# The Discovery of Pulsating Hot Subdwarfs in NGC 2808

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**Abstract.** We present preliminary results of a *Hubble Space Telescope* program to search for pulsating hot subdwarfs in the core of NGC 2808. These observations, obtained in March of 2013, were motivated by the recent discovery of such stars in the outskirts of $\omega$ Cen. Both $\omega$ Cen and NGC 2808 are massive globular clusters exhibiting complex stellar populations and large numbers of extreme horizontal branch stars. Our far-UV photometric monitoring of over 100 UV-bright stars has revealed at least six pulsating subdwarfs with periods ranging from 100 to 150 seconds. In the UV color-magnitude diagram of NGC 2808, all six of these stars lie immediately below the canonical horizontal branch, a region populated by the subluminous "blue hook" stars. Three of these six pulsators also have low-resolution far-UV spectroscopy that is sufficient to broadly constrain their atmospheric abundances and effective temperatures. Curiously, the spectroscopic and photometric data do not exhibit the uniformity one might expect from a well-defined instability strip.

## 1. Formation of Extreme Horizontal Branch Stars

The formation of extreme horizontal branch (EHB) stars has been an intriguing puzzle for decades. These stars are distinguished by their high temperatures ($T_{\rm eff}$ >20,000 K) and surface gravities (log $g$ >5), and are located at the hot end of the HB in globular clusters (GCs) with extended blue HB morphologies. Their analogs in the field, the subdwarf B (sdB) stars, are responsible for the "UV upturn" in the otherwise cool spectra of ellipticals (Brown et al. 1997, 2000). The EHB stars have extremely thin envelope masses ($< 10^{-2}$ $M_\odot$), implying that they have undergone extensive mass loss on the red-giant branch (RGB). The challenge has been to understand how a star can lose ~0.3 $M_\odot$ on the RGB while retaining enough envelope to ignite helium in the core and evolve to the EHB. Proposed mass-loss mechanisms include binary interactions involving Roche Lobe overflow, common envelope evolution, or white dwarf (WD) mergers (e.g., Han et al. 2002, 2003), as well as single-star avenues such as a strong stellar wind or even planet ingestion.

New insight into the formation of EHB stars in GCs has come from the discoveries of a double main sequence (MS) in $\omega$ Cen (Anderson 1997) and a triple MS in NGC 2808 (D'Antona et al. 2005; Piotto et al. 2007). These massive GCs apparently contain a significant (~20%) population of helium-rich ($Y \sim 0.4$) stars (Piotto et al. 2005), likely formed in a second stellar generation from the helium-rich ejecta of the first generation (see Bekki & Norris 2006). With enough scrutiny, no GC seems to be a simple stellar population, but the massive GCs exhibit significantly larger spreads in many heavy elements as well as clear evidence for helium-rich subpopulations (for a review, see Gratton et al. 2012). These helium-rich subpopulations may explain why massive GCs have HB morphologies that extend to high $T_{\rm eff}$ (D'Antona et al. 2002; Busso et al. 2007). Because the MS turnoff mass decreases strongly with increasing helium for a given GC age, a helium-rich star will arrive on the HB with a significantly lower mass and therefore a higher $T_{\rm eff}$ than a helium-normal star, assuming the same RGB mass loss. EHB stars in massive GCs are most likely the progeny of the most helium-rich subpopulation.

Recent observations have revealed that massive GCs also host a population of subluminous EHB stars that cannot be explained by canonical evolution theory. These subluminous stars were first discovered in $\omega$ Cen, where they form a "blue hook" at the hot end of the EHB (D'Cruz et al. 2000). D'Cruz et al. (2000) proposed that these blue-hook stars were the result of a delayed helium-core flash beyond the RGB tip. Brown et al. (2001) subsequently found a large population of blue-hook stars in the UV color-magnitude diagram (CMD) of NGC 2808 (Figure 1). Using new evolutionary and spectroscopic models, Brown et al. (2001) demonstrated that these blue-hook stars were the result of flash mixing on the WD cooling curve. Normally, stars ignite helium at the RGB tip (Figure 2), but stars that lose sufficient mass either through single- or binary-star mechanisms will leave the RGB and evolve to high $T_{\rm eff}$ before igniting helium (Castellani & Castellani 1993). If the helium-core flash is delayed until the WD cooling curve, the flash convection will mix the hydrogen envelope into the helium core (Sweigart 1997), leading to greatly enhanced surface abundances of helium and carbon as well as a much higher $T_{\rm eff}$ during the subsequent EHB phase. The higher $T_{\rm eff}$, together with the decreased hydrogen opacity shortward of the Lyman limit, make the flash-mixed stars subluminous in the UV and optical, as more of the flux is emitted in the EUV. In a later study, Brown et al. (2010) found blue-hook stars in 5 other massive GCs spanning a wide range of metallicity. Spectroscopic investigations of the blue-hook and normal EHB populations in $\omega$ Cen (Moehler et al. 2011) and NGC 2808 (Brown et al. 2012) have confirmed that, compared to the normal EHB stars, the blue-hook stars are both much hotter and enhanced in helium and carbon, thus providing unambiguous evidence for flash mixing. From an analysis of Space Telescope Imaging Spectrograph (STIS) spectra, Brown et al. (2012) found that the hottest blue-hook stars in NGC 2808 exhibit effective temperatures up to 50,000 K, carbon abundances orders of magnitude higher than in normal EHB stars, helium abundances of 99% by mass, and enormous enhancements in the iron-peak elements from radiative levitation.

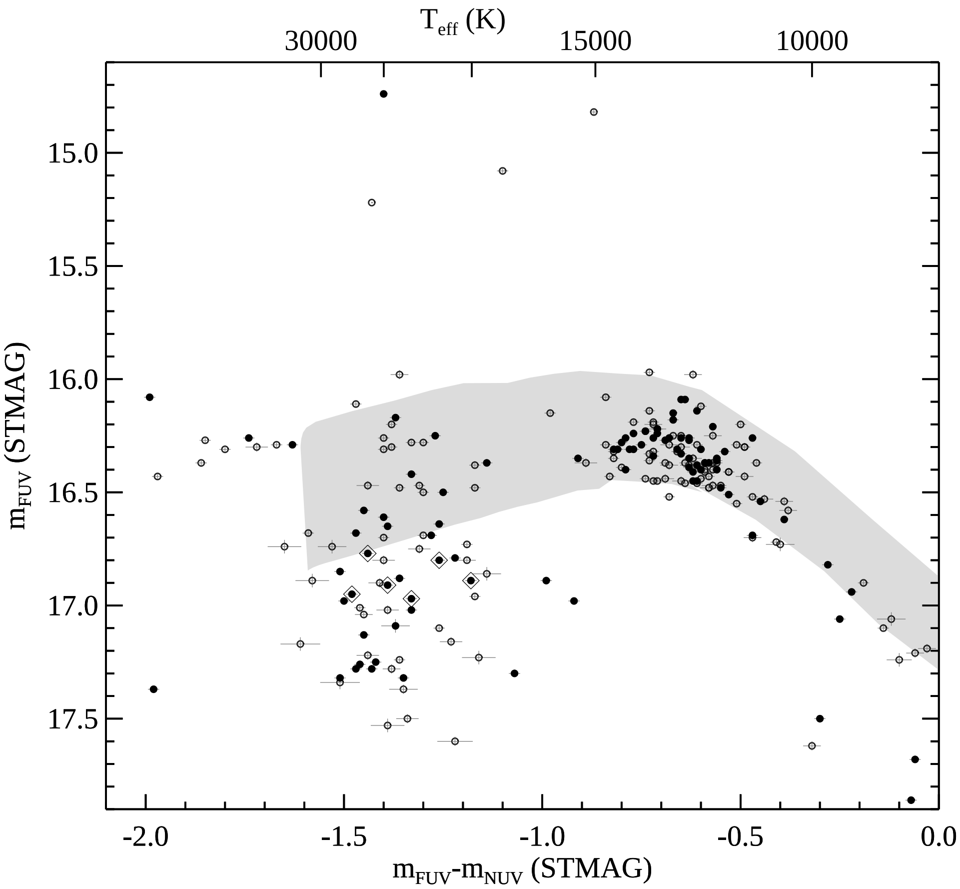


Figure 1. The UV CMD of NGC 2808. The full sample of Brown et al. (2001) is shown by circles, with photometric error bars indicated. The canonical HB locus is indicated by grey shading, bounded by the zero-age HB (ZAHB) and the point at which stars have completed 99% of the core helium-burning lifetime. NGC 2808 has a significant population of blue-hook stars lying below the canonical HB. Circles are filled for those stars monitored in our time-tag photometry. The six pulsators are highlighted with diamonds, spanning a wide range of color in the blue-hook region of the UV CMD.

## 2. Pulsating Subdwarfs

While it is clear that hot subdwarfs require significant mass loss, observations to date have not determined how this mass loss actually occurs. The high fraction of binaries among field subdwarfs suggests a binary mechanism for their production, such as common envelope evolution (e.g., Maxted et al. 2001; Napiwotzki 2006). In contrast, the binary fraction for GC subdwarfs is much lower (Moni Biden et al. 2006, 2009, 2011), indicating that single-star mass loss, or perhaps WD mergers, is more important. The fact that the fraction of HB stars falling on the EHB does not appear to vary significantly with radius in $\omega$ Cen or NGC 2808 (e.g., Whitney 1998; Iannicola et al. 2009)

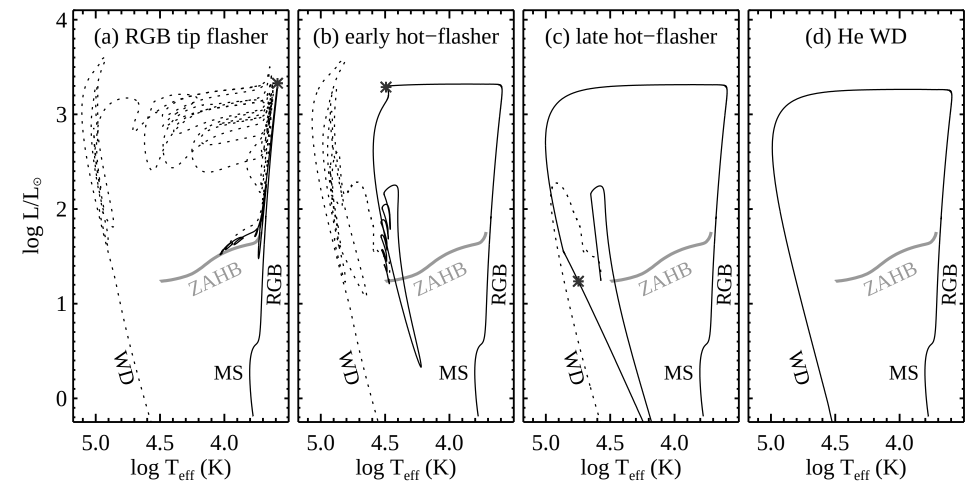


Figure 2. Various evolutionary paths for producing an HB star (from Brown et al. 2010). The ZAHB phase is highlighted in grey, while the pre-ZAHB evolution (solid curves) and post-ZAHB evolution (dashed curves) are in black. The peak of the helium-core flash is marked by an asterisk. The four panels show the evolution for progressively larger amounts of mass loss on the RGB. The evolution in the first two panels produces canonical HB stars in which the hydrogen-rich surface composition does not change during the helium-core flash. In the third panel, the helium-core flash occurs on the WD cooling curve, producing a flash-mixed star having a surface composition highly enriched in helium and carbon and a temperature significantly hotter than the canonical HB. In the fourth panel, the helium flash never occurs and the star dies as a helium WD.

would argue against a binary origin for the EHB stars. Indeed, there may be a greater diversity of formation mechanisms in the field subdwarf population than in GCs.

One of the exciting new avenues for exploring the formation and evolutionary status of hot subdwarfs has been asteroseismology. Pulsating hot subdwarfs are well-established in the field, where they are generally known as EC 14026 or V361 Hya stars (Kilkenny et al. 1997). These stars have short (∼100–200 s) non-radial pulsations apparently driven by a radiatively enhanced iron abundance, and inhabit an instability strip at 29,000 K $\lesssim T_{\rm eff} \lesssim$ 36,000 K (Charpinet et al. 1997). Asteroseismic analysis of hot subdwarfs can yield accurate structural parameters (e.g., $T_{\rm eff}$ to 0.6%, log $g$ to 0.03%, total mass to 1%, and envelope mass to 20%; Charpinet et al. 2009). For this reason, the Kepler mission has dedicated significant observing time toward asteroseismology of hot subdwarfs in the field (e.g., Østensen et al. 2010).

Asteroseismology in GCs has been a different story. Until very recently, all searches for pulsating subdwarfs in GCs had failed, suggesting distinct subdwarf formation channels in GCs and the field (e.g., Reed et al. 2006). However, Randall et al. (2011) have now discovered 4 hot pulsating subdwarfs in $\omega$ Cen. Compared to the field pulsators, these new pulsators have somewhat shorter periods (84–124 s) and higher temperatures (∼50,000 K), with pulsation amplitudes ranging from 0.9 to 2.7%. The $\omega$ Cen pulsators raise the exciting possibility of a new instability strip unseen among the field subdwarfs.

## 3. Times-Series Observations of NGC 2808

The best candidate for testing this hypothesis is NGC 2808, given its proximity and low reddening. Our previous far-UV photometry and spectroscopy of the NGC 2808 core revealed a large population of hot evolved stars, including blue-hook stars near ~50,000 K. With the $\omega$ Cen pulsators in mind, in March of 2013 we obtained new far-UV imaging of the NGC 2808 using the time-tag mode on STIS. In this mode, the arrival time of each photon is tagged to an accuracy of 125 $\mu$s. That time resolution, combined with the suppression of the dominant cool population when imaging in the far-UV, enables accurate time-series photometry of the hot stars in the crowded core of the cluster. We monitored over 100 UV-bright stars for 26 ksec (5 consecutive orbits), with four 2.5 ksec gaps due to occultations (Figure 1).

The STIS data were processed through the standard calibration pipeline, including corrections to the photon arrival times for general relativistic effects, displacement of *HST* from Earth center, and displacement of Earth from the solar system barycenter. The net count rate for each star was measured in two-second bins using aperture photometry and a local sky subtraction, although the background is extremely low in the STIS F25SRF2 bandpass. We then performed a Lomb Normalized Periodogram on the time-series photometry for each star, searching for periodic signals with >99% significance and periods between 50 and 300 sec, which produced six pulsators (Figure 1). Because of the irregular time sampling, we then performed a date-compensated discrete Fourier transform on their light curves, using the VSTAR software of the American Association of Variable Star Observers. This yielded accurate amplitudes and periods for each pulsator (Figure 3).

The characteristics of each pulsator are summarized in Table 1 and indicated in Figure 1. Three of the pulsators were included in the spectroscopic sample of Brown et al. (2012), and all have both far-UV and near-UV photometry from Brown et al. (2001). Surprisingly, the pulsators form a rather inhomogeneous group. Their periods range from 104 to 149 sec, with amplitudes of 2 to 8%. The 6 pulsators span 0.3 mag in UV color. The 3 pulsators with spectra span a $T_{\rm eff}$ range of 25,000 – 50,000 K, with both helium-rich and hydrogen-rich atmospheres present, and the enhancement of iron (relative to the cluster abundance) that is a common product of radiative diffusion in hot subdwarfs. The only obvious commonality in the set is that they all lie in a narrow range of far-UV luminosity, immediately below the ZAHB, among the blue-hook stars in the UV CMD. The luminosity of one of these stars (VAR1) is close enough to the ZAHB that it was identified as a normal EHB star by Brown et al. (2012).

## 4. Summary

Our far-UV time-series photometry of 110 UV-bright stars in the core of NGC 2808 has revealed 6 rapid pulsators with periods of 104 to 149 sec and amplitudes of 2 to 8%. These pulsators do not appear to form a homogeneous group, in contrast to the $\omega$ Cen pulsators (Randall et al. 2011). The relatively high yield of pulsating stars in our search may be due to selection bias, given that we focused our search on a sample consisting solely of UV-bright hot subdwarfs, and because the pulsation amplitudes are expected to be stronger in the UV than in the optical. Indeed, any distinctions drawn between the NGC 2808 pulsators and the $\omega$ Cen pulsators should be tempered by the fact that the pulsators were characterized via very distinct data and atmospheric diagnostics in

Table 1. Properties of NGC 2808 Pulsators

| Name | Alternate Name[a] | Periods (s) | Amplitude (%) | $T_{\rm eff}$[a] (K) | $Y$[a] | Fe enhancement[a] |
|---|---|---|---|---|---|---|
| VAR1 | EHB3 | 116, 108, 112 | 3.5 | 30,000 | 0.23 | 10x |
| VAR2 | – | 149, 130 | 3.3 | >20,000 | – | – |
| VAR3 | – | 121 | 2.9 | >20,000 | – | – |
| VAR4 | – | 104, 85 | 7.8 | >20,000 | – | – |
| VAR5 | BHk1 | 147 | 2.3 | 50,000 | 0.99 | 50x |
| VAR6 | BHk6 | 113 | 3.6 | 25,000 | 0.23 | 10x |

[a]Brown et al. (2012)

each cluster. Our survey of NGC 2808 demonstrates that this observational approach may be useful for finding pulsators in other massive GCs hosting large populations of hot subdwarfs.

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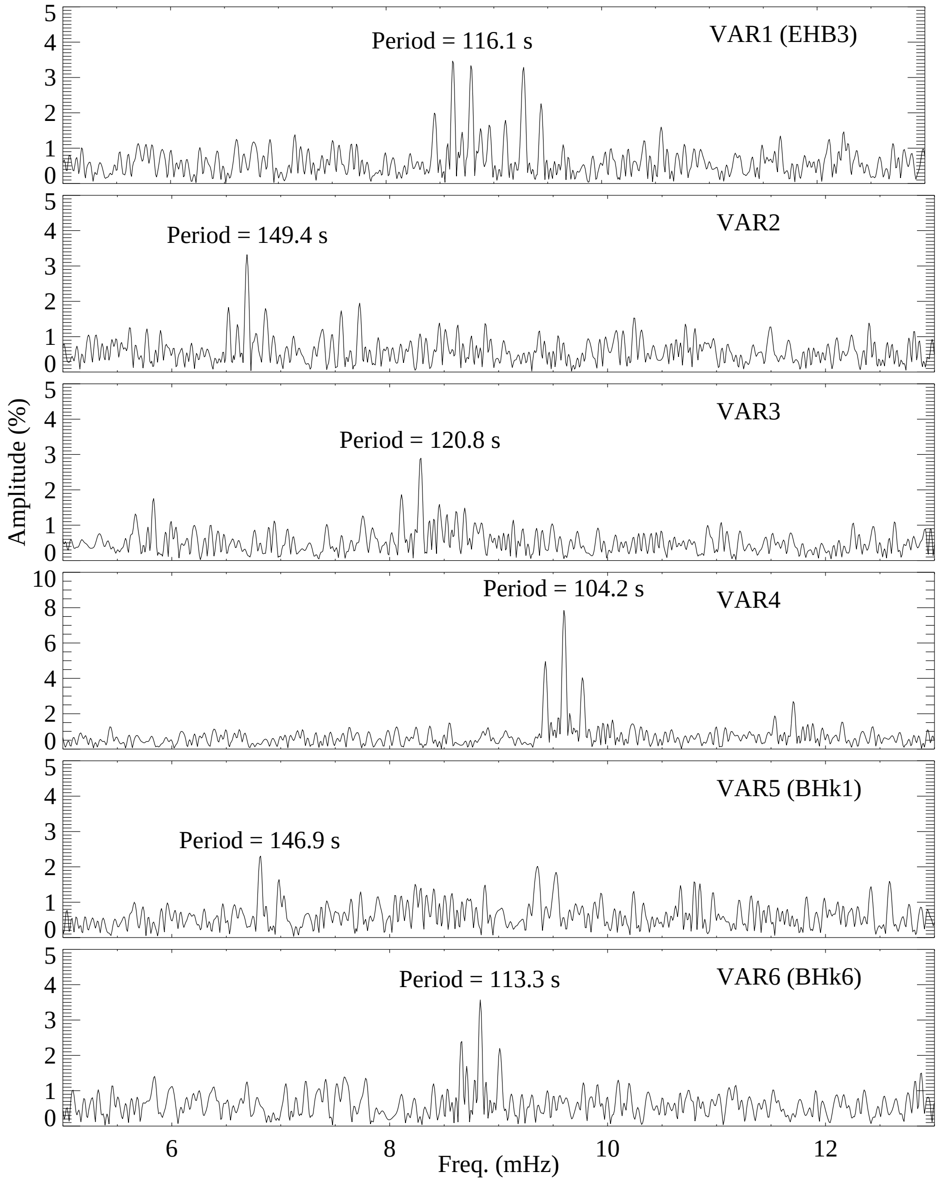


Figure 3. Fourier amplitude spectra of the 6 pulsators in NGC 2808, with the dominant period labeled for each. Three of the 6 pulsators have far-UV spectroscopy from Brown et al. (2012), with the names from that study indicated (EHB3, BHk1, BHk6).


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