THE IDENTIFICATION OF BLUE HORIZONTAL BRANCH STARS USING GALEX AND OTHER PHOTOMETRY

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ABSTRACT

Halo samples that have no kinematic bias have been successfully isolated by photometric observations. We show that the NUV magnitude of the GALEX All-Sky Survey can be used, together with Johnson BV magnitudes in a (NUV − V)0 versus (B − V)0 plot, to distinguish blue horizontal branch (BHB) from other A stars of the same (B − V) color for 12 < V < 18. In addition, we use SDSS gr magnitudes in a (NUV − r)0 versus (g − r)0 plot for 14 < r < 18. The faint limit will be extended by ∼3 mag for the GALEX Medium-Deep Survey. Attempts to use NUV in conjunction with 2MASS magnitudes and ROTSE m, magnitudes did not prove useful. The (NUV − V)0 versus (B − V)0 plot was used to examine BHB star candidates of varying quality near the south Galactic pole. We conclude that the addition of the GALEX NUV significantly adds to the reliability with which these stars can be identified.

Subject headings: Galaxy: halo—Galaxy: structure—stars: horizontal-branch

1. INTRODUCTION

Blue horizontal branch (BHB) stars together with RR Lyrae stars are the most-used probes of the Galactic halo. BHB stars can be distinguished from other blue stars (e.g., blue stragglers) by the width and shape of their Balmer lines and by the size of their Balmer jump. They have been discovered by using objective-prism spectroscopy (e.g., Sanduleak 1988; Beers et al. 1988; Christlieb et al. 2005) or photoelectric photometry (e.g., Philip 1967; Pier 1982, 1983, 1984; Sommer-Larsen et al. 1989; Preston et al. 1991; Kinman et al. 1994; Clewley et al. 2004; Sirko et al. 2004; Beers et al. 2007) either alone or in combination with slit spectroscopy. Preston et al. (1991) found that a separation of BHB from other A stars in a (U − B)0 versus (B − V)0 plot is only reliable in the color range −0.03 ≤ (B − V)0 ≤ 0.18 and, because of observational error, the classification is often ambiguous for stars near the ends of this range. Only in this color range can the Balmer jump and the shape and widths of the Balmer lines be used to distinguish the BHB stars (e.g., Clewley et al. 2002). Improved classification can also come from using high signal-to-noise ratio high-resolution spectra, but this has only been achieved so far for the brighter nearby BHB (Kinman et al. 2000; Behr 2003). One can also improve the photometric selection by using more than one photometric system. We here discuss the appropriate colors for identifying BHB stars in a variety of photometric systems with particular reference to the new UV photometry from the Galaxy Evolution Explorer (GALEX; Martin et al. 2005).

2. THE COLOR WINDOWS FOR BHB STARS USING GALEX MAGNITUDES

2.1. GALEX and Johnson BV Photometry

The GALEX surveys give a far-UV (FUV) magnitude and a near-UV (NUV) magnitude at effective wavelengths 1516 and 2267 Å, respectively; these are on the AB system. These surveys become nonlinear for stars brighter than 14th–15th magnitude (Morrisset et al. 2007) and so require faint BHB stars for calibration. A suitable BHB sample (11.4 < V < 16.5) near the north Galactic pole (NGP; where the extinction is low) is discussed in Kinman et al. (2007). The coordinates, photometry, radial velocities, and abundances of these stars are to be given in T. D. Kinman et al. (2007, in preparation), which will also list the blue non-BHB stars in the same fields. The techniques for selecting these stars are described in Kinman et al. (1994, 1996). Of this NGP sample, 31 BHB stars are in the GALEX releases GR2 and GR3, 40 in the Sloan Digital Sky Survey (SDSS) Data Release 5 survey (York et al. 2000; Adelman-McCarthy et al. 2006), and 15 are in both surveys. Thirty-nine non-BHB stars in the same NGP field were also identified in the GALEX releases. One BHB star and five non-BHB stars with NUV ≤ 14.0 [corresponding roughly to V = 12.0 for (B − V)0] were excluded in order to avoid nonlinearity effects. FUV and NUV were corrected for interstellar extinction using A(FUV) = 8.16E(B − V) and A(NUV) = 8.90E(B − V) (Rey et al. 2007); the E(B − V) were taken from Schlegel et al. (1998).

The photometric separation of BHB from other A stars can be achieved by plotting a gravity-sensitive indicator, such as (U − B), against a temperature indicator, such as (B − V). We find that (NUV − V)0 and (NUV − B)0 are effective surrogates for the gravity-sensitive (U − B). All photometric classifications are limited to an effective magnitude range. At the faint end, the photometric errors are too large for stars of different types to be separated; at the bright end, the detector becomes nonlinear. We do not use the FUV here because it has a small effective range for stars in the All-Sky Imaging Survey (AIS); it may prove useful when the deeper GALEX surveys are more complete. (NUV − V)0 and (NUV − B)0 are similar as gravity discriminators, but the former includes fewer c-type RR Lyrae stars and was therefore adopted. A plot of (NUV − V)0 versus (B − V)0 (Fig. 1a) shows that the BHB stars (filled circles) lie in a compact area (dotted parallelogram), whereas the non-BHB stars (open circles) largely lie outside this area (Fig. 1b). Eight c-type RR Lyrae stars are also shown. We do not know the epochs of the GALEX data, and so the phases of these variables at the times of their GALEX observations are not known. We therefore plotted them both for the case where the...
variable is at maximum light (filled triangles) and where it is at mean light (open triangles). Confusion of these variables with BHB stars is possible on this plot, and so the reddest BHB star candidates should be checked for variability. Most of our GALEX data comes from the AIS, for which the error in NUV \( \sim 0.15 \) mag at NUV = 20.0; the separation of BHB from non-BHB stars will become increasingly inefficient for stars fainter than this. The effective useful range of the AIS data is therefore 14.0 < NUV < 20.0, which corresponds roughly to 12.0 < V < 18.0 for BHB stars. A likely practical use of the (NUV – V)\(_0\) versus (B – V)\(_0\) plot is to provide improved selection where Johnson photometry is available (e.g., Beers et al. 2007). An example of this is given in § 2.4.

### 2.2. GALEX and SDSS Photometry

Sirko et al. (2004) have selected BHB stars in the SDSS system by using a \((u - g)\)_0 versus \((g - r)\)_0 plot together with spectroscopic criteria. The BHB stars in our NGP sample in the same plot (Fig. 2) lie in the ranges 1.14 \(\leq\) \((u - g)\)_0 \(\leq\) 1.28 and \(-0.24 \leq (g - r)\)_0 \(\leq\) -0.04 (as shown by the box). The color window \([-0.31 \leq (g - r)\)_0 \(\leq -0.13\] given in Figure 8 of Sirko et al. (2004) is significantly bluer than this and corresponds roughly to \(-0.09 \leq (B - V)\)_0 \(\leq\) 0.10. In both cases, however, the region occupied by the BHB stars (filled circles) is heavily contaminated by non-BHB stars (open circles). Figure 3a shows the \((u - g)\)_0 versus \((g - r)\)_0 plot, and Figure 3b shows the (NUV – r)\(_0\) versus \((g - r)\)_0 plot (with the same symbols) for the subset of stars in Figure 2 that have reliable GALEX data. The lower contamination of the BHB star region by non-BHB stars in Fig. 3a compared to Figure 2 may be a fluctuation produced by the smaller number of stars in Figure 3a and/or some selection effect produced by the GALEX survey itself. The presence of two non-BHB stars (bold open circles) in the BHB star region in both Figures 3a and 3b.
suggests an ambiguity in their classification. Otherwise, the use of \((NUV - r)_0\) clearly gives an effective and independent method of separating the BHB from non-BHB stars. The use of both SDSS and GALEX surveys materially adds to the accuracy of the classification process. Classification should be possible from the GALEX AIS survey for stars with \(14.2 < r < 18.0\); the bright limit is set by saturation in the SDSS data and the faint limit by the errors in NUV. The use of the GALEX Medium-Deep survey, which largely overlaps with the SDSS, should extend the faint limit by \(~3\) mag.

2.3. GALEX and Other Photometry

It is desirable to find an all-sky survey whose data could be used in conjunction with GALEX to identify the brighter BHB stars \((V < 14)\). Brown et al. (2004) suggested that Two Micron All Sky Survey (2MASS) data can be used to identify BHB candidates in a \((J - H)_0\) versus \((H - K)_0\) plot. Figure 4a shows

![Fig. 4.—(a) 2MASS \((J - H)_0\) vs. \((H - K)_0\) for BHB stars (filled circles) and non-BHB stars (open circles) at the NGP. The dotted rectangle shows the selection window used by Brown et al. (2004). (b) \((NUV - J)_0\) vs. \((J - K)_0\) for BHB stars (filled circles) and non-BHB stars (open circles) at the NGP.](image)

our NGP sample of BHB and non-BHB stars in this plot. It is seen that their color window (dotted rectangle) is not optimal and that there is little separation between the two types of star. It is found (Fig. 4b) that the \((NUV - J)_0\) versus \((J - K)_0\) plot is also ineffective since \((NUV - J)_0\) is not a possible gravity indicator. This is also true of \((NUV - m_r)\) (where \(m_r\) is the unfiltered CCD magnitude of the Northern Sky Variability Survey [NSVS]; Wozniak et al. 2004). Figure 5 shows the plot of \((NUV - m_r)\) versus \((m_r - J)_0\) for our NGP stars; only a weak separation between the BHB and non-BHB stars is seen (probably because \(m_r\) has such a broad bandwidth). The \(V\) magnitudes of the All Sky Automatic Survey (Pojmanski 2002) are available for declinations south of \(+28^\circ\), but the magnitude range in which both these \(V\) and NUV are accurate is rather limited. Apart from this, therefore, there does not seem to be a way of identifying the brighter BHB stars in currently published wide-field surveys.

2.4. GALEX and a Sample at the South Galactic Pole

An (unpublished) catalog of BHB candidates within \(10^\circ\) of the south Galactic pole (SGP) has been compiled from various sources (e.g., Christlieb et al. 2005; Beers et al. 1988; Lance 1988). The data is of varying accuracy, and (largely from their \(UBV\) colors) they were judged to be (1) most likely, (2) quite likely, and (3) not likely to be BHB stars. The first two classes are shown by filled and small open circles, respectively, in the plot of \((NUV - V)_0\) versus \((B - V)_0\) (Fig. 6a), where the dotted rectangle is that which encloses the NGP BHB stars in Figure 1a. The difference between the distributions of the filled and open circles is not marked, and with the exception of a few outliers, most of these stars probably are BHB stars. We suspect that the scatter is largely caused by the (unknown) errors in \((B - V)_0\) in this heterogeneous data. There may also be systematic differences between the northern and the southern hemisphere photometry standards that affect \((B - V)_0\) (Men-

![Fig. 5.—\((NUV - m_r)_0\) vs. \((m_r - J)_0\), where NUV is from GALEX, \(J\) from 2MASS, and \(m_r\) is from the NSVS. The filled and open circles show BHB and non-BHB stars, respectively, from the NGP field.](image)
Enclosed is the NGP BHB stars. The three marked with crosses are BPS CS 22882–32 and BPS CS 22942–34, whose radial velocities are 98 and 192 km s\(^{-1}\) (Pier 1983), respectively, and PS 2-58, whose radial velocity is 200 km s\(^{-1}\) (Rodgers 1971); these high radial velocities also support the classification of these stars as BHB stars. The efficiency in separating BHB stars from their interlopers using plots such as \((\text{NUV} - V)_{0}\) versus \((B - V)_{0}\) is dependent on the accuracy of the color used as the temperature indicator. Consequently, it would be advantageous to use a temperature indicator that combines the information from all the optical and infrared magnitudes that are available.

### 3. SUMMARY

It is shown that the \textit{GALEX} NUV magnitude can be used in conjunction with Johnson \(BV\) magnitudes in a \((\text{NUV} - V)_{0}\) versus \((B - V)_{0}\) plot to distinguish BHB from other A stars of the same \((B - V)_{0}\) color. A similar separation can be made using NUV and the SDSS \(gr\) magnitudes in a \((\text{NUV} - r)_{0}\) versus \((g - r)_{0}\) plot. These plots are effective for stars in the \textit{GALEX} AIS in the magnitude range 12 < \(V\) < 18 and 14 < \(r\) < 18 for Johnson and SDSS colors, respectively. The faint limit is ~3 mag fainter for the \textit{GALEX} Medium-Deep Survey. The bright limit is set by the onset of nonlinearity in the \textit{GALEX} detector in the case of the Johnson colors and by the saturation of the SDSS detectors in their case. Attempts to use NUV in conjunction with 2MASS magnitudes and Robotic Optical Transient Search Experiment \(m\) magnitudes to separate BHB from non-BHB stars were not successful. The \((\text{NUV} - V)_{0}\) versus \((B - V)_{0}\) plot was used to confirm BHB star candidates of varying quality near the south galactic pole. It is concluded that the addition of the \textit{GALEX} NUV to existing data gives a simple and powerful way of identifying these stars.

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