Propagating Waves in Hot-Star Winds: Leakage of Long-Period Pulsations

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Abstract

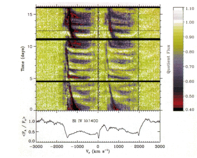
Massive stars have strong stellar winds that exhibit variability on time scales ranging from hours to years. Many classes of these stars are also seen, via photometric or line-profile variability, to pulsate radially or nonradially. It has been suspected for some time that these oscillations can induce periodic modulations in the surrounding stellar wind and produce observational signatures in line profiles or clumping effects in other diagnostics.

The goal of this work is to investigate the detailed response of a line-driven wind to a given photospheric pulsation mode and amplitude. We ignore the short-wavelength radiative instability and utilize the Sobolev approximation, but we use a complete form of the momentum equation with finite-disk irradiation and finite gas pressure effects. For large-scale perturbations appropriate for the Sobolev approximation, though, **the standard WKB theory of stable "Abbott waves" is found to be inapplicable.** The long periods corresponding to stellar pulsation modes (hours to days) excite wavelengths in the stellar wind that are large compared with the macroscopic scale heights. Thus, both non-WKB analytic techniques and numerical simulations are employed to study the evolution of fluctuations in the accelerating stellar wind.

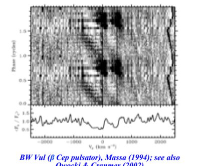
This poster describes models computed with 1D (radial) isothermal motions only. However, even this simple case produces a quite **surprising complexity** in the phases and amplitudes of velocity and density, as well as in the distribution of outward/inward propagating waves through the wind.

Brief Background

- In the Sun, convection-driven *p*-modes give rise to MHD waves that propagate out into the solar wind (e.g., Cranmer & van Ballegooijen 2005).
- Massive stars do not pulsate strongly enough to directly eject mass (like Miras do?), but there is much circumstantial evidence for a **"photospheric connection"** between stellar and wind variability (Fullerton & Kaper 1995)...



HD 64760 (B0.5 Ib), Prinja et al. (1995)



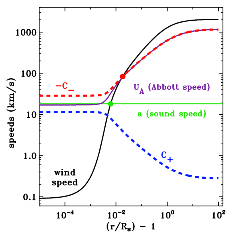
BW Vul (β Cep pulsator), Massa (1994); see also Owocki & Cranmer (2002)

- Not much theoretical work has been done to study pulsation leakage into the circumstellar gas (Castor 1986; Cranmer 1996; Townsend 2000a,b, 2007).
- Are the biggest **wind clumps** driven by pulsations? Is angular momentum in **Be-star disks** transported by "leaked" pulsational wave motion?

Time-Steady ("mCAK") Wind

- All models shown below are perturbations of a time-steady line-driven wind model computed in the Sobolev (1957) approximation. The basic CAK theory (Castor et al. 1975) is modified with a standard finite-disk correction factor.
- We model a **B0 V** star: $M_* = 17.5\,M_\odot$, $R_* = 7.7\,R_\odot$, and $\log(L_*/L_\odot) = 4.64$.
- We model an **isothermal** wind: $T = 24{,}000$ K **(sound speed $a \approx 18$ km/s).**
- CAK α=0.5, k=0.25, no δ factor. $\dot{M} = 3 \times 10^{-8}\,M_\odot$/yr, V_∞=2100 km/s.
- Justification for use of the Sobolev approximation: We can't properly understand departures from Sobolev until we understand Sobolev!
- Ignoring the (slowly varying) finite disk factor, the line force depends on:

$$g_{\rm CAK} \;\propto\; \left(\frac{1}{\rho}\frac{\partial v}{\partial r}\right)^{\alpha}$$



Linear Oscillations

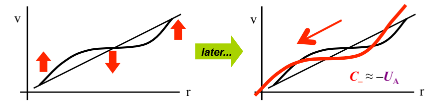
- Let us separate the velocity ($v = v_0 + v_1$) and density ($\rho = \rho_0 + \rho_1$) into steady-state "0th order" and small-amplitude "1st order" perturbations. The 1st order momentum conservation equation depends on the perturbed line force:

$$g_{\rm CAK} \;=\; g_{{\rm CAK},0} + g_{{\rm CAK},1} \;=\; g_{{\rm CAK},0} + \frac{\partial v_1}{\partial r}\left[\frac{\partial g_{\rm CAK}}{\partial(dv/dr)}\right]_0 + \rho_1\left[\frac{\partial g_{\rm CAK}}{\partial \rho}\right]_0$$

The "Abbott speed" U_A
Near the star, $U_A/a \approx (v_0/a)^{2\alpha-1}$
Far from the star, $U_A \approx \alpha\, v_0 >> a$

density perturbations are often neglected (which is okay for high-freq. waves...)

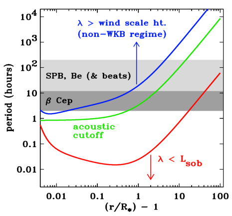
- "Steeper" velocity gradients give rise to stronger line forces. Strangely, a sinusoidal oscillation in v_1 wants to propagate **inwards!** (Abbott 1980)



Local "Abbott Wave" Analysis

- Assume v_1 and $\rho_1 \propto \exp(i\omega t - ikr)$, where frequency ω and wavenumber k are **locally constant.** Abbott (1980) derived the dispersion relation for ω(k), where the inertial-frame phase speed and amplitudes go as:

$$\frac{\omega}{k} \;=\; (v_0 + C_\pm) \;=\; v_0 - \frac{U_A}{2} \pm \sqrt{\frac{U_A^2}{4} + a^2} \qquad\qquad \frac{|v_1|}{C_\pm} \;=\; \frac{|\rho_1|}{\rho_0}$$



- This approximation is valid only when wavelengths ($\lambda = 2\pi/k$) are:
- **Small** compared to macroscopic scale heights ($v_0 / (\partial v_0/\partial r)$), but
- **Large** compared to the Sobolev length ($L_{\rm sob} \approx v_{\rm th} / (\partial v_0/\partial r)$); i.e., stable against the radiative instability (Owocki & Rybicki 1984, 1985; Owocki 2004).

This is a restrictively small range!

Global non-WKB Analysis

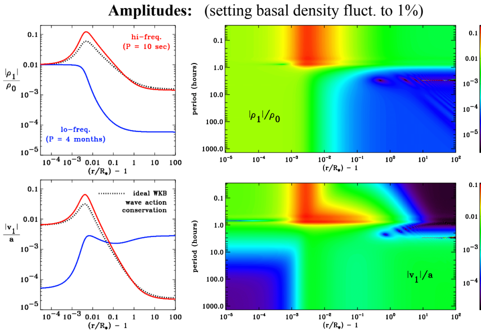
- To model lower frequencies, let us **discard** the idea of wavenumbers and solve directly for radial oscillation patterns, where v_1 and $\rho_1 \propto \exp(i\omega t + i\Psi_{v,\rho}(r))$.
- There are now 4 coupled ODEs (2 for amplitudes, 2 for Ψ's) that all become singular at the mCAK "critical point." We must integrate numerically up and down from this point for each frequency (see, e.g., Heinemann & Olbert 1980; Grappin et al. 1997; Cranmer & van Ballegooijen 2005).
- This method is valid for arbitrarily **low frequencies** (i.e., long periods!)
- To remain self-consistent, we need to keep the **density perturbations** to $g_{\rm CAK}$, which are important when

$$\left|\rho_0\left(\frac{\partial g_{\rm CAK}}{\partial \rho}\right)_0\right| \;\gtrsim\; \omega U_A$$

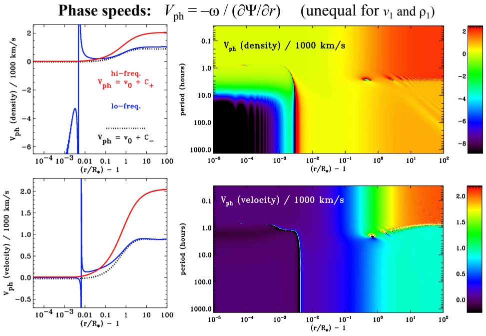
- In the supersonic wind, the LHS ≈ $\alpha v_0(\partial v_0/\partial r)$, the RHS ≈ $\alpha\omega v_0$. Thus, the density perturbation is important when $\omega < \partial v_0/\partial r$, i.e., when the local effective wavelength λ exceeds the scale height. This is the same as the **"non-WKB" criterion** that defines where the traditional Abbott-mode analysis is valid!

Non-WKB Model Results

Amplitudes: (setting basal density fluct. to 1%)



Phase speeds: $V_{\rm ph} = -\omega / (\partial\Psi/\partial r)$ (unequal for v_1 and ρ_1)

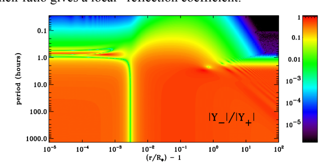


Reflection Coefficients:

- High-freq. waves behave like **outward (C_+)** Abbott modes.
- Low-freq. waves have ***some*** properties of "reflected" **inward (C_-)** Abbott modes (at least above the critical point).
- We can quantify the degree of local reflection by constructing "Elsasser-like" variables:

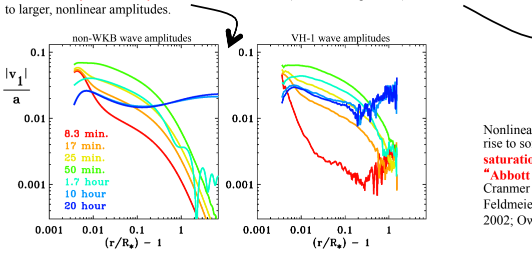
$$Y_\pm \;=\; v_1 - C_\mp\,(\rho_1/\rho_0)$$

- **Y_-** is zero for outward modes; **Y_+** is zero for inward modes. Their ratio gives a local "reflection coefficient:"

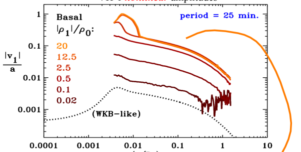


Numerical Simulations

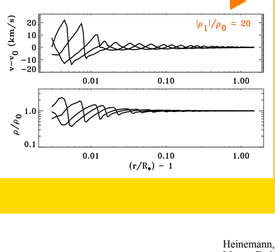
- We use the **VH-1 hydrodynamics code** (Blondin & Lufkin 1993), modified with the mCAK radiation force, to **verify the validity** of the non-WKB results (for small amplitudes) and to **extend** the models to larger, nonlinear amplitudes.



- The non-WKB method is generally validated for low basal amplitudes (10% above). There is similar agreement for the density amplitudes and phase speeds.



Nonlinear amplitudes give rise to some degree of wave **saturation,** and also to **"Abbott kinks"** (see, e.g., Cranmer & Owocki 1996; Feldmeier & Shlosman 2002; Owocki 2004):



Preliminary Conclusions

- For low frequencies typical of hot-star pulsations, the "classical" theory of Abbott waves is inapplicable; **non-WKB methods must be used.**
- The low-frequency velocity amplitude (at $r >> R_*$) is much **higher** than expected based on ideas of WKB "wave action conservation."
- Numerical models verify non-WKB theory for small amplitudes, but when increased, the amplitudes seem to **saturate** at low levels.

Questions that still need to be addressed:

- How do VH-1 models of long-periods (> 10 hr) & large-amplitudes behave?
- Do the waves affect the mean flow properties (V_∞ and $\dot{M}$) ?
- Will inclusion of pulsation-related L_* fluctuations affect perturbed $g_{\rm CAK}$?
- How does the theory generalize to **horizontal motions (from NRPs)?** Can they affect the circumstellar environment (e.g., Owocki & Cranmer 2002)?

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Image credits:

Sinusoidal Abbott-wave cartoon: Owocki (2004)

Artist's conception beneath conclusions: NASA illustration by Casey Reed; see also Sonneborn et al. (2007)

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