On the internal gravity waves generated by penetrative convection: effect on the internal rotation of low-mass stars

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with the collaboration of K. Belkacem and M. J. Goupil
Asteroseismology probes the stellar internal rotation

- Solid-body rotation observed in the solar radiative interior (e.g. Garcia, 2007)
- A lot of observations for evolved stars with CoRoT (2006-2014) and Kepler (2009)
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- … while it strongly contracts until helium fusion starts (Red Clump).
- In agreement with low rotation rates observed in white dwarfs (Kawaler et al., 1999).
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⇒ Problem: current stellar models do not reproduce the observations…
Internal gravity waves

- **Internal Gravity Waves (IGW):**
  - Restoring force = buoyancy
  - Excited in the convective zone
  - Propagate in the radiative zone

- **Efficiency of the transport of AM by IGW**
  - depends on the driving mechanism

- **Difficult point:**
  - Current simulations not realistic enough (Re, Pe numbers...)

⇒ Estimate by semianalytical models
Excitation mechanisms

- 2 kinds of excitation mechanisms
- Excitation by turbulent pressure in the convective bulk
  \- Kumar et al. (1999) ⇒ rigid solar rotation (Talon, 2002)
  ⇒ insufficient for Red Giants (Fuller, 2014)

3-D Simulations of the Sun (Alvan et al., 2014)
Excitation mechanisms

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- Excitation by penetration of convective plumes
  - observed in geophysics (e.g. Townsend, 1966) and numerical simulations (e.g. Dintrans, 2005)
  - But a model is still missing for stellar interior

\(\Rightarrow\) Are the plume-induced waves able to play a role and to be included in stellar models?
Excitation model by penetrative convection

- Wave equation + source term = pressure exerted by an ensemble of incoherent and spatially uniformly distributed plumes at the base of the convective zone

\[
\frac{\partial \vec{v}}{\partial t} + \frac{1}{\rho} \nabla p' - \frac{\rho'}{\rho} \vec{g} = - \frac{1}{\rho} \nabla (\rho \vec{V}_p \otimes \vec{V}_p)
\]

- Plumes description in the driving region:
  - Velocity and width (Rieutord & Zahn, 1995 ; Zahn, 1991)
  - Free parameters: - plume lifetime (~convective time by the MLT)
    - filling factor $A \sim 0.1$ (number of plumes)

(Pinçon, Belkacem, Goupil, 2016a)
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- **Excitation process in the Sun** (Pinçon, Belkacem, Goupil, 2016a)
  - Up to 5 times more efficient than turbulent pressure
  - Total wave energy flux ~ 1 % of the solar flux at the base of the convective zone

⇒ **Ability to transport angular momentum?**
Ability to transport angular momentum in the Sun

- Estimate of the effect of IGW on a given rotation profile

$T_L \sim \frac{\dot{J}}{J}$

Density of angular momentum $\rho r^2 \Omega$

Divergence of the radiatively damped wave flux

Local characteristic timescale on which IGW modify the rotation

$\Rightarrow$ To compare to the characteristic timescale of evolution/contraction $\Rightarrow$ efficiency?
Ability to transport angular momentum in the Sun

- Estimate of the effect of IGW on a given rotation profile

  Local characteristic timescale on which IGW modify the rotation
  \[ T_L \approx \frac{\rho r^2 \Omega}{\text{Divergence of the radiatively damped wave flux}} \]
  \[ J \]  

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- In the Sun, plume-induced IGW

  (Pinçon et al., 2016)
Ability to transport angular momentum in the Sun

- Estimate of the effect of IGW on a given rotation profile

  Local characteristic timescale on which IGW modify the rotation

  \[ T_L \sim J/J \]

  Density of angular momentum \( \rho r^2 \Omega \)

  Divergence of the radiatively damped wave flux

  \( T_L \) to compare to the characteristic timescale of evolution/contraction \( \Rightarrow \) efficiency?

- In the Sun, plume-induced IGW

  - modify the rotation on timescales \( T_L < T_{\text{nuc}} \approx 10 \text{Gyr} \)

  - more efficient than Kumar et al. (1999)

  - the higher the differential rotation, the more efficient the transport

(Pinçon et al., 2016)
**Ability to transport angular momentum in the Sun**

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**Figure:**
- Divergence of the radiatively damped wave flux
- Density of angular momentum $\rho r^2 \Omega$
- Local characteristic timescale on which IGW modify the rotation

**Graph:**
- Plume-induced waves
- Turbulence-induced waves
- Low differential rotation
- Strong differential rotation
- Core
- Sun (Pinçon et al., 2016)

**Equation:**
- $T_L \sim \frac{J}{\dot{J}}$

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- ✔ Estimate of the effect of IGW on a given rotation profile
- ✔ In the Sun, plume-induced IGW
- ✔ To compare to the characteristic timescale of evolution/contraction ⇒ efficiency?
Ability to transport angular momentum in the Sun

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\[ \rho r^2 \Omega \]

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\( \Rightarrow \text{Process efficient in the Sun!} \)

What about Subgiants and Red Giants?

\( \text{Sun} \) (Pinçon et al., 2016)
From the subgiants branch to the ascent of the RGB

- Fuller et al. (2014)

- IGW cannot reach the core: strong radiative damping near the H-burning shell...
- ...BUT as for the Sun, not so simple: depends on excitation and differential rotation (via damping)
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  - IGW cannot reach the core: strong radiative damping near the H-burning shell...
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- Calculations for several models on the subgiant and redgiant branches with IGW excited by penetrative convection

- Rotation profile for each model:
  - assumed smooth
  - different amplitudes for $\delta \Omega = \Omega_{\text{core}} - \Omega_{\text{BCZ}}$
2 examples: models M1 and M2
Red Giant (model M2)

The Red Giant case in a nutshell:

- Considering $0 < \delta \Omega < 12 \mu \text{rad s}^{-1}$ as in observed Red Giants (Mosser et al., 2012)

- $T_L > T_{\text{contraction}}$ in the core (below the H-burning shell)

  - Strong radiative damping near the H-burning shell (peak of the Brunt-Väisälä frequency)

  $\Rightarrow$ For the RGB stars: strong radiative damping prevents IGW from modifying the core rotation, confirms Fuller et al.'s result

- ...BUT IGW damped just near the H-burning shell:

  - Interaction with meridional circulation in the core? $\Rightarrow$ need for a complete calculation
Subgiant (model M1)

Characteristic timescale of contraction
Below the H-burning shell, $T_L > T_{\text{contraction}}$

Waves do not cross the barrier

Characteristic timescale of contraction

- Low differential rotation \Rightarrow Strong damping before the H-burning shell \Rightarrow IGW cannot overcome the « barrier »
Subgiant (model M1)

Below the H-burning shell, $T_L < T_{\text{contraction}}$

Waves cross the barrier

Characteristic timescale of contraction

- **Low differential rotation** $\Rightarrow$ Strong damping before the H-burning shell
  $\Rightarrow$ IGW cannot overcome the « barrier »

- **Progressive increase of $\delta\Omega$** $\Rightarrow$ above $\delta\Omega > 4 \mu\text{rad \ s}^{-1}$, IGW cross the « barrier »
  $\Rightarrow$ cf difference between prograde and retrograde waves with $\delta\Omega$

$\Rightarrow$ It exists a threshold value for the differential rotation above which IGW can modify the core rotation!

(Pinçon et al., 2016)
A possible regulation loop in Subgiants

End of the main sequence $\delta\Omega_0$

Evolution, log $g$

Initial condition

Threshold $\delta\Omega_{\text{thresh}}$

$\delta\Omega < \delta\Omega_{\text{thresh}}$

Core contraction $\delta\Omega$

$\delta\Omega = \delta\Omega + \varepsilon$

$\delta\Omega = \delta\Omega - \varepsilon'$

$\delta\Omega > \delta\Omega_{\text{thresh}}$

IGW braking $\delta\Omega$

Dynamical equilibrium

$\Rightarrow$ The system reaches a dynamical equilibrium: $\delta\Omega \sim \delta\Omega_{\text{thresh}}$

Subgiants branch $\delta\Omega \sim \delta\Omega_{\text{thresh}}$
A threshold close to the observations

- Observations of 6 subgiants 1Msun<M<1.45Msun (Deheuvels et al., 2014)
- Comparison with the threshold $\delta\Omega_{\text{threshold}}$ derived from stellar models?

(Pinçon et al. 2016b, in prep)
A threshold close to the observations

- Observations of 6 subgiants $1 \text{M}_{\odot} < M < 1.45 \text{M}_{\odot}$ (Deheuvels et al., 2014)

- Comparison with the threshold $\delta \Omega_{\text{threshold}}$ derived from stellar models?

- Amazing similarities between both
  - Same typical values
  - Decrease with $\log g$

  $\Rightarrow$ observations in agreement with a regulation effect coming from IGW

- Some discrepancies: mass effect, assumed rotation profile, threshold selection criterion, meaning of the mean observed $\delta \Omega$ (rotational splittings)...

(Pinçon et al. 2016b, in prep)
Concluding remarks

- New excitation model of IGW by penetrative convection...

- ... with consequences for the extraction of angular momentum:
  
  - on the RGB: \( \Rightarrow \) IGW cannot reach the core (cf Fuller et al.)

  - on the subgiant branch: \( \Rightarrow \) IGWs generated by penetrative convection are a good candidate to regulate the core rotation
Concluding remarks

✔ New excitation model of IGW by penetrative convection…

✔ … with consequences for the extraction of angular momentum :

- on the RGB : IGW can not reach the core (cf Fuller et al.)

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✔ Next steps :

- regulation in subgiants ⇒ promising and in progress (conservative?)

- role of IGW to be confirmed by means of a numerical resolution for the angular momentum transport (for example, on a static stellar model) and ...

- … to be implemented in a stellar evolution code with the interaction with other processes (in CESTAM with the collaboration of J. Marques, IAS)
Thank you for your attention!
**From the subgiants branch to the ascent of the RGB**

- **Fuller et al. (2014)**
  - *IGW cannot reach the core: strong radiative damping near the H-burning shell...*
  - *BUT as for the Sun, not so simple: depends on excitation and differential rotation (via damping)*

- Calculations for several models on the subgiant and redgiant branches with IGW excited by penetrative convection

- **Rotation profile for each model:**
  - *assumed smooth*
  - *different amplitudes for* \( \delta \Omega = \Omega_{\text{core}} - \Omega_{\text{BCZ}} \)

- Diagram showing the rotation profile with different amplitudes for \( \delta \Omega = \Omega_{\text{core}} - \Omega_{\text{BCZ}} \) for various masses. The range is given as \( 0.5 < \delta \Omega < 12 \, \mu \text{rad s}^{-1} \).
Red Giant (model M2)

\( T_L > T_{\text{contraction}} \)

Waves do not cross the barrier

\( T_L \) increases going deeper and \( T_L > T_{\text{contraction}} \) in the core for all \( \delta \Omega < 12 \text{ \mu rad s}^{-1} \)

- Waves strongly damped near the H-burning shell (peak of the Brunt-Väisälä frequency)
- \( \delta \Omega < 12 \text{ \mu rad s}^{-1} \) in observed Red Giants (Mosser et al., 2012)
  
  ⇒ For the RGB stars: radiative damping prevents IGW from modifying the core rotation

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