STELLAR ROTATION and EVOLUTION

Henny J.G.L.M. Lamers
Astronomical Institute, Utrecht University

- 22/09/09 Lect 1: Rotation and stellar structure
- 22/09/09 Lect 2: Rotation and stellar winds
- 24/09/09 Lect 3: Rotation and stellar evolution

ROTATION AND MASSLOSS

- Literature

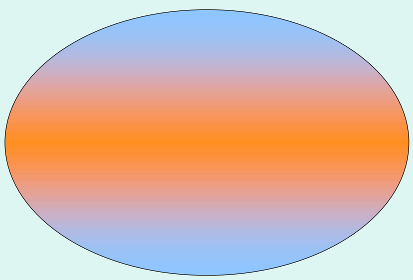
- Lamers & Cassinelli: Introduction to Stellar Winds,
- Cambridge, 1999

- Maeder & Meynet, The evolution of rotating stars,
- ARAA, 38, 113, 2000

- Bjorkmann, J.E. in “Stars with the B[e] phenomena”, 2005

Kudritzki & Puls, Hot star winds, ARAA 38, 613, 2000

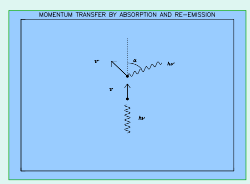
Von Zeipel effect (1924)

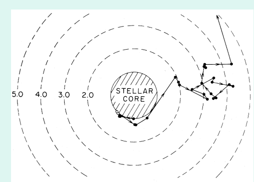


$F_{rad} \propto g_{eff}$

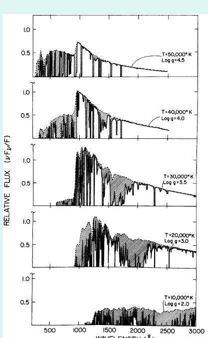
Hot stars: Line driven winds

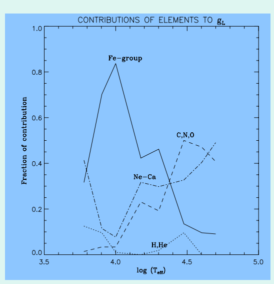
scattering of photons on abundant ions
→
transfer of momentum from radiation to gas





Lines and ions that drive the winds





Abbott

Predictions: scaling laws

Castor, Abbott, Klein 1975

$v_\infty \sim f(\alpha)\sqrt{(GM/R)} \sim (2 \text{ to } 3)\ v_{esc}$

$\dot{M}$dot $\sim g(\alpha)\ L^{1/\alpha}\ M^{(\alpha-1)/\alpha}$

α is linestrength parameter: $0.5 < \alpha < 1$ (best calculation $\alpha \approx 0.65$)

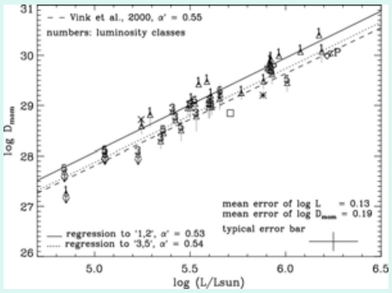
↓ Kudritzki et al 1989

$D \equiv$ Mdot $v_\infty \sqrt{R} \sim L^{1/\alpha}\ M^{0.5-(1-\alpha)/\alpha} \sim L^{1/\alpha}$

D = Modified wind momentum

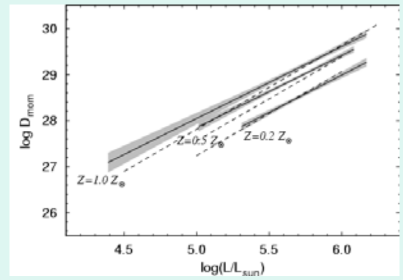
Observed mass loss rates

Galactic stars



Markova et al. 2004

Comparison between predicted and observed Wind Momentum



Galaxy

LMC

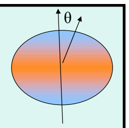
SMC

Large mass loss survey with ESO-VLT-FLAMES

Mokiem et al. 2007

Predictions from Vink et al. 2001, 2005

The influence of rotation



Von Zeipel: $F_{rad} \sim g_{eff}$

$$T_{eff}^{4}(\theta) \sim (1-\omega^2 \sin^2\theta)$$

Mass flux (in gram/cm^2.s) ~ $F_{rad}^{1/\alpha}$

$$F_m \sim g_{net}^{(\alpha-1)/\alpha} F_{rad}^{(1/\alpha)} \sim (1-\omega^2 \sin^2\theta)$$

increases to pole

Velocity $v_\infty \sim v_{esc}$ so

$$v_\infty(\theta) \sim v_{esc}(\theta) \sim \sqrt{R_* g_{net}(\theta)} \sim (1-\omega^2 \sin^2\theta)^{0.5}$$

increases to pole

Wind density $\rho \sim F_m / v\, r^2$

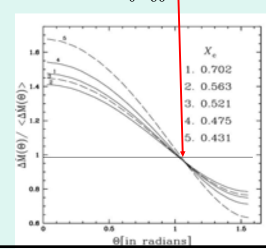
increases to pole

WIND THEORY IN ROTATING STARS

Maeder & Meynet 2000

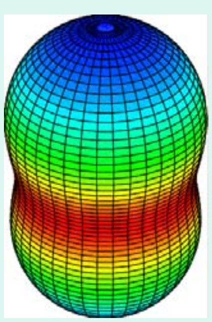
$$\dot{M}(\vartheta) = \frac{A\; g_{eff}(\vartheta)}{\left(1-\frac{\Omega^2}{2\pi G \rho_m}\right)^{\frac{1}{\alpha}} (1-\Gamma_\Omega)^{\frac{1}{\alpha}}}$$

Average mass loss is reached at θ= 60 ^{0}



See also Owocki et al. 1996; Pelupessy, Lamers, Vink 2000; Dwarkadas & Owocki 2002

Mass flux and velocity of the wind of a fast rotating star



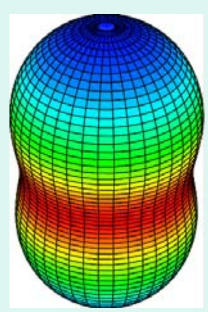
Shape = amount of local mass loss rate

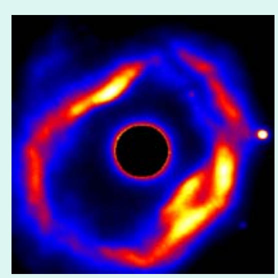
Colour = wind velocity

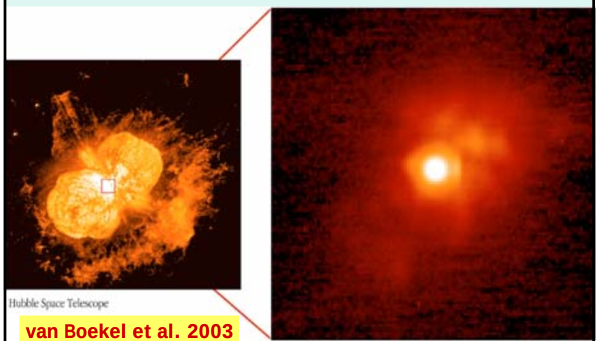
Together ~ isodensity surface

Maeder 1999

Nebula around Luminous Blue Variable AG Car







van Boekel et al. 2003

The Immediate Surroundings of Eta Carinae
(VLT YEPUN + NAOS-CONICA)

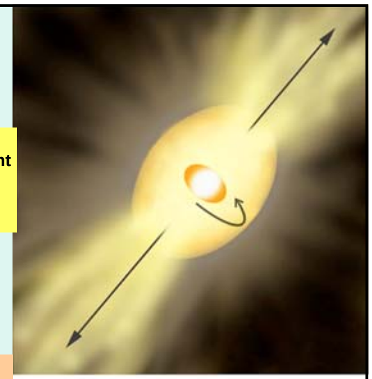
The present wind around Eta Carinae is elongated along a direction aligned with the Homunculus Nebula

Smith et al. 2003 also indicate a latitude dependent wind velocity, with the highest velocities near the poles

⇩

Support polar enhanced mass loss.

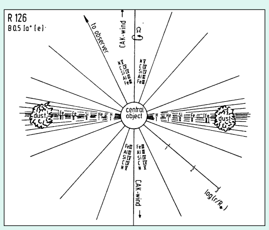
Eta Carinae should rotate at about 90% of the break-up velocity



The Highly Unstable Star Eta Carinae
(Artist's Impression)

What about hot stars with outflowing disks?

Be-stars or B[e]-supergiants

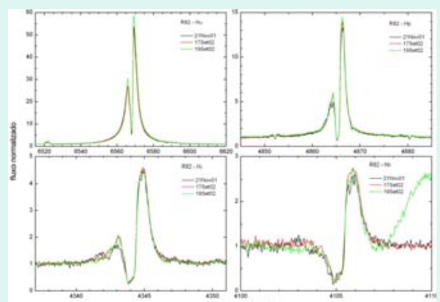


Schematic empirical picture of a B[e]-supergiant R126 (LMC)

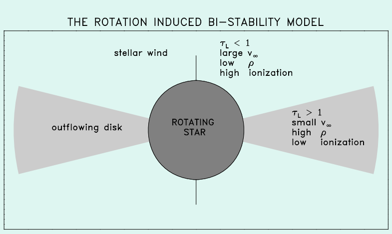
- hot supergiant (T ~ 20 000K)
- fast low density wind from poles (1000 km/s)
- high density disk (Hα)
- slowly outflowing (100 km/s)
- dust in the disk (IR excess)
- extended low density region in outer disk (forbidden Fe[II] lines)

Zickgraf et al. 1986

Line profiles of stars with outflowing disks



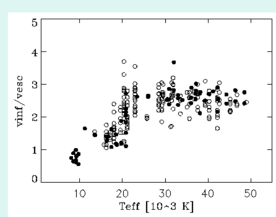
Rotation-induced bi-stability disks

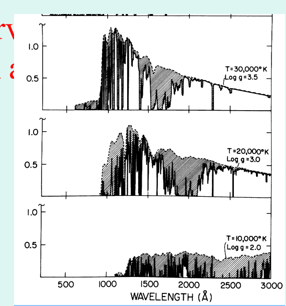


Lamers & Pauldrach 1991

Pelupessy et al. 2000

Jumps in the observ near 20 000 K a





O stars: $V_\infty \approx$ 1000 – 3000 km/s; vinf/vesc = 2.6

B-supergiants: $V_\infty \approx$ 300 – 1000 km/s; vinf/vesc = 1.3

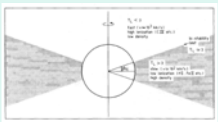
A-supergiants: $V_\infty \approx$ 100 – 200 km/s ; vinf/vesc = 0.7

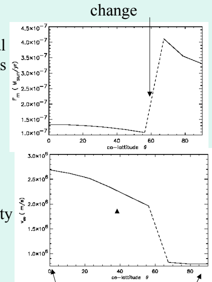
Due to sudden changes in the ionization:

FeIV → FeIII → FeII

Lamers et al. 1998

Bi-Stability & Disks





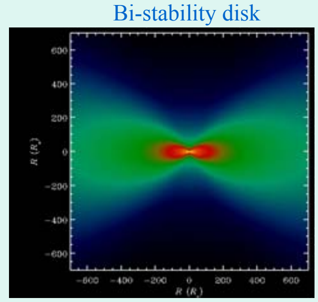
- Ionization shift at low latitudes
  - Higher mass loss
  - Lower terminal speed

Lamers & Pauldrach 1991

Pelupessy et al. 2000

sgB[e] Density (pure H model)

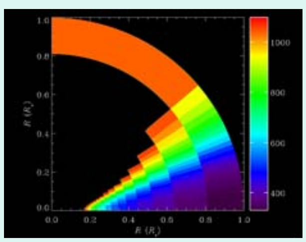
Bi-stability disk



J. Bjorkmann 2005

Dust formation

Bi-stability disk



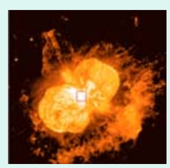
Dust can form in bi-stability disks

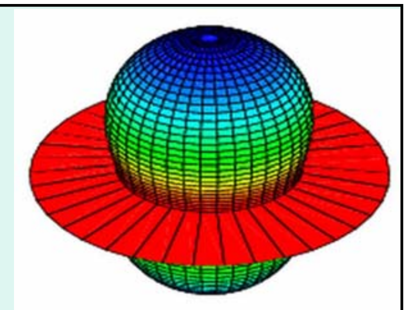
J. Bjorkmann 2005

$25\ 000\ K$

$L = 10^6\ L_0$

$\omega^2 = 0.64$





Model of a star with a bi-stability disk

Meynet 2005

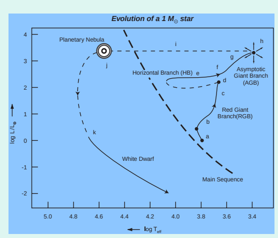
Models of outflowing sgB[e] disks

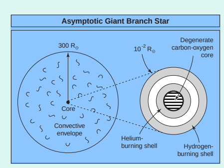
1. Simple bi-stability model (Lamers & Pelupessy)
   $v_{rot} < 0.7\ v_{crit}$: not enough density contrast
   ($\rho_{equ} / \rho_{pole} \approx 10$)

2. $v_{rot} > 0.7\ v_{crit}$: slow bi-stability solution with
   much higher contrast ($\rho_{equ} / \rho_{pole} \approx 10^3$)
   (Michel Cure)

3. Magnetic field ($B^2/4\pi > p\ a^2$) plus high rotation can
   create massive disks:
   plus line-driving by non-radial photons (Stan Owocki)

Cool stars:
Asymptotic giant branch stars (AGB)





Habing and Olofsson: AGB stars, A&A library , 2003

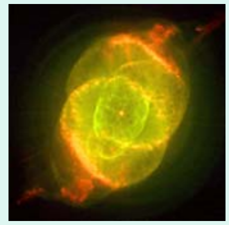
Willson , Mass loss from Cool Star, ARAA 38, 573, 2000

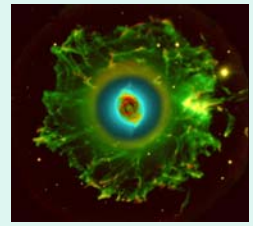
Many planetary nebulae are rotationally symmetric

Hourglass nebula

NGC 6543

inner nebula | outer nebula





Striking: outside is spherically symmetric

inside is bipolar

So : bipolarity occurs during the (very) last part of the AGB phase

Cool star winds: radiation driven by dust absorption

Winds of cool stars have dust

Dust is efficient absorber of radiation

↓

Strong radiation pressure

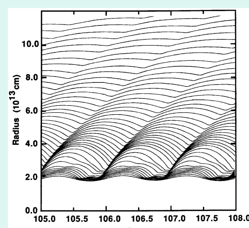
↓

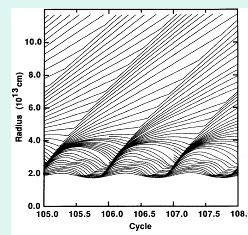
High mass loss rates

WRONG !! Does not work !!

Scaleheight problem

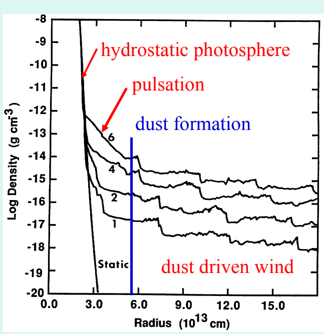
Pulsation + dust driven winds





Bowen 1988

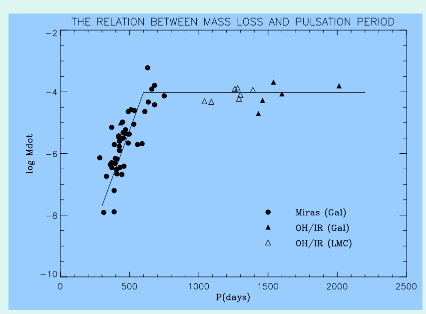
Density structure of pulsation+dust driven wind



Bowen 1988

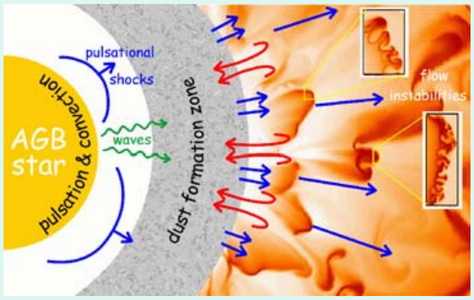
Lamers and Cassinelli 1999

The relation between mass loss rate and pulsation period for Miras



Vassiliades and Wood 1993

Hydro simulation



Woitke 2008

Rotating AGB winds ?

AGB star is (almost) fully convective : ~ solid rotator !!

no Von Zeipel effect !! (no hot pole) but it is flattened

As star climbs AGB three things happen:

- Star looses mass : ω decreases (lecture 1)
- Star expands : ω decrease (lecture 1)
- T_{eff} decreases : dust can form closer to the star

Why would the mass loss be higher from the equator?

higher pulsation amplitude at equator ?

larger scaleheight at equator: more density to form dust closer to star !

Dorfi 1999, Dorfi & Hofner 2001

CONCLUSIONS

Hot stars with line driven winds:

- rotation increases mass loss and wind velocity at pole
- for stars with 25000< Teff < 20 000 K the change in ionization Fe IV Fe III causes a bi-stability jump: higher mass loss and lower windvelocity from equator
→ slowly outfowing high density disks (B[e] supergiants)
- (this does not work for Be stars!)

Cool stars with dust driven winds, AGB stars

rotation may increase the equatorial mass loss rate if:

- pulsation amplitude increases towards the equator
- very close to tip of AGB due to larger density scaleheight and easier dust formation.

END OF LECTURE 2