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MULTICOMPONENT WINDS IN SDB STARS?

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Abstract. In previous diffusion calculations with mass-loss a steady outflow of all elements has been assumed. However, the existence of a chemically homogeneous wind requires an efficient momentum transfer via Coulomb interactions from the heavy elements to hydrogen and helium. For the example $T_{\rm eff} = 35\,000$ K and $\log g = 6.0$ it will be shown that hydrogen and helium would fall back onto the star if the mass-loss rate is below about $10^{-12} M_\odot/{\rm yr}$. This effect may change the predicted surface compositions.

Key words: stars: hot subdwarfs – stars: mass-loss – stars: winds, outflow – stars: diffusion

1. INTRODUCTION

In previous papers (Unglaub & Bues 2001 and Unglaub 2005) it has been shown that the effects of diffusion and weak winds with mass-loss rates $\dot{M} \approx 10^{-13} M_\odot/{\rm yr}$ may explain the helium abundances in sdB stars with number fractions H/He between about solar and 10^{-4}. However, the abundance anomalies of heavy elements can hardly be explained simultaneously, at least if a solar initial composition is assumed. In contrast to many observational results helium should always be more deficient than each of the elements C, N and O. A possible reason for this discrepancy may be the decoupling of metals on the one hand and H+He on the other hand in the wind region. This may happen if the momentum redistribution via Coulomb interactions between H, He and the metals is not sufficiently effective.

Vink & Cassisi (2002) calculated mass-loss rates for sdB stars with the assumption of a fixed velocity law. For "luminous" sdB stars with $5.0 \leq \log g \leq 5.5$ they obtain $10^{-11} M_\odot/{\rm yr} \leq \dot{M} \leq 10^{-10} M_\odot/{\rm yr}$ for solar composition and, for example, $\dot{M} \approx 10^{-12} M_\odot/{\rm yr}$ for $T_{\rm eff} = 35\,000$ K and $\log g = 6.0$. Our own hydrodynamical calculations, which will be published elsewhere (A&A, in preparation), are in good agreement with these results (within a factor of two). For the "compact" sdB stars with $\log g > 5.5$, however, $\dot{M}$ may be clearly lower especially if the CNO elements are deficient.

Possible wind signatures (Hα lines with a central line emission) have been detected by Heber et al. (2003) in four of the more luminous sdB stars. The spectral synthesis of Hα by Vink (2004) with $\dot{M} \approx 10^{-11} M_\odot/{\rm yr}$ showed a similar behavior of the line core. Insofar theoretical predictions seem to be in agreement with observational results. In the present paper, for the example $T_{\rm eff} = 35\,000$ K, $\log g = 6.0$ and a stellar mass $M_\star = 0.5 M_\odot$ it will be investigated for which mass-loss rates a one component wind solution may be consistent.

2. METHOD OF ANALYSIS

In the following the elements H and He, for which the radiative acceleration is assumed to be zero, will be denoted as "element" 1, whereas the metals are denoted as "element" 2. As in the supersonic region the gradient of the gas pressure can be neglected, the momentum equation for "element" 1 (H+He) reads:

$$g_{\mathrm{coll}} = g_{(r)} + v_1 \frac{dv_1}{dr} \ , \tag{1}$$

g_{coll} is the collisional acceleration on H and He due to Coulomb interactions with the metals and $g_{(r)}$ is the gravitational acceleration as a function of radius. The existence of a supersonic wind with increasing velocity in outward direction requires that the acceleration term $v_1 dv_1/dr$ is larger than zero. Thus this equation can only be valid if:

$$g_{\mathrm{coll}} > g_{(r)}. \tag{2}$$

H and He cannot be accelerated if this condition is violated. Then the assumption of a steady outflow of all elements is inconsistent. As derived by Burgers (1969) g_{coll} can be written as:

$$g_{\mathrm{coll}} = \frac{\rho_2}{m_1 m_2} \frac{4\pi q_1^2 q_2^2}{kT} \left(\ln \Lambda\right) G_{(x)} \ , \tag{3}$$

m_1 and m_2 are the mean masses of "elements" 1 and 2, respectively, and $\ln \Lambda = -1/2 + \ln\left(3kTR_{\mathrm{D}}/\left(q_1 q_2\right)\right)$, where R_{D} is the Debye radius. From Eq. (3) it can be seen that (apart from the weak dependence via $\ln \Lambda$) g_{coll} is proportional to the squares of the mean charges q_1 and q_2 of both "elements" and to the inverse of the temperature T. As g_{coll} is proportional to the density ρ_2 of the metals, it decreases if the metal abundances in the wind region are reduced.

In order to accelerate H and He via collisions with the heavy elements, the mean velocity in radial direction of the metals must be larger than the one for H and He. If this velocity difference is denoted with Δv, then x is defined as

$$x = \frac{\Delta v}{\alpha}, \tag{4}$$

where $\alpha = \sqrt{2kT/\mu}$ if μ is the reduced mass of both "elements". For $T = 35\,000$ K it is $\alpha = 22$ km/s. The Chandrasekhar function $G_{(x)}$ is defined as in Krtička et al. (2003) and as it is plotted, e.g., in Krtička & Kubát (2005). The important point is that $G_{(x)}$ increases with x for $x < 1$, reaches a maximum value for $x \approx 1$ and decreases for $x > 1$. Thus for given temperature, mean charges of the elements and density of the metals, g_{coll} cannot exceed some maximum value. If this maximum value is smaller than the gravitational acceleration, no velocity difference exists for which condition (2) is fulfilled.

The density of the metals ("element" 2) as a function of radius and velocity can be obtained from the equation of continuity $\eta_2 \dot{M} = 4\pi r^2 \rho_2 v_2$ where η_2 is the mass fraction of the metals. From this equation ρ_2 can be inserted into Eq. (3) so that

$$g_{\mathrm{coll}} = \frac{1}{m_1 m_2} \frac{\eta_2 \dot{M}}{4\pi r^2 v_2} \frac{4\pi q_1^2 q_2^2}{kT} \left(\ln \Lambda\right) G_{(x)} \tag{5}$$

As both $g_{\rm coll}$ and $g_{(r)}$ scale with r^{-2}, we calculate $g_{\rm coll}$ for $r = R_\star$ and compare this with the surface gravity of the star. For the velocity of the metals $v_2 = 1000$ km/s is assumed, which is of the same order of magnitude as the surface escape velocity of 1260 km/s. If with these values condition (2) is violated for all values of x, H and He decouple from the metals before the wind is accelerated to the surface escape velocity.

3. RESULTS

The collisional acceleration on H and He is calculated for solar abundances of the metals (represented by the CNO elements). So we obtain mean masses $m_1 = 2.13 \times 10^{-24}$ g for H and He and $m_2 = 2.44 \times 10^{-23}$ g for the heavy elements. The mass fraction of the metals is $\eta_2 = 0.0133$. To maximize $g_{\rm coll}$, the maximum value of $G_{(x)}$ at $x \approx 1$ is inserted, it is $G_{(1)} = 0.214$. The mean charges have been calculated with the LTE assumption for $T = 35\,000$ K and an electron density $n_{\rm e} = 5 \times 10^{14}$ cm^{-3}. We obtain $q_1 = 1.0 q_{\rm p}$ (where $q_{\rm p}$ is the proton charge) for H and He and $q_2 = 2.6 q_{\rm p}$ for the CNO elements. As in the outer parts of the wind region the electron density is much lower, the mean charge of the metals may be larger. Thus the results for $q_2 = 5.0 q_{\rm p}$ are presented in addition.

Table 1. $g_{\rm coll}^{\rm max}$ for several values of mass-loss rates, mean charges $q_2/q_{\rm p}$ ($q_{\rm p}$ = proton charge) of the metals and temperatures.

$\log \dot{M}$ $[M_\odot/{\rm yr}]$	–11.0			–12.0			–13.0		
$q_2/q_{\rm p}$	2.6	5.0	5.0	2.6	5.0	5.0	2.6	5.0	5.0
T [kK]	35	35	350	35	35	350	35	35	350
$\log g_{\rm coll}^{\rm max}$ [cgs]	6.7	7.3	6.4	5.7	6.3	5.4	4.8	5.3	4.4

In Table 1 the maximum values of $g_{\rm coll}$ (denoted with $g_{\rm coll}^{\rm max}$) are given for several mass-loss rates, temperatures and mean charges of the metals. $g_{\rm coll}^{\rm max}$ may be compared with the surface gravity of the star ($\log g = 6.0$).

For $\log \dot{M} = -11.0$ it is $g_{\rm coll}^{\rm max} > g$ in all cases. Thus for this mass-loss rate a steady outflow of all elements may exist.

For $\log \dot{M} = -12.0$ the situation is less clear. For $T = 35\,000$ K and $q_2 = 2.6 q_{\rm p}$ it is $\log g_{\rm coll}^{\rm max} = 5.7$ only. Thus H and He would fall back onto the star so that a one component wind solution is inconsistent. For $q_2 = 5.0 q_{\rm p}$ and the same temperature we obtain $\log g_{\rm coll}^{\rm max} = 6.3$, which is larger than the surface gravity. In this case the elements could be coupled. If, however, frictional heating (due to the velocity difference of the elements) increases the temperature, then the elements could decouple again. For $T = 350$ kK (instead of $T = 35$ kK) it is $\log g_{\rm coll}^{\rm max} = 5.4$ only. Thus for $\log \dot{M} = -12.0$ more detailed calculations are necessary.

Finally, for $\log \dot{M} = -13.0$ in all cases $g_{\rm coll}^{\rm max}$ is lower than $\log g$ by a factor of the order of ten at a distance where the velocity is 1000 km/s. This means that metals decouple from H and He clearly before the wind is accelerated to the surface escape velocity.

4. CONCLUSIONS

For the case $T_{\rm eff} = 35\,000$ K and $\log g = 6.0$ it has been shown that a one component description of winds is clearly inconsistent for a mass-loss rate of the order

$10^{-13} M_\odot$/yr as required from diffusion theory to explain the helium abundances. The Coulomb coupling between H, He and the metals in the supersonic region of the wind is not sufficient to accelerate or at least to levitate H and He. Thus these elements would fall back onto the star. This result is in agreement with the predictions of Krtička & Kubát (2005).

The decoupling of elements in the wind region probably will lead to surface compositions which are different from those predicted with the assumption of chemically homogeneous winds. So it seems to be possible that fractionated winds exist and lead to the large deficiencies of Si in some sdB stars as suggested by O'Toole (2004). Fontaine et al. (2006) suggested that weak winds of the order $10^{-15} M_\odot$/yr are responsible for the coexistence of pulsating and non-pulsating sdB stars with the same stellar parameters. As the actual mass-loss rate in a multicomponent wind is unclear, this may be a viable explanation.

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