# CONVECTION, ATMOSPHERES AND WINDS OF RED SUPERGIANT STARS

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## Abstract

Red supergiant stars (RSG) constitute a key-phase in the evolution of massive stars, characterized by strong mass loss of unknown origin. On-going radiative hydrodynamics (RHD) simulations of these stars with $CO^5BOLD$ show a peculiar convection pattern, with giant cells.
We present high-resolution, multi-epoch spectroscopy of a sample of RSG, which provides a diagnostic of their atmospheric dynamics. We show synthetic spectra based on 3D RHD models. We suggest that convective motions are important in the generation of the observed mass-loss rates.

Key words: Hydrodynamics – Stars: atmospheres – Stars: mass loss – Stars: supergiants – Stars: individual: $\alpha$ Ori

## 1. Introduction

Red supergiant stars (hereafter RSG) represent a key-phase in the evolution of massive stars ($\sim$10 to 40 $M_\odot$), preceeding WC and SN II. They play a key-role in galactic chemical evolution, being the main source of CNO and secondary s-elements. Furthermore, thanks to their high luminosity peaking in the near-infrared, they may be used as distance indicators.

It is thus striking that their structure and evolution is still so poorly known. Convection in RSG is among the puzzling questions. The idea of giant convective cells in their atmosphere was suggested for the first time by Stothers & Leung (1971). From considerations about pressure scale heights and extrapolation from solar values, Schwarzschild (1975) suggested that the entire surface of a RSG should be occupied by at most a dozen convective cells. Recent radiative hydrodynamics simulations by Freytag et al. (2002) seem to cinfirm this idea.

This peculiar convective structure may have strong impact on the mass loss process, which results into rates $\geq 10^{-6}$ $M_\odot$ $yr^{-1}$.

## 2. Sample, observations and tomography

We performed multi-epoch spectroscopy of a sample of RSG with the ELODIE echelle spectrograph (R = 42000), mounted on the T193cm at the Observatoire de Haute Provence (F) during 1.5 year. The sample is presented in Table 1. The observations are analyzed with the tomographic technique developed by Alvarez et al. (2001). The spectra are convolved with a set of numerical masks which probe different stellar atmospheric layers, from the innermost (mask C1, containing high-excitation lines) to the outermost layers (mask C8, low-excitation lines). The cross-correlation functions (CCF) may be understood as line profiles typical of a given depth of formation, with higher signal-to-noise and resolution than the original data. Typical CCF for a RSG are displayed in Fig. 1.

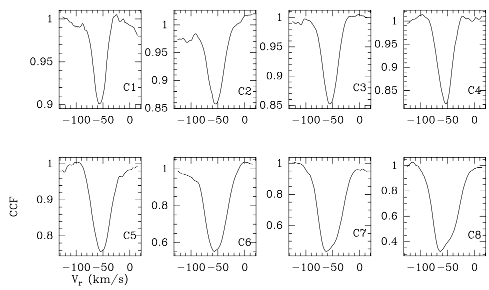


*Figure 1. Example of CCFs for the RSG TZ Cas.*

*Table 1. Observed sample of RSG.*

| Name | spectral type |
|---|---|
| HS Cas | M4 Iab |
| V466 Cas | M2 Ib |
| AD Per | M3 Iab |
| FZ Per | M1 Iab |
| $\alpha$ Ori | M2 Iab |
| V336 Vul | M 2-3 I |
| BD+24 3902 | M1 Ia |
| BI Cyg | M3 Ia-Iab |
| BC Cyg | M3.5 Ia |
| SW Cep | M3.5 I |
| $\mu$ Cep | M2 Iab |
| RW Cep | G8 Ia |
| ST Cep | M2 Ib |
| TZ Cas | M2 Iab |

## 3. Analysis of the observations

### 3.1. Atmospheric dynamics

The CCFs present a wide variety of shapes, for each star from one mask to another, and from one star to another. We find velocity shifts between the weak and strong lines, with values up to $\sim$25 km s$^{-1}$, thus sometimes supersonic. Weaker lines generally appear blueshifted relative to stronger lines. The correlation profiles (and thus the line profiles) also display strong departures from symmetry, with, in some cases, two or more components. As shown in Figs. 2 and 3, the profiles vary with time, in shape, depth, and velocity.

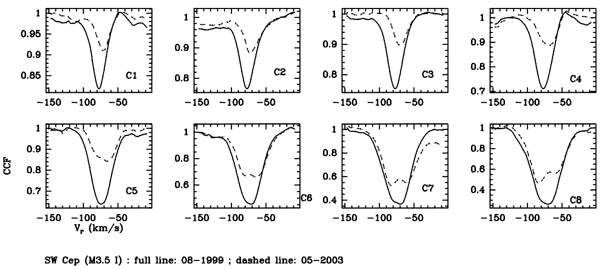


*Figure 2. Comparison of the CCFs of SW Cep at two epochs (full line: August 1999; dashed line: May 2003). Each panel is labelled with the numerical mask (see text).*

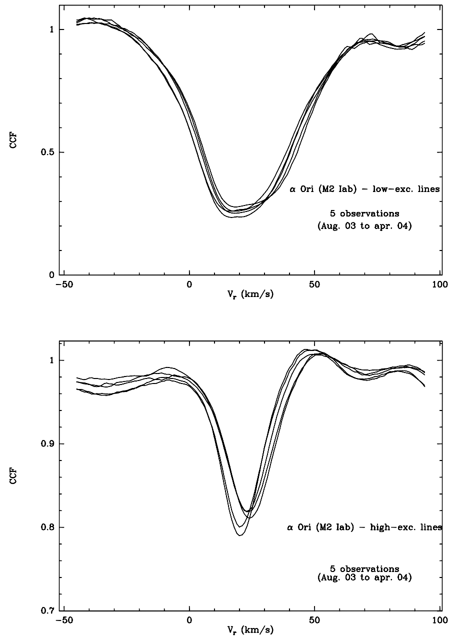


*Figure 3. Time variations of the CCFs for $\alpha$ Ori. Lower panel: mask C1, which probes the innermost atmospheric layers; upper panel: mask C8, which probes the outermost layer.*

The observed velocity fields may reflect convective motions. Indeed, line shifts and time variations are in qualitative agreement with the characteristics displayed by 3D hydrodynamical models (Freytag et al. 2002; see below). Our observations thus tend to confirm Schwarzschild's original idea of giant convective cells.

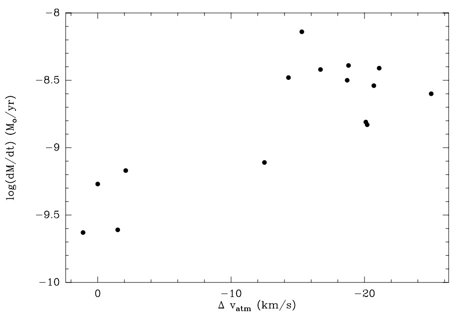


*Figure 4. Relation between observed atmospheric velocities and dust mass-loss rates, estimated by Josselin et al. (2000).*

### 3.2. Link between convection and mass loss?

The amplitude of the observed atmospheric velocities seems to correlate with both stellar radius (Josselin et al. 2003) and dust mass-loss rate (Fig. 4). As the escape velocity varies as $R^{-1/2}$, $v_{\rm esc}/\Delta v_{\rm atm}$ decreases as the stellar radius increases. Convective motions in low-gravity stars could thus provide the required energy for mass loss. Possible mechanisms include acoustic and alfvenic waves (Hartmann & Avrett 1984, Cuntz 1997). This would explain the observed increase of the mass-loss rate with $\Delta v_{atm}$.

## 4. Radiative transfer in 3D hydrodynamic models

3D radiative hydrodynamics (RHD) models of RSG are developed by Freytag et al. (2002). One of the remarkable predictions of these models is the peculiar convective pattern with very few cells. We performed LTE radiative transfer through snapshots of one of these models. The characteristics of the chosen model are: mass = 5 $M_\odot$, radius = 650 $R_\odot$, effective temperature = 3500 K.

The emerging spectra were first compared with those obtained from a 1D, static MARCS model (Gustafsson et al. 2003) with similar stellar parameters (Fig. 5). Convolution of the MARCS model spectrum with a macroturbulent velocity of $\sim$15 km s$^{-1}$ brings the weaker lines in approximate agreement with the 3D model spectrum. This value of 15 km s$^{-1}$ is typical in analyses of RSG spectra using 1D models (see e.g. Carr et al. 2000).

In 3D model spectra weak lines are blue-shifted, just as shown by the observations. Strong lines appear closer to rest wavelength, but they are filled in compared to the 1D static case. Temporal variations of the calculated line profiles are also in qualitative agreement with our observations (Fig. 6) but the amplitude of the variations seems too high (Freytag et al., 2004).

We are now carrying out detailed comparison of the calculated spectra with observations.

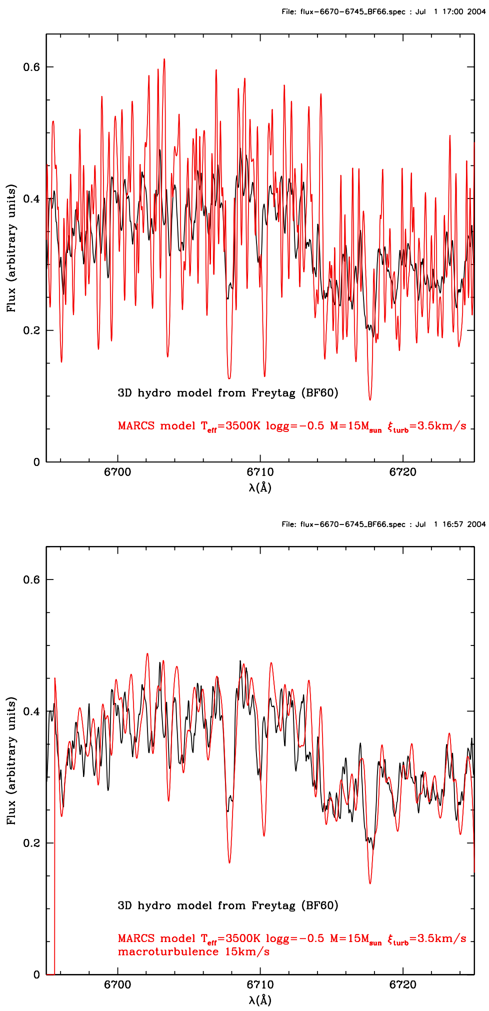


*Figure 5. Comparison of the spectra emerging from a 3D RHD model (black curve) and a MARCS hydrostatic model (red curve). In the lower panel the hydrostatic spectrum has been convolved with a macroturbulent velocity of 15 km s$^{-1}$.*

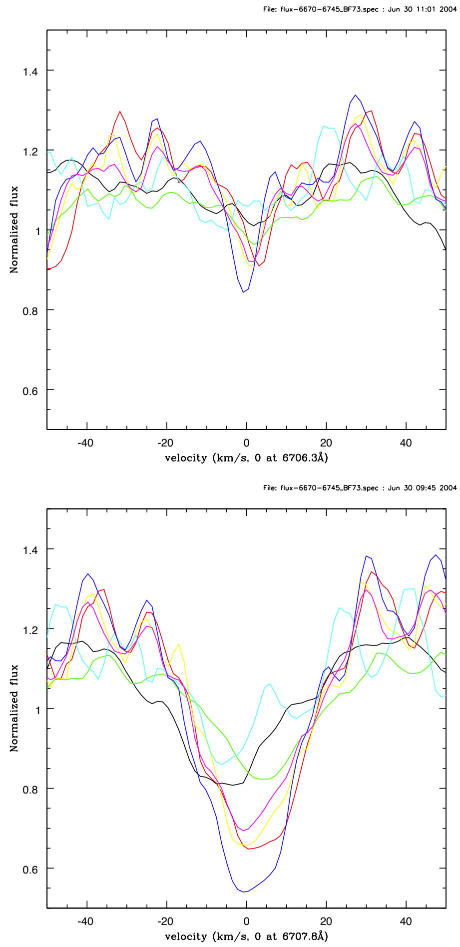


*Figure 6. Variations of a high-excitation line profile (upper panel) and a low excitation line profile (lower panel) emerging from a 3D RHD model of a RSG. The time step is 2 10$^6$ s (∼ 3 weeks).*

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