Washington Photometry of the Multiple Populations of the Globular Cluster NGC 1851

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Introduction:

- NGC 1851 is our first of many globular clusters (GCs) we are observing with the Washington filters to see how effective and efficient they are for detecting and analyzing multiple populations (MPs) in GCs, which are no longer considered to be simple stellar populations (e.g., B04, P07, H09, Ca10).
- UV filters have been key to detecting MPs (e.g., H09, L09, S11) because they contain CN, CH, and NH bands that can significantly vary in strength between populations, but these filters are inefficient and require significant telescope time to observe these typically faint GCs. However, the Washington C filter is broader than and centered redward of the other UV filters used before, hence it is more efficient and still covers the important molecular bands (See Figure 1).

Comparison of NGC 1851 Observations:

- Ours: SWOPE 1m; C (11,400 s), T1 (1300 s), and T2 (3900 s).
- H09: Blanco 4m; 5,239 s total with Johnson UVI. Effectively ~5 times more telescope time.
- L09: SMARTS 1m; 49,710 s total with Strömgren filters. Effectively ~3 times more telescope time.

Photometric Results:

- Figure 2 shows our color magnitude diagrams (CMDs) of the red giant branch (RGB), subgiant branch (SGB), and horizontal branch (HB) results without any cuts.
- The C-T1, C-T2, and C-V CMDs show both the second population's fainter and redder branch in both the SGB and RGB that were observed in L09, H09, but as expected T1-T2 shows no second branch. This is consistent with the populations having only differing C magnitudes.
- The bimodal red and blue HB is also clearly seen in all CMDs, but for the first time we see in C-T1 strong evidence for 2 sequences in the red HB. Further analysis unexpectedly shows these sequences to be caused by a differing T1 magnitude and not C.
- Figure 3 focuses on the main sequence (MS) by looking at stars with low color error (<0.07) outside of the crowded core from 4.5 to 6 arcminutes from the center. Quite remarkably we are able to detect a clear second sequence that has never before been observed, and its distribution in the 3 CMDs argues the two populations have only differing C magnitude and that it is not a binary sequence.

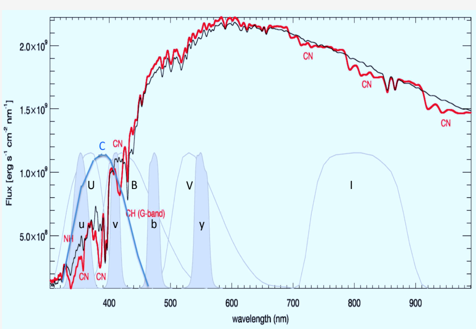

Figure 1. Two synthetic spectra of varying CNO overplotted on various filter band passes, including Johnson U, Strömgren u, and Washington C. Note C is broader and centered more redward, hence is significantly more efficient. (Figure from S11 with C bandpass added.)

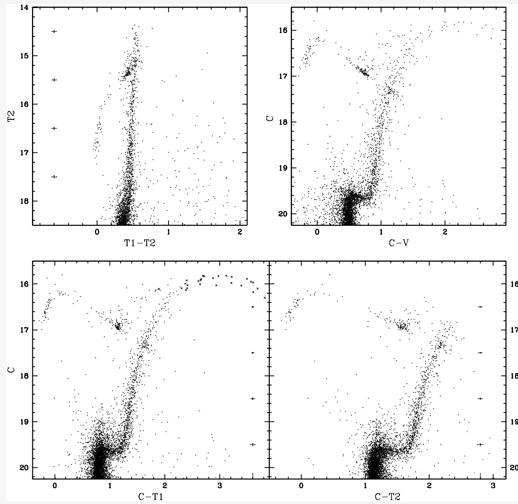

Figure 2. Our photometry with the broad SGB and RGB that suggest there are two branches. Additional bright C and T1 data taken from G99 are shown with x's.

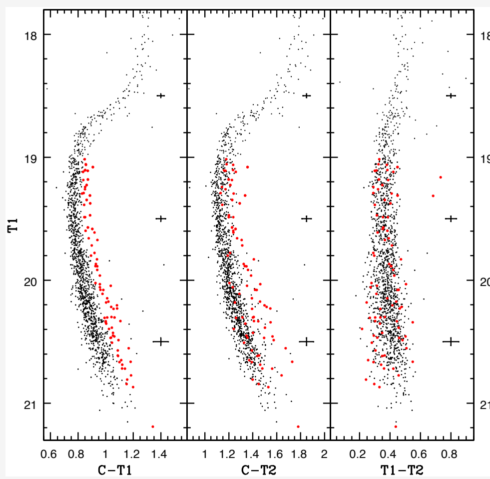

Figure 3 The MS shown in 3 CMDs. The second MS is defined in red using C-T1 and these same stars are marked in the others CMDs.

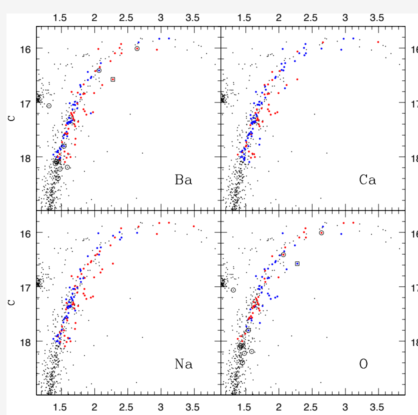

Figure 4. Matched abundances to our RGB with red data points representing rich stars and blue representing poor stars in the respective element of each panel. The Ba and Na-poor stars, and Ca-poor stars to a lesser extent, are clearly consistent with the blue RGB, while the rich stars are broadly distributed and create the red RGB. In contrast, O-rich stars are consistent with the blue RGB, while O-poor stars are broadly distributed and create the red RGB. CN-normal stars (marked with circles) and CN-rich stars (marked with squares) are shown from H82.

Comparison to Spectroscopic Abundances:

- The RGB abundances from Ca11 are very useful for analyzing potential differences between these 2 populations. Figure 4 shows several abundance matchings to our RGB. Remarkably, Na and Ba-poor stars, and to a lesser extent Ca-poor and O-rich stars, typically create a blue and narrow sequence. In contrast the Na, Ba, and Ca-rich and O-poor stars create a broadly distributed population. This broad distribution creates the sparser red RGB sequence.
- A more complex analysis may show why some of these stars have such significant differences in C magnitude. Ca11b suggest it is based on CNO abundances and only stars that are both C-rich **and** O-poor will have strong enough CN, CH, and NH bands to significantly decrease UV magnitudes.
- Ca11 provide O, and Ba should trace C abundance. Figure 5 simultaneously considers both Ba and O in the left panel and Ba and Na, which anticorrelates with O, in the right panel. Consistent with the model of Ca11b, the red RGB is composed primarily of Ba-rich and Na-rich/O-poor stars, and the blue RGB are all other abundance types.

Conclusions:

- The Washington C filter is very successful at efficiently detecting MPs in GCs.
- Not only have we been able to detect the previously observed double RGB and SGB but have been able to discover a double MS and double red HB.
- Abundance matchings suggest that Ba, Na, and O are good elements for distinguishing the two populations and that tracing CNO abundance by looking at Ba and Na or Ba and O simultaneously cleanly separates the red and blue RGB.
- The significant increase in efficiency for analyzing MPs in GCs using the Washington filter system means that detecting MPs in the Magellanic Clouds using larger telescopes or even in Andromeda using HST may now be possible.

References:

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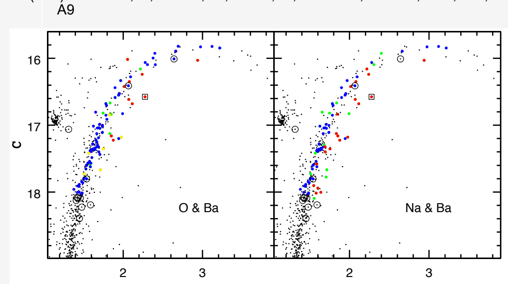

Figure 5. Simultaneously considering O & Ba and Na & Ba. For O & Ba: Red (Ba-rich and very O-poor), green (Ba-rich and moderately O-poor), yellow (Ba-rich with O upper limits that make them at least moderately O-poor), and blue (all Ba-poor or Ba-rich and O-rich). For Na & Ba: Red (Ba-rich and very Na-rich), green (Ba-rich and moderately Na-rich), and blue (all Ba-poor or Ba-rich and Na-poor). Both show the blue data is consistent with the blue RGB, the green data is slightly shifted to the red, and the red data are consistent with the red RGB.