Chapter 10

Conclusions et perspectives

The motivation of this thesis was the idea that our understanding of RSG stars would benefit greatly from the use of three-dimensional simulation.

The state-of-the-art of these simulations has been quantitatively explored and compared to the observations. For this purpose, I have written a three-dimensional radiative transfer code that takes into account Doppler shifts as well as millions of molecular and atomic lines simultaneously. I have validated it by comparing it to the Turbospectrum and LINFOR3D codes.

The first step was to determine the granulation size in the three-dimensional simulation at different wavelengths.
In the near-IR, the convective pattern is characterized by bright regions surrounded by dark intersection filaments corresponding to infalling gas. The surface is covered by large (400-500 $R_{\odot}$) convective cells with a lifetime longer than the 3.5 years span by the simulation. There are also smaller structures that evolve with a lifetime of a few months to one year.
In the optical, the intensity contrast is reversed and the surface appears more patchy.

In the next part of my analysis, I studied the velocity fields in the atmosphere of RHD simulations using the cross correlation functions and compared them to the observations. I found that the velocity amplitudes in the simulation are in agreement with the observations. I also provided the characteristic velocities in the atmosphere, line bisectors and radial velocity correction due to the convection motions. I have also found that the predominant shape of the TiI line (6261.11 Å) bisector is a reversed "C" as observed for α Ori. These predictions shall be tested by future observations.

Finally, I studied the particular signature of the convection-related surface structures on interferometric visibility curves and phases. I produced a number of predictions for future detection and measurement of the granulation pattern with today interferometers. I also provided new limb darkening coefficients adapted for the intensity profile of RSGs.

I also compared the RHD simulations to the interferometric observations of: (i) μ Cep in the K band and I found that the model cannot reproduce the data in the first lobe. Therefore, I tried to explore the possibility of the existence of a MOLsphere around the star. However, even with my an ad-hoc model I could not explain the data. (ii) α Ori in the K and H band and I found that RHD models can explain the data at high spatial frequencies where the UD and LD parametric models fail. I concluded that the surface of α Ori, in the H and K bands, appears to be covered by convective cells that contribute to the visibility at high frequencies.

Let's now recall the questions listed in the beginning of my thesis:

- *Are the three-dimensional models consistent enough for the interpretation of observations?*
  The RHD simulations have been compared to spectroscopic and interferometric observations which reveal that they can explain the observations, especially the interferometric data.
  The spesctroscopic comparisons (Sect. 6.2.3, 6.2.4) show that the temperature gradient is too shallow and the absorption lines are saturated. This is a consequence of the grey treatment of the opacity and it is the principal problem in RHD simulation. The introduction of the frequency dependance of the opacities introduces a closer coupling to the radiative equilibrium temperature stratification and strongly influences the evolution of the flow features (Stein & Nordlund 1998 and Ludwig et al. 1994). The convective overshoot could increase the temperature gradient and may also change the dynamics of the atmosphere.
  The exploratory model I have tested in Chapter 9 hints toward this explanation since the temperature gradient increases. However, the changes in the spectrum are not strong because the model was not relaxed. Major efforts, both in terms of human and computer calculations are necessary if we wish to implement the non-grey treatment in the near future.

- *What does the surface of a RSG look like? How can the convection pattern be detected and characterized?*
  Convection pattern of RSG is wavelength dependent. In the near-IR, there are only few large scale granules (typically 400-500 $R_\odot$) with a lifetime of years. Small scale structures are also visible and they have a life time of few months to one year.
  In the optical the situation is completely different; the intensity contrast is reversed and the surface appears more patchy. The prediction of the photocenter variations, particularly for the more active optical region, are of extreme interest for future and present missions (GAIA and SIM).
  From a spectroscopic point of view, the predictions of RHD simulations show line shifts and asymmetries as well as the line bisectors resembling a reversed-"C" shape which has recently been observed in α Ori by Gray (2008). However, at this moment in time, interferometers are the best way of detecting and characterizing the convection pattern of RSGs. Surface granulation causes angular and temporal visibility fluctuations that, in the first lobe, add an additional uncertainty to the determination of the stellar radius, and in the second, third and fourth lobe carry the clear

signature of departure from circular symmetry.
The interferometric observations must reach higher spatial frequencies, beyond the simple determination of the stellar radius and limb darkening coefficient. These measurements will allow us to determine the typical size of the convective cells and to investigate the granulation contrast using the visibility fluctuations.
I want to stress that high spectral resolution is crucial in order to analyze the variations between different spectral features and continuum. This is especially true for the H band, which is a good target for measuring the angular and temporal fluctuations of the visibility curves and closure phases. The combination of the angular and spectral information will help uncover the size of the granulation and its contrast.
Finally, with the increasing spatial resolution of interferometers like ESO's VLTI, resolved images of RSGs will be obtained in the near future. These images will give us an additional information about the inhomogeneities and other dynamic modes at play on the stellar surface which will then be used to constrain the RHD simulation.

- *How does the convection affect the spectral lines? Are the three-dimensional models better than the one-dimensional ones?*
  The high resolution synthetic spectra from RHD simulations show evolving line shifts and asymmetries. This is a consequence of the velocity field and of the temperature inhomogeneities on the surface. The RHD simulation approximately reproduces the width and depth of the weak CO line (see Sect. 6.2.1) without invoking any free parameters such as micro or macroturbulence which is always necessary in 1D modeling.
  If the RHD models would are used to determine the temperature scale based on the fit of TiO bands, they show an effective temperature scale cooler than what one-dimensional models show (e.g., Levesque et al. 2005). But which scale is correct? The RHD simulations use a grey treatment of the opacities while the one-dimensional models compute a detailed spectral synthesis, but with an incorrect description of convection.
  For the many reasons listed in this thesis, I think that RHD simulations of RSGs present a great improvement for the interpretation of the observations. However, they are CPU costly (e.g., about 100 days more or less continuously on a MacPro Intel, 4 processors with a clock speed of 3 GHz), they have a considerable output (about 100Gb per relaxed model), and the radiation transfer should be more detailed. On the other hand, one-dimensional models have been extensively developed over the past 3 decades with many improvements especially in the detailed opacity description that has lead to a good match of spectra and photometry with cool stars in general (e.g., Bessell et al. 1998; Massey et al. 2005) and they are rapidly computed.
  Thus the one-dimensional models are still important to corroborate the predictions of three-dimensional models. However, in order to be able to interpret observed spectra in terms of abundances and fundamental stellar parameters, it is crucial to fully characterize the convection in RSGs which can only be done with RHD simulations (e.g., for the Sun, Asplund et al. 2006 and other works; Caffau et al. 2007-2008 papers).

- *What are the velocity fields in RSGs and what is the origin of their mass-loss?*
  In Chapter 5, I have found that the characteristic velocities measured with CCF show that the RHD models agree qualitatively with the observations. The most important task is to establish the link between these CCF velocities and the RHD velocities that contribute in the simulation. In order to do this, it is necessary to analyze the behavior of these velocities at each depth in the atmosphere. The characterization of the RSG velocities is crucial in order to find precursor of the mass-loss. Josselin & Plez suggested that the mass loss in RSG stars could be initiated by the combined effect of a vigorous convection and radiative pressure on molecular lines. The radiative pressure term must eventually be included in CO^5BOLD in order to study the RSG wind formation process.

Presently, more observations will be compared in order to verify the prediction of the models in terms of: (i) line bisectors and asymmetries (e.g., further comparison to Gray 2008), and the velocity field (a larger temporal survey of RSGs by Josselin & Plez 2007), (ii) detection and measure of the granulation pattern and surface contrast with interferomentric observations (passed and future VLTI-AMBER proposals, see Appendix B), (iii) investigation of the MOLsphere presence osberving in the N and L bands using differential interferometry.

In the near future, developments of OPTIM3D will consist in the development of Opacity Sampling based on MARCS OS tables. The low resolution spectra are necessary to compare the models with spectrophotometric observations (e.g., Lançon & Wood 2000 and Levesque et al. 2005).
Levesque et al. (2006) suggested that there is an inconsistency in the IR fluxes predicted by the one-dimensional models for a given TiO band depth. The difference reaches 40% in the K flux. Also Ryde et al. (2006) found that a MARCS model at 3600K, that can fit TiO bands in the optical, is not able to explain the water vapor lines at 12 μm, and he showed that this was possible with a cooler (3250K) model.
Surface inhomogeneities on RSGs could explain the wavelength-dependence of the effective temperature and RHD simulations present a unique opportunity to solve this puzzle. Thus, the OS with OPTIM3D will provide the spectra necessary for this investigation.

On a longer time-scale, the inclusion of the scattering in OPTIM3D appears to be fundamental to achieve appropriate synthetic spectra in the blue part of the spectrum of RSGs as shown by tests with one-dimensional MARCS models.
Concerning the RHD simulation, a major improvement will be the inclusion of the non-grey treatment of opacities with a set of opacity tables that cover the whole temperature and density extension of the simulations. This work will be done in a near future with the collaboration of Dr. B. Freytag and Dr. H.-G. Ludwig. Also, the inclusion of the radiation pressure is necessary. I plan to collaborate with Dr. B Freytag in order to make it available for the study of the mass-loss problem.
Finally, a natural extension of my work goes to other types of stars like AGBs and RGBs with the determination of the spectroscopic and interferometric observables with OPTIM3D. Different models are available, both three-dimensional (CO^5BOLD local models)

for Red Giants and one/three-dimensional for AGBs (e.g., Höfner 1999 and Freytag & Höfner 2008).