On The Origin Of Subdwarf B Stars and Related Metal-Rich Binaries

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Abstract. Mounting evidence from subdwarf B (sdB) stars in the galactic field and their recently discovered counterparts in old open clusters indicates that at least two thirds of local disk sdB stars are binaries. Our recent radial velocity survey showed that sdB binaries naturally divide into two groups with contrasting spectroscopic and kinematic properties. Those with detectable spectral lines from a cooler companion invariably have periods longer than a year, while very short period sdB’s have essentially invisible companions. We derive typical orbital separations for the components of the composite spectrum sdB’s from their velocities. The current systems must have been produced by Roche lobe overflow/mass transfer from low mass, metal-rich giants near the first red giant branch tip, without undergoing common envelope evolution. The same process should also occur at slightly lower red giant luminosities, producing a wide binary with a helium white dwarf instead of an sdB star. Most short period sdB’s probably result from a common envelope following Roche lobe overflow of the initial secondary onto the white dwarf. Rare post-common envelope sdB + main sequence (MS) binaries also exist, but available data suggest that most such systems involving lower MS companions end up merging. The small and nearly identical masses of the two known MS survivors in short period sdB binaries imply that both components must have lost a large fraction of their initial mass in the common envelope process.

1. Introduction

Field subdwarf B (sdB) stars are core helium burning objects commonly found in the galactic disk, and also recently identified in two old open clusters (Liebert, Saffer, & Green 1994). They are believed to be extreme horizontal branch stars with $M_{\text{sdB}} = 0.5 M_\odot$ (e.g. Saffer et al. 1994), produced when the envelope is stripped from a low mass giant near the first red giant branch tip. Whether this is due primarily to mass transfer followed by common envelope ejection in binaries (Mengel, Norris, & Gross 1976) or enhanced mass loss in single stars (D’Cruz et al. 1996) is still not clear. The mechanisms for the extreme mass
loss required to create significant numbers of sdB’s and low mass white dwarfs in low density environments are important for understanding the evolution of many astrophysically interesting systems, including millisecond pulsars, low-mass X-ray binaries, double degenerate white dwarfs, and possibly the origin of type Ia supernovae, yet they remain very poorly understood. SdB’s are also the main candidate for the unexpected far-UV excesses seen in many external galaxies (O’Connell 1999, and references therein). They would be a valuable probe of ages and metallicities if their evolutionary behavior could be uniquely modeled. Most recent investigators consider sdB stars a result of single star evolution (e.g. Bressan, Chiosi, & Fagotto 1994; Dorman, O’Connell, & Rood 1995; Park & Lee 1997; Yi, Demarque, & Oemler 1998; Yong, Demarque, & Yi 2000).

Meanwhile, studies of local field sdB’s provide increasing evidence for a large binary fraction, initially including estimates from broadband flux distributions (Allard et al. 1994), more recently from growing numbers of newly discovered short period sdB’s (Menzies 1986; Kilkenny et al. 1998; Koen, Orosz, & Wade 1998; Moran et al. 1999; Billères et al. 1999; Maxted et al. 2000). Our radial velocity survey for a large sample of bright field subdwarf B stars (Saffer, Green, & Bowers, this volume) has now demonstrated that at least two thirds of disk sdB’s are in binaries. Some 20% show spectral lines from a cool turnoff or subgiant companion, and have relatively long periods of at least a year. Another 45% of sdB’s are clearly post-common envelope binaries with periods of hours or days, whose companions are always too faint to be detected spectroscopically.

Using our observed data for field sdB’s and their probable progenitors in old open clusters, we propose two related scenarios to explain the evolution of both types of sdB binaries, and discuss the implications for common envelopes.

2. Discussion

2.1. Clues from Old Open Clusters

The only open clusters known to contain sdB stars, NGC 6791 and NGC 188, are also the metal-richest ([Fe/H] = +0.4 and −0.05, respectively) of the very old open clusters. Thus, their stellar properties include both lower turnoff masses (1.1 − 1.25M⊙, Chaboyer, Green, & Liebert 1999; Liu & Chaboyer 2000) and larger giant radii (150 ≲ R ≲ 200 at the first red giant tip, Salasnich et al. 2000) than most disk stars. NGC 6791 contains two of the three cataclysmic variables so far found in open clusters (Kaluzny et al. 1997). Curiously, both clusters also show an enormous fraction of blue stragglers, Nblue straggler/Nhorizontal branch ≳ 3 (Green 2000, in preparation). In M80, a postulated pre-core collapse cluster with the highest known blue straggler frequency of any globular, the same ratio is only about 1 (Ferraro et al. 1999).

2.2. The Composite Spectrum SdB Stars are the Key

The velocity differences between the two components of the composite spectrum sdB binaries can be used to estimate typical values for their orbital periods and separations. The mean |Δv sin i| from 89 observations of 19 composite binaries over a two year period was about 11.5 km s⁻¹ (the largest difference was 30 km s⁻¹). Assuming random orbital inclinations and typical old disk
turnoff/subgiant masses of $1.0 - 1.3 M_\odot$ for the companions (required to match the observed luminosity contributions), the current periods average $3 - 4$ years with separations of $540 - 650 R_\odot$. If the sdB’s evolved without interacting with their companions, their prior separations can be estimated by assuming $a(M_1 + M_2) = \text{constant}$ (Tout et al. 1997). With initial sdB progenitor masses similar to the turnoff masses in NGC 6791 and NGC 188, and mass loss of $\sim 0.3 M_\odot$ on the first giant branch, typical separations just prior to the He core flash would have been $415 - 520 R_\odot$. The corresponding effective radii of the giants’ Roche lobes (Eggleton 1983) would have been $155 - 185 R_\odot$. These are of the order of, and in most cases slightly smaller than, the required radii at the red giant tip!

The inescapable conclusion is that composite spectrum sdB’s were stripped of their envelopes due to Roche lobe overflow of their progenitor giants just before the first red giant tip, without developing a common envelope. Therefore, despite canonical expectations (Iben & Livio 1993), nearly stable Roche lobe overflow on the upper giant branch must occur relatively often, given the right circumstances. We suggest that sufficiently low mass ($\lesssim 1.3 M_\odot$), preferentially metal-rich ($[\text{Fe/H}] \gtrsim 0.0$) red giants in suitably wide binaries may transfer enough mass to initially massive secondaries during the giant’s normal slow mass loss phase, to reduce the mass ratio close to the critical value required for stable mass transfer. Complete stability would not be required initially, as long as the near-solar mass secondary is able to accept the dynamic mass transfer of the first couple of tenths of a solar mass without filling its giant size Roche lobe ($\sim 170 R_\odot$ and increasing).

2.3. Further Speculations

When the primary in the above scenario attains a large enough core mass prior to Roche lobe overflow to enable eventual He-burning, the result is a composite spectrum sdB with a probable blue straggler companion in a widened orbit. Overflow at slightly lower luminosities would produce a He white dwarf instead of an sdB, everything else remaining the same. We propose that a significant fraction of the blue straggler+white dwarfs become post-common envelope sdB+wd binaries following Roche lobe overflow of the initial secondary, since the observed number of short period sdB binaries is more than twice the number of composite sdB’s. Populations that produce these sdB stars require fairly low densities for their lengthy evolution and will contain many long period blue stragglers.

A common envelope will occur if the first Roche lobe overflow begins after the primary develops a deep convective envelope but before sufficient mass is lost/transferred to the secondary, or if the initial mass of the secondary is too small. Both cases would be assumed to produce numerous low mass cataclysmic or pre-cataclysmic variables. However, any reasonable initial mass function ought to create many more post-common envelope sdB+MS binaries than long period composite spectrum sdB’s, since only the most massive secondaries can avoid a common envelope. Yet, we note that only two short period sdB+MS binaries have been found, compared to at least four sdB+wd systems (and counting), despite extensive photometric monitoring of several hundred sdB’s (Koen et al. 1998). This implies a genuine scarcity of post-common envelope sdB+MS binaries, which are much more easily detected by reflection effects and eclipses. (MS stars with masses $\gtrsim 0.14 M_\odot$ have larger radii than sdB stars.) Thus, most
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MS companions in common envelope systems with initial mass ratios, \( M_2/M_1 \), sufficiently below unity might end up merging.

The \( \sim 0.14M_\odot \) mass secondaries in the two known eclipsing sdB+MS systems would then represent the surviving remnants from a very narrow initial mass range: too small to escape a common envelope, but large enough to avoid merging. If so, they must have lost a large fraction of their original mass along with the sdB progenitor in the common envelope process.

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