

UOCS XX: ultraviolet signatures of binary evolution in the open cluster Berkeley 21

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ABSTRACT

We present a multiwavelength study of the intermediate-age (~ 2.1 Gyr) open cluster Berkeley 21 using ultraviolet observations from *AstroSat*/UVIT together with archival optical and infrared data. A machine learning-based membership analysis (ML–MOC) applied to *Gaia* DR3 identifies 325 cluster members, of which ten are detected in the UVIT/F172M filter, including four blue straggler stars (BSSs), five main-sequence (MS) stars, and one red clump (RC) star. We construct ultraviolet-to-infrared spectral energy distributions (SEDs) to derive stellar parameters and search for unresolved companions. The BSSs are well reproduced by single-component SEDs, suggesting either merger origins or companions too cool to be detected in the UV. In contrast, four MS stars and the RC star exhibit significant UV excess (> 50 per cent), requiring binary-component SEDs. The inferred hot companions have effective temperatures of $\sim 26\,000$ – $49\,000$ K and properties consistent with low-mass ($\leq 0.4M_{\odot}$) white dwarfs. Such white dwarfs cannot form through single-star evolution within a Hubble time, indicating a binary mass-transfer origin. The detection of hot companions in the MS stars identifies them as blue lurker candidates, while the RC star also shows evidence for past binary interaction. Our results demonstrate that binary evolution, most likely through Case-B mass transfer, plays a major role in shaping the hot stellar population of Berkeley 21, with at least five of the ten UV-detected sources formed through mass transfer.

Key words: blue stragglers – open clusters and associations: individual: blue lurker – ultraviolet: stars.

1 INTRODUCTION

Binary star interactions lead to a fundamentally different path of stellar evolution compared to single stars. The Roche model (A. Orlov 1961) and the concept of common envelope evolution during dynamic mass transfer (B. Paczynski 1967) laid the foundation for binary evolution studies in the 1980s. Over the last two decades, it has been conclusively shown that most massive stars form in binary or multiple systems (D. Vanbeveren, C. De Loore & W. Van Rensbergen 1998; H. Sana et al. 2012, 2013; H. A. Kobulnicky et al. 2014; M. Moe & R. Di Stefano 2017). As a result, understanding their evolution is challenging since the interactions with their companions, can significantly alter their properties and observable features compared to single stars (P. Podsiadlowski, P. Joss & J. Hsu 1992; S. De Mink et al. 2013; C. Wang et al. 2020). These binary interactions are expected to produce a variety of non-standard stellar populations, such as blue stragglers (BSSs).

Although BSSs were first discovered in the globular cluster (GC) Messier 3 (A. R. Sandage 1953), they have now been identified in a wide range of environments, including open clusters (OCs; J. Ahumada & E. Lapasset 1995), dwarf galaxies (Y. Mo-

many et al. 2007), and the Galactic field (G. W. Preston & C. Sneden 2000). Their location on the CMD is unexpected, as stars of comparable mass in coeval stellar populations should have already evolved off the main sequence (MS). Despite this apparent contradiction, BSSs are relatively common and are among the most massive stars in stellar environments (M. M. Shara, R. A. Saffer & M. Livio 1997; R. L. Gilliland et al. 1998; G. Beccari et al. 2006; R. Gratton et al. 2006; G. Fiorentino et al. 2014).

After several decades of investigation, BSS formation is now understood to proceed primarily through three channels: direct stellar collisions, binary mass transfer, and merger or mass-transfer of the inner binaries in hierarchical triple systems. Direct collisions are expected to be efficient mainly in high stellar-density environments, such as the cores of GCs, where close encounters are frequent (M. B. Davies, G. Piotto & F. D. Angeli 2004; S. Chatterjee et al. 2013). In contrast, binary evolution is believed to dominate in lower-density environments such as OCs and Galactic fields, where primordial binaries are more likely to survive and interact through mass transfer (W. H. McCrea 1964). In this framework, the nature of the final binary system depends strongly on the evolutionary stage of the donor star when mass transfer occurs. Case A mass transfer, in which the donor is on the MS, produces either a rejuvenated BSS or a short-period binary with a main-sequence companion (R. F. Webbink 1976). Case B mass transfer occurs when the donor ascends the red giant branch

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(RGB), typically yielding a short-period BSS binary with a helium white dwarf (WD) companion, while Case C mass transfer from an asymptotic giant branch (AGB) donor leads to long-period systems with carbon–oxygen WD companions (X. Chen & Z. Han 2008; N. M. Gosnell et al. 2014). Recent large-scale observational studies strongly support binary evolution as the dominant formation channel for BSSs in Galactic OCs. Using *Gaia* EDR3 data, M. Rain et al. (2024) demonstrated, for the first time, a statistically significant correlation between the number of BSSs and the host cluster binary fraction, providing direct empirical evidence that binary evolution governs BSS production in these environments. However, the observational picture is not entirely uniform. While several studies have found similar evidence for a close connection between BSS populations and cluster binary fractions (A. Milone et al. 2012), others have reported weaker or statistically insignificant correlations (G. Cordoni et al. 2023). These results suggest that although binary evolution is widely considered to be the primary formation mechanism for BSSs in open clusters, the relative importance of different formation channels may depend on cluster properties and remains an active area of investigation.

Furthermore, the bulk distribution of BSSs in *Gaia* CMDs was shown to be well reproduced by composite evolutionary sequences derived from detailed binary evolution models, reinforcing the binary origin of most BSSs in OCs. Hierarchical triple systems provide an additional pathway, particularly relevant for producing massive or long-period BSSs. Secular dynamical effects such as Kozai–Lidov cycles can induce mergers or mass transfer within the inner binary, resulting in either a single, unusually massive BSS or a binary BSS with a wide tertiary companion (H. B. Perets & D. C. Fabrycky 2009).

Owing to their elevated effective temperatures, BSSs are substantially brighter in the ultraviolet (UV) than the majority of cluster members, making UV observations particularly effective for their identification and characterization. In addition, the presence of a hot WD companion in BSS produces excess UV emission, providing a powerful diagnostic for detecting such companions and constraining the underlying formation pathways. The utility of UV observations in this context has been well demonstrated in previous studies. Using far-UV *Hubble Space Telescope* observations of the OC NGC 188, N. M. Gosnell et al. (2014) identified four hot and three cool WD companions to BSSs. Similarly, A. Subramaniam et al. (2018) employed *GALEX* imaging of the OC M67 to detect 18 BSSs, 3 WDs, 4 YSSs, 2 subgiant stars, and 25 X-ray sources. Moreover, the Ultraviolet Imaging Telescope (UVIT) aboard *AstroSat* has significantly advanced the study of hot and exotic stellar populations in both star clusters and the Galactic field. Its observations have enabled the detection and characterization of such populations in open clusters, including NGC 2682 (V. V. Jadhav, N. Sindhu & A. Subramaniam 2019; N. Sindhu 2019), NGC 7789 (K. Vaidya et al. 2022), NGC 6940 (A. Panthi & K. Vaidya 2024), NGC 2506 (A. Panthi et al. 2022), and King 2 (V. V. Jadhav et al. 2021). In addition, these studies have identified BSS systems with hot companions in the Galactic field (A. Panthi et al. 2023), highlighting the role of UV observations in probing interaction-driven stellar evolution across diverse environments.

Mass transfer and interactions between cluster members give rise to several stellar populations beyond BSSs. One such population is yellow straggler stars (YSSs), sometimes referred to as yellow giants, which occupy the region between the BSS sequence and the RGB in the CMD and are brighter than the subgiant

branch (W. Landsman et al. 1997; E. Corsaro et al. 2012; E. Leiner et al. 2016; R. Handberg et al. 2017). Early studies of M67 revealed that the majority of YSSs are spectroscopic binaries (R. D. Mathieu & D. W. Latham 1986), supporting an interaction-driven origin. Subsequent UV observations have detected WD companions to YSSs (W. Landsman et al. 1998; A. Panthi et al. 2022; A. Panthi & K. Vaidya 2024), while E. Leiner et al. (2016) proposed that some YSSs may form through mergers or stellar collisions, particularly in dynamically evolved cluster environments.

Another intriguing population associated with binary interaction is blue lurkers (BLs; E. Leiner et al. 2019), which are MS stars that have undergone mass accretion but remain photometrically indistinguishable from normal MS stars in optical CMDs. A recent study by V. V. Jadhav, K. K. Rao & E. Reggiani (2026) provides a physically motivated framework for identifying BLs, showing that they can be recognized through any of these multiple diagnostics; however, an individual BL candidate may not satisfy all of these criteria simultaneously. These diagnostics are as follows (i) unusually rapid rotation compared to stars of similar mass, indicative of recent accretion; (ii) the presence of companions that can only form through mass transfer, such as extremely low-mass (ELM) or low-mass (LM) WDs; and (iii) chemical signatures of past accretion, including Li/C/O depletion or s-process element enhancement. They carried out an observational survey of BL candidates in OCs and identified 97 new BL candidates across 35 clusters, making the total number of known or BL candidates to be 133. They also highlight that given the current ~ 3 per cent completeness of BL detections, thousands of BLs are likely to remain hidden within cluster MS. UV observations, when combined with rotational information, have proven to be particularly effective in identifying and characterizing BLs. A. Panthi & K. Vaidya (2024) identified 11 BL candidates in the OC NGC 6940 as MS stars near the turnoff with high rotational velocities ($v \sin i \gtrsim 50 \text{ km s}^{-1}$) and UV counterparts in the UVIT/F169M filter. Out of these, nine sources were analysed in detail, while two were excluded due to source contamination. Among the nine, three sources required binary-component SED fits and were found to host WD companions, including two LM WDs and one normal-mass WD. The presence of LM WDs suggests formation via Case-B mass transfer, whereas the normal-mass WD points to either Case-C mass transfer or merger channels.

In addition to these interaction-driven populations, the red clump (RC) comprises a prominent group of evolved stars commonly observed in large Galactic surveys (L. Girardi 2016). RC stars are characterized by core helium burning surrounded by a hydrogen-burning shell and a hydrogen-rich convective envelope. Their relatively narrow locus in the CMD makes them valuable standard candles and important for determining cluster distances and ages through isochrone fitting.

Berkeley 21 (RA = 05:51:42, Dec. = + 21:47:00) is an intermediate-age OC located toward the Galactic anticenter. It is among the most distant known OCs in this direction and is considered one of the more metal-poor systems in the Galactic OC population (M. Tosi et al. 1998). Its large Galactocentric distance and low metallicity makes it a valuable environment for studying stellar populations in the outer regions of the Galactic disc. Early photometric studies by C. Christian & K. Janes (1979) suggested a young age and high reddening; however, subsequent CCD photometry and synthetic CMD analyses revised its age to $\sim 2\text{--}3$ Gyr and confirmed its significant reddening and distance (R. L. Phelps, K. A. Janes & K. A. Montgomery 1994; M. Tosi

et al. 1998). Spectroscopic studies have reported a metallicity in the range $[\text{Fe}/\text{H}] \sim -0.5$ to -1.0 , with uncertainties arising from the dependence on reddening estimates (E. D. Friel et al. 2002). More recent abundance analyses indicate that outer disc clusters such as Berkeley 21 exhibit a metallicity around $[\text{Fe}/\text{H}] \sim -0.5$ (D. Yong, B. W. Carney & M. L. T. De Almeida 2005). Despite its well-established global properties, the hot and exotic stellar populations in Berkeley 21 remain largely unexplored, particularly at UV wavelengths. In this work, we present the first detailed UV study of Berkeley 21 using *AstroSat*/UVIT observations. By combining UV data with multiwavelength SED analysis, we identify and characterize BSS and related populations, and investigate the role of binary evolution in shaping the stellar content of this distant OC.

2 OBSERVATIONS AND DATA REDUCTION

UVIT is a payload onboard India's first multi-wavelength space observatory, *AstroSat*, launched by the Indian Space Research Organisation (ISRO). It consists of one telescope operating in the visible channel and two co-aligned 38-cm telescopes covering the far-UV (FUV; 1300–1800 Å) and near-UV (NUV; 2000–3000 Å) wavelength ranges. All three channels observe simultaneously over a circular field of view with a diameter of 28 arcmin, achieving spatial resolutions (FWHM) of approximately 1.2 arcsec in the NUV and 1.5 arcsec in the FUV. Detailed descriptions of the instrument design, calibration, and in-orbit performance are provided by S. Tandon et al. (2017) and A. Subramaniam et al. (2016). Berkeley 21 was observed with UVIT under proposal ID A12_097T02_9000005542.

We process the raw UVIT images using the CCDLAB software (J. E. Postma & D. Leahy 2017). This pipeline performs flat-field correction, spacecraft drift correction, and geometric distortion correction to generate science-ready images. The final image obtained in the F172M (Silica) filter has a total effective exposure time of 3493.24 s.

3 DATA ANALYSIS

3.1 Cluster membership and UV photometry

We determine the cluster membership using a machine learning-based algorithm, ML-MOC (M. Agarwal et al. 2021), applied to *Gaia* DR3 data. First, we selected the sources within a radius of 40 arcmin from the cluster center. These sources have complete astrometric (positions, proper motions, and parallaxes) information, along with reliable photometry in the *Gaia*G, G_{BP} , and G_{RP} bands. Additionally, we retain only sources with non-negative parallaxes and uncertainties in G magnitude smaller than 0.005. This initial data set is referred to as the `All_sources` sample. To estimate the cluster's mean astrometric properties, we employ the k-nearest neighbours (kNN) algorithm to derive representative values of proper motion and parallax. Applying kNN directly to the full data set is computationally expensive and prone to bias from field-star contamination. Therefore, we iteratively restrict the parameter space to isolate likely cluster members. For proper motions ($\mu_{\alpha*}$, μ_{δ}), we begin with a window of width 5 mas yr^{-1} and progressively shift and refine its size until the mean values within the window converge to those obtained from the kNN estimation. A similar strategy is adopted for parallaxes, where the initial window width is guided by the expected cluster distance. The sources contained within these refined ranges are defined

as the `Sample_sources`. We then apply a Gaussian Mixture Model (GMM) to the `Sample_sources` in the combined proper motion and parallax space. This unsupervised clustering technique models the distribution as a superposition of two Gaussian components, corresponding to cluster members and field stars, and assigns a membership probability to each source. Our primary selection includes stars with membership probabilities greater than 0.6. To improve completeness, we additionally include sources with intermediate probabilities in the range 0.2–0.6. Using this approach, we identify a total of 325 likely cluster members, of which 255 have high membership probabilities ($P > 0.6$). The proper motion, spatial distribution, and parallax distributions of both the `sample_sources` and the confirmed members are shown in Fig. 1. To further assess the reliability of the membership classification, we examine the proper-motion distribution in different *Gaia* magnitude intervals following the approach of E. Lagioia et al. (2014). The CMD is divided into five magnitude bins, and the corresponding vector-point diagrams are shown in the lower-right panel of Fig. 1. In each bin, the final ML-MOC members remain tightly clustered around the cluster proper-motion centroid, while the remaining sample sources exhibit a much broader distribution. We also compute the proper-motion dispersion of the selected members in each magnitude interval and overplot the corresponding 3σ confidence ellipse. As expected, the dispersion of the member distribution increases slightly towards fainter magnitudes because of the larger *Gaia* astrometric uncertainties. Nevertheless, the selected members continue to define a compact and well-separated overdensity relative to the surrounding field population across all magnitude ranges, demonstrating that the ML-MOC membership determination remains robust over the full magnitude range considered.

We perform point-spread function (PSF) photometry on the UVIT image using the DAOPHOT package within IRAF (P. B. Stetson 1987). First, we use the `imexamine` task to estimate the background level and the full width at half maximum (FWHM) of the stellar profiles. Then we detect the sources using `daofind` task, selecting objects above a threshold typically set between 3 and 10 times the background noise. Subsequently, we perform aperture photometry using the `phot` task. To construct the PSF model, we first select suitable stars using `pstselect`, followed by generating the PSF with the `psf` task. The `allstar` routine is then used to obtain PSF magnitudes for all detected sources through iterative fitting. We convert the instrumental magnitudes to the AB magnitude system using the zero-point values provided by S. Tandon et al. (2020). We further apply aperture corrections derived from the *curve-of-growth* method, along with PSF and saturation corrections, following S. Tandon et al. (2020). Finally, we crossmatch the UVIT observed sources with *Gaia* DR3 cluster members using TOPCAT (M. Taylor 2011), adopting a matching radius of 2 arcsec. In total, 6439 sources are observed using UVIT in F172M filter and 10 are crossmatched with *Gaia* DR3 based ML-MOC members.

4 RESULTS

4.1 Colour-magnitude diagram

Star clusters provide ideal laboratories for investigating stellar populations, as their members are largely homogeneous in age, distance, and chemical composition (K. Janes & R. Phelps 1994; E. Friel 1995; C. Bonatto et al. 2006). Accurate determination of key properties, such as distance, age, mass, density, and dynamical

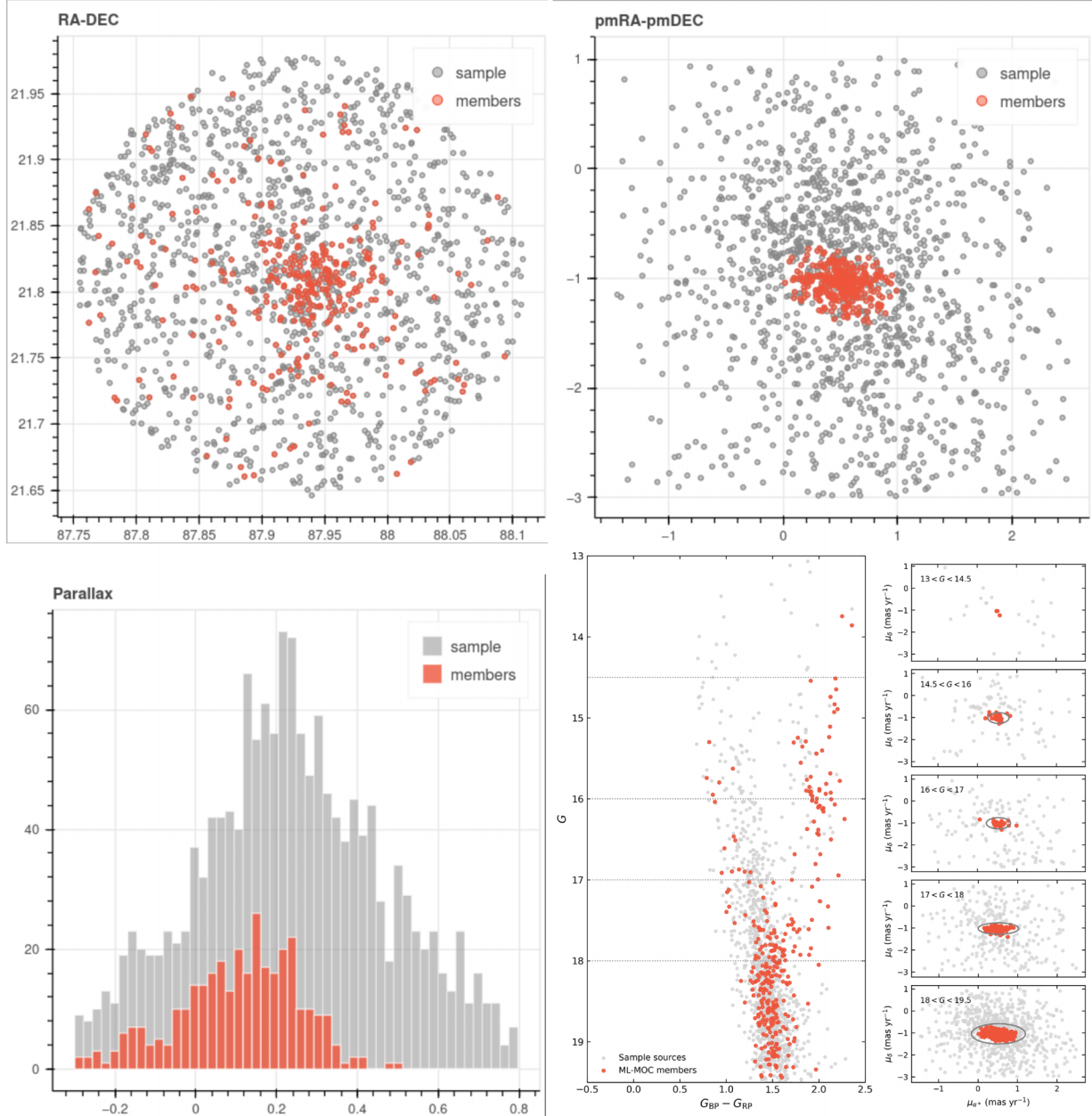


Figure 1. Upper left: Spatial distribution, upper right: proper-motion distribution, and lower left: parallax distribution of the sample sources and the ML-MOC members determined using the ML-MOC algorithm. Lower right: *Gaia* colour-magnitude diagram together with proper-motion distributions in different magnitude intervals for the sample sources and the ML-MOC members.

cal time-scales, is essential for constraining theoretical models. However, OCs located near the Galactic plane are strongly affected by interstellar reddening and field-star contamination (C. Bonatto et al. 2006 and references therein), which can bias these estimates. In particular, spatial variations in extinction (differential reddening) broaden cluster sequences in CMDs and complicate member identification, including that of BSSs. Correcting for differential reddening is therefore critical for reliable analysis. The differential reddening of Berkeley 21 have been also reported by M. Tosi et al. (1998) and (D. Yong et al. 2005).

We construct the differential reddening-corrected optical CMD using the *Gaia* DR3 photometry of the ML-MOC cluster members. The differential reddening correction is performed follow-

ing the procedure developed by A. Milone et al. (2012) and subsequently adopted by E. Lagioia et al. (2014). We first select a clean sample of upper main-sequence stars to serve as reference stars and construct a fiducial sequence by fitting a spline through their median positions. Then we rotate the CMD such that the reddening vector becomes horizontal while the main sequence is nearly vertical. In this rotated reference frame, the local differential reddening is estimated from the displacement of nearby reference stars relative to the fiducial sequence, and the corresponding correction is applied along the reddening vector to each star. Since this method corrects only the spatial variations in reddening across the cluster field while preserving the mean cluster reddening, it improves the internal consistency of the photometry

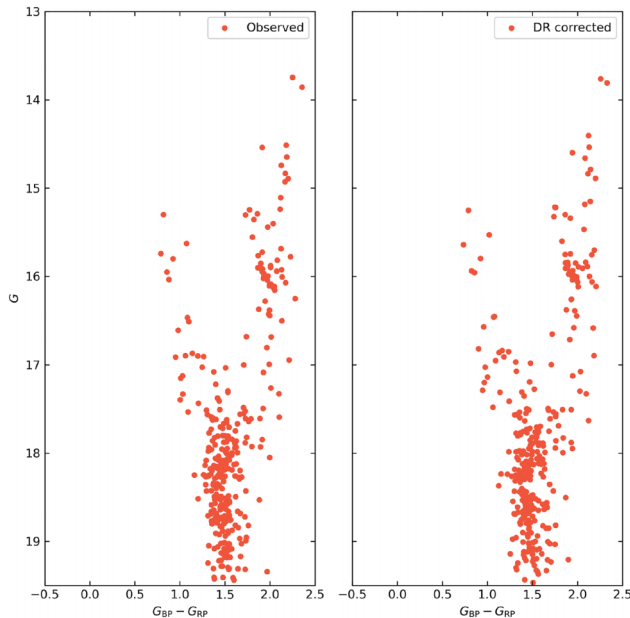


Figure 2. The observed CMD (left panel) and differential reddening corrected CMD (right panel).

without altering the overall location of the cluster sequence in the CMD.

The resulting differential reddening-corrected CMD is shown in Fig. 2. The corrected main sequence appears marginally tighter than in the original CMD, although the improvement is modest. This is expected because Berkeley 21 is a relatively sparse open cluster and exhibits only a small level of spatial differential reddening compared to the globular clusters for which this technique has been widely applied.

We construct the differential reddening corrected optical CMD using *Gaia* DR3 data, where the cluster members identified through the ML-MOC algorithm are shown as green points in Fig. 3, color-coded by their membership probability. We overplot a PARSEC isochrone (A. Bressan et al. 2012) corresponding to an age of 2.1 Gyr, distance of 6417 pc, and metallicity $[\text{Fe}/\text{H}] = -0.21$ (M. Tosi et al. 1998; D. Yong et al. 2005; A. Bragaglia et al. 2022; S. Randich et al. 2022), after applying extinction corrections of $A_G = 1.972$ and $E(BP - RP) = 1.039$ (C. M. Dutra & E. Bica 2000). To identify BSSs in the cluster, we construct an equal-mass binary sequence by shifting the fitted isochrone by 0.75mag to account for unresolved binaries. Stars that are brighter than the MSTO and located blueward of this binary sequence are classified as BSS candidates. Based on these criteria, we identify a total of 14 BSS candidates. Out of the 14 BSS reported identified in this work, only 4 are observed in the UVIT. Their detection can be understood as a combined effect of intrinsic brightness and local extinction. BSS2 and BSS3 are the brightest BSSs in the *Gaia* CMD, and this high intrinsic brightness makes them detectable in the UV despite the fact that BSS2 lies in a high-extinction region and BSS3 is in a moderate-extinction region. BSS1 and BSS4 are fainter than BSS2 and BSS3, but they lie in relatively lower-extinction regions, which likely helps their UV detection. The remaining BSSs are optically fainter than BSS1 and BSS3 in the *Gaia* CMD and are therefore expected to be fainter in the UV as well; hence, even moderate or variable extinction can push them below the UVIT detection limit. This suggests that the UVIT

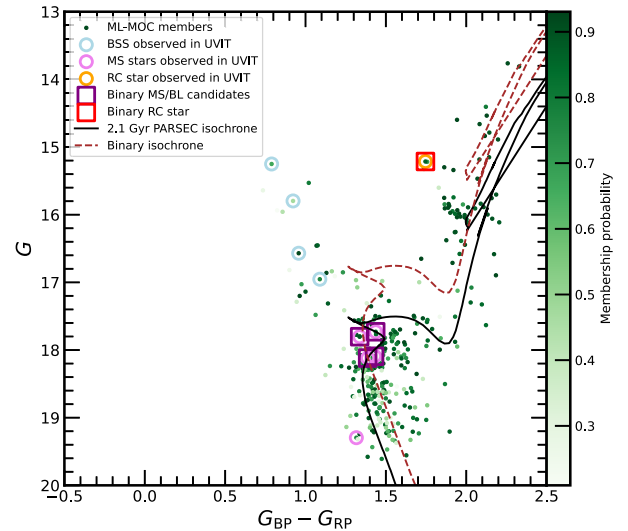


Figure 3. Optical CMD of Berkeley 21 constructed using *Gaia* DR3 data. Cluster members identified through the ML-MOC algorithm are shown as green points, colour-coded by their membership probability. Sources observed using UVIT are highlighted with open circles, with blue, pink, and orange corresponding to BSSs, MS stars, and the RC star, respectively. Binary candidates among these populations are indicated by open squares (blue: binary BSSs; purple: binary MS/BL candidates; red: binary RC star). The best-fitting PARSEC isochrone (age = 2.1 Gyr, $[\text{Fe}/\text{H}] = -0.21$) is shown as a solid black curve, while the equal-mass binary sequence, obtained by shifting the isochrone by 0.75 mag, is shown as a brown dashed line.

detections are governed by both optical brightness and the local reddening distribution. We note that the two brightest BSS candidates exhibit relatively low membership probabilities; however, their positions in the CMD being significantly brighter than the MSTO and lying well within the defined BSS region, strongly support their classification as BSSs. Moreover, the detection of their UV counterparts adds confidence to their BSS nature.

4.2 Spectral energy distributions

We construct the SEDs of the BSSs, MS stars, and RC star observed in UVIT to derive their fundamental parameters and investigate the presence of possible hot companions. As a preliminary step, we examined all sources using *Aladin* to identify nearby contaminants within a radius of 3 arcsec. One object (BSS4) was found to have a neighbouring source within this radius and was therefore excluded from further SED analysis. For the remaining sources, we construct SEDs using the Virtual Observatory SED Analyzer (VOSA; A. Bayo et al. 2008), incorporating multiwavelength photometric data spanning from the UV to the infrared. Apart from UVIT/F172M flux, the UV data are obtained from the *Galaxy Evolutionary Explorer* (GALEX; D. C. Martin et al. 2005), optical data from *Gaia* DR3 (C. Babusiaux et al. 2023) and Pan-STARRS (E. A. Magnier et al. 2020), near-infrared data from 2MASS (M. Cohen, W. A. Wheaton & S. Megeath 2003), and mid-infrared data from WISE (E. L. Wright et al. 2010). The observed fluxes are corrected for interstellar extinction using values derived from 3D dust maps (G. M. Green et al. 2019), and the extinction-corrected fluxes used for SED fitting are listed in Table 1.

Table 1. Coordinates of all the sources in Columns 2 and 3, extinction values (A_V) in Column 4, UVIT F172M flux in Column 5, PANSTARRS and *Gaia* DR3 fluxes in Columns 6–13, 2MASS J, H, and Ks fluxes in Columns 14–16, and *WISE* W1, W2, and W3 fluxes in Columns 17–19. All flux values are extinction corrected and listed in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$.

Name	RA	Dec.	A_V	UVIT.F172M $\pm$ err
PS1.g $\pm$ err	GAIA3.Gbp $\pm$ err	GAIA3.G $\pm$ err	PS1.r $\pm$ err	PS1.i $\pm$ err
GAIA3.Grp $\pm$ err	P.S1.z $\pm$ err	PS1.y $\pm$ err	2MASS.J $\pm$ err	2MASS.H $\pm$ err
2MASS.Ks $\pm$ err	WISE.W1 $\pm$ err	WISE.W2 $\pm$ err	WISE.W3 $\pm$ err	WISE.W4 $\pm$ err
BSS1	87.92441	21.82043	1.9686 $\pm$ 0.5	6.8950e-15 $\pm$ 9.956e-17
5.817e-15 $\pm$ 1.314e-17	4.745e-15 $\pm$ 2.360e-17	2.752e-15 $\pm$ 7.255e-18	3.065e-15 $\pm$ 6.179e-18	1.709e-15 $\pm$ 4.54e-18
1.556e-15 $\pm$ 7.065e-18	1.177e-15 $\pm$ 2.994e-18	9.488e-16 $\pm$ 2.716e-18	4.175e-16 $\pm$ 1.423e-17	1.564e-16 $\pm$ 6.916e-18
6.047e-17 $\pm$ 4.957e-18	–	–	–	–
BSS2	87.95195	21.77664	1.7881 $\pm$ 0.5	3.498e-14 $\pm$ 3.950e-17
1.747e-14 $\pm$ 1.528e-16	1.430e-14 $\pm$ 4.957e-17	7.965e-15 $\pm$ 2.043e-17	8.892e-15 $\pm$ 1.687e-17	4.814e-15 $\pm$ 1.372e-17
4.359e-15 $\pm$ 1.627e-17	3.167e-15 $\pm$ 9.139e-18	2.532e-15 $\pm$ 9.974e-18	1.094e-15 $\pm$ 2.721e-17	3.757e-16 $\pm$ 1.073e-17
1.422e-16 $\pm$ 5.370e-18	2.737e-17 $\pm$ 7.310e-19	7.539e-18 $\pm$ 2.847e-19	–	–
BSS3	88.02262	21.73827	2.2382 $\pm$ 0.5	2.210e-14 $\pm$ 2.291e-16
1.707e-14 $\pm$ 5.842e-17	1.356e-14 $\pm$ 6.786e-17	7.218e-15 $\pm$ 1.866e-17	8.051e-15 $\pm$ 1.461e-17	4.164e-15 $\pm$ 7.359e-18
3.760e-15 $\pm$ 1.574e-17	2.744e-15 $\pm$ 1.008e-17	2.219e-15 $\pm$ 8.921e-18	9.007e-16 $\pm$ 2.489e-17	3.258e-16 $\pm$ 1.200e-17
1.198e-16 $\pm$ 5.849e-18	2.219e-17 $\pm$ 5.926e-19	6.154e-18 $\pm$ 2.664e-19	–	–
MS2	87.87687	21.77603	1.7614 $\pm$ 0.5	1.744e-15 $\pm$ 3.817e-17
7.609e-16 $\pm$ 6.484e-18	6.882e-16 $\pm$ 1.420e-17	5.423e-16 $\pm$ 1.607e-18	5.879e-16 $\pm$ 3.208e-18	4.225e-16 $\pm$ 4.081e-18
3.925e-16 $\pm$ 4.977e-18	3.330e-16 $\pm$ 4.575e-18	2.870e-16 $\pm$ 3.860e-18	1.596e-16 $\pm$ 1.308e-17	6.247e-17 $\pm$ 8.918e-18
2.834e-17 $\pm$ 5.272e-18	4.378e-18 $\pm$ 2.379e-19	9.620e-19 $\pm$ 1.994e-19	–	–
MS3	87.92926	21.74359	1.9251 $\pm$ 0.5	1.820e-15 $\pm$ 3.944e-17
1.245e-15 $\pm$ 6.192e-18	1.122e-15 $\pm$ 2.080e-17	8.055e-16 $\pm$ 2.295e-18	8.861e-16 $\pm$ 4.407e-18	6.099e-16 $\pm$ 5.618e-18
5.482e-16 $\pm$ 5.743e-18	4.561e-16 $\pm$ 2.016e-18	3.912e-16 $\pm$ 4.288e-18	1.861e-16 $\pm$ 1.234e-17	8.253e-17 $\pm$ 6.765e-18
3.055e-17 $\pm$ 5.092e-18	7.906e-18 $\pm$ 3.131e-19	2.404e-18 $\pm$ 2.081e-19	–	–
MS4	87.95268	21.79737	1.7674 $\pm$ 0.5	2.122e-15 $\pm$ 4.092e-17
1.049e-15 $\pm$ 6.448e-18	1.002e-15 $\pm$ 1.350e-17	7.834e-16 $\pm$ 2.268e-18	8.421e-16 $\pm$ 3.731e-18	6.147e-16 $\pm$ 5.223e-18
5.649e-16 $\pm$ 3.400e-18	4.741e-16 $\pm$ 2.600e-18	4.065e-16 $\pm$ 2.160e-18	2.379e-16 $\pm$ 1.381e-17	8.797e-17 $\pm$ 8.265e-18
4.251e-17 $\pm$ 4.894e-18	6.372e-18 $\pm$ 3.404e-19	–	–	–
MS5	87.96405	21.78590	1.6071 $\pm$ 0.5	1.286e-15 $\pm$ 2.211e-17
6.847e-16 $\pm$ 4.754e-18	6.348e-16 $\pm$ 1.659e-17	4.983e-16 $\pm$ 1.485e-18	5.493e-16 $\pm$ 1.893e-18	3.957e-16 $\pm$ 1.954e-18
33.596e-16 $\pm$ 5.721e-18	3.123e-16 $\pm$ 1.849e-18	2.690e-16 $\pm$ 2.050e-18	1.690e-16 $\pm$ 1.136e-17	8.080e-17 $\pm$ 7.070e-18
2.654e-17 $\pm$ 5.280e-18	5.983e-18 $\pm$ 3.086e-19	9.569e-19 $\pm$ 1.807e-19	–	–
RC1	87.87158	21.68862	1.4064 $\pm$ 0.5	4.873e-16 $\pm$ 1.043e-17
5.027e-15 $\pm$ 9.343e-18	5.430e-15 $\pm$ 3.148e-17	5.570e-15 $\pm$ 1.430e-17	5.842e-15 $\pm$ 9.368e-18	5.166e-15 $\pm$ 9.512e-18
4.928e-15 $\pm$ 1.805e-17	4.503e-15 $\pm$ 9.336e-18	4.106e-15 $\pm$ 1.126e-17	2.792e-15 $\pm$ 5.657e-17	1.697e-15 $\pm$ 2.969e-17
6.967e-16 $\pm$ 1.476e-17	1.416e-16 $\pm$ 3.261e-18	3.841e-17 $\pm$ 8.136e-19	1.033e-18 $\pm$ 3.541e-19	–

VOSA determines the best-fitting stellar parameters by performing a reduced χ^2 minimization between the observed and synthetic fluxes, computed using filter transmission curves. The reduced χ^2 is given by:

$$\chi_r^2 = \frac{1}{N - N_f} \sum_{i=1}^N \frac{(F_{o,i} - M_d F_{m,i})^2}{\sigma_{o,i}^2}, \quad (1)$$

where N is the number of photometric data points, N_f is the number of free parameters, $F_{o,i}$ and $F_{m,i}$ are the observed and model fluxes, respectively, $\sigma_{o,i}$ is the uncertainty in the observed flux, and $M_d = (R/D)^2$ is the scaling factor, with R being the stellar radius and D the distance to the source.

We use Kurucz stellar atmosphere models (F. Castelli, R. G. Gratton & R. L. Kurucz 1997), allowing the effective temperature (T_{eff}) and surface gravity ($\log g$) to vary within the ranges 3500–50 000 K and 3–5, respectively. The metallicity is fixed at $[\text{Fe}/\text{H}] = -0.5$, corresponding to the closest available value in VOSA and consistent with the cluster metallicity ($[\text{Fe}/\text{H}] \sim -0.21$; A. Bragaglia et al. 2022). We first perform single-component SED fitting for all sources. The BSSs (BSS1, BSS2, and BSS3) do not exhibit significant UV excess and are well reproduced by single-component SEDs (Fig. 4). On the other hand, MS1 has insuffi-

cient photometric coverage, with flux measurements available in only a few filters, preventing reliable SED fitting. The remaining sources (MS2, MS3, MS4, MS5, and RC1) show substantial UV excess, quantified by a fractional UV residual greater than 0.5. We note that UV excess in single stars can also arise from chromospheric activity or hot spots. To rule out such scenarios, we examined archival *XMM-Newton* and *Chandra* observations; however, the cluster is not detected in X-rays. This strongly supports the interpretation that the observed UV excess originates from hot companions. We therefore perform binary-component SED fitting using the Python-based code *BINARY SED FITTING* developed by V. V. Jadhav et al. (2021), which employs χ^2 minimization to model composite SEDs. First, we explored the Koester WD atmosphere models (D. Koester 2002) for the hot companions; however, these fits consistently converged to the upper temperature limits of the model grid (e.g. $\sim 80\,000$ K), leading to physically implausible solutions. Therefore, we adopt Kurucz models for both components to obtain stable and consistent fits across the sample.

The inclusion of a hot component significantly improves the fits and reduces the residuals compared to the single-component models (Table 2). The fitting routine provides statistical uncertainties; however, in some cases, the reduced χ^2 values remain

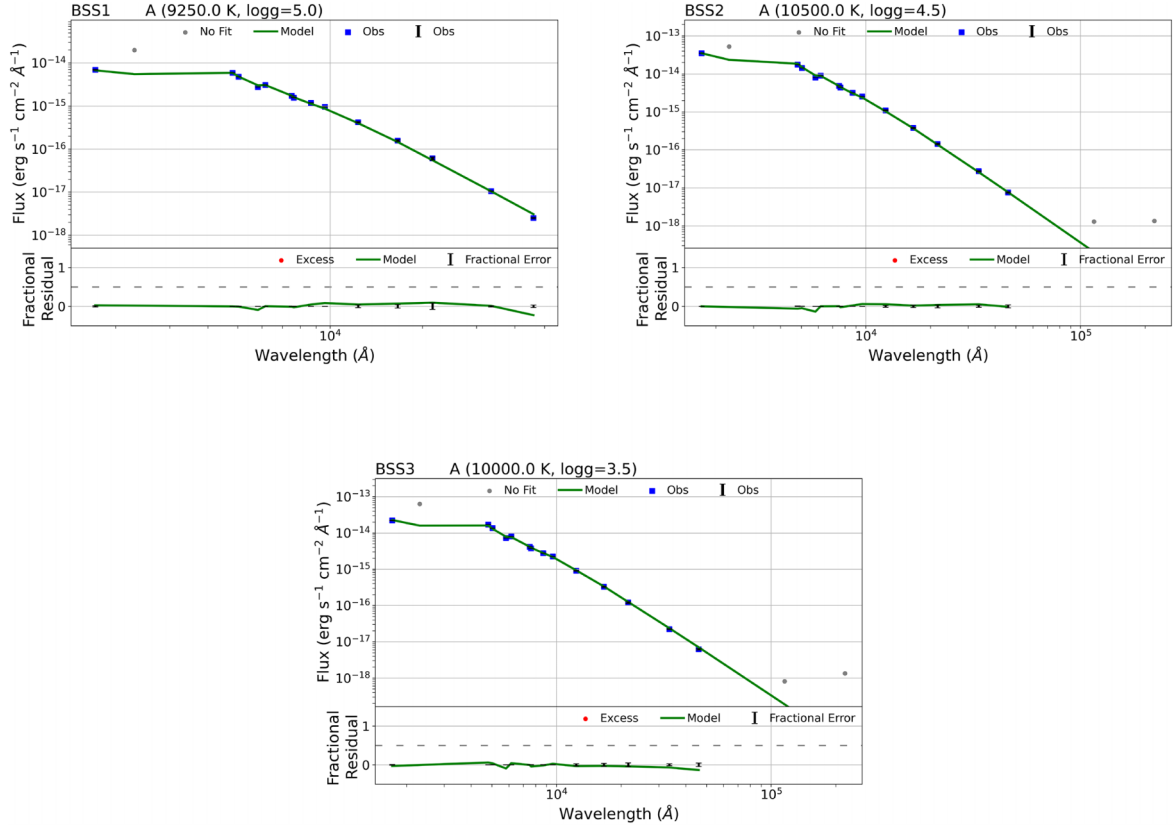


Figure 4. The single-component SEDs. The upper panels show the extinction-corrected fluxes (blue squares) with their associated uncertainties (black error bars). The best-fitting model is shown as the green curve. Data points excluded from the fitting by VOSA are indicated as grey dots, either due to poor photometric quality or because they represent upper limits. The lower panels display the residuals between the extinction-corrected observed fluxes and the model fluxes across wavelengths from the UV to the infrared.

Table 2. The best-fitting parameters of all UVIT sources obtained from SED fitting. Column 2 lists the component (A: primary/cooler; B: secondary/hot companion), Columns 3–5 list the effective temperature, luminosity, and radius, Column 6 lists the surface gravity (logg), Column 7 gives the reduced χ_r^2 values, Column 8 lists the scaling factor, Column 9 gives the number of data points used for fitting (N_{fit}), and Column 10 lists the vgf_b parameter.

Name	Component	T_{eff} (K)	Luminosity ($L_{\odot}$)	Radius ($R_{\odot}$)	logg	χ_r^2	Scaling factor	N_{fit}	vgf_b
BSS1	Single	9250 ± 125	38.37 ± 14.74	2.11 ± 0.41	5	390.20	$8.34\text{e-}23$	15	5.1
BSS2	Single	10500 ± 125	125.90 ± 48.36	3.16 ± 0.61	4.50	762.71	$1.87\text{e-}22$	17	2.45
BSS3	Single	10000 ± 125	116.60 ± 44.79	3.09 ± 0.593	3.5	447.5	$1.79\text{e-}22$	17	4.32
MS2	A	6250 ± 125	4.55 ± 1.76	1.78 ± 0.34	4.50	167.51	$5.96\text{e-}23$	16	8.57
	B	39000^{+3000}_{-1000}	$4.73^{+4.7}_{-2.67}$	0.05 ± 0.01	4.5	43.15		14	1.51
MS3	A	6500 ± 125	6.62 ± 2.56	2.00 ± 0.384	3.5	166.60	$7.52\text{e-}23$	16	8.1
	B	49000^{+3000}_{-1000}	$8.26^{+7.38}_{-4.59}$	$0.04^{+0.01}_{-0.01}$	3.5	26.17		14	0.89
MS4	A	6000 ± 125	6.38 ± 2.47	$2.300.44$	3.5	226.90	$9.93\text{e-}23$	16	11.21
	B	39000^{+3000}_{-1000}	$6.10^{+6.06}_{-3.44}$	$0.05^{+0.01}_{-0.01}$	3.5	60.47		13	1.60
MS5	A	5750 ± 125	4.11 ± 1.59	2.01 ± 0.38	3.0	278.41	$7.51\text{e-}23$	16	9.27
	B	39000^{+3000}_{-1000}	$3.86^{+3.84}_{-2.18}$	$0.04^{+0.01}_{-0.01}$	3.0	38.38		14	1.95
RC1	A	4750 ± 125	50.19 ± 19.35	10.30 ± 1.97	3.5	445.50	$1.98\text{e-}21$	14	8.16
	B	26000^{+3000}_{-1000}	$0.93^{+1.18}_{-0.55}$	$0.05^{+0.01}_{-0.01}$	3.5	314.58		15	0.52

high despite visually good fits, likely due to underestimated photometric uncertainties. To address this, we compute a modified reduced χ^2 , referred to as the visual goodness-of-fit parameter (vgf_b), defined as:

$$\text{vgf}_b = \frac{1}{N - N_f} \sum_{i=1}^N \frac{(F_{o,i} - M_d F_{m,i})^2}{b_i^2}, \quad (2)$$

where $b_i = 0.1F_{o,i}$ if $\sigma_{o,i} \leq 0.1F_{o,i}$, and $b_i = \sigma_{o,i}$ otherwise. Values of $\text{vgf}_b < 15$ indicate acceptable fits, and all our binary SED fits satisfy this criterion (Table 2).

The best-fitting binary SEDs are shown in Fig. 5, while the derived parameters of the BSSs, MS stars, RC star, and their hot companions are listed in Table 2.

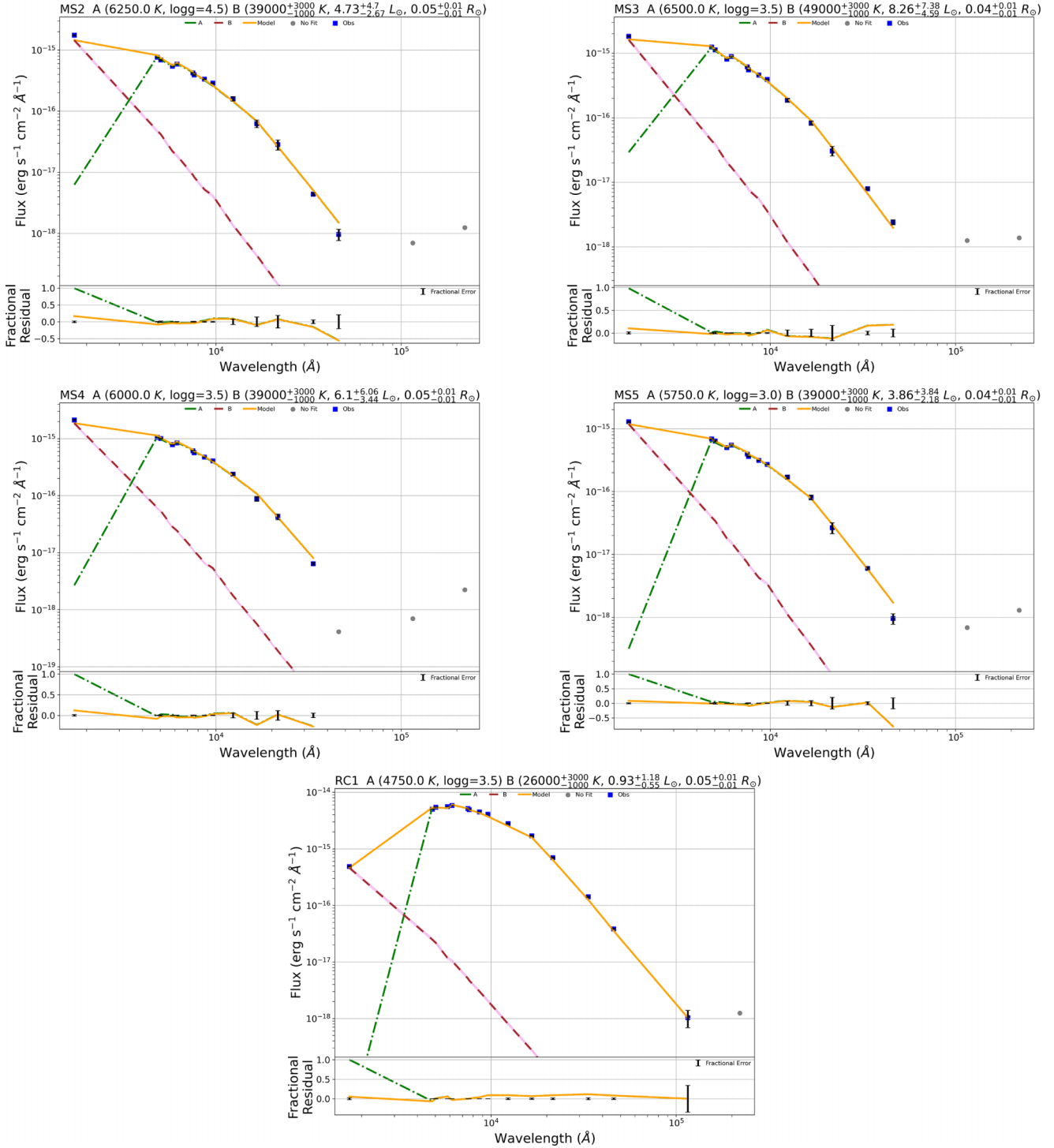


Figure 5. Binary-component SEDs of the sources showing UV-excess. The upper panels show the extinction-corrected fluxes (blue squares) with associated uncertainties (black error bars). The combined best-fitting model is shown by the orange curve, while the individual contributions from the cooler (primary) and hot (secondary) components are represented by the green and red dashed curves, respectively. The derived parameters of each source and its hot companion are listed at the top of each panel. Data points excluded from the fitting are indicated as grey dots, either due to poor photometric quality or because they represent upper limits. The lower panels display the residuals between the extinction-corrected observed fluxes and the combined model across wavelengths from the UV to the infrared.

5 DISCUSSION

From the single-component SED fits, we derive the fundamental parameters of the BSSs, MS stars, and the RC star. The BSSs

span effective temperatures of ~ 9250 – $10\,500$ K and luminosities of ~ 38.37 – $125.90 L_{\odot}$, with radii in the range ~ 2.11 – $3.16 R_{\odot}$, consistent with their location above the MSTO. On the other hand, the MS stars exhibit lower temperatures (~ 5750 – 6500 K)

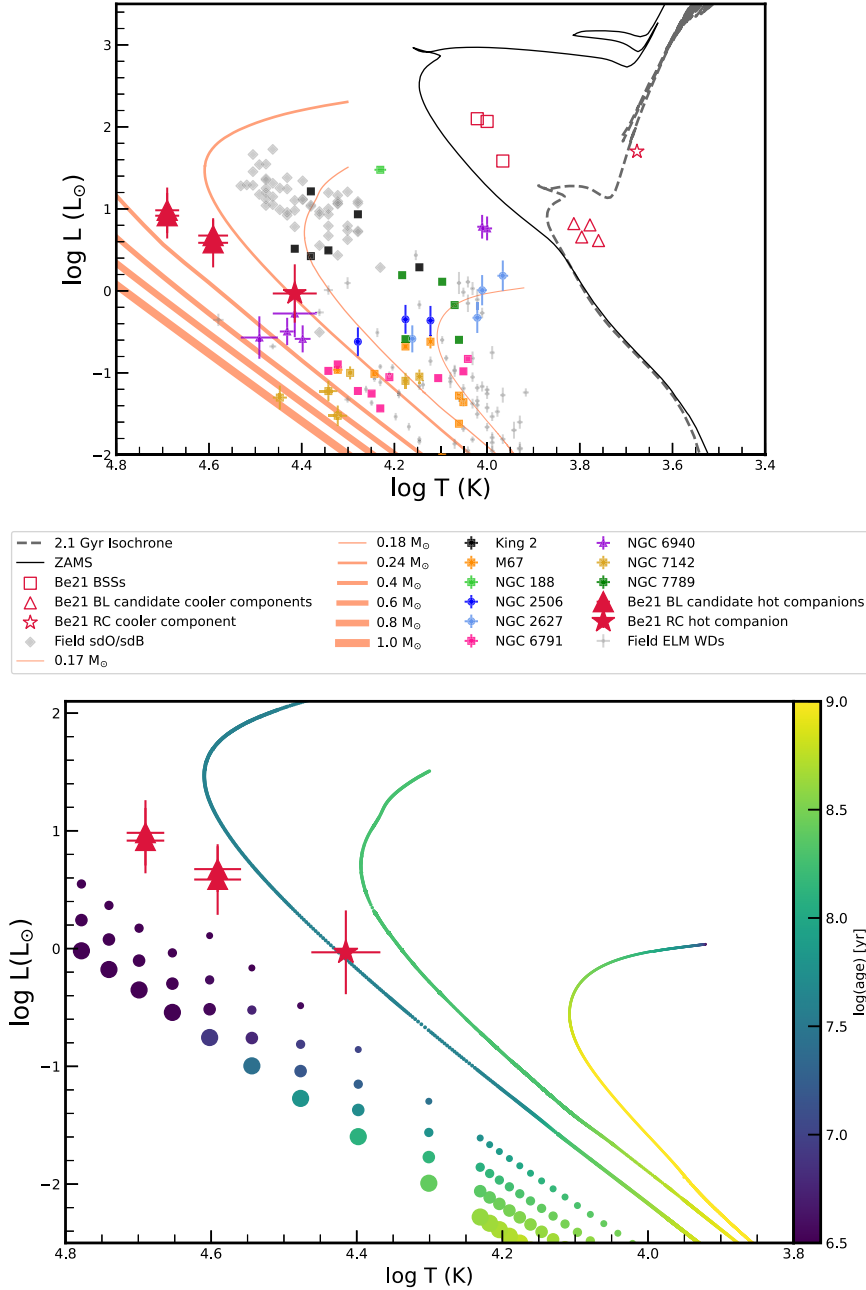


Figure 6. Upper panel: HRD showing the stellar populations of Berkeley 21 along with comparison samples. The 2.1 Gyr isochrone (dashed line) and the zero-age MS (ZAMS; solid black line) are overplotted for reference. BSSs, BL candidates, and RC stars in Be 21 are shown with their respective cooler and hot components derived from SED analysis. Also shown are field subdwarf (sdO/sdB) stars and ELM WDs, along with WD cooling tracks for different masses (0.17–1.0 $M_{\odot}$). For comparison, hot companions identified in other OCs are shown as closed squares in different colours. Lower panel: HRD with the hot companions of BL candidates and RC star lying on the cooling curves of WDs of different ages, indicating their approximate cooling ages.

and luminosities (~ 4.11 – $6.61 L_{\odot}$), with radii of ~ 1.78 – $2.3 R_{\odot}$. The RC1 is characterized by a significantly lower temperature (~ 4750 K) and a much larger radius ($\sim 10.30 R_{\odot}$), along with a higher luminosity ($\sim 50.19 L_{\odot}$), consistent with its evolved helium-burning phase.

As discussed above, MS2, MS3, MS4, MS5, and RC1 exhibit significant UV excess (> 50 per cent), and are therefore modeled using binary-component SED fitting. The inclusion of a hot companion leads to a substantial improvement in the fits

for all sources. For MS2, the hot companion has an effective temperature of 39000^{+3000}_{-1000} K, luminosity $4.73^{+4.70}_{-2.67} L_{\odot}$, and radius $0.05 \pm 0.01 R_{\odot}$. The reduced χ^2 decreases from 167.5 (single-component) to 43.15 (binary-component), while vgf_b improves from 8.57 to 1.51. For MS3, the hot companion has a temperature of 49000^{+3000}_{-1000} K, luminosity $8.26^{+7.38}_{-4.59} L_{\odot}$, and radius $0.04 \pm 0.01 R_{\odot}$. The reduced χ^2 improves from 166.6 to 26.17, and vgf_b from 8.10 to 0.89. Similarly, MS4 shows a hot companion with $T_{\text{eff}} = 49000^{+3000}_{-1000}$ K, luminosity $9.62^{+8.60}_{-5.34} L_{\odot}$, and radius $0.04 \pm$

0.01 $R_{\odot}$. The reduced χ^2 decreases from 226.9 to 50.17, and vgf_b from 11.2 to 1.56. For MS5, the hot companion has a temperature of 39000^{+3000}_{-1000} K, luminosity $3.86^{+3.84}_{-2.18} L_{\odot}$, and radius $0.04 \pm 0.01 R_{\odot}$. The reduced χ^2 improves from 278.4 to 31.81, and vgf_b from 9.27 to 1.89. Finally, RC1 hosts a comparatively cooler hot companion with $T_{\text{eff}} = 26000^{+3000}_{-1000}$ K, luminosity $0.93^{+1.18}_{-0.55} L_{\odot}$, and radius $0.05 \pm 0.01 R_{\odot}$. The reduced χ^2 decreases from 445.5 to 314.58, while vgf_b improves from 8.16 to 0.52.

To further investigate the nature of the hot companions identified from the binary-component SED fitting, we place them on the Hertzsprung–Russell (H–R) diagram, as shown in Fig. 6. The upper panel of the figure includes the 2.1 Gyr isochrone and the ZAMS as references for normal stellar evolution, along with theoretical WD cooling tracks spanning a wide range of masses. The ELM and LM WD cooling sequences are taken from J. A. Panei et al. (2007) and L. G. Althaus, M. M. Miller Bertolami & A. H. Corsico (2013), while the cooling tracks for normal and high-mass WDs are taken from P. Bergeron et al. (2011). In addition, we include field ELM WDs and sdO/sdB stars from V. V. Jadhav, A. Subramaniam & R. Sagar (2023) for comparison. Furthermore, from the lower panel of Fig. 6, it is evident that the hot companions of the BL candidates lie close to the WD cooling curves corresponding to $\log(\text{age}/\text{yr}) \sim 7.0\text{--}7.5$. On the other hand, the hot companion of the RC star lies closer to the comparatively older cooling-age region of $\log(\text{age}/\text{yr}) \sim 7.5\text{--}8.0$. These results suggest that the WD companions associated with the BL candidates are relatively young systems with cooling ages of the order of tens of Myr, while the RC companion appears comparatively older. The locations of these companions along the WD cooling tracks indicate that the mass-transfer events in these systems likely occurred relatively recently.

For clarity, we plot only the hot companions of BSSs, BL candidates, and RC stars from other OCs studied using UVIT, enabling a direct comparison with the Berkeley 21 population. Notably, most of the hot companions in other clusters occupy regions consistent with the field ELM WD population, closely following the LM WD cooling sequences. The hot companions of BSSs in NGC 7142 have masses from ELM WDs to high-mass WDs, whereas, the hot companions of King 2 BSSs overlaps with the field sdO/sdB region, indicating hotter and more luminous stripped-envelope stars. However, the hot companions of MS stars and RC star in Berkeley 21 are offset from the bulk of the field ELM WD distribution and exhibit relatively higher luminosities. Their positions are broadly consistent with low-mass WD cooling tracks of masses $0.2\text{--}0.4 M_{\odot}$, suggesting Case-B MT as their formation pathways. The detection of hot companions in four out of five MS stars indicates that these systems have likely experienced past mass-transfer episodes. These stars can therefore be classified as BL candidates that have accreted mass from a companion and now host a compact remnant. This represents the first identification of BL candidates in Berkeley 21.

It is also important to note that the UV SEDs are constrained by only a single FUV data point from UVIT, with no complementary GALEX or additional UV measurements, which limits the robustness of the temperature and luminosity estimates. Therefore, the interpretation of these systems would benefit from high-resolution spectroscopic follow-up to determine radial velocities, orbital periods, and chemical abundances. At present, no radial velocity information is available in the literature for these sources, preventing direct constraints on their binary properties.

6 CONCLUSIONS

The work presented in this paper can be summarized as follows:

(i) We identify 325 cluster members in Berkeley 21 using the machine learning–based ML–MOC algorithm applied to *Gaia* DR3 data. Among these, 10 sources are observed in the UVIT/F172M filter, including four BSSs, five MS stars, and one RC star.

(ii) We construct multi-wavelength SEDs for all UVIT-observed sources using photometric data spanning from the UV to the infrared. All the three BSSs are well fitted by single-component SEDs, indicating that either they have formed via binary merger or the companions are cooled beyond the UVIT detection limit. On the other hand, four out of five MS stars and the RC star show strong UV excess (>50 per cent), requiring binary-component SED fitting.

(iii) The BSSs have effective temperatures in the range $\sim 9000\text{--}10\,500$ K, luminosities of $\sim 38.37\text{--}125.90 L_{\odot}$, and radii of $\sim 2.11\text{--}3.16 R_{\odot}$. The MS stars exhibit temperatures in the range $\sim 5750\text{--}6500$ K, luminosities of $\sim 4.11\text{--}6.61 L_{\odot}$, and radii of $\sim 1.78\text{--}2.30 R_{\odot}$, while the RC star has a temperature of ~ 4750 K, luminosity of $\sim 50.19 L_{\odot}$, and radius of $\sim 10.30 R_{\odot}$, consistent with core helium-burning evolution.

(iv) The hot companions of the MS and RC stars have effective temperatures in the range $\sim 26\,000\text{--}50\,000$ K, luminosities of $\sim 0.93\text{--}9.62 L_{\odot}$, and radii of $\sim 0.04\text{--}0.05 R_{\odot}$. The inclusion of a hot component significantly improves the SED fits, reducing the reduced χ^2 values and confirming the presence of unresolved companions.

(v) The positions of these hot companions on the H–R diagram, when compared with WD cooling tracks, suggest that they are LM WDs with masses $\lesssim 0.4 M_{\odot}$. Such objects cannot form through single-star evolution within a Hubble time, implying that these systems are products of binary mass transfer.

(vi) The detection of hot companions in four out of five MS stars strongly suggests that these systems have undergone past mass-transfer episodes. These stars are therefore strong candidates for BLs, representing accretion products that remain photometrically indistinguishable from normal MS stars. This constitutes the first identification of BL candidates in Berkeley 21.

(vii) The analysis is limited by the availability of only a single FUV data point from UVIT, which introduces uncertainties in the derived parameters. Furthermore, the absence of radial velocity measurements prevents direct constraints on orbital properties and binary evolution pathways.

(viii) Overall, our results strongly support binary mass transfer as the dominant formation mechanism for the UV-excess sources in Berkeley 21, with at least 50 per cent of the UVIT observed population formed via Case-B MT channel.

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Mumbai, several centres of Indian Space Research Organisation (ISRO), and Canadian Space Agency (CSA).

DATA AVAILABILITY

The data underlying this article are publicly available at https://astrobrowse.issdc.gov.in/astro_archive/archive/Home.jsp. The derived data generated in this research will be shared on reasonable request to the corresponding author.

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