Clumping in Hot Star Winds
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Wind emission of OB supergiants and the influence of clumping

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The influence of the wind to the total continuum of OB supergiants is discussed. For wind velocity distributions with $\beta > 1.0$, the wind can have strong influence to the total continuum emission, even at optical wavelengths. Comparing the continuum emission of clumped and unclumped winds, especially for stars with high β values, delivers flux differences of up to 30% with maximum in the near-IR. Continuum observations at these wavelengths are therefore an ideal tool to discriminate between clumped and unclumped winds of OB supergiants.

1 Introduction

The spectra of hot stars show often excess emission at IR and radio wavelengths that can be ascribed to free-free and free-bound (ff-fb) emission from their wind zones (see e.g. Panagia & Felli 1975).

Waters & Lamers (1984) have investigated this excess emission for $\lambda \geq 1\,\mu$m and winds with a β-law velocity distribution of varying β, pointing already to the sensitivity of the wind emission to the chosen velocity distribution.

Over the last few years, two major effects have become obvious that both strongly influence the wind continuum emission: (i) the winds of hot stars seem to be clumped, and (ii) many OB supergiants have winds with $1.0 \leq \beta \leq 3.5$ (see Table 1).

We investigate the wind continuum emission of OB supergiants especially at optical wavelengths. First, the influence of high β values is discussed, and later on the effects of clumping are studied.

2 Continuum of OB supergiants

The calculation of the continuum emission of a typical OB supergiant is performed in three steps: (i) we first calculate the stellar emission of the supergiant with no stellar wind, (ii) then we calculate the emission of the wind with the stellar parameters ($R_*, T_{\rm eff}$) as boundary conditions, (iii) and finally we combine the two continuum sources whereby the stellar emission still has to pass through the absorbing wind. To simulate a typical OB supergiant we adopt the following set of stellar parameters: $T_{\rm eff} = 28\,000$ K, $R_* = 27.5\,R_\odot$, $\log L_*/L_\odot = 5.62$, and $\log g = 3.1$. With these parameters we compute the stellar continuum emission with the code of Kubát (2003), suitable for the calculation of NLTE spherically-symmetric model atmospheres.

Table 1: Range of β values found for OB supergiants in the Galaxy (Markova et al. 2004 = Ma; Crowther et al. 2006 = Cr; Kudritzki et al. 1999 = Ku) and the Magellanic Clouds (Evans et al. 2004 = Ev; Trundle & Lennon 2005 = TL; Trundle et al. 2004 = Tr).

Sp. Type	β	Ref.
O4 – O9.7	0.7 – 1.25	Ma
O9.5 – B3	1.2 – 3.0	Cr
B0 – B3	1.0 – 3.0	Ku
O8.5 – B0.5	1.0 - 3.5	Ev
B0.5 – B2.5	1.0 - 3.0	TL
B0.5 – B5	1.0 - 3.0	Tr

The spherically symmetric wind is assumed to be fully ionized, isothermal, and in LTE. This reduces the problem to a pure 1D treatment of the simplified radiation transfer (e.g. Panagia & Felli 1975). The electron temperature is fixed at 20 000 K, and the density distribution in the wind follows from the equation of mass continuity, relating the density at any point in the wind to the mass loss rate and the wind velocity.

The velocity of hot star winds can be approximated with a β-law

$$v(r) = v_0 + (v_\infty - v_0)\left(1 - \frac{R_*}{r}\right)^\beta \qquad (1)$$

where β describes the steepness of the velocity increase at the base of the wind, and v_0 defines the velocity on the stellar surface. A more detailed description of the calculations will be given elsewhere.

2.1 The influence of the velocity

The range in β found for Galactic and Magellanic Cloud OB supergiants is listed in Table 1. Increasing β means that the wind is accelerated more slowly. Consequently, the density in these regions is enhanced because $n_e(r) \sim \dot{M}/v(r)$. These density peaks close to the stellar surface with respect to the wind density with $\beta = 1.0$ are shown in Fig. 1.

Even though these density peaks are rather narrow in radius, they strongly influence the optical depth and therefore the emission of the ff and especially the fb processes. Now, the wind can become (at least partially) optically thick even at optical wavelengths. This leads to an enhanced wind emission meanwhile the stellar flux suffers from the simultaneously increasing wind absorption.

Our test supergiant is assumed to have a wind with $\dot{M} = 5\times10^{-6}\,M_{\odot}\mathrm{yr}^{-1}$, $v_{\infty} = 1550\,\mathrm{km\,s^{-1}}$, and we calculate the continuum emission for $\beta = 1, 2$, and 3. The results are shown in Fig. 2. It is obvious that with increasing β the wind creates a near-IR excess, absorbs more of the stellar emission, and contributes to the total emission even at optical wavelengths.

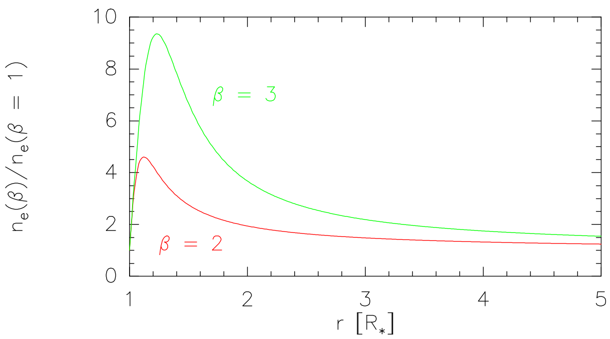

Figure 1: Pronounced density peaks close to the surface (compared to the density for $\beta = 1$) that grow with increasing β.

2.2 The influence of clumping

Hillier et al. (2003) introduced a formalism to account for the presence of wind clumping, and in our calculations we use their filling factor defined by

$$f(r) = f_{\infty} + (1 - f_{\infty})e^{-v(r)/v_{\rm cl}} \qquad (2)$$

and setting $f_{\infty} = 0.1, v_{\rm cl} = 30\,\mathrm{km\,s^{-1}}$, and $v(R_*) = v_{\rm thermal}$. Since f depends on the velocity distribution, this filling factor is a function of radius as well, constructed such that it quickly reaches its terminal value (top panel of Fig. 3). This way of clumping introduction requests, however, that in order to maintain the same radio flux, the mass loss rate has to be decreased, i.e. $\dot{M}_{\rm cl} = \sqrt{f_{\infty}}\,\dot{M}_{\rm smooth}$, while the absorption coefficient of the ff-fb processes increases, $\langle\kappa\rangle_{\rm cl} = f(r)^{-1}\,\kappa_{\rm smooth}$, due to its density squared dependence. Our clumped models automatically account for this mass loss reduction.

At those positions in the wind where $f(r) = f_{\infty}$ there is no difference between the clumped and the unclumped wind. However, in those regions where $f(r) \neq f_{\infty}$, which are also the regions where β has its strongest influence, the wind opacity is sensitive to the clumping. But while β enhances the density, clumping (for the same input $\dot{M}_{\rm smooth}$) reduces the density again. A wind with high β and clumping will therefore have a different opacity in the innermost wind region than a wind with low β and clumping, and the clumped wind will have a different opacity than the smooth wind. This is shown in the lower panel of Fig. 3 where we plotted the opacity ratio of the clumped with respect to the smooth wind for different values of β. The higher β, the stronger the effect. In Fig. 4 we compare the continuum of a clumped with an unclumped wind for $\beta = 3.0$.

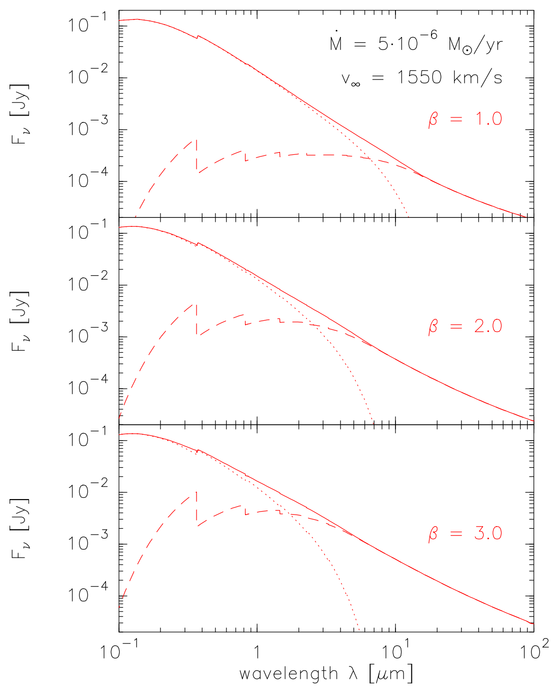

Figure 2: Continuum emission of the test OB supergiant for different values of β. Shown are the stellar emission having passed through the absorbing wind (dotted), the ff-fb emission from the wind (dashed) and the total continuum (solid).

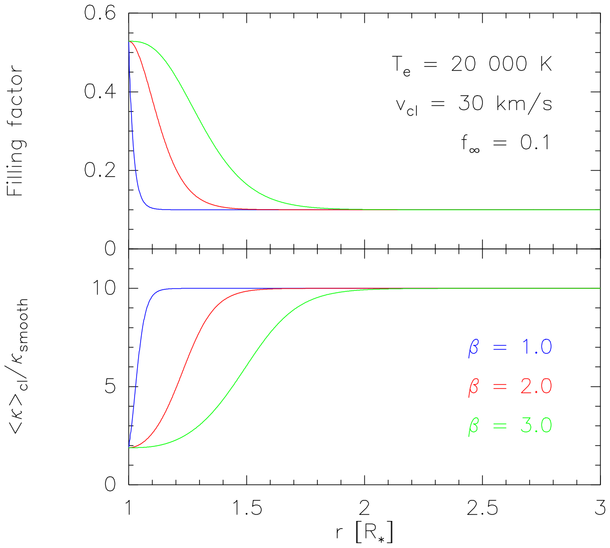

Figure 3: Top: Filling factor for different values of β. Bottom: Opacity ratio between clumped wind model and unclumped wind model.

It is obvious that the clumped model generates less wind emission for $\lambda < 10\,\mu$m. For a better visualization we calculated the flux ratios between unclumped and clumped models (Fig. 5). They show a maximum of up to 30% at near-IR wavelengths. Continuum observations at these wavelengths are therefore an ideal tool to discriminate whether the winds of OB stars with $\beta > 1.0$ are clumped.

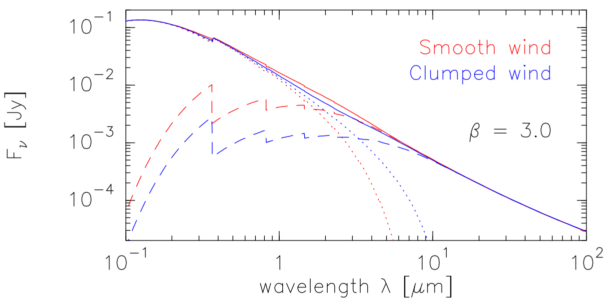

Figure 4: Clumped versus unclumped wind with $\beta = 3.0$. The clumped model produces less wind emission for $\lambda < 10\,\mu$m, resulting in a lower total near-IR flux.

3 Conclusions

For OB supergiants with high β values the ff and especially the fb emission can strongly influence the total continuum, even at optical wavelengths.

Clumping, introduced by the filling factor approach, also influences the wind opacity and therefore the continuum emission. Whether the wind of an OB supergiant is clumped or not can be checked based on continuum observations in the optical and near-IR region. Especially winds with high β are found to have fluxes that differ by about 30% (see Fig. 5). The optical and near-IR continuum are therefore ideal to discriminate between clumped and unclumped winds.

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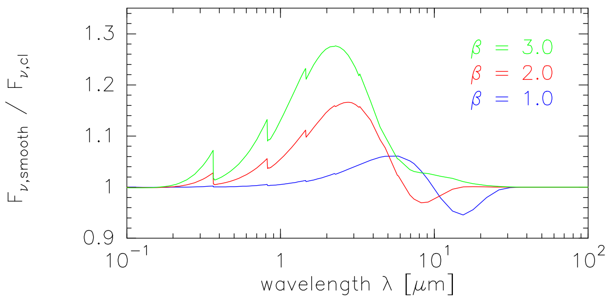

Figure 5: Continuum flux ratio between the unclumped and clumped wind models. The ratio increases with β having a maximum in the near-IR.

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Cohen: Have you considered non-isothermal winds?

Kraus: A non-isothermal wind will not change the spectrum significantly. The free-free emission is hardly temperature dependent, and the free-bound emission, which does depend on temperature, is created in the innermost wind region where the wind temperature is highest. An isothermal wind at high electron temperature is therefore a reasonable assumption for our continuum calculations.