WINDS OF COOL GIANT STARS: MODELS AND OBSERVATIONS

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Abstract

This review describes recent advances in models and observations of cool winds of asymptotic giant branch stars, focusing on infrared spectroscopy and interferometric methods, in combination with self-consistent time-dependent models of atmospheres and winds. The progress in these fields is leading to a more comprehensive picture of the complicated physical processes which cause the significant mass loss of these cool, evolved stars.

Key words: AGB stars, stellar winds, dust, spectroscopy, interferometry, hydrodynamics, radiative transfer

1. Introduction

Looking at the wide range of stars discussed at a typical *Cool Stars Workshop*, it seems necessary to start this review with a definition. In the context of this contribution, stars are considered which have effective temperatures of about 3000 K and below, and luminosities of at least a few thousand solar luminosities. In particular, this review focuses on asymptotic giant branch (AGB) stars, i.e. low and intermediate mass stars which have gone through their phase of core helium burning and are now producing their energy by alternate burning of hydrogen and helium in shells surrounding a degenerate core consisting of carbon and oxygen.

The coolest and most luminous of these AGB stars are undergoing heavy mass loss due to slow winds which are probably driven by radiation pressure on newly formed dust grains, a phenomenon which dramatically influences their further evolution. Eventually, mass loss becomes the dominant factor, transporting material away from the stellar surface faster than nuclear reactions change the stellar interior. Finally, a planetary nebula forms, and the core of the star turns in to a white dwarf.

Major progress has been made during the past decade regarding models of such cool, massive stellar winds. Time-dependent dynamical models including a detailed description of micro-physical processes have been developed to investigate possible wind driving mechanisms, and to predict observable properties. In combination with new observational possibilities, in particular IR spectroscopy and interferometry, a more comprehensive picture of the causes and consequences of mass loss is emerging.

2. Modelling: Mechanisms, Structures, Dynamics

Any stellar wind model needs two basic ingredients: a force which accelerates the material, and a 'reservoir' where this material is taken from. The force, together with the surface gravity of the star, largely determines the final outflow velocity of the wind. The mass loss rate, on the other hand, depends both on the wind velocity, and the density of the gas in the reservoir.

In the case of cool luminous AGB stars, typical outflow velocities are on the order of 10-30 km/s, reflecting the low surface gravity of these objects. The typical mass loss rates range from about $10^{-7} M_{\odot}$/yr up to $10^{-4} M_{\odot}$/yr which – in connection with the low wind velocity – implies high gas densities at the base of the wind acceleration zone. The most widely accepted scenario for the formation of these winds is based on a two-step process: stellar pulsation[1] causes propagating shock waves which lead to a levitation of the outer atmospheric layers. The dense, cool environment of these layers makes the formation of molecules and dust grains much more efficient than in a hydrostatic atmosphere. Subsequently, radiation pressure accelerates the newly formed dust and gas in the levitated zones away from the star. Detailed models based on this scenario can account both for typical wind characteristics, and many observable properties of these stars, as will be discussed below.

For a general discussion of the physical background of AGB atmospheres and winds, see, e.g., Gustafsson & Höfner (2004) and Simis & Woitke (2004).

2.1. Current Wind Models

At present, several 'strains' of dynamical wind models are used to compute time-dependent structures, observable properties, and mass loss rates. The common characteristics of these models can be summarized as follows: The computational domain is a spherical shell reaching from

[1] Stars on the AGB are usually long-period variables, mainly Mira stars or semi-regular variables. The variability is caused by large-amplitude pulsations, as, e.g., indicated by velocities deduced from high-resolution spectra (cf. Sect. 3.1).

layers below the stellar photosphere up to about 30 stellar radii where the wind usually has reached its terminal velocity. In this range, the equations describing conservation of mass, momentum and energy of the gas are solved simultaneously with a more or less sophisticated treatment of radiative transfer to account for energy transport by radiation and radiation pressure. Most models contain a description of dust formation, either in the form of a detailed time-dependent process, or as a parameterized additional opacity. Stellar pulsation is simulated by variations at the inner boundary of the models, e.g., by a sinusoidally moving membrane (piston models), and a prescribed variation of the luminosity.

In the following, three currently used groups of wind models are discussed, presenting their main characteristics and results. A detailed comparison of the input physics of these and other models can be found in the recent review by Woitke (2003).

2.1.1. Time-dependent Dust Formation

The wind models originally developed by the group around E. Sedlmayr in Berlin (e.g. Fleischer et al. 1992, Winters et al. 2000b) specialize in a detailed description of the formation, growth and evaporation of dust grains. The so-called moment method (Gail & Sedlmayr 1988, Gauger et al. 1990) allows to determine the degree to which condensible material is actually incorporated into grains, as well as mean grain properties like typical grain radii, etc.

This detailed time-dependent description is a crucial part of dust-driven wind models since dust condensation may proceed far from equilibrium, on similar time scales as the thermodynamical changes introduced by pulsation and shock waves. In this process, temperature acts mainly as a threshold while gas density and chemical abundances determine the efficiency of dust formation and grain growth. This can lead to the formation of discrete dust shells in the dense gas behind shock waves and complex spatial patterns of the dust distribution in the innermost parts of the circumstellar envelope. Furthermore, a complicated temporal behavior of the wind formation zone may occur since the time scales of dust condensation and radiative acceleration are not directly linked to the pulsation period. As soon as the material is accelerated away from the star, dust formation becomes a race against falling densities, and grain growth will eventually come to a halt, often with only a fraction of the condensible material actually condensed into grains.

The first generation of these models with a detailed description of dust formation was limited to stars with C/O>1 which form dust grains consisting of amorphous carbon. Recently, a description of dust formation in stars with C/O<1 has been successfully implemented, and first results of wind models for M-type stars have been presented by Jeong et al. (2003).

The wind models of the Berlin group have been used to derive formulae for mass loss rates as a function of stellar parameters, which in turn have been applied to evolutionary calculations (cf. Wachter et al. 2002, Schröder et al. 1999, 2003).[2] Regarding the computation of synthetic observable properties these models are, however, limited to features originating in the dusty winds. This is due to a crude (grey) treatment of radiative transfer which, in particular, affects the structure of the stellar atmosphere. Consequently, they have been mainly used to investigate observable properties at long wavelengths (probing the cool wind region), or global energy distributions for stars which are heavily obscured by the surrounding circumstellar dust shell (cf. Sect.3).

2.1.2. Frequency-dependent Radiative Transfer

The characteristic feature of the wind models by Höfner et al. (2003) is that they are based on a simultaneous solution of time-dependent dynamics and frequency dependent radiative transfer. These models bridge the gap between classical hydrostatic atmospheres which include detailed radiative transfer but neglect dynamical effects on the atmospheric structure (shock waves, wind acceleration), and time-dependent dynamical wind models with grey radiative transfer.

The coupling of frequency-dependent radiative transfer and dynamics is a prerequisite for including the intrinsically non-grey effects of molecular and dust opacities properly, leading to much more realistic atmospheric density-temperature structures than grey models. This is crucial for obtaining reliable wind properties like mass loss rates which are influenced by the conditions in the upper atmosphere. Furthermore, the inclusion of non-grey effects in the dynamical simulations makes it possible to study observable features created in different layers, reaching from the stellar photosphere out into the wind region, with one consistent model.

Recently, Gautschy-Loidl et al. (2004) presented a comparison of synthetic low resolution spectra based on the non-grey models of Höfner et al. (2003) with observations of several C-rich AGB stars, finding good agreement over a wide wavelength range. A comparison of synthetic and observed high-resolution spectra (line profile variations) probing different zones in the atmosphere and wind is currently in progress (Nowotny et al. 2004).

In the hydrostatic limit, the non-grey models can be compared to classical hydrostatic model atmospheres, showing that even a comparatively small number of frequency points (typically 50) is sufficient to obtain reasonably real-

[2] Theoretical predictions of mass loss rates and their application to stellar evolution calculations have been discussed in a special splinter session organized by K.-P. Schröder and will not be taken up in this contribution. In addition to the references given above, see also the review by Willson (2000) on this topic.

istic structures. This is important since a typical modelling run for a given set of stellar (and dynamical) parameters spans 40.000-80.000 time steps.

A previous (grey) generation of these models (Höfner et al. 1995, Höfner & Dorfi 1997) was used to study dust-driven winds of C-rich AGB stars, like the Berlin models discussed above, based on comparable physical input (similar description of dust formation) but using a completely different numerical method. Systematic studies showed results in accordance with those of the Berlin group, including characteristic features like formation of discrete dust shells, multi-periodicity, a dust-induced instability, and comparable mass loss rates. A qualitatively similar behavior of dust-related processes and wind dynamics is also found in the new non-grey models but there are significant quantitative differences, both in density-temperature structures and mass loss rates.

2.1.3. Efficiency of Cooling

While it seems to be generally accepted now that stellar pulsation and the resulting propagating shock waves in the atmosphere play an important role for the strong mass loss of AGB stars, some of the physical details are still under discussion. One of these uncertainties concerns radiative cooling of shock-heated gas.

In addition to creating pioneering wind models with a simple, parameterized dust opacity, Bowen (1988) investigated the possibility of a wind driven by thermal pressure due to inefficient cooling behind shocks. Reasoning that models using an LTE treatment of cooling may overestimate the effect, he introduced a modified description of the source function to simulate non-LTE effects. This could lead to a situation where the cooling behind shocks is not sufficient to reduce the gas temperature back to the equilibrium value before the arrival of the next shock wave, creating an extended warm zone above the photosphere ('calorisphere') which provides a high gas pressure for driving the stellar wind.

In this scenario, dust is not necessary to accelerate the wind but it is unclear if it is possible to form the observed grains in the outflow, at a distance from the star where the temperature has dropped below a critical value (see the discussion about dust formation above). Furthermore, the actual values of the cooling rates are still controversial (e.g. Willson & Bowen 1998, Woitke 1998). Unfortunately, consistent synthetic spectra or other observable properties which could help to clarify the question are presently not available for this type of models. It could be expected that a calorisphere as predicted by the models would create observable signatures.

2.2. Trends and Ongoing Projects

Apart from the question about the relevance of non-LTE processes there are other issues that have been addressed during the past few years but have not yet become 'standard components' of wind models. In the following, we will discuss several examples.

2.2.1. Physical Assumptions

One problem that has been discussed since the first stationary dust-driven wind models were created is how closely dust and gas are coupled, i.e. how efficiently they exchange energy and momentum. The limit of complete momentum coupling (all momentum gained by the dust from radiation directly transfered to the gas) has been used extensively, especially in time-dependent models. Another wide-spread assumptions is that dust and gas drift relative to each other with an equilibrium relative velocity (balance between momentum gain and loss terms for both components). Only recently these assumptions have been relaxed and tested in the context of time-dependent wind models with a detailed description of dust formation.

Simis et al. (2001) constructed two-fluid models for winds of AGB stars, including a consistent description of gas phase chemistry, dust formation (moment method, see above) and momentum transfer between dust and gas. They studied the formation of large-scale radial structures (dust shells) caused by the less efficient and time-dependent momentum exchange processes between dust and gas (corresponding to variations of mass loss on time scales of several hundred years) and compared these structures to observations of circumstellar dust shells (see also Sect. 3.3).

Sandin & Höfner (2003ab) introduced a separate equation of motion for the dust grains and terms treating momentum exchange between dust and gas into the radiation-hydrodynamics code (with dust formation) described in Höfner et al. (1995) and Höfner & Dorfi (1997). The resulting models where compared to the original models without drift presented in these earlier papers, finding that the effects of drift are significant and cannot be simply predicted from the models without drift due to the non-linear couplings between dynamics, radiation and dust formation. In most drift models, however, the winds are less pronounced than in the corresponding non-drift models. Furthermore, the dust grains tend to accumulate in the regions of high gas densities behind shocks where the interaction between gas and dust grains is strong, leading to low drift velocities. As a consequence, the models which include drift show usually more pronounced spatial structures and stronger variability in the dust component. Sandin & Höfner (2004) improved the drift models further by including a description of the effects of drift in the grain growth rates. While most of the properties of the models are similar to the previous drift models, the microphysical details of the grain growth process change. This leads to an increased efficency of dust condensation with different molecules becoming the main contributors to grain growth for different values of the drift velocity, depending on how strongly the molecules are bound to the grain surface.

Another aspect of dust microphysics was taken up by Andersen et al. (2003), who tested the influence of various material properties of amorphous carbon grains (e.g. opacities measured in the laboratory) on dynamical wind models. This has become more crucial in the context of the new generation of non-grey models where, e.g., the (difference between gas and) grain temperature depends strongly on the wavelength-dependence of the grain opacity. The main conclusions is that consistent assumptions for the chemical and optical properties of the grains are important both for the wind characteristics, and observed photometric colors.

An important problem which has not yet been solved in a satisfactory way in the context of stellar wind models is the description of stellar pulsation. As discussed above, the effects of pulsation on the atmospheres and winds of AGB stars are usually introduced in the form of variable boundary conditions at the innermost layers of the models, somewhere below the stellar photosphere. In practice, this means that a number of parameters (in addition to the usual stellar parameters) have to be introduced to describe the variability of the boundary conditions (e.g., period, velocity amplitude, variation of radiative flux). At present, there is a lack of a suitable grid of pulsation models which could give relations between the basic stellar parameters and quantities describing the pulsation, and in some cases observed period-luminosity relations are used instead. The ultimate goal, however, should be models that describe both the pulsation, and the atmosphere and wind in a consistent way. First steps in this direction have been taken by Bessell et al. (1996) and Hofmann et al. (1998) who used pulsation models to deduce boundary conditions for atmospheric models. The model atmospheres are a 're-computation' with higher spatial resolution and more complex micro-physics of the outermost layers of the pulsation models. They are, however, pure pulsating atmospheres which do not describe stellar winds.

2.2.2. Structures and Geometry

All wind models discussed so far have one basic assumption in common: spherical symmetry. However, there is an increasing number of observations which indicate deviations from this simple picture at different scales. On the one hand, interferometric observations indicate non-spherical stellar shapes of AGB stars, as well as complicated structures in the innermost parts of the circumstellar dust shells (e.g. Weigelt et al. 1998, 2002, Hofmann et al. 2000, Monnier et al. 2004; see Scholz 2003 for a recent review on interferometry). On the other hand, there are indications for clumpiness of the gas in the outer atmospheres and wind acceleration regions from maser studies (see Humphreys 2003 for a recent overview). In the light of these observations, it is necessary to investigate the possible consequences of non-spherical effects, and models for such phenomena are beginning to emerge, in spite of considerable computational difficulties.

Woitke et al. (2000) studied a possible instability of dust formation in a non-homogeneous circumstellar envelope by considering small perturbations of the opacity and radiation intensity in a linearized 3D radiative transfer problem. This instability is caused by the shielding from stellar radiation provided by denser regions with more dust, leading to improved conditions for dust formation in the shadows cast by the denser regions. Recently, these simplified preliminary studies where followed up by fully non-linear 2D simulations of the dust-forming regions (Woitke, this volume) which also show instabilities and evolving dust structures. These models focus on the circumstellar dust shell, excluding the central star, and the initial inhomogeneities are an external input.

Freytag has taken a complementary approach, investigating a possible origin of this phenomenon. His 3D radiation-hydrodynamical 'star-in-a-box' models of supergiants and AGB stars (Freytag 2003, Freytag & Höfner 2003) show giant convection cells which cause shocks in the upper stellar atmosphere, leading to variable, non-spherical structures in atmospheric densities and temperatures. Recently, Freytag & Höfner included a detailed, time-dependent description of dust formation (moment method, see above) into the CO^{5}BOLD code to study the influence of these giant convection cells on grain formation. As discussed above, the formation and growth of dust particles in AGB star atmospheres may proceed far from equilibrium, with temperature acting as a threshold and densities of condensible material controlling the efficiency of grain growth. This leads to the expectation that the inhomogeneities of the gas density and temperature caused by the convection cells are reflected by the dust distribution around the star. Preliminary results seem to confirm this expectation (cf. Höfner et al. 2004, Fig.3 and corresponding text) and more detailed simulations are currently being performed.

3. Observations and Interpretations

The possibilities for observing winds of AGB stars have improved dramatically over the last decades, in particular regarding the technical progress at IR and radio wavelengths. The following overview is far from complete but tries to give representative examples taken from the extensive literature on this subject. The observational results discussed below are not arranged by observation techniques but by the measured physical quantities and phenomena, always stressing the connection with models.

3.1. Shock Waves & Velocities

The flow velocity of gas in atmospheres and winds is probably the most directly accessible physical quantity that can be compared to models. A 'classical' method to determine the terminal wind velocities relies on radio observations of CO rotational lines (e.g. Olofsson et al. 1993, Schöier & Olofsson 2001). High-resolution IR spectra show complex and variable spectral line profiles affected by Doppler shifts due the velocity fields. In some cases, the interpretation of the profiles in terms of velocities is comparatively simple, in particular for P Cygni-type line profiles formed in the wind region, but variable lines originating in the pulsating atmospheres often pose a more difficult problem as discussed below.

Various molecular and even atomic lines have been used to study the kinematics of AGB star atmospheres and winds (e.g. Hinkle et al. 2000, Lebzelter et al. 2001, and references therein) but the most widely-used molecule is CO because it has several advantages over other species: it is abundant, exists both in M- and C-type stars, forms at relatively high temperatures deep in the atmosphere, and stays chemically inert over a wide radial range. Lines corresponding to different transitions are formed in different layers, allowing to probe the velocity structure from the photosphere out into the wind region with just one molecule. In particular, vibration-rotation lines of CO in the near-IR have been used intensively for temporal monitoring of long-period variables (e.g. Hinkle et al. 1982).

A detailed interpretation of the observations, and in particular the derivation of absolute velocities is often a non-trivial process which requires the computation of synthetic lines from model structures, and comparison with the observations. The studies by Keady et al. (1988) and Keady & Ridgway (1993) are examples how semi-empirical models for molecular line profiles are used to deduce information about the velocity structure of atmospheres and winds. The following discussion, however, concentrates on the comparison of observations with synthetic line profiles resulting from self-consistent dynamical models.

Winters et al. (2000a) studied synthetic CO fundamental and first overtone lines based on their dust-driven wind models and compared these results to observations of the extreme C-rich Mira star IRC+10216. The CO fundamental lines at 4.6 μm are formed in the zone where the wind has more or less reached its final outflow velocity, showing strong P Cygni profiles and little temporal variation. In contrast, the first overtone lines at 2.3 μm probe the dust formation and wind acceleration region, and the authors interpret the observed variations in terms of shocks and the formation of new dust shells. They encounter problems when attempting to get a consistent fit for the strengths and shapes of the lines, indicating that the mass loss rate of the model is too high by about a factor of 3 while the dust distribution seems consistent with observations (as deduced from the spectral energy distribution). A possible explanation for the problems could be the fact that the dynamical models where calculated using grey radiative transfer (cf. the discussion in Sect. 2.1).

Nowotny et al. (2004) computed synthetic line profiles of CO fundamental, first and second overtone lines, as well as CN 0-2 red bands (at 2μm) using non-grey dynamical models of Höfner et al. (2003). The preliminary results show qualitative agreement with observations, e.g., reproducing the S-shaped radial velocity curves observed for CO second overtone lines and CN, including line doubling around light maximum which is caused by a shock wave passing through the line formation zone. The amplitudes of the variations obtained with the models, however, are smaller than the observed variations. Due to the large computational effort required, only a few models have been investigated so far, and therefore it is unclear at present, if this is a general problem, or a matter of adjusting some of the stellar parameters which are not sufficiently constrained by low-resolution spectra (used to obtain a first guess).

Scholz & Wood (2000) calculated synthetic CO first and second overtone lines and OH first overtone lines based on the dynamical model atmospheres by Bessell et al. (1996) and Hofmann et al. (1998). They derived conversion factors which relate velocities obtained from the Doppler profiles to the actual radial velocities directly above and below the shock waves in the models. Applying these correction factors to observed velocities they conclude that Mira variables are fundamental mode pulsators.

An alternative method to observe the propagation of shock waves through AGB star atmospheres was developed by Alvarez et al. (2000, 2001ab). Applying a mask to rather crowded optical regions of the spectrum, they where able to detect line doubling in absorption lines around light maximum and other velocity effects, in accordance with the results from IR molecular lines. The interpretation of line doubling being due to a shock wave crossing the line formation zone is strengthened by the simultaneous appearance of Balmer lines in emission. The latter has long been interpreted as a signature of strong shock waves (e.g. Merrill 1955).

Another recent example of observations of Balmer and metallic emission lines as a function of pulsation phase is the paper by Richter & Wood (2001). In a follow-up paper, Richter et al. (2003) modelled FeII and [FeII] emission lines with detailed non-LTE radiative transfer to analyze the physical conditions in the shocked gas.

3.2. Structures & Mass Loss Mechanism

As discussed in the beginning of Sect. 2, the most widely accepted scenario for cool massive winds of AGB stars is that of pulsation-enhanced radiation-driven winds, probably with dust as the main opacity source. Putting aside the question about the dominant accelerating force, there seems to be a general agreement that shock waves caused by stellar pulsation and/or convection play an important role in the mass loss process by enhancing the densities of the upper atmospheric layers dramatically compared to hydrostatic stratifications. We will therefore first look at the effects of shock waves on the atmospheric structure before returning to the question which role dust grains play in the acceleration of the stellar wind.

The most direct evidence for the presence of strong radiating shock waves in atmospheres of AGB stars comes from variations of absorption line profiles and the occurrence of Balmer emission lines during certain phases of the light cycle, as discussed in the previous section. More indirect indications are out-of-phase variations of photometric colors which sample different layers of the atmospheres (e.g. Alvarez & Plez 1998) or the temporal behavior of IR molecular features (e.g. Hron et al. 1998).

The levitation and dynamics of the upper atmosphere and wind acceleration region can be studied by modelling time series of low-resolution spectra which cover a wide wavelength range (ideally from optical to mid-IR wavelengths), and therefore contain information about the structure of the atmosphere and wind out to a few stellar radii. Such a coverage can be obtained, e.g., by combining ISO-SWS spectra with ground-based observations.

Hron et al. (1998) presented a first comparison of ISO-SWS spectra of R Scl with synthetic spectra based on the dynamical models of Höfner et al. (1998). While these (grey) models were still too crude to allow for a quantitative fit, they could reproduce the variation of molecular features qualitatively. Since then, the dynamical models have been improved by including non-grey radiative transfer, which turned out to be crucial for obtaining more realistic structures (Höfner 1999, Höfner et al. 2003). The observable properties resulting from this new generation of dynamical models show a dramatic improvement compared to earlier grey models.

Recently, Gautschy-Loidl et al. (2004) have performed a systematic comparison of spectra resulting from the non-grey models of Höfner et al. (2003) with observations of the C-rich AGB stars TX Psc, WZ Cas, V460 Cyg, T Lyr and S Cep (ISO spectra, spectra from KAO and ground-based observations, narrow-band colors between 0.5 and 1.1 μm). In the wavelength range between 0.5 and 5 μm, they find good agreement between observations at different phases and a single model for each star.

An interesting discrepancy occurs at longer wavelengths for relatively warm, only weakly pulsating stars like TX Psc: both, non-grey dynamical models without wind (studied by Gautschy-Loidl et al. 2004), and hydrostatic model atmospheres (Jørgensen et al. 2000) show a strong absorption feature around 14 μm (due to C_2H_2 and HCN) which is not seen in observations, while the synthetic spectra fit the data very well at shorter wavelengths, including features caused by the same molecules. In models with dust-driven winds, on the other hand, the 14 μm feature is often considerably weaker, not visible at all, or even slightly in emission, since the photospheric absorption is filled in by emission from the circumstellar material, which offers a first self-consistent explanation for this interesting phenomenon.

Tej et al. (2003b) discuss synthetic optical and NIR spectra for M-type Miras resulting from the dynamical models of Bessell et al. (1996) and Hofmann et al. (1998). They find reasonable agreement of the overall energy distribution between 0.5 and 2.5 μm with spectra obtained by Lançon & Wood (2000). In contrast to Gautschy-Loidl et al. (2004), however, they do not attempt to identify a single 'best fit' dynamical model for each star, since the sample of dynamical models is small and various spectra from different models may reproduce the observed spectra equally well. Furthermore, they discuss the problem of fitting the region around 1 μm which can possibly be attributed to missing or incorrect molecular opacities.

Another method for studying atmospheres and wind acceleration regions of AGB stars is a comparison of synthetic spatial intensity distributions (visibilities) and monochromatic radii derived from dynamical models with interferometric measurements. These studies are gaining more and more importance with the impressive progress of interferometrical techniques (e.g., Weiner et al. 2003, Woodruff et al. 2004, Jacob et al. 2004). By carefully selecting spectral regions which represent various contributions of molecular opacities, such observations can help to constrain the extension and other properties of molecular layers in the dynamical atmospheres (e.g. Weiner 2004). On the other hand, when attempting to determine fundamental stellar parameters, it is important to avoid regions with significant molecular opacities which would lead to an overestimation of the stellar diameters.

Jacob and Scholz (2002) discuss the contamination of IR near-continuum band-passes by molecular opacities and the possible consequences for radius determinations of M-type Mira stars, based on the dynamical models of Bessell et al. (1996) and Hofmann et al. (1998). Tej et al. (2003a) use the same models to study how dense layers of H_2O caused by shock waves influence the shape of the center-to-limb intensity variations, and, consequently, the determination of radii from interferometric measurements.

Hron et al. (2003) present synthetic radii and visibilities at IR wavelengths for carbon stars, using the non-grey dynamical models of Höfner et al. (2003). They discuss the influence of molecular opacities at different wavelengths and the differences between the dynamical models and hydrostatic model atmospheres, comparing the results to the expected capabilities of the VLTI.

Apart from making it possible to determine fundamental stellar parameters, and to constrain pulsation properties and dynamical atmospheric structures, interferometric observations are also important for investigating the driving mechanism(s) for stellar winds. To determine whether dust plays a decisive role in the acceleration of the wind, or if it is just a by-product of the outflow, it is important to measure the distance of the inner edge of the dust shell from the stellar photosphere. Danchi et al. (1994) measured the inner radii of dust shells for different types of cool stars with the Infrared Spatial Interferometer (ISI) at 11 μm. They conclude that Mira variables, as well as semi-regular and irregular variables form dust close to the star, at distances of only a few stellar radii. This gives strong support to the dust-driven wind models which predict dust formation typically at 2-3 stellar radii, and is in line with the good agreement between observed and synthetic spectra resulting from the models.

Ridgway & Keady (1988) had obtained similar results with lunar occultation and interferometric observations at shorter wavelengths for the dust-enshrouded carbon star IRC+10216. Winters et al. (1995) computed synthetic brightness distributions and visibilities of C-rich LPVs with heavy mass loss, based on their dynamical wind models. They interprete variable structures in observed visibility functions as a sign of discrete radial layers in the circumstellar dust shell. In this context, however, it is important to remember that interferometric observations show strong indications of inhomogeneous structures in circumstellar dust shells (e.g. Weigelt et al. 1998, 2002).

In addition to the different types of thermal radiation discussed above, maser emission is an interesting tool for studying stellar winds. In particular, maser emission of SiO which originates close to the star, probably below the dust formation region, may provide insights into the mass loss mechanism by probing the physical conditions and velocity fields in the circumstellar material. Humphreys et al. (2001, 2002) have modelled H_2O and SiO maser emission, using a dynamical model of Bowen. H_2O maser emission originates further away from the star, probably inside the circumstellar dust shell, and the temporal variations are less regular and not as well correlated with the optical light curves of Miras and SRVs as in the case of SiO.

3.3. Large Scales & Mass Loss History

The models discussed so far describe the dynamical atmospheres and inner wind regions of AGB stars, investigating possible mass loss mechanisms, and predicting mass loss rates and observable properties. There is, however, and additional group of models which study time-dependent processes on much larger spatial and temporal scales.

Simis et al. (2001) investigated an instability of dust-driven winds caused by non-equilibrium drift between dust and gas, as shortly discussed in Sect. 2. This instability leads to variations of the mass loss rates, and formation of spherical dust layers (without the influence of stellar pulsation) on time scales of several hundred years. The resulting spatial scales are approximately comparable to the structures detected around IRC+10216 by Mauron & Huggins (1999, 2000).

Steffen & Schönberner (2000) studied the influence of changes in stellar luminosity and mass loss rate due to stellar evolution on the large-scale structure of the circumstellar envelope. They used a two-component radiation-hydrodynamics code (without a detailed description of dust formation), varying the stellar luminosity and mass loss rate at the inner boundary of their envelope model according to results from stellar evolution calculations, in order to produce geometrically thin gas shells.

The existence of such detached shells was expected from excesses in IRAS 60 μm fluxes, and confirmed through spatially resolved observations of CO emission by Olofsson et al. (1998, 2000) and recent imaging in scattered light by Gonzalez Delgado et al. (2001, 2003).

An overview of various phenomena in circumstellar envelopes, both on small and large scales, can be found in Olofsson (2004).

4. Conclusions

During the last decade, the research on cool winds of AGB stars has made considerable progress. New observational possibilities have opened up, allowing us to get a more comprehensive picture of the complex interacting physical processes. In particular, infrared spectroscopy (e.g. the wide simultaneous wavelength coverage of ISO) and the high spatial resolution obtained with interferometry should be mentioned here.

These observational developments have been accompanied by significant progress in modelling of cool stellar winds. Current dynamical atmosphere and wind models come in two basic flavors: spherically symmetric models including detailed micro-physics (which is necessary to study mass loss mechanisms and to obtain realistic synthetic spectra), and proto-types of 2D/3D models based on simpler physics (constrained mainly by computing time) which make it possible to study non-spherical structures on different scales. These two types of models are complementary and will exist side by side for the foreseeable future.

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