Single and Composite Hot Subdwarf Stars in the Light of 2MASS Photometry

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ABSTRACT

Utilizing the Two Micron All Sky Survey (2MASS) All-Sky Data Release Catalog, we have retrieved near-IR magnitudes for just over 800 hot subdwarfs (sdO and sdB stars) drawn from the *Catalogue of Spectroscopically Identified Hot Subdwarfs* (Kilkenny, Heber, & Drilling 1988, 1992). This sample size greatly exceeds previous studies of hot subdwarfs. Examining 2MASS photometry alone or in combination with visual photometry (Johnson *BV* or Strömgren *uvby*) available in the literature, we show that it is possible to identify hot subdwarf stars that exhibit atypically red IR colors that can be attributed to the presence of an unresolved late type companion. Utilizing this large sample, we attempt for the first time to define an approximately volume limited sample of hot subdwarfs. We discuss the considerations, biases, and difficulties in defining such a sample.

We find that, of the hot subdwarfs in Kilkenny et al., about 40% in a magnitude limited sample have colors that are consistent with the presence of an unresolved late type companion. Binary stars are over-represented in a magnitude limited sample. In an approximately volume limited sample the fraction of composite-color binaries is about 30%.

I. THE SAMPLE AND DATA COLLECTION

We studied hot subdwarf stars listed in the *Catalogue of Spectroscopically Identified Hot Subdwarfs* (Kilkenny et al. 1988) as updated and expanded in an electronic version by Kilkenny, c. 1992 (hereafter KHD). This catalog contains 1527 entries ($\sim$2/3 of which are from the PG survey, Green et al., 1986).

Coordinates for KHD objects were updated and improved (to $\sim 2''$ or better) by comparing original finding charts with the USNO A2.0 Catalog (Monet et al. 1996); or with Tycho-2 (Høg et al. 2000) or Hipparcos (Perryman et al. 1997) for the brightest objects. For this study we had improved coordinates for 1459 objects (excluding 11 duplicates), while 57 objects remained unrecovered and are not included.

Two sub-samples were created based on the first KHD classification:

1. "*sdB*": sdB, sdB–O, & sd
2. "*sdO*": sdO, sdO(A), sdO(B), sdO(C), sdO(D), & sdOB

We made no further attempt to improve upon, regularize, or rationalize the various classifications summarized in KHD.

Infrared photometry (J, H, and K_S) from the 2MASS All-Sky Data Release was collected by searching within $\sim 10''$ of the the updated coordinates. 2MASS counterparts were found for 1220 KHD objects (70% of which are also in PG):

2MASS Detection	*sdB*	*sdO*	non-subdwarfs
Both J & K_S	602	212	42
J only	258	103	3

Errors are $\sigma(J-K_S) \lesssim 0.2$ mag for $\sim$80% of the objects; with $\langle\sigma(J-K_S)\rangle \approx 0.12$ mag.

Visual photometry (*BV* or *uvby*) was taken from KHD, or a few other post-1992 publications (typical errors are $\lesssim$0.02 mag). Visual photometry for hot subdwarfs with *both* J and K_S detections was available for:

Photometry	*sdB*	*sdO*
BV or *uvby*	384	155
V only	9	4

II. IDENTIFYING COMPOSITE SYSTEMS

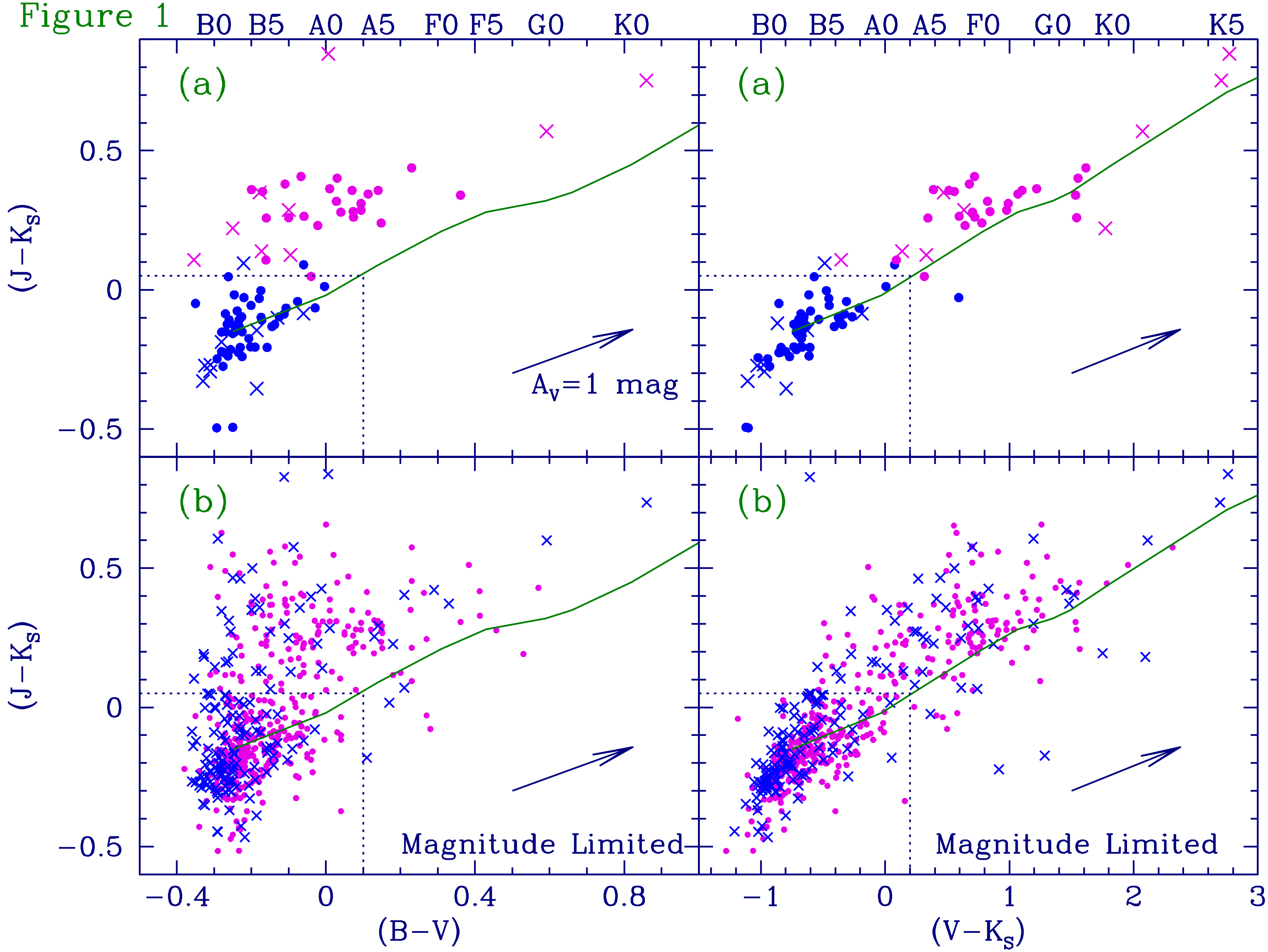
We focused on $(J-K_S)$ vs. $(B-V)$ and $(J-K_S)$ vs. $(V-K_S)$. The locations of single and composite hot subdwarfs in these color spaces were determined using hot subdwarfs reported as single and composite in the literature. These are shown in Figure 1a (relative to the Pop I main sequence, green line) as follows:

33 composite: 24 sdB ($\bullet$) 9 sdO ($\times$)
59 single: 48 sdB ($\bullet$) 11 sdO ($\times$)

Single hot subdwarfs are primarily contained in: $(B-V) \lesssim +0.1$, $(V-K_S) \lesssim +0.2$, and $(J-K_S) \lesssim +0.05$ (marked by a dashed box in Figure 1a) — the same area as other OB-type stars. On the other hand, reported composite hot subdwarfs (both sdB and sdO) occupy a separate and distinct region of color space: they have redder colors (most notably in $J-K_S$) than single subdwarf stars.

The entire 2MASS sample with $J-K_S$ and visual photometry is plotted relative to the Pop I MS (green line) in Figure 1b ($\bullet$ = *sdB* and $\times$ = *sdO*).

Figure 1



B0 B5 A0 A5 F0 F5 G0 K0
B0 B5 A0 A5 F0 G0 K0 K5
(a)
(a)
(b)
(b)
A_V=1 mag
Magnitude Limited
Magnitude Limited
(J−K$_S$)
(J−K$_S$)
(B−V)
(V−K$_S$)

III. MODELING THE DISTRIBUTION

We modeled the locations of composite subdwarfs in color space by combining the colors of a typical sdB with those of late type stars. A typical sdB was taken as:

$(B-V)_{\mathrm{sdB}} \approx -0.25$ $\quad$ $(V-K_S)_{\mathrm{sdB}} \approx -0.75$ $\quad$ $(J-K_S)_{\mathrm{sdB}} \approx -0.15$

($\sim$center of the "clump" of single stars, Figure 1). Color indices for late type dwarf stars were taken from Johnson (1966); assuming $K \approx K_S$.

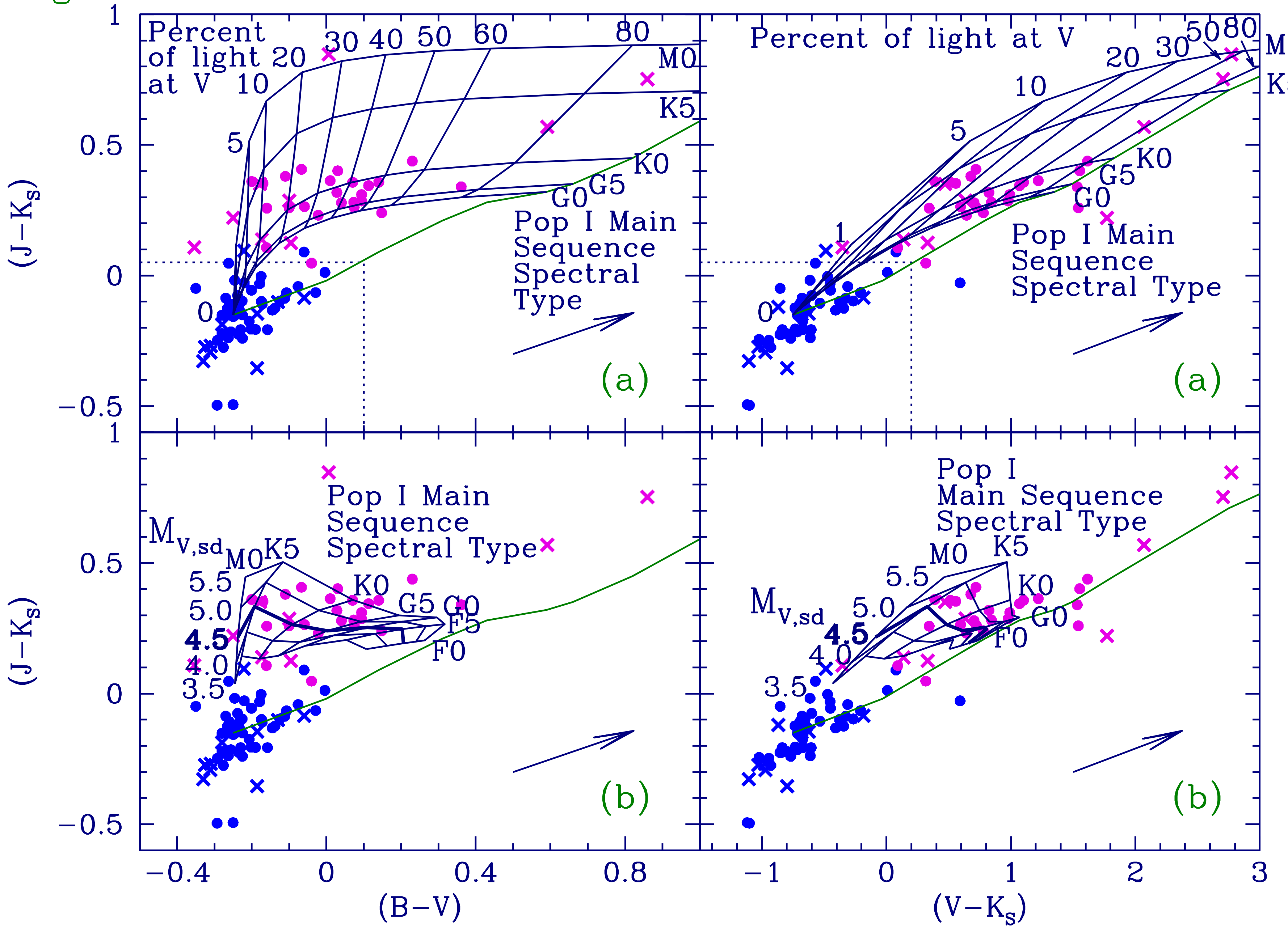
Method 1 (Figure 2a): varied the fraction of light at V due to companion (from 0–100%). Composites are best fit by contributions from the companion of $\sim$10–60% at V, and spectral types G–K.

Method 2 (Figure 2b): assumed Pop I late type main sequence (MS) companions ($M_{V,\mathrm{MS}}$ from Drilling & Landolt 2000), and a range of $M_{V,\mathrm{sdB}} = 3.5$, 4.0, 4.5, 5.0, and 5.5. Composites are best fit by Pop I MS G–K-type companions when $M_{V,\mathrm{sdB}} \approx 4.5-5.0$ mag. This same pattern can be created by fixing $M_{V,\mathrm{sdB}}$ and varying the companion M_V away from the MS values (e.g., subgiant companions).

These simple models give results consistent with previous studies of companion spectral types and light contributions.

Note: due to uncertainties in the photometry and reddening, we cannot invert these calculations to give reliable *individual* values of $M_{V,\mathrm{sdB}}$ given M_V for a companion, nor *vice versa*. Similarly, we cannot infer companion spectral types for individual objects.

Figure 2


Percent of light at V
Pop I Main Sequence Spectral Type
(a)
(b)
$M_{V,sd}$
(J−K_s)
(B−V)
(V−K_s)

IV. BIASES AND TRENDS IN THE SAMPLE

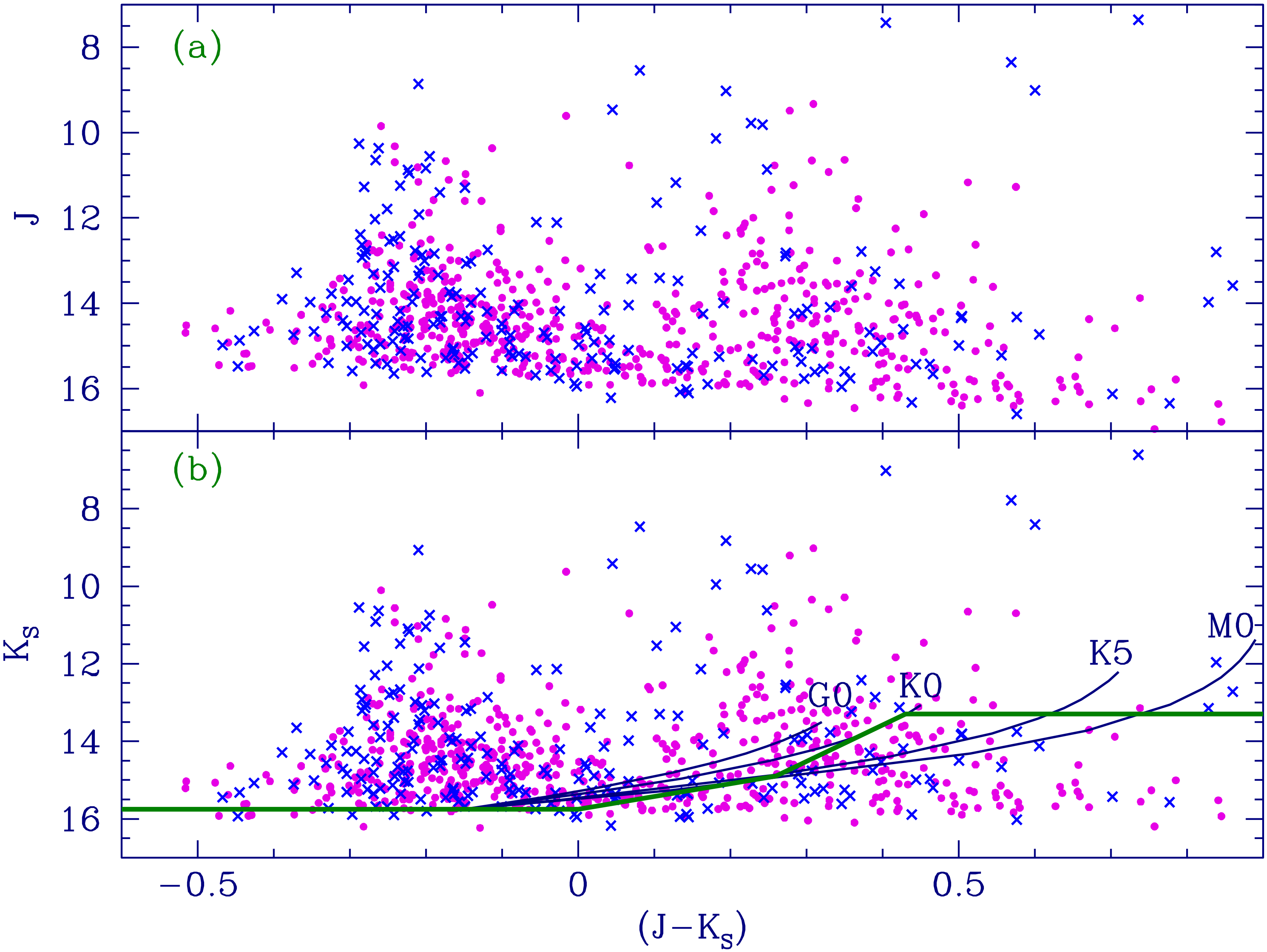
KHD itself is likely *not* representative of the true hot subdwarf population. There are completeness issues, including heterogeneous magnitude limits and different classification criteria used by KHD's sources (although about $^2/_3$ of KHD is from the PG survey, Green et al. 1986, which has rather well-defined properties). Additionally, *composite subdwarfs may be underrepresented* in KHD "by design." For example, Green et al. 1986 omitted UV excess stars if their spectra showed a Ca II K line.

A further selection bias exists in the 2MASS-KHD sample. Since 2MASS is a *magnitude* limited survey, 2MASS-KHD is a *magnitude* limited sample (MLS). In a MLS, *composite subdwarfs are overrepresented* (the presence of a late type companion increases the distance to which a composite remains brighter than the limiting magnitude).

In the $(J,\ J-K_S)$ and $(K_S,\ J-K_S)$ color-magnitude diagrams for the 2MASS MLS (Figure 3; where: • = *sdB* and × = *sdO*), several interesting patterns are noted:

1. Two groupings in $J-K_S$ exist (one blue and one red). Both cover the entire magnitude range. (See §VI–VII for significance and further discussion.)
2. Most objects with extreme $J-K_S$ colors (either blue or red) are at the faintest magnitudes (consistent with increased photometric errors).
3. The sample is limited by detections in the K_S band: there is a clear cut-off at $K_S \approx 15.75$, while the J cut-off varies by color (redder objects that are detected in *both* J and K_S run to a fainter J magnitude than bluer objects).

Figure 3



V. A “VOLUME LIMITED” SAMPLE

Having identified the major biases and selection effects of the 2MASS-KHD sample, we define a *statistical* approximately volume limited sample (VLS) of KHD hot subdwarfs.

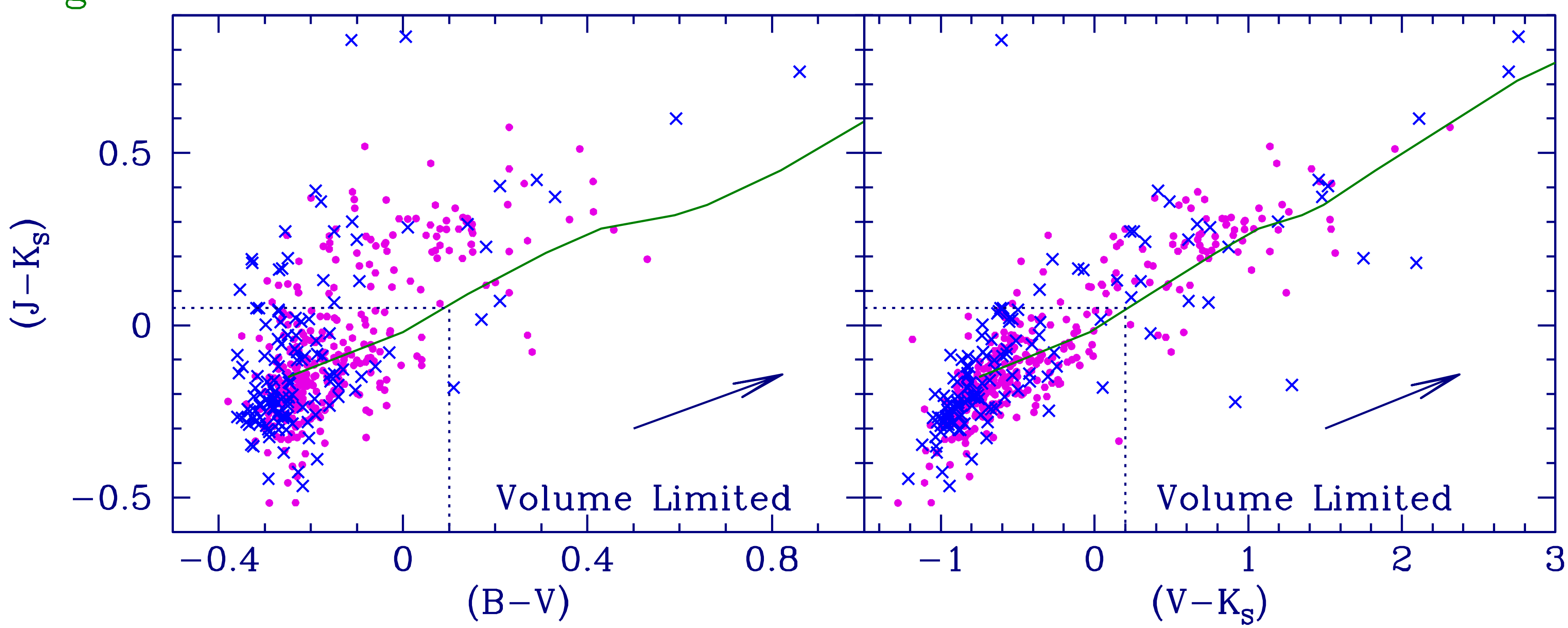
Using the models from §III (method 1, shown in Figure 2a) and the cut-off magnitude $K_S \approx 15.75$ (from Figure 3b), we calculated the corresponding composite apparent magnitudes for companions of several spectral types (shown as solid, dark blue lines in Figure 3b). Composite stars below these lines would not have been detected at K_S by 2MASS if they had instead been single subdwarfs. (Note that *no assumption was made about the absolute magnitude of either the hot subdwarf or the cool companion.*)

We replaced the family of lines with a single representative line (thick, green line in Figure 3b) chosen to pass though the middle of the known composite sdBs in Figures 1a and 2. All hot subdwarf stars that fall above this representative line in (K_S, $J-K_S$) (Figure 3b) are included in the *statistical* VLS.

The resulting sample size is 617 hot subdwarfs (450 *sdB* and 167 *sdO*), with $\langle\sigma(J-K_S)\rangle \approx 0.10$ mag (slightly reduced from the 0.12 mag of the MLS).

The hot subdwarfs in the *statistical* 2MASS VLS with visual photometry are plotted relative to the Pop I MS (green line) in Figure 4 ($\bullet$ = *sdB* and $\times$ = *sdO*). (Note that many of the extreme red objects seen in Figure 1b have been removed.)

Figure 4



(J−K_S)
0.5
0
−0.5
−0.4
0
0.4
0.8
(B−V)
Volume Limited
−1
0
1
2
3
(V−K_S)
Volume Limited

VI. DISTRIBUTION IN $J-K_S$ COLOR

There is a more distinct separation between composite and single subdwarfs in $J-K_S$ than other colors, thus it is useful to examine their distribution in $J-K_S$ alone. Figure 5 shows histograms of $J-K_S$ for: the MLS (5a; 814 subdwarfs: 602 sdB, 212 sdO), and the VLS (5b; 617 subdwarfs: 450 sdB, 167 sdO). Both plots reveal a bimodal distribution (in both the total and *sdB* only sub-samples) with peaks at:

$$J-K_S \approx \begin{cases} -0.15 & (\sim\text{B2–B3 spectral type}) \\ +0.30 & (\sim\text{G5 spectral type}) \end{cases}$$

We postulate that stars within the blue peak of the $J-K_S$ distributions ($J-K_S <$ +0.05) are single stars (or sd+WD pairs, with colors indistinguishable from single hot subdwarfs), and that stars in the red peak ($J-K_S >$ +0.05) are composite (sd+late type) systems. We find:

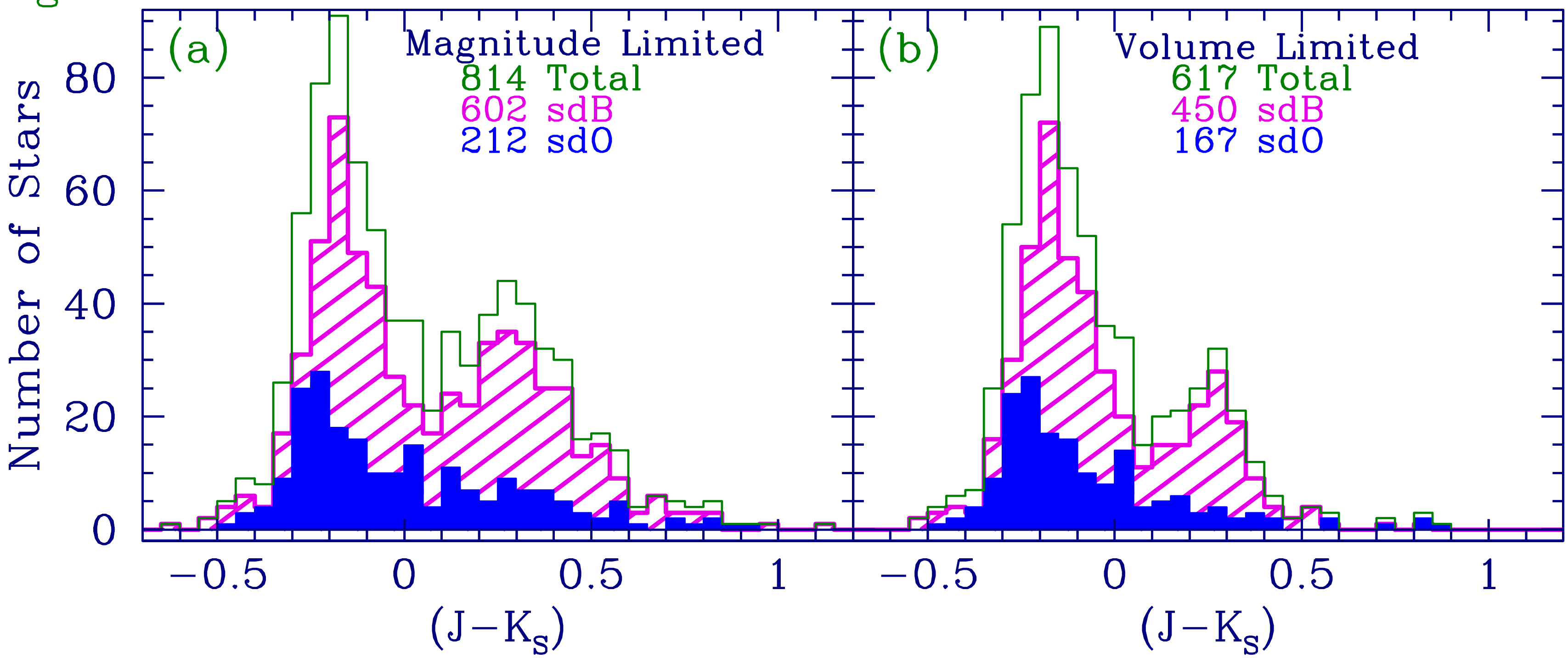
	Magnitude Limited Sample					**Volume Limited Sample**				
	Numbers			Percentages		Numbers			Percentages	
Group	Total	Blue	Red	Blue	Red	Total	Blue	Red	Blue	Red
sdB	602	330	272	$55\pm4\%$	$45\pm4\%$	450	318	132	$71\pm4\%$	$29\pm4\%$
sdO	212	139	73	$66\pm6\%$	$34\pm6\%$	167	132	35	$79\pm6\%$	$21\pm6\%$
Both	814	469	345	$58\pm3\%$	$42\pm3\%$	617	450	167	$73\pm4\%$	$27\pm4\%$

(The quoted 95% confidence errors are sampling errors computed from the binomial distribution.)

The fraction of composite-color systems observed by 2MASS in KHD:

Group	**MLS**	**VLS**
sdB	$45\pm4\%$	$29\pm4\%$
sdO	$34\pm6\%$	$21\pm6\%$
Total	$42\pm3\%$	$27\pm4\%$

Figure 5



(a)
Magnitude Limited
814 Total
602 sdB
212 sdO
(b)
Volume Limited
617 Total
450 sdB
167 sdO
Number of Stars
0
20
40
60
80
−0.5
0
0.5
1
(J−Ks)

VII. FITTING THE sdB $J-K_S$ DISTRIBUTION

The bimodal $J–K_S$ distribution of sdB stars alone was fit as the sum of two Gaussians centered on the blue and red peaks by minimizing χ^2 (Figure 6).

	Magnitude Limited Sample		Volume Limited Sample	
Parameter	Blue Gaussian	Red Gaussian	Blue Gaussian	Red Gaussian
Center	$-0.172^{+0.001}_{-0.004}$	$+0.282^{+0.009}_{-0.002}$	$-0.153^{+0.003}_{-0.002}$	$+0.254^{+0.008}_{-0.002}$
Amplitude	59^{+5}_{-2}	31^{+2}_{-1}	60^{+2}_{-4}	25 ± 2
Dispersion	$0.097^{+0.002}_{-0.006}$	$0.189^{+0.005}_{-0.001}$	0.104 ± 0.001	$0.096^{+0.007}_{-0.002}$
Area Proportion	49 :	51	72 :	28
Integral of Fit	581		433	
χ^2, χ^2_R (DOF)	26.76, 1.07 (25)		20.96, 1.10 (19)	

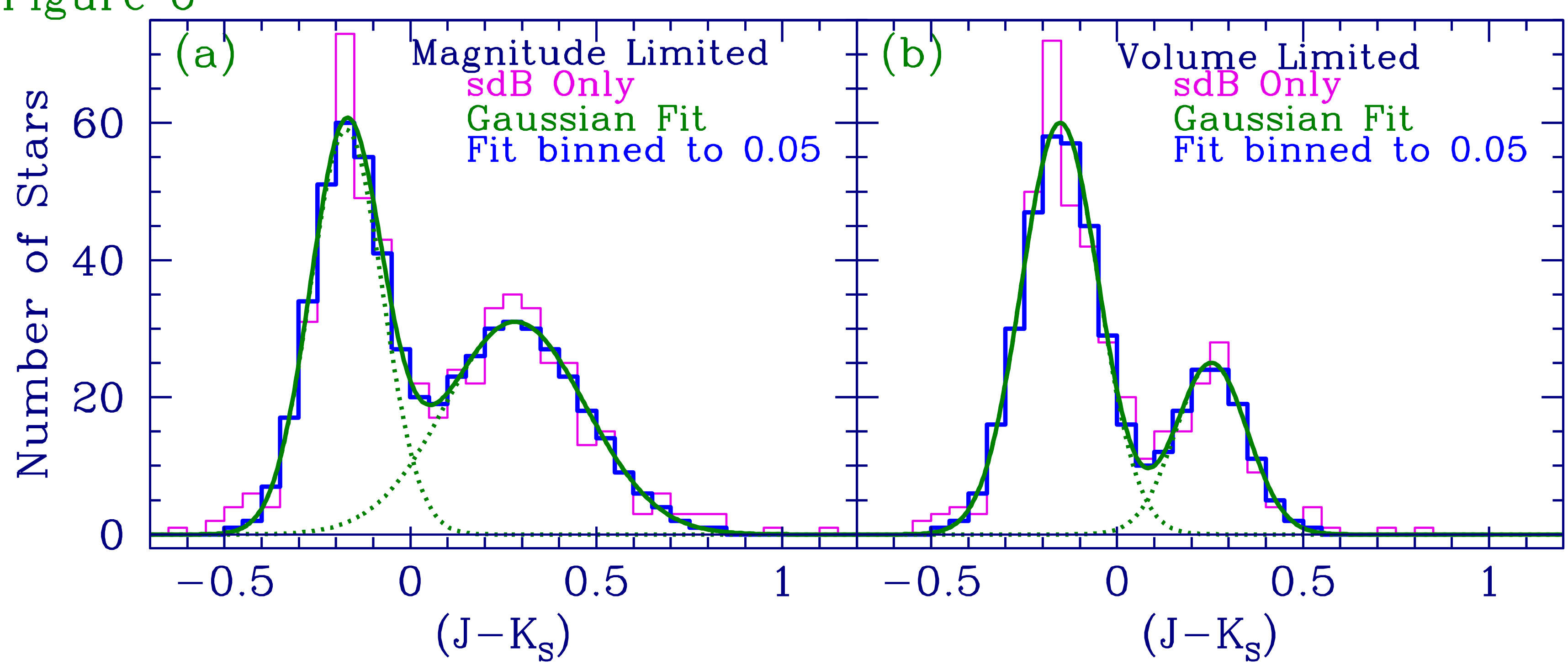
(Errors given are 95% confidence intervals.)

To the extent that the distributions of single and composite sdB stars are accurately represented by two Gaussians, while there is some overlap in $J-K_S$ color index between the two groups of stars in the MLS, there is very little overlap in the VLS.

Compared with the binomial result from a sharp demarcation at $J-K_S = +0.05$, the MLS Gaussian areas favor more composite systems than binomial (51% vs. the binomial 45%), while the VLS Gaussian areas are consistent with the binomial result.

The dispersions of the blue Gaussians are consistent with the average 2MASS photometric errors for these samples, implying that there is little intrinsic spread in the $J-K_S$ color index of single sdB stars. Similarly, the dispersion of the VLS red Gaussian (which is much less than the MLS red Gaussian), is consistent with the 2MASS photometric error for the VLS (≈ 0.10 mag); this implies that there is also very little intrinsic spread in the $J-K_S$ color index of the companions in the VLS.

Figure 6


(a)
Magnitude Limited
sdB Only
Gaussian Fit
Fit binned to 0.05
(b)
Volume Limited
sdB Only
Gaussian Fit
Fit binned to 0.05
Number of Stars
0
20
40
60
−0.5
0
0.5
1
(J−K_S)

VIII. CONCLUDING REMARKS

Since KHD is the most complete single compilation of field hot subdwarfs available, we analyze it despite its inherent biases and completeness issues. However, since KHD is dominated by objects from the PG survey ($\sim$ ²⁄₃ of the catalog), our 2MASS-KHD sample is largely reflective of the PG stars alone (which have relatively well defined properties). In time, objective prism-based surveys (such as the Hamburg Schmidt telescope survey in progress) may provide a catalog of hot subdwarfs that more clearly represents the Galactic population.

In keeping with the exploratory nature of this work and the large sample size, we have favored a statistical approach, in contrast to the attempt to find a best characterization of individual binaries. (The relatively large mean errors of the 2MASS photometry also figured in the decision to use this approach.)

In the same spirit, we have contented ourselves with "naive" modeling of the colors, e.g., adopting single values for the colors and magnitudes of the subdwarfs — our goal in the modeling is to support the division of the sample into single and composite groups, by demonstrating the plausibility of such modeling.

We observe that, of the hot subdwarfs from KHD, $\sim$40% in a MLS, and $\sim$30% in a VLS, are consistent with the presence of an unresolved late type companion. We cannot determine evolutionary states (MS and/or subgiant) for these companions, nor do we know if these companions interacted with the hot subdwarf progenitor.

(Also see poster by Wade & Stark, discussing resolved hot subdwarf–cool star pairs.)

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- the USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station (http://www.nofs.navy.mil/data/fchpix/).
- the SIMBAD database, operated at CDS, Strasbourg, France.
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