Hot Horizontal-Branch Stars in the Galactic Bulge

D.M. Terndrup

Department of Astronomy, Ohio State University, Columbus, Ohio 43210, USA

R.C. Peterson

Astrophysical Advances, Palo Alto, California 94301, USA

E.M. Sadler

School of Physics, University of Sydney, Sydney NSW 2006, Australia

A.R. Walker

Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile

Abstract.   We report the discovery of hot horizontal branch stars in the nuclear bulge of the Milky Way. Spectra from the 2dF instrument of the Anglo-Australian Telescope allow us to confirm their membership in the bulge through radial velocities. We also review the current observational information on hot horizontal branch stars in Milky Way clusters and the Local Group, and discuss the relevance of star-by-star studies in the bulge for the ultraviolet-excess phenomenon seen in large ellipticals.

1.   The Ultraviolet Light of External Galaxies

It has been known for some time that elliptical galaxies and the bulges of other spirals emit considerably more ultraviolet ($\lambda \leq 2500$ Å) light than can be accounted for by the old, metal-rich stellar population which dominates at visible and infrared wavelengths (Code & Welch 1979; Faber 1983; Bertola et al. 1980; O'Connell, Thuan & Pushell 1986). This is called the extragalactic ultraviolet excess (UVX) phenomenon, and is characterized by increasing flux towards shorter wavelengths in the nuclear spectra of these systems. Much has been learned about it from the study of extragalactic integrated light. As summarized by O'Connell (1993), there is increasing evidence which shows that evolved low-mass stars are the principal source. For example, the spatial distribution of the ultraviolet light is close to that in the visible (Bohlin et al. 1985; O'Connell et al. 1992) and does not contain the emission-line features which would be produced by ionized gas (e.g., Ferguson et al. 1991). The stellar light cannot come from *massive* stars, since the ultraviolet flux is faint shortward of Lyman-α where main-sequence O stars would make a strong contribution (Ferguson et al.

1991; Brown, Ferguson & Davidsen 1995). The most likely candidate seems to be hot horizontal-branch (HB) stars (Dorman, O'Connell & Rood 1995).

There has also been considerable effort to explore the evolution of HB stars, particularly to elucidate what determines the color distribution of HB stars in different populations. Early theoretical work (e.g., Rood 1973) showed that HB stars can be hotter than the RR Lyrae instability strip when metallicity is low and age high. Because the color of an HB star is determined by the ratio of core mass to envelope mass, the stars with the least hydrogen envelope remaining after the red giant evolutionary phase are the hottest. These are called the sub-dwarf B (sdB) stars because He I lines are seen in their spectra. As core helium is exhausted, these stars evolve to higher temperatures as luminosity increases, instead of moving to the asymptotic red-giant branch (Greggio & Renzini 1990; Horch, Demarque & Pinsonneault 1992; Dorman, Rood & O'Connell 1993; Yi, Demarque & Oemler 1997, 1998; and references in these papers). Though short ($t \sim 10^6$ yr), the duration of the hot evolutionary phases is sufficient to provide a significant contribution to the ultraviolet flux in stellar population models.

The nature of stellar UVX sources is not fully understood, however, because we lack statistically significant samples for detailed study. The sdB and sdO stars are very rare in globular clusters, especially at high metallicity when the distribution of stars along the HB shifts to warmer temperatures (more and more hot HB stars are being found, however: for examples, see Rich et al. 1997; Sosin et al. 1997). Importantly, however, the old metal-rich open cluster NGC 6791, which has [Fe/H] = $+0.4 \pm 0.1$ (Peterson & Green 1998), has four sdB/O stars (Leibert, Saffer & Green 1994) and several cooler HB stars whose radial velocities support membership in the cluster; since the strength of the ultraviolet flux in galaxies is positively correlated with metallicity (below), NGC 6791 may be a unique local example of a stellar population which produces sdB/O stars as inferred to exist in more distant systems. Finally, there seem to be several distinct ways to produce stars with a low ratio of core/envelope masses (Dorman et al 1995; D'Cruz et al. 1996; Sweigart 1997; Yi et al. 1998): these include high mass loss in the red giant phase, enhanced light-element abundances, or helium enrichment. Binarity may be a factor also, since most field (Allard et al. 1994) and cluster (Green et al. 1998) sdB/O stars appear to be binaries.

2.   The Bulge as a Probe of Hot HB Stars

There are many reasons why the bulge of the Galaxy is an important labora-tory for the study of hot HB stars. The bulge is mostly old and metal-rich, akin in stellar density and star formation history to the population in ellipti-cals and other spirals. The metallicity distribution in the inner bulge runs from [Fe/H] = -1.0 to $+0.3$ and possibly higher (Rich 1990; McWilliam & Rich 1994; Sadler, Rich & Terndrup 1996), resembling the distribution expected in theoret-ical models of elliptical formation (e.g., Yoshii & Arimoto 1987) and matching at the high end the abundances inferred for large ellipticals (Worthey 1992). There is also considerable evidence that the relatively high abundance of light elements seen in bulge stars (McWilliam & Rich 1994; Sadler et al. 1996) is like that which may exist in the central regions of other galaxies (e.g., Worthey, Faber & González 1992). Finally, the bulge is near enough so that we may ob-
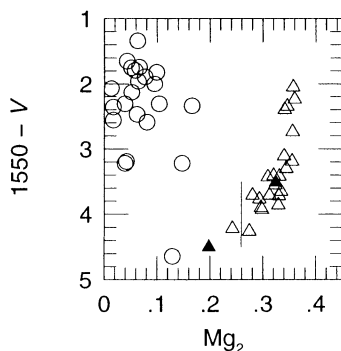
Figure 1.   Strength of the ultraviolet emission against metallicity in globular clusters (open circles), and in ellipticals and spiral bulges (triangles). The vertical line shows the UV color anticipated from the Mg_2 feature strength in the Baade's Window field of the Galactic bulge. See text for details.

tain complete detections of even the hottest stars, and can obtain temperature or metallicity estimates for some of them spectroscopically. In contrast, even in the local-group members M31 and M32, it has so far been possible to detect only the brightest individual ultraviolet-bright stars (Brown, this meeting; Brown et al. 1998), which do not account for the total UV flux in these systems.

The bulge population is also important because the strength of the extra-galactic ultraviolet flux (which is positively correlated with metallicity) is quite different from that in the Galaxy's globular clusters. We show this in Fig. 1, which plots the strength of the ultraviolet flux (as indicated by the $1550\,\text{Å} - V$ color) against metallicity (as characterized by the Mg_2 index of Faber et al. 1985). The data in this plot are all taken from the literature: the open circles are for Milky Way globulars (Dorman et al. 1995), while the triangles are for ellipticals and spiral bulges (Burstein et al. 1988). Lower values of $1550 - V$ indicate stronger ultraviolet flux; the globular with the weakest flux is 47 Tucanae. The filled triangles show the values for the local-group members M32 (left) and M31 (right). We cannot put our own bulge on this plot, because the high extinction towards the galactic center precludes a direct measurement of the bulge's ultraviolet flux. The mean Mg_2 strength in the Baade Window field of the bulge, however, has recently been measured by Idiart, de Freitas Pacheco & Costa (1996), and is plotted as the short vertical line on Fig. 1. Unless the bulge somehow lies far off the correlation exhibited by the galaxies on this figure, we would expect that the number density (and/or typical temperatures) of hot sdB/O stars in the bulge would be intermediate between that of M32 and M31.

3.   Our Survey

To characterize the proportions of sdB/O and cooler BHB stars in a stellar population like that in the inner regions of large galaxies, we have undertaken a comprehensive survey of the BHB stars in the bulge. The main goal is to identify the primary factors which control the production of these stars by determining
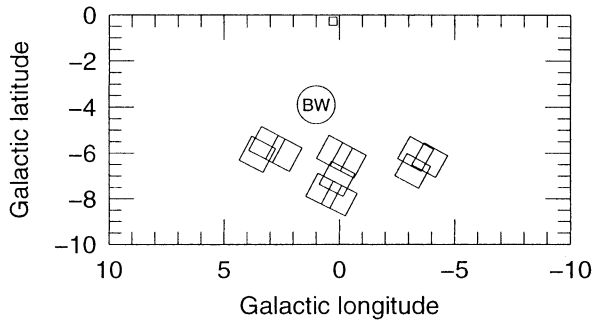
Figure 2. Location of the targeted fields in our survey. The squares show the areas we have currently imaged in *UBV* at CTIO. The location of Baade's Window is also shown. The small square near the galactic center shows an area in the bulge equivalent in size ($0.35° \times 0.35°$) to the areas imaged by Brown et al. (this conference) in the far ultraviolet in M31 and M32 ($14'' \times 14''$).

the temperature distribution of BHB stars as a function of metallicity. We are doing this by obtaining photometry of bulge windows at various distances from the galactic center, with follow-up spectroscopy to confirm candidates and derive temperatures and metallicities by comparison with synthetic spectra calculated from first principles.

In 1995, we began our survey by obtaining deep ($V \leq 19$) CCD images in *UBV* of 12 square degrees in the outer bulge. The CMDs are not deep enough to detect the hottest (sdO) HB stars in the bulge (if they exist), but were adequate for finding sdB stars with temperatures $\leq 18\,000$ K (the hottest HB stars are the subjects of future work). The survey areas are shown in Fig. 2, along with the location of Baade's Window. For comparison, we have also plotted (the small square near the Galactic center) a box showing an area in the bulge equivalent to that imaged by Brown et al. (1998) in their survey of hot (post)-HB stars in M31 and M32. Bulge HB stars with $T \geq 8000$ K are readily detected on our CMDs because they have very blue colors, though at the cool end they are mixed with a dense swarm of disk turnoff stars which are intrinsically cooler but less reddened (see Ng et al. 1996 for an extended discussion of bulge CMDs). We find a fairly high surface density (100-200 per square degree) of hot HB candidates on the CMDs in all the areas surveyed; thus we expect that we will obtain about 10^3 hot HB stars in the bulge, which will be rather more than the number currently known in all globulars in the Galaxy.

In 1997, we obtained 3 hrs of time at the Anglo-Australian Telescope as part of the Science Verification Phase of the 2dF spectrograph. We obtained spectra of 130 stars at a resolution of ≈ 3 Å. Of these, 38 are hot bulge stars (spectral types A-B), while the rest are foreground disk dwarfs of types F-G or distant halo stars. Importantly, the velocity dispersion of the bulge HB stars is high ($\sigma \approx 115$ km s^{-1}), identical with that of the bulge K giants (e.g., Sadler et al. 1996), and markedly different from that of the disk turnoff stars ($\sigma \approx 60$ km s^{-1}). Representative spectra of bulge HB stars are shown in Fig. 3.
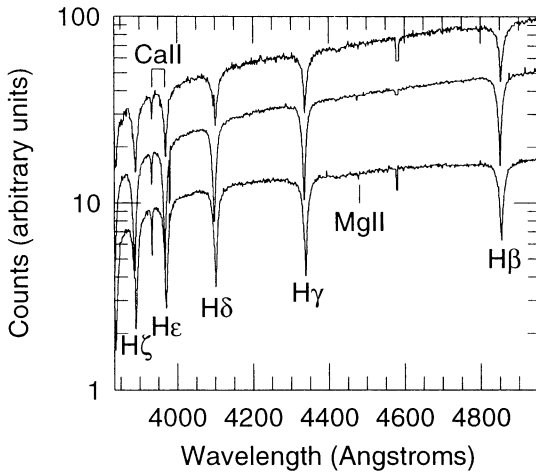
Figure 3. Examples of spectra of blue HB stars from our initial survey on the 2dF instrument at the AAT. The strongest metal line in the spectra is that of Mg II at 4481 Å. The depression near 4600 Å is from a bad column on the detector, and the Ca II lines arise mostly from the interstellar medium.

We have just started to examine the spectra in detail. The two hottest stars have weak He I $\lambda\lambda 4026, 4471$ Å lines, suggesting temperatures about 12 000 K. Most of the HB stars with $B - V \leq 0.6$ have weak Mg II $\lambda 4481$ Å (equivalent widths ~ 250 mÅ), and so are probably metal-poor like the bulge RR Lyraes (Walker & Terndrup 1991), though the spectra may show a variety of abundances at each temperature. We are now generating grids of synthetic spectra to better measure the temperatures and abundances of these and future spectra.

At this stage, we have not uncovered stars hot enough to be significant contributors to the bulge's ultraviolet light; these are considerably fainter than our current spectroscopic survey because of their high bolometric corrections in the blue portion of the spectrum. In the next couple of years, we plan to extend our survey to larger areas of the bulge and to much fainter limits, and see how the number and average temperatures of the hottest HB stars in the bulge depend on the metallicity distribution of the underlying population. At cooler temperatures where diffusion is less important, we aim to get a good abundance distribution across the whole temperature range of the bulge HB, which will yield the first constraints on how metallicity (and mass loss) control the production of HB stars in the bulge and by implication in the central regions of other galaxies.

References

Allard, F., Wesemael, F., Fontaine, G., Bergeron, P., Lamontagne, R. 1994, AJ, 107, 1565

Bertola, F., Capaccioli, M., Holm, A.V., Oke, J.B. 1980, ApJ, 237, L65

Bohlin, R.C., Cornett, R.H., Hill, J.K., Hill, R.S., O'Connell, R.W., Stecher, T.P. 1985, ApJ, 298, 37

Brown, T.H., Ferguson, H.C., Davidsen, A.F. 1995, ApJ, 454, L15

Brown, T.H., Ferguson, H.C., Stanford, S.A., Deharveng, J.-M. 1998, ApJ, 504, 113

Burstein, D., Bertola, F., Buson, L.M., Faber, S.M., Lauer, T.R. 1988, ApJ, 328, 440

Code, A.D., Welch, G.A. 1979, ApJ, 228, 95

D'Cruz, N.L., Dorman, B., Rood, R.T., O'Connell, R.W. 1996, ApJ, 466, 359

Dorman, B., O'Connell, R.W., Rood, R.T. 1995, ApJ, 442, 105

Dorman, B., Rood, R.T., O'Connell, R.W. 1993, ApJ, 419, 596

Faber, S.M. 1983, Highlights Astron., 6, 165

Faber, S.M., Friel, E.D., Burstein, D., Gaskell, C.M. 1985, ApJS, 57, 711

Ferguson, H.C., et al. 1991, ApJ, 382, 69

Green, E.M., Leibert, J., Peterson, R.C., Saffer, R.A. 1998, in: *Third Conference on Faint Blue Stars*, (eds.) A.G. Davis Phillip et al. (Schenectady: L. Davis Press), in press

Greggio, L., Renzini, A. 1990, ApJ, 364, 35

Horch, E., Demarque, P., Pinsonneault, M. 1992, ApJ, 388, L53

Idiart, T.P., de Freitas Pacheco, J.A., Costa, R.D.D. 1996, AJ, 111, 1169

Liebert, J., Saffer, R.A., Green, E.M. 1994, AJ, 107, 1408

McWilliam, A., Rich, R.M. 1994, ApJS, 91, 749

Ng, Y.K., Bertelli, G., Chiosi, C., Bressan, A. 1996, A&A, 310, 771

O'Connell, R.W. 1993, in: *The Globular Cluster–Galaxy Connection*, (eds.) J.P. Brodie & G.H. Smith, ASP Conf. Ser., 48, 530

O'Connell, R.W., et al. 1992, ApJ, 395, L4

O'Connell, R.W., Thuan, T.X., Puschell, J.J. 1986, ApJ, 303, L37

Peterson, R.C., Green, E.M. 1998, ApJ, 502, L39

Rich, R.M. 1990, ApJ, 362, 604

Rich, R.M., et al. 1997, ApJ, 484, L25

Rood, R.T. 1973, ApJ, 184, 815

Sadler, E.M., Rich, R.M., Terndrup, D.M. 1996, AJ, 112, 171

Sosin, C., et al. 1997, ApJ, 480, L35

Sweigart, A.V. 1997, ApJ, 474, L23

Walker, A.R., Terndrup, D.M. 1991, ApJ, 378, 119

Worthey, G. 1992, Ph.D. Thesis, University of California

Worthey, G., Faber, S.M., González, J.J. 1992, ApJ, 398, 69

Yi, S., Demarque, P., Oemler, A. 1997, ApJ, 486, 201

Yi, S., Demarque, P., Oemler, A. 1998, ApJ, 492, 480

Yoshii, Y., Arimoto, N. 1987, A&A, 118, 13

Discussion

Brown: (1) I want to point out that many metal-rich hot horizontal branch stars appear in the Galactic field. It's surprising you don't find them in the Bulge. Saffer also finds a gap at $T_{\rm eff} \approx 15\,000 - 20\,000$ K so you may also have a scarcity of stars in this range. (2) When (if) you get spectra of any hot HB stars, it may be hard to classify them because of diffusion processes. These will suppress some absorption lines and enhance others. (3) You mentioned the 15 Gyr time-scale for the rise of the UV upturn. There are groups that show it rising earlier, at 6-10 Gyr (e.g., Bressan et al. 1994, Tantalo et al. 1996) with both simple and infall models.

Terndrup: (1) I wasn't clear in my talk about the sensitive limits of our survey. We've only explored the cooler blue HB stars. The hotter ones which are optically fainter, are the subjects of future study. We are just getting started. (2) I agree. We'll have approximate temperatures only for the hottest stars. We'll get spectra only for stars cooler than about $15\,000$ K. (3) You are right. I only had time to show one example of models.