Hot And Cool: Bridging Gaps in Massive Star Evolution
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Radiative Transfer Modeling of the Winds & Circumstellar Environments of Hot And Cool Massive Stars

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Abstract. We present modeling research work of the winds and circumstellar environments of a variety of prototypical hot and cool massive stars using advanced radiative transfer calculations. This research aims at unraveling the detailed physics of various mass-loss mechanisms of luminous stars in the upper portion of the H-R diagram. Very recent 3-D radiative transfer calculations, combined with hydrodynamic simulations, show that radiatively-driven winds of OB supergiants are structured due to large-scale density- and velocity-fields caused by rotating bright spots at the stellar equator. The mass-loss rates computed from matching Discrete Absorption Components (DACs) in *IUE* observations of HD 64760 (B Ib) do not reveal appreciable changes from the rates of unstructured (smooth) wind models.

Intermediate yellow supergiants (such as the yellow hypergiant ρ Cas, F−G Ia0), on the other hand, show prominent spectroscopic signatures of strongly increased mass-loss rates during episodic outbursts that cause dramatic changes of the stellar photospheric conditions. Long-term high-resolution spectroscopic monitoring of cool hypergiants near the Yellow Evolutionary Void reveals that their mass-loss rates and wind-structure are dominated by photospheric eruptions and large-amplitude pulsations that impart mechanical momentum to the circumstellar environment by propagating acoustic (shock) waves.

In massive red supergiants, however, clear evidence for mechanical wave propagation from the sub-photospheric convection zones is lacking, despite their frequently observed spectroscopic and photometric variability. Recent spatially resolved HST-*STIS* observations inside Betelgeuse's (M Iab) very extended chromosphere and dust envelope show evidence of warm chromospheric gas far beyond the dust condensation radius of radiative transfer models. Models for these long-term spectroscopic observations demonstrate that the chromospheric pulsations are not spherically symmetric. The *STIS* observations point to the importance of mechanical wave propagation for heating and sustaining chromospheric conditions in the extended winds of red supergiants.

1. Introduction

The winds and circumstellar environments of massive stars are unique laboratories for studying the detailed physics of stellar mass-loss mechanisms. In many luminous hot and cool supergiants large spectroscopic variability is observed on time-scales of weeks to years. Long-term spectroscopic monitoring of massive-star variability over the past three decades therefore has provided a wealth of information about the driving physics and active structuring mechanisms in these stars with very extended winds. This paper provides a brief overview of important research results for a hot, intermediate, and cool supergiant obtained with advanced radiative transfer modeling of the spectroscopic variability.

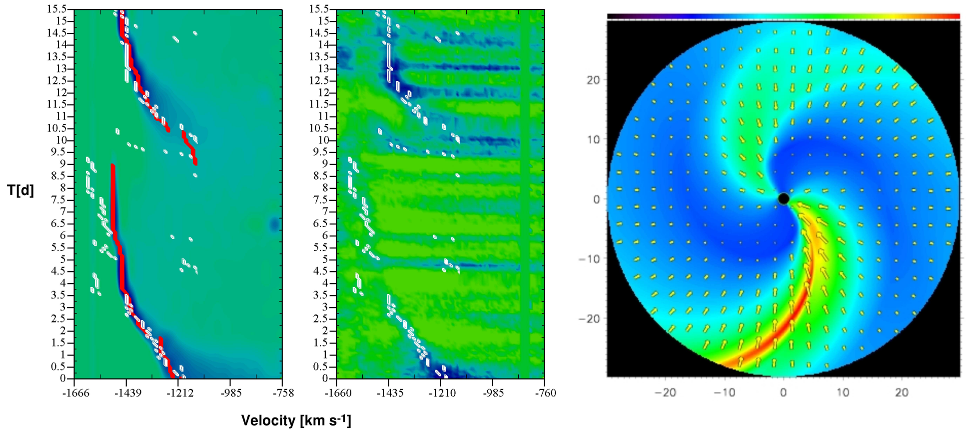

Figure 1. *Panel left:* 3-D non-LTE radiative transfer fit with WIND3D to the DACs in Si IV λ1395 compared to *IUE* observations of HD 64760 (*middle panel*). *Panel right:* Density contrast of the hydrodynamic input model computed with ZEUS3D. Two unequally bright spots produce large-scale wind-velocity structures and density enhancements. The size of the over-plotted arrows indicates the magnitude of the velocity deceleration with respect to the smooth unperturbed wind. The bright spots cause rotating density waves in the equatorial wind of the hot supergiant (*see text*).

2. 3-D Modeling the Wind of Hot Supergiant HD 64760 (B Ib)

In recent years it has become clear that mass-loss rates of hot massive stars are considerably overestimated because the clumping of their winds has not been taken into account. Understanding the physical nature of these wind clumping processes, determining the amount of wind clumping, and revising the total stellar mass-loss rates are therefore hot topics in current massive star research. Detailed information about the wind structure can be obtained with accurate numerical models. We develop a parallel computer code WIND3D which solves the 3-D transport of radiation in the scattering winds of massive stars. It calculates the detailed shape of resonance lines that form in very extended winds (e.g., P Cygni profiles) in non-LTE.

We apply WIND3D for the detailed modeling of DACs observed in the Si IV resonance lines of HD 64760 (B0.5 Ib), a key massive hot star. The study provides new evidence that the DACs are in fact large-scale spiraling density- and velocity-structures in the equatorial wind. These wind structures are due to rotating hotspots at the stellar surface. The bright spots do not co-rotate with the stellar surface, but lag five times behind the fast surface rotation. A hydrodynamic model with two spots of unequal brightness and size on opposite sides of the equator, with opening angles of 20° ±5° and 30° ±5° diameter, and that are 20±5% and 8±5% brighter than the stellar surface, respectively, provides the best fit to the observed DACs (*Fig. 1*). The mass-loss rate of the structured wind model does not exceed the rate of the spherically symmetric smooth wind model by more than 1% (Lobel & Blomme 2008).

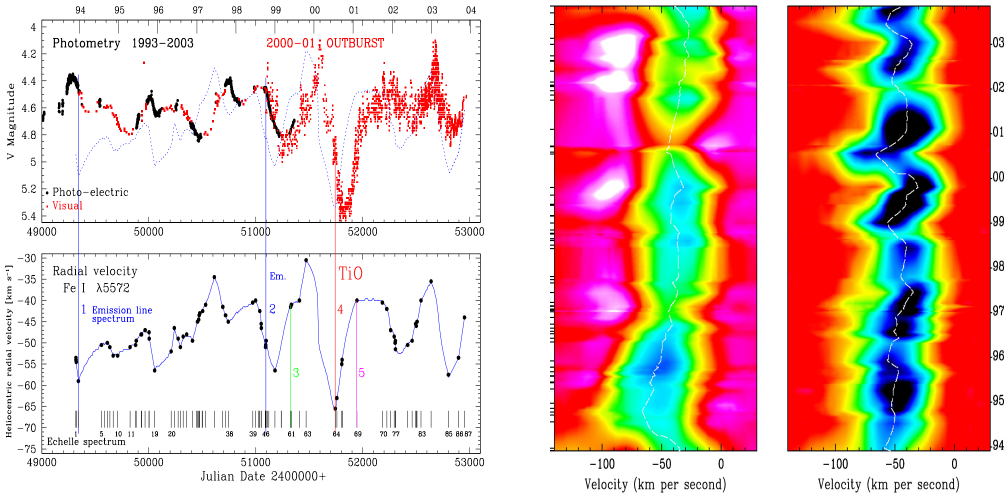

Figure 2. *Panel left:* Visual brightness changes observed in ρ Cas between 1993 and 2003 (*upper panel*) are compared to the radial velocity variability (*lower panel*) of an unblended photospheric absorption line of Fe I λ5572. *Panel right:* Dynamic spectra of Hα (*left*) and Fe I λ5572 (*right*). Observations are marked with left-hand tickmarks. The Fe I line strongly blue-shifts during the large outburst of mid 2000 when the atmosphere cools by 3000 K (*see text*).

3. The Millennium Outburst of Yellow Hypergiant ρ Cas (F–G Ia0)

Yellow hypergiants are post-red supergiants, rapidly evolving toward the blue supergiant phase (de Jager 1998). They are among the prime candidates for progenitors of Type II supernovae in the Galaxy. In July 2000 we observed the formation of new TiO bands in F-type hypergiant ρ Cas during a strong V-brightness decrease of $\sim 1^{\rm m}.4$ (*Fig. 2*). Synthetic spectrum calculations reveal that $T_{\rm eff}$ decreased by at least 3000 K, from 7250 K to $\simeq$4250 K, and the spectrum became comparable to an early M-type supergiant. The TiO bands signal the formation of a cool circumstellar gas shell with $T_{\rm gas} < 4000$ K due to the supersonic expansion of the photosphere and upper atmosphere. We observe a shell expansion velocity of $\sim$35$\pm$2 km s^{-1} from the TiO bands. From the synthetic spectrum fits to the bands we compute an exceptionally large mass-loss rate of $\dot{M} \simeq 5.4 \times 10^{-2}$ M$_{\odot}$ yr^{-1}, ($\sim$5% of M$_{\odot}$ in 200 d). It is therefore one of the largest stellar outburst events that has directly been monitored so far (Lobel et al. 2003). The right-hand panel of Fig. 2 shows dynamic spectra of Hα and Fe I λ5572 observed between 1993 and late 2003. The radial velocity curves of the Hα absorption core and the photospheric Fe I lines (*white dashed lines*) reveal a velocity stratified dynamic atmosphere. A strong collapse of the upper Hα atmosphere and the lower photosphere precedes the outburst event during the large-amplitude pre-outburst pulsation cycle of 1999.

Based on radiative transport calculations Gorlova et al. (2006) presented a model for the near-IR CO emission emerging from cool atmospheric layers in the immediate vicinity of ρ Cas' photosphere. The gas kinetic temperature minimum in the model results from a periodical pulsation-driven shock wave.

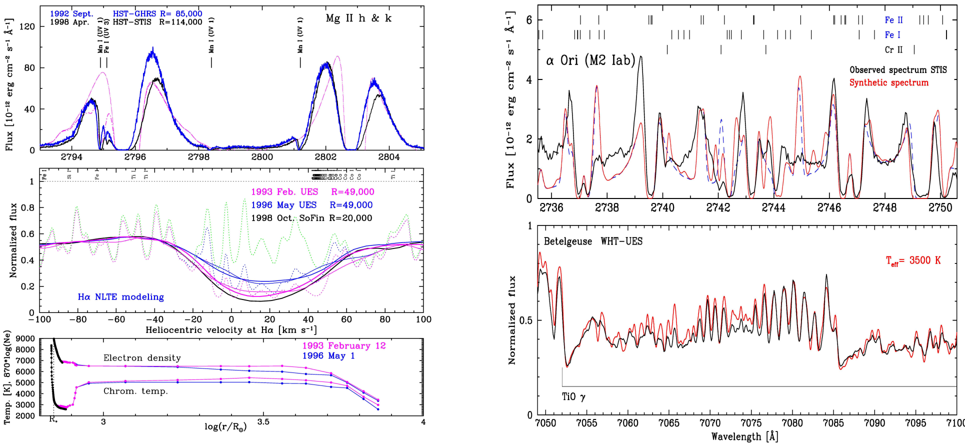

Figure 3. *Panels left:* Large spectral resolution observations of the Mg II h & k and Balmer Hα lines (*boldly drawn lines*) reveal long-term chromospheric variability in α Ori. Best non-LTE fits (*thin drawn lines*) constrain the gas kinetic temperature and electron density structure of the inner chromosphere. The model of the photosphere below the chromosphere has $T_{\rm eff}$=3500 K. (*bottom panel*). *Panels right:* The chromospheric emission line spectrum (*upper panel*) is well-reproduced using only iron lines (*dashed drawn line*), and a model $T_{\rm gas}$ maximum $\simeq$5550 K. The lower panel shows the best fit (*thin line*) to the optical spectrum around strong γ-system band-heads of TiO.

4. Modeling Chromospheric Dynamics of Red Supergiant Betelgeuse

1-D models of the thermodynamic and dynamic structure of α Ori's photosphere and inner chromosphere (to $\sim$10 R$_*$) are developed in Lobel & Dupree (2000). Modern methods in radiative transfer modeling venture well beyond outdated approaches that, for example, can only consider escape probabilities and radio fluxes. The latter flux-integrated models completely fail to produce fundamental chromospheric lines (e.g., Balmer H, and Mg II, Ca II, K I resonance lines, etc.). Accurate models (1-D or multi-D) for these important spectral lines are required for unraveling the wind-driving mechanism and related heating physics in the outer atmospheres of cool stars. The transport of radiation does not discriminate between so-called 'warm and cool gas components'. In transfer calculations (irrespective of the number of dimensions), the model temperature and electron density structures ($N_{\rm e}$) must properly excite chromospheric absorption (e.g., Hα, Hβ) and emission lines, including the central self-reversals of optically thick emission lines. The model in Fig. 3 shows the radial mean values of $T_{\rm gas}$ and $N_{\rm e}$ up to $\sim$10 R$_*$, based on detailed fits to the classical chromospheric indicators observed in α Ori. It correctly produces the observed near-UV emission line spectrum. A model without a gas kinetic temperature structure increasing to $\sim$5550 K in the inner chromosphere cannot excite the subordinate Hα-transition of $\sim$300 mÅ. The entire absorption line would become invisible with respect to strong TiO absorption in the cooler photosphere (Lobel & Dupree 2000). The Mg II h & k emission lines would also vanish. The fully intensity-saturated self-scattered cores of these broad lines (about the strongest chromospheric emission lines observed in any cool star) result from a

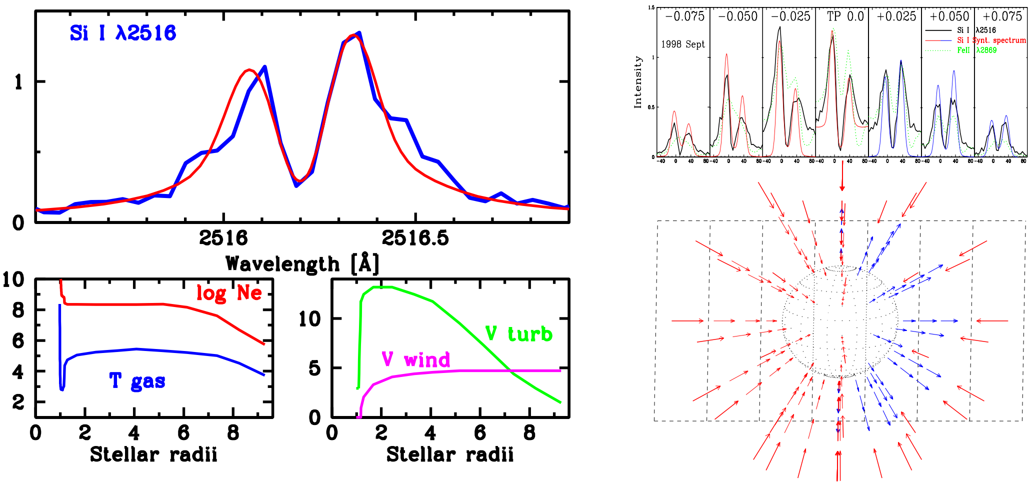

Figure 4. *Panels left:* Detailed non-LTE fit (*thin line in upper panel*) to the spatially resolved Si I λ2516 emission line observed in α Ori at 75 mas with HST-*STIS* (*boldly drawn line*). The radial structures of the model are shown in the lower panels. $T_{\rm gas}$ is in kK units, and Vwind and Vturb in km s^{-1}. *Panels right:* 3-D mean flow velocities are inferred from detailed fits (*thin drawn lines in upper panel*) to the asymmetric shape of the Si I line (*bold lines*). The reversal of the emission line component intensity reveals simultaneous up- and downflow across the front hemisphere in 1998 September.

very large column of (warm) chromospheric plasma that dominates the overall gas kinetic temperature- and density-structure of the inner chromosphere. A much steeper outwardly decrease of $N_{\rm e}$ (i.e., by an order of magnitude over 2 R$_*$) yields too large decrements of total widths computed for spatially resolved chromospheric emission lines. Large variations of chromospheric emission line widths are consistently not observed in spatially resolved raster scans across the inner chromosphere with HST-*STIS* in 1998−1999. The macro-broadening velocity is supersonic (9$\pm$1 km s^{-1}), and observed to be highly isotropic and homogeneous (Lobel & Dupree 2001) across the inner chromospheric disk.

Detailed transfer fits to the temporal variability and spatial intensity reversals observed in the emission line components of Si I λ2516 reveal that the inner chromosphere oscillates asymmetrically with simultaneous up-and downflow ($\pm$4 km s^{-1}) across the front hemisphere (*Fig. 4*). Interestingly, Freytag & Höfner (2008) recently presented 3-D hydrodynamic models with large asymmetric movements of the photosphere and strong ($M_{\rm rad}$>2) radially propagating shock waves. Strong shock waves are an efficient mechanism for transporting mechanical momentum very far from the stellar surface. They can support the co-existence of dust-sustaining low-temperature conditions ($T_{\rm dust}\simeq$600 K) and (possibly shock-excited) chromospheric emission lines observed with *STIS* far inside the circumstellar dust envelope (*Fig. 5*; Lobel 2005) up to 3$''$ (>100 R$_*$).

5. Conclusions

Mechanical wave action (provided by circumstellar density waves, propagation of pressure waves, and astrophysical turbulence) due to atmospheric pulsation is

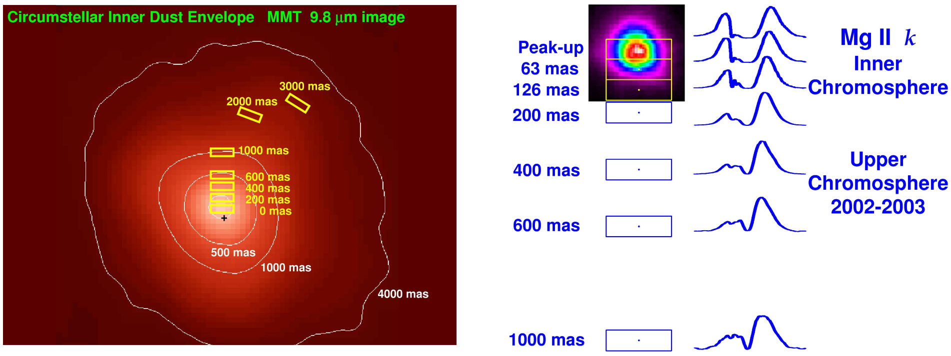

Figure 5. *Panel left:* Relative aperture positions of spatially resolved spectroscopic observations with HST-*STIS* in 2002-2003 compared to a 9.8 μm image (MMT-*MIRAC*2) of α Ori's inner circumstellar dust envelope (*adapted from Hinz et al. 1998*). *Panel right:* The Mg II k resonance emission line observed across the inner and upper chromosphere with the 63×200 mas aperture compared to a false color near-UV image (HST-*FOC*). The line is scaled to equal intensities and reveals important profile shape changes of the central self-scattering core, signaling outward acceleration of the chromospheric wind.

a very important aspect for studying the detailed physics of active structuring, acceleration, and heating mechanisms of the extended winds and circumstellar environments of hot and cool massive stars. Recent advances in quantitative spectroscopy that combine 3-D radiative transfer methods with multi-D hydrodynamic and semi-empiric modeling provide powerful new methods for pinpointing these mechanisms.

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