STOCHASTIC PROCESSES AND THE ORIGIN OF STELLAR WINDS

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In this chapter, we present results which provide insight into the origin of stellar winds in five selected stars: a typical RR Lyrae star (A7-F5 III), δ Cephei (F5-G2 I b), α Bootis (K1.5 III), α Orionis (M2 Ib), and a representative AGB star. These stars have been chosen because up-to-date ab initio models exist which attempt to explain stellar mass loss behavior. The stars exhibit different ranges of wave modes including acoustic modes and radial pulsation modes, which have been incorporated in recent models of nonlinear pulsation. For α Boo and α Ori, wave models based on Alfvén waves have also been discussed. The generation of wave modes within the stellar bodies operates as an inner boundary condition for the atmospheres which often leads to the generation of mass loss. Important processes also occur in the atmospheres and winds themselves. These processes include shock-shock interaction and the “sudden” onset of molecule and dust formation which usually occurs in a highly stochastic manner. Both processes can result in the generation of episodic mass loss events.

I. INTRODUCTION

It is a well-known fact that most types of stars have significant mass loss, which often impacts the course of stellar evolution. The mass loss of stars depends crucially on the position of the star in the HR diagram. It is controlled by the evolutionary status of the star and is related to a relatively broad set of physical parameters, including “basic parameters” like effective temperature, gravity and stellar rotation rate and other parameters like the magnetic field strength on the stellar surface and the presence of radial and nonradial oscillation modes. In some cases a direct dependence on the metal abundances also exists. In this chapter, it is our task to discuss the origin of stellar winds considering that stochastic processes occur. We argue that two distinct types of stochastic processes are relevant: processes that occur in the atmospheric layers and processes associated with the stellar body. We consider processes as stochastic, when accurate predictions of the relevant physical variables fail. This can occur due to the nature of the atmospheric boundary conditions.
or due to nonlinear processes operating in the atmospheric computational domain. Examples attributable to the behavior of the atmospheric boundary condition include the excitation of wave modes in an irregular manner. Examples for stochastic processes operating in atmospheric layers include episodic molecule and dust formation due to small changes in the atmospheric thermodynamic conditions. These effects can promote complicated hydrodynamic effects including the generation of episodic outflow events. Processes associated with the stellar body include stellar pulsation. Stellar pulsation modes as well as acoustic modes with extremely long periods (if existent; see below) and certain types of MHD modes tend to increase drastically the scale height of the atmospheric pressure and density, which is an important condition in order that the mass loss generated becomes appreciable. These modes also generate atmospheric velocity fields which impact many physical processes.

Over the last two decades or so, various mass loss mechanisms have been identified (see, e.g., Holzer and MacGregor 1985). These mechanisms include the thermal pressure gradient, momentum transfer by acoustic waves, Alfvén waves, stellar pulsation modes, and radiation force in atomic and molecular lines, and on dust grains. As discussed in the literature, it seems that all of these mechanisms are relevant in certain parts of the HR diagram, but for most stars one or a few of these mechanisms dominate. In some cases, the relevance of a proposed mechanism can be evaluated without performing model computations in detail. For instance, mass loss rates based on the thermal pressure gradient are significant only when the star possesses coronal-type structures for solar gravity. In noncoronal stars, on the other hand, the mass loss rates remain extremely low. Assuming an outer atmospheric temperature of 20,000 K as inferred from IUE data, Haisch et al. (1980) have explored the possibility of a thermally driven wind in α Boo (K1.5 III). They found a very low mass loss rate of \( \sim 10^{-16} \text{ M}_\odot \text{ yr}^{-1} \). In most cases, mass loss cannot occur via acoustic energy dissipation. Acoustic waves in the context of this chapter are nonmagnetic waves of relatively short periods compared to the acoustic cutoff period and small or moderately large velocity amplitudes compared to the sound speed at the inner atmospheric boundary. It is found that acoustic waves tend to dissipate most of their energy immediately beyond the stellar photosphere and therefore fail to produce significant stellar winds. For cases in which the energy requirement of the wind is dominated by the potential energy term of the stellar wind momentum equation, it has been shown that the length scale of the dissipated mechanical energy flux must be on the order of or larger than a stellar radius (see, e.g., Holzer and MacGregor 1985). Acoustic waves usually fail to meet this criterion. For α Boo, Cuntz (1990) investigated the mass loss rate produced by propagating shock waves. He found a mass loss rate between \( 10^{-14} \) and \( 10^{-16} \text{ M}_\odot \text{ yr}^{-1} \) depending on the adopted model parameters, which is well below the values suggested by observations (see Judge and Stencel 1991, and references therein).

In this chapter we discuss the origin of stellar winds in five selected stars: δ Cephei (F5-G2 Ib), α Bootis (K1.5 III), and α Orionis (M2 Iab), as well as a typical RR Lyrae, and an AGB star. These stars have been chosen because up-to-date ab initio models exist that attempt to explain the stellar mass loss behavior. Note that we have not selected η Ceti (M5-9 IIIe), which is considered in the chapter by Willson et al. The star η Ceti is characterized by photospheric fundamental mode pulsation with a period of 332 days caused by the hydrogen ionization instability of the stellar envelope. Gillet et al. (1985) and others have presented studies of shock-excited emission lines such as H α and have shown that line profile variations follow the stellar pulsation cycle in a very characteristic manner. Early calculations of mass loss from AGB stars (Wood 1979; Willson and Hill 1979) using the two limiting cases of isothermal or adiabatic shock waves, lead either to too low or too high mass loss rates. Bowen (1988) has performed numerical calculations of so-called piston models for Mira-type stars based on a number of simplifying assumptions concerning the radiation transport and the formation of dust. In these computations the stellar pulsation is initiated by a moving inner boundary. More recent results have been given by Bowen (1990,1992). Fleischer et al. (1992) have extended such calculations by including the detailed treatment of time-dependent dust formation and evaporation, and used the Lucy approximation for the radiation field (Lucy 1971, 1976). These results show the development of a number of dust driven wind shells. Feucht et al. (1993) have done similar calculations, solving the full radiation hydrodynamical equations which reveal the importance of the location of the pulsation zone for the resulting lightcurves. Höfner et al. (1995) have performed the first numerical simulations containing the full coupled system of gas, radiation and time-dependent dust formation. Some results of these computations will be presented in Sec. III.D.

Now we shall discuss some basic features of our target stars: δ Cephei is the prototype of the Cepheid variables, which are highly regular pulsators. The pulsation period of δ Cephei itself is 5.3663 days. We note that because of their period-luminosity relation, Cepheid stars have received a great deal of attention as "standard candles" for galactic and extragalactic distance determinations. A recent discussion has been provided by Saslaw and Karovska (1994), who also considered the effect of pulsational shocks on the δ Cephei brightness distribution. The study of the δ Cephei mass-luminosity relationship was particularly relevant to clarifying stellar evolution scenarios and was an important motivation for computing up-to-date opacities for stellar interiors. For more information see Buchler et al. (1990), Moskalik et al. (1992), and references therein. Buchler and his group have studied stellar oscillation modes in Cepheids (and other types of variable stars) using the so-called amplitude equation formalism. In this method, photospheric oscillation modes are deduced based on a detailed stability analysis of the stellar interior. An updated version of this method which now also includes stochastic driving has been given by Buchler et al. (1993). It is important to note, however, that this type of method treats the stellar atmosphere as a "perfect filter" and therefore ignores feedback mechanisms whenever they exist.
The red supergiant α Ori (M2 Ia), on the other hand, is a semi-regular pulsator on various different time scales. Dupree et al. (1990) have presented results from a six-year monitoring program and found unequivocal evidence for variabilities in visible and ultraviolet continua as well as in the Mg II h and k lines. Dupree et al. (1987,1990) identified a major ∼1.15-yr period which was also found by Smith et al. (1989) in photospheric low-amplitude radial velocity variations. We note that the atmosphere of α Ori is also shaped by time-dependent stochastic processes. Not long ago, Carpenter et al. (1994a) presented novel results from a HST-GHRS study of flow velocities based on emission and absorption features of various metallic lines. These lines indicate a broad range of velocities, ranging from (supersonic) inflows of 8 km s⁻¹ to (supersonic) outflows of 13 km s⁻¹, indicative of stochastic velocity structures. A further feature in the outer atmosphere of α Ori is the occurrence of hydrochemical processes leading to episodic formation and destruction of molecules and dust. Molecules and dust are relevant for generating mass loss as these species are able to capture photon momentum. Up-to-date models which include a detailed description of nonequilibrium chemical reaction rates as well as the influence of the chromospheric or interstellar ultraviolet radiation field are given by Glassgold and Huggins (1986), Mamon et al. (1987), and Beck et al. (1992). Evidence that radiation pressure in molecular lines can also support mass loss was described by Maciel (1976,1977), Eliotzur et al. (1989), and Jorgensen and Johnson (1992). Hydrochemical processes have also received special attention as they have been identified as the probable cause of phenomena revealed by "nonstandard" observations such as the occurrence of sudden dips in the radio continuum flux at 2, 3.6, and probably 6 cm (Drake et al. 1992). These observations may indicate radiative cooling instabilities which lead to the onset of molecule formation at different positions in the outer stellar atmosphere (see, e.g., Muchmore et al. 1987; Cuntz and Muchmore 1994). All these processes are potentially relevant to the origin of mass loss in this star. Last but not least, we included α Boo (K1.5 III) in our sample, a star which shows little activity at all.

We now discuss aspects of the origin of mass loss in more detail. Philosophically, mass loss is generated in the stellar body itself. Stars have distinct internal structures which give rise to certain types of wave modes present on the stellar surface. A further basic feature in stars is the level of magnetic activity produced by stellar rotation (Noyes et al. 1984) or by the decay of an active dynamo which existed at an earlier stage of stellar evolution (chapter by Charbonneau et al.). Magnetic activity can also lead to mass loss. Stellar winds produced by Alfvén waves are important examples of this phenomenon. Nevertheless, the physical processes operating on the stellar surface are only a part of the physical picture of mass loss generation. It is also crucial to focus on physical processes that operate in stellar envelopes. Stellar winds start in stellar photospheres, but in many cases the velocity fields present there are very small when compared to the thermal velocity or the sound speed. At greater atmospheric heights, the velocity increases and in many types of stars (for instance, the Sun) it exceeds the sound speed. In all cases, however, the stellar wind needs to exceed the local escape speed as otherwise the matter would remain bound to the star. In this respect we point out that in many stars, detailed observations indicate the presence of outer atmospheric flow patterns which in some cases even consist of supersonic motions. Nevertheless, it is clearly a misconception to infer the presence of mass loss from this type of observation or even to present determinations of "observed" mass loss rates as long as estimates of the local escape speed are not at hand. Important exceptions include supergiant stars, that are primary stars of ζ Aurigae binary systems. For such stars, information about the geometrical resolution of the wind is available allowing the approximate determination of the local escape speed, and improved estimates of the mass loss rates can be given (see, e.g., Schröder 1985).

In the last two decades or so, much work has been done to explore the physical nature of processes relevant to the generation of mass loss. A "homogeneous" approach, however, does not exist. The most important reason is that most relevant processes are usually strongly coupled leading to very complicated physical scenarios. This prevents us from considering all relevant physical processes simultaneously. This limitation makes it impossible to gain a full picture of all relevant processes occurring, even when considering the full set of the observations available. Ab initio models are therefore never able to explain the full set of observations that exist. As a consequence, we have decided to explore the most important theoretical and observational features in a limited number of well-studied objects and to consider existing ab initio models whenever possible. The chapter is structured as follows: in Sec. II we describe pivotal observations for our selected stars; in Sec. III we present results from theoretical models and conclusions are given in Sec. IV.

II. OBSERVATIONAL RESULTS

A. RR Lyr Stars (A7-F5 III)

RR Lyrae stars are low mass $M \approx 0.5 M_\odot$ variable stars with a relatively low metal content as they are Population II stars. These stars exhibit a narrow range of visual magnitudes and their periods range typically from about 0.2 to 1.2 days. The longest known period is that of UX Nor which is $P = 2.4$ days (Diethelm 1981). A large sample containing 90 RR Lyrae lightcurves in 6 colors has been given by Lub (1977). Depending on the amplitude, period and the shape of the lightcurve, several different classes of pulsations have been introduced. The catalog of variable stars given by Kukarkin et al. (1976) lists about 5800 RR Lyrae stars. The RRab subclass is characterized by a steep ascending branch with generally asymmetric lightcurves, whereas the RRc subclass exhibits almost sinusoidal lightcurves. The spectral types of RR Lyrae stars fall between A7 and F5. Note also that the boundaries of this range depend on the ΔS-factor which has been introduced by Preston (1959) to describe the spectra and the metal abundances of the stars. Note that the
spectral range deduced from the Ca II lines can differ from the spectral range obtained from the hydrogen lines. Since early observations, it has become evident that a number of RR Lyrae stars exhibit hydrogen emission lines that are split into two components during the ascending part of the lightcurve (Struve 1947). Without having a detailed theory of this emission phenomenon available, it is generally believed that shock waves run through the outer stellar atmospheres. The typical range of luminosities peaks at about 60 $L_\odot$ which makes these stars less suitable to estimate the distances of external galaxies. Hence, observational studies are restricted to our Galaxy. Furthermore, it is well known that these stars undergo nonlinear pulsation in the fundamental mode, in the first overtone or in both modes simultaneously. A large number of numerical computations have been carried out by various authors (see, e.g., Stellingwerf 1975; Kovács and Buchler 1988) to explore the stability of the RR Lyrae models.

B. $\delta$ Cep (F5-G2 1b)

Cepheids are the most important building block for calibrating the cosmic distance scale for nearby galaxies (see, e.g., Feast and Walker 1987). Extensive information concerning observations and theory of Cepheids can be found in the book edited by Madore (1985). The understanding of Cepheid pulsations is a long-standing problem in astrophysics with relevance to several other topics. It is known that a number of discrepancies are encountered when theoretical models are compared with observations (see, e.g., the reviews of Cox 1980 and Simon 1987). In particular, mass determinations of Cepheids differ depending on the method used, i.e., there are mass determinations from stellar evolution calculations, from the Baade-Wesselink method, from the pulsation theory and from special features of the lightcurves, usually referred to as bump and beat masses. As stated by Moskalik et al. (1992), the discrepancies are decreasing (but not disappearing) when recent theoretical and observational improvements are taken into account. The most significant improvement in this respect is due to more accurate stellar opacities (Rogers and Iglesias 1992; Seaton et al. 1994). The most recent calculations favor a smaller mass, radius and luminosity for $\delta$ Cep. All results presented in this chapter are obtained using these up-to-date opacity tables. Specifically, we show some very recent results for the nonlinear pulsation of $\delta$ Cep.

In order to relate the observations to a theoretical model of $\delta$ Cep we must discuss the values of fundamental stellar parameters of $\delta$ Cep like mass, radius, effective temperature and luminosity given in the literature. Due to the discrepancies mentioned above, the parameter estimates for $\delta$ Cep vary between 4.7 $M_\odot$ and 6.6 $M_\odot$, 44 $R_\odot$ and 51 $R_\odot$, 3130 $L_\odot$ and 2460 $L_\odot$, respectively (see, e.g., Cox 1980). The effective temperature is about $T_{\text{eff}} = 6100$ K. More recent measurements of the properties of $\delta$ Cep (as well as T Vul and X Cyg) using infrared photometry lead to a mean radius of $R_\text{eff} = 37.28$ $R_\odot$, an evolutionary mass of $M_\text{E} = 5.7$ $M_\odot$, a Baade-Wesselink mass of $M_\text{BW} = 2.51$ $M_\odot$, a luminosity of $L = 1723$ $L_\odot$ and an effective temperature of $T_{\text{eff}} = 6056$ K (Fernley et al. 1989). Estimates of the radius of $\delta$ Cep are summarized in Turner (1988, Table I). These estimates range from 37 $R_\odot$ to 45 $R_\odot$. Turner gets a mean radius of 42.7 $R_\odot$ based on the Baade-Wesselink method. Some recent spectral observations of $\delta$ Cep have been performed by Breitfellner and Gillet (1993) indicating that shock waves induce atmospheric motions which modify certain spectral features related to turbulence during the pulsational cycles. They found that the amplitude of the pulsation modes at the photospheric level is about 11% to 13% of the photospheric radius $R_\text{ph}$ depending upon which value for $R_\text{ph}$ is adopted. The values which are used include $R_\text{ph}=43$ $R_\odot$ (Turner 1988) and $R_\text{ph}=37$ $R_\odot$ (Fernley et al. 1989). We furthermore note that the value of the observed period of $P = 5.3663$ days of $\delta$ Cep is slowly decreasing by $7.6 \times 10^{-9}$ days per cycle or 0.04 s per year (Szabados 1980).

C. $\alpha$ Boo (K1.5 III)

The star $\alpha$ Boo (K1.5 III) is the prototype of an inactive, noncoronal, yellow giant star. Ayres and Linsky (1975), Ayres et al. (1982,1986,1995) and Judge (1986) have studied observational and semi-empirical constraints of the outer atmosphere, which point to chromospheric structures with temperatures up to about 20,000 K, perhaps accompanied by tiny layers of somewhat higher temperatures. A search for detectable X-ray fluxes failed (Ayres et al. 1981,1991; Maggio et al. 1990), which is a strong indication for the lack of magnetic activity. The mass loss rate of $\alpha$ Boo for the ionized component of the wind has been estimated as $6.9 \times 10^{-11}$ $M_\odot$ yr$^{-1}$ based on radio continuum observations at 6 cm (Drake and Linsky 1986), suggesting a total mass loss rate of about $2 \times 10^{-10}$ $M_\odot$ yr$^{-1}$ (see, e.g., Judge and Stencel 1991). Schrijver (1987) and Ruten et al. (1991) noted that the Ca II and Mg II emission line fluxes in $\alpha$ Boo coincide with the deduced chromospheric "basal" flux limits, which is evidence that the chromosphere is heated by acoustic shocks. Stencel and Mullan (1980) and Stencel et al. (1980) analyzed the Mg II $h$ and $k$ line emission cores which indicate an outward directed chromospheric wind flow. A high level of atmospheric activity can be seen in the He I $\lambda 10,830$ line. O'Brien and Lambert (1979) reported that the He I $\lambda 10,830$ line shows profiles which vary between a P Cygni shape, a pure absorption feature, and no feature at all. Lambert (1987) showed a sequence spanning about 6 weeks in which the profile varied smoothly from a P Cygni profile (very weak emission) to a broad, shallow, blue-shifted absorption line. Another observational property of $\alpha$ Boo is the presence of low-amplitude radial velocity variations. Smith et al. (1987) reported the detection of variations with a $1.842\pm0.005$-day (or $2.183\pm0.005$-day) period and an amplitude of $160\pm10$ m s$^{-1}$. Further detections were reported by Cochran (1988) and Irwin et al. (1989). Belmonte et al. (1990) presented new evidence for radial velocity variations in Arcturus in a relatively broad range of periods with the highest amplitude at ~2.7 days. The authors also presented weak evidence for an ~8.3-day period, which could possibly be interpreted as the fundamental pulsation mode. Hatzes and
Cochran (1994) have meanwhile re-analyzed the presence of photospheric low-amplitude oscillations in α Boo. They found periods of ~2.46, ~4.03, and ~8.52 days, periods that are similar to those previously given by Belmonte et al.

D. α Ori (M2 Iab)
The star α Ori (M2 Iab) is the visually apparent brightest red supergiant and has been the most thoroughly studied. It is a variable star with respect to many different observational features. Dupree et al. (1990) have presented detailed results from a six-year monitoring program and found unequivocal evidence for variabilities in the λλ 2950–3050 ultraviolet continuum and the Mg II h and k lines, which are reflected in variations of the B magnitude. Dupree et al. (1987, 1990) identified a major ~1.15-yr period, which was also found in photospheric low-amplitude oscillations (Smith et al. 1989). α Ori is a non-coronal star, as indicated by the absence of detectable transition layer emission lines (Linsky and Haisch 1979; Haisch et al. 1990). Judge and Stencil (1991) analyzed the global energy and momentum requirements of the chromosphere and wind of this star and found that the chromospheric emission is relatively weak and is consistent with the extrapolated chromospheric basal flux limits. This result provides evidence that the chromosphere of α Ori is dominated by non-magnetic heating. α Ori shows no detectable X-ray flux, indicative of coronal activity, to a low upper limit. Radio emission measurements suggest a spherically symmetric, partially ionized, chromospheric region extending from 1 to 4 Rs (Newell and Hjellming 1982). Evidence for episodic chromospheric activity has been given by Toussaint and Reimers (1989). They reported a 35% increase of the flux in the chromospheric Ca II K flux from February 1988 to February 1989 implying a localized increase in the chromospheric nonradiative heating rate. This result coincides with the appearance of a bright spot on the stellar surface at wavelengths 633, 700, and 710 nm (Buscher et al. 1990). The mass loss rate of α Ori is between 2 and 4 × 10^{-6} M_⊙ yr^{-1} inferred from circumstellar K I emission line profiles as observed 5 and 7.5 arcsec from the star (Mauro 1990). α Ori is surrounded by a huge shell of dust and gas extending from a few R_* above the photosphere out to ~10^3 R_* or more (see, e.g., Bernat et al. 1978). Different components moving at different radial velocities are seen, but the direction of flow apparently alternates between infalling and outfalling motion, possibly as a result of drastic events such as sporadic mass ejections or simply a consequence of stellar pulsation or waves. Irregular short-period fluctuations of the photospheric energy flux also occur (see, e.g., Goldberg 1984). Schwarzschild (1975) and Antia et al. (1984) suggested that the surface of a low-gravity star like α Ori might be covered by a relatively small number of extremely large convective cells, which are expected to impact largely the photospheric and chromospheric dynamics and initiate convective overshooting.

Querci and Querci (1986) have summarized observations of the blue and ultraviolet Fe II emission core velocities which have been described in detail by Boesgaard and Magnan (1975), Boesgaard (1979), and Carpenter (1984). These observations were obtained between 1970 and 1978. They indicate complex velocity structures in the atmosphere of this star, including changes from inflow to outflow and from outflow to inflow. The changes are significant and are unpredictable. Due to the lack of data, however, it is impossible to determine the relevant time scales precisely. They possibly range between 10^6 and 10^8 s. An important problem for interpreting the data correctly is that changes in overlying absorption features can easily imitate velocity fields in the line formation region which do not exist. Moreover, the observations described were not performed at the same wavelengths implying that they may refer to different atmospheric layers. A further result which demonstrates the existence of complicated dynamic features in the atmosphere of α Ori is the presence of multiple absorption lines in Na I, K I, and CO (see, e.g., Goldberg et al. 1975; Bernat et al. 1979; Bernat 1981). Jura (1984) interpreted these results as evidence for multiple circumstellar shells produced by the action of radiative forces on dust grains formed during distinct epochs of mass ejection. These observations again suggest that different atmospheric components moving at different radial velocities are present, and that the direction of the flow varies greatly with time and atmospheric height.

Drake et al. (1992) reported results from a radio continuum observation monitoring program for α Ori. These authors found variations in the form of dips, most pronounced at 2 cm, evident also at 3.7 cm, and possibly present at 6 cm. The variations behave stochastically and the changes at different wavelengths do not appear to be correlated. The amplitude of the variations is about 25% which shows that a large portion of the outer atmosphere must be involved. The authors also found that the variations can occur on a time scale of one month, which is unequivocal evidence that the physical cause is not related to rotation. A tempting explanation of these observations is that radiative instabilities in the wind region occur as suggested by Muchmore et al. (1987) and Cuntz and Muchmore (1994). Radiative instabilities potentially lead to rapid molecule formation and to a drastic decrease in the degree of hydrogen ionization. Similar results for the solar chromosphere regarding CO have been given by Ayres (1981) and Kneer (1983).

Further evidence for the presence of stochastic stellar wind flows in α Ori was given by Ayres (1981) and Kneer (1983). They presented results from a HST-GHRS study of flow velocities based on emission and absorption features from multiple ions indicative of dynamic chromospheric structures. The results obtained are extremely intriguing. The ultraviolet chromospheric emission lines indicate a broad range of velocities, ranging from (supersonic) inflows of 8 km s^{-1} to (subsonic) outflows of 13 km s^{-1}. The majority of the lines indicate a (subsonic) outflow of about 3 km s^{-1}. For the circumstellar shell probed by Fe I and Mn I, an outflow velocity of about 10 km s^{-1} was found which is commensurate with earlier determinations of Knapp et al. (1980) and others. The most dramatic difference in the radial velocities and velocity bisectors was found for the Mg II h and k lines. The Mg II h line indicates
III. STELLAR WIND CALCULATIONS

A. RR Lyr and δ Cep Stars: Examples for Radial Pulsators

The state of the art of theoretical modeling of radial stellar pulsations up to the year 1989 is contained in a book edited by Buchler (1990). Since then a number of new developments based on the method of adaptive grids (Dorfi and Feuchtinger 1991; Gehmeyr 1992a, b) have led to better numerical techniques for simulating a pulsating star. The most recent models of Feuchtinger and Dorfi (1994) are able to treat the pulsating object simultaneously with a gray stellar atmosphere. In such cases, nonlinear waves can be followed running through the outer atmospheric layers. Nevertheless, mass loss rates estimated from such theoretical pulsation calculations are not yet as high as the models do not extend to atmospheric layers in which the flow velocities generated by the shock waves surpass the local escape velocities. However, recent improvements in nonlinear stellar pulsation calculations may provide theoretical mass loss rates for a number of pulsating stars in the near future. Because RR Lyr stars are extensively studied objects observationally as well as by theoretical modeling, any result based on a new development can be compared to a number of results available in the literature. In Fig. 1 we present the nonlinear full-amplitude pulsations of a radiative RR Lyr star with the following stellar parameters: \( M = 0.578 \, M_\odot \), \( L = 64.3 \, L_\odot \), \( T_{\text{eff}} = 6500 \, \text{K} \). These computations adopt recent opacity tables from Rogers and Iglesias (1992) and Seaton et al. (1994) for a chemical composition of \( X = 0.7 \), \( Y = 0.299 \) and \( Z = 0.001 \) and an appropriate equation of state (Wuchterl 1991) for the same mixture. Fokin (1992) has performed calculations for RR Lyr variables using an explicit numerical scheme. An advantage of such an approach consists in an easier implementation of frequency-dependent radiative transfer and its coupling to the gas dynamics. However, this explicit nature makes it very hard to detect the limiting cycle of the pulsation even when running the calculations over a long time period.

The variations in the stellar luminosity are given in panel A of Fig. 1, the gas velocity at the photosphere is given in panel B, and the changes in the radius of the photosphere are presented in panel C, where the mean photospheric radius is given as \( R_{\text{ph}} = 6.29 \, R_\odot \). The period of the pulsation is \( P = 0.828 \) days. Every grid point denotes a computational timestep showing that the temporal evolution of the pulsation is also well represented by the adaptive radiation hydrodynamical code. The gas velocity at the external computational boundary at \( R_{\text{ext}} = 6.464 \, R_\odot \) can be seen in panel D where the pulsations trigger shock waves running through the atmosphere. At this radius \( R_{\text{ext}} \), a Lagrangian boundary condition is formulated and hence \( R_{\text{ext}} \) represents only the mean value during the pulsation cycle. Clearly at these low densities the velocity variations are much more pronounced compared to the photospheric velocities, which have an amplitude of about \( \pm 100 \, \text{km s}^{-1} \) at the radius of our outer boundary \( R_{\text{ext}} \). Note that these large velocities are still below the local escape velocity, which is \( v_{\text{esc}} = 185 \, \text{km s}^{-1} \). Although the pulsation is very regular in photospheric layers, we note that the velocity variations above the photosphere also depend on the nonlinear response of the stellar atmosphere. This effect leads to a less regular velocity pattern (Fig. 1B vs D) which can be accompanied by episodic mass loss behavior. Note that the gas velocity shows a steepening due to the outgoing nonlinear waves. However, a more quantitative estimate of mass loss from RR Lyr stars must await further computations based on adaptive grids, that are able to resolve the structure of a pulsating star from the driving zones up to the atmospheric layers that escape from the star.
In contrast to all earlier pulsation calculations these models also include the stellar atmosphere. The radial structure of the hydrostatic initial model is plotted in Fig. 2. Every grid point is shown individually to illustrate the good resolution of the physical quantities. In this case, the stellar parameters are given by $M = 0.578 \, M_\odot$, $L = 64.3 \, L_\odot$, and $T_{\text{eff}} = 6700$ K. Focusing on the outer parts of the model, we can identify the stellar atmosphere by the rapid spatial decrease of the density (panel B), temperature (panel C), gas energy (panel F), and pressure (panel H). Within this structure we see a density inversion due to the opacity (panel G). In this layer, it is important to resolve the very steep gradients of the physical quantities. The thermodynamic quantity $\nabla_{\text{ad}} = \partial \ln T / \partial \ln P$ mirrors the stellar driving zones (panel E) and varies within the ionization zones (see, e.g., Kippenhahn and Weigert 1990). It is therefore essential to distribute enough grid points in these regions to obtain an accurate description of the stellar pulsation. At a radius of about $3.9 \times 10^{11}$ cm, we find the He II ionization zone. At $4.14 \times 10^{11}$ cm, the H ionization zone is superimposed on the broader He I ionization zone. The quantity in panel D displays the point concentration and reflects the clustering of the grid points near steep physical features.

**Figure 2.** Radial structure of an initial hydrostatic RR Lyrae model between $3.8 \times 10^{11}$ cm and $R_{\odot} = 4.127 \times 10^{11}$ cm. The total mass is given by $M = 0.578 \, M_\odot$, the luminosity by $L = 64.3 \, L_\odot$, the effective temperature $T_{\text{eff}} = 6710$ K. All relevant physical variables are resolved on the adaptive grid using 300 grid points; (A) the integrated mass; (B) the gas density; (C) the temperature; (D) the point concentration showing the resolution achieved at the opacity peak; (E) the adiabatic gradient $\nabla_{\text{ad}} = \partial \ln T / \partial \ln P$; (F) the specific internal gas energy; (G) the opacity; (H) the gas pressure.

**Figure 3.** Pulsating model of $\delta$ Cephei with the adopted stellar parameters of $M = 5 \, M_\odot$, $L = 2000 \, L_\odot$, $T_{\text{eff}} = 6000$ K. The adopted period is $P = 5.25$ days; (A) the stellar luminosity; (B) the photospheric temperature; (C) the photospheric radius; (D) the negative photospheric gas velocity.

Figure 3 shows the pulsation modes obtained for $\delta$ Cep computed using the new adaptive radiation hydrodynamics computer code (Dorfi and Feuchtiger 1991; Feuchtiger and Dorfi 1994). Every computational timestep is again plotted by a single dot. At this stage of numerical modeling we did not try a detailed fit to the large number of observations available for $\delta$ Cep. We present, however, a pulsation calculation performed with the following stellar parameters: $M = 5 \, M_\odot$, $L = 2000 \, L_\odot$, $T_{\text{eff}} = 6000$ K, OP-OP opacities (Seaton et al. 1994), and an equation of state with solar composition.
(Wuchterl 1991) yielding a pulsational period of $P = 5.25$ days. Panel A displays the stellar luminosity in units of $10^{37}$ erg s$^{-1}$. The effective temperature in panel B varies between 6720 K and 5490 K, which is at the maximum found to be very close to the observed values of 6800 K but shows a large difference at the observed minimum of 3760 K. Two points are important for this comparison. First, as already mentioned, pulsational models were only calculated for a single set of stellar parameters. Considering the uncertainties discussed above, a better agreement between theoretical results and observations can easily be achieved. Second, it is not always straightforward to identify the location within the pulsating atmosphere of observationally deduced temperatures. The variations of the photospheric radius are plotted in panel C in units of the solar radius $R_\odot$ changing between 43.1 $R_\odot$ and 39.6 $R_\odot$. The negative photospheric gas velocity is shown in panel D and plotted in this way to allow an easier comparison with observations. An expanding velocity (positive values as the radius of the star increases) is directed towards the observer and hence mostly displayed by negative values. Note that these figures represent the full amplitude nonlinear pulsation where the kinetic energy (not shown here) of the star remains constant indicating that the limit cycle of the pulsation cycle has been reached.

**B. α Boo (K1.5 III): A Difficult Candidate**

For α Boo a broad variety of observations exists, but the origin of its stellar wind is far from understood. The wind model which received most attention is that of Hartmann and MacGregor (1980). They investigated the response of an outer atmosphere model appropriate to α Boo due to momentum transfer by Alfvén waves. Important features of these models include the following: (1) the propagation of the Alfvén waves is treated in a time-independent manner leading to stationary outflows; (2) the treatment of the Alfvén waves is based upon the WKB approximation; (3) the degree of hydrogen ionization is assumed to be constant; and (4) the dissipation length of the waves is also assumed to be constant, either 1 $R_\odot$ or infinity. In order to be relevant, these models must face three significant tests: first, they must reproduce (or must be consistent with) the observed thermal structures. These structures can in principle be inferred from optical and IUE data (see, e.g., Ayres and Linsky 1975). Second, the models have to predict the mass loss rate somewhat correctly. For the single inactive K giant Arcturus, it seems to be most appropriate to rely on the interpretation of the 6 cm radio continuum flux measurements. A third criterion regards the final flow speed of the wind. In Arcturus it is believed that the final flow speed of the wind is 40 km s$^{-1}$ (Drake 1985). This last criterion is most crucial when constraining the computed models. It was found that when a dissipation length of 1 $R_\odot$ was assumed, the models computed were most useful. Hartmann and MacGregor found that the dissipation of Alfvén waves with an energy flux of $3 \times 10^6$ erg cm$^{-2}$ s$^{-1}$ and a magnetic field strength of 10 Gauss lead to a mass loss rate of $\sim 10^{-9} M_\odot$ yr$^{-1}$. The final flow speed of the wind is $\sim 60$ km s$^{-1}$ and the adopted temperature of the atmosphere is 5000 K or 10,000 K, depending on the model. These results have been considered a big success for the model proposed. Nevertheless, a detailed comparison between computed and observed spectral features was never made. Equally important is the fact that these models suffer from serious technical restrictions, including the choice of the damping length of the waves as a free parameter, the treatment of the atmosphere thermodynamics, and the so-called WKB approximation for the waves. Wave models with variable damping length have meanwhile been computed by Holzer et al. (1983). Rosner et al. (1981) have presented results, which also include Alfvén wave reflection. MacGregor and Charbonneau (see their chapter) have presented a preliminary study of non-WKB waves in an atmosphere somewhat appropriate to that of α Ori (see below). The results of this study are relevant when the wave periods are long enough that non-WKB effects dominate. They found that the mass loss rate is reduced and the final flow speed of the wind increases in comparison with the WKB results. Both tendencies, however, make the agreement between theoretical and observed values worse. Recent improvements in the treatment of Alfvén wave propagation including the consequences on the associated magnetic field topology have been given by Rosner et al. (1995).

Cuntz (1987) studied the response of the outer atmosphere of α Boo to acoustic shock waves, which are an ultimate consequence of stellar convection. These models thus consider solely short-period waves as predicted by the models of acoustic energy generation by Bohn (1981, 1984). The models of Cuntz show strong time-dependent episodes of momentum and energy deposition which give rise to substantial chromospheric heating. Note, however, that the short-period shock-wave models fail completely in producing significant mass loss. Cuntz (1990) re-investigated the mass loss in α Boo produced by propagating shock waves by exploring the impact of a large range of wave periods. It was found again that wave modes associated with stellar convection are able to produce chromospheric temperatures, but the mass loss rates remain extremely low (i.e., between $10^{-14}$ and $10^{-16}$ $M_\odot$ yr$^{-1}$ depending on the model parameters). These models confirm that mass loss occurs only when the dissipation length of the mechanical energy flux of the shocks is on the order of or larger than a stellar radius, because the global energy requirement of the wind is completely dominated by the potential energy term (see, e.g., Holzer and MacGregor 1985; Hamner 1988). Cuntz (1990) also found that adiabatic shock waves with periods larger than 5.6 $\times$ 10$^5$ s (6.5 days) lead to mass loss rates between $10^{-10}$ and $10^{-11}$ $M_\odot$ yr$^{-1}$. Unfortunately, the wave periods and amplitudes considered have no observational support.

This topic was meanwhile revisited by Sutmann and Cuntz (1995). They have studied the possibility that the radial velocity variations in α Boo have significant influence on the outer atmospheric dynamics of this star, including the generation of mass loss. The models calculated were based on the observational data from Belmonte et al. (1990) and Hatzes and Cochran (1994). Sutmann and Cuntz found that this is not the case as most of the wave modes
remains evanescent ("mode trapping") as the wave periods are well above the acoustic cutoff. The propagation of energy into higher atmospheric layers remains therefore marginal. Nonlinear effects are found to be negligible because of the small wave amplitudes. They also checked to see if low-amplitude radial velocity variations can support mass loss. They found that this is not the case as the energy required to lift the wind out of the gravitational potential of the star remains many orders of magnitude below the wind energy flux constrained by observations, which have been discussed by Judge and Stencel (1991) and others. They argued that the energy contained in the observed oscillation modes is about 20 times greater than the energy required to drive the wind. Unfortunately, the authors have not considered the phase difference between the velocity and density, which drastically reduces the energy flux associated with these modes. In case that the modes are assumed to be associated with waves having sawtooth profiles, the energy remains insufficient for mass loss generation (Sutmann and Cuntz 1995). Considering the fact that acoustic wave models also fail to produce significant time-averaged mass loss rates (Cuntz 1990), it is safe to say that mass loss in noncoronal yellow giants like α Boo cannot be initiated by a nonmagnetic mechanism. This result is particularly astonishing, when taking into account that chromospheric heating in this type of stars can probably be explained fully by acoustic energy dissipation (Schröjer 1987; Rutten et al. 1991). Cuntz and Luttermoser (1990) also argued that the appearance and time-dependent behavior of the He I λ 10,830 line in this star might also be attributable to the propagation of stochastic acoustic waves.

C. α Ori (M2 lab): Ab-initio Calculations Based on Shock Waves, Alfvén Waves, Molecules and Dust

For α Ori several different models exist which attempt to explain the onset of the stellar wind. Unfortunately, each model is able to explain only a small subset of the existing observations. The model which is cited most is that of Hartmann and Avrett (1984) which is based on momentum transfer by Alfvén waves. They found that Alfvén waves are able to drive a steady outflow having a realistic mass loss rate, and the integrated line fluxes of the Mg II k and CII λ 2325 lines match the observations to within a factor of 3. They also found that the dissipation of Alfvén waves with an energy flux of \(1 \times 10^5\) erg cm\(^{-2}\) s\(^{-1}\) and a magnetic field strength of 2 Gauss leads to a mass loss rate of \(1.4 \times 10^{-6}\) M\(_{\odot}\) yr\(^{-1}\). The final flow speed of the wind was found to be 25 km s\(^{-1}\) and the maximum of the chromospheric temperatures 8050 K. Hartmann and Avrett have computed a further model in which an energy flux of \(9 \times 10^5\) erg cm\(^{-2}\) s\(^{-1}\) and a magnetic field strength of 5 Gauss has been used. In this case, the mass loss rate increases by more than a factor of 10. The final flow speed of the wind is now 20 km s\(^{-1}\) and the maximal chromospheric temperature is 7100 K.

We note that most dynamical properties of this wind model seem to be consistent with values expected for a "typical" inactive cool supergiant. On the other hand, the models of Hartmann and Avrett are not very successful in reproducing observed chromospheric emission line features inferred from IUE data. They computed fluxes and profiles for various chromospheric emission lines utilizing the PANDORA radiative transfer code and found that the line fluxes agree within a factor of 3 with observations, except for Ca II K, where the disagreement reaches a factor of 2 or 3. Gross discrepancies, however, were found for the line profiles. These discrepancies suggest that the α Ori chromosphere is much more turbulent than indicated by the Alfvén wave models computed and that episodic inflow and outflow events play a pivotal role in the energy and momentum balance of the outer α Ori atmosphere. Moreover, in the view of recent HST-GHRS spectra (Carpenter et al. 1994a), which provide unequivocal evidence for stochastic chromospheric velocity fields (see Sec. 1.2), it seems that the models of Hartmann and Avrett have only limited relevance for most atmospheric layers. A further important criticism inherent to all Alfvén wave-driven wind models of cool giants and supergiants is the lack of reliable magnetic field measurements in the photospheres. Marcy and Brumire (1984) have shown that the magnetic fields on the surfaces of cool giants are below a relatively high upper limit (i.e., several hundred Gauss). The magnetic field strengths adopted in the models of Hartmann and MacGregor (1980) and Hartmann and Avrett (1984) range from 1 to 10 Gauss. We have already noted that the Alfvén wave-driven wind models computed also observe several serious limitations. One of these limitations is the adoption of the so called WKB approximation. MacGregor and Charbonneau (see their chapter) have presented a preliminary study of non-WKB waves in an atmosphere somewhat appropriate to that of α Ori. They have concluded that in models in which non-WKB waves dominate, the mass loss rate is reduced and the final flow speed of the wind increases. Both tendencies make the agreement between theoretical and observed values worse. On the other hand, non-WKB wave modes may be able to reproduce some of the observed time-dependent behavior of the atmosphere but detailed model computations must still be performed. Also note that Alfvén waves now deserve some special attention because they are possibly capable of reproducing the coronal dividing line in the HR diagram (Rosner et al. 1991,1995), which is still a major unsolved problem in modern stellar astrophysics.

A further study aimed at investigating the onset of the stellar wind in α Ori addresses the propagation and interaction of short-period acoustic waves in chromospheric layers (Cuntz 1992). Cuntz has studied the response of an α Ori atmosphere model to the propagation of stochastic wave modes, which have been selected according to results from traditional acoustic convection zone models. Figure 4 shows a panel of 8 snapshots of a time-dependent stochastic wave calculation. The snapshot series has been started from a monochromatic wave model computed for a fixed wave period of \(2 \times 10^4\) s and a fixed initial wave amplitude of 0.10 Mach. Then shock waves with stochastically changing wave periods are introduced into the atmosphere. The panel demonstrate the generation of an episodic inflow and outflow event caused by efficient shock-
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Figure 4. Snapshots of a stochastic acoustic wave calculation for chromospheric layers in α Ori (M2 lab) given by Cuntz (1992). The stellar effective temperature is $T_{\text{eff}} = 3900$ K, the radius is $R = 860$ R$_{\odot}$, and the gravity is log $g = -0.4$ (Tsui 1989). The flow speed $U$ (solid line), the radiation damping function $D$ (dotted line), the temperature $T$ (dashed line), and the hydrogen ionization degree $X_H$ (dashed-dotted line) are shown as functions of height. The numbers in the upper left corners denote the time after switching on the acoustic frequency spectrum that was employed.

shock interaction. The numbers in the upper left corners denote the time after allowing the wave period to change stochastically. The time scale for typical changes in the wave propagation is $1 \times 10^6$ s. The time between the episodic outflow and inflow event is about $5 \times 10^7$ s and ranges from $2 \times 10^7$ to $2 \times 10^8$ s in further models, which is consistent with constraints from observations (see, e.g., Querci and Querci 1986, and references therein). The atmospheric models are characterized by a complicated hydrodynamic structure containing a nonuniform distribution of shocks. The shock strengths and the shock speeds differ substantially and change nonmonotonically with height. This result is a clue to the basic physics which is going on; after allowing the wave period to change stochastically, shocks with different strengths are introduced into the atmosphere. Different shock strengths cause different shock speeds, which lead to interacting, overtaking and merging of shocks (= shock cannibalism). As the strength of an overtaking shock combines with the shocks it engulfs, its speed increases, so it overtakes more and more shocks in front of it attaining an even greater strength. Consequently, the amount of momentum and energy deposition that occurs in the atmospheric layer varies drastically. The direction of the flow alternates between inflowing and outflowing motions depending on the strengths of the shocks and the hydrodynamic history of the flow. The radiation losses which predominantly occur behind shocks decrease with increasing atmospheric height showing that the waves behave more and more adiabatically when propagating outward. The temperatures behind the shocks are somewhat similar to those of the semi-empirical chromosphere model of Basri et al. (1981), who computed a semi-empirical chromosphere model for α Ori based upon the Ca II K and Mg II h and k emission lines from IUE spectra. Note, however, that a detailed comparison between observed and computed line spectra is still unavailable. Basri et al. found a steady increase of the atmospheric temperature starting from 2820 K in the temperature minimum up to 7000 K at a column mass density of $1.0 \times 10^{-6}$ g cm$^{-2}$.

Figure 5 shows the minimal and maximal flow speed in a time-dependent monochromatic and time-dependent stochastic wave model as functions of the atmospheric height. The monochromatic model is based upon a wave period of $5 \times 10^6$ s. For the computation of the stochastic model, 16 wave periods have been introduced into the atmosphere covering a timespan of $6.9 \times 10^6$ s. The minimum wave period introduced is $1.2 \times 10^6$ s, and the maximum is $1.6 \times 10^6$ s. The results are quite impressive: in the stochastic wave model the maximal outflow velocity is 24.1 km s$^{-1}$ and the maximal inflow velocity is $-17.4$ km s$^{-1}$. The corresponding Mach numbers are 3.10 and 3.33, respectively, demonstrating that in stochastic wave models supersonic flow patterns can easily be generated without ad-hoc assumptions. In monochromatic wave models which do not include shock-shock interaction, it was found that the flow speeds are substantially lower and never exceed the sound speed. The fact that in the stochastic wave model relatively high inflow and outflow velocities are found within chromospheric layers provides some
the potential energy term (see, e.g., Holzer and MacGregor 1985). Significant mass loss is expected only when waves with long periods are used. For α Ori it might be important also to consider the 1.15-yr period caused by pulsation (Dupree et al. 1987, 1990; Smith et al. 1989) as well as other periods (Goldberg 1984).

A further type of model aimed to explain the onset of mass loss in α Ori considers radiation pressure on dust grains. Beck et al. (1992) have studied the nonequilibrium chemistry in inner regions of an oxygen-rich circumstellar shell appropriate to that of α Ori. They considered a total of 38 species and a system of 342 reactions. They assumed a steady (i.e., time-independent) outflow with a prescribed mass loss rate and temperature structure chosen in accordance to the model of Glassgold and Huggins (1986). As a crucial feature of the models, the authors also included the effect of the ultraviolet chromospheric radiation field. The chromospheric ultraviolet radiation was also included in the models of Clegg et al. (1983) and Glassgold and Huggins (1986). These authors, however, have only treated steady-state concentrations for the species which considerably simplified the models. Most importantly, Beck et al. showed that the ultraviolet radiation field largely impacts the atmospheric chemistry. Figure 6 shows the number densities for various species at a fixed atmospheric height as a function of a changing chromospheric ultraviolet radiation field; this chromospheric ultraviolet radiation plays a pivotal role in the molecular chemistry. Whenever the ultraviolet radiation flux becomes appreciable, photoions and radicals determine the physical structure of large portions of the circumstellar shell. In this case, the main modes of molecule formation involve charge-exchange, exothermal ion-radical, radiative dissociation, and radiative association reactions. It was found that the ultraviolet flux level attributed to α Ori is very close to the borderline at which dust formation is possible. If the ultraviolet flux in α Ori would be slightly stronger, the ultraviolet photons would completely suppress any nucleation process leading to the formation of dust.

We note, however, that the models of Beck et al. (1992) do not properly treat the physical structures of the stellar photosphere and chromosphere. The models start at 2 \( R_* \), where the density has a prescribed value. This approach implies that stars like α Ori must have a finite mechanism, which carries a sufficient amount of matter to the dust formation radius. Based on results from observational studies, it seems that stellar pulsation modes are the most promising candidate mechanism (besides Alfvén waves) to provide this missing link. The models of Beck et al. (1992) also provide important clues as to why outer atmospheric structures in stars like α Ori behave stochastically; as the wave modes traveling from underneath are changing the density and temperature of the wind in an irregular manner, it is unavoidable that the mass loss rate enhanced by radiation pressure on dust grains also varies. In addition, variability in the formation of dust and by implication in the resulting mass loss rate can also be introduced by fluctuations of the ultraviolet radiation field. As discussed in Sec. II.D, it is known that in α Ori (and probably also in similar
loss in AGB stars. We concentrate our description on low mass stars (up to an initial main-sequence mass less than about 8 $\text{M}_\odot$) with cool extended atmospheres as mass loss in more massive and consequently in hotter stars occurring via radiation force in atomic lines is covered elsewhere. Note that the winds in these stars can also exhibit a number of fluctuations which are attributable to an instability in the expanding wind (see, e.g., review by Owocki 1990). A similar phenomenon occurring in dust-forming atmospheres will be illustrated in this section. The stellar evolution properties of low mass stars have been reviewed by Iben and Renzini (1983).

Most of these late-type stars have extended convection zones in their outer hydrogen-rich envelopes and are pulsationally unstable. As summarized by Wood (1990), the theoretical models do not match the observed properties in a satisfactory way. We are therefore faced with the problem that no pulsation theory of these long-period variables can explain their temporal variations. Because mass loss plays a fundamental role in these stars, Pijpers (1993) suggested that modifications of the outer boundary conditions may be necessary to get an adequate description for pulsating stars. Again, it is clear that only a fully hydrodynamical calculation ranging from the stellar interior up to the wind zone can give a quantitative answer to this problem.

From a number of observations of cool extended stars it is well documented that these atmospheres are sites of heavy dust production (see, e.g., the review of Lafon and Berruyer 1991). The radiation pressure on the newly condensed dust grains provides an effective force to drive a slow but massive stellar outflow with mass loss rates up to $M \approx 10^{-5}$ $\text{M}_\odot$ yr$^{-1}$. These winds provide the most important source of dust particles for the interstellar medium (see, e.g., Gail 1990). Self-consistent models for stationary outflows have been constructed by Dominik et al. (1989). These models show that certain combinations of stellar parameters (e.g., low photospheric temperatures and high luminosities) can produce such stellar winds. Nevertheless, the observed correlation between the infrared excess, which is interpreted as mass loss, and the pulsation period (de Gioia-Eastwood et al. 1981; Jura 1986; Anandarao et al. 1993) indicates that mass loss is a time-dependent phenomenon and can be characterized by a two-step process (see, e.g., Jones et al. 1981). The pulsations seem to be necessary to levitate the stellar material into the region where dust forms. If enough material condenses into dust particles, a stellar outflow develops, which is clearly modulated by the stellar pulsations as pulsation lifts the material up to the condensation zone. Based on these assumptions, a number of models with various levels of simplified physical assumptions have been constructed. These models simulate the stellar pulsation by an oscillating inner boundary condition (Wood 1979; Bowen 1988; Fleischer et al. 1992; Feuchtiger et al. 1993; also see the chapter by Willson et al. for more details).

The process of dust formation is linked to a relaxation time scale $\tau_{\text{rel}}$ towards equilibrium values for given thermodynamical conditions (Höfner and Dorfi 1992). Taking typical values for the gas density and the temperature of the wind, this timescale is of the order of 10$^5$ yr.
this time scale can be on the order of the pulsation period of AGB stars leading to a rather subtle interplay between stellar pulsations and dust formation. A shock wave running through a zone of dust formation will generally increase the density and temperature. However, due to the interaction with the radiation field, it is a priori not clear at which location in the downstream region optimal conditions for nucleation and growth of dust particles are produced. Hence, in one case it might be possible to create dust particles immediately behind the shock transition, whereas in other cases the gas must first cool down and only in far downstream regions effective dust formations may take place (Höfner et al. 1995). In other words, we expect that dust-driven winds of pulsating stars in certain stellar parameter regimes should be a rather irregular and time-dependent process. In this case, the stochasticity of the mass loss behavior is not directly initiated by the boundary conditions, but due to the nonlinearity of the processes operating in the computational domain. (For the time-dependent \( \alpha \) Ori chromosphere models previously described, the stochasticity of the flow occurred due to the randomly changing wave frequencies which have been specified at the inner atmospheric boundary.) Figures 7 and 8 illustrate the irregular behavior of a dust driven mass loss from an AGB star.

The results presented are obtained by solving the full system of radiation hydrodynamical equations coupled to the equations which describe the time-dependent formation, growth, and evaporation of dust particles. These equations consist of a system of 12 nonlinear partial differential equations (see Dorfi and Feuchtinger [1991] for the description of the numerical method, and Höfner et al. [1995] for a discussion of the physical equations). The initial conditions are stated for an atmosphere of a carbon-rich AGB star, \( M = 1 \, M_\odot \), \( T_{\text{eff}} = 2600 \, K \), \( L = 10^4 \, L_\odot \) and a ratio of carbon to oxygen as \( e_C/e_O = 2.5 \) (i.e., a cool carbon star). These parameters lead to a stellar radius of \( R_* = 3.43 \times 10^{13} \, \text{cm} \) corresponding to \( 493 \, R_\odot \). The computational domain extends from \( 1 \, R_* \) to \( 30 \, R_* \). The simulations run on an adaptive grid with 500 radial grid points. Figure 7 shows the temporal evolution of the velocity in \( \text{km s}^{-1} \), the gas temperature in \( K \), and the mass loss rate in \( \dot{M}_\odot \, \text{yr}^{-1} \) between 40 and 120 \( \text{yr} \) at a radius of \( 30 \, R_* \) after the computation has been started from an initially dust-free hydrostatic configuration. It is easy to trace the different shock waves reaching this radius of \( 30 \, R_* \) based on the increase of the velocity, the mass loss rate and the gas temperature which are followed by radiating cooling zones. A corresponding radial structure is plotted in Fig. 8.

We note that this model does not rely on stellar pulsation modes employed at the inner boundary of the atmosphere, but on a self-excited instability associated with the formation of dust. The combination used of stellar parameters with a large value of the carbon abundance \( e_C \) shows that the previously mentioned effect that the dust formation itself influences the radiation field can result in an unstable situation provoking two entirely different solutions (Winters et al. 1994; Höfner et al. 1995). Because the radiation is blocked by the formation of dust particles, the gas inside the dust layer is heated up to a temperature which inhibits further dust formation. This dust-free zone is
loss of Fig. 7, with the lower carbon to oxygen ratio, i.e., $e_C/e_O = 2.3$. The figure displays the gas velocity $u$, the gas temperature $T_g$, the radiation temperature $T_r$, the fraction of carbon $f_{\text{cond}}$ condensed into grains and the Eddington factor $f_{\text{edd}}$. Comparing the stationary solutions, we observe a number of significant differences. First, the average velocity is about a factor of 3 larger, which is about 30 km s$^{-1}$. This is due to the lower amount of carbon condensed into grains which reduces the radiative acceleration for stationary winds. Second, the gas temperature follows nicely the stationary structure except in the vicinity of shock waves where we find shock-heated gas cooling down towards the equilibrium temperature. Third, the temperature increases inside the innermost shock waves caused by the effective blocking of the radiation field as seen, e.g., in the behavior of the radiation temperature. This behavior is also illustrated in the deviation of the Eddington factor $f_{\text{edd}}$ from the stationary value. These lower values of $f_{\text{edd}}$ are typical for a more isotropic radiation field produced by the dense dust shells. Although this particular example exhibits an irregular solution for a dust-driven wind, we point out that such deviations from the stationary values also occur in regular dust driven winds (see, e.g., Höfner et al. 1995). Again, we emphasize that the AGB star provides constant inner boundary conditions in these computations and that the wind modulations obtained are solely initiated by an atmospheric dust-induced $\kappa$-mechanism. Similar results which point to the same physical mechanism have meanwhile been given by Fleischer et al. (1995).

We should point out here that ultraviolet observations of optically bright carbon stars demonstrate that many of these stars have also chromospheric emission (Querci and Querci 1985; Johnson and Luttermoser 1987). Whether this emission comes from a chromospheric-type layer, as in warmer stars, or from outward propagating individual shocks, as shown in the models above, remains open to debate. Luttermoser et al. (1989) have modeled the ultraviolet emission lines seen in carbon stars and have demonstrated that this emission must come from circumstellar regions at temperatures in excess of 5000 K. A radio survey of N-type (i.e., cool) carbon stars at 6 cm have further demonstrated that this chromospheric-type region cannot have temperatures in excess of 10,000 K (Luttermoser and Brown 1992). As can be seen in the models presented above, the weak shocks generated have insufficient temperatures to give rise to the ultraviolet emission seen in some carbon stars. This demonstrates that long-period pulsational-driven waves may be important in these stars as well as for the AGB Mira-type variables.

IV. CONCLUSIONS

It has been the purpose of this chapter to discuss the origin of stellar winds considering the impact of stochastic processes. Stochastic processes can be initiated by the stellar body by providing distinct boundary conditions for the stellar atmosphere. They can also occur in the atmospheres themselves.
Shock-shock interaction and the "sudden" onset of molecule and dust formation due to marginal changes in the atmoospheric thermodynamical conditions are key examples for this behavior. In fact, it can be said that a broad variety of different physical processes is usually involved when mass loss behavior occurs. Most significantly, it is found that in late-type stars, the energy requirement of the wind is dominated by the potential energy term of the stellar wind momentum equation (see, e.g., Holzer and MacGregor 1985), implying that the length scale of the dissipated mechanical energy flux must be on the order of or larger than a stellar radius. Acoustic waves usually fail to meet this criterion as they dissipate the lion's share of their mechanical energy flux immediately beyond the stellar photospheres (Hartmann and MacGregor 1980; Cuntz 1990; Sutmann and Cuntz 1995). On the other hand, as found by Cuntz (1987,1992), acoustic waves are very efficient in producing episodic outflow events, largely due to shock-shock interaction in the stochastic wave field, particularly in stars of low gravity. In addition, they enhance the atmospheric turbulence which is an important feature in most stellar photospheres and chromospheres. Stellar pulsation is very efficient in producing significant continuous outflows. Momentum transfer due to strong shocks can expand the atmospheres enormously and can drive the atmospheric matter to velocities beyond the escape speed. Model calculations for α Ceti (M5-9 IIIe) given by Bowen (1988) and Willson et al. (see their chapter), among others are key examples. Another important mechanism for producing continuous outflows in late-type stars might be momentum transfer by Alfvén waves. In this case, however, significant discrepancies between theoretical models and observational results still remain, indicating the need for further studies. In all these cases, it is very important to consider results both from observations and theory to ensure an appropriate assessment of the mechanism. Because of the complexity of the phenomena involved we have focused on a list of distinct stars: δ Cep (F5-G2 Ib), α Boo (K1.5 III), α Ori (M2 Iab) and a representative RR Lyrae star and an AGB star. These stars differ vastly in their stellar parameters as well as types of atmospheric activities, thus providing an interesting set selected for tutorial purposes.

For RR Lyra and δ Cep stars, improved models in conjunction with accurate stellar opacities have meanwhile become available. These models include the simulation of the driving zones together with the stellar atmosphere by applying an adaptive grid to resolve the running waves in the atmospheres. Current simulations on RR Lyrae variables are found to be in better agreement with the observations and can eventually also provide theoretical mass loss rates. This task requires that the stellar atmospheres be extended to lower densities where the material reaches escape velocities. The stellar material is accelerated by the shock waves. It is expected that the resulting mass loss may not be regular due to the nonlinear response of the outer layers on the pulsational modes. Most recent efforts in modeling pulsating δ Cepheids also open up the possibility of considering photospheric pulsation on the stellar photospheric brightness distribution. This is extremely relevant when

δ Cephei stars are utilized for extragalactic distance determinations (Sasselov and Karovska 1994). A difficult candidate with respect to the generation of mass loss is the noncoronal yellow giant α Boo. Acoustic waves and global photospheric oscillation are both present and lead to a variety of stochastic effects in the stellar atmosphere. Nevertheless, they are found to be unimportant for the origin of the stellar wind in this type of star (Sutmann and Cuntz 1995). This result points to the importance of a magnetic field-related mechanism or mechanisms, as discussed by Hartmann and MacGregor (1980). More studies are needed to clarify the basic physics of mass generation in this type of star.

For α Ori, several different models exist which attempt to explain the onset of the stellar wind. Unfortunately, each model is able to explain only a small subset of the existing observations. It seems that Alfvén wave-driven wind models (Hartmann and Avrett 1984) may be relevant for explaining some of the observed properties, despite the fact that major discrepancies between the results from the theoretical models and the observations remain. It is also noteworthy that the photospheric magnetic field strength which is a key quantity in this type of model is unconstrained by observations as it is in the model for α Boo; this reduces the significance of the models substantially. Another important feature in this star is the effect of the ~1.15-yr pulsation period and of other periods found in extensive monitoring programs. Unfortunately detailed model calculations are still missing. In addition, flow patterns associated with radiation pressure on molecules and dust are expected to play a significant role in the outer atmospheric dynamics in this star. Beck et al. (1992) as well as Glassgold and Huggins (1986) and Mamon et al. (1987) have demonstrated that radiation pressure on dust grains can be an important mass loss mechanism. In addition, the chromospheric ultraviolet radiation field is found to be pivotal for the molecule and dust chemistry in α Ori-type stars as the ions and radicals formed change the efficiency of most molecular reaction rates. Hydrodynamic refrigeration due to quasi-adiabatic cooling by strong shocks formed in the stochastic wave field besides thermal instabilities due to newly formed molecules and dust may also play an important role for the mass loss. The complexity of these different mechanisms and effects ensures that mass loss in stars like α Ori should behave stochastically which is in agreement with observations. Nevertheless, further theoretical studies which employ the action of stellar oscillations (and perhaps also momentum transfer by magnetic field-related mechanisms) as well as molecular and dust chemistry are needed to clarify the origin of the stellar wind in this star. Höfner and Dorfi (1992) have already focused on the generation of dust-driven winds in AGB stars, caused by the interaction of different effects operating on different time scales. They focused particularly on episodic dust formation due to self-excited thermal instability. In this case, episodic mass loss is expected to occur even in the absence of the propagating shocks that exist. Höfner and Dorfi found that backwards reactions due to backwarming are important for explaining stochastic dust formation and can furthermore change the stellar pulsation period. The development of shell-like dust-driven structures in this
type of stars impinges on the stellar radiation field which necessitates calculations of the Eddington factor. The different features involved in the mass loss of AGB stars demand a fully consistent treatment of the coupled system of dust, radiation and gas dynamics which is a basic issue of current research.

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