STELLAR ROTATION and EVOLUTION

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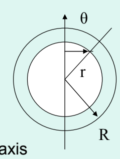
- 22/09/09 Lect 1: Rotation and stellar structure
- 22/09/09 Lect 2: Rotation and stellar winds
- 24/09/09 Lect 3: Rotation and stellar evolution

ROTATION AND STELLAR STRUCTURE

- Literature

- Tassoul: Stellar Rotation ,
- Cambridge, 2000
- Maeder & Meynet, The evolution of rotating stars,
- ARAA, 38, 113, 2000
- Kippenhahn & Weigert: Stellar structure & Evolution,
- Springer, 1994
- De Boer & Seggewiss, Stars and Stellar Evolution,
- EDPS 2008
- Lamers & Cassinelli: Introduction to Stellar Winds,
- Cambridge, 1999

Centrifugal forces



Assume solid rotator near the surface

$$g_{\rm rot} = \Omega^2 r sin\Theta = v^2/r\ sin\Theta$$

ω = angular velocity
θ = 0 along rotation axis
θ = π/2 on equator

This corresponds to a potential

$$\Phi_{\rm rot} = \frac{\Omega^2 (r\ sin\Theta)^2}{2}$$

with $g_{rot} = d\Phi_{rot}/dr$

The gavitational potential

$$\Phi_{\rm grav} = -\frac{GM}{r}$$

with $g_{grav} = d\Phi_{grav}/dr$

Total potential is

$$\Phi_{\rm tot} = -\frac{GM}{r} + \frac{\Omega^2 (r\ sin\Theta)^2}{2}$$

Equipotential surfaces

The equation for equipotential surfaces

$$r^3(\Theta)\Omega^2 sin^2\Theta - \frac{2GMr(\Theta)}{r_0} + 2GM = 0$$

At the poles: sin θ = 0

$r(\theta=0) = r_0$ so r_0 is the polar radius.

At the equator: sin θ =1 so r_{eq} is given by

$$r_{\rm eq}^3 - \frac{2GM\ r_{\rm eq}}{r_0\Omega^2} + \frac{2GM}{\Omega^2} = 0$$

This equ. gives r_{eq} for any value of Ω, but there is a limit

$g_{rot} + g_{grav} < 0$

Critical rotation velocity

Atmosphere must be bound, so $g_{net} < 0$

$g_{rot} + g_{grav} < 0$

This implies a critical (maximum) value for Ω and v_{eq}

$$\frac{v_{\rm rot}^2}{r_{\rm eq}} < \frac{GM}{r_{\rm eq}^2}$$

This gives

$$v_{\rm crit} = \sqrt{GM/r_{\rm eq}} = v_{\rm esc}/\sqrt{2} \quad \text{or} \quad \Omega_{\rm crit} = \sqrt{\frac{GM}{r_{\rm eq}^3}}$$

From now on we express the rotation rate in terms of

$$\omega \equiv v_{\rm eq}/v_{\rm crit} \equiv \Omega/\Omega_{\rm crit}$$

Intermezzo: Effective mass M_{eff}

For hot stars the effective gravity is smaller than GM/R^2 because of the radiation pressure by electron scattering.

Radiation pressure by electron scattering

$$g_{\rm rad}^e = \frac{\sigma_e}{c}\frac{L}{4\pi R^2}$$

$\sigma_e = 0.30$ cm²/g for fully ionized atmosphere

$$M_{\rm eff} = M(1-\Gamma_e)$$

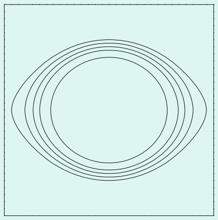
$$\Gamma_e = \frac{\sigma_e L}{4\pi c G M} \simeq 2.1\ 10^{-5}\ L/M$$

Γ_e can be as large as 0.5 to 0.8 for luminous O-stars, but ~0 for later MS stars
This may reduce the critical velocity considerably

$$v_{\rm crit} = \sqrt{GM_{\rm eff}/r_{\rm eq}}$$

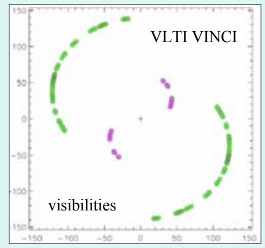
Equipotential surfaces

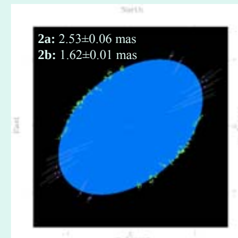
Equipotential surface for solidly rotating star with ω=0.54



At critical rotation (ω=1) : $R_{eq}=1.5\ R_{pole}$!

Alpha Eri (Be) v sin i= 250 km/s





M=5 Msun R=7 Rsun

v_{crit}= 370 km/s : ω>0.67

Flattening: 1.41 ± 0.05 !!

Domiciano de Souza et al. 2003

Kervella & Domiciano de Souza 2006

This is so far the only photosphere (?) of a star where this could be measured.

The extension of several stars with disks (!) have been measured.

Distortion and the Von Zeipel effect (1924)

Hydrostatic Equilibrium

Non rotating star:

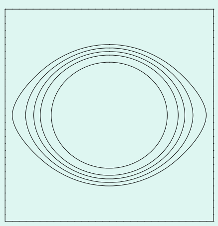
dP/dr = - g ρ = - ρ GM/R²

Rotating star

$$\nabla P = -\rho \nabla \Phi_{tot}$$

Equipotential lines are:

- lines of constant pressure
- lines of constant density
- lines of constant temperature (if P ~ ρ T)



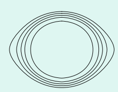
For stars in radiative equilibrium (not convective near the surface) $F_{rad} \sim d\ \sigma T^4 /dr$

so pole has higher flux than equator (per cm²)

so pole has higher effective temperature than equator: $T_{eff}^4(\theta) \sim g_{net}(\theta)$

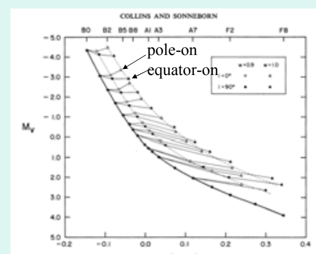
$$T_{eff}^4(\theta) = T_{eff}^4(\text{pole})\ (1-\omega^2 \sin^2\theta)$$

The von Zeipel effect on photometry



$f_{eq} / f_{pole} = 1-\omega^2$

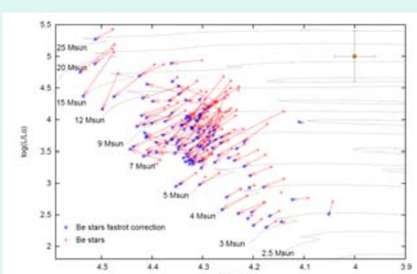
$T_{eq} / T_{pole} = (1-\omega^2)^{0.25}$



Sonneborn & Collins, 1977

Pole-on stars and equator-on stars are both redder than non-rotating stars of the same volume (!), because strongly flattened stars have larger surface.

The Von Zeipel effect in SMC B and Be stars

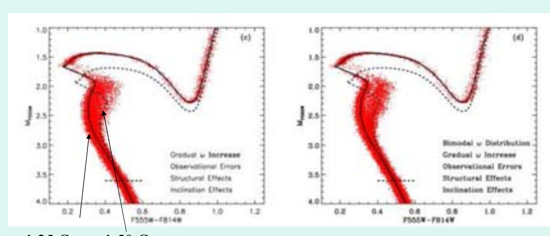


Martayan et al, 2007

Red = apparent T and L from spherical models

Blue = after correcting for Von Zeipel effect with $\Omega/\Omega_{crit} = 0.95$

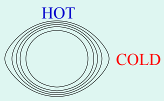
Widening of the main sequence of 1.25 Gyr cluster by rotation

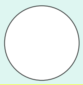


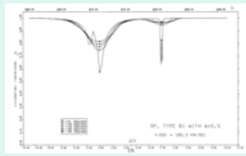
1.25 Gyr 1.50 Gyr

Bastian & de Mink, 2009

The von Zeipel effect on spectroscopy







Sonneborn & Collins, 1977

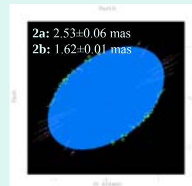
WARNING !!

If you do not take into account the von Zeipel effect (assume spherical star) you underestimate v sin i from linewidth, especially in blue / UV because most of the flux comes from the the polar regions where v_{rot} is small.

OPPORTUNITY !!

In principle, one can derive sin i by studying the difference in linewidth between photospheric lines in the UV / visual / red

An example: Alpha Eri (Be) v sin i= 250 km/s



1. The flattening of R_{eq} / R_{pole} = 1.41 shows that it is close to critical rotation $\omega > 0.90$!
2. But v sin i = 250 km/s = 0.67 v_{crit} , so v sin i was underestimated seriously
3. Best model shows: $T_{pole}/T_{eq}=(1-\omega^2)^{0.25}$ → T_{pole} = 20 000 K, T_{eq} = 10 000 K

Evolution of rotation velocity

Angular momentum $L = M\Omega R_{gyr}^2 \propto MvR$, $R_{gyr} \propto R$

1. Only expansion: no mass loss $L = M\,v\,R = Constant$

$v \sim R^{-1}$, $\omega = \frac{g_{rot}}{g_{grav}} = \frac{v^2 R}{M}$ } ⟶ $\omega \sim R^{-1}$ ω decreases during expansion

Evolution of rotation velocity

Angular momentum $L = M\Omega R_{gyr}^2 \propto MvR$, $R_{gyr} \propto R$ $R_{gyr} \sim 0.5$ R

1. Only expansion: no mass loss $L = M\,v\,R = Constant$

$v \sim R^{-1}$, $\omega = \frac{g_{rot}}{g_{grav}} = \frac{v^2 R}{M}$ } ⟶ $\omega \sim R^{-1}$ ω decreases during expansion

2. Only mass loss, no coupling = not convective (hot stars):

specific angular momentum, ℓ, (per gram) = constant

v = constant, $\omega \simeq v^2\,R/M$ } ⟶ $\omega \sim M^{-1}$ ω increases during mass loss

Evolution of rotation velocity

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3. Only mass loss from solid rotator = convective (cool stars)

Wind carries away more specific angular momentum than average :

average ℓ decreases: stars spins down → ω decreases during mass loss

Evolution of rotation velocity

Non spherical mass loss

Mass loss from poles:

Carries no/little angular momentum → average ℓ increases → spin-up

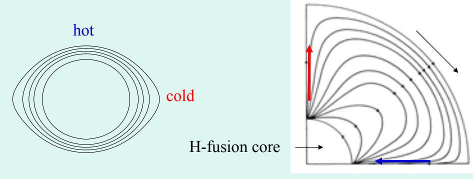
Mass loss from equator:

Carries more angular momentum that average → average ℓ decreases → spin-down

Coupling by magnetic fields: very fast spin-down

ROTATION AND INSTABILTIES

Von Zeipel effect causes meridional circulation



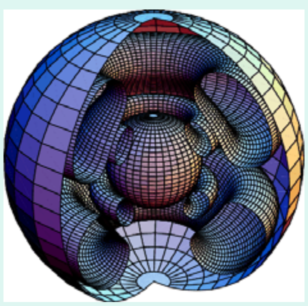
Iso-potential lines have constant P, T and rho

But the radiative flux is higher near polar region $F \sim -dT^4/dr$

So the gas in polar regions get more radiative heating than at equator.
The gas in the polar region is hotter than in the equatorial region,
so it tends to rise at the poles and sink at the equator.

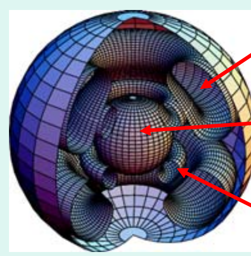
Circulation pattern arises with timescale << t_{MS} → Mixing!!

The complex cicrulation pattern in a fast rotating massive MS star

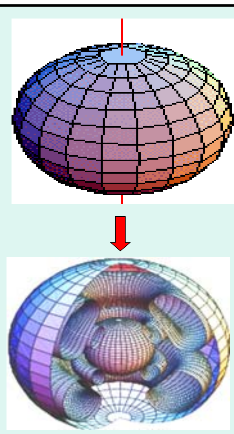


Maeder & Meynet, 2005

Different types of instbilities in a fast rotating massive MS star



All these motions help to transport nuclear products from the core to the surface !



PHYSICS OF ROTATION

STRUCTURE
- Oblateness (interior, surface)
- New structure equations

MIXING
- Meridional circulation
- Shear instabilities
- Horizontal turbulence

⇩

- Advection + diffusion of angular momentum
- Transport + diffusion of the chemical elements

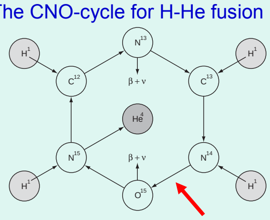
MASS LOSS
- Increase of mass loss by rotation
- Anisotropic losses of mass

END OF PART 1

Expected changes in surface composition due to mixing

Expected changes in surface composition due to mixing

The CNO-cycle for H-He fusion

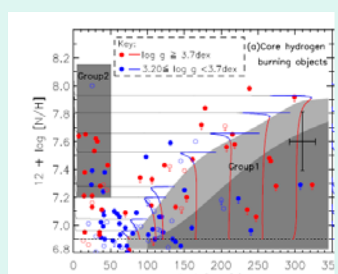


Slowest step !!

So there is a pile-up of N^{14}

at the expense of C12

Observed N-enhancement in OB stars

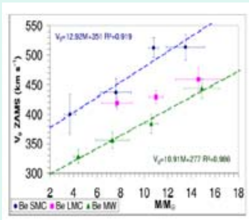


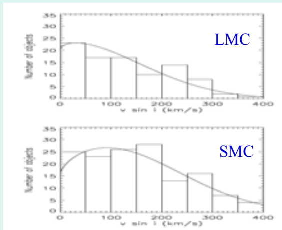
Initial N/H

Tracks = predicted rotation + mixing of M= 13 Msun
Vertical = main sequence
Horizontal = expansion after MS

I.Hunter et al, 2009

Rotation of stars depends on their metallicity !





Martayan et al 2007

LMC: <v sin i>=100 km/s, width=150 km/s

SMC: <v sin i> =175 km/s, width=150 km/s

Hunter et al. 2008

Evolution of rotation velocity

3. Non spherical mass loss

$\Delta M = \mu M$ Total mass loss

$\Delta M_{eq} = f \mu M$ With angular momentum

$\Delta M_{pole} = (1-f)\mu M$ Without angular momentum

Angular momentum loss $\Delta L = \Delta M_{eq} v_{eq} R_{eq} = (1-\mu f) M v R$

$L = M v R$

$L' = L - \Delta L = M' v' R'$

M' = M (1-μ)

$$\Bigg\} \longrightarrow \frac{v'}{v} = \frac{R}{R'} \frac{1-\mu f}{1-\mu}$$

$$\omega = \frac{g_{rot}}{g_{grav}} = \frac{v^2 R}{M}$$

$$\frac{\omega'}{\omega} = \frac{R}{R'} \left\{ \frac{1-\mu f}{1-\mu} \right\}^2 \frac{1}{1-\mu}$$

If most of mass is lost from pole (f ~0) : $\omega'/\omega \sim (1-\mu)^{-3}$