NLTE wind models of hot subdwarf stars

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Abstract We calculate NLTE models of stellar winds of hot compact stars (central stars of planetary nebulae and subdwarf stars). The studied range of subdwarf parameters is selected to cover a large part of these stars. The models predict the wind hydrodynamical structure and provide mass-loss rates for different abundances. Our models show that CNO elements are important drivers of subdwarf winds, especially for low-luminosity stars. We study the effect of X-rays and instabilities on these winds. Due to the line-driven wind instability, a significant part of the wind could be very hot.

Keywords stars: winds, outflows; stars: mass-loss; stars: early-type; stars: horizontal-branch; planetary nebulae: general

1 Subdwarf stars and the stellar wind

Despite being low-luminous, the horizontal branch stars may still have stellar winds due to their large effective temperatures and low stellar radii. The winds of these stars is thus similar to those of luminous OB stars (Vink & Cassisi 2002; Unglaub 2008), which are driven mainly by photon absorption in lines of heavy elements, e.g., C, N, O, or Fe (see Owocki 2004; Krtička & Kubát 2004; Puls et al. 2008 for a review; or Hamann 2010).

The main wind parameters are the mass-loss rate \( \dot{M} \) and the terminal velocity \( v_\infty \). The mass-loss rate depends on the stellar luminosity \( L \) as \( \dot{M} \sim L^{1/\alpha'} \) (Puls et al. 2008), where \( \alpha' \approx 0.6 \) for O stars (Krtička & Kubát 2009a). This scaling implies that the mass-loss rate increases with luminosity. Because the wind is driven by metal lines, the mass-loss rate depends also on the mass fraction of heavier elements, \( Z \). For O stars the scaling \( \dot{M} \sim Z^{0.67} \) is roughly valid (Krtička 2006). In contrast, the wind terminal velocity is proportional to the surface escape speed, \( v_\infty \propto v_{\text{esc}} \).

Here we complement the studies of hot subdwarf winds provided by Vink & Cassisi (2002) and Unglaub (2008).

2 Wind models

The stellar radiative flux (at the inner wind boundary) is taken from static, spherically symmetric NLTE model atmospheres calculated with the code of Kubát (2003). For calculation of wind models we apply the NLTE wind code of Krtička & Kubát (2004). The wind is modelled assuming a spherically symmetric, stationary flow. Ionization and excitation are derived from the solution of the statistical equilibrium equations. Ionic models adopted from the TLUSTY code (Lanz & Hubeny 2007) are based on data from the Opacity and Iron Projects (Seaton et al. 1992; Hummer et al. 1993).

The derived excitation and ionization are used to calculate the radiative force and radiative heating. These terms are inserted in the corresponding hydrodynamical equations (continuity, momentum, and energy). These equations may be solved for each component of the flow separately.

From the obtained wind structure we calculate the mass-loss rate and the terminal velocity. These values can be compared with parameters derived from observations.
3 Stellar winds of central stars of planetary nebulae

Up to now, the wind models of Krtička & Kubát (2004) were applied only to stellar winds of luminous O stars. Because there is a large gap between the parameters of luminous O stars and O subdwarfs (see Fig. 1), we first decided to calculate wind models of central stars of planetary nebulae (CSPN). This enables us to test the applicability of our wind models for stars with low luminosity.

For this test we chose the dataset of Pauldrach et al. (2004), who derived the stellar and wind parameters of selected CPSNs from observations.

A comparison between wind mass-loss rates and terminal velocities derived by us and by Pauldrach et al. (2004) see Fig. 2 showed good agreement.

The contribution of individual elements to the radiative force (Fig. 3) shows that iron contributes to the radiative force particularly close to the star. Lighter elements are important in the outer wind regions. This is similar to stellar winds of luminous O stars. We conclude that stellar wind of CSPN resembles that of luminous O stars.

4 Subdwarf stars

Turning now our attention to subdwarf stars, we selected a grid of effective temperatures $T_{\text{eff}}$ and surface
gravity acceleration $g$ that well covers the area of subdwarf parameters (see Fig. 4). We assumed a fixed stellar mass $M = 0.5 \, M_\odot$, different values of metallicity $0.3 \, Z_\odot$, $1 \, Z_\odot$, $3 \, Z_\odot$, $10 \, Z_\odot$, and helium-to-hydrogen ratios $N(\text{He})/N(\text{H})$ of 0.085, and 100 (by number).

The low luminosity of subdwarf stars implies also low mass-loss rates (see Fig. 5). Contrary to the wind of CSPNe, the radiative force is dominated by lines of lighter elements everywhere, similarly to the wind of early B main-sequence stars (see Fig. 6). The wind terminal velocity $v_\infty$ is of the order of the surface escape speed $v_{\text{esc}}$ (Fig. 7).

5 Contribution of different elements

To understand how different elements contribute to the radiative force in different situations, let us mention that the radiative force due to a particular line is given by the line optical depth and the radiative flux. The line optical depth in Sobolev approximation is

$$\tau_S \sim f_{ij} n_i \left( \frac{dv_r}{dr} \right)^{-1},$$

where $f_{ij}$ is the oscillator strength, $n_i$ is the number density of atoms in a given state, and $\frac{dv_r}{dr}$ is the velocity gradient [Puls et al. 2008]. The radiative force due to optically thick lines ($\tau_S > 1$) does not depend on level populations $n_i$, whereas the radiative force in optically thin lines ($\tau_S < 1$) depends on level populations.

To describe the contribution of individual lines to the radiative force, let us divide them into strong ones (typically resonance lines of dominant ionization stages of C, N, O), intermediate ones (strongest iron lines), and weak ones (cf. Vink & de Koter 2005). For high wind density both strong and intermediate lines are optically thick, consequently each such line contributes by a similar amount (given by the radiative flux) to the radiative force. However, because there are much more iron lines than lines of CNO elements, iron lines dominate at large densities. On the other hand, at low densities strong lines may be still optically thick (and consequently contribute to the radiative force), whereas iron lines become optically thin. As the radiative force by optically thin lines depends on the abundance of its element, which is relatively low in the case of iron, the contribution of iron to the radiative force is small in a low-density environment [Puls et al. 2000; Vink et al. 2001; Krtička et al. 2000].

The stellar winds of CSPNe or O stars have relatively high density close to the star and low density in the outer parts. Consequently, the iron lines dominate the radiative driving for small radii, whereas the lighter
elements are important at large radii (see Fig. 3). On the other hand, the stellar wind of subdwarf stars or main sequence B stars has relatively low density everywhere. Consequently, lines of light elements dominate at all radii (see Fig. 6).

6 Multicomponent wind structure

There are more similarities between the stellar winds of hot subdwarf stars and of early main-sequence B stars. One of them is connected with inefficient transfer of momentum from the radiatively driven ions to the passive ions of hydrogen and helium.

In line driven winds, momentum from radiation is transferred to heavier ions, whereas hydrogen and helium practically do not receive any momentum from the radiation field. Because heavier elements constitute only a very small part of the stellar wind (of about 1% in mass), momentum shall be transferred from these heavier ions to the passive ones. As the stellar wind of hot stars is ionized, Coulomb collisions provide the most efficient way of such transfer of momentum.

For stars with relatively high wind-density, the transfer of momentum between individual heavier ions (denoted by $i$) and the hydrogen-helium component ($p$) is efficient, because the velocity difference between these components is relatively small. However, for low density stellar winds the momentum transfer becomes inefficient and two effects may emerge: frictional heating and decoupling of wind components (e.g., Krtička & Kubát 2001, Owocki & Puls 2002, Votruba et al. 2007, Unglaub 2008).

The importance of these effects can be assessed from the value of the non-dimensional velocity difference

$$x_{ip} = \frac{|v_i - v_p|}{\alpha_{ip}},$$

where $v_i$, and $v_p$ are the velocities of the components, $\alpha_{ip}^2 = \frac{2k (m_i T_p + m_p T_i)}{m_i m_p}$, is the mean thermal speed, where $m_i$, and $m_p$ are the ionic masses, and $T_i$, $T_p$ the corresponding temperatures.

For small velocity differences, $x_{ip} \lesssim 0.1$, the flow is well coupled and multicomponent effects are negligible. For larger velocity differences, $x_{ip} \gtrsim 0.1$, frictional heating becomes important (Fig. 5), and for $x_{ip} \gtrsim 1$ the wind components may decouple. After decoupling, hydrogen and helium leave the star if the decoupling occurs at velocities larger than the escape speed, or fall back on the stellar surface if the decoupling occurs at velocities lower than the escape speed (e.g. Votruba et al. 2007, 2010).

The parameter domains, in which multicomponent effects are important are given in Fig. 9. From our calculations we conclude (in agreement with Unglaub)
log \( g \) [CGS]

\[T_{\text{eff}} \text{[kK]}\]

studied stars

Dorman et al. (1993)

\(5.0\)
\(5.5\)
\(6.0\)
\(6.5\)

\(20\)
\(30\)
\(40\)
\(50\)

\(0.471 \, \text{M}_\odot\)
\(0.473 \, \text{M}_\odot\)
\(0.475 \, \text{M}_\odot\)

frictional heating
decoupling

Fig. 9  Multicomponent effects in the \( T_{\text{eff}} - \log g \) diagram

\(\varepsilon_x\)

\(r / R_\ast\)

\(10^{-4}\)
\(10^{-3}\)
\(10^{-2}\)
\(10^{-1}\)
\(0.1\)
\(1\)

\(10^0\)
\(10^1\)
\(10^2\)

\(10^3\)

HD 203064 (O6IIe)
HD 210839 (O6Iab)
subdwarf star
weak wind problem star
normal O star

Fig. 10  Dependence of the ratio of cooling and hydrodynamical time scales on radius for individual stars

2008) that coupled subdwarf winds with \( M \lesssim 10^{-12} \, \text{M}_\odot \, \text{yr}^{-1} \) do not exist.

7 Inefficient shock cooling

The last similarity between the stellar winds of B stars and subdwarf stars mentioned here is connected with inefficient shock cooling. Hot star winds are known to be subject of the instability of radiative driving. As a result of this, a small part of the wind material of luminous O stars is very hot and emits X-rays (Owocki et al. 1988; Feldmeier et al. 1997).

However, for low-luminosity stars (e.g., the subdwarf stars) the hot part of the stellar wind may be significantly larger (Cohen et al. 2008; Krčíčka & Kubát 2009a). This can be seen from the ratio of cooling and hydrodynamical time scales plotted in Fig. 10. For O stars of normal luminosity this ratio is very small, indicating that only a very small part of the wind is very hot. On the other hand, for stars with weaker winds this ratio could be relatively large, indicating that once a shock occurs in the wind, the material has too low density to cool down significantly radiatively. Consequently, for low-luminosity stars a significant portion of the wind can be very hot, and it can be difficult to observe such winds.

For low-luminosity O stars this can explain the so-called “weak wind problem” (see Krčíčka & Kubát 2009a). The same effect could be also present in subdwarf stars (Fig. 10).

8 Similarity to the first stars

Stellar winds of hot subdwarf stars are also similar to the stellar wind of the first stars in the Universe. First stars formed from the pristine gas that emerged from the primordial nucleosynthesis. Consequently, these stars were pure hydrogen-helium, and were very massive \((M \sim 100 \, \text{M}_\odot, \text{e.g., Omukai & Palla 2003})\) and hot. Hydrogen and helium lines are not able to accelerate the wind from these stars (Krtíčka & Kubát 2009b), however, during the core He-burning phase the CNO elements (primary nitrogen) emerge at the surface due to mixing (Meynet et al. 2006). Consequently, similarly to subdwarfs stars, evolved first stars had CNO-driven winds (Gräfener & Hamann 2008; Krtíčka & Kubát 2009b).

9 Importance of the stellar winds

Although stellar winds of hot subdwarf stars are rather weak, they can still have some observable effects.

Weak stellar winds were invoked for the explanation why some subdwarf stars pulsate whereas others do not (e.g., Fontaine et al. 2006). In agreement with Unglaub (2008), our results do not support this explanation, because weak stellar winds are expected to be decoupled.

On the other hand, weak stellar winds in binaries consisting of a subdwarf star and a compact object (neutron star or a black hole) may lead to production of X-rays. Last but not least, interaction of the stellar wind from a subdwarf star with a planetary companion may also cause observable effects (Geier 2010).

10 Conclusions

We have shown that stellar winds from central stars of planetary nebulae resemble stellar winds of luminous O stars. In contrast, stellar winds of hot subdwarf stars are much weaker and resemble stellar winds of B stars in several important aspects. They
• are driven mainly by lighter elements,
• show multicomponent effects,
• may be very hot in outer parts due to inefficient shock cooling.

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