The coupling between pulsation and mass loss in massive stars

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Abstract. To what extent can pulsational instabilities resolve the mass-loss problem of massive stars? How important is pulsation in structuring and modulating the winds of these stars? What role does pulsation play in redistributing angular momentum in massive stars? Although I cannot offer answers to these questions, I hope at the very least to explain how they come to be asked.

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INTRODUCTION

What constitutes a ‘massive’ star? For simplicity, I’m going to lump together under this label all the stars that fall into the O and B spectral types on the main sequence. I’m also going to include the Wolf-Rayet (W-R) stars that are the late evolutionary states of high-mass O stars; but not, however, the central stars of planetary nebula, which can also show W-R spectra.

As will become apparent, massive stars are very different from their cooler cousins that comprise the principal focus of this conference. Throughout their lifetimes they shed a significant fraction of their initial mass, and they often exhibit periodic or episodic variability somehow associated with the large-amplitude excitation of one or more pulsation modes. In the following section, I briefly review the twin topics of mass-loss and pulsation; then, I explore three different themes arising in the coupling between these phenomena.

BACKGROUND

Mass loss from massive stars

The evolutionary biologist Dobzhansky (1964) once famously remarked that “Nothing in biology makes sense except in the light of evolution”. With little massaging, we can convert this quote into an equally-important truism for stellar astrophysicists: “Nothing in massive-star evolution makes sense except in the light of mass loss”. As I discuss below, to ignore mass loss when attempting to model the evolutionary trajectory of a massive star is often so poor an approximation that it isn’t worth even considering.
First, however, I shall briefly review what we know observationally of the mass loss. In spectra, the appearance of P Cygni-type line profiles, having symmetric emission superimposed over blueshifted absorption (see Rottenberg, 1952, and references therein), is the unmistakable fingerprint of a circumstellar envelope that is accelerating away from the star — in other words, a wind. Measurements of the violet edge of the absorption indicate wind terminal velocities extending up to $v_\infty \sim 2,500 \text{km s}^{-1}$ (e.g., Prinja et al., 1990), significantly faster than found in the Solar wind ($\sim 500 \text{km s}^{-1}$) or in the dusty winds of AGB stars ($\sim 15 \text{km s}^{-1}$). Diagnostics based on H$\alpha$ and radio emission indicate corresponding mass-loss rates that reach up to $\dot{M} \sim 10^{-5} \text{M}_\odot \text{yr}^{-1}$ (e.g., Lamers & Leitherer, 1993); again, to place this value in context, the Sun has $\dot{M} \sim 2 \times 10^{-14} \text{M}_\odot \text{yr}^{-1}$ (Wood et al., 2002), around nine orders of magnitude smaller.

What causes these winds? In the case of the Sun, it is simply the gas pressure in the hot ($\sim 10^6 \text{K}$) corona that drives the outflow. However, to reach the terminal velocities seen in massive stars would require temperatures reaching up to $T \sim (2,500 \text{km s}^{-1})^2 m_p/k \sim 5 \times 10^8 \text{K}$ (here, $m_p$ is the proton mass, and $k$ is Boltzmann’s constant), which clearly contradicts observations that reveal wind temperatures not too different from that of the star. In fact, massive-star winds are driven directly by radiation; UV continuum photons are scattered by resonance lines of metallic ions, and in the process impart some of their momentum to the ions. Through Coulomb coupling, these ions in turn share the momentum with hydrogen and helium ions. If the net rate of momentum deposition exceeds the local force of gravity, then a wind outflow will ensue. This mechanism was first suggested by Lucy & Solomon (1970), but the full theory of radiatively driven winds was developed in a groundbreaking paper by Castor, Abbott & Klein (1975). A lucid introduction to this eponymous ‘CAK’ theory can be found in the extensive review by Owocki (2004), and this review also covers the so-called ‘line-driven instability’, that leads to self-seeded structure in massive-star winds.

As I have already remarked, mass loss in a radiatively driven wind can have a dramatic effect on the evolution of a star. As discussed by Chiosi & Maeder (1986), a high-mass ($\gtrsim 50 \text{M}_\odot$) star in the absence of a wind will evolve to the red supergiant part of the HRD; ignite helium; and remain there for the rest of its lifetime. However, a very different picture emerges when the mass loss is included. Figure 8 of Langer et al. (1994) shows a typical scenario: a $60 \text{M}_\odot$ star makes only a brief evolutionary excursion to the red side of the HRD, before returning to the blue, eventually crossing over the ZAMS. This return arises because the star sheds its hydrogen-rich envelope, revealing a hot, helium core showing nucleosynthetic enrichments at first of nitrogen, and then of carbon. The realisation that such wind-bared helium cores are none other than Wolf-Rayet stars (e.g., Conti et al., 1983, and references therein) provides the basis for unified narratives for massive-star evolution (e.g., Langer et al., 1994; Smith & Conti, 2007).

Lest this all sound too straightforward, let me end this section by highlighting a few significant unsolved problems (in accordance with the overall theme of the conference!). Most significantly, there is mounting evidence that the presence of wind clumping has led to over-estimates in literature wind mass-loss rates (see, e.g., Smith & Owocki, 2006, and references therein). From diagnostics that are insensitive to clumping, such as UV absorption lines (Fullerton et al., 2006), it seems likely that a reduction in $\dot{M}$ by a factor 3-10 is in order. This raises an obvious problem: how then can we form a (relatively
low-mass) Wolf-Rayet star from a massive star, if the latter only sheds a small fraction of its mass during its hydrogen-burning phase? Smith & Owocki (2006) address this issue by suggesting that all stars above $\sim 40 - 50M_\odot$ go through a luminous blue variable (LBV) phase, during which they shed copious amounts of mass in eruptions similar to the 19th century outburst of $\eta$ Carinae. However, the mass-loss mechanism involved in such eruptions remains unknown; I discuss one possibility below.

Another area of significant uncertainty concerns rotation. Massive stars are systematically rapid rotators; in a survey of 373 O and B stars, Howarth et al. (1997) found a distribution of projected equatorial velocities $v \sin i$ with a peak at $\sim 100\text{km s}^{-1}$, and an extended tail reaching up to $\sim 400\text{km s}^{-1}$. Recent evolutionary calculations that incorporate rotation (see Maeder & Meynet, 2000, and references therein) reveal that in some cases massive stars can pass through phases of super-critical rotation, during which the centrifugal force exceeds the equatorial gravitational force. These phases appear likely to be associated with significant equatorial mass loss; but how to model this mass loss correctly remains unclear (e.g., Meynet et al., 2006). In this respect, the Be stars — characterized by the episodic formation of decretion disks, perhaps due to critical rotation (Townsend et al., 2004) — could be Rosetta stones; but as I indicate below, pulsation also appears to be playing a role in these enigmatic objects.

Pulsation of massive stars

To introduce the topic of massive-star pulsation, I present a potted history of the field. Interest in this area of stellar astrophysics grew initially from the strange case of $\beta$ Canis Majoris. Radial velocity measurements of this star (Struve, 1950) indicate two closely-spaced periods that are difficult to reconcile with either binary motion or the radial pulsations seen in classical ($\delta$) Cepheid stars. A seminal paper by Ledoux (1951) resolved this issue by arguing that the star was undergoing nonradial oscillations in a pair of rotationally split quadrupole modes. Although the formalism of nonradial pulsation had been developed almost a century previously (Thomson, 1863), this was the first-ever example of a star oscillating in this manner.

Subsequently, the Sun rather stole the limelight as the prime exemplar of a nonradial oscillator (Leighton et al., 1962). However, interest in massive-star pulsation continued to grow with the discovery of other stars like $\beta$ Canis Majoris, leading to the recognition of a distinct class of variables: the ‘$\beta$ Cepheid’ stars. (I confess to being ignorant as to why $\beta$ Canis Majoris was demoted from its status as the archetype.) Osaki (1971) brought a great deal of quantitative rigour to the field, by reproducing the distinctive line-profile variations (lpv) seen in time-series spectra of $\beta$ Cep stars. Smith (1977) later discovered a distinct class of early- to mid-B type pulsators, characterized by similar lpv but exhibiting longer periods. During the 1980s this class was referred to as ‘53 Per’ stars, after the archetype; but Waelkens (1991) recognised that these stars are the spectroscopic counterparts of photometric variables discovered by Waelkens & Rufener (1985). This led him to establish a new ‘slowly pulsating B’ (SPB) class, unifying the two groups.
FIGURE 1. Instability strips in the upper part of the HRD (after Pamyatnykh [1999], his Fig. 3). The $\beta$ Cep and SPB instability strips associated with the iron-bump $\kappa$ mechanism are shown as the shaded regions; the approximate locations of unstable mixed Rossby-gravity modes, strange modes, and deep-opacity $g$ modes are also illustrated. The dotted lines indicate the zero-age (ZAMS) and terminal-age (TAMS) lines, and selected initial masses are indicated along the ZAMS.

In the 1990s, theorists finally caught up with these observational strides, by uncovering the process(es) responsible for exciting massive-star pulsations. Previously, Stellingwerf [1978] had attempted to invoke an opacity (‘$\kappa$’) mechanism based on helium second ionisation, as successfully applied to classical Cepheids (Zhevakin, 1953). Although ultimately unsuccessful, Stellingwerf was prescient in surmising that opacity is the key. With the completion of the OPAL and OP opacity calculations (Rogers & Iglesias, 1992; Seaton et al., 1994), it became apparent that a new opacity peak at a temperature $\log T \sim 5.3$ — due to same M-shell transitions of iron and nickel — would destabilise $p$ modes (with periods on the order of hours) in $\beta$ Cepheids,
and $g$ modes (with periods on the order of days) in SBP stars (e.g., Cox et al., 1992; Dziembowski et al., 1993; Dziembowski & Pamyatnykh, 1993).

Fig. 1 illustrates the instability strips in the HRD diagram associated with this ‘iron-bump’ $\kappa$ mechanism. As demonstrated for instance by Pamyatnykh (1999), the correspondence between these strips and the observed positions of $\beta$ Cep and SBP stars is extremely good. The figure also indicates the approximate regions associated with other instabilities that can excite pulsations in massive stars. For mid-B type stars, Savonije (2005) and Townsend (2005) have independently shown that mixed Rossby-gravity modes — in which the restoring force on displaced fluid elements is a combination of buoyancy and inertia — are unstable due to the same iron-bump $\kappa$ mechanism. Moreover, for Wolf-Rayet stars Townsend & MacDonald (2006) have demonstrated that $g$ modes are unstable due to an opacity bump at $\log T \sim 6.25$, this time arising from K-shell bound-free transitions of iron. Finally, a number of authors have investigated so-called ‘strange’ instabilities, that cause violent radial and nonradial pulsations in objects characterized by large luminosity-to-mass ratios (see Saio et al., 1998, and references therein). These strange instabilities are discussed further in the following section.

**THEMES**

**Pulsation-driven mass loss**

What limits the mass of the star? There is strong observational evidence that the initial mass function (IMF) in the Milky Way is truncated at the high-mass end, with no single star exceeding 150$M_\odot$ (Figer, 2005). However, the underlying cause of this upper mass limit remains a puzzle. Historically, it was thought that radial pulsations driven by the $\epsilon$ mechanism — an instability due to the large temperature exponent of CNO burning — would disrupt any star having a mass above $\sim 60M_\odot$ (Schwarzschild & Hämäläinen, 1959). This expectation was lent support by Appenzeller (1970), although his calculations suggested a higher theoretical limit for complete disruption, $\gtrsim 300M_\odot$. However, subsequent investigations by Papaloizou (1973a,b) gave the contrary result that no mass loss is expected to be driven by $\epsilon$-mechanism pulsation. Interest in the issue then subsided, overshadowed perhaps by the then-rapid advances in understanding wind mass loss.

The situation changed two decades later, when Glatzel & Kiriakidis (1993) discovered strange-mode instabilities whose theoretical location in the HRD appeared to be correlated with the observational Humphreys-Davidson (HD) limit (Humphreys & Davidson, 1979). To explain why this is significant, I shall first attempt to shed some light on the confusing topic of strange modes and strange instabilities. Amongst the various differing definitions suggested for strange modes, my preference is for the one given by Saio et al. (1998): “As strange modes we identify those eigenfrequency branches that behave differently from those that change only very slowly under the change of a control parameter”. Typically, the ‘control parameter’ that these authors refer to is the age of a star; and thus a strange mode can be thought of as one whose frequency changes rapidly as the star evolves, in contrast to the slower variation in the frequencies of ordinary modes.

A good example of such behaviour can be seen in the top-left panel of Fig. 2 of
Saio et al. (1998). It originates because of the way in which the modes are trapped in the star. For ordinary $p$ modes, the trapping depends on the variation in adiabatic sound speed $c_{\text{ad}}$ throughout the star; steep gradients in $c_{\text{ad}}$ tend to reflect acoustic waves, establishing the boundaries of trapping zones. Glatzel & Kiriakidis (1993) argued that strange modes are acoustic waves that trapped in the outer layers of the star by steep gradients of some appropriately defined sound speed $c$. In some cases $c = c_{\text{ad}}$, meaning that the strange modes are essentially ordinary $p$ modes; these are what Saio et al. (1998) term ‘adiabatic strange modes’. In other cases, non-adiabatic effects can mean that $c$ departs significantly from $c_{\text{ad}}$, and there is no obvious relation between strange and $p$ modes, apart from the fact that both originate in acoustic waves. In all cases, however, the quality that makes a mode strange is that it is trapped in the outer layers of the star; these layers tend to change rapidly as the star evolves, giving rise to correspondingly rapid changes in the mode’s frequency.

This brings me back to the relationship between strange modes and mass loss. Being confined to the surface layers of a star means that the growth timescale $\tau$ of these modes — when some suitable driving mechanism is operative — can be on the same order as the dynamical timescale $\tau_{\text{dyn}}$ of the star. In practice, the driving mechanism could be a He-ionisation $\kappa$ mechanism (e.g., Glatzel & Kiriakidis, 1993); it could be the iron-bump $\kappa$ mechanism (e.g., Kiriakidis et al., 1993); or it could be the strange instability, which I discuss further below. In each case, as $\tau \to \tau_{\text{dyn}}$ the prospect of significant hydrodynamical mass loss arises. Determining the ultimate outcome involves following the instability into the nonlinear regime; this is an extremely challenging radiation-hydrodynamics problem, but Grott et al. (2003, 2004, 2005) appear to be making good initial progress.

Let me turn now to the strange instability — which although related to strange modes, should not be confused with them. The strange instability arises in circumstances where the gas pressure $p_{\text{gas}}$ is small compared to the radiation pressure $p_{\text{rad}}$. Ordinarily, the converse is true, and the total pressure $p$ can be approximated by the ideal gas pressure,

$$p \approx p_{\text{gas}} = \frac{\rho kT}{\mu}.$$  

This means that perturbations to the density $\rho$ are proportional to perturbations to the pressure,

$$\delta \rho \propto \delta p,$$

and disturbances propagate as acoustic waves. When $p_{\text{gas}} \ll p_{\text{rad}}$, however, the relation between density and pressure perturbations should be obtained from the radiative diffusion equation,

$$F_{\text{rad}} = \frac{1}{3\kappa \rho} \nabla p_{\text{rad}} \approx \frac{1}{3\kappa \rho} \nabla p.$$  

Assuming that the radiative flux $F_{\text{rad}}$ remains constant (which is appropriate in the envelopes of very massive stars, because the radiative relaxation time is so short), then density perturbations are governed by

$$\delta \rho \propto \nabla \delta p.$$
The gradient operator on the right-hand side introduces a quarter-cycle phase shift in the dispersion relation governing disturbances, and instead of obtaining wave solutions we find exponential growth corresponding to instability.

The foregoing discussion gives the simplest-possible view of the strange instability, and glosses over many important issues; for a rigorous treatment, refer to the discussion §4.2 of Saio et al. (1998). Nevertheless, this basic analysis captures the fundamental character of the strange instability — namely, that it is driven directly by radiation pressure, rather than relying on a Carnot-cycle heat engine as found in ‘ordinary’ instabilities such as the $\kappa$ and $\epsilon$ mechanisms.

**Pulsation and stellar winds**

At amplitudes that are too small to eject mass directly, pulsations can still play an important role in modulating mass-loss from a massive star, by coupling to the star’s radiatively driven wind. Observationally, there is persuasive evidence that such coupling takes place. Extended time-series spectra obtained using *IUE* reveal that the UV P Cygni absorption lines of many O and B stars exhibit discrete absorption components (DACs), that migrate from red to blue in a cyclical fashion (see, e.g., Prinja 1988; Prinja et al. 1992; Howarth et al. 1993). At the same time, a survey of optical line profiles in these stars by Fullerton et al. (1996) found statistically significant $\ell p v$ in 77% (23/30) of their sample. It is natural to speculate that these two types of variability must be causally linked; but the direct evidence confirming such a ‘photospheric connection’ has proven quite difficult to come by.

The impasse appears to have been at least weakened by Kaufer et al. (2006), who have conducted a detailed analysis of the optical $\ell p v$ of the B0 supergiant HD 64760. This star shows some of the most dramatic UV variations of any massive star, consisting of the episodic appearance of migrating DACs superimposed over periodic (1.2 d and 2.4 d) modulations in the absorption troughs of resonance line profiles (Massa et al. 1995). Building on an idea first proposed by Mullan (1986), Fullerton et al. (1997) proposed that the periodic modulations are due to the passage of corotating interaction regions (CIRs) across the face of the star. As shown in earlier hydrodynamical simulations by Cranmer & Owocki (1996), these CIRs can be formed by collisions between fast and slow wind streams that are rooted in flow inhomogeneities at the stellar surface.

Kaufer et al. (2006) demonstrated a pulsational origin for these surface structures, by showing that beating between three closely-spaced, high-order ($\ell = 6 - 10$) modes would lead to a 6.8 d period that is directly observed in wind-sensitive lines such as H$\alpha$. This *almost* amounts to a confirmation of a photospheric connection; but a stumbling block remains the mismatch between the 6.8 d period in the photosphere and wind base, and the 1.2 d/2.4 d modulation period seen in the UV absorption lines formed further out into the wind. Indeed, the 6.8 d period seems to correspond better with the typical recurrence time of the DACs superimposed over the periodic UV modulations.

Turning now to theoretical issues, progress has been slow in understanding how pulsation and wind mass-loss can interact with one another. The present author (Townsend, 2000a,b) examined the possibility that pulsation waves are not completely reflected at
the stellar surface, and instead leak through into the wind, possibly seeding structure at the wind base that evolves into a CIR. In principle this mechanism could work, but in practise the frequency of the pulsation modes typically seen in massive stars fall in between the twin critical frequencies $\omega_{c1}, \omega_{c2}$ of the photosphere, meaning that in all cases complete wave reflection occurs.

Significantly, however, this analysis did not account for the prior existence of a wind. The expected impact of a wind is twofold. First, it leads to a shallower stratification in the surface layers of a star, with the density falloff transitioning from $e^{-r}$ to $r^{-2}$; this tends to make it more difficult for wave reflection to occur. Second, the mean flow associated with a wind modifies the wave propagation, meaning that even for frequencies between the formal critical frequencies, complete reflection cannot occur. To my knowledge, this latter effect has only been studied locally, and in the simple case of an isothermal atmosphere (see Cranmer, 1996); no attempt has been made to include it into a global pulsation code. Certainly, there is much scope for progress here.

To complete the discussion, I shall say a few words on small-scale atmospheric structure due to pulsation. In the majority of pulsating massive stars, we only detect a handful of modes — in spite of the fact that a linear analysis suggests hundreds if not thousands should be unstable. Are these modes in fact damped? Or is it rather that their amplitudes are too small for present-day instrumentation to pick up? The COROT mission and similar endeavours will help resolve this issue, by pushing down detection thresholds to the micromagnitude level. In the meantime, we can ask ourselves whether we already see the signatures of many small-amplitude pulsation modes in massive stars, under the twin guises of microturbulence and macroturbulence? Both of these ‘phenomena’ arise from the inability to fit photospheric line profiles without assuming an additional source of Doppler broadening; they only differ in the scale of the velocity structures they assume, with micro (macro) being smaller (larger) than photon mean free paths. To obtain consistent fits to Helium lines of O-type supergiants, Smith & Howarth (1998) had to assume microturbulent velocities on the order of $\sim 15 \text{ kms}^{-1}$. Likewise, Ryans et al. (2002) found that macroturbulent velocities on the order of $\sim 50 \text{ kms}^{-1}$ were necessary to obtain acceptable fits to the line profiles of B-type supergiants.

The origins of micro- and macroturbulence are of interest not only to spectroscopists. A recent paper by Lucy (2007) has highlighted the idea that the mass-loss rate in a radiatively driven wind can be sensitive to the degree of microturbulence in the subsonic parts of the outflow. Moreover, macroturbulence may impact observational $\dot{M}$ measurements, by modulating the wind clumping discussed previously. In the absence of photospheric perturbations, the line-driven instability (Feldmeier & Owocki, 1998) causes small-scale wind clumping to arise spontaneously at a few tenths of a stellar radius above the stellar surface. However, the character and extent of the clumping may change dramatically in the presence of macroturbulent/pulsation velocity fields in the photosphere.

Related to this discussion is the issue of super-Eddington mass loss. In a star whose surface layers are formally above the Eddington limit (so that the electron-scattering radiative force exceeds gravity), the resulting continuum-driven wind will be characterized by a mass-loss rate far in excess of the $\dot{M}$ typical to line-driven winds. Smith & Owocki (2006) argue that the LBV eruptions they invoke, to allow the transition to a Wolf-Rayet star, take the form of continuum-driven winds. As discussed by Owocki et al. (2004),
steady continuum driving requires some way to modulate the electron-scattering opac-
ity, and one way to do this is to invoke an instability-driven porous atmosphere (Shaviv,
2001). It is not yet clear how Shaviv’s instability fits into a pulsational framework, but it
seems likely to be related to the strange instability discussed previously.

Pulsation and rotation

The Be stars (see Porter & Rivinius, 2003) appear to be an ideal laboratory for learn-
ing about the interplay between pulsation, rotation, and mass loss. For a long time, the
study of these objects was dominated by arguments over whether their lpv and photo-
metric variations were due to pulsations or to rotational modulation of spots and cir-
cumstellar structures (e.g., Baade & Balona, 1994). However, the detection of multiple
periods in the lpv of the B2e star $\mu$ Cen by (Rivinius et al., 1998), and the successful
modeling of these lpv by Rivinius et al. (2001), gave considerable weight to the pul-
sational interpretation. A subsequent investigation by Rivinius et al. (2003), using the
same BRUCE/KYLIE modeling codes as before (see Townsend, 1997), revealed that the
photospheric lpv of the majority of variable Be stars can be attributed to nonradial pul-
sation in retrograde, $\ell = m = 2$ modes.

An interesting result from the analysis of $\mu$ Cen is that the outbursts of the star,
during which additional H$\alpha$ emission appears, seem to be correlated with beating of the
pulsation modes. This appears to support an idea advanced by Ando (1986) and Osaki
(1986), that the Be phenomenon arises when pulsation waves deposit sufficient angular
momentum in the stellar surface layers for these layers to reach critical rotation. The
resulting lifting of material into orbit then forms a viscous decretion disk, as envisaged
by Lee et al. (1991). Hydrodynamical simulations by Owocki (2005) seem to support
such a process, but only for modes that are propagating in the prograde direction.
Unfortunately, as mentioned above the preponderance of Be stars — including $\mu$ Cen — instead exhibit retrograde pulsation. One way out of this seeming contradiction has
been suggested by Townsend (2005): the mixed Rossby-gravity modes that are unstable
in B-type stars show a retrograde phase velocity, but a prograde group velocity. Thus,
they be able simultaneously to satisfy the observational and theoretical constraints.

Perhaps, however, the problem is that the hydrodynamical simulations by Owocki
(2005) are not able to capture the full physics of the situation. The net deposition of
angular momentum in the surface layers requires either that prograde pulsation modes
are dissipated there, or (in a recoil effect) that retrograde modes be excited there.
The latter scenario is what arises in SPB and $\beta$ Cep pulsators; work functions for unstable modes in these stars (e.g., Dziembowski et al. 1993, their Fig. 1) reveal an outer
excitation region associated with the iron-bump $\kappa$ mechanism, and an inner dissipation
region associated with radiative damping. So, in fact it seems more likely that retrograde
modes are required to spin up the surface layers of these stars. That the simulations by
Owocki (2005) did not confirm this result, may be due to the boundary conditions that
were adopted.

Continuing with this theme of angular momentum transport, the proximity of the
excitation and dissipation regions in $\beta$ Cep and SPB stars suggests that we should
naturally expect a shear layer to develop between them. This layer represents a source of free energy that could, for instance, be tapped into to generate a magnetic field. This is a particularly intriguing possibility, especially in light of the reported detection of magnetic fields in 11 out of a sample of 25 SPB stars (Hubrig et al., 2007). Further calculations are needed to gauge the magnitude of the shear, which will be set by the strength of the diffusive processes that act in competition with the wave transport. At this early stage, I shall only remark that the typical angular momentum luminosities due to massive-star pulsations are expected to be orders-of-magnitude greater than found in solar-type stars (see, e.g., Charbonnel, these proceedings); this is simply because of the much-higher amplitudes of the instability-driven modes in the former, as compared to the stochastically excited modes in the latter. Are we therefore missing an important ingredient in our understanding of the rotational evolution of massive stars?

SUMMARY

To summarize my discussion, I restate the questions that I posed in the abstract:

• To what extent can pulsational instabilities resolve the mass-loss problem of massive stars?
• How important is pulsation in structuring and modulating the winds of these stars?
• What role does pulsation play in redistributing angular momentum in these stars?

The first question is relatively new, arising both from the discovery of strange modes and strange instabilities, and from the recent realisation that wind mass-loss rates are too small for Wolf-Rayet stars to form. However, the latter two questions extend back at least two decades, to a 1985 workshop held at the Joint Institute for Laboratory Astrophysics (Boulder, Colorado). In a fascinating series of connected papers, under the main title “The Connection Between Nonradial Pulsations and Stellar Winds in Massive Stars”, Abbott et al. (1986) and other authors reviewed many of the topics I have discussed in this contribution. That these questions still remain as Unsolved Problems in Stellar Astrophysics is frustrating, for — as I hope I have been able to convey — the need to understand the coupling between pulsation and mass loss is even more pressing today than it was all those years ago.

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