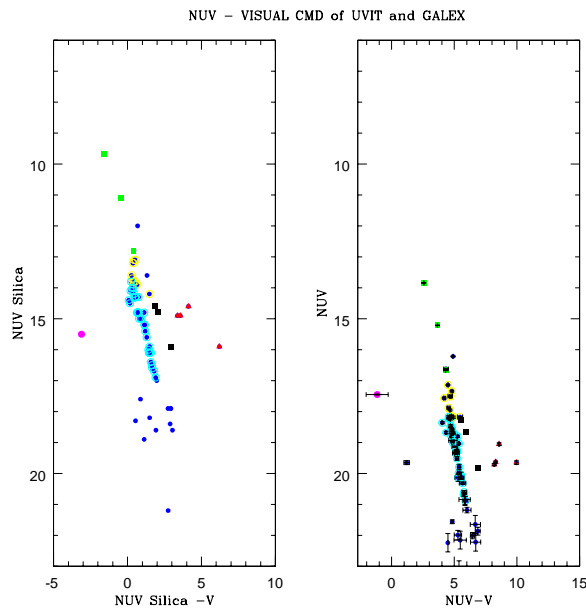
Fig. 18 Comparison of NUV-*V* CMD plot of UVIT and GALEX. The error bars are not shown for a few stars, whose errors in *V* are not available.
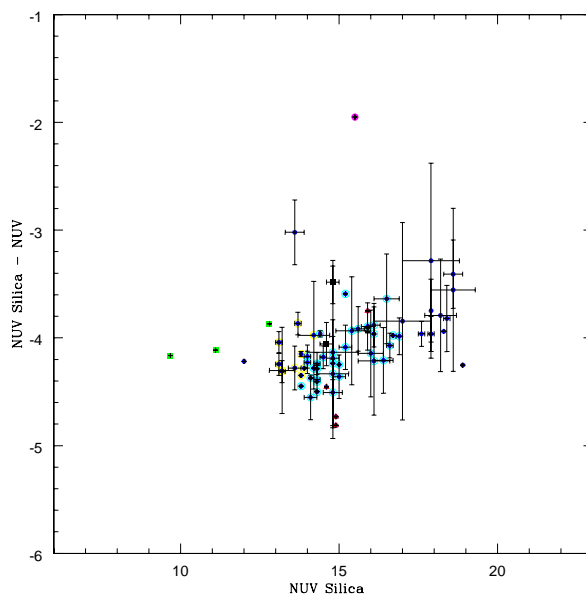

Fig. 19 The simulated NUV Silica magnitude is shown as a function of the difference between the simulated NUV Silica magnitude and GALEX NUV magnitude. The error bars are not shown for a few stars, whose errors in *V* are not available. The error bar is not shown for (NUV Silica-NUV) = −1.9502 and NUV Silica =15.5, since it is too large.

We compared our simulated CMDs in the NUV with those obtained from GALEX and UVOT. The locations of stars at various evolutionary phases are found to be comparable. The magnitudes of simulated stars match those of GALEX well, in both NUV and FUV, after accounting for the difference in the zero point. While studying this cluster using the UVIT, there could be a shift in the position of the entire colour and magnitude depending on the photometric zero point value for various filters. However, the relative position of stars in the cluster with respect to each other is expected to remain the same. This indicates that the pattern of the CMD that we observe in the simulated FUV CMD, NUV CMD and NUV-Visual would be similar. Hence we would like to stress that the magnitudes should be taken with caution and the CMDs presented here are indicative to the extent that they help us in planning efficient observations. Using the study, we also demonstrate that it is important to prepare diagnostic tools using the available filter combinations to do science with UVIT. The ground calibration estimates as well as tools related to the ETC are available to execute such studies. We plan to extend such studies to other topics, such as young star clusters, globular clusters, star forming galaxies, etc.

We summarise our results below:

- We have presented simulated CMDs of three old open clusters for various combinations of FUV, NUV and optical (V) filters. It is observed that the FUV CMDs will only be able to identify the blue stragglers and WDs in these open clusters. They can be separated and grouped with the help of various FUV filters. The upper MS and the turn off are detected in the NUV CMDs in M67 and NGC 188, but the turn off is only seen in NGC 6791. The CMDs generated using NUV and V magnitudes are found to be very useful.
- From the analysis of the FUV CMDs, we observe that the blue stragglers have increased FUV magnitude range, which would help in grouping them. We point out that the increased range in the FUV magnitude is also likely to help in the study of the turn off of younger open clusters to obtain better resolution in age. We plan to study younger clusters in the future.
- In the NUV CMDs, the upper MS, the turn off, sub-giants as well as the red giants are located very close to each other, which would make it difficult to differentiate them from one another. Identification of these stars from the optical CMD is thus essential.
- The spatial appearance of the three clusters in the broad band FUV and NUV filters is presented, and less crowding of stars is observed. These can be used as finding charts during the actual observations to help us identify the field.
- Our simulations compare well with the estimations from GALEX and SWIFT-UVOT.
- A tool to estimate count rates of a large number of stars in all the UVIT filters is developed as part of this work, which will be made available to the community as a web tool.

References

Buzzoni, A., Bertone, E., Carraro, G., & Buson, L. 2012, ApJ, 749, 35
Caputo, F., Chieffi, A., Castellani, V., et al. 1990, AJ, 99, 261
Chaboyer, B., Green, E. M., & Liebert, J. 1999, AJ, 117, 1360
Kaluzny, J., & Rucinski, S. M. 1993, MNRAS, 265, 34
Landsman, W., Bohlin, R. C., Neff, S. G., et al. 1998, AJ, 116, 789
Leonard, P. J. T., & Linnell, A. P. 1992, AJ, 103, 1928
Liebert, J., Saffer, R. A., & Green, E. M. 1994, AJ, 107, 1408

Mathieu, R. D. 2000, in Astronomical Society of the Pacific Conference Series, 198, Stellar Clusters and Associations: Convection, Rotation, and Dynamos, eds. R. Pallavicini, G. Micela, & S. Sciortino, 517

McClure, R. D., & Twarog, B. A. 1977, ApJ, 214, 111

Montgomery, K. A., Janes, K. A., & Phelps, R. L. 1994, AJ, 108, 585

Montgomery, K. A., Marschall, L. A., & Janes, K. A. 1993, AJ, 106, 181

Sarajedini, A., von Hippel, T., Kozhurina-Platais, V., & Demarque, P. 1999, AJ, 118, 2894

Siegel, M. H., Porterfield, B. L., Linevsky, J. S., et al. 2014, AJ, 148, 131

Subramaniam, A. 2012, in Astronomical Society of India Conference Series, 4, 165

VandenBerg, D. A., & Stetson, P. B. 2004, PASP, 116, 997

Worthey, G., & Jowett, K. J. 2003, PASP, 115, 96

Zombeck, M. V. 1990, Handbook of space astronomy and astrophysics (Cambridge: Cambridge Univ. Press)