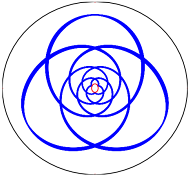
Seismology of rapidly, differentially rotating stars with gravity waves

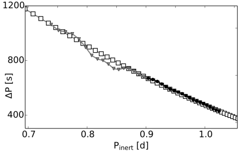


Vincent Prat

in collaboration with

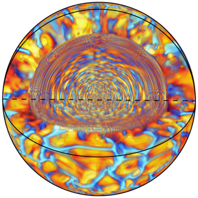
Stéphane Mathis, Kyle Augustson, Lucie Alvan, Allan Sacha Brun (CEA Saclay)
François Lignières, Jérôme Ballot (IRAP, Toulouse)

Importance of gravity waves

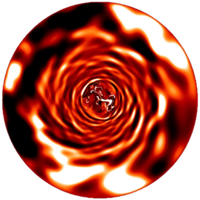


Van Reeth et al. (2016)

- seismic diagnoses (intermediate-mass/massive stars)
- transport of angular momentum
  - low-mass stars (Talon & Charbonnel, 2005; Alvan et al., 2014, 2015)
  - massive stars (Lee et al., 2014; Fuller et al., 2015; Rogers, 2015)

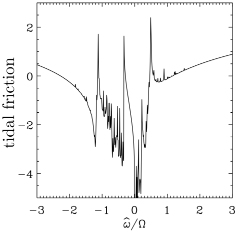


Alvan et al. (2015)



Rogers (2015)

- tidal dissipation in close-in planetary/stellar systems (Zahn, 1975; Ogilvie & Lin, 2004, 2007)



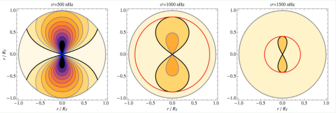
Ogilvie & Lin (2004)

State of the art

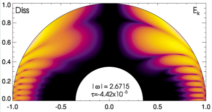
Vast majority of studies in solid-body rotation

Studies with differential rotation

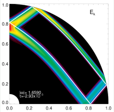
- in the traditional approximation (Mathis, 2009)



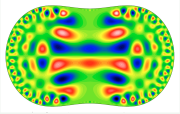
- shellular rotation (Mirouh et al., 2016)



- inertial waves (Baruteau & Rieutord, 2013; Guenel et al., 2016)



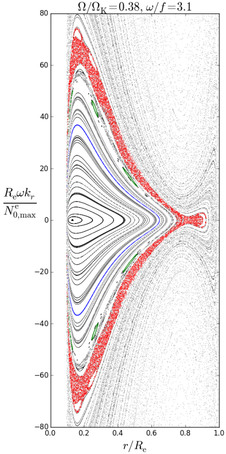
- acoustic waves in deformed stars (Reese et al., 2009)

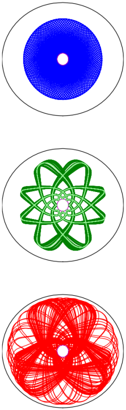


The case of uniform rotation

Powerful asymptotic theory: ray dynamics

- acoustic waves (Lignières & Georgeot, 2008, 2009; Pasek et al., 2011, 2012)
- gravity waves (Prat et al., 2016)





3 types of modes

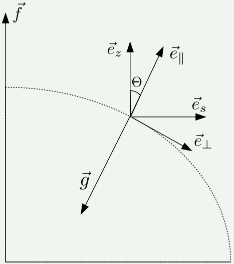
- regular modes
  → regular period spacings (Prat et al., 2017)
- island modes
  → specific spectral patterns
- chaotic modes
  → statistical spectral properties

General dispersion relation with differential rotation

$$\boxed{\omega^2 = \frac{f(f+Q_s){k_z}^2 + N^2{k_\perp}^2 - fQ_z(k_s k_z + k_\parallel k_\perp) + f\cos\Theta(f\cos\Theta + Q_\perp){k_c}^2}{k^2 + {k_c}^2}}$$

Features

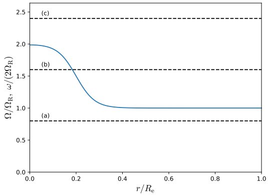
- full Coriolis acceleration ($f = 2\Omega$)
- general 2D differential rotation ($\vec{Q} = r\sin\theta\vec{\nabla}\Omega$)
- centrifugal deformation
- back-refraction of waves near the surface (k_c)
- baroclinic effects: coupling structure/rotation



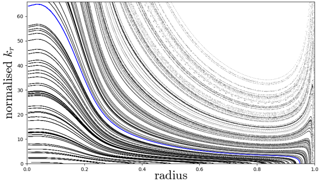
We focus on axisymmetric waves as a first step
+ fully radiative models

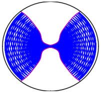
Radial differential rotation: fast core

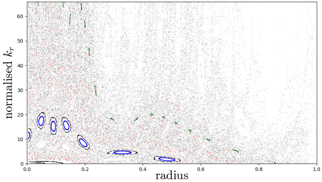
Rotation profile

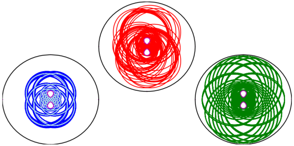


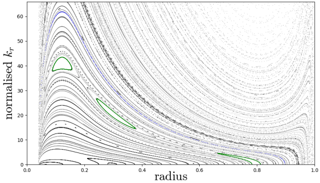
- sub-inertial
  - regular modes
- trans-inertial (new)
  - chaotic modes
  - island modes
- super-inertial
  - regular modes
  - island modes





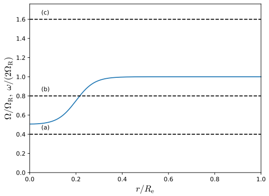


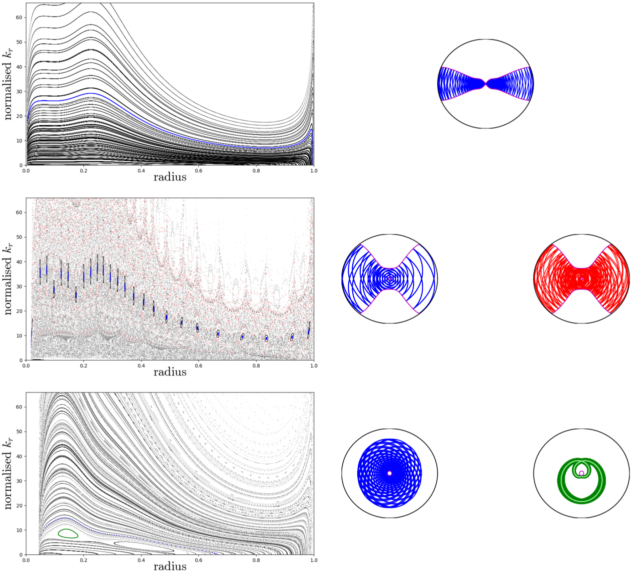




Radial differential rotation: slow core

Rotation profile



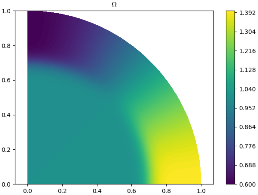


- sub-inertial
  - regular modes
- trans-inertial (new)
  - chaotic modes
  - island modes
- super-inertial
  - regular modes
  - island modes

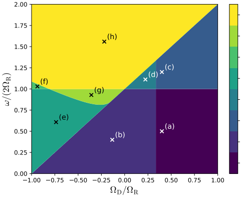
Same conclusion as for the fast core

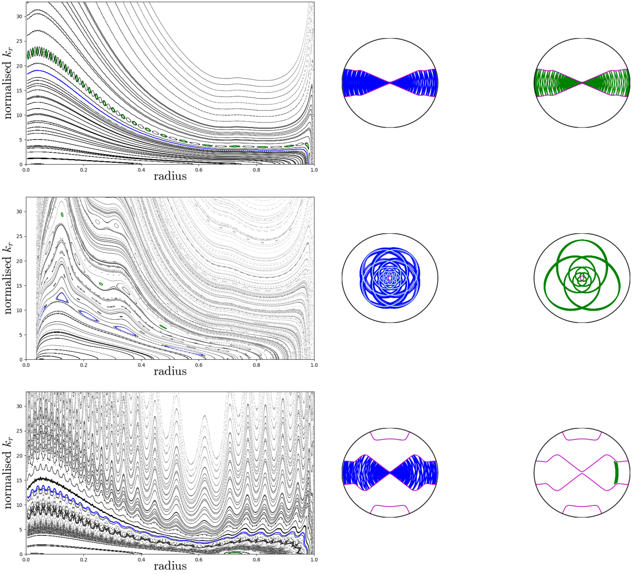
Latitudinal differential rotation

Ex. of rotation profile



Various regimes

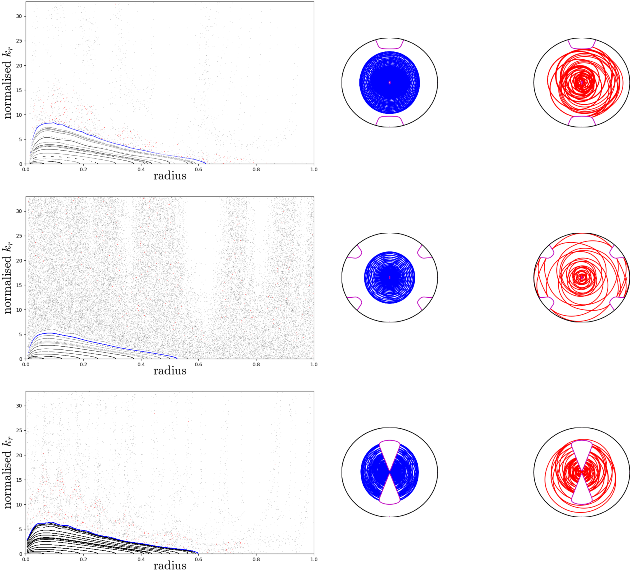




Regimes close to purely sub- or super-inertial

Latitudinal differential rotation (cont'd)

- similar dynamics:
  - regular modes
  - chaotic modes
- but different propagation domains



Important consequences for stellar physics

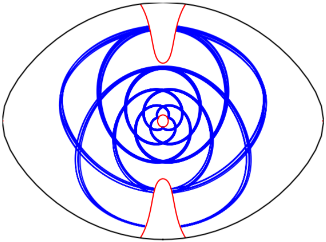
Variety of propagation domains

- waves probe various cavities → potentially a lot of information to extract
- important for the interaction of waves with excitation/damping regions
  - amplitude of modes (Townsend, 2000; Mathis et al., 2014)
  - transport of angular momentum (Pantillon et al., 2007; Mathis et al., 2008)
  - tidal dissipation (Ogilvie & Lin, 2004, 2007)

Seismic diagnoses (*cf.* Prat et al. 2017 for uniform rotation)

- low-frequency dynamics dominated by regular modes
- possibility to derive new seismic diagnoses for differential rotation

Next steps: transport of angular momentum, magnetic field



Thank you for your attention.

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