The Binary Origins Of Hot Subdwarfs: New Radial Velocities

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Abstract. Multiple radial velocity observations have been obtained for a large sample of local field subdwarf B (sdB) stars over a period of two years. SdB stars appear to fall into three distinct groups based on their kinematic and spectroscopic properties. The sdB’s in Group I have no detectable spectral lines from a cool companion, and show only small or insignificant velocity variations. They represent about 35% of all sdB stars, which defines the upper limit for the total fraction of non-binary sdB’s. Group II sdB’s are single-lined spectroscopic binaries, comprising about 45% of the sample. Their spectra resemble those in the first group, but they have significant or large velocity variations and probable orbital periods on the order of a day. The third group contains the remaining ~20% of sdB’s, those showing additional spectral lines from a cool (FGK) main sequence or subgiant companion. All Group III sdB’s have slowly varying or nearly constant velocities, indicating periods of many months to several years. Group II sdB’s are obvious post-common envelope systems, in strong contrast to the wide binaries of Group III. Current data are insufficient to rule out the possibility that some sdB’s in Group I might be analogs of Group III binaries, with undetectably faint companions. The clear division into three groups with such disparate properties suggests very different evolutionary histories even though the current physical states are essentially indistinguishable.

1. Observations and Reductions

We have obtained multiple precise velocities for more than 70 bright subdwarf B stars, using the MMT Blue Channel spectrograph at 1Å resolution from 4000–4930Å. Typically, each sdB star was observed five to seven times over a 1 to 2 year period. Most stars were observed at intervals of 1 to 2 days, 1 to 2 months, 3 to 6 months, and 12 to 18 months. We were able to determine very precise velocities, $1 < \sigma_v < 2 \text{ km s}^{-1}$ in most cases, primarily by exposing to a rather...
high S/N of about 70 to 100 for each exposure and taking extraordinary care at every stage of the reductions, but also due to a relatively long CCD (3Kx1K pixels) with good cosmetics and readnoise.

The data were reduced with standard IRAF reduction routines and analyzed with IRAF’s radial velocity cross-correlation task FXCOR, which uses the method of Tonry & Davis (1979). Our relatively high resolution and high S/N allowed us to set the Fourier filter parameters to cross-correlate on only the narrowest spectral features, primarily helium and various weak metal lines, with only a small contribution from the sharp cores of the Balmer lines.

We initially used a set of multiply-observed, bright, narrow-lined O and B stars as radial velocity standards (Fekel & Morse, as reported by Stefanik & Latham 1992). Perversely, the only good cross-correlation templates for sdB stars are the stars themselves. The observations for individual sdB’s were correlated against each other, corrected to an approximate rest velocity with roughly the same zero point as the OB standards, and combined into a preliminary template. The individual spectra were cross-correlated against the combined spectrum and the process was iterated. Final velocities for each sdB were obtained from correlations with an extremely high S/N super-template consisting of the sum of the ten most similar combined sdB spectra (after iteratively readjusting the velocities of the combined spectra to ensure a consistent zero point.)

A precise understanding of the velocity errors is crucial for understanding the binary properties of sdB stars. We conducted an exhaustive Monte Carlo error analysis, following the procedures of Pryor, Latham, & Hazen (1988) and Armandroff, Olszewski, & Pryor (1995), to determine the proper scaling factors between the true velocity errors and the relative values of VERR that were output by FXCOR. A comparison of our estimated errors for two stars in the sample with well-determined, unique orbits, PG0941+280 and PG1101+249 (Green, in preparation), shows very good agreement. The standard deviations of the MMT residuals about the predicted velocity curve are 1.54 and 1.41 km s$^{-1}$, respectively, and the Monte-Carlo derived errors are 1.65 and 1.47 k/s.

A subset of sdB’s, whose spectra show additional spectral lines from a cool companion, required further processing. They were cross-correlated against super-templates of main sequence spectral types from F6 to K5. The best match, determined by the lowest FXCOR error values, was used as a template to derive the velocity of the cool companion. The same super-template was also velocity-shifted, scaled and subtracted from each individual composite spectrum to recover the spectrum of the sdB component alone. The resulting, comparatively lower S/N sdB spectra were cross-correlated against the best-matching high S/N “pure” sdB super-templates described above to derive the sdB velocities.

2. Discussion

The non-composite sdB’s comprise a kinematically unbiased sample that naturally divides into two groups on the basis of the observed velocity variations. The

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22 sdB's in our Group I show only small velocity variations, $1 < \sigma_v < 4$ km s$^{-1}$. The distribution of the statistical probabilities of finding the observed variations is far from a normal gaussian. There are too many stars with bigger velocity variations than expected from a random distribution with the known errors: 2/3 of the $\chi^2$ probabilities are less than 10% and 1/3 are less than 0.1%. However, it is conceivable that pulsations could be responsible for these small amplitude motions, leaving no compelling evidence either for or against binarism in the stars in this group.

The 29 sdB's in Group II have large velocity variations, with $\sigma_v$ distributed fairly uniformly from 7 to 91 km s$^{-1}$. For stars in this group, the velocity change over a one day interval was typically a large fraction of the total observed velocity range, indicating likely periods on the order of a few hours to a few days.

Our Group III consists of 21 composite spectrum sdB stars\footnote{N.B. We observed additional sdB's already known to have composite spectra, in order to increase the number of stars in our sample in Group III.} for which we determined the velocities of each component separately. The velocity variations for both of the individual components as well as the difference between the two components were always small, less than a few km s$^{-1}$. Thus, the composite spectrum sdB's appear to have relatively long periods of many months to several years.

The stars in all three groups appear to be bonafide sdB stars. Figure 1 shows representative examples of combined spectra for individual sdB's in each group. The Group I sdB's, in particular, must be old disk stars with little halo contamination, given their line-of-sight velocity dispersion of $\sigma_{\text{los}} = 34.3$ km s$^{-1}$.

![Representative spectra of sdB's in Groups I, II, and III.](image)
The reason for the dramatically different kinematic behavior between Groups I and II is unknown. There are no significant differences between their distributions in the log $g$ vs $T_{\text{eff}}$ plane (Figure 2), as derived from Balmer line profile fitting. Both groups cover a surprisingly large range of helium and metal line strengths, although there is a puzzling tendency for the nearly-constant velocity Group I stars to have stronger line strengths, on average, than the short timescale velocity variables in Group II. Group I stars might also be somewhat brighter than those in Group II, although this is hardly a significant result (7%) due to the small number of stars in both groups.

![Fig. 2 – Existing log $g$ vs $T_{\text{eff}}$ data for stars in Groups I (filled circles) and II (open triangles) relative to evolutionary tracks and the He-burning MS.](image)

We conclude that the clear division into three groups with such disparate properties indicates quite different evolutionary histories. The sdB’s in Groups I and III cannot have been through a common envelope phase, whereas Group II sdB’s must all be post-common envelope systems. It is not yet clear whether any of the Group I sdB’s are binaries or not. Given our velocity accuracy, no more than one sdB in Group I is likely to be a face-on example of a Group II binary. However, the small velocity variations of the Group I sdB’s are similar to those of the sdB components of the majority of the Group III binaries, leaving open the possibility that at least some of the Group I stars could be wide binaries with undetected companions.

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