Mass loss predictions for Subdwarf B stars

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Abstract. We present the results of Monte Carlo mass-loss computations for hot low-mass stars, specifically for Subdwarf B (SdB) stars. It is shown that the mass-loss rates on the Horizontal Branch (HB) computed from radiative line-driven wind models are not high enough to create SdB stars. We argue, however, that mass loss plays a role in the chemical abundance patterns observed both in field SdB stars, as well as in cluster HB stars. The derived mass loss recipe for these (extremely) hot HB stars may also be applied to other groups of hot low-mass stars, such as post-HB (AGB-manqué, UV-bright) stars, over a range in effective temperatures between \(\approx 10000 - 50000\) Kelvin. Finally, we present preliminary spectral synthesis on the more luminous SdB stars for which emission cores in H\(\alpha\) have been detected (Heber et al. 2002). We find that these line profiles can indeed be interpreted as the presence for a stellar wind with mass-loss of the order of \(10^{-11}\) \(M_\odot\) yr\(^{-1}\).

Keywords: Stars: horizontal-branch – subdwarfs – Stars: mass-loss – Stars: winds – Stars: evolution – Galaxy: globular clusters

1. Introduction

Extreme Horizontal Branch (EHB) stars are extremely hot (\(T_{\text{eff}} \geq 30000\) K) HB stars of \(\approx 0.5\) \(M_\odot\), consisting of a helium core and a very thin layer of hydrogen (\(\leq 0.02\) \(M_\odot\)) on top (see e.g. Dorman et al. 1993). This hydrogen layer is so thin that EHB stars cannot undergo helium shell burning, which prevents them from ascending the Asymptotic Giant Branch (AGB). Instead, they are believed to directly evolve towards the white dwarf cooling track as “failed” AGB (or AGB manqué stars). Subdwarf B (SdB) star is the other well-known name. Although the “EHB” nomenclature is mostly found in the context of globular cluster HB stars, the SdB term is generally used to describe the objects in the field. The evolutionary status of EHB/SdB stars is as yet a mystery, so the correct evolutionary scenario has yet to be identified. One of the key observational constraints that can help distinguish between the different proposed evolutionary channels (see e.g. Sweigart, Podsiadlowski, Jeffery, and others in these proceedings) involves the stellar abundances in SdB stars. Interestingly, SdB stars are characterised by strong chemical abundance anomalies: (i) helium is severely depleted: underabundances by factors of hundreds to thousands are not uncommon, while (ii) metals (such as carbon, oxygen and nitrogen) show similarly unexplained wide spreads. Gravitational settling and
radiative levitation have been suggested as the most natural cause for the striking abundance anomalies, but in recent years the necessity for a stellar wind has become clear: without a wind, helium “sinks in” (due to gravity) in too short a timescale compared to the evolutionary lifetime of an EHB object (Fontaine & Chayer 1997, Unglaub & Bues 2001). Current atmospheric diffusion calculations treat SdB mass loss as a free parameter, but these diffusion computations can be made more robust if reliable mass-loss rates are provided. One way to reach such goal would be via observational results, however sensitive observational techniques are yet lacking (but see Sect. 5 for an outlook). One therefore needs to rely on the theory of radiative line-driven winds. In this context, Vink & Cassisi (2002) have recently computed radiation-driven wind models for HB stars, and discussed stellar winds in the context of the “zoo” of problems governing HB morphology in globular clusters occurring at $T_{\text{eff}} \simeq 11000$ K. They have argued that stellar winds can resolve these issues in a natural way: a stellar wind that is set-up by the increase in metallicity (due to radiative levitation) for HB stars with $T_{\text{eff}} \geq 10000$ K.

2. Motivation for accurate mass-loss rates

We identify five reasons as to why one should be concerned about the mass-loss rates for (E)HB/SdB stars:

1. Does mass loss on the HB affect the evolution of HB stars? This question was recently posed by Yong et al. (2000). The authors hypothesised that a stellar wind on the HB could strip enough matter off the stellar core so that a blue HB star naturally evolves into an EHB/SdB star. If this scenario were correct, the problem of the existence of SdB stars would be solved. Since accurate mass-loss rates for HB stars were lacking, Yong et al. had the freedom to apply mass-loss rates on order of $10^{-9} M_\odot \text{yr}^{-1}$, which appear a posteriori on the high side. Nonetheless, even mass-loss rates a few magnitudes lower than this number, approximately $10^{-11} M_\odot \text{yr}^{-1}$, might still directly influence stellar evolution models (see Vink & Cassisi 2002 for details).

2. Do stellar winds affect the observed spectra of (E)HB stars? For massive O stars, it is well-known that the neglect of winds can lead to severe errors in the spectroscopic mass determination compared to evolutionary models: “the mass discrepancy” (see e.g. Herrero et al. 1992). Since there also appears to be “log $g$” problem (i.e. a mass discrepancy) in Blue HB stars (Moehler et al. 1995, 2000),
one may wonder whether there could be potential problems using hydrostatic model atmospheres for these objects also (see Vink & Cassisi 2002 for results on the gravity sensitive Hγ line).

3. Does mass loss affect the angular momentum distribution in a rotating (E)HB star? Vink & Cassisi (2002) have shown that the difference in predicted mass-loss rate between 'cool' ($T_{\text{eff}} < 10\,000$ K) and 'warm' ($T_{\text{eff}} > 10\,000$ K) HB stars is a factor of 100, because of an increased metal abundance above this temperature. Since this coincides exactly with an unexplained drop in the rotational velocities above this temperature (Behr 1999, 2000), it is tempting to attribute this to the removal of angular momentum by a stellar wind (see also Sweigart 2000).

4. Does mass loss affect SdB abundances? Computations performed by both Fontaine & Chayer (1997), as well as Unglaub & Bues (2001) have shown a need for the presence of stellar mass loss in the range of $10^{-14} \leq \dot{M} \left(\frac{M}{\text{yr}}\right) \leq 10^{-12}$.

5. Last, but not least: how does radiative driving behave over the Hertzsprung-Russell Diagram? In the following, we describe the Monte Carlo technique simulating photon transfer through a unified stellar atmosphere (including a wind). The technique has been very successful in (i) explaining the bi-stability jump in B supergiants (Vink et al. 1999), (ii) the mass-loss rates of massive O stars (Vink et al. 2000), and (iii) the capricious mass loss behaviour of Luminous Blue Variables (Vink & de Koter 2002). By extending the computational method to different domains of the Hertzsprung-Russell Diagram, our understanding of radiative line driving can be further enhanced.

3. The Monte Carlo Method

The description of the radiative wind driving with our method is based on a Monte Carlo method that was first introduced by Abbott & Lucy (1985). This approach naturally accounts for multi-line transfer simulating photon-interactions with different metal ions, both lines as well as continua, while the photons attempt to escape the gravitational well of the star. In the models used here, the ionisation and excitation for the dominant ionic species are properly computed using the non-LTE unified Improved Sobolev Approximation code (isa-wind; de Koter et al. 1993, 1997), which treats the photosphere and wind in a unified
manner. The chemical species that are correctly calculated are H, He, C, N, O, and Si. The iron-group elements however are treated only approximately using a generalised version of the “modified nebular approximation” developed by Lucy (1987).

One of the main assumptions implicit in our method is that the plasma behaves as a single fluid. As long as a large number of collisions between the accelerating (C, N, O, and Fe-group) and non-accelerating (H and He) particles ensures a strong coupling, one can safely treat the wind as a single fluid. Test calculations performed in Vink & Cassisi (2002) have shown that Coulomb coupling is fulfilled (albeit only within an order of magnitude). Lastly, it remains yet to be seen if the use of the Sobolev approximation is valid for weaker winds (see Owocki & Puls 1999).

4. Mass loss rates

The mass loss rates for EHB/SdB stars are readily obtainable from the mass loss recipe presented by Vink & Cassisi (2002):

\[ \log \dot{M} = -11.70 \pm 0.08 + 1.07 \pm 0.08 \log(T_{\text{eff}}/20000) + 2.13 \pm 0.09 (\log L_\ast - 1.5) - 1.09 \pm 0.05 \log(M_\ast/0.5) + 0.97 \pm 0.04 \log(Z_\ast) \]

derived for:
\[ 12,500 \leq T_{\text{eff}} \leq 35,000 \text{ K} \]
\[ 1.3 \leq \log L_\ast \leq 1.7 \]
\[ 0.5 \leq M_\ast \leq 0.7 \]
\[ 0.1 \leq Z_\ast \leq 10 \]

(1)

where \( T_{\text{eff}} \) is in Kelvin and \( L_\ast, Z_\ast, \text{ and } M_\ast \) are all given in solar units. One of the outcomes is that bi-stability jumps (due to iron recombinations) in the mass-loss rate are absent on the HB, as the winds are “thin” compared to those of OB supergiants. The many weak lines of the element iron (Fe) are not as dominant in setting the mass-loss rate, as they are in denser winds (such as OB supergiants). Instead, lighter metals, such as carbon, nitrogen, and oxygen, which have fewer, but
stronger lines are capable of playing an important role in determining the mass loss in thinner winds, such as low metallicity O star winds (see Vink et al. 2001 for a fuller discussion). Note that for helium rich SdB stars (He-SdB, blue hook stars), which may be explained by the helium mixing scenario (Castellani & Castellani 1993, Brown et al. 2001, Cassisi et al. 2003), carbon is predicted to be enriched, which may therefore increase the expected mass loss to values above those following from the Vink & Cassisi recipe.

Nonetheless, Eq. 1 may be applied to hot, low-mass stars, of the types: (E)HB, sdB, sdOB, post-HB, AGB-manqué, UV-bright stars, in a range of $T_{\text{eff}}$ between 10 000 and 50 000 K. Central Stars of Planetary Nebulae (CSPN) are more resemblant to massive O stars, and therefore the OB star recipe of Vink et al. (2001) is recommended for these objects. Computer routines (IDL) for both mass loss recipes are available on the web.

The important points regarding the actual mass-loss values are: (i) the computed rates do not support the evolutionary channel of producing SdB stars by mass loss on the HB, but (ii) they are in the appropriate range of the values deemed necessary in the diffusion computations of Unglaub & Bues (2001), i.e. the observed chemical patterns can only be explained if mass-loss rates are in the range $10^{-14} \leq \dot{M} (M_\odot \text{yr}^{-1}) \leq 10^{-12}$. Higher rates would prevent the effect of diffusion, whereas for lower rates helium would sink in too short time scales.

We conclude that our mass-loss rates are in the right ballpark as far as consistency with diffusion calculations is concerned. Nonetheless, what one finally seeks is confirmation by observations.

5. Outlook on observational tests

The most sensitive diagnostic for hot star winds is generally accepted to be the metal resonance lines in the ultraviolet part of the electromagnetic spectrum (e.g. Lamers & Morton 1976). However, similar data for SdB stars is currently not available. Another potential diagnostic is Hα emission, but SdB stars generally show this line in absorption. One may wonder whether there is any chance for detecting wind emission in these low luminosity (and thus low wind density) objects at all. The positive aspect is that SdB stars have small radii, and thus the more relevant parameter for detecting mass loss in these objects, does not concern the mass-loss rate, but rather the mass flux. Based on the results of the Monte Carlo presented above, one may expect similar mass fluxes.

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1. http://astro.ic.ac.uk/~jvink/
Figure 1. The thick solid line represents the observed H\textalpha line of PG 1000+408 – a typical H\textalpha anomaly presented by Heber et al. (2002). The thin solid, dashed, and dotted lines represent spectral models for mass loss rates of $\log \dot{M} (M_{\odot} \text{yr}^{-1}) = -10.5$, -11.0, and -11.5 respectively. These models are calculated for a mass of $M = 0.5M_{\odot}$, $\log(L/L_{\odot}) = 1.51$, and solar abundance. Note that these are not intended to be fits to the observed profile (see text for a discussion).

is SdB stars as in the more massive late-O-type/early-B-type main sequence stars. Interestingly, Heber et al. (2002) detected anomalous H\textalpha lines in four SdB stars, and proposed that these anomalies could be the signature of a weak stellar wind.

To test this hypothesis, we have made a preliminary spectral synthesis of H\textalpha using the isa-wind code (de Koter et al. 1993) for extended atmospheres, and first results are presented in Fig. 1. The thick solid line shows the observed H\textalpha profile of PG 1000+408, a typical H\textalpha
anomaly presented by Heber et al. (2002): a small, but clear, emission at line centre. Interestingly, our spectral synthesis (the three thin lines in Fig. 1) shows similar behaviour of the line core. Note that the three thin lines (solid, dashed and dotted) are not fits to the observed profile, i.e., we would need to (i) apply rotational and instrumental convolution to our predicted profiles, and (ii) synthesise the entire blue and red parts of the spectrum, as to find consistent wind and photospheric parameters (most notably log $g$).

The stellar parameters for PG 1000+408 (as determined from hydrostatic stellar atmosphere analysis) are: $T_{\text{eff}} = 36,000$ K, log $(L/L_{\odot}) = 1.51$, assuming a stellar mass of $M = 0.5 M_{\odot}$. Our strategy was the following. Adapting the hydrostatic stellar parameters, and assuming solar abundances, we made a mass loss prediction using the Vink & Cassisi mass-loss recipe. The mass loss that is expected for PG 1000+408 is $\log \dot{M}(M_{\odot}\text{yr}^{-1}) = -11.40$. Since mass loss depends almost linearly on metal abundance (as $\log \dot{M} \propto Z^{0.97}$; Eq. 1) and the abundances of the objects are not known, the actual mass loss could be somewhat different. Therefore, we show the effect of varying the mass-loss rate on the predicted line profiles of H$\alpha$ in Fig. 1. The thin solid, dashed, and dotted lines represent mass loss rates of $\log \dot{M} (M_{\odot}\text{yr}^{-1}) = -10.5$, -11.0, and -11.5 respectively. It is reassuring to find that the strength of the central line emission, now interpreted as wind emission, is a function of wind density. Although this is a preliminary analysis, the results are encouraging, and indicate that the future of SdB mass loss determinations using optical lines may not at all be as hopeless as has previously been thought.

6. Summary & Conclusions

We have made mass loss predictions for SdB stars using a Monte Carlo method simulating multi-line interactions in a moving stellar atmosphere. The results show that HB winds are too weak to directly influence stellar evolution, and cannot create SdB stars as the sole effect. However, the puzzling chemical abundance patterns found in both field and cluster EHB stars are interpreted as due to the competing effects of gravitational settling and radiative levitation in the presence of a stellar wind. We have succeeded in providing a set of constraints on the wind strengths of EHB/SdB stars, and in turn, these predictions appear to meet the constraints set by atmospheric diffusion calculations, as well as the first observational tests. The future for mass loss in Subdwarf B stars looks bright!
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