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THE NATURE OF LATE-TYPE COMPANIONS IN HOT SUBDWARF COMPOSITE-SPECTRUM BINARIES

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Abstract. We present the results of a study of late-type companions in hot subdwarf composite spectrum binaries. The exact nature of these late-type companions has been disputed in the literature – some argue that they are main-sequence stars, and others have claimed they are subgiants. To determine the properties of the late-type companions, we first conducted a survey utilizing the Two Micron All Sky Survey (2MASS) All-Sky Data Release Catalog to identify composite-colored binaries in the *Catalogue of Spectroscopically Identified Hot Subdwarfs* (Kilkenny et al. 1988, 1992). We then conducted a spectroscopic study of a sub-sample of the 2MASS composite-colored hot subdwarfs. The sample consists of photometrically and spectroscopically single and composite hot subdwarfs (14 single and 51 composite). We also obtained spectra of 59 single late-type stars with Hipparcos parallaxes for calibration. We used measured equivalent width (EW) indices from the composite systems to estimate the temperature and gravity of the late-type star, taking into account the dilution of its spectral features by light from the hot subdwarf. Results from combining the spectroscopic data with model energy distributions indicate that the late-type companions in composite-spectrum systems are best described by main-sequence companions overall.

Key words: binaries: spectroscopic – stars: horizontal–branch

1. DEFINING THE SAMPLE

For this investigation we studied hot subdwarf stars listed in the *Catalogue of Spectroscopically Identified Hot Subdwarfs* (Kilkenny, Heber & Drilling 1988, KHD) as updated and expanded in an electronic version by D. Kilkenny in 1992. While the KHD catalog contains all varieties of hot subdwarfs, we primarily focused on the more numerous sdB stars. The sdB are understood to be relatively homogeneous and probably have a common evolution history from the zero-age extended horizontal branch (ZAEHB), while sdO stars likely follow multiple evolutionary pathways and might be expected to be less homogeneous and to have less simply explained properties.

To make a comparison of the KHD data with existing databases (such as 2MASS) or to obtain new observations of the correct star, accurate coordinates on

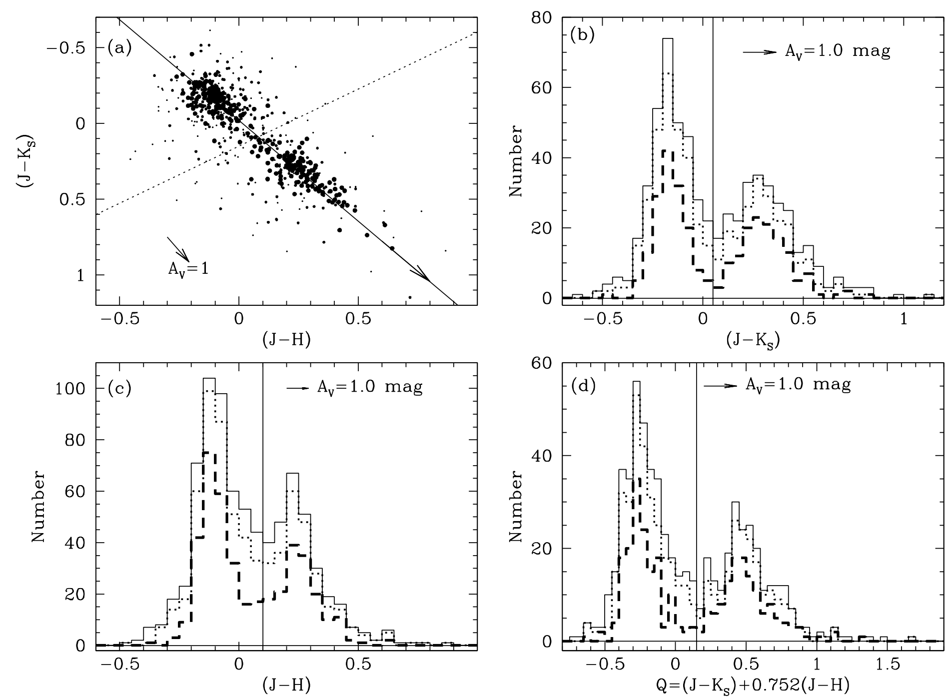

Fig. 1. Panel a. Two color plot for 2MASS colors of sdBs only with a linear fit to the points shown as the solid line, the parameter Q increases along this line as indicated. The dashed line is mathematically perpendicular to the linear fit line, and demonstrates a contour of constant Q (the two lines cross at $Q = +0.15$). All other panels contain histograms (bin sizes 0.05) of 2MASS color indices: $J-K_S$ (panel b), $J-H$ (panel c) and Q (panel d). In the three histograms (panels b–d), the solid line is for all sdB, the dotted line is for sdB with both $\sigma(J-K_S)$ and $\sigma(J-H) < 0.2$ the dashed line is for sdB with both $\sigma(J-K_S)$ and $\sigma(J-H) < 0.1$. Single sdBs fall in the left peak ($Q < 0.15$), composites fall in the right peak ($Q \geq 0.15$). The effect of 1 mag of extinction ($A_V = 1$) is indicated.

a consistent system are required. For each entry the object's position was verified by referring whenever possible to original published finding charts or by contacting knowledgeable observers, then locating the object on a chart prepared from the USNO A2.0 Catalog (Monet 1998, see also Stark & Wade 2003).

2. 2MASS RESULTS

We collected readily available visible and near-IR flux measurements of hot subdwarfs from the 2MASS All-Sky Data Release (ASDR) Catalog and identified those whose colors indicate the presence of a late type companion (for more information see Stark & Wade 2003; Stark et al. 2005). We thus determined the fraction of hot subdwarfs that exist in composite spectrum binaries (~40% of sdBs from KHD are composite in a magnitude limited sample). We defined an approximately volume limited sample of hot subdwarfs from KHD for statistical purposes (see Stark & Wade 2003; Stark et al. 2005), and found that ∼25% of sdBs are composite in a volume limited sample (VLS).

We defined the color parameter $Q = 0.752(J-H) + (J-K_S)$, which gives the clearest separation between composite and single hot subdwarfs based on 2MASS photometry alone. We compared the distributions in J–K_S, J–H and Q, and found them all to show a bimodally distributed population (Figure 1). In a histogram of the IR color indices $J-K_S$ and Q, the two peaks of the bimodal distribution can be understood as single stars (blue peak at $J-K_S = -0.170$, $Q \approx -0.275$) and composite systems (red peak at $J-K_S = +0.289$, $Q \approx +0.500$). This bimodal distribution is also present in the approximately VLS, again with the two peaks at $J-K_S = -0.167$ and $+0.248$ and $Q \approx -0.275$ and $+0.475$.

There are no (or very few) F or dM companions of the hot subdwarfs in the KHD catalog. This is evident from the bimodal distribution in 2MASS colors (Q, $J-K_S$ and $J-H$). Were there a large population of F or dM companions, their composite colors would have filled in the gap between the two bimodal peaks. However, the distribution in 2MASS colors can be described by only a very small (or no) spread in the colors of the late-type companions. In the case of F-type and earlier companions, should they actually exist, it is likely that most of them were never identified as containing a hot subdwarf. The F-type star would dominate the light at visual wavelengths, and the combined light would look spectroscopically like a metal-poor Population II star (the metal lines of the Population I star being diluted by the hot subdwarf so they look like a metal-deficient star). So, it is understandable that there are very few of these objects in the current KHD catalog. The dM stars on the other hand, have no obvious reason to be selected against in surveys that have identified hot subdwarfs. The dM is significantly fainter than the hot subdwarf, so that it should be basically undiscernible in the visible (both photometrically and spectroscopically). So, the fact that there are no (or very few) dM companions in the KHD sample represents a true trend in the hot subdwarf population (as opposed to a possible selection bias as in the case of the F-type and earlier stars).

The observed distribution of hot subdwarfs in 2MASS colors can be reproduced equally well by either assuming main-sequence companions with M_V(sdB) $\approx$ 4.5–5.0 mag, or by assuming subgiant companions with more luminous sdB stars (M_V(sdB) $\approx$ 2.5–3.0 mag) – photometric data alone cannot distinguish between these two possibilities.

3. SPECTROSCOPY OF COMPOSITE HOT SUBDWARFS

Spectroscopy of a sub-sample of the 2MASS composite-colored hot subdwarfs was obtained to break the degeneracy between main-sequence and subgiant companions present in the 2MASS and visual photometry alone. Observations were made primarily at the Kitt Peak National Observatory (KPNO) 2.1 m telescope using the GoldCam spectrograph, but some additional observations came from the McDonald Observatory 2.7 m telescope with LCS. Both sets of observations cover roughly 4500–9000 Å with ∼ 3.3 Å resolution (∼ 1.3 Å/pix) using two spectrograph settings. This wavelength region covers Hβ, Mg I b, He I 5875 Å, Na I D, Hα, He I 6678 Å and the Ca II IR Triplet (CaT). The sample of observed stars consists of photometrically and spectroscopically single and composite hot subdwarfs (14 single and 51 composite). We also obtained spectra of 59 single late-type stars from

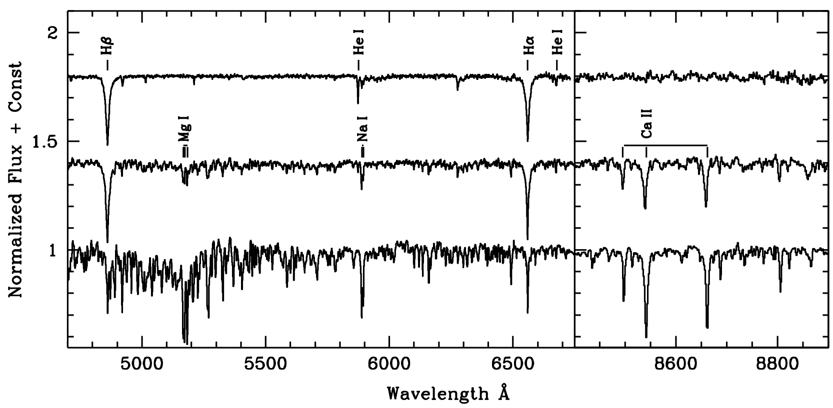

Fig. 2. Normalized spectra for a "typical" single hot subdwarf (top, LS IV+00°21), a composite hot subdwarf (middle, PB 6107), and a single HIP standard star (bottom, HIP 13081). Left panel shows the region from Hβ to Hα, right panel shows the CaT. Prominent spectral features are labelled.

both the main sequence and subgiant branch with Hipparcos (HIP) parallaxes for calibration. Example spectra from KPNO GoldCam (of a single, composite, and standard star) are shown in Figure 2. Our analysis focused on Mg I b, Na I D and CaT equivalent widths (EWs). Each of these lines has a very different behavior with $T_{\rm eff}$ and $\log g$, so they are useful for constraining the dilution by the hot subdwarf, as well as $T_{\rm eff}$ and M_V of the late-type companion, thus breaking the main sequence-subgiant degeneracy present in the 2MASS and visual photometry alone.

The observations (2MASS and visual photometry combined with EWs) for each composite hot subdwarf were compared with diluted models based on HIP standard star observations, models of ZAEHB stars (Caloi 1972), terminal-age EHB (TAEHB) stars (Dorman et al. 1993), and Kurucz (1998) spectral energy distributions, in order to determine the combination of sdB+late-type star that best explained all observations. In most cases the actual fit was driven primarily by the measured EWs, and secondarily by $J-K_S$ color (this agrees with the previous determination that photometry alone cannot distinguish between main-sequence and subgiant companions in these cases). With a few exceptions, it was found that the late-type companions in composite-spectrum systems are best identified as main sequence. The majority of the well constrained main-sequence companions have $0.5 \lesssim (B-V)_{\rm comp} \lesssim 1.1$ (spectral types $\sim$F6–K5, see Figure 3). The spectra and identifications of four composite subdwarfs are compared in Figures 4 and 5.

There are some interesting objects identified through our spectroscopy. These include:

• Two new emission line objects, LS IV$-$08°03 (possible X-ray binary) and PB 5333 (NLTE emission in the core of Hα). One possible new NLTE core emission object, TON 264.

• Nine objects that are best fit with subgiant companions (assuming ZAEHB or TAEHB hot subdwarfs), with an additional six best fit with subgiants assuming

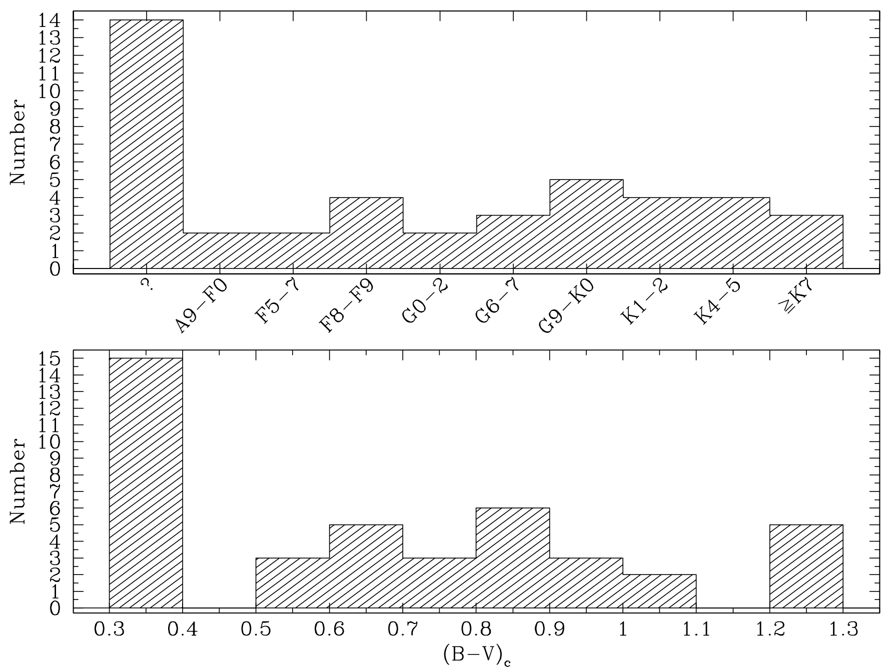

Fig. 3. Histogram showing the distribution of late-type companions in $B-V$ (bottom) and approximate Spectral Type (top). Objects in the last bins on either end of the histograms are upper or lower limits and either (1) have problems with their fits or (2) belong outside the range of parameters examined (see discussion at the end of §3). PG 0232+095 and those stars fitted with subgiant companions (assuming ZAEHB hot subdwarfs) have been excluded from this plot.

TAEHB hot subdwarfs. PG 0232+095's late-type companion seems to show molecular features indicative of a giant star (e.g., possible CN-red molecular bands), but the CaT appears too weak for a giant star – this object requires further study.

- A possible *resolved* visual double sdB+sdB (or sdB+HBB), HZ 18 (Figure 6), which may also contain an inner short-period binary (based on the velocity difference between the spectra for the two stars).

There were 18 cases in which the late-type companion was poorly fitted by our models (namely the best-fit parameters fell right at or near the edge of our model grid). The EWs in some of these objects may be erroneous due to an interstellar contribution. Additional refinement of the models, extension of the models to include a larger temperature range in both the late-type stars (by obtaining more observations of standards) and the hot subdwarfs (more models over a larger temperature range), or adjustments to correct for interstellar contributions, are needed to accurately fit these objects.

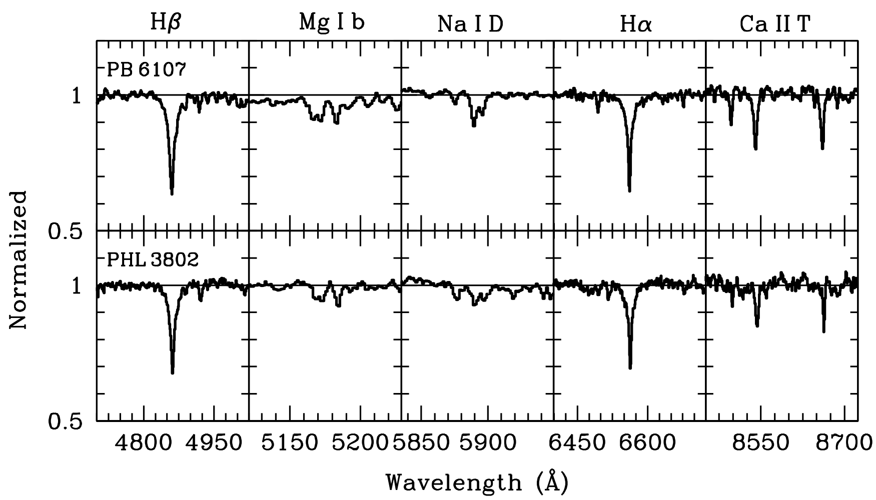

Fig. 4. Comparison of the major spectral features in the spectra of PB 6107 and PHL 3802. Panels from left to right show: Hβ, Mg I b, Na I D, Hα and CaT. These two stars were both fit with similar hot subdwarfs ($B-V = -0.246$ & -0.233 and $M_V = 4.43$ & 4.22 for PB 6107 and PHL 3802 respectively) and companions (G9V–K0V), so their spectra look similar. (Continuum fits shown were *not* used for the calculation of EWs.)

4. LIMITATIONS AND DIRECTIONS FOR FUTURE WORK

Our modeling procedure is limited in the range of both hot subdwarf and late-type stars included. These models could be greatly improved by including a greater range in temperatures for both the companion and particularly for the hot subdwarf. Specifically we have trouble identifying and coping with the hottest sdBs and the sdOs. We are also using the assumption that the hot member is in fact a true sdB-type star; if it is in fact a HBB or post-EHB star, then the modeling breaks down, giving bogus fits. Additional information to help constrain the properties of hot subdwarf would be of value (including whether it is sdB, sdO, post-EHB, or HBB). This additional information could include UV observations or spectra with coverage farther to the blue. Also, including additional late-type spectral features from our spectra would help better constrain the fits.

Future work related to, or stemming from, this project includes:

1. Classification of more composite hot subdwarfs.
2. Long-term RV studies of composite spectrum systems to determine periods (or at least set lower limits on the periods).
3. Follow-up observations of "unusual" objects identified, including (for example): PG 0232+095, TON 264, HZ 18 and the emission-line objects.
4. Further observations of the resolved visual doubles, including proper motions, and better classifications of the companions (particularly HZ 18, which may be a resolved sdB+sdB or sdB+HBB system).

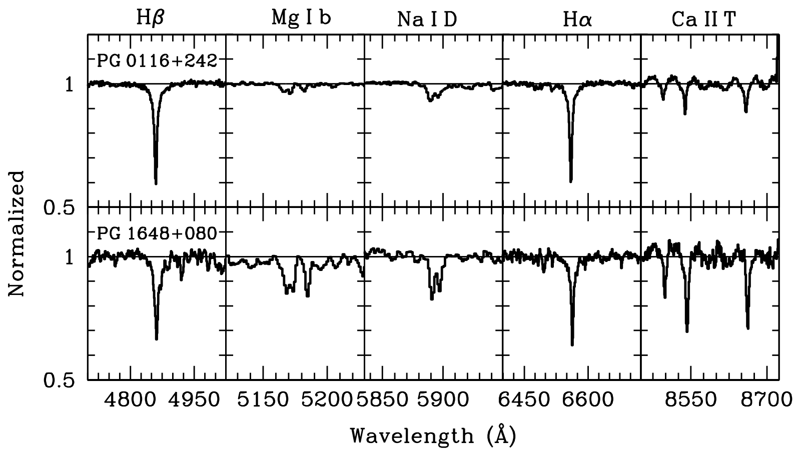

Fig. 5. Comparison of the major spectral features in the spectra of PG 0116+242 and PG 1648+080. Panels from left to right show: Hβ, Mg I b, Na I D, Hα and CaT. These two stars were fit with similar companions (G0 IV) but different hot subdwarfs (PG 1648+080 was fit with a hotter, fainter hot subdwarf, while PG 0116+242 was fit with a cooler, brighter hot subdwarf). In PG 1648+080, the late-type companion dominates over the hot subdwarf so its lines appear much stronger in the combined spectra, while in PG 0116+242, the brighter hot subdwarf washes out the features from the late-type star making them appear much weaker. (Continuum fits shown were *not* used for the calculation of EWs.)

5. IMPLICATIONS

Han et al. (2002, 2003) predict that for companions that are later than $\sim$G, all companions in short-period systems are main-sequence stars (in post-CE binaries) and all companions in long-period systems ($P > 40$ days) are subgiant or giant stars (in post-Roche lobe overflow binaries). RV studies of composite spectrum hot subdwarfs with FGK-type companions (i.e., Orosz et al. 1997; Maxted et al. 2001; Saffer et al. 2001), have found that the orbital periods must be long, many months to years or more. In the Han et al. scenario this would imply that they contain subgiant or giant companions. Han et al., however, assume that hot subdwarfs with subgiant and giant companions, i.e., these same long-period systems, were excluded from surveys for hot subdwarfs. Indeed, in our study, the majority of composite companions are consistent with main-sequence stars (although we have identified some subgiant companions, so this exclusion is not complete).

If the GK-type companions are main-sequence stars, why do they seem to be in long-period binaries? At face value, there is something incorrect or incomplete in the Han et al. binary formation scenario or its interpretation as applied to existing samples of hot subdwarfs. It may be that aspects of the Han et al. study (binary evolution model, or mapping onto observables) are at the heart of the matter; or perhaps the apparent contradictions can be resolved via discovering some subtlety of different sample selection for the RV studies reported so far and our present spectroscopic analysis. (The latter possibility can be assessed, for example, by an RV study of the composite binaries in our study.)

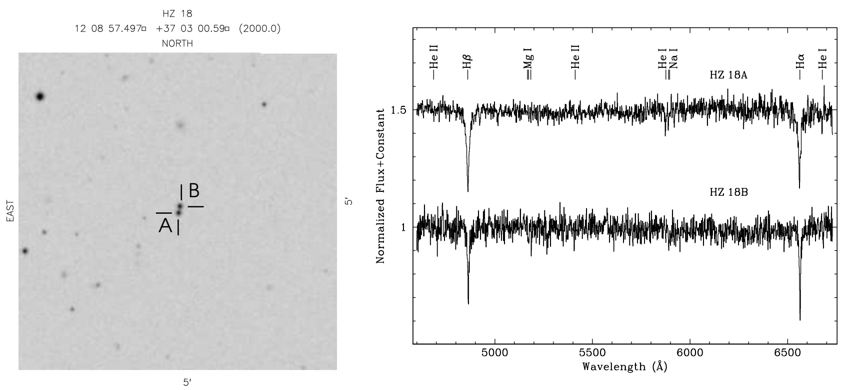

Fig. 6. Finding chart and spectra for the two components of HZ 18 (=A).

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