The Hot Stars of Old Open Clusters: M67, NGC 188 and NGC 6791

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ABSTRACT

We analyze ultraviolet (≈ 1500 Å) images of the old open clusters M67, NGC 188, and NGC 6791 obtained with Ultraviolet Imaging Telescope (UIT) during the second flight of the Astro observatory in March 1995. Twenty stars are detected on the UIT image of M67, including 11 blue stragglers, seven white dwarf candidates, and the yellow giant – white dwarf binary S1040. The ultraviolet photometry of the blue stragglers F90 (S975) and F131 (S1082) suggests that these stars have hot subluminous companions. We present a semi-empirical integrated ultraviolet spectrum of M67, and show that the blue stragglers dominate the integrated spectrum at wavelengths shorter than 2600 Å. The number of white dwarfs in M67 is roughly consistent with the number expected from white dwarf cooling models. Eight candidate sdB/sdO stars are detected in NGC 6791, and two are detected in NGC 188. The luminosity range 1.10 < log L/L☉ < 1.27, derived from the ultraviolet photometry of the six sdB candidates, is consistent with theoretical models of metal-rich hot horizontal branch (HB) stars. The fraction of hot HB stars in both NGC 6791 and NGC 188 is about 30%, implying that the integrated spectra of both clusters should show a UV turnup at least as strong as that observed in any elliptical galaxy.

Subject headings: open clusters and associations: individual (M67, NGC 188, NGC 6791) – stars: white dwarfs — stars: blue stragglers — ultraviolet: stars

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1. Introduction

As a stellar population ages, the main-sequence turnoff becomes cooler and fainter, until, after an age of about 2 Gyrs, the ultraviolet ($\sim 1500$ Å) flux is no longer dominated by stars near the main-sequence, but instead must be due to a more exotic population of hot stars, such as blue stragglers, hot subdwarf (sdB, sdO) stars, hot post-asymptotic giant branch (post-AGB) stars, white dwarfs, or interacting binaries. The blue stragglers and hot subdwarfs are of particular interest since they might have significant roles, respectively, in two current problems in extragalactic astronomy: the age-dating of old galaxies from their rest-frame near-UV ($\sim 2600$ Å) spectra, and understanding the origin of the observed UV-upturn in elliptical galaxies. In the absence of blue stragglers, the rest-frame near-UV spectrum of an old galaxy should be dominated by the turnoff population, and thus fitting the spectrum to population synthesis models should be a reliable method for age-dating the galaxy, although metallicity effects also need to be properly disentangled (Heap et al. 1998, Bruzual & Magris 1997). However, as noted by Spinrad et al. (1997), a significant underestimate of the galaxy age could result if blue stragglers contribute a large fraction of the galaxy near-UV flux, but are not included in the adopted population synthesis model.

Greggio & Renzini (1990) outlined the various candidates for the origin of the observed UV-upturn in elliptical galaxies, which is characterized by a rising UV flux shortward of 1800 Å (Bica et al. 1996b, Brown et al. 1997). Among these candidates, white dwarfs and hot post-AGB stars have the advantage of being relatively well-understood phases of stellar evolution, but lack sufficient fuel to explain the strongest UV-upturn galaxies. The more promising candidates are currently the extreme horizontal-branch (EHB) stars and their hot progeny; the AGB-manqué stars, which miss the AGB phase entirely, and the post-early AGB stars, which leave the AGB before the thermally pulsing phase. Although the horizontal branch (HB) morphology of the globular clusters becomes generally redder with increasing metallicity, a significant EHB population is theoretically expected at metallicities above solar (and an age larger than about 5 Gyr), if reasonable assumptions are made concerning the metallicity dependence of the mass loss rate and helium abundance (Dorman et al. 1995, Yi et al. 1997a). Spectroscopically, EHB and AGB-manqué stars are expected to appear, respectively, as sdB and sdO stars, and the measured effective temperatures and gravities of the field hot subdwarf stars is consistent with this scenario (Saffer et al. 1994). However, the field hot subdwarfs apparently have a large binary fraction (Theissen et al. 1995, Green et al. 1998b), which instead suggests that binary interactions might be involved in their formation (Bailyn 1995).

Despite their probable contributions to the ultraviolet spectra of galaxies, blue stragglers and hot subdwarfs are either neglected or poorly constrained in existing
population synthesis models of old stellar populations. The currently favored explanations for the origin of blue stragglers involve binary interactions, either through mass-transfer processes, binary mergers, or direct stellar collisions (Bailyn 1995, Leonard 1996), but the large parameter space of these binary processes limits their inclusion in synthesis models to special cases (e.g. Pols & Marinus 1994). Some attempts have been made to include EHB stars in synthesis models of metal-rich populations, but these are hampered by large uncertainties, for example, in the dependence of mass loss and helium abundance on metallicity (Bressan et al. 1994, Yi et al. 1997b). The modeling of galaxy ultraviolet spectra should clearly benefit from empirical studies of the ultraviolet content of resolved, old, metal-rich stellar populations.

Here we report on ultraviolet (\( \sim 1600 \) Å) images of the three old (> 4 Gyr) open clusters M67, NGC 188, and NGC 6791, which were obtained in March 1995 using the Ultraviolet Imaging Telescope (UIT, Stecher et al. 1997) during the second flight of the Astro observatory. The 40' diameter field of view of UIT is sufficiently large to allow a complete census of the hot stellar population in the observed clusters. Thus, the UIT images of these three clusters can be used for an empirical study of the ultraviolet content of old, metal-rich stellar populations. As it turns out, M67 contains blue stragglers, but no hot subdwarfs, whereas NGC 188 and NGC 6791 contain hot subdwarfs, but are too old, distant and reddened for the blue stragglers to be detectable with UIT. M67 is also sufficiently nearby that all the white dwarfs hotter than \( \sim 21,000 \) K should have been detected on the UIT image. In the population synthesis models of Magris & Bruzual (1993), white dwarfs supply about 10% of the 1750 Å flux in elliptical galaxies with a weak UV-upturn, and in Section 3.2 we re-examine the white dwarf contribution to galaxy ultraviolet spectra, using more recent stellar atmospheres and evolutionary models.

A brief summary of this work was given by Landsman & Stecher (1997). A subsequent paper will discuss the UIT observations of the intermediate age (\( \sim 2 \) Gyr) clusters NGC 752 and NGC 7789, which are sufficiently young to allow the turnoff population to be detected in the ultraviolet.

2. Observations

Table 1 gives the adopted fundamental parameters of the observed clusters, and Table 2 lists the deepest exposure obtained with each UIT filter, along with the coordinates of the UIT image center. The UIT image center was chosen to provide a target for the co-pointed spectroscopic instruments on the Astro observatory, and could be offset by as much as 11' (in the case of NGC 6791) from the cluster center. M67 was observed with the B1 filter,
which has a peak wavelength of 1520 Å and a bandwidth of 350 Å (see Figure 3). NGC 6791 was observed with the B5 filter, which has a peak wavelength of 1620 Å and a bandwidth of 230 Å. NGC 188 was observed with both the B1 and the B5 filter. (The less sensitive B5 filter was used on the daytime side of the Shuttle orbit, because it suppresses O I 1300 Å dayglow emission.) Ultraviolet magnitudes on the B1 and B5 images are denoted here as $m_{152}$ and $m_{162}$, respectively, and are given on the monochromatic system, where \[ m_\lambda = -2.5 \log(F_\lambda) - 21.1, \] and $F_\lambda$ is the observed flux in units of erg cm$^{-1}$ s$^{-1}$ Å$^{-1}$.

Only a few stars in each cluster are detected on the UIT images, so that ultraviolet magnitudes could be derived from simple circular aperture photometry. However, the absolute calibration of the UIT images is somewhat problematic. As discussed by Stecher et al. (1997), comparison of fluxes from UIT and the International Ultraviolet Explorer (IUE) indicated that the sensitivity of the UIT during the Astro-2 mission appeared to decrease with exposure time. The cause of this behaviour has not been determined, and instead an empirical correction to the exposure time was adopted that, for most images, brought the IUE and UIT fluxes to within 15% of each other. For M67, this mean calibration could be tested, and an aperture correction determined, by direct comparison with spectra from IUE and the Goddard High-Resolution Spectrograph (GHRS) of five stars in the cluster. The NGC 6791 calibration was modified by comparison with a single star (NGC 6791-B4) with a GHRS observation, while for NGC 188 we had to rely on the mean UIT calibration. Thus while the photometry of all the clusters has a random uncertainty of about 0.1 mag, we estimate an uncertainty in the absolute photometry of about 0.1 mag for M67, and about 0.15 mag for NGC 6791 and NGC 188.

All IUE spectra in this paper used the NEWSIPS (Nichols & Linsky 1996) reduction, with the fluxes multiplied by 1.06, as suggested by Colina & Bohlin (1994).

3. M67

M67 is a well-studied, nearby (820 pc), solar-metallicity open cluster with an age of about four Gyr. Twenty stars are detected on the UIT image of M67 (Figure 1), including eleven blue stragglers, seven white dwarf candidates, the yellow-giant S1040 (from the catalog of Sanders et al. 1977), and the probable non-member S1466. The integrated 1520 Å flux of M67 is completely dominated by the blue stragglers, and in particular, by the bright, hot (V = 10.03, $B-V = -0.09$) blue straggler F81. Figure 2 shows a color-magnitude diagram (CMD) of a 30′ field centered on M67 taken from Montgomery et al. (1993, hereafter MMJ93), with circles identifying the sources detected in the ultraviolet. In general, the stars that are detected in the ultraviolet are ones with the bluest $B-V$ colors,
with the notable exception of the star S1040, which has $V = 11.52$ and $B - V = 0.82$. S1040 is a known spectroscopic binary and Landsman et al. (1997) used GHRS spectroscopy of S1040 to show that the ultraviolet flux is due to a hot white dwarf companion of the yellow giant. Landsman et al. also constructed a mass-transfer history for S1040 that explains its unusual “red straggler” location in the CMD (0.2 mag blueward of the giant branch), relatively long orbital period (42d), and the unusually low mass ($\sim 0.23 M_\odot$) of the white dwarf companion. In their scenario, S1040 originated as a short-period ($\sim 2$ d) binary, in which the more massive star (the donor) fills its Roche lobe while on the lower giant branch. A period of rapid mass transfer reverses the mass-ratio of the donor and accretor (but without creating a common envelope), and is followed by an extended period ($\sim 800$ Myr) of stable mass transfer. During the mass transfer, the orbital period increases, and the accretor eventually becomes a blue straggler, more massive than the cluster turn-off stars. Mass transfer ends when the donor’s envelope is depleted, leaving a low mass helium white dwarf, and a blue straggler, which has since evolved redward to its current location in the CMD.

3.1. Blue Stragglers

Eleven of the thirteen blue stragglers in M67 listed by Milone & Latham (1994) are detected on the UIT image. The first two columns of Table 3 contain, respectively, the Fagerholm and the Sanders (1977) identifications of the detected blue stragglers, the third and fourth columns list the $V$ and $B - V$ magnitudes tabulated by MMJ93, and the fifth column gives the observed UIT magnitude, $m_{152}$. The brightest and hottest blue straggler is F81 ($V = 10.03$, $B - V = -0.07$), which is saturated even on the shortest exposure (109s) UIT image. Optical and IUE spectra of F81 were studied by Schönberner & Napiwotzki (1994), who derived $T_{\text{eff}} = 12,750$ K, $\log g = 4.26$ and a spectroscopic mass of $3.1 \pm 0.3$ $M_\odot$. Comparing the IUE spectra of F81 with the UIT photometry of the remaining stars in M67, we find that F81 supplies more than 90% of the total 1520 Å flux of M67. Despite the extreme properties of F81, the evidence is strong from both astrometric (Girard et al. 1989) and radial velocity (Milone et al. 1992) studies that it is a cluster member.

In order to search for evidence of a subluminous hot companion, or an unusual ultraviolet spectrum, we compare the UIT photometry of the blue stragglers with model atmosphere predictions, using stellar parameters derived from optical photometry. Temperatures and gravities for most of the blue stragglers are calculated from the Strömgren photometry tabulated by Hauck & Mermilliod (1998), using the code of Napiwotzki et al. (1993), and assuming $E(b-y) = 0.73E(B-V) = 0.018$ for all stars. No Strömgren
photometry is available for F90, and so the values of $T_{\text{eff}}$ and $\log g$ for this star are taken from Mathys (1991), who derived them using Geneva photometry. The predicted $m_{152}$ magnitude is then calculated from the derived $T_{\text{eff}}$ and $\log g$ using the 1995 Kurucz LTE model atmospheres as tabulated by Lejeune et al. (1997). This version of the Kurucz models includes the modification of the convective overshoot algorithm discussed by Castelli (1996), which eliminates the discontinuities in color indices for $6500 \, \text{K} < T_{\text{eff}} < 8000 \, \text{K}$ that was present in earlier versions of the Kurucz grid. The models are normalized to the stellar V magnitude, and reddened using the parameterization of Cardelli et al. (1989) with $R_V = 3.1$. The calculated values of $T_{\text{eff}}$ and $\log g$ are listed in columns 5 and 6 of Table 3, and the predicted $m_{152}$ magnitudes are given in column 7.

For the range of effective temperatures considered here (6500 – 8500 K), the UIT 1520 Å bandpass is located shortward of the blackbody peak, and thus is very sensitive both to the exact value of $T_{\text{eff}}$ and to the accuracy of the model atmosphere. An uncertainty of 200 K in the value of $T_{\text{eff}}$ corresponds to about a 0.5 mag uncertainty in the predicted UIT magnitude. Archival IUE spectra are available for the blue stragglers F280, F156, F153, and F190, and these provide a much more robust comparison with the model atmospheres. Figure 3 compares the IUE spectra with Kurucz models with $[\text{Fe/H}] = -0.1$, and $T_{\text{eff}}$ and $\log g$ from Table 3, normalized to the stellar V magnitude. No parameters were adjusted to improve the fit. The model spectra provide a good fit to both F280 and F156, and the model fits for F153 and F190 can be improved by adopting values of $T_{\text{eff}}$ that are lower by 60 K and 140 K, respectively, than the values listed in Table 3; a change that is within the uncertainty of the Strömgren photometry. In addition, the somewhat poorer fit for F153 may be related to its Am star abundance peculiarities (Mathys 1991), while the poorer fit for F190 may be related to its 0.02 mag $\delta$ Sct pulsations (Gilliland & Brown 1992), since the flux variations of $\delta$ Sct stars are known to be much larger in the ultraviolet (Monier & Kreidl 1994). We conclude that the IUE spectra provide no evidence for a subluminous companion in any of the four stars. The lack of a hot subluminous companion for F190 is especially noteworthy, because it is a single-lined spectroscopic binary with a 4.2d period, and suspected to be currently undergoing mass transfer (Milone & Latham 1992). We also note that if we let the reddening be a free parameter in the model atmosphere fits, then lower reddening values ($0.015 < E(B-V) < 0.025$) are consistently favored over the higher values in the range usually considered acceptable for M67 ($0.015 < E(B-V) < 0.052$; Fan et al. 1996).

For the remaining blue stragglers, taking into account the $\sim 0.5$ mag uncertainty in the predicted UIT flux, and the 0.14 mag uncertainty in the measured UIT flux, there is strong evidence for a UV excess only for the two stars F131 (S1082) and F90 (S975). In the case of F131, the observed 1520 Å flux is a factor of six higher than predicted from the
optically derived $T_{\text{eff}}$. Mathys (1991) found evidence for an additional broad component in the Na I D and O I absorption lines of F131, which he suggested was due to a hot, fast-rotating secondary. F131 is also a ROSAT source with an X-ray luminosity of $4 \times 10^{30}$ erg s$^{-1}$ (Belloni et al. 1993). The X-ray emission and the presence of a hot, subluminous secondary together suggest that F131 is an Algol-type mass-transfer binary. Milone (1991) reports that F131 is a radial velocity variable, with a small amplitude and a long period, but no orbit has yet been determined.

The UIT magnitude of F90 is probably uncertain by close to a factor of two, because F90 is located in the wings of the heavily saturated image of F81. Nevertheless, the detection of F90 with UIT is quite robust, and likely due to a hot subluminous companion, since the predicted ultraviolet magnitude from the optically-derived $T_{\text{eff}}$ is about 1.9 mag fainter than the UIT detection limit. Latham & Milone (1996) report that S975 is a binary with a period of 1221 days, and a small eccentricity $e = 0.088 \pm 0.060$. The probable presence of a hot subluminous companion in F90, along with a nearly circular binary orbit, suggests that its blue straggler origin is also due to a binary mass-transfer process. Note that while the hot companion of F131 is probably not a white dwarf (since it is detected in the Na I D and O I absorption lines), the nature of the hot companion of F90 is unknown.

The star S1466 occupies the blue straggler region of the HR diagram, and is located 7$'$ from the center of M67. However, the star is usually considered to be a non-member based on proper motion studies. The most precise proper motion study of M67 is that of Girard et al. (1989), who give a 21% probability of cluster membership for S1466. Further study of S1466 is perhaps warranted, given that a blue straggler might acquire a peculiar velocity if its formation process is due to stellar interactions (e.g. Leonard 1996).

To study the contribution of blue stragglers at other wavelengths, we perform a semi-empirical computation of the integrated M67 ultraviolet spectrum, using the list of stars with at least 80% probability of cluster membership from the astrometric studies of (in order of preference) Girard et al. (1989), Zhao et al. (1993), and Sanders (1977). Although the list of proper motion members does not extend fainter than about $V = 15$ (Figure 2), the fainter main-sequence stars should contribute negligible light below 3000 Å. For all but two of the proper motion members, V and $B-V$ magnitudes could be obtained from the catalogs of MMJ93, Sanders (1989), Girard et al. (1989) or Fan et al. (1996). Effective temperatures are estimated from the dereddened $B-V$ colors, using the $T_{\text{eff}} - B-V$ relation of Lejeune et al. (1997). Gravities are approximated by assuming a mass of 1.25 $M_\odot$ for stars brighter than $V=13$, and assuming $\log g = 4.5$ for fainter stars. From the $T_{\text{eff}}$ and $\log g$ of each star, a model synthetic ultraviolet spectrum from the compilation of Lejeune et al. (1997) is assigned, normalized to the star’s dereddened V magnitude. Figure
4 shows the predicted integrated ultraviolet spectrum of M67, with the blue straggler contribution shown separately from all other stars. Even neglecting the possibly anomalous star F81, the blue straggler contribution still dominates the integrated M67 spectrum at wavelengths shorter than 2600 Å.

The lower panel of Figure 4 compares the integrated spectra with synthetic spectra derived from the solar-metallicity isochrones computed by Bruzual & Charlot, and tabulated in Leitherer et al. (1996, also see Charlot et al. 1996). The synthetic spectra are computed for an instantaneous starburst and a Salpeter initial mass function. (We do not attempt to fit the integrated spectra shortward of 2100 Å, because the Bruzual & Charlot models include a contribution from the short-lived hot post-AGB stars, which do not exist in the relatively small population of M67.) If the blue stragglers are excluded, than a 4.5 Gyr model provides the best fit to the semi-empirical integrated spectrum, which is in agreement with the age of M67 estimated from color-magnitude diagrams. However, if all the blue stragglers except F81 are included in the integrated spectrum, then a 2.5 Gyr isochrone provides the best fit, and, in particular, provides a good fit of the spectral break at 2600 Å. Thus, in this case, the neglect of blue stragglers in a population synthesis model of the unresolved ultraviolet spectrum would lead to a significant underestimate of the cluster age.

There are at least two ways in which the blue straggler population of M67 might differ from that of galaxies of similar age. First, dynamical interactions of M67 with the Galaxy have enhanced the relative contribution of blue stragglers to the integrated spectrum, because the low-mass stars have evaporated from the cluster, while blue stragglers are concentrated toward the cluster center (MMJ93). A more important question concerns the origin of blue stragglers themselves; whether they arise from primordial binaries either via mass transfer processes or stellar mergers, or whether they originate from stellar collisions enhanced by the moderately high stellar density ($20 \text{ pc}^{-3}$; Leonard 1996) in the M67 center. While this stellar density is often exceeded in the cores of many elliptical galaxies (Lauer et al. 1995), the typical star density in elliptical galaxies or stellar bulges will be at least an order of magnitude lower.

In fact, there is good evidence that both mass-transfer and stellar collision processes contribute to the M67 blue straggler population. The short-period (4.2d) binary F190 has long been a good candidate for ongoing mass transfer (Milone & Latham 1992), and the present work provides evidence that both F90 and F131 are Algol-type mass-transfer systems. As noted above, Landsman et al. (1997) showed that the yellow giant S1040 is almost certainly a blue straggler descendant, and a product of early case B mass transfer. On the other hand, the bright blue straggler F81 has a mass larger than twice the turnoff mass, and the blue stragglers F55, F238, and F555 (S997) have orbits with appreciable
eccentricities (Latham and Milone 1996). Neither of these properties can be easily understood with a mass-transfer scenario, or mergers of primordial binaries, but are easily accommodated with binary-binary or binary-single star collisions (Leonard 1996).

Is the large contribution of blue stragglers to the integrated ultraviolet spectrum of M67 typical of other open clusters? Spinrad et al. (1997) estimate that the blue straggler contribution to the cluster ultraviolet spectrum is higher for M67 than for any of the seven clusters they examined. Ahumada & Lapasset (1995) have compiled a catalog of blue stragglers in 390 open clusters, in which they tabulate both Nbs, the number of blue stragglers in the cluster, and N2, the number of stars on the main sequence to two magnitudes below the turnoff. The ratio Nbs/N2 is 0.15 for M67, about twice the mean of the entire open cluster population. We do not pursue this comparison any further here, but instead make the following two points. First, the best way to detect the presence of blue stragglers in an unresolved population is to have wide spectral coverage, including both ultraviolet and visible bandpasses. Second, evolutionary models of close binaries including mass transfer (e.g. Pols & Marinus 1994) would be a useful addition to galaxy population synthesis models, especially for those spectral regions expected to be dominated by the stellar turn-off population.

### 3.2. White Dwarfs

Figure 2 shows that three UIT sources are coincident with faint hot sources in MMJ93, and occupy the white dwarf region in the lower left-hand corner of the HR diagram. Four other UIT sources are outside of the region studied by MMJ93, but are coincident with faint, hot stars in the BATC (Beijing-Arizona-Taipei-Connecticut) intermediate-band spectrophotometric survey of Fan et al. (1996). The UIT photometry of these seven white dwarf candidates, along with that of the yellow giant – white dwarf binary S1040 is given in column 4 of Table 4. The BV photometry is given in columns 2 and 3, where the intermediate-band photometry of the BATC survey is converted to V and $B-V$ magnitudes using equations (3) and (4) in Fan et al. (1996). Column 5 gives the distance of the white dwarf candidates from the star S1023, assumed to be the cluster center.

The brightest of the white dwarf candidates (and the fifth brightest source in M67 at 1520 Å) is MMJ 5670 ($V \sim 18.6$), which is also star G152 in Gilliland et al. (1991). This star was suspected to be responsible for the soft component of a blended ROSAT X-ray source in M67 discovered by Belloni et al. (1993). Subsequent optical spectroscopy by Pasquini et al. (1994) and Fleming et al. (1997) demonstrated that MMJ5670 is a hot DA white dwarf. Fleming et al. derive $T_{\text{eff}} = 68,230 \pm 3200$ K, and $\log g = 7.58 \pm 0.16$ from a
model atmosphere fit to the Balmer lines. Using a pure hydrogen model atmosphere with this $T_{\text{eff}}$ and log $g$ and normalizing to $V = 18.71$, and assuming $E(B-V) = 0.025$, yields a predicted UIT magnitude of $m_{152} = 14.11$, in reasonable agreement with the observed value of $m_{152} = 13.92$. Only 10% of hot (> 20,000 K) white dwarfs are X-ray luminous (Fleming et al. 1996), and this fraction is much lower for white dwarfs with $T_{\text{eff}} > 50,000$ K, because the X-ray emission in hot white dwarfs can be strongly suppressed by the presence of radiatively supported trace metals in the photosphere (Marsh et al. 1997, Wolff et al. 1998). Thus, MMJ 5670 must have have a remarkably pure hydrogen atmosphere. The high $T_{\text{eff}}$ of MMJ 5670 also indicates a young age; according to the 0.6 M$_\odot$ white dwarf cooling models of Wood (1995), MMJ 5670 began its descent on the white dwarf cooling curve within the past $10^6$ yr.

Fleming et al. (1997) also obtained an optical spectrum of MMJ 5973 ($V \sim 19.7$), after learning of its detection on the UIT image. They find that MMJ 5973 has a DB spectrum, and they derive $T_{\text{eff}} = 17,150 \pm 310$ K, and log $g = 7.77 \pm 0.47$ from a model atmosphere fit. Presuming cluster membership (see below), MMJ 5973 is the first DB white dwarf found in an open cluster, and shows that both DB and DA white dwarfs can be produced in the same cluster. The origin of the distinction between DA and DB white dwarfs is still a matter of some debate. The high surface helium abundance of DB white dwarfs might arise if the DB stars are descended from stars that left the asymptotic giant branch (AGB) during a helium shell flash (e.g. Dehner & Kawaler 1995). As opposed to this “primordial” scenario, surface phenomena such as mass loss, gravitational settling and convective overturn might provide an evolutionary path between DB and DA white dwarfs, provided that the hydrogen surface layer is sufficiently thin (Fontaine & Wesemael 1997).

Remarkably, all three of the spectroscopically studied white dwarfs in M67 have turned out to have unusual characteristics; MMJ 5670 is a very hot X-ray-luminous DA, MMJ 5973 is a DB, and the S1040 companion is a very low mass core-helium white dwarf. No spectra exist for the five faintest white dwarf candidates in Table 4. The three faintest sources (MMJ 6061, BATC 2776, BATC 3337) are near the UIT detection limit, and are best considered as three sigma detections. The sources BATC 4672 ($B-V = 0.46$) and BATC 3009 ($B-V = 0.24$) have redder optical colors than expected for a hot white dwarf, and thus might be white dwarf–red dwarf binaries.

The approximate sensitivity limit of the UIT image of M67 at 1520 Å is $m_{152} = 16.6$ or $8 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$. Using the field white dwarf luminosity function and scale height (275 pc) of Boyle (1989), only 1.26 white dwarfs brighter than this limit are predicted to be within the UIT 40′ diameter field of view at the Galactic latitude and reddening of M67. (Since the luminosity function is given in terms of $M_V$, we used the log $g = 8.0$ pure
hydrogen model atmospheres of Bergeron et al. (1995) to compute absolute magnitudes, $M_V$, and $m_{152} - V$ colors as a function of $T_{\text{eff}}$. This low contamination rate is consistent with a general lack of white dwarf candidates in other random UIT fields. In view of this low expected contamination rate, and the clustering of the white dwarf candidates toward the cluster center, most of the stars in Table 4 are likely cluster members. Fleming et al. do raise a caveat about the cluster membership of MMJ 5670 and MMJ 5973. They compute absolute magnitudes for the two stars using a mass-radius relation, and the $T_{\text{eff}}$ and log $g$ values derived from the best-fit model atmosphere, and find that the very hot DA star MMJ 5670 is 1 mag too bright, and the DB star MMJ 5973 is 0.7 mag too faint to be consistent with a cluster distance modulus of $m - M = 9.7$. However, there are several large uncertainties in these absolute magnitude determinations. The S/N of the white dwarf spectra are low ($\sim 20$), and there are known problems with model atmospheres for both DB stars and very hot DA stars. The optical photometry of MMJ 5973 is near the detection limit of MMJ93, and there is a 0.4 mag difference between MMJ93 and Gilliland et al. (1991) in the photometry of MMJ 5670. Nevertheless, the absolute magnitude differences are still uncomfortably large, and proper motion studies of the two stars would be very desirable to verify cluster membership.

M67 has a core radius of 5.2′ and a tidal radius of about 75′ (Zhao et al. 1996), whereas the UIT image has a diameter of 40′ and is offset by 4.2′ from the center of M67. To estimate the incompleteness of the UIT white dwarf sample, we note that 85% of the 222 stars with membership probabilities greater than 90% in the wide field astrometric study of Zhao et al. (1993), are located within UIT field of view. Thus, one or two white dwarf cluster members brighter than the UIT detection limit might be missing from Table 4.

How many white dwarfs brighter than the UIT detection limit are expected in M67, based on the cluster size and age? Using pure hydrogen model atmospheres with log $g = 8.0$, and the mass-radius relation of Wood (1995), the temperature of a 0.6 $M_\odot$ WD at the distance and reddening of M67 at the UIT detection flux limit is computed to be 21,300 K. From the white dwarf cooling models of Wood (1995), the time for a 0.6 $M_\odot$ WD to cool to this temperature is about 60 Myr. Thus, all the white dwarfs in M67 less than 60 Myr old should be detectable on the UIT image, including those that would be optically hidden in binary systems with late-type companions. (Only possible white dwarf companions of the hottest blue stragglers would remain undetected on the UIT image.) The question now becomes – how many white dwarfs should have been created in M67 in the last 60 Myrs? A quick estimate of about seven white dwarfs can be made by simply comparing with the seven observed red clump stars, which are expected to have a similar lifetime ($\sim 70$ Myr, Tripico et al. 1993). Alternatively, Dorman et al. (1995) estimate that there should be 0.076 stars leaving the main sequence per Gyr per $L_\odot$ for a 4 Gyr solar metallicity
isochrone. Multiplying this number by 0.060 Gyr and the cluster visible luminosity of $L/L_\odot = 1660$ (Battinelli et al. 1994) gives an estimate of 7.6 WDs. Thus, the predicted number of WDs is in reasonable agreement with the eight detected white dwarf candidates. We conclude that the stellar evolution timescale and the hot white dwarf cooling timescale are not in major disagreement, and that most of the young ($< 60$ Myr) white dwarfs have not yet evaporated from the cluster. Note that although there is a marked deficit of 0.6 M_\odot main-sequence stars in M67 (MMJ93), no evaporation of the white dwarfs is expected on a time scale of 60 Myr (von Hippel 1998). Stronger assertions will be possible once spectra and proper motion studies have been obtained for all the white dwarf candidates.

Because the relatively small population of M67 does not include any post-AGB or hot HB stars, its integrated ultraviolet spectrum will be dominated by the hot white dwarfs at wavelengths shortward of Lyman $\alpha$. Would white dwarfs be detectable in the integrated ultraviolet spectra of galaxies? Bica et al. (1996a,b) pointed out the presence of features at 1400 Å and 1600 Å in IUE spectra of some early-type galaxies, and suggested that these might correspond to the Lyman $\alpha$ satellite lines observed at these wavelengths in intermediate temperature (9000 - 18,000 K) DA white dwarfs (Kielkopf & Allard 1995). However, these features are not present in spectra of the same galaxies observed with the Hopkins Ultraviolet Telescope (HUT: Brown et al. 1997). In addition, the satellite lines at 1400 and 1600 Å are not unique to white dwarfs, but also appear in the spectra of low-metallicity A-type and horizontal branch stars (Holweger et al. 1994). Nevertheless, the population synthesis models of Magris & Bruzual (1993) do suggest that white dwarfs are a small but non-negligible contributor to the ultraviolet spectrum of ellipticals with a small UV upturn. They find that, at 1750 Å, the contribution of white dwarfs is 10% of the contribution of hot post-AGB stars in galaxies older than 8 Gyr.

We have performed our own estimate of the white dwarf contribution to the ultraviolet spectrum of an old stellar population. We use the carbon-core cooling models of Wood (1995) with thick hydrogen and helium envelopes, and the pure hydrogen model atmospheres of Bergeron et al. (1995). To allow an easy comparison of the contribution of white dwarfs with that of other ultraviolet sources, we follow Dorman et al. (1995) and compute the energy $E_\lambda$ integrated over the cooling curve in units of $L_{V}^\odot$ Gyr Å$^{-1}$, where $L_{V}^\odot = 4.511 \times 10^{32}$ ergs s$^{-1}$ is the visible solar luminosity. Figure 5a shows the resultant ultraviolet spectrum for both a 0.6 M_\odot and a 0.9 M_\odot cooling white dwarf. The time required for the 0.9 M_\odot model to cool to 20,000 K is 190 Myr, whereas only 75 Myr are needed for a 0.6 M_\odot to cool to this temperature. Despite this large difference in cooling age, the integrated fluxes, $E_\lambda$, along the two tracks differ by only $\sim 15\%$ outside of the Lyman lines, because the radii in the more massive model are typically 30% smaller, which partially compensates for the longer cooling time. Other complications, such as the presence of DB white dwarfs, and...
variations in the envelope mass, probably do not cause flux variations much larger than 15%. Figure 5 also shows that the main contribution to the integrated spectrum at 1500 Å comes from white dwarfs with $T_{\text{eff}} > 20,000$ K, so that the Lyman α satellite line at 1400 Å, characteristic of cooler DA white dwarfs, is barely detectable. The integrated energy, along the 0.6 $M_\odot$ track at 1500 Å is $\log E_{1500} = -4.23 L_\odot$ Gyr Å$^{-1}$. By comparison, Dorman et al. (1995) estimate $\log E_{1500} = -2.97 L_\odot$ Gyr Å$^{-1}$ for their lowest core mass (0.546 $M_\odot$) post-AGB track, and $\log E_{1500} = -1.6 L_\odot$ Gyr Å$^{-1}$ for typical EHB tracks. Since the use of a low core mass probably somewhat overestimates the true post-AGB contribution, we confirm the result of Magris & Bruzual (1993) that white dwarfs contribute a small, but non-negligible ($\sim 10\%$) fraction of the ultraviolet flux due to post-AGB stars. However, the EHB population will dominate the UV spectrum, even if only a small fraction ($\sim 5\%$) of core helium-burning stars follow EHB tracks.

4. NGC 6791

NGC 6791 is noteworthy for being among the oldest, most populous, and most metal-rich of the Galactic open clusters (Friel 1995). Liebert et al. (1994) discovered another noteworthy property of NGC 6791 with their spectroscopic detection in the cluster of an sdO star and four sdB stars with 24,000 K < $T_{\text{eff}}$ < 32,000 K. They speculated that these were the metal-rich analogue of the hot HB stars found in globular clusters, and that the existence of these stars in NGC 6791 was connected with the super-solar metallicity of the cluster. Recent stellar evolution models of high-metallicity, low-mass stars provide support for this idea, and have also been used to show that such metal-rich hot HB stars could be primarily responsible for the UV-upturn observed in the spectra of elliptical galaxies (Bressan et al. 1994, Dorman et al. 1995, Yi et al. 1997b).

Twenty stars are detected on the UIT image of NGC 6791 but twelve of these are certain non-members, either because they are identified with bright ($V < 13$) field stars, or because they are more than 10′ from the cluster center. The detected probable cluster members include the five hot subdwarfs discussed by Liebert et al. (B2, B3, B4, B5, and B6), plus the additional two sdB/O candidate stars, B9 and B10, reported by Kaluzny & Rucinski (1995). The star B1, suspected to be a cooler ($T_{\text{eff}} = 15,000$ K) member blue HB star by Green et al. (1998a), is detected on the UIT image at the three sigma level. The other two blue HB stars studied by Green et al., K1943 and K5695, are too cool to be detected with UIT. Neither of the cataclysmic variables, B7 and B8, reported by Kaluzny et al. (1997) are detected with UIT. Even during their outburst phase, these cataclysmic variables have redder optical colors than the sdB/O candidates, and probably remain below
the UIT detection limit of \(m_{162} \sim 16.1\). Table 5 presents the UIT photometry of the possible cluster stars, along with the visible photometry from Kaluzny & Rucinski (1995).

Figure 6 shows archival GHRS low-dispersion (G140L) spectra covering the wavelength region 1300 – 1600 Å of the sdO star B2 and the sdB star B4. Also shown are high-dispersion IUE spectra of the field sdO star Feige 67 (SWP 20488), and the field sdB star PG 0342+026 (SWP 27466), smoothed to the approximate GHRS resolution, and reddened to match the NGC 6791 reddening. From ultraviolet and optical spectrophotometry, Theissen et al. (1995) found \(T_{\text{eff}} = 25,000\) K, \(\log g = 5.25\) and \(E(B-V) = 0.10\), for PG 0342+026, while Saffer et al. (1994) found \(T_{\text{eff}} = 26,200\) K, \(\log g = 5.63\) from fitting the Balmer lines. The best-fit Kurucz model atmosphere (normalized to the V magnitude and reddened by \(E(B-V) = 0.17\)) to the GHRS spectrum of B4 has \(T_{\text{eff}} = 26,800\) K, \(\log g = 5.0\), and \([\text{Fe/H}] = 0.2\).

While a good fit to B4 can also be achieved using a solar metallicity model, Figure 6 shows that a low metallicity (\([\text{Fe/H}] = -0.5\)) model does not match the depressed continuum longward of 1500 Å, which is primarily due to the lines of Fe III and Fe IV (Brown et al. 1996).6 This result is of some importance because abundance depletions are known to exist in sdB stars, due to diffusion and other particle transport processes in the high-gravity atmosphere. For example, Liebert et al. (1994) found the sdB stars in NGC 6791 (including B4) to be helium-poor, as is typical of field sdB stars (Saffer et al. 1994), and Lamontagne et al. (1987) summarizes the evidence for depletions of carbon and silicon in the field sdB stars (also see Brown et al. 1996). Nevertheless, the carbon and silicon depletions are smaller for the sdB stars than for hotter (> 30,000 K) stars, and other major ultraviolet opacity sources such as iron are not depleted. Thus, our rough analysis of the GHRS spectrum of B4 suggests that ultraviolet population synthesis models which incorporate evolutionary tracks of metal-rich hot HB stars should also adopt stellar atmosphere models of an equal metallicity. A more detailed comparison of the GHRS spectrum of B4 with spectral synthesis models would be desirable to verify this point.

Liebert et al. (1994) did not derive atmospheric parameters for the sdO star B2, but showed that its optical spectrum is similar in appearance to the hot (\(T_{\text{eff}} \sim 60,000\) K) field sdO stars Feige 67 and Feige 110. Figure 6 shows that Feige 67 and B2 have a similar continuum slope in the 1300 – 1600 Å region, and many absorption lines are in common, although the spectra clearly differ in many details. Due to the large number of lines of ionized iron and nickel in the ultraviolet spectra of sdO stars, a quantitative

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6Note that the Kurucz models use a solar iron abundance of -4.37 dex from Anders & Grevesse (1989), whereas the current best estimate for the solar iron abundance is -4.50 dex (Grevesse et al. 1996).
analysis requires fully line-blanketed NLTE model atmospheres, which have only recently become available (e.g. Lanz et al. 1997, Haas et al. 1996). Becker & Butler (1995) derived \( T_{\text{eff}} = 70,000 \) K, \( \log g = 5.2 \) for Feige 67, and found it to have a low surface abundance of helium \( (\text{N(He/H)} = 0.05) \), but a high iron abundance \( ([\text{Fe/H}] = 1.0) \). We do not attempt to further estimate the atmospheric parameters of B2, but limit ourselves to the following remarks. First, the identification of B2 as an AGB-manqué star may be suspect, because the evolutionary tracks of AGB-manqué stars do not spend much time at such high effective temperatures \( (\sim 60,000 \) K). Second, despite the higher \( T_{\text{eff}} \) of the sdO stars in Figure 6, they have flatter continua than the two sdB stars, mostly likely due to the large number of Fe V lines in the 1300 – 1600 Å region (Becker & Butler 1995). Thus, accurate population synthesis of the UV-upturn in elliptical galaxies may need to include NLTE line-blanketed model atmospheres to properly model AGB-manqué stars. Unfortunately, the few field sdO stars which have had a detailed model atmosphere analysis of their ultraviolet spectra have shown a wide variety of strong elemental (including iron) under- and over-abundances (Lanz et al. 1997, Haas et al. 1996, Becker & Butler 1995), most likely due to the effects of radiative levitation and diffusion. The question of the appropriate model atmosphere to use for population synthesis of the ultraviolet spectra of metal-rich AGB-manqué stars remains a problematic one.

The UIT photometry is especially useful for estimating the luminosities of the sdB stars, since the bolometric correction at 1620 Å for sdB stars is relatively small. The effective temperature and luminosity of the sdB stars B3, B4, B5, B6, and B9 as derived from the UIT photometry is tabulated in columns 5 and 6 of Table 5. (No spectra exist for the star B9, but its ultraviolet and visible magnitudes are similar to those of the four spectroscopically identified sdB stars.) Temperatures are estimated by finding the Kurucz model with \( [\text{Fe/H}] = 0.2 \), and \( \log g = 5.0 \), which best matches the observed \( m_{162} \) – \( V \) color, for an assumed reddening of \( E(B-V) = 0.17 \). Luminosities are then derived from the \( m_{162} \) magnitude, using the (small) bolometric correction for the adopted Kurucz model. The values of \( T_{\text{eff}} \) derived from \( m_{162} \) – \( V \) are consistently about 1200 K hotter than those derived by Liebert et al. (1994) using (pure hydrogen) model fits to the Balmer lines.

Table 5 shows that the five sdB stars in NGC 6791 have a narrow luminosity range, \( 1.10 < \log L/L_\odot < 1.27 \). This luminosity range is consistent with that predicted for metal-rich hot HB stars by Dorman et al. (1993) and Yi et al. (1997a). For example, the hottest models of Yi et al. (with \( Z = 0.04 \) and a main-sequence helium abundance \( Y = 0.31 \)), have a luminosity range during core helium burning of \( 1.05 < \log L/L_\odot < 1.28 \). The observed \( T_{\text{eff}} \) range of the sdB stars is perhaps slightly higher than predicted, since the \( T_{\text{eff}} \) of the hottest HB models decreases slightly with increasing metallicity (Dorman et al. 1993). The hottest models of Yi et al. and Dorman et al. (with envelope masses less than
0.005 M⊙) with Z = 0.04 have T_{eff} \sim 23,000 K.

The narrow range of luminosities of the sdB stars in NGC 6791 rules out certain binary star mechanisms for their origin, such as the merger of helium white dwarfs (Iben 1990), since these predict a wide range of helium core masses, and hence luminosities. However, Green et al. (1998a) found that B1 and the other two blue HB stars in NGC 6791 are spectroscopic binaries. (The sdB stars are too faint for a radial velocity study, so their binary status is unknown.) The situation is reminiscent of that of the field sdB stars, which occupy a narrow region in the T_{eff} – log g diagram, consistent with single star evolution (Saffer et al. 1994), but for which there is increasing evidence for a large binary population (Allard et al. 1994, Theissen et al. 1995, Green et al. 1998b). One binary star mechanism consistent with a narrow range of gravity or luminosity is the scenario discussed by Mengel et al. (1976, also see Bailyn et al. 1992), in which an evolving red giant loses mass to a companion, so that it arrives on the horizontal branch with a small envelope mass. In effect, the mass transfer to the companion substitutes for the high mass-loss rate required for the production of sdB stars in single star evolution models. One difficulty with both the high mass-loss rate and mass-transfer scenarios is the amount of fine-tuning required (Liebert et al. 1994), since a red giant which loses too much mass never reaches the helium flash, and instead ends up as a helium white dwarf (but see D’Cruz et al. 1996). Note that the maximum envelope mass for which a star still follows AGB-manqué tracks increases with increasing metallicity (Yi et al. 1997a, Dorman et al. 1995), so that the binary star mechanism for the production of sdB stars might still show a metallicity dependence.

The brightest source in NGC 6791 at 1620 Å is B10, which has m_{162} = 13.60. Kaluzny & Rucinski (1995) report that B10 is a blend of two stars with ΔV \sim 2.0 mag and an angular separation of about 0.7″. The photometry in Table 5 is from the 2.1-m telescope observations of Kaluzny & Rucinski (1995), in which the photometry of the hot star is better isolated. Nevertheless, the hot star might still have a composite spectrum because its ultraviolet color (m_{162} – V = –2.68) is somewhat inconsistent with its relatively red B – V color (B – V = 0.014 ± 0.014). Green et al. (1998a) obtained three spectra of B10 in which the neighboring cool star apparently dominates the spectrum. They find a radial velocity consistent with cluster membership, and no evidence for velocity variations, although it is not clear whether these results also apply to the hot star. Minimum values of T_{eff} > 22,900 K and logL/L⊙ > 1.75 for B10 can be derived from the UIT photometry by neglecting any contribution to the V light from a possible red companion. B10 appears to be a good candidate for a AGB-manqué star.
5. NGC 188

Seven stars are detected on the UIT image of the old (∼ 6 Gyr) solar-metallicity open cluster NGC 188, but four of these are certain non-members (Table 6). The early photometry of Sandage (1962) included the hot star II-91 (V = 13.82, $B-V=-0.22$), but only recently has this star been shown to be a probable proper-motion cluster member (Dinescu et al. 1996), and to have an sdB spectrum (Green et al. 1998a). Green et al. also report that II-91 is a spectroscopic binary. As with the sdB stars in NGC 6791, the effective temperature and luminosity of II-91 can be estimated from its UIT magnitude and $m_{152} - V$ or $m_{162} - V$ color, for the adopted cluster distance (1700 pc) and reddening ($E(B-V)=0.12$). Use of either the $m_{162}$ or $m_{152}$ magnitude yields a temperature of about 30,000 K and luminosity of $\log L/L_\odot = 1.14$. Thus, the temperature and luminosity of II-91 falls into the same range found for the sdB stars in NGC 6791.

The brightest source in NGC 188 at 1520 Å is the star D702, from the catalog of Dinescu et al. (1996), who give $V = 13.70$ and $B-V = 0.26$ from their photographic photometry, and also assign a 80% probability of cluster membership on the basis of its proper motion. Dinescu et al. also remark, however, that D702 is part of a blended image, so that it has large proper motion errors, and possibly erroneous photometry. D702 is also E43 in the catalog of Caputo et al. (1990), who give $V = 14.04$ and $B-V = 0.28$ from their CCD photometry. Here we adopt the photometry ($V = 14.18$, $B-V = 0.26$) quoted by Green et al. (1998a). The ultraviolet photometry shows that D702 must have a composite spectrum, because its relatively red $B-V$ color is inconsistent with its blue ultraviolet colors ($m_{152} - V = -1.89$; $m_{152} - m_{162} = -0.11$). A minimum value of $T_{\text{eff}} = 15,000$ K can be derived for D702 from the observed $m_{152} - V$ color by neglecting any contribution of a red companion to the V magnitude; the $T_{\text{eff}}$ could be much higher, if the V magnitude includes significant contamination from the companion. One possible decomposition of D702 consistent with the visible and ultraviolet photometry is that it consists of a turnoff star with $V = 14.9$ and $B-V = 0.69$, and a hot companion with $V = 14.9$ and $B-V = -0.04$ and $T_{\text{eff}} = 15,000$ K. Alternatively, the hot companion could be similar to II-91 with $V = 16.2$ and $T_{\text{eff}} = 30,000$ K, in which case the primary would be a blue straggler with $V = 14.36$ and $B-V = 0.36$.

Unlike the case for M67, none of the blue stragglers in NGC 188 or NGC 6791 are detected with UIT (with the possible exception of D702), nor would any detections be expected. This is partly because these clusters are more distant and more reddened, and their UIT exposures shallower than that of M67, but also because these older clusters have a blue straggler population with redder $B-V$ colors.

A final UIT source, located 13′ from the cluster center, and designated here as UIT-1,
could not be identified with any sources in the NGC 188 star catalogs. However, it is located 1.4" from the source U1725_00042710 in the USNO-SIA.0 sky survey of Monet et al. (1996). In their photometric system defined by the IIIa-J and IIIa-F emulsions, U1725_00042710 has the very blue colors, \( r = 18.7 \) and \( b = 18.0 \). However, a 4000 – 5000 Å spectrum of this star obtained at Calar Alto in 1996 August (S. Moehler, personal communication) showed a very red continuum with no evidence of broad Balmer lines. Whether this discrepancy indicates an eclipsing binary, or is due to a misidentification is currently unknown. The star is robustly detected in both UIT filters, and the ultraviolet color \( m_{152} - m_{162} = -0.17 \) indicates a hot (> 20,000 K) spectrum.

The CMD of NGC 188 shown by Dinescu et al. (1995) has five red clump stars, so the two sdB candidates detected by UIT provide 28% of the HB population. The CMD of NGC 6791 given by Kaluzny & Rucinski (1995) shows about 23 red clump stars, so the eight hot stars detected by UIT, plus the two cooler blue HB stars discussed by Green et al. (1998a), form about 30% of the HB population. By comparison, Dorman et al. (1995) found that they could fit the ultraviolet spectra of even the strongest UV-upturn galaxies if only 25% of the core helium-burning stars followed EHB tracks, while Brown et al. (1997) needed an EHB fraction of at most 10% to model the HUT spectra of six ellipticals. Thus, the integrated spectra of NGC 6791 and NGC 188 would likely show a strong UV-upturn, although the present incompleteness of the cluster membership information prevents us from computing semi-empirical integrated spectra for the two clusters, as we did for M67 in Section 3.1.

The similarity of the EHB fraction for NGC 188 and NGC 6791 might suggest that the super-solar metallicity of NGC 6791 is not an essential ingredient in the origin of its hot subdwarf population. However, there are several reasons why this conclusion might be premature. First, high percentage of sdB stars in NGC 188 could simply be an artifact of small number statistics. Second, apart from NGC 188, no sdB stars have yet been found in any other open cluster with a metallicity less than or equal to solar. Finally, both sdB candidates in NGC 188 are in binary systems, and, as pointed out by Green et al. (1998a), NGC 188 is known to have a rich binary population, whereas NGC 6791 appears to have a relatively low binary fraction.

6. Summary

There are at least three ways in which Galactic open clusters are an inadequate model for understanding the stellar populations of old galaxies. First, the open clusters have experienced dynamical interactions which can alter the stellar population mix; for example,
by leading to evaporation of low-mass stars while concentrating the blue stragglers toward the cluster center. Second, the higher mean stellar density of open clusters might result in enhanced stellar interactions and possibly increased blue straggler or hot subdwarf formation. Finally, due to the relatively small population of open clusters, the rapid evolutionary phases may not be adequately sampled. For example, hot post-AGB stars are believed to be a significant (although not the dominant) contributor to the observed UV-upturn in elliptical galaxies, but consistent with their short ($\sim 10^5$ yr) lifetime, there are no post-AGB stars present in M67, NGC 188, or NGC 6791. And while hot subdwarfs have now been detected in NGC 188 and NGC 6791, their total number ($< 8$) remains uncomfortably low to draw any robust conclusions.

Keeping this limitations in mind, we summarize below the main results derived from the UIT observations of M67, NGC 188, and NGC 6791, and their implications for the study of the integrated ultraviolet spectra of old stellar populations.

1. The UIT image of M67 is dominated by the eleven detected blue stragglers; in particular, the blue straggler F81 contributes 90% of the integrated flux of M67 at 1520 Å. The ultraviolet flux of the two blue stragglers, F90 and F131, is significantly higher than that predicted on the basis of optical photometry, and probably indicates the presence of hot, subluminous companions. A semi-empirical calculation of the integrated ultraviolet spectrum of M67 shows that, even when neglecting the possibly anomalous star F81, the blue stragglers dominate at wavelengths shorter than $\sim 2600$ Å. As pointed out by Spinrad et al. (1997), neglect of blue stragglers in population synthesis model fits of the rest-frame near-ultraviolet spectra of a galaxy will result in an underestimate of the galaxy age.

2. Eight white dwarf candidates are identified in the UIT image of M67, including the core-helium white dwarf companion of the yellow giant S1040. Optical spectroscopy of two of these sources has been obtained by Fleming et al. (1997): G152 is a hot ($T_{\text{eff}} \sim 68,000$ K) DA white dwarf, and MMJ 5973 is cooler ($T_{\text{eff}} \sim 18,000$ K) DB white dwarf. The number of white dwarf candidates is in reasonable agreement with that expected from theoretical white dwarf cooling models and a cluster age of 4 Gyr. The integrated ultraviolet flux at 1500 Å along a white dwarf cooling model is $\log E_{1500} = -4.23 \, L_{\odot}^{\odot} \, \text{Gyr} \, \text{Å}^{-1}$, and the contribution of white dwarfs to the integrated spectra of old galaxies is roughly 10% of that expected from hot post-AGB stars.

3. Eight probable cluster members are detected on the UIT image of NGC 6791, including the five hot subdwarfs studied spectroscopically by Liebert et al. (1994), and the two additional sdB/O candidates, B9 and B10, reported by Kaluzny & Rucinski
Three probable cluster members are detected on the UIT image of NGC 188, including the sdB spectroscopic binary II-91. The star D702 in NGC 188 is probably a composite including a hot subdwarf, since it has a hot ultraviolet color ($m_{152} - m_{162} = -0.11$), but a relatively cool optical color ($B - V = 0.26$). The derived luminosity range, $1.10 < \log L/L_\odot < 1.27$, of the five sdB stars in NGC 6791, and II-91 in NGC 188, is consistent with that expected for metal-rich, hot HB stars. The fraction of hot HB stars in both clusters is about 30%, implying that the integrated spectra of both clusters should show a pronounced UV-upturn, as strong as that observed in any elliptical galaxy.

We thank the many people involved with the Astro-2 mission who made these observations possible. We thank P. Bergeron for his white dwarf atmosphere models, A. Milone for providing the latest status of the M67 radial velocity monitoring, and D. Dinescu for providing an electronic version of her NGC 188 catalog.
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Fig. 1.— A 19′ square section of the UIT image (left) of M67, along with a matching visible image (right) from the STScI Digitized Sky Survey. The blue stragglers are marked by squares, the white dwarf candidates by circles, and the yellow giant – white dwarf binary S1040 is marked with a triangle. The stellar centroid of M67 is marked with a plus sign on the UIT image.
Fig. 2.— The visible color-magnitude diagram of M67 from MMJ93. The bright non-members (mainly stars with $V < 15$) from the proper motion study of Girard et al. (1989) have been removed. Stars detected on the 1520 Å UIT image are circled. The probable non-member S1466 is shown in the blue straggler region as a circle without a central dot. The solid line shows a 4 Gyr solar-metallicity isochrone from Bertelli et al. (1994) with $m-M = 9.65$ and $E(B-V) = 0.025$. 
Fig. 3.— IUE spectra of the blue stragglers F280, F156, F153, and F190 (solid lines) are compared with Kurucz model spectra (dotted lines), normalized to the V magnitudes, reddened by $E(B-V) = 0.025$, and with $[\text{Fe/H}] = -0.1$, and $T_{\text{eff}}$ and $\log g$ derived from Strömgren photometry. No adjustment to the parameters were made to improve the fit. The filter response of the UIT B1 filter is indicated by a dot-dashed line on the spectrum of F190.
Fig. 4.— The integrated spectrum of M67 computed with Kurucz model atmospheres, using temperature and luminosities derived from the $V$ and $B-V$ colors of the proper-motion members. In the upper panel, the integrated M67 spectrum is broken into three components: (1) dashed line – the bright blue straggler F81, (2) dotted line – the remaining ten blue stragglers, and (3) solid line – all other stars in the cluster. In the lower panel, the lower solid line shows the integrated spectrum excluding all blue stragglers, and the dashed line shows the best-fit Bruzual & Charlot synthesis spectrum, which has an age of 4.5 Gyr. The upper solid lines show the integrated spectrum excluding only F81, and the dotted line shows the best-fit Bruzual & Charlot synthesis spectrum, which has an age of 2.5 Gyr.
Fig. 5.— (a) The ultraviolet spectrum of a 0.6 M\(_\odot\) (solid line) and 0.9 M\(_\odot\) (dotted line) white dwarf integrated over its cooling track. (b) the relative contribution per unit log T to the integrated white dwarf flux at 1500 Å for cooling white dwarfs of masses 0.6 M\(_\odot\) (solid line) and 0.9 M\(_\odot\) (dotted line).
Fig. 6.— GHRS low-resolution spectra of NGC 6791-B2 and NGC 6791-B4 are shown along with IUE spectra of the field sdO star Feige 67 (reddened by $E(B-V)=0.17$), and the field sdB star PG 0342+026 (reddened by $E(B-V)=0.06$). The dotted line in the NGC 6791-B4 panel shows a Kurucz model with $T_{\text{eff}}=26,800$ K, $\log g=5.0$, and $[\text{Fe/H}]=0.3$, while the dashed line shows a model with $T_{\text{eff}}=25,200$ K, $\log g=5.0$, and $[\text{Fe/H}]=-0.5$. The flux scale for the field stars Feige 67 and PG 0342+026 is divided by 1000.
### Table 1. Observed Clusters

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### Table 2. UIT Observing Log.

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<td>08 51 11.0</td>
<td>+11 47 14</td>
</tr>
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<td>632</td>
<td>00 48 41.6</td>
<td>+85 20 58</td>
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<td></td>
<td>B5</td>
<td>316</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 6791</td>
<td>B5</td>
<td>984</td>
<td>19 20 55.0</td>
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Table 3. M67 Blue Stragglers

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<th>$m_{152}$</th>
<th>$T_{eff}$</th>
<th>log $g$</th>
<th>$m_{152}$(pred)</th>
<th>Comment</th>
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<td>-0.09</td>
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<td>12750</td>
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<td>0.10</td>
<td>12.06</td>
<td>8600</td>
<td>3.89</td>
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<td>13.15</td>
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<td>13.04</td>
<td>Am</td>
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<td>0.17</td>
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<td>7620</td>
<td>4.00</td>
<td>14.90</td>
<td>P = 1003d</td>
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<td>14.16</td>
<td>P = 4.2d, δ Sct</td>
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<td>15.33</td>
<td>δ Sct</td>
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<td>0.34</td>
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<td>...</td>
<td>Nonmember?</td>
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<td>975</td>
<td>11.08</td>
<td>0.43</td>
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Table 4. M67 White Dwarf Candidates

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<th>$m_{152}$</th>
<th>d(')</th>
<th>Notes</th>
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<td>18.61</td>
<td>-0.11</td>
<td>13.92</td>
<td>1.7</td>
<td>DA1</td>
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<td>-0.10</td>
<td>15.61</td>
<td>6.7</td>
<td>DB</td>
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<td>S1040</td>
<td>11.52</td>
<td>0.82</td>
<td>15.82</td>
<td>1.0</td>
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<td>BATC 4672</td>
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<td>0.46</td>
<td>15.84</td>
<td>10.1</td>
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<tr>
<td>BATC 3009</td>
<td>17.02</td>
<td>0.24</td>
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<td>14.2</td>
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<td>MMJ 6061</td>
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<td>7.5</td>
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Table 5. UIT Photometry in NGC 6791

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<th>ID</th>
<th>V</th>
<th>B − V</th>
<th>( m_{162} )</th>
<th>( T_{\text{eff}} ) (K)</th>
<th>( \log L/L_\odot )</th>
<th>( T_{\text{eff}} ) (K)</th>
<th>Sp.T</th>
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<tbody>
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<td>16.97</td>
<td>0.07</td>
<td>16.20:</td>
<td>...</td>
<td>...</td>
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<tr>
<td>B2</td>
<td>17.43</td>
<td>−0.12</td>
<td>14.47</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>sdO</td>
</tr>
<tr>
<td>B3</td>
<td>17.77</td>
<td>−0.12</td>
<td>14.96</td>
<td>24,170</td>
<td>1.21</td>
<td>22,900</td>
<td>sdB</td>
</tr>
<tr>
<td>B4</td>
<td>17.87</td>
<td>−0.13</td>
<td>14.85</td>
<td>26,790</td>
<td>1.27</td>
<td>25,200</td>
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<td>−0.10</td>
<td>15.21</td>
<td>22,770</td>
<td>1.10</td>
<td>21,800</td>
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</tr>
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<td>15.07</td>
<td>25,290</td>
<td>1.17</td>
<td>23,800</td>
<td>sdB</td>
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<td>14.91</td>
<td>30,050</td>
<td>1.25</td>
<td>...</td>
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<tr>
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<td>&gt; 22,660</td>
<td>&gt; 1.74</td>
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\(^a\)Spectral type and \( T_{\text{eff}} \) from Liebert et al. (1994) or Green & Liebert (1998a)

Table 6. UIT Sources in the NGC 188 field

<table>
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<th>ID</th>
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<th>B − V</th>
<th>( m_{152} )</th>
<th>( m_{162} )</th>
<th>Comment</th>
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</thead>
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<tr>
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<td>9.96</td>
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<td>HD 4816</td>
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<td>0.20</td>
<td>12.45</td>
<td>11.65</td>
<td>A5V, nonmember</td>
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<td>Hipp 3354(^a)</td>
<td>9.58</td>
<td>0.50</td>
<td>16.13</td>
<td>...</td>
<td>F3/F5V, nonmember</td>
</tr>
<tr>
<td>Tyc 4619(^a)</td>
<td>11.28</td>
<td>0.08</td>
<td>15.13</td>
<td>14.38</td>
<td>nonmember</td>
</tr>
<tr>
<td>II-91</td>
<td>16.31</td>
<td>−0.17</td>
<td>12.55</td>
<td>12.78</td>
<td>sdB</td>
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<td>D-702</td>
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<td>0.26</td>
<td>12.29</td>
<td>12.40</td>
<td>Dinescu et al. (1996)</td>
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<tr>
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<td>...</td>
<td>13.95</td>
<td>14.12</td>
<td>USNO 1725-00042710?</td>
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\(^a\)Identification and BV photometry from the Hipparcos or Tycho catalogs (ESA 1997)

\(^b\)Located at 00\(^h\) 53\(^m\) 0.7 +85°25′34″