Surface Instabilities

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+ many
Causes for S Dor cycles

Outline

• Eddington Limit Mass Loss
• Bi-stability Limit
• Eddington Limit Inflation
Uppermost HRD
Eddington Limit

\[ g_{\text{rad}} = \frac{\kappa F}{c} = \frac{\kappa L}{4\pi R^2 c} \]
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\[ \Gamma = \frac{g_{\text{rad}}}{g_{\text{grav}}} = \frac{\kappa L}{4\pi c GM} \]
EVOLUTION = MASS LOSS
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VMS evolve ‘Chemically Homogeneously‘

(Graefener et al. 2011)
Line-driven winds

Lucy & Solomon (1970)  
Castor, Abbott & Klein (1975)
Monte Carlo approach

Abbott & Lucy (1985)

Vink, de Koter & Lamers (2000) \[ \frac{dM}{dt} = f(L, M, Z, T_{\text{eff}}) \]
Two new aspects

- Wind dynamics
- New parameter range: Masses 60-300 Msun (high Gamma)
Velocity of a line-driven wind

\[ v \left( \frac{dv}{dr} \right) = \left( -\frac{GM}{r^2} \right) + g_{\text{rad}} \]
Line acceleration: $g(r)$

Mueller & Vink (2008)
Mass-loss iteration

Mueller & Vink (2008) and Muijres et al. (2012)
Gamma-dependence
Wind efficiency

\[ \eta = \frac{\dot{M} v_\infty}{L/c} \]
KINK in Mass loss - Gamma Dependence

Vink et al. (2011)
Transition Point Of/\text{WN}

- Below KINK Gamma: $\frac{dM}{dt} = \Gamma^2$
Transition Point Of/WN

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- Above KINK Gamma: \( \frac{dM}{dt} = \Gamma^5 \)
Transition Point Of WN

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• Above KINK Gamma: \( \frac{dM}{dt} = \Gamma^5 \)

Vink et al. (2011) (Vink 2006).

See also co-moving frame computations by Graefener & Hamann (2008)

Empirical Evidence: Graefener et al. (2011)
Transition Point Of/WN

- ETA = TAU = 1
  
- \( \frac{dM}{dt} = \frac{L}{vc} \)
  
  Vink & Graefener (2012)
BISTABILITY

Pauldrach & Puls (1990) for P Cygni
LBVs in the HRD
Slow and dense LBV winds
Change in mass loss

\[ \frac{dM}{dt} \text{ jumps up by factor 5} \] (Vink et al. 1999)
Bi-stability Jump

HOT (O stars)
- modest $dM/dt$
- fast wind
- Fe IV

COOL (B supergiants)
- large $dM/dt$
- slow wind
- Fe III
Does bi-stability Jump exist?

Against:

Halpeta (dM/dt) in B supergiants too low

(Vink et al. 2000; Trundle et al. 2004; Markova & Puls 2008)

FOR:

Vinf drops by factor 2

(Lamers et al. 1995; Crowther et al. 2006)

(dM/dt) local maximum

(Benaglia et al. 2007)
The reason for the word *jump*

- Temperature drops
  - Fe recombines from Fe IV to Fe III
  - Line force increases
  - $dM/dt$ up
  - density up
  - $V(\text{inf})$ drops

  → “Runaway”
The mass loss of AG CAR

Groh et al. (2011)  also: Vink & de Koter (2002)
Radio supernova lightcurves

Soderberg et al. (2006)

Ryder et al. (2004)

2001ig

2003bg
Radio supernova lightcurves

Kotak & Vink (2006)

LBV !?
Do LBVs explode?

Trundle et al. (2008)
Changing mass loss!

Groh & Vink (2011)
Causes for S Dor cycles
Do LBVs make pseudo-photospheres?

Smith, Vink, de Koter (2004)
INFLATION

Ishii et al. (1999)  Petrovic et al. (2006)
Radius Inflation

\[ \frac{\partial P_{\text{gas}}}{\partial P_{\text{rad}}} = \frac{1}{\Gamma} - 1 \]

Graefener, Owocki & Vink (2012)
Radius Inflation

\[
\frac{\partial P_{\text{gas}}}{\partial P_{\text{rad}}} = \frac{1}{\Gamma} - 1
\]

\[
\Gamma = 1: \quad \frac{\partial P_{\text{gas}}}{\partial P_{\text{rad}}} = 0
\]
Radius Inflation

\[
\frac{R_{\text{out}}}{R_{\text{in}}} = \frac{1}{1 - W},
\]

\[
W = \frac{\Delta P_{\text{rad}} R_{\text{in}}}{GM \rho_{\text{mean}}}
\]
Summary

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- Formula for Envelope Inflation
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- \( \eta = \tau = 1 \)
- Used to calibrate wind \( \frac{dM}{dt} \)

- Close to \( \Gamma = 1 \) “Inflation”
- Formula for Envelope Inflation
- \( W \) - Instability