Flux latitude distribution in late-type rotating stars or “gravity” darkening in late-type stars

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Outline

1. Introduction
2. The simulations
   - No magnetic field
   - With magnetic fields
3. Conclusions

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An old problem for eclipsing binaries

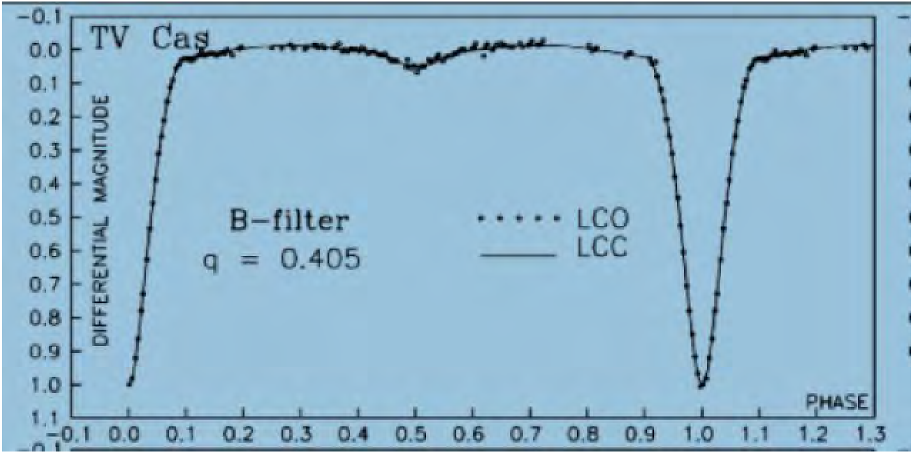

FIGURE : The light curve of TV Cas.

Modelling the light curve I
Djurasevic et al. 2003, 2006

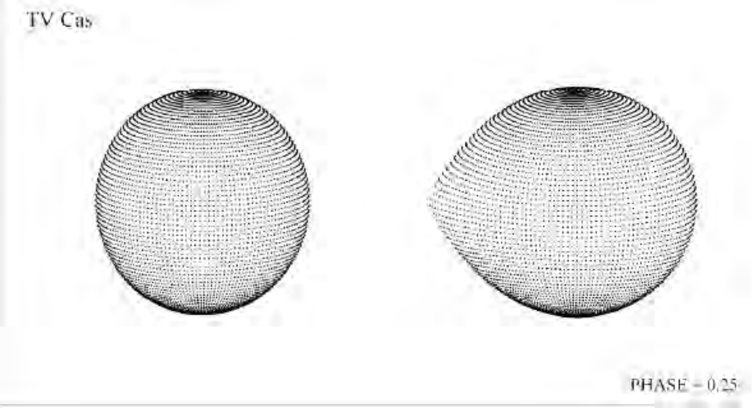

FIGURE : A model of TV Cas : T_{cooler}=5400 K.

Modelling the light curve II
Djurasevic et al. 2003, 2006

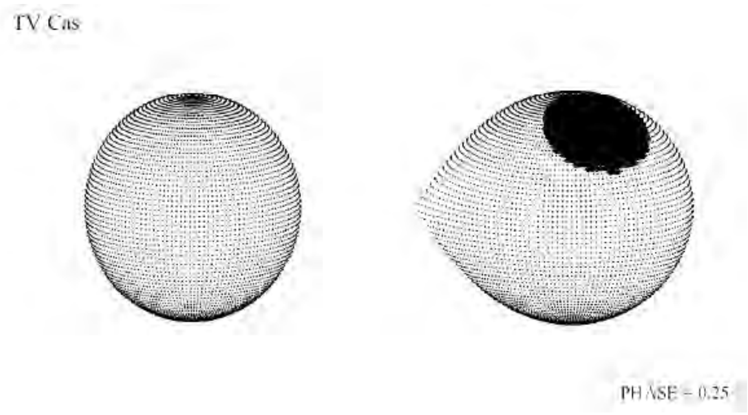

FIGURE : Another model of TV Cas : T_{cooler}=5500 K.

Conclusions

- The flux distribution influences the output of the modelling, namely the fundamental parameters of the stars.
- Binaries are difficult : let's consider single (fast) rotating stars.

Gravity darkening in rotating stars

A simple approach assuming a barotropic radiative envelope shows that

$$\vec{F} = -\chi \vec{\nabla} T$$

if barotropic $T \equiv T(\Phi)$ and

$$\vec{F} = -\chi(\Phi) T'(\phi) \vec{\nabla}\Phi \implies \vec{F} \propto \vec{g}_{\rm eff}$$

von Zeipel (1924). So less effective gravity means less flux.
VZ24 is approximate because stars are not exactly barotropic...

$$T_{\rm eff} \propto g_{\rm eff}^{\beta}, \qquad \text{with} \qquad \beta = 1/4 \qquad \text{for} \qquad \text{VZ24}$$

ESTER input

$$T_{\text{eff}} \propto g_{\text{eff}}^{\beta}$$

With 2D-stellar models (computed with ESTER), we studied this problem and could establish that

$$\beta \sim \frac{1}{4} - \frac{\varepsilon}{3}$$

where $\varepsilon = (R_e - R_p)/R_e$ is the centrifugal flattening of a star.
Ref : Espinosa Lara & Rieutord (2011), Rieutord (2015).

Altair

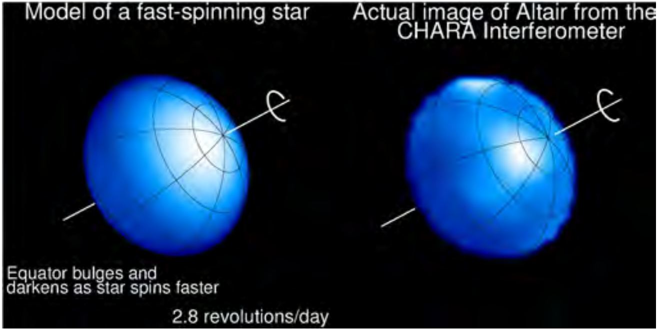

FIGURE : Altair seen by CHARA (Monnier et al. 2007).

Gravity darkening exponents : theory versus observations

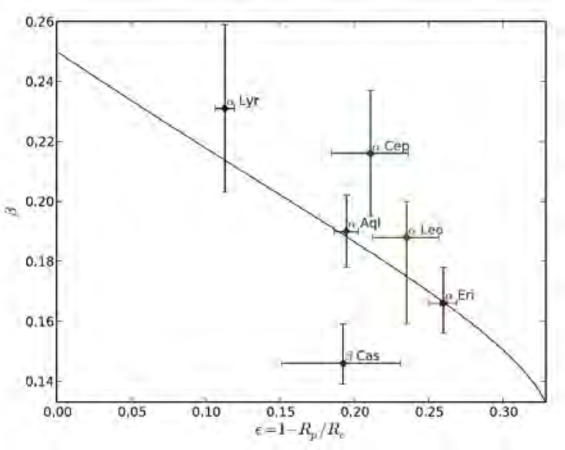

FIGURE : β versus ε. β Cas is F2, α Cep is A7...

Conclusions

The flux distribution also influences the output of the modelling, namely the fundamental parameters of the stars.

- The situation of early-type stars is well understood
- the case of late-type stars is not understood.

Until now people have used Lucy (1967) prescription which says

$$\beta \sim 0.08$$

for solar-type stars. We have shown that this exponent comes from the opacity laws imposed by H^- ions in solar type stars and therefore from the flux distribution of the upper photosphere.

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The problem

- In a convective envelope the flux is governed by buoyancy which is perturbed by the Coriolis acceleration.
- Convection is less super-critical at the poles than at the equator $\Longrightarrow$ pole darkening.
- Buoyancy is weaker at equator than at pole, $\Longrightarrow$ equator darkening.

Who wins ? Coriolis effect ? Centrifugal effect ?

what about magnetic fields ?

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The simulations

- We want to understand the role of the Coriolis force which is the main source of anisotropy.
- Make simulations of convection in a rotating spherical shell.
- Use the MAGIC code at the anelastic approximation (Gastine & Wicht 2012, Icarus).
  Impose :
  - the entropy drop (Rayleigh number)
  - rotation rate (Ekman number, Rossby number)
  - density stratification

The simulations

A look at the flow

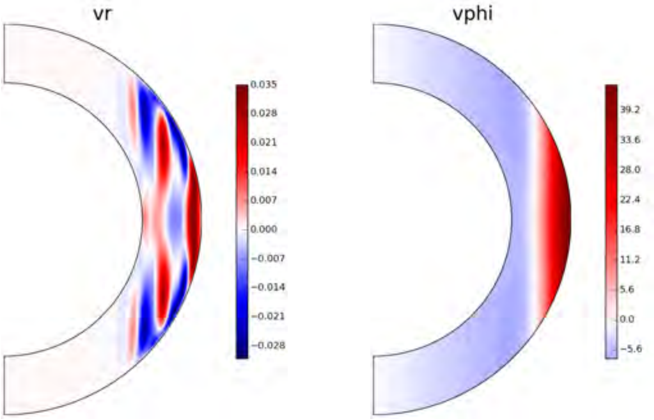


FIGURE : Axisymmetric parts of the flow at Ra/Ra$_c$=1.5 and $N_\rho = 2$.

The simulations

Flux distribution while increasing convection strength

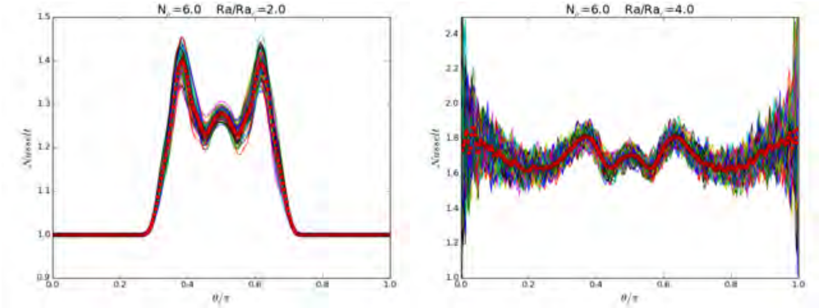
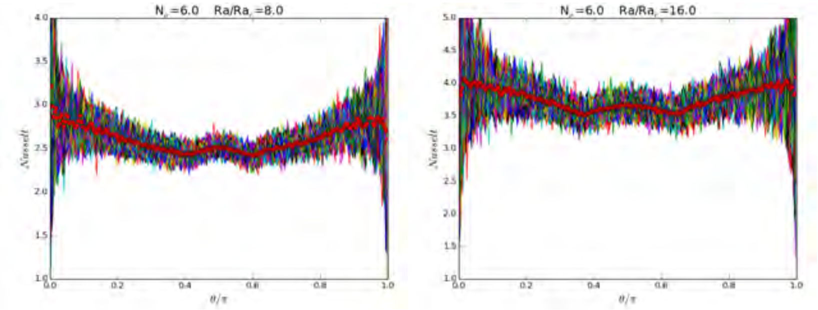


FIGURE : Flux distribution in latitude. Ek=3×10^{-4}, $n = 2$, $\mathcal{P} = 1$, $\eta = 0.7$, $N_\rho = 6$, $\text{Ra}_c^M = 1.038 \times 10^6$.

Flux distribution in latitude



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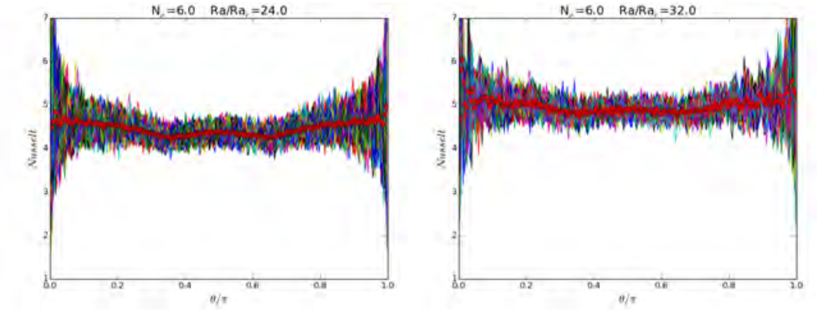
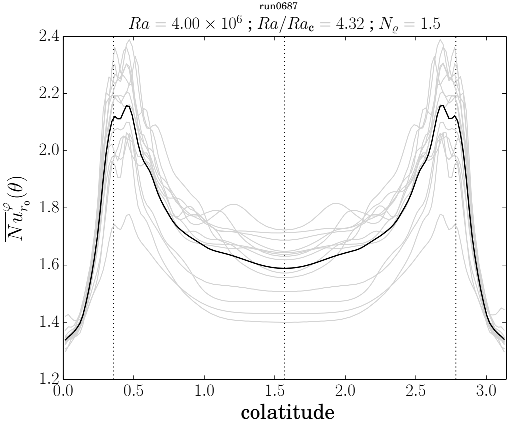
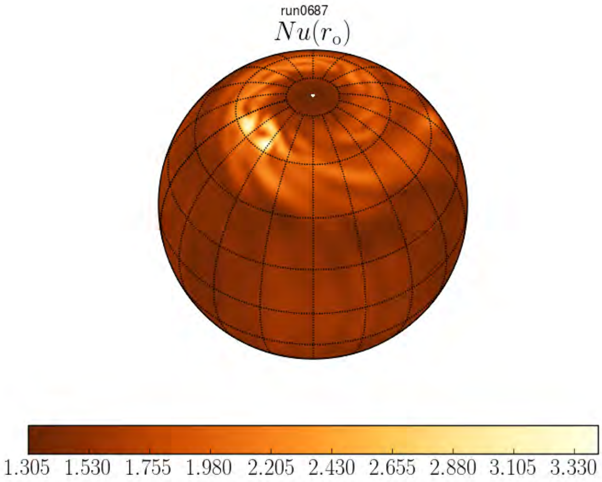


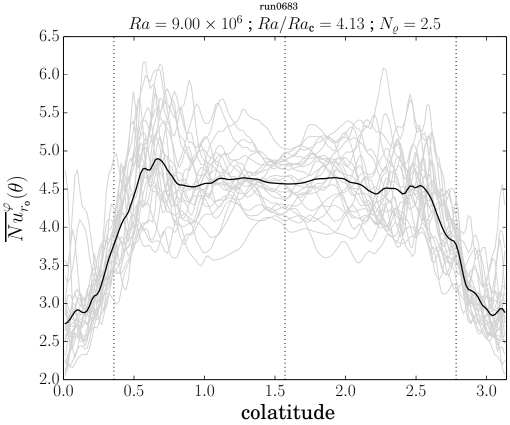
Flux distribution in latitude : thick shell



Flux distribution on the outer sphere (thick shell)



Flux distribution in latitude, with magnetic fields



Flow with magnetic fields

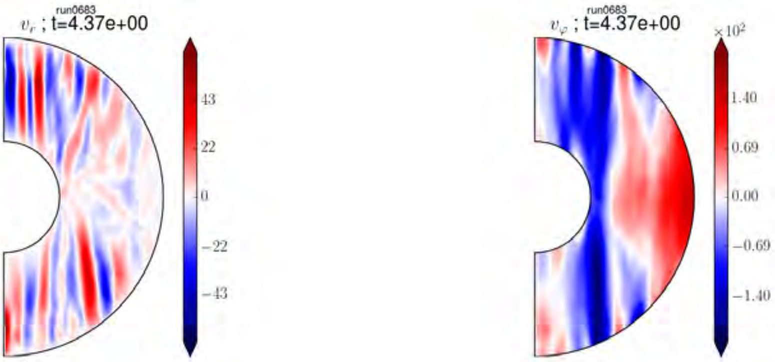
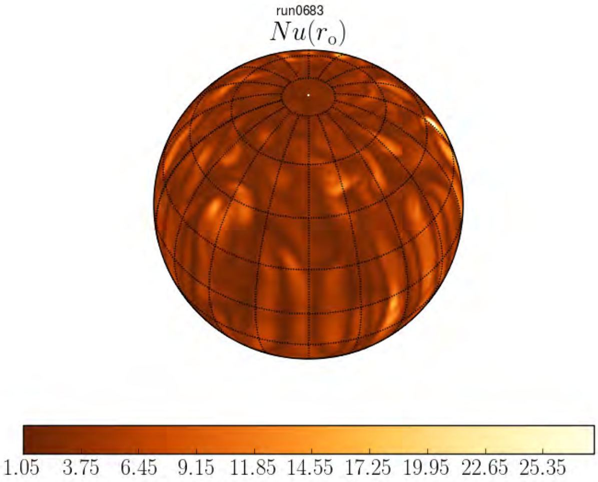


FIGURE : Axisymmetric parts of the flow at Ra/Ra$_c$=4.1 and $N_\rho = 2.5$, $\eta = 0.35$.

Flux distribution on the outer sphere with $\vec{B}$



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Preliminary conclusions

- Without $\vec{B}$: there is marked influence of Coriolis at Ra/Ra$_c \leq 20$ and at low density contrast.
- At high density contrast upper layers have short turn-over times : screening effects of deep anisotropic flows.
- Magnetic fields seem to redistribute the fluxes

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Outlooks

- If Coriolis effect is screened, then centrifugal effects might show up
- ... as long as magnetic fields do make spots on a large fraction of the surface.
- We'll observe θ Sco and ε Sgr with VLTI (Armando Domiciano, F. Vakili & I). They are fast rotating cool and big stars.
- Observing rapidly rotating F-stars (main-sequence) would be very interesting.

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