Winds of red giants and supergiants: Basic physical processes, structure and appearance

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Abstract. Red giants and supergiants usually exhibit three important phenomena:

i) effective grain formation manifested by large infrared excesses, ii) considerable mass loss carried by slow, massive stellar winds, and iii) pronounced spectral variability induced by more or less regular stellar pulsations.

We discuss the specific relevance of these different aspects for the reliable modelling of dust forming circumstellar shells surrounding these objects. Particular emphasis is given to the strong nonlinear couplings among the basic physical processes (dust formation, thermodynamics, hydrodynamics and chemistry) which allow for a consistent modelling and a quantitative interpretation of the observed phenomena characterizing the objects in the upper right region of the Hertzsprung–Russell diagram.

1 Introduction

In the last decade considerable progress has been achieved both in observing and in modelling dust forming objects. This is due to the availability of excellent new instruments (e.g. IRAM, SEST, NTT, HHT, IRAS, ISO, HST, ...) covering the full spectral range and to the development of appropriate theoretical descriptions allowing for a reliable modelling of the physical and chemical processes involved. In the context of circumstellar dust formation, in particular a variety of effects and processes have been disclosed which provide very detailed insight into the complex interplay between the physical and chemical processes determining the structure of the objects.

In the following we confine our discussion to the extended shells of cool red giants and supergiants, Miras and LPVs, and to episodic phenomena like RCrB stars, i.e. those objects where dust formation is well known to be an important ingredient which strongly influences the structure of the shells and their temporal behavior.

The appearance of red giants and supergiants usually is dominated by a substantial reddening of the radiation field caused by effective dust formation in those regions of the shells where favorable conditions are encountered (e.g. Woolf & Ney 1969, Gillet et al. 1971). P-Cygni line profiles indicate the presence of velocity fields (e.g. Keady et al. 1988, Keady & Ridgway 1993) showing a distinct subsonic–supersonic transition and giving rise to a substantial mass loss of the order of 10^{-6} to $10^{-4} M_{\odot}/\mathrm{yr}$ (e.g. Knapp & Morris 1985). Detailed observations resolve the radial shell structure yielding spatial intensity profiles, brightness distributions and the corresponding visibility functions, which in case of pulsating variables indicate a layered structure of the shells (Ridgway & Keady 1988 , Danchi et al. 1994). Besides pronounced infrared bands and rotational line structures measuring the radially increasing complexity of the chemistry, in some cases (in particular early M giants) also emisssion lines are found which seem to be clear signatures of chromospheres located inside the dust shell. As in the outer shell region, where the chemical situation is strongly affected by the interstellar UV field, initiating a photochemistry, also chromospheres introduce substantial non–LTE effects which also may cause severe problems for a reliable modelling of the inner shell region.

With these observations, theory – attempting a reliable modelling of these objects – is confronted. Due to the complexity of the problem, a complete theoretical description proves to be a hopelessly underdetermined problem. For this reason, any reliable description has to be based on a self–consistent approach comprising hydrodynamics, thermodynamics, radiative transfer, chemistry, and dust formation and growth. Hitherto, this problem only has been solved for the (quasi)stationary situation of dust driven winds (e.g. Sedlmayr & Dominik 1995), the solution of which is fully determined by the prescription of four fundamental stellar parameters (e.g. stellar mass, stellar luminosity, effective temperature and chemical abundances ϵ_{i}), and for LPVs and Miras (cf. Fleischer et al. 1992), where two additional parameters (the pulsation period and its amplitude at the base of the atmosphere) have to be introduced. In contrast to these objects, where dust formation and the shell structure seem to be controlled by a self–regulating process – guarantying a secular stability of the time averaged appearance of the shell – episodic phenomena like the occultation of RCrB seem to be singular critical events, triggered by the interplay among shock waves, chemistry, and the actual cooling functions.

2 VLTI and dust forming objects

Although the observations already available have provided excellent material with regard to the spectral appearance and to the spatial structure of dust forming objects, the consistent theoretical description based on the fundamental laws of physics and on appropriate theories describing the local processes needs even more detailed local, time resolved information for specifying the required input quantities and the appropriate minimum level of approach in order to arrive at a satisfactory description. This concerns in particular the local chemical structure which not only provides the transport coefficients and consequently the temperature and density structure, but also the dust formation and growth process, where the nucleating primary molecules and finally the growth species entering into the dust formation theories have to be determined. In this view, the detailed information obtained by interferometric measurements can be conceived as a necessary complement to the local processes and resulting global structures modelled by the theory. Figure 1 shows a schematic plot of this complementary view. Usually, observations focus on the more prominent features determining the appearance of the object and characterizing its general properties. In many

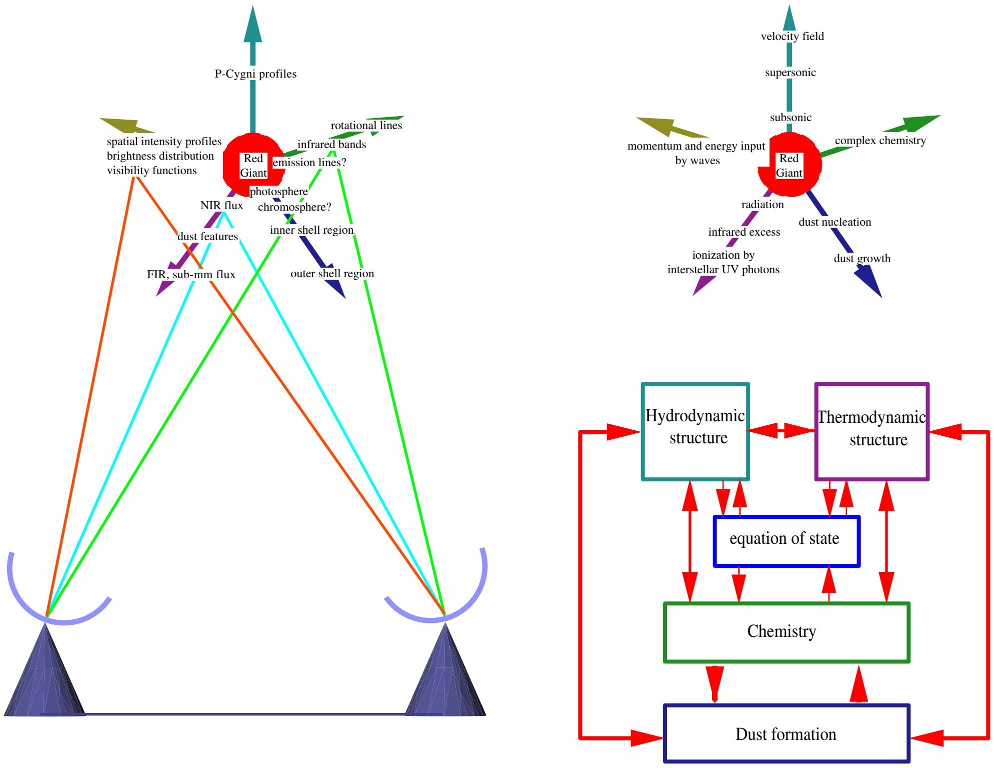

Fig. 1. Observational (l.h.s) and theoretical (r.h.s.) view of circumstellar dust shells around AGB objects. The interferometer (l.h.s.) provides very detailed information on the spatial and spectral appearance of the shell whereas the theoretical model (r.h.s.) aims at the description of the physical processes and their interrelations relevant for the structure of the shell.

cases however, these features are not primary for the understanding of the local physics which occasionally is determined by processes which are not immediately observable. Generally any reliable modelling of such a system introduces a variety of nonlinear couplings whose strength is decisive for the explanation of the local physics and the dynamical evolution of important structures. In this respect valuable information can be gained by applying interferometric methods providing a detailed local insight. As for dust forming winds the condensation process is decisive both for the local momentum transfer and for the thermal energy balance, this concerns for example the dust formation pathway, in particular the decisive critical clusters, which due to their bottleneck property hardly can be observed with other methods. In this context high resolution interferometric measurements are valuable to study the evolution of chemical complexity along the condensation pathways and to localize the transition between the nucleation and the growth regime which in all dust formation theories is crucial for the understanding of the actual condensation process.

Also detailed spatial information about the velocity field is highly needed for constraining the local conditions, in particular the concentrations of the molecular species, in order to arrive at a reliable level of theoretical modelling.

In the following, we discuss the specific value of interferometric methods for stationary dust driven winds, pulsational variables, and RCrB stars.

2.1 Stationary dust driven winds

The self–consistent solution for the problem of spherically symmetric stationary dust driven winds (Gail & Sedlmayr 1987) has been applied to the prominent carbon star IRC +10216 (Winters et al. 1994a). The solution is completely determined by the four fundamental stellar parameters, which for the case of IRC +10216 yield the values $M_\star = 0.7 M_\odot$, $L_\star = 2.4\,10^4 L_\odot$, $T_\star = 2000\,\mathrm{K}$, and an overabundance of carbon to oxygen $\epsilon_\mathrm{C}/\epsilon_\mathrm{O} = 1.40$. From the spectral energy distribution and the visibility functions a distance of $d = 160 \pm 20\,\mathrm{pc}$ is derived. In this model, classical nucleation theory is used to describe the formation of amorphous carbon grains, which leads to effective dust formation rather close to the star at $\approx 1.7 R_\star$ (see Fig. 2 where two synthetic intensity profiles for this model are shown).

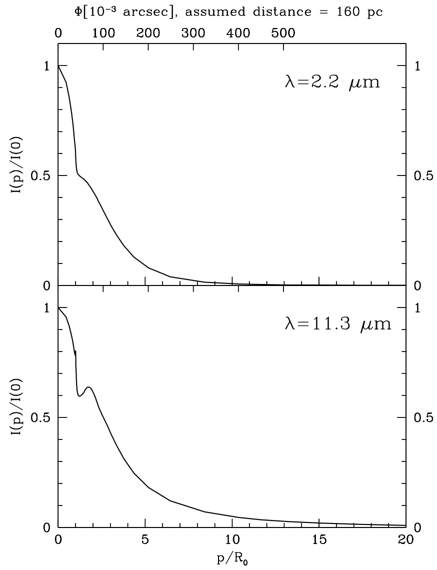

Fig. 2. Synthetic intensity profiles at $\lambda = 2.2\mu$m and $\lambda = 11.3\mu$m resulting from the stationary model for IRC +10216 (for details see Winters et al. 1994a).

In order to test the applicability of classical nucleation theory in a carbon–rich circumstellar shell and, as a byproduct, to obtain a more precise distance for individual objects, it is essential to determine the actual location of the inner shell boundary e.g. of IRC +10216 by a spatially highly resolved observation. Additional high spectral resolution would provide very valuable information also on the chemical structure of the inner shell region (e.g. the radial density distribution of the C_2H_2 molecule which is of particular importance in the context of carbon dust formation).

In fact, the comparison between calculated and observed spectral energy distribution indicates the presence of inhomogeneities in the circumstellar dust shell around IRC +10216 which by now have not been modelled by means of a consistent description. From these considerations, the following observational aims for VLTI can be derived: • resolve the inner edge of the dust shell, deduce information about the nucleation process • determine the chemical structure of the inner shell region • resolve inhomogeneities in the dusty envelope.

2.2 Pulsating atmospheres

Most objects on the Asymptotic Giant Branch (AGB) are known to be variable (e.g. Jura 1986). In order to model in detail the structure of the CDS of these objects the theoretical description has to include the effects of pulsation and thus has to be time–dependent. Since a self–consistent model of stellar pulsation which includes convection is still missing for AGB objects we apply the so–called "piston–approximation" to simulate the interior variation of the star. This approach introduces two additional parameter compared to the stationary winds (see Sect. 2.1): the pulsation period P, and the pulsation amplitude Δu. The resulting model structures show a complex interaction among the various physical components.

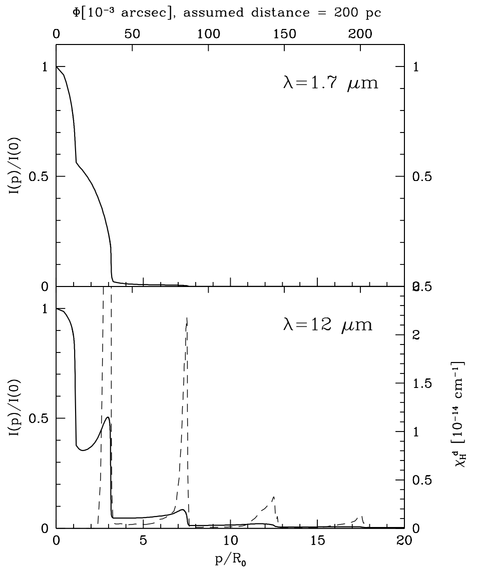

Fig. 3. Synthetic intensity profiles at $\lambda = 1.7\mu$m and $\lambda = 12\mu$m resulting from a dynamical dust shell model (for details see Fleischer et al. 1992).

Especially, it turns out that the shock waves travelling through the atmosphere are not caused by the interior pulsation alone but are due to a re-amplification mechanism caused by radiation pressure on dust (for details see Fleischer et al. 1992). Figure 3 shows synthetic intensity profiles for a time–dependent model calculation with the following parameter: $M_\star = 1.0 M_\odot$, $L_\star = 1.0\,10^4 L_\odot$, $T_\star =$ 2600 K, overabundance of carbon to oxygen $\epsilon_C/\epsilon_O = 1.80$, $P = 650d$, and $\Delta u =$ $2kms^{-1}$. A general result of the the time–dependent models is that the dust is concentrated in rather narrow discrete layers (indicated by the radial distribution of the flux–mean extinction coefficient χ_H^d), leading to characteristic structures in the intensity profiles (cf. the 12μm profile in Fig. 3, a detailed discussion is given in Winters et al. 1995) and also in the calculated light curves (Winters et al. 1994b). As the strength and the shape of these structures depend on wavelength, they contain important information about the internal structure of the dust grains actually formed in the CDS and about the grain size distribution finction.

From the time–dependent models, the following observational aims for VLTI can be derived: • resolve the layered structure of the CDS and follow its temporal behavior at different wavelengths • determine the grain material, the internal structure, and the size distribution of the grains.

2.3 The occultation phenomenon of RCrB stars

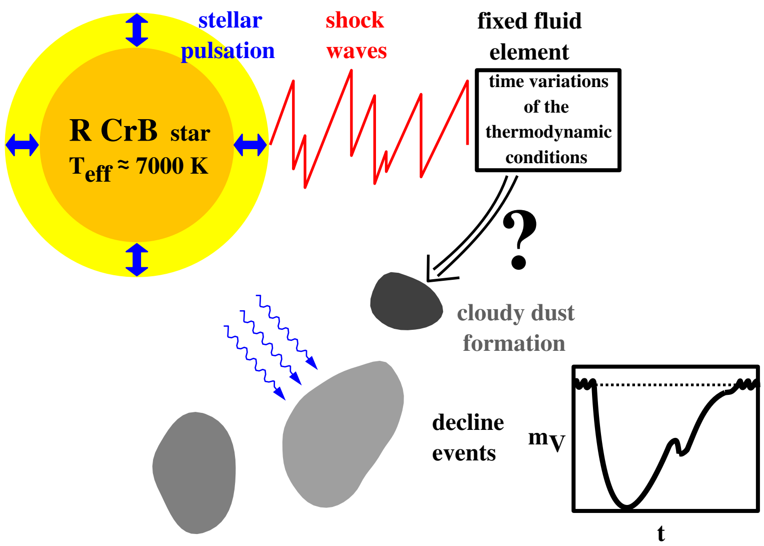

Fig. 4. Sketch of the occultation phenomenon in RCrB star atmospheres

Though being caused by instantaneous carbon grain formation, the occultation phenomenon characterizing the light curves of RCrB stars (sketched in Fig. 4) is much less understood than the more continuous dust formation process in stationary winds or pulsating atmospheres. This is due to the episodic occurrence of the phenomenon, the initial conditions of which are not really known. Several attempts have recently been made to explain the sudden dust formation either as being caused by critical conditions for the relevant thermal quantities or by a sort of episodic "blob"–event giving rise to rather rapid local cloud formation (Goeres & Sedlmayr 1992, Asplund et al. 1996). Both suggestions seem to be able to resolve the long–standing discrepancy between the observational findings (indicating a condensation radius rather close to the photosphere at only a few stellar radii) and the theoretical needs (requireing temperatures well below 1200K, which in the usual equilibrium description are encountered only far outside at about 10 stellar radii) by taking into account effective molecular cooling which for certain pressure regimes may produce very low kinetic temperatures and consequently high supersaturation ratios for the dust forming species already in the vicinity of the stellar photosphere.

In order to decide whether such type of a mechanism in fact is responsible for cloud formation and hence for the occultation phenomenon in an RCrB atmosphere it would very important to have available temporally and spatially highly resolved measurements which not only yield the evolution of the local physical and chemical conditions but also provide the critical values which have to be surmounted in order for the phenomenon to start.

Such type of observations might not only have immediate relevance for the RCrB phenomenon which may be seen as an example representing more general types of instabilities giving rise to cloudy structures in various types of dust forming objects.

3 Conclusion

The capabilities of the VLTI are ideally suited for a substantial improvement of the observations of dust–forming objects. The possibility to resolve circumstellar structures on small scales will lead to new insights in the local physics determining the evolution of these environments.

However, in order to arrive at a reliable interpretation of these new observational results, the measurements have to be complemented by (self–)consistent theoretical models. These models are already at hand for the circumstellar dust shells surrounding cool giants and supergiants. They include (time–dependent) hydrodynamics, the formation, growth and thermal evaporation of dust grains, chemistry, and radiative transfer, and at least equally important they also include the important couplings among the physical components. The theoretical models can be used to interpret the observations, and in turn, observational results will provide a test for the models and could indicate the need for improvements of the physical description of certain components, e.g. the chemistry.

A necessary prerequisite for the fruitful interplay between observation and theoretical modeling is the availability of highly time resolved observational data. Therefore, a small LPV key program should be defined for VLTI such that the objects of this program are continuously monitored, e.g. once per month.

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