HOT SUBDWARF STARS AMONG THE OBJECTS REJECTED FROM THE PG CATALOG: A FIRST ASSESSMENT USING GALEX PHOTOMETRY

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ABSTRACT

The hot subdwarf (sd) stars in the Palomar Green (PG) catalog of ultraviolet excess (UVX) objects play a key role in investigations of the frequency and types of binary companions and the distribution of orbital periods. These are important for establishing whether and by which channels the sd stars arise from interactions in close binary systems. It has been suggested that the list of PG sd stars is biased by the exclusion of many stars in binaries, whose spectra show the Ca II K line in absorption. A total of 1125 objects that were photometrically selected as candidates were ultimately rejected from the final PG catalog using this K–line criterion. We study 88 of these “PG- Rejects” (PGRs), to assess whether there are significant numbers of unrecognized sd stars in binaries among the PGR objects. The presence of an sd should cause a large UVX, compared with the cool K–line star. We assemble GALEX, Johnson V, and Two Micron All Sky Survey photometry and compare the colors of these PGR objects with those of known sd stars, cool single stars, and hot+cool binaries. Sixteen PGRs were detected in both the far-ultraviolet (FUV) and near-ultraviolet GALEX passbands. Eleven of these, plus the 72 cases with only an upper limit in the FUV band, are interpreted as single cool stars, appropriately rejected by the PG spectroscopy. Of the remaining five cases, three are consistent with being sd stars paired with a cool main-sequence companion, while two may be single stars or composite systems of another type. We discuss the implications of these findings for the 1125 PGR objects as a whole. An enlarged study is desirable to increase confidence in these first results and to identify individual sd+cool binaries or other composites for follow-up study. The GALEX All-sky Imaging Survey data have sufficient sensitivity to carry out this larger study.

Key words: binaries: close – stars: horizontal-branch – subdwarfs – ultraviolet: stars

Online-only material: machine-readable and VO tables

1. INTRODUCTION

The subdwarf B (sdB) stars are the field analog of cluster stars lying on the Extended Horizontal Branch (EHB), with 18,000 K $\lesssim T_{\text{eff}} \lesssim$ 30,000 K and log $g \approx$ 5.5–6. Some subdwarf O (sdO) stars form an extension of the EHB to higher temperatures. We will refer to these two groups together simply as “hot subdwarf” (sd) stars. These stars may be an important source of ultraviolet (UV) light in early-type galaxies (O’Connell 1999; Brown et al. 2000; Han et al. 2007; Yi 2008), and it is important to understand their origins so that their contribution can be properly estimated.

The sd stars are core He-burning stars, with typical total mass $\sim 0.5 M_\odot$ but only very small H envelopes ($M_H \lesssim 10^{-2} M_\odot$) (Saffer et al. 1994). To become a sd, a low-mass star must lose its H envelope on its first ascent of the giant branch, within 0.4 mag of the tip (D’Cruz et al. 1996). Since all red giants do not end up on the EHB, some process must enhance the mass loss in stars that do become sd stars. Such a process could be the interaction of the proto-sd star with a close companion star, promoting mass loss either via Roche lobe overflow (RLOF) or a common envelope (CE). Such a model was first proposed by Mengel et al. (1976), and a much more detailed model has been put forward by Han et al. (2002, 2003), including a population synthesis study. In the Han et al. scenario, the RLOF channels often lead to a sd star paired with an A or early-F companion, the companion’s mass being increased by exchange from the proto-sd star. The CE channels usually result in a late-F, G or K dwarf companion (or a white dwarf (WD) companion, if the second star to evolve is the one that becomes the sd star at the present epoch). A binary merger channel leading to isolated sd stars also exists. Thus, an additional reason for determining the evolutionary pathways that lead to sd stars is that they may serve as a calibrating population, to enable the theory of binary mass loss/exchange to be applied more confidently in other contexts.

We have used the Two Micron All Sky Survey (2MASS) Point Source Catalog in combination with $B$, V photometry to study the near-infrared (NIR) and optical–NIR colors of a large sample of sd stars (Stark & Wade 2003; Stark et al. 2004). In a volume-limited sample, about 25% of these stars show an infrared excess, suggesting a composite spectral energy distribution. Spectroscopy of a subset of these is consistent with the companions being mostly late-F, G, and K dwarfs (Stark 2005; Stark & Wade 2006). Lisker et al. (2005) also have found late-F, G and K companions to sds, based on $B–J$ color and/or optical spectroscopy. These sd+G/K systems are in accord with one prediction of the binary origin scenario for sd stars. Where are the sd+A/F binaries that Han et al. (2003) also predict? Are the existing catalogs of identified sd stars missing a large number of sd stars in binary systems?

With about 900 sds, the magnitude-limited Palomar Green (PG) catalog of ultraviolet-excess (UVX) objects (Green et al. 1986) is the dominant contributor to the Kilkenny et al. (1988) catalog of sd stars. The PG sds are often the subject of detailed study, either individually or for statistical purposes. The PG

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4 We will use the term “G/K” to include late-F stars as well as G and K stars. We will use the term “A/F” to refer to A and early-F stars.
Candidate sample was constructed from a $U-B$ photographic survey. Candidates showing a Ca II K-line were culled from the final PG catalog, on the supposition that this line indicated the UVX arose in a relatively cool, metal-poor (Population II) star with reduced UV line blocking (a subdwarf F/G star: sdF/ G),\(^5\) which was not of interest in a survey for quasars and hot stars. Such K-line objects with a modest $U-B$ excess, however, would also describe how an unresolved binary composed of a hot sd star and a cool main-sequence (MS) star of type F should appear. A relatively bright F companion would contribute a K-line that is strong enough to be seen in the PG survey spectra (which are of modest signal-to-noise ratio), whereas a typical sd star would dominate over the optical spectrum and colors of an MS G or K companion. Thus, it is possible that bona fide sd+MS binaries, especially those with early-F companions but also late-F, G, or K companions in some cases, are missing from the final PG catalog, although they were selected as candidates in the PG survey. Han et al. (2003) noted this possible bias in the PG catalog as an obstacle to confirming their binary formation scenario for hot subdwarf stars, giving it the name "GK selection effect." (Because of their large Balmer jumps and their higher luminosities, A stars paired with sds would not likely have been selected in the initial PG survey for $U-B$ excess. On the other hand, an atypically low-luminosity sd star, paired with an MS G or K companion, might also have a detectable K-line in the PG survey spectra. As noted above, G/K companions are indeed found for many of the PG hot sd stars, based on NIR colors; thus, many sd+G/K systems are not subject to the "GK selection effect," and the term is to some degree a misnomer.)

It is desirable to have a catalog of sd stars that is truly representative of the space distribution of these objects. While the PG catalog, by its design, would not be sensitive to sd+A systems, the question has lingered among sd aficionados whether it is less complete than it could be with respect to sd+MS binaries where the MS star is of type F–G–K. Some brief quotations from recent conference papers illustrate the concern: (1) "the PG survey is biased against companions of G and K spectral type as any target with a spectrum showing Ca II H-lines [sic] was taken off the survey. This should be taken into account when looking at the companions of sdBs as most of the ones from the PG survey will be WDs instead of main sequence stars. This has important consequences when one intends to compare binary formation models with observations. It is difficult to assess how important this bias is" (Morales-Rueda et al. 2004, pp. 303–304); (2) "The PG catalogue is biased against targets that show a Ca II H-line [sic] (as these were taken out of the catalogue), and thus, against sdB binaries with main sequence companions" (Morales-Rueda et al. 2005, p. 333); and (3) "to avoid the uncertain biases of the Palomar Green and other surveys..." (Morales-Rueda et al. 2006 p. 187).

There are 1125 K-line stars rejected from the PG catalog, but retained in an unpublished list. If many or most of these are in fact found to be sd+MS binaries rather than sdF interlopers as Green et al. (1986) supposed, and they turn out to have short orbital periods, the Han et al. (2003) evolution scenario (which predicts them) may be strengthened and a missing class of sdBs found; at the same time there would be a large increase in the total numbers of sd stars from the PG survey. There would be important implications for the origins and also the space density, progenitors, and formation rates of such objects. If, however, the list of rejected PG candidates does not contain a large fraction of composite sd+MS binaries, it is still important to know what kinds of objects were excluded in the spectroscopic filtering of PG candidates, so that model sd populations can be "observed" in the same way the PG catalog was constructed. Which is the actual situation?

Optical studies (broadband photometry, moderate resolution spectroscopy) cannot easily distinguish an sdF star from an sdB+F composite. Metal-poor sdF stars lie above the Population I MS in the $U-B$, $B-V$ two-color diagram, owing to reduced line blocking, and thus may possibly be confused with composite sd+F systems, where the UV excess comes from the sd's contribution. Likewise, an sd star would dilute the metal lines in a Population I F star's spectrum while maintaining the strength of the hydrogen lines (since these appear in both spectra). Similar arguments apply to the confusion between sdG and sd+B+MS systems, if the sd star has a lower luminosity; such low-luminosity hot subdwarfs are predicted by Han et al. (2002, 2003) to come about via evolution from intermediate-mass stars which undergo RLOF mass loss. In the (rocket) UV, however, the distinction between sdF/sdG systems and sdB+MS composites is easy to make. With its UV sensitivity, positional accuracy and precision, and wide sky coverage, the GALEX satellite provides an opportunity to determine the nature of the stars rejected from the PG survey.

We note that the combination of UV photometry from space with ground-based work has led to the identification of sd+MS systems in the past. An early example is the case of HD 17576, studied with the S2/68 experiment about the TD-1 satellite (Darius & Whitelock 1978; Olsen 1980). Although this system is actually a visual binary with an angular separation of 1.8, the photometry was of the blended sdO+G pair. Another example is that of HD 15351, an sd+F5V system (Darius 1984). Had these been fainter systems, they might have been selected as candidates in the PG survey, then rejected owing to the presence of a K-line in the optical spectrum.

To summarize, the leading scenario for the formation of sdB stars predicts that many sd+MS systems should exist, constituting a large fraction of all sds, but sd+A/F systems are hard to identify from optical studies. The K-line stars rejected from the PG survey are the obvious and first place to look for some of these objects. A study using GALEX photometry for a subset of the PG rejects, combined with existing visible and NIR information on these stars, allows a clear sorting into mutually exclusive categories of metal-poor sdF/G stars and the more interesting sd+MS cases. If these objects are in fact sd+MS binaries, they will be strongly detected in both the near-ultraviolet (NUV) and far-ultraviolet (FUV) GALEX passbands. If they are actually sdF/G stars, as originally supposed by the compilers of the PG catalog, then they will be readily detected in the GALEX NUV band but not in the FUV band. Such a study addresses the origin of sd stars very directly. Further, if the yield of sd+MS binaries from these rejected PG candidates is high, it may help to create an enlarged and more representative catalog of such objects.

In this paper, we present a first assessment of the sd+MS binary content among the PG-rejected stars. In Section 2, we present the UV, visible, and NIR photometry for a sample of 88 objects. We also present results for a small number of known hot subdwarfs and other stars, and for field F stars, to facilitate interpretation of the results in terms of modeled colors. We interpret the results in Section 3, where we discuss five individual objects that can be interpreted as composite hot+cool

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\(^5\) Note that despite the name, subdwarf O/B stars are not necessarily from Population II. They merely appear below the main sequence in a color–magnitude diagram.
objects, but only three of which are likely consistent with being sd+MS binaries. We also discuss the implications for the entire group of 1125 PG-rejected stars as a whole, and we point out the desirability of an enlarged study, both to increase confidence in this preliminary results and to identify individual sd+MS or other composite objects for follow-up study. We summarize our findings in Section 4.

2. PHOTOMETRY OF PG-REJECTS

The essential idea underlying this study is to test, for each “PG-Reject” (PGR) object, whether the UV energy distribution indicates the presence of a hot stellar source accompanying the star that is responsible for the K line or the G band. If no hot subdwarf is present, the FUV flux will fall steeply toward shorter wavelength, and an UV-based color will be very “red.” In this case, the favored interpretation is that the PGR is a single, late-type MS star, possibly metal-poor owing to its method of selection. (We use solar-metallicity stars to model the composite systems, since we expect the supposed sd in such a system to have formed from an intermediate mass star.) We use the GALEX archive to collect the UV flux information. The GALEX spacecraft is currently performing a number of imaging surveys over most of the sky, using an “FUV” band (1350–1750 Å) and an “NUV” band (1750–2750 Å). See Martin et al. (2005) for a general description of GALEX and Morrissey et al. (2007) for details of the instrument calibration and data products. We also make use of NIR photometry to aid in classifying the cool stars in these systems (Section 2.3).

We use F and N in formulas as symbols for the AB magnitudes measured in the FUV and NUV bands, respectively. The $F-N$ color is the main quantity of interest, but interpretation is enhanced with the addition of the $N-V$ color, where $V$ is from the Johnson $UBV$ system. We employ synthetic photometry as a guide to the expected colors of single or blended objects.

From the 1125 PGRs, we selected 88 as the subject of this first assessment using GALEX. These 88 are the majority of the PGRs for which GALEX photometry was available in data release GR1. Table 1 presents the names of these objects along with the names of their 2MASS (Skrutskie et al. 2006) counterparts. The IAU-registered names are of the form PGR 12345678, where minutes of right ascension (R.A.) are truncated after the first decimal. The designation style is distinct from that used for PG objects, and is sufficiently detailed to give a unique name to each PGR object. These names are based on the coordinates of the objects as recovered from the USNO-A2 catalog (Monet et al. 1998), which is based on the Palomar Observatory Sky Survey (POSS) plates taken in the 1950s. (The original finding charts for the PGRs are enlarged prints from the POSS.) The 2MASS names are also in equatorial coordinate form, based on observations at a much more recent epoch. The 2MASS names suffice to allow precise and unambiguous identification of the star, thus we do not provide separate columns with R.A. and declination.

2.1. GALEX Photometry

UV photometry of the PGRs as obtained by GALEX is presented in Table 2, along with an estimate of the $V$ magnitude (see Section 2.2), color excess $E(B-V)$, and colors derived from the photometry. GALEX Release 2/3 was most recently interrogated in 2008 May, using the cross-correlation search page of the Multimission Archive at Space Telescope (MAST). The search radius used was 6 arcsec.

Table 1

| PGR Name     | 2MASS Designation | Notes          |
|--------------|-------------------|----------------|
| PGR J00021+0251 | 2MASS J00020846+0251282 |               |
| PGR J00036+0013 | 2MASS J00033771+0013085 |               |
| PGR J00040+0251 | 2MASS J00045226+0251534 |               |
| PGR J00075+0542 | 2MASS J00073216+0542017 |               |
| PGR J00373+0628 | 2MASS J00371927+0628165 |               |
| PGR J00388+1228 | 2MASS J00385212+1228112 |               |
| PGR J00410+0157 | 2MASS J00041039+0157473 |               |
| PGR J00418+0345 | 2MASS J00415150+0345285 |               |
| ...            | ...               | ...            |
| PGR J08431+4606 | 2MASS J08430627+4606269 | 1, 2          |

Notes.
1. Positional offset between USNO-A2 and 2MASS exceeds 1.5 (80th percentile of offset size).
2. There is a second 2MASS object within 10” of the USNO position.

Table 2 lists $F$ and its error in the AB system (Morrissey et al. 2007) or an upper limit on $F$. It also lists $N$ and its error. All the PGRs discussed here were detected by GALEX in the NUV band. Sixteen were also detected in the FUV band. In the case of multiple observations of a source by GALEX, we merged the data into single best estimates of $F$ and $N$ using weighted averages. The quoted errors refer to these best estimates. Magnitudes and colors are rounded to two decimal places, with a floor of 0.01 mag placed under the magnitude errors. When a source was not detected in the FUV band, we calculated the flux upper limit as three times $fuv_ncat_fluxerr$, which is the tabulated error in the net FUV flux, measured at the position of the NUV detection. This flux limit is translated to AB magnitude units; the $\sigma(F)$ error column in Table 2 is left blank for upper limits.

Of the 16 FUV detections, 12 were from short GALEX observations that were part of the All-sky Imaging Survey (AIS), one was from a longer Medium Imaging Survey (MIS) observation, two were from longer Guest Investigator (GI) observations, and one was from a very long observation in the direction of the Lockman hole (LOCK). FUV-band nondetections of the other 72 PGRs were generally for sources only observed in AIS fields, but in a few cases MIS, GI, LOCK, or Nearby Galaxy Atlas (NGA) observations were able to set more stringent upper limits on the FUV flux. Remarks in Table 2 indicate whether observations other than AIS were available.

2.2. Visual Photometry

Estimates of $V$ are generally only photographic, since the PGRs are generally too faint to have been the subject of individual photoelectric photometry and too bright to be observed without saturation by the Sloan Digital Sky Survey (SDSS) in the area of overlap. For the photographic $V$ estimates, we used the prescription from Salim & Gould (2003) to convert from the USNO-A2 red and blue magnitudes:

$$V = R_{USNO} + 0.32(B_{USNO} - R_{USNO}) + 0.23.$$  

These are indicated in Table 2 by the symbol “A” in the “Ref” column. The symbol “B” in this column indicates that $V$ is estimated from SDSS $g$ and $r$ magnitudes according to the
prescription of Jester et al. (2005):

\[ V = g - 0.58(g - r) - 0.01. \]

We only used SDSS data that were unsaturated in both \( g \) and \( r \). Symbol “\( C \)” indicates photometric \( UBV \) photometry carried out by R.F.G. during the original PG survey. Symbol “\( D \)” indicates photometric \( CCD \) photometry in \( V \) and \( I \) by the All Sky Automated Survey\(^7\) (ASAS; Pojmanski 2002). In total, 24 PGRs in Table 2 have photometric data. The tabulated \( V \) magnitudes are rounded to 0.1 mag. Based on the references cited or our own investigations, the uncertainties in the transformed or measured \( V \) magnitudes are \( \sigma(V) \approx 0.03 \) for objects observed photometrically by SDSS; \( \sigma(V) \approx 0.07 \) mag for R.F.G.; and \( \sigma(V) \approx 0.05 \) for ASAS. Photographic estimates have \( \sigma(V) \approx 0.25 \) mag.

Colors \( F-N \) and \( N-V \) are given in Table 2, along with a dereddened color \( (N - V)_0 \), where we have taken the color excess to be

\[ E(N - V) = 4.8 E(B - V) \]

as suggested by the \( GALEX \) exposure time calculator for a flat-spectrum source \( (f_\nu = \text{const}) \) and assuming that \( A(V) = 3.2 E(B - V) \). The interstellar reddening of \( F-N \) is small, \( E(F - N) \approx -0.1 E(B - V) \), and this correction has been neglected. The tabulated \( E(B - V) \) estimates are those returned from the MAST query, based on the Schlegel et al. (1998) reddening maps. They represent the full galactic extinction along the line of sight and should be appropriate for these PGR objects, which are generally expected to lie well above the Galactic plane. Color errors can be estimated by combining in quadrature the errors of the individual bands.

The \( V \) magnitude range is 11.2–16.3 (median near 14.7, although for PGRs with detected flux in the FUV band the median \( V \) is 13.3). The range of \( N \) magnitudes is 13.7 to 20.4. Detected \( F \) magnitudes range from 13.5 to 24.3; \emph{upper limits} on \( F \) range from 21.1 to 23.5. Color excess \( E(B - V) \) from Schlegel et al. (1998) ranges from 0.008 to 0.264 mag.

Figure 1 presents a \( (F - N), (N - V) \) two-color plot of the observations. Solid lines show model loci for solar and metal-poor synthetic spectra at \( \log g = 5.0 \) (Kurucz 1998), convolved with the \( GALEX \) FUV and NUV bandpasses and an approximate Johnson \( V \) bandpass. The \( GALEX \) post-launch response curves were obtained from the \( GALEX \) Guest Investigator website. The \( V \) bandpass was approximated as having a square response over 5150–5950 Å. The metal-poor locus is truncated at 8000 K, somewhat hotter than the Population II turnover. Dotted lines show the colors of composite models, combining an “sd” and a cool MS star (see Section 2.5).

\(^7\) http://www.astrouw.edu.pl/asas/

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Table 2

\( GALEX \) and \( V \)-band Photometry of PGR Objects

| Name              | \( F \) (mag) | \( \sigma(F) \)a | \( N \) (mag) | \( \sigma(N) \) | \( V \) (mag) | \( \sigma(V) \) | \( \text{Ref} \)b | \( (F - N) \) a | \( (N - V) \) | \( E(B - V) \) c | \( (N - V) \)  |
|-------------------|--------------|----------------|-------------|----------------|-------------|---------------|---------------|---------------|-------------|---------------|-------------|
| PGR J00021+0251   | 21.97        | ...            | 18.14       | 0.04           | 14.2        | A             | > 3.83        | 3.94          | 0.022       | 3.83         | ...          |
| PGR J00036+0013   | 21.73        | ...            | 19.03       | 0.08           | 14.8        | A             | > 2.70        | 4.23          | 0.030       | 4.09         | ...          |
| PGR J00040+0251   | 21.75        | ...            | 18.38       | 0.06           | 14.8        | A             | > 3.37        | 3.58          | 0.021       | 3.48         | ...          |
| PGR J00075+0542   | 13.47        | 0.01           | 13.72       | 0.01           | 13.0        | D             | −0.25         | 0.72          | 0.031       | 0.57         | hot          |
| PGR J00373+0628   | 22.03        | ...            | 18.92       | 0.05           | 15.1        | A             | > 3.11        | 3.82          | 0.022       | 3.71         | ...          |
| PGR J00388+1228   | 21.49        | ...            | 19.69       | 0.11           | 15.7        | A             | > 1.80        | 3.99          | 0.085       | 3.58         | ...          |
| PGR J00410+0157   | 21.75        | ...            | 19.02       | 0.08           | 14.7        | A             | > 2.73        | 4.32          | 0.018       | 4.23         | ...          |
| PGR J00418+0345   | 21.83        | ...            | 17.76       | 0.04           | 15.0        | A             | > 4.07        | 2.76          | 0.020       | 2.66         | ...          |
| PGR J00434+0704   | 21.58        | ...            | 17.85       | 0.03           | 14.6        | A             | > 3.73        | 3.25          | 0.038       | 3.07         | ...          |
| PGR J00446+1055   | 21.73        | ...            | 19.33       | 0.09           | 14.8        | A             | > 2.39        | 4.53          | 0.061       | 4.24         | ...          |

Notes.

a If no error is reported, then the \( F \) magnitude is an upper limit—in this case the \( (F - N) \) color is also a limit and is preceded by a “>” symbol.

b Reference for the adopted \( V \) magnitude (see Section 2.2).

c From Schlegel et al. (1998), as returned by the MAST query.

d Dereddened \( (N - V) \) color, using \( E(N - V) = 4.8 \times E(B - V) \).

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
ion MS star. The MS stars are represented by models having \([\text{Fe}/\text{H}] = 0.0\), \(\log g = 5.0\) and \(T_{\text{eff}}\) ranging from 4000 K to 9750 K. Absolute \(V\) magnitudes of the cool models are adopted MS values. The loci of composite models “loop back” to the left in the Figure, as the MS component’s \(N-V\) color index decreases with increasing \(T_{\text{eff}}\) at the same time that the MS component begins to dominate the combined light of the sd+MS system. For the adopted ZAHBB absolute magnitudes, this happens when the MS star has an F spectral type.

Open circles in Figure 1 show the colors of six stars classified by Green et al. (1986) as sd stars (Table 3). Estimated reddening is again from Schlegel et al. (1998) via MAST; here we have dereddened both \(F-N\) and \(N-V\) to facilitate comparison with the model loci. Note, however, that nonlinearity of the \textit{GALEX} photometry at these magnitudes may be important (Morrissey et al. 2007). From 2MASS photometry (see, e.g., Stark & Wade 2003), PG 0105+276 and TON 349 are regarded as photometrically “composite” while the remaining stars are regarded as single. Note that PG 0105+276 is a close visual pair with separation \(\approx 4\); we treat the \(F, N,\) and \(V\) measurements for this object as referring to the combined light from this pair.

2.3. Near-Infrared Photometry

NIR colors from 2MASS for all of the PGR stars in this study are shown in panel (a) of Figure 2. The MS locus of Bessell & Brett (1988) is also shown, converted to 2MASS colors using the prescription of Carpenter (2001). Panel (b) of Figure 2 shows the NIR colors of stars selected from the abundance compilation of Cayrel de Strobel et al. (2001), with \(V > 8.5, T_{\text{eff}} > 5000\) K, \(\log g > 3.5,\) and \(E(B-V) < 0.20\). We retained 27 Cayrel stars with \([\text{Fe}/\text{H}]\) between \(-0.3\) and \(+0.3\) (“solar”) and 27 stars with \([\text{Fe}/\text{H}]\) between \(-1.8\) and \(-1.2\) (“metal-poor”). These two groups are indistinguishable by location in the NIR two-color diagram; moreover, the NIR colors of PGR objects closely follow the same locus within the errors of measurement.

3. DISCUSSION

3.1. Overview

Inspection of Figure 1 shows that among the PGRs with detections in the FUV band, three lie near the hot end of the stellar locus (“hot” is noted in the Remarks column of Table 2 for these). Eleven lie near the loci shown for single stars at \(T_{\text{eff}} \sim 7000\) K, and two lie above and to the right of this position (“comp?” in Table 2). We summarize the \textit{GALEX}, visual, and NIR photometry for the five “hot” or “comp?” stars in Table 4.
3.2. Validity of GALEX Photometry

The three “hot” PGRs all have $F$ and $N$ magnitudes brighter than 15.4. The measured count rates in the GALEX detectors for these brightness levels may be subject to nonlinearities and other “saturation” or “fatigue” effects, characterized statistically by “roll-off curves” (see Morrissey et al. 2007, Figure 8). For the brightest of the three “hot” PGRs, PGR J00075+0542, MAST returned two distinct entries, with $F$ differing by 1.0 mag and $N$ differing by 0.3 mag in the opposite sense. Clearly, the vertical position of this object in Figure 1 is uncertain by ~0.5 mag, much larger than the formal error bars reported by MAST and tabulated here. Fortunately for this study, even an error of 0.5 mag in $F-N$ does not vitiate the conclusion as to the nature of this object, which clearly contains a hot star. (As we did for all other stars with multiple observations, we have averaged the magnitudes for PGR J00075+0542.)

Some of the scatter in $F-N$ (and $N-V$) for the known hot subdwarfs of Table 3 may also be due to the “nonlinearity” and other performance issues in GALEX photometry of bright point sources, as discussed above. In this paper, we take the reported photometry and errors at face value for discussion purposes, since it does not affect the bulk of our sample. Detailed modeling of bright composite objects should not rely too heavily on GALEX photometry, however.

3.3. Validity of Model Loci

Despite the uncertainty in positioning the known sds in Figure 1, it is evident that the synthetic photometry is in reasonable agreement with the observations of these hot stars. PG 0105+276 has been classified as sdB-O and sdB+K7 (visual double). PG 0212+148 has $T_{\text{eff}} \approx 25,000$ K. PG 2356+167 is classified sdB-O by Green et al. (1986) but “non-sd” by Saffer (1991) who notes the Ca II line in the spectrum; Saffer et al. (1997) estimate $T_{\text{eff}} = 23,800$ K, log g = 4.70, while Lynn et al. (2004) classify this object as B2V (evolved) and estimate $T_{\text{eff}} \approx 20,000$ K and log g = 4.3. The remaining stars are classified “sdO(B)” or “sdB” by Green et al. (1986).

To see how well the model loci of cooler single atmospheres match the GALEX observations, we collected photometry for a sample of 30 lightly reddened F star candidates ($E(B-V) < 0.04$), selected on the basis of their 2MASS colors. The intrinsic 2MASS colors of F0–F7 dwarfs were determined from stars classified on the MK system by Houk & Swift (1999). $V$ magnitudes for the sample discussed here were collected from ASAS and range between 11.2 and 12.5. The GALEX $N$ magnitudes range from 14.6 to 17.0 with nominal errors $\sigma(N) < 0.03$, while $F$ ranges from 18.9 to 23.2 with median error $\sigma(F) = 0.23$ (maximum $\sigma(F) = 0.52$). These stars are displayed in the $(F-N)$, $(N-V)_0$ two-color diagram in Figure 3, where typical 1σ error bars are the size of the plotting symbol or smaller. The model loci for single stars from Figure 1 are supplemented with additional loci.

3.4. Interpretation of the Two-Color Diagrams

Stark & Wade (2003) showed that sd stars with $J - K_s > 0.15$ form a distinct group which can be modeled as photometrically composite, with the cool companion star consistent with a dwarf of spectral type (SpT) F, G, or K. This result is confirmed by spectra of a subset of such systems (Stark 2005; Stark & Wade 2006). Of course, late-type stars that are single also have red $J - K_s$ colors, thus 2MASS data alone do not suffice to indicate whether a red object is a composite system with an sd and a cool star. It is the combination of GALEX and 2MASS data that allows a composite system to be recognized.

| Name          | $(F-N)$      | $(N-V)$      | $V$      | $(V-K_s)$  | $(J-H)$      | $(J-K_s)$ | Remarks |
|---------------|--------------|--------------|---------|------------|--------------|-----------|---------|
| PGR J00075+0542 | $-0.25 \pm 0.01$ | $+0.57 \pm 0.05$ | 13.0 $\pm 0.05$ | $+0.7 \pm 0.05$ | 0.15 $\pm 0.03$ | 0.18 $\pm 0.03$ | hot     |
| PGR J02040+1500 | $+3.16 \pm 0.47$ | $+0.07 \pm 0.26$ | 14.3 $\pm 0.25$ | $+1.9 \pm 0.25$ | 0.36 $\pm 0.04$ | 0.37 $\pm 0.04$ | comp?   |
| PGR J08401+4421 | $+3.77 \pm 0.23$ | $+3.57 \pm 0.25$ | 13.2 $\pm 0.25$ | $+1.6 \pm 0.25$ | 0.26 $\pm 0.04$ | 0.34 $\pm 0.04$ | comp?   |
| PGR J122451+2134 | $-0.11 \pm 0.01$ | $-0.09 \pm 0.25$ | 14.4 $\pm 0.25$ | $+2.0 \pm 0.25$ | 0.40 $\pm 0.03$ | 0.45 $\pm 0.03$ | hot     |
| PGR J23025+2602 | $-0.27 \pm 0.01$ | $-0.13 \pm 0.25$ | 15.1 $\pm 0.25$ | $+1.6 \pm 0.25$ | 0.21 $\pm 0.04$ | 0.27 $\pm 0.04$ | hot     |

Table 4: GALEX and 2MASS Photometry of Selected PGR Objects
Based on the GALEX photometry shown in Figure 1, there is a hot star present in each of the three PGRs labeled “hot” in Table 4. Considering also their NIR and \( V - K_s \) colors, they are all photometrically composite. If PGR J00075+0542 were a single star, its NIR colors would indicate an SpT near F2, but the cool star may be slightly later than this, given the dilution by the hot component. Dilution should be more evident in the \( V - K_s \) color index, and indeed it suggests an SpT near F0 under a single-star interpretation. By the same reasoning PGR J22451+2134 contains a cool star with SpT somewhat later than K0. PGR J23025+2602’s cool component must have SpT later than about F8. The GALEX photometry supports this ordering by color (given the uncertainty in the measured \( N \) magnitudes). In particular, PGR J00075+0542 has the earliest cool component based on visual and NIR colors, and has the reddest \( (N - V)_0 \) color among the three “hot” PGRs, a result entirely consistent with combining some hot ZAEHB dwarf with MS companions of different temperatures and luminosities in the three cases.

Schuster et al. (2004) independently studied PGR J00075+0542, their name for this object being BPS CS 31070−0080. They classified it as a “sub-luminous blue horizontal-branch star” (SL-BHB).

The \( (N - V)_0 \) indices are consistent with roughly equal absolute \( V \) magnitudes of the hot and cool components in each system. The interpretation that these three PGRs are sd+MS systems is perhaps not unique; however, the spectroscopic type of “sdG” assigned by Green et al. (1986) in each case supports the argument that the cool components are dwarfs rather than evolved stars. Pending further study to establish more accurate temperatures, gravities, and metallicities, we adopt the sd+MS picture as the best interpretation of the data.

Based on GALEX and \( V \) data alone, the two “comp?” stars in Table 4 might simply be F or G dwarfs with high activity levels: they lie within the extreme limits of the scattering of candidate F stars in Figure 3. On the other hand, a composite system is not ruled out in either case, although it would not be consistent with an MS star paired with a ZAEHB star. The NIR colors for PGR J08401+4421 correspond to a (single) dwarf of SpT near G0, while \( V - K_s \) suggests the SpT is near G5 and \( (N - V)_0 \) suggests \( T_{\text{eff}} \approx 6800 \) K. These are slightly inconsistent with the expectation for a hot+cool binary, in terms of the ordering of implied temperature by wavelength. Nevertheless, we conducted numerical experiments, adding a hot component to a Kurucz model with \( T_{\text{eff}} \approx 6800 \) K. The results suggest that such a hot component would need to be about 4 mag fainter than the cool star at \( V \); in order to reproduce the GALEX colors. In such a case, the hot star would be fainter than a typical sd, or the cool star would need to be brighter than an MS star. A WD is a possible hot component, although \( T_{\text{eff}} \geq 30,000 \) K is required if its radius is that of a \( \sim 0.6 M_\odot \) remnant. The cooling time of such hot WDs is short (Wood & Winnefeld 1989). A similar analysis applies for PGR J02040+1500, whose NIR and \( V - K_s \) colors suggest an SpT near G5 or G8, but whose \( (N - V)_0 \) index suggests a warmer star with \( T_{\text{eff}} \approx 6500 \) K (using the solar metallicity loci). The \( F-N \) and \( (N - V)_0 \) colors can be roughly matched by combining a \( T_{\text{eff}} \sim 6500 \) K star and a hot star that is \( \sim 4 \) mag fainter at \( V \). Improved visual photometry of these systems and accurate luminosity (and metallicity) classifications of their cool stars would help clarify the nature of the hot component.

The remaining eleven PGR objects that were detected in the FUV band lie close to the low-metallicity (Population II) MS locus in Figure 1, although with some scatter. This is consistent with the spectroscopic classification of “sdG” (with slight variants) given to these objects in the original PG survey. No indication of the presence of a hot stellar component is given by the GALEX photometry of these stars. The 72 upper limits for other PGRs shown in the Figure are sufficiently far removed from the locus of composite sd+MS loci that they likewise support the original sdG classifications of these objects as single stars. The NIR colors of the ensemble are consistent with a single-star interpretation, although it should be noted that the (Population I) SpTs indicated extend to K0 (\( T_{\text{eff}} \approx 5200 \) K), whereas the \( (N - V)_0 \) data suggest a lower bound of \( T_{\text{eff}} \gtrsim 5700 \) K (solar metallicity) or \( T_{\text{eff}} \gtrsim 5200 \) K (metal-poor).

Three stars, PGR J09281+6503, PGR J09395+6353, and PGR J10273+5758, for which \( UBV \) data are available, lie slightly above the Hyades MS in the \( (U-B) \), \( (B-V) \) two-color diagram with \( B-V \) in the range +0.50 to +0.63 and \( U-B \) in the range −0.124 to +0.07, just where reduced metal line blanketing would place an sdG star. The first of these stars was detected in the FUV band and lies very near the low-metallicity locus in Figure 1, near \( T_{\text{eff}} = 6000 \) K.

The occasional large offsets between USNO-A2 and 2MASS catalog positions, noted in Table 1, suggest that a few stars of high proper motion may be included in this sample of PGR objects. This view is confirmed by proper motion data for 61 stars of the sample, obtained from the Second U.S. Naval Observatory CCD Astrograph Catalog (UCAC2; Zacharias et al. 2004). Stars with large Table 1 offsets tend to have larger than average components of proper motion to the west, with amplitudes \( \mu_x \sim -25 \) mas yr\(^{-1} \) (corresponding to transverse velocities \( v_T \sim 100 \) km s\(^{-1} \) for distances \( d \sim 1000 \) pc). The direction of motion is opposite to that of the local standard of rest, and thus an interpretation in terms of thick disk or galactic halo rotation for this group of stars is tempting, although only weakly indicated.

3.5. Implications for the PGRs as a Class

The PG catalog is the single largest contributor to the list of spectroscopically identified sd stars (Kilkenny et al. 1988). Because it has reasonably well-defined magnitude and color limits, it is often used as the source of moderately bright sdB/sdO stars on which to do timeseries photometry, radial velocity orbital studies, etc. It also has been used for comparison against population synthesis models in studies of the origin of sds. Every catalog that strives to be complete will suffer from two types of errors, that of including objects that do not belong, and that of excluding objects that do belong. Concerns have been raised about the sd part of the PG catalog, in regard to this second type of error. For this reason we looked again at a sample of the stars rejected from the PG catalog.

Only three of the 88 PGR objects examined in this paper show a photometrically composite character, consistent with a sd+MS system. Two additional objects may be photometrically composite, although in these cases the data do not support an sd+MS interpretation. The great majority of the PGR stars appear to be consistent with single stars on the lower MS, perhaps chromospherically active, perhaps metal poor. Additional data, such as \( UBV \) colors for a few stars, support a metal-poor classification in those cases. As originally explained by Green et al. (1986), the PG survey photographic photometry was imprecise enough to allow the selection of numerous candidate UVX stars which were in fact not “hot” in the desired sense of meeting a color threshold of \( U - B < -0.46 \). The survey spectroscopy was used to weed these out, leaving only “hot”
objects in the final PG catalog. That the rejected candidates (PGRs) are almost entirely metal-weak sdF or sdG stars is entirely consistent with the nature of the PG survey; this is because the most likely contaminant, based on a measured $U-B$ color accidently crossing the color threshold for the survey, would be an F or G star with reduced metal line blanketing. That a few systems were rejected which do in fact contain a hot star (likely a subdwarf B or subdwarf O star) should not be especially surprising, if they were paired with cooler stars, depending on which star dominates the photographic region of each blended spectrum.

This paper exploits the wider wavelength range enabled by the GALEX and 2MASS projects to further characterize these systems. The quantitative result is that the fraction of such hot+cool systems among the PGR objects that comprise the present sample is small. An important question is whether this conclusion extends to the entire list of 1125 PGRs. The PGR list is not uniform with respect to $U-B$, nor with respect to limiting magnitude. This is because in some PG survey fields, classification spectroscopy was started before a final magnitude. This is because in some PG survey fields, classification spectroscopy was started before a final magnitude. Thus, some UV-excess candidates were rejected that were ultimately measured to be redder than the color cutoff of the PG survey. The present sample was drawn from a subset of PG survey fields that was observed early in the GALEX observational program, and it may draw more or less heavily from PG fields with an “extra” supply of PGRs. A wider study of the PGR list is therefore needed to confirm whether the present result, a $\sim 3/88$ rate of incidence of sd+MS systems, is representative of the PGR stars overall. Because of the nonuniformity of the PGR list, this would be not merely a refinement in the statistical precision of the present result, but a necessary confirmation or improvement. An additional benefit of a significantly larger sample would be to more firmly establish the ratio of F-type companions to G- or K-type companions in the sd+MS systems that are found. In the Han et al. (2002, 2003) binary population synthesis models, this ratio is strongly related to the critical mass-ratio parameter, which serves to separate stable and unstable mass transfer cases. Finally, it is important to identify those individual PGR stars from the entire list that are photometrically composite, for appropriate follow-up studies, including the measurement of orbital periods.

We can attempt a cautious extrapolation of the results of the present sample of 88 stars to the full 1125 PGR objects. At present, there is no evidence to suggest that the present sample of 88 differs systematically from the full sample, so such extrapolation may be a useful guide to what may be expected, bearing in mind the caveats stated above. Taking 3/88 as the rate of incidence of sd+MS systems in the full sample, we predict $\sim 38$ “new” sd systems will be found among the PGR stars. This is to be compared with the $\sim 40\%$ of sdB stars in the Kilkenny et al. (1988) catalogue that were found by Stark et al. (2004) to have a cool companion; applied to the $\sim 900$ PG stars in Kilkenny et al. (1988), this amounts to $\sim 360$ sd+MS stars. The “new” sd+MS systems that might result from a study of the full PGR list thus represent a $\sim 10\%$ increase in this roughly magnitude-limited sample. We would not be surprised to find that the rate of incidence of sd+MS systems in the full PGR list may be $\sim 2 \times$ smaller or larger than 3/88 (3.5%), either from small-number statistics or “bad luck” in drawing our small sample from a few fields. Thus, the addition of new hot sd+MS systems from among the PGR objects to those found in the PG catalog may plausibly be expected to be at the 5%–20% level, a consequence of the large numbers of PGR objects, coupled with a fairly small rate of incidence of sd+MS binaries in the PGR list.

4. SUMMARY

We have presented UV, visual, and NIR photometry of a sample of candidate objects rejected from the final PG catalog. We analyzed the photometry in color–color diagrams, aided by synthetic photometry of single and binary stars and by empirically determined colors of stars of various types. Sixteen of the 88 PGRs were detected in both the FUV and NUV channels of GALEX imaging. Of these, eleven are consistent with being single cool stars, as are the 72 cases where only an upper limit on the FUV flux was obtained. Thus, most of these PGRs have colors that are consistent with those of single cool stars, possibly metal-poor. This is consistent with the removal of these candidate UVX stars from the PG survey, based on spectroscopy. Of the remaining five stars, three exhibit composite colors consistent with a sd+MS interpretation, and the other two may be single or composite.

The GALEX AIS survey is sufficient to detect a hot component in a PGR, if one is present. Thus, it should be possible to extend the present study of 88 PGRs to include most of the 1125 objects in the full list, which is desirable given the nonuniform nature of the PGR list. Such an extension would establish definitively whether the PGR list does or does not harbor a large number of sd+MS binaries or other hot+cool systems, putting to rest the concern about the completeness of the PG catalog (within its declared magnitude and color limits) with regard to sds, hot WDs, etc. It would provide a more robust measurement of the frequency of occurrence of early-F companions, compared with late-F/G/K companions. Finally, it would identify those individual PGRs that are photometrically composite, to allow appropriate follow-up studies. We are currently undertaking this larger study.

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Facility: GALEX
REFERENCES

Allard, F., Wesemael, F., Fontaine, G., Bergeron, P., & Lamontagne, R. 1994, AJ, 107, 1565
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Brown, T. M., Bowers, C. W., Kimble, R. A., Sweigart, A. V., & Ferguson, H. C. 2000, ApJ, 532, 308
Caloi, V. 1972, A&A, 20, 357
Carpenter, J. M. 2001, AJ, 121, 2851
Cayrel de Strobel, G., Soubiran, C., & Ralite, N. 2001, A&A, 373, 159
Darius, J. 1984, Ap&SS, 99, 273
Darius, J., & Whitelock, P. A. 1978, Nature, 275, 428
D’Cruz, N. L., Dorman, B., Rood, R. T., & O’Connell, R. W. 1996, ApJ, 466, 359
Green, R. F., Schmidt, M., & Liebert, J. 1986, ApJS, 61, 305
Han, Z., Podsiadlowski, P., & Lynas-Gray, A. E. 2007, MNRAS, 380, 1098
Han, Z., Podsiadlowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, MNRAS, 341, 669
Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R., & Ivanova, N. 2002, MNRAS, 336, 449
Houk, N., & Swift, C. 1999, Michigan Catalogue of Two-dimensional Spectral Types for the HD Stars, Vol. 5 (Ann Arbor, MI: Univ. of Michigan)
Jester, S., et al. 2005, AJ, 130, 873
Kilkenny, D., Heber, U., & Drilling, J. S. 1988, South Afr. Astron. Obs. Circ., 12, 1
Kurucz, R. 1998, Solar Abundance Model Atmospheres for 0, 1, 2, 4, 8 km s$^{-1}$. (Cambridge, MA: SAO) (http://kurucz.harvard.edu/)
Lisker, T., Heber, U., Napiwotzki, R., Christlieb, N., Han, Z., Homeier, D., & Reimers, D. 2005, A&A, 430, 223
Lynn, B. B., Keenan, F. P., Dufin, P. L., Saffer, R. A., Rolleston, W. R. J., & Smoker, J. V. 2004, MNRAS, 349, 821
Martin, D. C., et al. 2005, ApJ, 619, L1
Mengel, J. G., Norris, J., & Gross, P. G. 1976, ApJ, 204, 488
Monet, D., et al. 1998, The USNO-A2.0 Catalogue (Washington, DC: US Naval Obs.) (http://www.nofs.navy.mil/data/fchpix/)
Morales-Rueda, L., Maxted, P. F. L., & Marsh, T. R. 2004, Ap&SS, 291, 299
Morales-Rueda, L., Maxted, P. F. L., Marsh, T. R., Kilkenny, D., & O’Donoghue, D. 2005, in ASP Conf. Ser. 334, 14th European Workshop on White Dwarfs, ed. D. Koester & S. Moehler (San Francisco, CA: ASP), 333
Morales-Rueda, L., Maxted, P. F. L., Marsh, T. R., Kilkenny, D., & O’Donoghue, D. 2006, Baltic Astronomy, 15, 187
Morrissey, P., et al. 2007, ApJS, 173, 682
O’Connell, R. W. 1999, ARA&A, 37, 603
Olsen, E. H. 1980, Inf. Bull. Var. Stars, 1770, 1
Pojmanski, G. 2002, Acta Astron., 52, 397
Saffer, R. A. 1991, PhD thesis, Univ. of Arizona
Saffer, R. A., Bergeron, P., Koester, D., & Liebert, J. 1994, ApJ, 432, 351
Saffer, R. A., Keenan, F. P., Hambly, N. C., Dufin, P. L., & Liebert, J. 1997, ApJ, 491, 172
Salim, S., & Gould, A. 2003, ApJ, 582, 1011
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schuster, W. J., Beers, T. C., Michel, R., Nissen, P. E., & García, G. 2004, A&A, 422, 527
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Stark, M. A. 2005, PhD thesis, The Pennsylvania State University
Stark, M. A., & Wade, R. A. 2003, AJ, 126, 1455
Stark, M. A., & Wade, R. A. 2006, Balt. Astron., 15, 175
Stark, M. A., Wade, R. A., & Berrian, G. B. 2004, Ap&SS, 291, 333
Wesemael, F., Fontaine, G., Bergeron, P., Lamontagne, R., & Green, R. F. 1992, AJ, 104, 203
Wood, M. A., & Winget, D. E. 1989, in Lecture Notes in Physics 328, IAU Colloq. 114: White Dwarfs, ed. G. Wegner (Berlin: Springer), 282
Yi, S. K. 2008, in ASP Conf. Ser. 392, Hot Subdwarf Stars and Related Objects, ed. U. Heber, C. S. Jeffery, & R. Napiwotzki (San Francisco, CA: ASP), 3
Zacharias, N., Urban, S. E., Zacharias, M. I., Wycoff, G. L., Hall, D. M., Monet, D. G., & Rafferty, T. J. 2004, AJ, 127, 3043