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

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15 mars 2016
Outline

1. Introduction

2. The simulations
   - No magnetic field
   - With magnetic fields

3. Conclusions
1 Introduction

2 The simulations
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3 Conclusions
An old problem for eclipsing binaries

**Figure**: The light curve of TV Cas.

$B$-filter

$q = 0.405$

LCO

LCC

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**Figure:** A model of TV Cas: $T_{\text{cooler}}=5400$ K.
Modelling the light curve II
Djurasevic et al. 2003, 2006

Figure: Another model of TV Cas: $T_{\text{cooler}} = 5500$ 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

\[ \vec{F} = -\chi(\Phi)T'(\phi)\vec{\nabla}\Phi \implies \vec{F} \propto g_{\text{eff}} \]

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

\[ T_{\text{eff}} \propto g_{\text{eff}}^\beta, \quad \text{with} \quad \beta = 1/4 \quad \text{for} \quad \text{VZ24} \]
With 2D-stellar models (computed with ESTER), we studied this problem and could establish that

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

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

where $\varepsilon = (R_e - R_p)/R_e$ is the centrifugal flattening of a star. Ref: Espinosa Lara & Rieutord (2011), Rieutord (2015).
**Figure**: Altair seen by CHARA (Monnier et al. 2007).
Gravity darkening exponents: theory versus observations

Figure: $\beta$ versus $\epsilon$. $\beta$ Cas is F2, $\alpha$ Cep is A7...
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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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 $\Rightarrow$ pole darkening.

Buoyancy is weaker at equator than at pole, $\Rightarrow$ equator darkening.

Who wins? Coriolis effect? Centrifugal effect?

what about magnetic fields?
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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 $N_\rho = 2$.  

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Flux latitude distribution in late-type rotating stars
The simulations

Flux distribution while increasing convection strength

**Figure:** Flux distribution in latitude. $E_k=3 \times 10^{-4}$, $n = 2$, $P = 1$, $\eta = 0.7$, $N_\rho = 6$, $Ra_c^M = 1.038 \times 10^6$. 

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Flux latitude distribution in late-type rotating stars
Flux distribution in latitude

- **Introduction**
- **The simulations**
- **Conclusions**

No magnetic field
With magnetic fields

Flux latitude distribution in late-type rotating stars

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Flux distribution in latitude
Flux distribution in latitude

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Flux latitude distribution in late-type rotating stars
Flux distribution in latitude: thick shell

$R \alpha = 4.00 \times 10^6; R \alpha / R \alpha_c = 4.32; N = 1.5$

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Flux distribution on the outer sphere (thick shell)

run0687
$$N u(r_o)$$

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Flux latitude distribution in late-type rotating stars
Flux distribution in latitude, with magnetic fields

\[ Ra = 9.00 \times 10^6 \; ; \; Ra/R_{ac} = 4.13 \; ; \; N_\phi = 2.5 \]

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Flux latitude distribution in late-type rotating stars
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 $\vec{B}$

Run0683
$Nu(r_o)$

1.05  3.75  6.45  9.15  11.85  14.55  17.25  19.95  22.65  25.35
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Preliminary conclusions

- Without $\vec{B}$: there is marked influence of Coriolis at $\text{Ra/Ra}_c \leq 20$ 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 $\theta$ Sco and $\varepsilon$ 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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