



## A HOT COMPANION TO A BLUE STRAGGLER IN NGC 188 AS REVEALED BY THE ULTRA-VIOLET IMAGING TELESCOPE (UVIT) ON ASTROSAT

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### ABSTRACT

We present early results from the Ultra-Violet Imaging Telescope (UVIT) on board the ASTROSAT observatory. We report the discovery of a hot companion associated with one of the blue straggler stars (BSSs) in the old open cluster, NGC 188. Using fluxes measured in four filters in UVIT's far-UV (FUV) channel, and two filters in the near-UV (NUV) channel, we have constructed the spectral energy distribution (SED) of the star WOCS-5885, after combining with flux measurements from *GALEX*, Ultraviolet Imaging Telescope, Ultraviolet Optical Telescope, *SPITZER*, *WISE*, and several ground-based facilities. The resulting SED spans a wavelength range of 0.15  $\mu\text{m}$  to 7.8  $\mu\text{m}$ . This object is found to be one of the brightest FUV sources in the cluster. An analysis of the SED reveals the presence of two components. The cooler component is found to have a temperature of  $6000 \pm 150$  K, confirming that it is a BSS. Assuming it to be a main-sequence star, we estimate its mass to be  $\sim 1.1\text{--}1.2 M_{\odot}$ . The hotter component, with an estimated temperature of  $17,000 \pm 500$  K, has a radius of  $\sim 0.6 R_{\odot}$  and  $L \sim 30 L_{\odot}$ . Bigger and more luminous than a white dwarf, yet cooler than a sub-dwarf, we speculate that it is a post-AGB/HB star that has recently transferred its mass to the BSS, which is known to be a rapid rotator. This binary system, which is the first BSS with a post-AGB/HB companion identified in an open cluster, is an ideal laboratory to study the process of BSS formation via mass transfer.

*Key words:* binaries: general – blue stragglers – open clusters and associations: individual (NGC 188)

### 1. INTRODUCTION

Old open clusters are important tools for understanding the advanced stages of stellar evolution for both single and binary stars. Such clusters are well studied in optical and near-IR passbands, but only a handful have been studied in the ultraviolet (UV). In the old open clusters M67, NGC 188, and NGC 6791, populations of hot stars were studied by Landsman et al. (1998) using images from the Ultraviolet Imaging Telescope (UIT). Analysis of wide-field UV photometry of nearby clusters M67, NGC 188, NGC 2539, and M79 obtained with the *Swift* Ultraviolet Optical Telescope (UVOT) showed that UV-bright stars can be readily identified using the UV color–magnitude diagram (CMD; Siegel et al. 2014).

Blue straggler stars (BSSs) are cluster members that are brighter, and bluer, than stars on the upper main sequence (Sandage 1953). The BSS population of the open cluster NGC 188, in addition to a few sub-giants and yellow giants, comprises approximately 25% of the evolved cluster population (see Mathieu & Geller 2015 and references therein). BSSs are believed to have gained mass by some process and hence have a rejuvenated lifetime on the main sequence. The BSS are found in a wide variety of environments, such as open clusters, globular clusters, Galactic field, and in elliptical galaxies. Suggested formation mechanisms include mergers in hierarchical triples (Perets & Fabrycky 2009), collisions during dynamical encounters (Knigge et al. 2009; Leigh & Sills 2011),

and mass transfer (Chen & Han 2008) on the red giant or asymptotic giant branches (RGB and AGB, respectively). Recently, Gosnell et al. (2014, 2015) used *HST* to study BSSs in NGC 188 in the UV region, detecting white dwarf (WD) companions to seven BSS and thereby confirming that at least some BSSs can form by mass transfer. Three of their BSSs were found to have cool WD companions; four were found to have hotter WDs. To date, though, no BSS belonging to an open cluster has been found that possesses a post-AGB/RGB star as a companion.

NGC 188 is a well-studied open cluster thanks to its richness, high metallicity, and relatively old age. The age of the cluster is determined to be 7 Gyr, with a reddening of  $E(B - V) = 0.09 \pm 0.02$  mag and a distance of 2047 pc (Sarajedini et al. 1999), though some variations are found (see Hills et al. 2015). Proper motion studies from the WIYN Open Cluster Study (WOCS; Platais et al. 2003) suggest that 1050 stars are members of the cluster. A total of 24 BSS candidates were cataloged by Ahumada & Lapasset (2007), with Geller et al. (2008) showing 20 BSSs to be confirmed members based on their radial velocities. In their UIT study, Landsman et al. (1998) identified three stars with exceptionally blue colors.

In this Letter, we report the detection of a hot companion to the star WOCS-5885 using data from the Ultra-Violet Imaging Telescope (UVIT). Below, we introduce the instrument,

**Table 1**  
UVIT Flux Measurements for WOCS-5885

| Filter           | $\lambda_{\text{eff}}$ | Unit Conv | Flux     | Error    |
|------------------|------------------------|-----------|----------|----------|
| FUV Channel      |                        |           |          |          |
| F148W (CaF2-1)   | 1480.8                 | 0.292E-14 | 5.09E-14 | 0.25E-14 |
| F154W (BaF2)     | 1540.8                 | 0.345E-14 | 4.73E-14 | 0.19E-14 |
| F169M (Sapphire) | 1607.7                 | 0.428E-14 | 4.09E-14 | 0.20E-14 |
| F172M (Silica)   | 1716.5                 | 0.106E-13 | 3.51E-14 | 0.18E-14 |
| NUV Channel      |                        |           |          |          |
| N219M (B15)      | 2195.5                 | 0.545E-14 | 2.06E-14 | 0.21E-14 |
| N279N (N2)       | 2792.3                 | 0.364E-14 | 1.19E-14 | 0.06E-14 |

**Note.** Columns 1–5 record the filters, the effective wavelength in Å, the unit conversion factor for each filter, the measured flux (in units of  $\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$ ), and its associated error. The measured flux is the product of the count rate and the unit conversion for each filter (see Tandon et al. 2016 for details).

describe the data and analysis methods, and follow with a discussion of the results.

## 2. UVIT DATA

The UVIT instrument contains two 38 cm telescopes: one for the far-ultraviolet (FUV) region (130–180 nm); and the other for the near-ultraviolet (NUV; 200–300 nm) and visible (VIS) region (320–550 nm) ranges; these are divided using a dichroic mirror for beam-splitting. UVIT is primarily an imaging instrument, simultaneously generating images in the FUV, NUV, and VIS channels over a 28' diameter circular field.<sup>10</sup> Each channel can be divided into smaller passbands using a selectable set of filters. Full details on the telescope and instruments can be found in Tandon et al. (2016) and Subramaniam et al. (2016), along with the initial calibration results. The primary photometric calibration for all FUV filters and two of the NUV filters were performed using observations of HZ4, a white dwarf spectrophotometric standard star. Note that the present calibrations for the UVIT filters cover the central region of  $\sim 7$  arcmin.

NGC 188 was observed as UVIT's "first light" object on 2015 November 30. The cluster was observed every month to track the variation in UVIT sensitivity over the first six months of its operation. In this Letter, we present the calibrated flux of WOCS-5885, located near the center of the UVIT field, in four FUV and two NUV passbands. All data used in the analysis were obtained on 2016 January 26. The star studied here is repeatedly observed, and we have detections within the central 5 arcmin. The variations in the count rates suggest the sensitivity variation to be about 2%–3%, calibration error of 2%–3% and the photon noise to be 1%–2%, with a cumulative effect of about 5%. In the case of the specific filter, B15, we noticed that the above estimates are almost double, which sets the error to be 10%.

Images were corrected for distortion, flat-field illumination, and spacecraft drift using the customized software package CCDLAB (J. Postma et al. 2016, in preparation). Aperture photometry was performed on the images to estimate the counts after correcting for the background and saturation effects. The

<sup>10</sup> A low-resolution, slit-less spectroscopic mode is also available in the FUV and NUV channels.

**Table 2**  
The Basic Parameters of WOCS-5885

|                        |                                  |
|------------------------|----------------------------------|
| R.A. (2000) (hh:mm:ss) | 00:48:20.19                      |
| Decl. (2000)(dd:mm:ss) | +85:13:27.1                      |
| $V$ (mag)              | 14.13                            |
| $(B - V)$ (mag)        | 0.25                             |
| Membership prob        | 53%, 80%                         |
| Binary                 | Yes                              |
| Reddening $E(B - V)$   | 0.09 mag                         |
| Distance (pc)          | 2047                             |
| Estimated Parameters   |                                  |
| Cool Component         |                                  |
| Temperature            | 6000( $\pm 150$ ) K              |
| Mass                   | $\sim 1.1\text{--}1.2 M_{\odot}$ |
| Radius                 | $\sim 1.1\text{--}1.6 R_{\odot}$ |
| Luminosity             | $\sim 1.4\text{--}2.8 L_{\odot}$ |
| Hot Component          |                                  |
| Temperature            | 17000 ( $\pm 500$ ) K            |
| Radius                 | $\sim 0.6 R_{\odot}$             |
| Luminosity             | $\sim 30 L_{\odot}$              |

**Note.** The coordinates and binarity are taken from Geller et al. (2008); magnitudes, reddening, and distance from Sarajedini et al. (1999); membership probabilities from Stetson et al. (2004) and Dinescu et al. (1996).

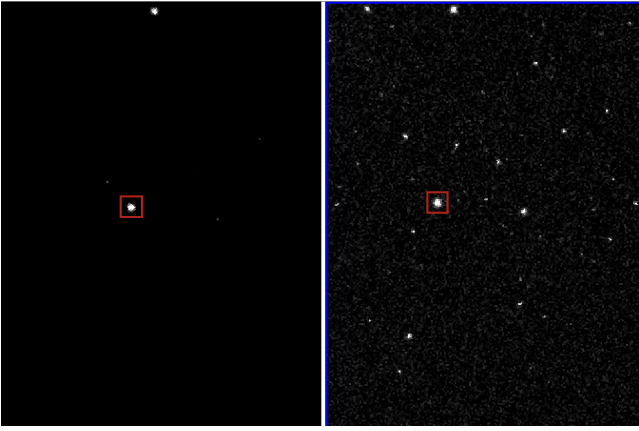
filters, their effective wavelength, the unit conversion factor, and estimated fluxes and errors are recorded in Table 1.

## 3. SPECTRAL ENERGY DISTRIBUTION (SED)

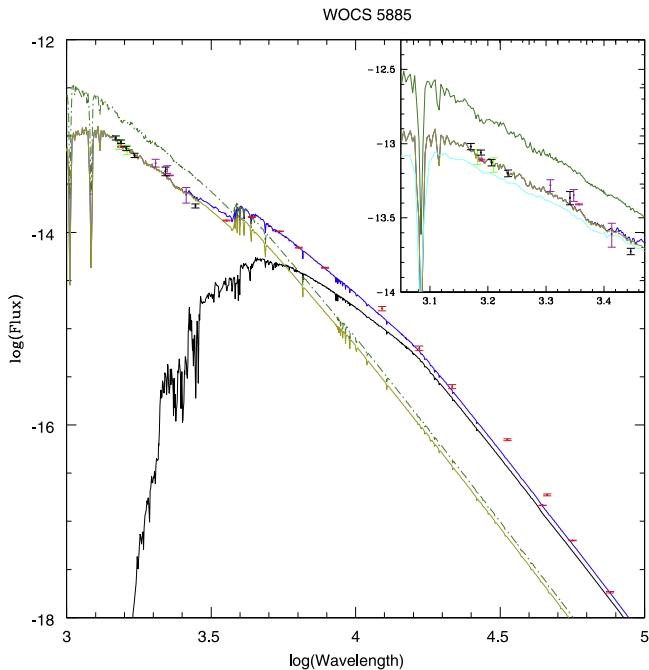
We describe the SED for the BSS, WOCS-5885 (Table 2), located in the inner region of NGC 188. This is known to be a single-lined spectroscopic binary of uncertain membership (Geller et al. 2008). They found the star to be a rapid rotator and mentioned that they could not establish membership and designated it as an uncertain member due to a lack of measurements. Stetson et al. (2004) found a membership probability of 53% (SMV-8422) and Dinescu et al. (1996) assigned a probability of 80% (D-702, found to be an extended object). It is considered to be a BSS based on its location in the CMD. Landsman et al. (1998) mentioned that this may have a composite spectrum, as suggested by its colors, with a possibility of a very hot star and a BSS as components. Siegel et al. (2014) suspected this to be a red giant and a pre-WD binary.

Our UVIT images clearly show the star to be brighter in the FUV than in the NUV, and much fainter in optical images. The star is not found to have any significant elongation or any extended feature in the UVIT images (Figure 1). In order to characterize the temperature and the evolutionary status of the star, we created a multi-wavelength SED using UVIT data, supplemented by literature data. We combined flux measurements from *GALEX* (FUV and NUV), *UIT* (2 passbands), *Swift*-UVOT (3 passbands; Siegel et al. 2014), UVBRI (Sarajedini et al. 1999), JHK (2MASS), I2, I3, I4 (*Spitzer*), and W1, W2 (*WISE*).<sup>11</sup> The final SED consists of 26 data points spanning the wavelength range of 0.15–7.80  $\mu\text{m}$

<sup>11</sup> We did not include the W3 and W4 data due to larger point-spread function (PSF) and low signal-to-noise ratio (S/N). We obtained the UVOT magnitudes from Siegel et al. (2014), from their Figure 5. The magnitude in uvw1 as found from the bottom two figures differ by about 0.2 mag; we adopted the mean value. The adopted magnitudes and errors are uvw2 =  $15.0 \pm 0.1$ , uvw1 =  $15.1 \pm 0.2$ .



**Figure 1.** FUV (left) and NUV (right) images of NGC 188 taken in the CaF2 and N2 filters, respectively. WOCS-5885 is marked by the red square. The images obtained on 2016 February 18 are aligned with north up and east toward the left.



**Figure 2.** Extinction-corrected spectral energy distribution (SED) of WOCS-5885. The black (UVIT), magenta (*GALEX*) and green (UIT), pink (UVOT) points indicate the UV fluxes (shown in the inset as well); all other flux measurements are shown in red. Kurucz Model spectra ( $\text{Log}(g) = 5.0$ ) for the separate components are shown in gold (17,000 K) and black (6000 K), with the composite spectrum in blue. For comparison, we have shown a hotter spectrum of temperature (20,000 K) in dark green. We have also shown the helium-rich model spectrum for a temperature of 16,000 K,  $\log g = 4.0$ ,  $H = 0.30$ ,  $He = 0.70$ , and  $CN = 0.00005$  from Jeffery et al. (2001) in cyan. Scaling factors of  $4.45\text{E-}22$  and  $3.1\text{E-}23$  have been used to combine the 6000 K and 17,000 K spectra, respectively. The unit of wavelength is  $\text{\AA}$  and flux is  $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ . The data points that were not considered for the final reduced  $\chi^2$  value are *GALEX*(NUV), U, W1, W2, I2, and I3.

(Figure 2). It can be seen from Figure 2 that the UVIT fluxes are in good agreement with those estimated by UIT, UVOT, and *GALEX*.

We used the virtual observatory tool, VOSA (VOSED analyzer; Bayo et al. 2008), which allows the user to perform a statistical test to compare the observed data with the selected

model. The tool uses the filter transmission curve to calculate the synthetic photometry of the theoretical model which is compared with the observed flux. The tool also corrects the observed flux for extinction in the respective band (Fitzpatrick 1999; Indebetouw et al. 2005) and then SED fitting with the model for a selected star is performed. We adopted a reddening of  $E(B - V) = 0.09$ . To extinction correct the UVIT and UIT fluxes, we used the reddening law of Cardelli et al. (1989). The reduced  $\chi^2$  value is estimated using the expression

$$\chi^2 = \frac{1}{N - 4} \sum_{i=1}^N \left\{ \frac{(F_{o,i} - F_{m,i})^2}{\sigma_{o,i}^2} \right\},$$

where  $F_{o,i}$  is the observed flux,  $F_{m,i}$  is the scaled model flux, and  $\sigma_{o,i}^2$  is the error in the observed flux. The synthetic flux values of the UVIT filters were computed by us, whereas for other filters, we used the values computed by VOSA, except for the UIT filters. The rise in flux for UV wavelengths can be clearly seen in Figure 2, suggesting the presence of a hot component. In order to fit the SED, we need spectra which have coverage over the UV to IR wavelength range. We used Kurucz models (Castelli et al. 1997) because the spectra need both a large wavelength and temperature coverage. Although Next-Gen models could also be used, the study by Subramanian et al. (2016) suggested that the Kurucz models are preferred for temperatures hotter than 3500 K.

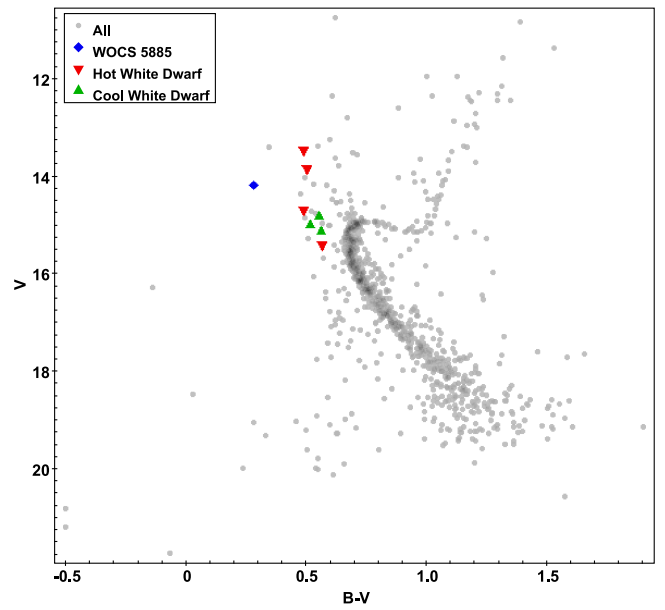
We tried initially to fit the full SED with a single temperature but found this approach to yield unsatisfactory results. The UV part of the SED seems to suggest a relatively hot temperature, whereas the IR part suggests a cooler temperature. Therefore, we created a composite spectrum comprising two components. We fitted the UV range and the optical–IR range separately using the VOSED. The temperatures and errors are estimated by the tool. The combination that best fits the observed SED (with the least  $\chi^2$  value) was found to have temperatures of  $17,000(\pm 500)$  K and  $6000(\pm 150)$  K. The reduced  $\chi^2$  value using 24 data points are 87 (12), 2698 (1169), and 7582 (868) for composite, cool, and hot components, respectively. The reduced  $\chi^2$  values for well-fitting 18 data points, identified by the tool, followed by a visual inspection are shown in the parentheses. In Figure 2, we also show the SED fitted with two spectra, along with a composite spectrum. For comparison, we have also shown a model spectrum of the temperature of 20,000 K. The N279N flux and the U-band flux are lower, whereas the *WISE* fluxes are higher with respect to the fitted spectrum. The N279N filter is centered on the Mg II spectral line and line absorption could be a possible reason for the reduced flux. Although the temperatures are reliable, the derived  $\log g$  ( $\sim 5.0$ ) are not very accurate since the range of values available in the models is limited. In order to compare with special models, such as helium-rich models for hot stars, we have shown the model LTE spectrum for a temperature of 16,000 K, from Jeffery et al. (2001), in Figure 2. The helium-rich model shows a reduction in flux in the U band, which may support the observed reduction in the U-band flux. In general, both the models appear comparable.

The high temperature of the hotter component ( $17,000 \pm 500$  K) is clearly revealed by the UVIT data, especially in the flux measured using the F148W and F154W filters; the inset in Figure 1 suggests that the UV flux is rising at least until 1481  $\text{\AA}$ . The data also confirm that the temperature of the hot component is not high enough to be classified as a

sub-dwarf, as demonstrated by the slope of the FUV part of the SED. The estimated temperature of the cooler component confirms that it is indeed a BSS, as it is similar to the temperature of other BSSs in NGC 188 (Table 1; Gosnell et al. 2015) and higher than the turnoff temperature of NGC 188 ( $\sim 5500$  K, based on the turnoff color). The optical region of the SED is fitted well by the combined flux from the two components. The Padova models (Marigo et al. 2008) suggest a mass of  $1.1\text{--}1.2 M_{\odot}$  for a star of similar temperature on the MS. This is also similar to the mass of other BSSs in NGC 188 (Perets 2015).

In obtaining the composite spectrum, the flux of each component is scaled by a factor that is equal to  $(R/D)^2$ , where  $R$  is the radius and  $D$  is the distance. We estimated the radii of the component stars, using the relation  $R/R_{\odot} = (T_{\odot}/T)^2(L/L_{\odot})^{0.5}$ ; the luminosity is estimated from the absolute magnitude, bolometric correction, and a distance of 2 kpc. For the BSS, we also estimated the luminosity using the relation given in Table 3 of Eker et al. (2015) and Padova models. The BSS is found to have a radius of  $\sim 1.1\text{--}1.6 R_{\odot}$ , and the luminosity of  $\sim 1.4\text{--}2.8 L_{\odot}$ , whereas the hot component is found to have a radius of  $\sim 0.6 R_{\odot}$ , and a luminosity of  $\sim 30 L_{\odot}$ . Hence, the hot component is much larger than a WD ( $R \sim 0.01\text{--}0.02 R_{\odot}$ ; Tremblay et al. 2016 and references therein). The hot star is about three times more luminous than hot B sub-dwarfs ( $T_{\text{eff}} > 27,000$  K  $L \sim 10 L_{\odot}$ ) and blue horizontal branch stars ( $L \sim 10 L_{\odot}$ ; Heber 2016). Also, the FUV luminosity is found to be much higher than those of the BSS+WD of similar temperature (e.g., WOCS-4540, WOCS-5379) as estimated by Gosnell et al. (2015). These two observations suggest that the hot component cannot be a WD or a sub-dwarf, therefore we speculate that it is a post-AGB star or a post-HB star (depending on the initial mass of the star). Thus, WOCS-5885 is likely to be an example of the rare class of BSS + post-AGB/HB binary stars. This also suggests that the BSS acquired mass quite recently from the post-AGB/HB star—a scenario that is supported by its rapid rotation, as the BSS can get spun up due to mass transfer (Ivanova 2015). Mathieu & Geller (2009) found that many NGC 188 BSSs are rotating more rapidly than the main-sequence stars and speculated that the rapid rotation of blue stragglers may place upper limits on their ages.

As the BSS has a mass of  $1.1\text{--}1.2 M_{\odot}$  and the turnoff mass of NGC 188 is  $\sim 1.0 M_{\odot}$ , the mass gained by the BSS is at least  $0.1\text{--}0.2 M_{\odot}$ . The mass of the progenitor of the post-AGB/HB is likely to be slightly more massive to evolve first. Recently, Milliman et al. (2015) suggested that mass transfer from AGB stars to be the dominant formation mechanism for BSSs in NGC 188. The evolution of the primary star, once the mass transfer starts, is complicated and is addressed by a few authors for a few specific cases (see reviews by Sills 2015; Ivanova 2015). As there are no similar objects observed or modeled, we are unable to compare or comment on the estimated parameters of the hot component. In this study, we have considered the two components to be physically associated. In the direction of NGC 188, approximately one hot star is expected per sq. degree, as per Figure 10 of Bianchi et al. (2011). As there are at least three hot stars in this cluster field suggesting an overdensity, the hot component is likely to be associated with the cluster.



**Figure 3.** Color–magnitude diagram (CMD) of NGC 188 showing the location of WOCS-5885 and the seven BSS+WDs sources studied by Gosnell et al. (2014). The members (proper motion and radial velocity) of the cluster are shown in the CMD, using the optical photometry of Sarajedini et al. (1999).

#### 4. DISCUSSION

We have presented early science results from UVIT that demonstrate its UV imaging capabilities. Observations in four filters in the FUV and two filters in the NUV channel were used. The UVIT flux clearly demonstrates the rising flux of the hot component in the FUV bands; these measurements allow accurate temperature estimates from SED fitting. The estimated fluxes are based on the available calibrations and will be improved as calibrations continue. The UVIT fluxes are in good agreement with those from UIT, *GALEX*, and UVOT. We therefore demonstrate that accurate flux measurements can be carried out with UVIT in the  $0.150\text{--}0.30 \mu\text{m}$  wavelength range.

We have combined our UVIT data with flux measurements from other missions, as well as from ground-based optical/IR telescopes, to demonstrate that WOCS-5885 could be a rare BSS+post-AGB/HB binary—the first of its kind to be identified in an open cluster. WOCS-5885 is probably the progenitor of systems composed of a BSS and hot-WD companion, like those identified by Gosnell et al. (2015). The temperature of the companion rules out the possibility this has a red giant along with a pre-WD, as suggested by Siegel et al. (2014). Figure 3 shows the location of this star, along with the other BSS+WDs in this cluster, in the cluster color–magnitude diagram. WOCS-5885 is the relatively blue object, while the five BSS+WD binaries are redder in comparison.

Recently, Milliman et al. (2015) identified a few BSSs in NGC 6819 to be enhanced in barium, likely to be formed through mass transfer from an AGB star, but none of these stars are found to be binaries. Sivarani et al. (2004) studied a possible field BSS and found large overabundances of s-process elements, due to accreted material from a companion, formerly an AGB star. Ryan et al. (2002) studied rapidly rotating lithium deficient stars that are possible field BSSs. WOCS-5885 is unique such that this is a BSS where a possible post-AGB star is found as a companion, a target for testing the above findings. This is an interesting target for BSS surface

composition studies and possible chemical signatures of recent accretion events. The physical parameters of the components can thus be used to constrain mass transfer models of BSS formation (Chen & Han 2008).

## 5. CONCLUSIONS

Our analysis of UVIT imaging for the open cluster NGC 188 has allowed us to reach the following conclusions concerning WOCS-5885, a likely BSS and confirmed UV-bright source belonging to the cluster:

1. We find the star to be a certain binary and use UVIT to characterize its two components.
2. The cooler component ( $6000 \pm 150$  K) is found to be a BSS, whereas the hot component ( $17,000 \pm 500$  K) is speculated to be a post-AGB/HB star based on its luminosity and radius. We therefore argue that WOCS-5885 is likely to be a BSS+post-AGB/HB binary.
3. The mass of the BSS is estimated to be  $\sim 1.1\text{--}1.2 M_{\odot}$ . The initial mass of the donor star is estimated to be  $\geq 1.2 M_{\odot}$ .
4. This rare system is the first of its kind to be identified in an open cluster is an ideal candidate to study the chemical composition of the BSS and constrain the theories of BSS formation via mass transfer.

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