Possible Links Between Pulsations & Line-Driven Mass Loss in Massive Stars

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IAU Colloquium #185
Leuven, Belgium
July 26-31, 2001
Outline

• Key properties of line-driven mass loss

• Wind variability
  – Discrete Absorption Components
  – Periodic Absorption Modulations

• Candidates for Pulsation Wind Connection
  – BW Vul
  – EZ CMa = WR 6

• Possible role of pulsation in initiating mass loss
  – WR winds
  – $B_e$ disks
For strong, optically thick lines:

\[ g_{\text{thick}} \sim \frac{g_{\text{thin}}}{\tau} \sim \frac{1}{\rho} \frac{dv}{dr} \]

\[ \tau \equiv \kappa \rho \frac{V_{th}}{dv/dr} \]

L_{sob}
CAK model of steady-state wind

Equation of motion:

\[ \mathbf{v} \mathbf{v}' \approx -\frac{GM(1 - \Gamma)}{r^2} + \frac{QL}{r^2} \left( \frac{r^2 \mathbf{v} \mathbf{v}'}{\dot{M}Q} \right)^\alpha \]

- inertia
- gravity
- CAK line-force

Solve for:

- Mass loss rate
- Velocity law

\[ \dot{M} \approx \frac{L}{c^2} \left( \frac{Q \Gamma}{1 - \Gamma} \right)^{\frac{1}{\alpha} - 1} \]

\[ v(r) \approx v_\infty (1 - R_*/r) \]

\[ \sim v_{esc} \]

Wind-Momentum Luminosity Law

\[ \dot{M} v_\infty \propto L^{\frac{1}{\alpha}} \]

\[ \alpha \approx 0.6 \]

0 < \alpha < 1

CAK ensemble of thick & thin lines
Inward-propagating Abbott waves

\[ \frac{\partial v}{\partial t} = g_{\text{rad}} \]

\[ \delta v \sim e^{i(kr-\omega t)} \]

\[ -i\omega \delta v = \frac{\partial g_{\text{rad}}}{\partial v'} \delta v' \]

\[ \equiv U \ ik \delta v \]

Abbott speed

\[ U = \frac{\partial g_{\text{rad}}}{\partial v'} \]

\[ \sim \frac{g_{\text{rad}}}{v'} \sim \frac{v'}{v} \sim v \]

\[ w/k = -U \]
Line-Driven Instability

for $\lambda < L_{\text{sob}}$:

$\frac{\delta g}{g} \sim \delta u$

Instability with growth rate

$\Omega \sim \frac{g}{v_{\text{th}}} \sim \frac{v}{L_{\text{sob}}} \sim 100 \frac{v}{R}$

$\Rightarrow e^{100}$ growth!
Growth and phase reversal of periodic base perturbation

Radius ($R_*$)

Radius ($R_*$)
Time snapshot of wind instability simulation

![Graph showing velocity and density changes with height](image)

- Velocity (km/s)
- Density (log(ρ) g/cm³)
- Height (R*)

CAK
Wave-leakage into outflowing wind

Cranmer 1996, PhD.

Linear (SMALL-AMPLITUDE) Waves
Acoustic Cut-off: $P = 6.62$ hours

$P = 1 \text{ hr}$

$P = 2.5 \text{ hr}$

$P = 6 \text{ hr}$

$P = 8 \text{ hr}$

$P = 15 \text{ hr}$

$P = 30 \text{ hr}$

$P = 60 \text{ hr}$
Pulsation-Induced Wind Variations in BW Vul

Steve Cranmer, Harvard-Smithsonian
Stan Owocki, Bartol/U. of Del.
BW Vul light curve
Wind variations from base perturbations in density and brightness

- radiative driving modulated by brightness variations
- wind base perturbed by $\delta \rho/\rho \sim 50$
- Abbott-mode “kinks”
- velocity “plateaus”
- shock compression
Radial velocity

Observations

Model

Radial Velocity

July 30, 2001
IAUC 185
Observations vs. Model

C IV

Model line
Monitoring campaigns of P-Cygni lines formed in hot-star winds also often show modulation at periods comparable to the stellar rotation period.

These may stem from large-scale surface structure that induces spiral wind variation analogous to solar Corotating Interaction Regions.
Phase Bowing
HD 64760 (B0Ia)

Si IV observation

kinematic model with $m=l=4$ NRP
WR6 - Pulsational model

\[ m=4 \text{ dynamical model} \]  

NIV in WR 6
The Puzzle of Be Disks

- Be stars are too old to still have protostellar disk.
- And most Be stars are not in close binary systems.
- They thus lack outside mass source to fall into disk.
- So disk matter must be launched from star.

How do Be stars do this??
Key Puzzle Pieces

• **Stellar Rotation**
  – Be stars are generally rapid rotators
  – $V_{\text{rot}} \sim 200-400 \text{ km/s} < V_{\text{orbit}} \sim 500 \text{ km/s}$

• **Stellar Wind**
  – Driven by line-scattering of star’s radiation
  – Rotation can lead to Wind Compressed Disk (WCD)
  – But still lacks angular momentum for orbit

• **Stellar Pulsation**
  – Many Be stars show Non-Radial Pulsation (NRP) with $m < 1 = 1 - 4$

• **Magnetic Spin-Up**
  – $B_{\text{dipole}} < 100 \text{ G} \Rightarrow$ moment arm $R_a < \text{few } R_\ast \sim R_{\text{corotation}}$

• **Here examine combination of #’s 1, 2, & 3**
Launching into Be star orbit

- Requires speed of
  ~ 500 km/sec.

- Be star rotation is often
  > 250 km/sec at equator.

- Launching with rotation
  needs < 250 km/sec

- Requires < a quarter of the
  energy!

- Localized surface ejection
  self selects orbiting material.
Line-Profile Variations from Non-Radial Pulsation

NRP-distorted star (exaggerated)

Line-Profile with:

- Rotation
- Rotation + NRP

Wavelength ($V_{rot}=1$)
NRP Mode Beating

- \( l=3, m=2 \)
- \( l=2, m=1 \)
- \( l=4, m=2 \)
NonRadial Radiative Driving

- Light has momentum.
- Pushes on gas that scatters it.
- Drives outflowing “stellar wind”.
- Pulsations distort surface and brightness.
- Could this drive local gas ejections into orbit??
CIR from Symmetric Bright Spot on Rapidly Rotating Be Star

\[ V_{\text{rot}} = 350 \text{ km/s} \]
\[ V_{\text{orbit}} = 500 \text{ km/s} \]

Spot Brightness = 10
Spot Size = 10°
Symmetric Spot with Stagnated Driving
Symmetric Prominence/Filament
Time Evolution of $m=4$ Prograde Spot Model
Summary

• High-freq. p-modes feed line-driven instability
• g-modes can “leak” into wind
• Radial pulsational light curve modulates mass loss
  – distinctive Abbott kinks with velocity plateaus
• NRP light variations can lead to CIRs
• in Be stars NRP resonances might induce “orbital mass ejection”