Radial and Nonradial Pulsations as Probes of Stellar Physics
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C. Aerts, T. Bedding, and J. Christensen-Dalsgaard

The Link between Radiation-Driven Winds and Pulsation in Massive Stars

S. P. Owocki

Bartol Research Institute, University of Delaware, Newark, DE 19716 USA; owocki@bartol.udel.edu

S. R. Cranmer

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138 USA; scranmer@cfa.harvard.edu

Abstract. Hot, luminous, massive stars have strong stellar winds driven by line-scattering of the star's continuum radiation. They are also often observed to exhibit radial or non-radial pulsations. Such pulsations are possible candidates for providing the base perturbations that induce large-scale structure in the overlying wind, and as such they could help explain various observational manifestions of wind variability, e.g. absorption enhancemens or modulations in UV P-Cygni lines of OB stars, and perhaps even moving bumps in optical emission lines of Wolf-Rayet (WR) stars. Here we review the physics of line driving with emphasis on how perturbations induce variations in a wind outflow. In particular, we present results of a time-dependent dynamical simulation of wind variations induced by the radial pulsation of the beta Cehpeid variable BW Vulpeculae, and show that obervation variability in UV wind lines can be quite well reproduced by synthetic line profiles for this model. We conclude with a discussion of recent evidence that resonances among multiple modes of non-radial pulsation on Be stars play a role in inducing mass ejections that contribute to formation of a circumstellar disk.

1. Introduction

Massive stars ($M > 10 M_{\odot}$) are characteristically quite hot ($T_* > 10,000\,K$) and luminous ($L = 10^4 - 10^6 L_{\odot}$), and scattering of this large luminosity by UV spectral lines of heavy, minor ions drives strong stellar winds, with mass loss rates ranging up to $10^{-5} M_{\odot}$, and flow speeds several times the surface escape speed, $v > 1000$ km/s. Such winds are evident, for example, from the asymmetric P-Cygni profiles of UV lines from O and B stars, and from the broad optical emission lines of WR stars. For OB stars, these overall wind properties are well reproduced by modern extensions of the classic, steady-state, line-driven wind theory formulated originally by Castor, Abbott, and Klein (1975; hereafter CAK); but modelling the relatively large mass loss rates inferred for WR stars requires further extensions to include, e.g., effects of ionization stratification, and multiple scattering in both lines and continuum.

In both OB and WR winds, there is often evidence of extensive structure and variability, for example from soft X-ray emission, or even direct variabilty in line profiles. Some of this appears to be stochastic, small-scale structure that may arise from intrinisic instabilities in the line-driving. But there is also evidence for relatively large-scale structure, for example in the form of irregularly recurring Discrete Absorption Components (DACs), as well as more regular Periodic Absorption Modulations (PAMs) detected in long-term IUE monitoring of UV wind lines from OB and WR stars. The DACs may arise from perturbations and/or outbursts, perhaps associated with magnetic activity on the underlying star. The PAMs and some more regular recurring DACs might, on the other hand, might result from stellar *pulsations*, either radial or nonradial, which indeed are often also directly detected in high-resolution photospheric spectra of such massive stars. The review here will examine theoretical issues of how pulsation can be expected to influence such a radiatively driven wind outflow.

2. Physics of Line Driving

Let us first briefly review the physics of radiative driving. For a star of luminosity L, continuum scattering of the radiative flux $F = L/4\pi r^2$ by free electrons with opacity κ_e yields a radiative acceleration $g_e = \kappa_e F/c$, with c the speed of light. For a stellar mass M, the ratio to the gravity $g = GM/r^2$ defines the so-called Eddington parameter $\Gamma_e = \kappa_e F/gc = \kappa_e L/4\pi GMc$. For massive stars, this ratio can approach unity, but fully overcoming gravity in a continous stellar wind requires the additional acceleration from scattering by a large enemble of spectral lines. For optically thin lines, the acceleration has a similar scaling to electron scattering, $g_{thin} = (\kappa_l v_{th}/c)F/c$, where v_{th} is the ion thermal speed. But for optically thick lines, self-absorpton within the lines reduces the effective flux by a factor given by the Sobolev optical depth, $\tau \equiv \kappa_l \rho l$, where $l \equiv v_{th}/v'$ is the Sobolev length, with ρ the mass density and v' the flow velocity gradient. This yields an optically thick line acceleration $g_{thick} = g_{thin}/\tau = Fv'/\rho c^2$. Within the standard CAK formalism in which the number of lines is taken to be a power law in line opacity, the cumulative acceleration from a mixture of thick and thin lines has an intermediate scaling

$$g_{cak} \sim \frac{g_{thin}}{\tau^\alpha} \sim \frac{\bar{Q}\kappa_e F}{c} \left[\frac{1}{\bar{Q}\kappa_e \rho c}\frac{dv}{dr}\right]^\alpha \tag{1}$$

where α is the CAK power index, and $\bar{Q} \sim 10^3$ is a dimensionless factor related to the CAK line normalization constant through $k = (v_{th}/c)^\alpha \bar{Q}^{1-\alpha}/(1-\alpha)$ (Gayley 1995).

This scaling is key to understanding the dynamical properties of both steady and variable flows driven by line-scattering. For example, in a steady outflow both the outward driving and the resulting flow acceleration must be comparable to the effective gravity, $g(1-\Gamma_e) \sim vv' \sim g_{cak}$. This can be solved to yield a scaling for the mass flux,

$$\dot{m} \equiv \rho v \sim \frac{F}{c^2}\left(\frac{\bar{Q}\Gamma_e}{1-\Gamma_e}\right)^{-1+1/\alpha} \tag{2}$$

which in the CAK model of a steady, spherically symmetric wind yields the usual CAK scaling of the mass loss rate $\dot{M} = 4\pi r^2 \dot{m} \sim L^{1/\alpha}$ with luminosity L. However, in a pulsating star with spatial and/or temporal variations in surface flux F or density ρ, such variations can be expected to induce corresponding modulations in the overlying stellar wind.

3. Wave Leakage into Wind

At the subsonic base of such generally highly supersonic wind outflows, inclusion of the gas pressure term allows for a smooth match onto a nearly hydrostatic atmosphere, with an exponential stratification of density and pressure to balance the stellar gravity. Stellar pulsations generated by various driving mechanisms in the stellar interior can propagate propagate upward toward the atmosphere as either relatively high-frequency gas pressure (p-mode) waves, or as lower-frequency gravity (g-mode) waves. In pulsation models that assume a purely hydrostatic atmosphere at the outer boundary, these waves generally become evananscent at some layer, thus forcing the wave energy to be reflected back into the interior. However, analyses (e.g., Cranmer 1996; Townsend 1997) that include an overlying wind show how flow advection in the supersonic part of the outflow can carry away wave energy that has "tunneled" through a limited evanescent region of the subsonic atmosphere. It is thus through this "wave leakage" that pulsations in a star can seed wave perturbations in the outflowing wind. A much more extensive discussion of the linear propagation of atmospheric waves into an overlying wind can be found in Chapter 7 of Cranmer (1996).

4. Large-Wavelength Abbott Waves and Small-Scale Instability

To analyze the properties of linear wave modes *within* a line-driven stellar wind, Abbott (1980) assumed the perturbed line acceleration would also scale with the velocity gradient

$$\delta g_{cak} = \frac{\partial g_{cak}}{\partial v'} \delta v' = U\, ik\delta v \,, \tag{3}$$

where the latter relation assumes a sinusoidal perturbation $\delta v \sim e^{ikr-\omega t}$ of wavenumber k and frequency ω, with $U \equiv \partial g_{cak}/\partial v'$ defining the "Abbott speed". Neglecting for simplicity gas pressure terms in comparison to the much stronger line-forces that drive these highly supersonic outflows, we find from a simple inertial force balance, $\delta g_{cak} = \partial \delta v/\partial t = -i\omega\delta v$, which implies a stable wave with coherent, phase propagation that is *inward* in the comoving wind frame,

$$\frac{\omega}{k} = -U. \tag{4}$$

Figure 1 provides a graphical depiction of how an outward radiative flux causes such an inward propagation of a perturbation to the background wind acceleration. Although derived for a sinusoidal perturbation, note that the propagation speed does not depend on wavenumber, and so implies a dispersionless inward group propagation with this same Abbott speed. Moreover, since the mean wind acceleration $g_{cak} \sim vv'$, we find $U \sim \partial g_{cak} \partial v' \sim g_{cak}/v' \sim v$, implying that this

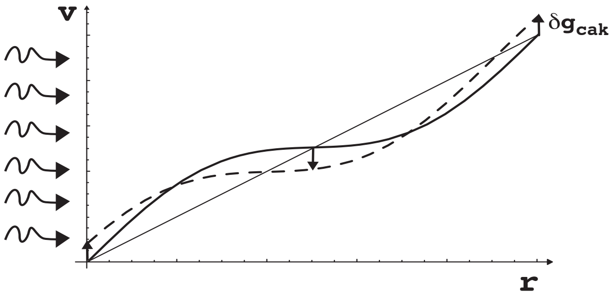

Figure 1. Inward propagation of a sinusoidal perturbation in a line-driven flow acceleration. The up and down arrows indicate the enhanced and reduced line-force associated with regions of enhanced or decreased velocity gradient, thus inducing a relative acceleration or deceleration that implies an inward phase propagation of the perturbation.

inward Abbott wave propagation speed is comparable to the mean wind outflow speed. Indeed, Abbott (1980) argued that a net inward wave propagation is possible up to the CAK critical point, and that this inward communication of information provides a means by which the subcritical wind adjusts to the mass loss and speed appropriate for the CAK critical solution.

However, this Abbott analysis really only applies for perturbations $kl \ll 1$ with a wavelength larger than the Sobolev length l. For short-scale perturbations $kl \gtrsim 1$ with a wavelength at or below the Sobolev l, the perturbed line force scales with the perturbed velocity (Owocki and Rybicki 1984, 1985), $\delta g \sim \delta v$, implying a strong instability, with a characteristic exponential growth rate that exceeds the wind expansion rate by a factor of order $R/l \lesssim 100$. Numerical simulations suggest that this should lead to extensive small-scale structure in the wind, either seeded by acoustic perturbations at the wind base (Owocki, Castor, and Rybicki 1987; Feldmeier et al. 1997), or generated intrinsically within the wind itself (Owocki and Puls 1999).

For the idealized case of pure-absorption lines, analytic Green's function analyses show that large-scale Abbott waves cannot actually carry inward information faster than an ordinary sound wave (Owocki and Rybicki 1986). But subsequent numerical models that include line-scattering suggest that the Abbott speed does rougly approximate the speed for an inward propagation front associated with the perturbed scattering force (Owocki and Puls 1999). This thus again provides a physical mechanism for line-driven winds to approach a averaged state that is well-approximated by the CAK critical solution.

5. Dynamical Simulations of Pulsation-Induced Wind Variabililty

The beta Cepheid variable BW Vulpeculae shows a quite large amplitude radial pulsation at a period of 4.82 hours, significantly longer than the characteristic acoustic cutoff period of ~ 1.5 hours (Burger et al. 1982; Blomme and Hensbere

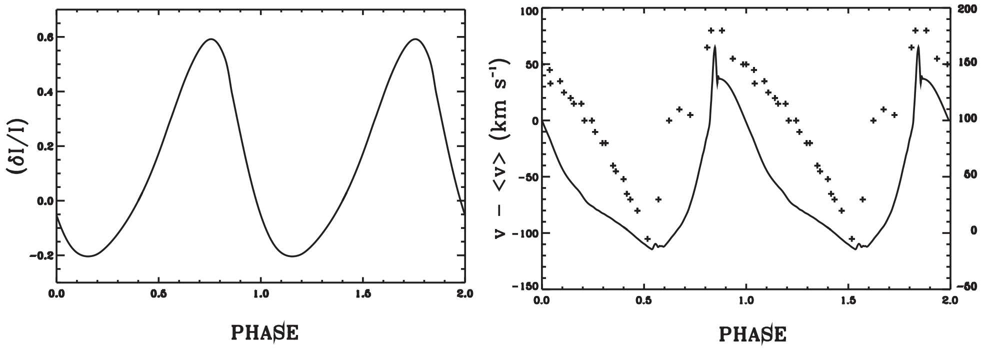

Figure 2. Observationally inferred variations of the photospheric surface brightness (left) and surface velocity (right, points) for BW Vulpeculae. The solid curve in the right panel shows the computed surface velocity in a hydrodynamical wind model that assumes the observed brightness variations and then computes the resulting variations in the line-driven wind outflow.

1985; Furenlid et al. 1987). There are observed variations in both the brightness and radial velocity of the optical photosphere (figure 2), as well as associated variations in UV wind lines like C IV 1550 (figure 4, left; Massa 1994). Thus BW Vul is a very good candidate for modelling the coupling of stellar pulsations to variations in the stellar wind.

Figure 3 illustrates the results of such a time-dependent wind model, computed with a 1D hydrodynamical code that uses the above-described CAK, Sobolev form for the line-driving force, assuming a periodic variation in both the stellar surface brightness and density. Specificallly, within our Eurlerian code with a fixed location for the inner boundary, the inferred oscillation of the stratified atmosphere is mimicked by imposing a large (factor 60) variation in the boundary density above and below some mean value. The associated brightness variations were then computed from adiabatic pulation theory (Buta and Smith 1979), and approximate those inferred from the optical continuum observations. The curves in figure 3 show snapshots of the resulting radial variation of wind velocity (left) and density (right) at regular time intervals of 1/20 the pulsation period, i.e. $\Delta t \approx 875$ sec.

The results show that the base variations induce a wind structure with fast rarefactions that ram into slower flows, inducing a shock that compresses material into a dense shell. However, unlike in usual gas dynamics, in this line-driven flow the interaction also induces a flat velocity plateau that is separated from the accelerating wind by a "kink", or a discontinuity in the velocity gradient. This plateau and kink are unique features of line-driven wind that arise from the fast inward propagation associated with the above-described Abbott waves (Cranmer 1996). Moreover, it turns out it is these plateaus, and not the dense shells, that have the greatest effect on line profiles (Cranmer and Owocki 1996). Figure 4 shows that variations of a line profile synthesized for this dynamical model provide a quite good agreement with those observed in the C IV line.

Cranmer and Owocki (1996) used an analogous 2D model with azimuthal variations in surface brightness on a rotating star to generate spiral "co-rotating

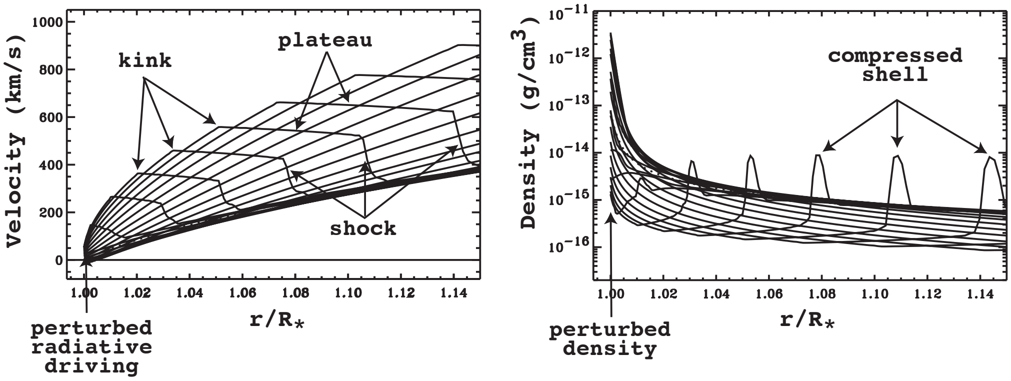

Figure 3. Plots of the radial variation of velocity (left) and density (right) at fixed 875-second intervals in a time-dependent hydrodynamical of a line-driven wind model that assumes the observed, 4.86-hour, periodic variation in surface brightness shown in figure 1a, together with a photospheric base density that varies by a factor 60 above and below a central value. Labels identify key features (shock, kink, plateau, compress shell) of the evolving flow structure.

interaction regions" (CIRs) in the wind, and thereby derive periodic variations in UV wind lines that have many of the properties of observed DACs and PAMs. For the PAMs observed in extended IUE monitoring of the B0.7 Ib star HD 64760, Owocki, Cranmer and Fullerton (1995) developed a 3-D kinematic model of spiral wind density patterns traced to a l=m=4 spherical harmonic variation on the rotating stellar surface. Further work is needed to carry out dynamical versions of such 3D models of NRP-induced wind variability.

6. Pulsation-Induced Mass-Ejection for Be Disks

We conclude by mentioning briefly recent observational results that suggest a link between resonances in non-radial pulsation modes in Be stars and apparent episodes of circustellar mass ejections that supply material to an orbiting disk (Rivinius, Baade, Stefl 2001). Be stars are generally rapid rotators, with equatorial rotation speeds that are often 50% or more of the critical rotation speed of roughly ~ 500 km/s, at which material can maintain a near-surface orbit. But even for material ejected in the prograde direction of rotation (see, e.g. Kroll 1995 and Kroll and Hanuschik 1997) the velocity boost required to reach orbit is still > 100 km/s, much larger than the typical velocity amplitude of pulsation, which are of order the sound speed, $a \sim 20$ km/s.

Since a direct pulsation-driving of these mass ejections thus seems untenable, we have been recently examining a Radiatively Driven Orbital Mass Ejection (RDOME) paradigm for Be disk formation. We suppose the pulsation resonance leads to temporary localized bright regions on the surface. Figure 5 shows the time evolution of the mass outflow from a 10 degree wide, factor 10 brightness enhancement that lasts for 100 ksec, or just over a day. To prevent the tendency to drive the excess material completely away from the star, this model

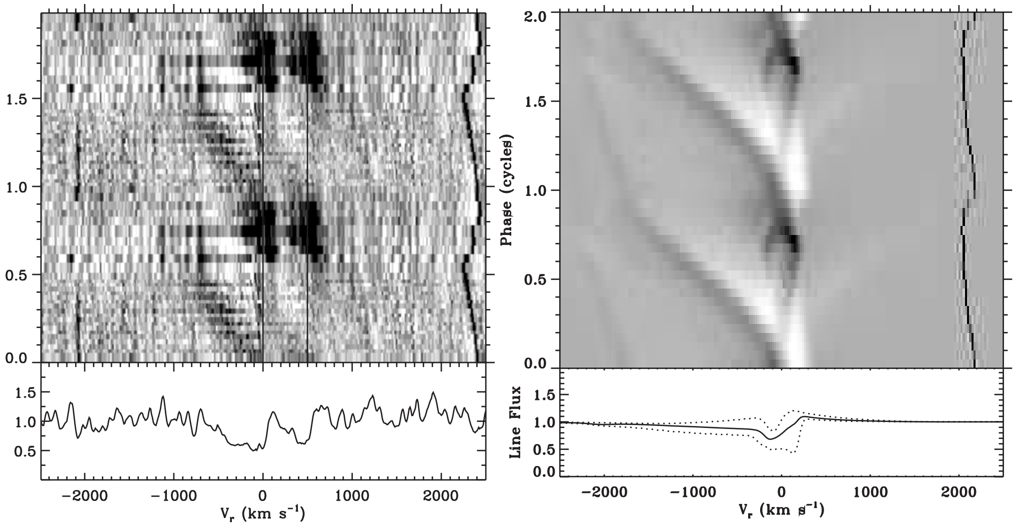

Figure 4. left: Observed variations in the CIV line-doublet, subtracted from mean profile (shown at the bottom), and plotted as a grayscale representation versus phase and wavelength. right: Analogous synthetic wind-line profile variations from the hydrodynamical model shown in figure 3.

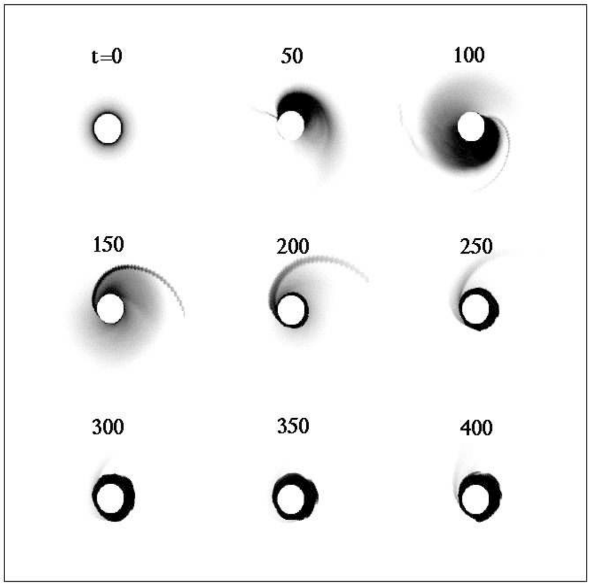

Figure 5. Time snapshots (labeled in equal intervals of 50 ksec) of the density in the equatorial plane for a 2D simulation of Radiatively Driven Orbital Mass Ejection from a localized bright region on the equator of star rotating at 350 km/s.

assumes the locally enhanced brightness is highly limb-brightened, as might be expected from a prominence above the ambiant stellar surface. Under this and other conditions we have explored for limiting the outward radial driving, we find lateral acceleration by radiation can indeed propel material into an orbiting disk, as illustrated in fig. 5.

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Discussion

L. Balona : Do you think radiative driving is strong enough in late Be stars to account for mass ejection?

S. Owocki : Of course late Be stars are expected to have an overall lower luminosity and thus a weaker radiative driving. Thus localized brightness increases would have to be quite extreme to drive a substantial mass ejection to feed a circumstellar disk. On the other hand, the weaker overall luminosity also implies a lower level of radiative and wind ablation that degrades the disk, and this may make it possible to maintain a substantial disk emission with a relatively modest rate of surface mass ejection.