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Blue Straggler Stars of NGC 7789 and NGC 2506 Using *AstroSat*/UVIT

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Abstract

Blue straggler stars are intriguing objects that seem to defy the standard theory of single-star evolution. They manage to elongate their main-sequence lifetimes by acquiring mass either in a direct stellar collision or through mass transfer in a binary or in mergers. We study the candidate blue straggler stars in two intermediate-age open clusters NGC 7789 and NGC 2506 using the far-UV and near-UV observations from the UV imaging telescope of *AstroSat* in combination with other multi-wavelength data. Around 45% of blue straggler star candidates show an excess in the UV wavelengths and are fitted with two-component spectral energy distributions. We detect most of these blue straggler stars to contain a low-mass or extremely low-mass white dwarf as a hot companion, whereas some yellow straggler stars and red clump stars with white dwarfs of normal mass or high mass as a companion. Based on our analysis, we infer that around 36% of blue straggler stars have likely formed via mass transfer by the Case-A/Case-B mechanism in these two clusters.

Keywords: Open clusters, Stars, Exotic stars, Blue straggler stars, Yellow straggler stars

1. Introduction

About seven decades after their discovery in a globular cluster M3 (Sandage, 1953), blue straggler stars (BSS) have come to be known as core hydrogen-burning stars that underwent a rejuvenation process resulting in their extended main-sequence lifetimes. There are three widely accepted formation mechanisms by which the BSS progenitors gain mass and undergo rejuvenation: direct stellar collisions during dynamical encounters (Leonard, 1989), mass-transfer in a binary (McCrea, 1964), and mergers (Perets and Fabrycky, 2009). Mass-transfer mechanism can be further divided into three categories depending on the evolutionary status of the primary while transferring mass to the secondary, i.e., Case-A: primary is a main-sequence star (Webbink, 1976), Case-B: primary is in the red giant branch phase (McCrea, 1964), and Case-C: primary is in the asymptotic giant branch phase (Chen and Han, 2008). Whereas direct stellar collisions are known to be feasible only in dense stellar environments such as the cores of the globular clusters (Press and Teukolsky, 1977), mass-transfer, and mergers are plausible in all kinds of stellar environments. In addition to the BSS, star clusters may also contain stars located between the main sequence and the giant branch, normally referred to as the yellow straggler stars (YSS), and considered to be the evolved BSS (Boffin et al., 2015). One of the significant topics of interest related to BSS is, knowing the relative importance of different formation mechanisms in diverse stellar environments. It has been shown that more than one kind of formation mechanism can be at work in the same cluster (Ferraro et al., 1997).

In the case of open clusters, extensive work has been done on the BSS populations of two clusters, NGC 188 and M67. A large majority, $\sim 80\%$, of BSS have been confirmed to be in binary systems in these two clusters (Mathieu and Geller, 2009; Geller et al., 2015). Over the period of last decade, UV-based surveys have played an instrumental role in shedding light on the nature of the hot companions of many of the binary BSS of these two and several other open clusters. As post-mass-transfer binaries in wider orbits ($p > 10$ days) with hot white-dwarf (WD) companions can be identified in UV surveys, such an approach has been used on several open clusters in the last decade. Gosnell et al. (2015) discovered WD companions of seven BSS using HST observations in far-ultraviolet (FUV) filters. Using the UV imager, Ultra-Violet Imaging Telescope (UVIT), on board the *AstroSat* telescope, BSS populations of more than half a dozen open clusters and multiple globular clusters are studied extensively. In open clusters, these studies have detected unresolved hot companions of diverse nature such as a post-AGB/HB companion in M67 (Subramaniam et al., 2016), low-mass (LM) and extremely low-mass (ELM) WD in M67 (Sindhu et al., 2019; Pandey et al., 2021), and hot sub-dwarf B stars in King 2 (Jadhav et al., 2021), among others.

We studied the BSS populations of two intermediate-age open clusters, NGC 7789 and NGC 2506, using *AstroSat*/UVIT. NGC 7789 ($\alpha = 23\,\mathrm{h}\,57\,\mathrm{m}\,21.6\,\mathrm{s}$, $\delta = +56^\circ\,43'\,22''$, J2000) is a populous open cluster, of 1.6 Gyr age, at a distance $\sim 2000\,\mathrm{pc}$ (Gim et al., 1998). Nine et al. (2020) identified 12 BSS including four single-lined spectroscopic binaries as cluster members of NGC 7789 on the basis of time-series radial velocity data from Hydra Multi-Object spectrograph on the WIYN 3.5 m telescope. Rao et al. (2021) had identified four additional BSS of this cluster on the basis of *Gaia* DR2 members. NGC 2506 ($\alpha = 08\,\mathrm{h}\,00\mathrm{m}\,1.0\,\mathrm{s}$, $\delta = -10^\circ\,46'\,12''$, J2000) is a ~ 2 Gyr old open cluster, at a distance of $\sim 3000\,\mathrm{pc}$. Vaidya et al. (2020) identified BSS in this cluster using *Gaia* DR2 data. None of these two clusters have been studied using UV wavelengths before. With a reasonably large BSS population and a handful of YSS in NGC 2506, these two open clusters are significant targets to study with *AstroSat*/UVIT.

2. Observations and Data Reduction

The UVIT is one of the main payloads onboard India's first multi-wavelength space observatory *AstroSat* that was launched in 2015 (Singh et al., 2014). It generates simultaneous images in the FUV, near-UV (NUV), and visual (VIS) channels with a circular field of view of $28'$ diameter and an angular resolution of $\leq 1.8'$. For more details on the instrument, the readers are referred to Kumar et al. (2012). The UV data of NGC 7789 were obtained in July 2017 with *AstroSat*/UVIT in one FUV filter F169M, and in three NUV filters N245M, N263M, and N279N with exposure times 609 s, 3219 s, 1142 s, and 1021 s, respectively. The *AstroSat*/UVIT data of NGC 2506 were obtained in October 2019 in three FUV filters F148W, F154W, and F169M with long exposure times of 9224 s, 7499 s, and 7027 s, respectively. We produced science-ready images in each filter by performing data reduction on raw images using CCDLAB (Postma and Leahy, 2017, 2021). Thereafter, we performed point-spread function (PSF) photometry on the images using DAOPHOT/IRAF tasks (Stetson, 1987) and obtained the final UV magnitudes of sources in the AB system by performing aperture corrections, PSF corrections, and saturation corrections (Tandon et al., 2020) on the PSF magnitudes. All of the 16 BSS of NGC 7789 and nine BSS of NGC 2506 are detected in the UVIT filters. Additionally, in NGC 2506, three YSS and three red clump (RC) stars are detected in UVIT filters. Upon examining these sources visually in multiple *Gaia* images, we found a nearby ($\leq 3''$) source in three BSS. Therefore, we constructed the spectral energy distributions (SEDs) of 22 BSS of the two clusters, and three YSS and three RC stars of NGC 2506 using multi-wavelength photometric information.

3. Spectral Energy Distributions

Spectral energy distributions (SEDs) of stars constructed over a long wavelength range are very useful in characterizing the BSS, as well as to search for any unresolved hot companion. To construct the SEDs, we used the Virtual Observatory of SED Analyzer (VOSA; Bayo et al., 2008) platform. VOSA compiles the photometric fluxes of the sources in selected filters, applies extinction correction using the standard extinction law, and calculates the synthetic photometry based on the selected model. We compiled the photometric data of these sources in NUV from *GALEX*, optical from *Gaia* EDR3 (Gaia Collaboration et al., 2021), and Pan-STARRS, near-IR from Two Micron All Sky Survey (2MASS), and mid-IR from Wide-field Infrared Survey Explorer (WISE) using VOSA. Next, the fluxes were corrected for extinction according to the extinction law by Fitzpatrick (1999) and Indebetouw et al. (2005) by providing the mean value of extinction of the clusters (Vaidya et al., 2022; Panthi et al., 2022). We used Kurucz stellar models (Castelli et al., 1997) to fit the SEDs. To fit the model, we kept the $T_{\rm eff}$ and $\log g$ values as free parameters and allowed them to range from 5000 to 50000 K and 3 to 5, respectively, whereas, we fixed the value of metallicity, [Fe/H] = 0.0 for NGC 7789 (Jacobson et al., 2011), and [Fe/H] = -0.5 for NGC 2506 (Knudstrup et al., 2020). VOSA returns the best-fit SEDs selected on the basis of χ^2-minimization. The SED of one BSS from each cluster, fitted with a single temperature component, is shown in Fig. 1.

Seven out of 15 BSS in NGC 7789 and three out of seven BSS in NGC 2506 showed UV

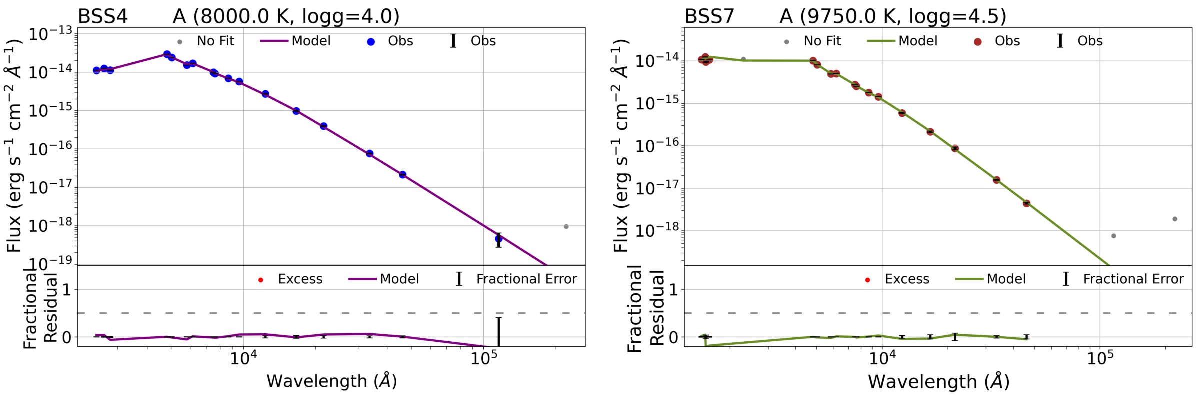

Figure 1: Single-component SED of (*left*) BSS4 reproduced from Fig. 2 in Vaidya et al. (2022), and (*right*) BSS7 reproduced from Fig. 3 in Panthi et al. (2022). The top panels of each figure show the extinction-corrected SEDs fitted with Kurucz stellar models. The bottom panels show the fractional residual across the filters with a dashed horizontal at a fractional residual of 0.3 to mark the threshold in excess.

excess greater than a fractional residual equal to 0.3. All of the three YSS and three RC stars of NGC 2506 also showed UV excess. We attempted a double-component SED fitting using a python code, `Binary_SED_Fitting` (https://github.com/jikrant3/Binary_SED_Fitting; Jadhav et al. (2021)) to fit two component SEDs to all these BSS, YSS, and RC stars. A total of eight BSS, two of the three YSS, and all the RC stars, were successfully fitted with double-component SEDs. Fig. 2 shows an example SED of BSS10 of NGC 7789 (Vaidya et al., 2022) that is fitted with a double-component SED.

4. Discussion

We find that $\sim 45\%$ of BSS and $\sim 66\%$ of YSS studied in this work show UV-excess. The SED fitting allows us to determine the properties of all the BSS, YSS, and RC stars, as well as their companions. The BSS in these two clusters are relatively hotter with their temperatures ranging from 7250 ± 250 K to 10250 ± 250 K. Such high temperatures in BSS are found consistent with the relatively young age of the open clusters. The temperatures of all the YSS and RC in NGC 2506 are approximately 6500 K and 5000 K, respectively. The temperatures of hot companions, on the other hand, of the BSS range from $\sim 11,000$ K to $\sim 19,000$ K, of the YSS range from $\sim 26,000$ K to $\sim 29,000$ K, and of the RC stars range from $\sim 25,000$ K to $\sim 31,000$ K.

Figure 3 shows that the hot companions of NGC 7789 are located near the ELM WD track of $0.18 M_\odot$. Two of the hot companions of NGC 2506 BSS are also located near the ELM WD track of $0.18 M_\odot$, whereas one hot companion of the third NGC 2506 BSS is found near the LM WD track of $0.24 M_\odot$. This finding confirms mass-transfer event in these systems. ELM or LM WDs cannot form from a single star evolution in the Hubble time, therefore, their discovery as a companion of these binary BSS systems implies that these BSS have formed via

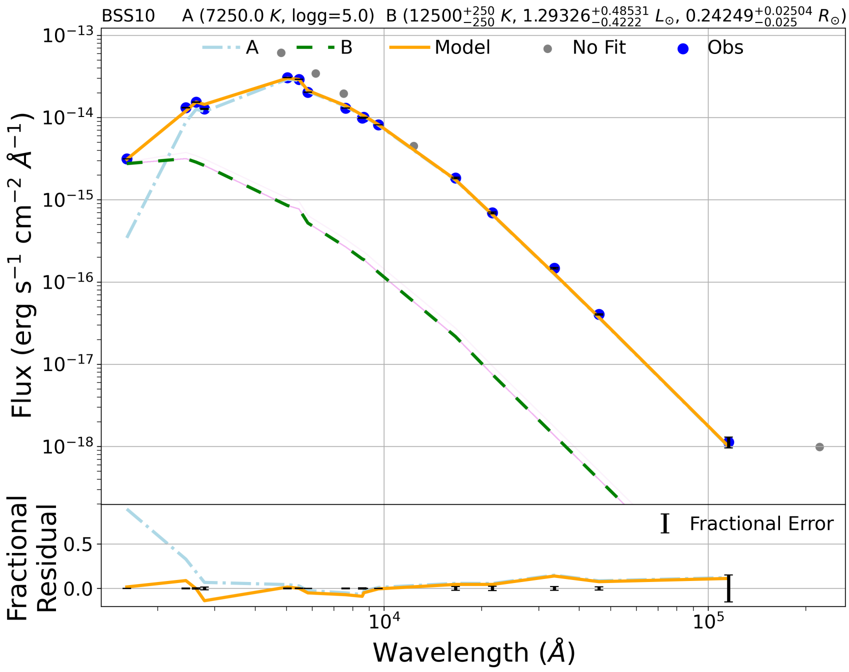

Figure 2: An example of a double-component SED from NGC 7789 reproduced from Fig. 4 in Vaidya et al. (2022). The top panel shows the extinction corrected fluxes and the model SED with the cool (A) component in the blue dashed line, hot (B) component in the green dashed line along with residuals of iterations shown as light pink lines, and the composite fit in the orange solid line. The fitted data points are shown as blue points with error bars according to flux errors and the data points not included in the fit are shown as grey data points. The bottom panel shows the fractional residual for both single fit (blue) and composite fit (orange).

mass-transfer by Case-A/Case-B mechanism. The hot companions of one YSS and two RC stars are found near the track of $0.6 M_\odot$ WD. These WD may be formed from the cluster turnoff stars. However, the hot companions of one YSS and one RC star are found near the track of $0.8 M_\odot$ WD. Such a high mass WD indicates that these YSS and RC star may be in a triple system, with the progenitors of these two WDs likely BSS. We conclude that at least 36% of the BSS of these two clusters and significantly more (66%) YSS of NGC 2506 have formed via the mass-transfer mechanism.

5. Summary

Using a UV-based approach, we studied exotic stellar populations, mainly BSS, a handful of YSS, plus some RC stars of open clusters NGC 7789 and NGC 2506. $\sim 45\%$ of BSS and all the YSS show UV-excess, of which $\sim 36\%$ BSS and 66% YSS are successfully fitted with double-component SEDs. Additionally, all RCs are successfully fitted with double-component SEDs. All of the eight BSS have an ELM/LM WD as a companion and hence have likely

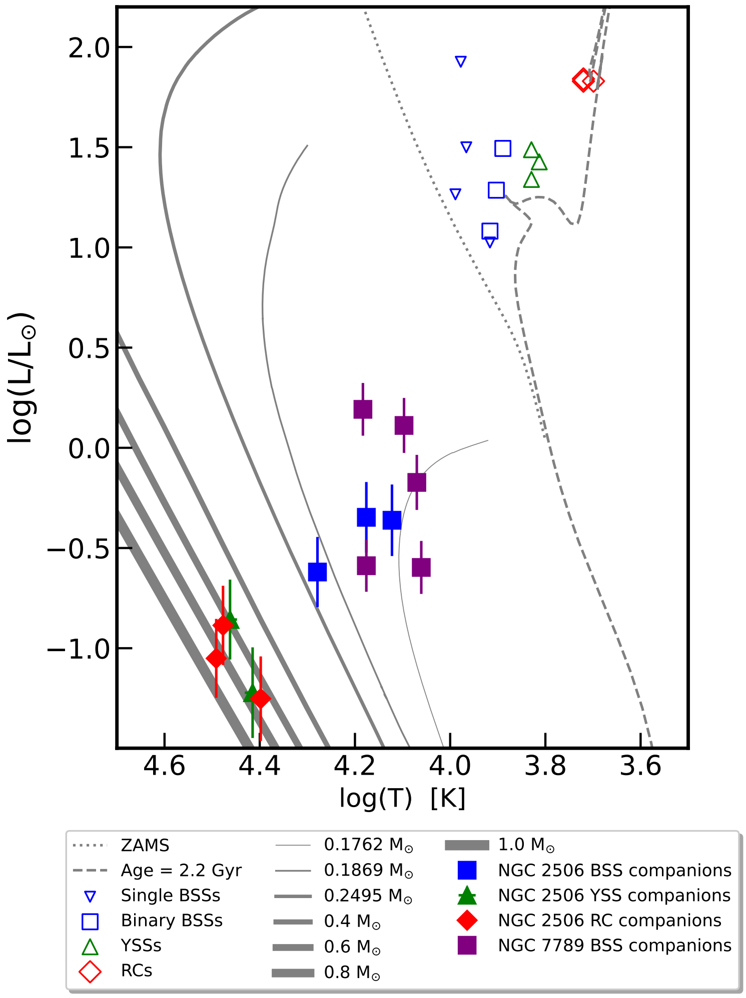

Figure 3: The H–R diagram of NGC 2506 showing the BSS (single-component: blue open triangles, double-component: blue open squares), YSS (green open triangles), and RC stars (red open diamonds). A PARSEC isochron of 2.2 Gyr (dashed curve), a zero-age main-sequence (ZAMS; dotted curve), and WD cooling curves of various masses from Panei et al. (2007) and Althaus et al. (2013) are overplotted on the diagram. The hot companions are shown as filled symbols of the same colors. The hot companions of the NGC 7789 are shown as filled purple squares.

formed via Case-A/Case-B mechanism. The YSS and RC stars contain either normal-mass or high-mass WD as a companion and have likely formed via mass-transfer in a binary or a triple system.

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Conflicts of interest

The authors declare no conflict of interest.

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