Internal rapid rotation and its implications for stellar structure and pulsations

D. R. Reese

July 11, 2014

UNIVERSITY OF BIRMINGHAM

SpaceInn.eu

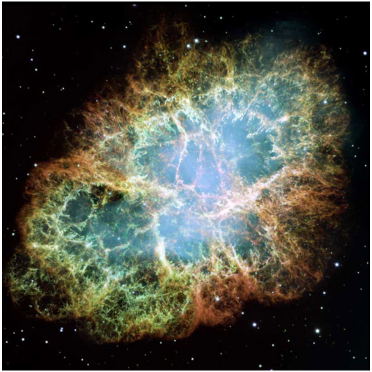
CoRoT 3 - KASC 7

STELLAR ASTROPHYSICS CENTRE

Massive stars

- dominant role in chemical evolution of galaxies
- supernovae
- progenitor of gamma-ray bursts

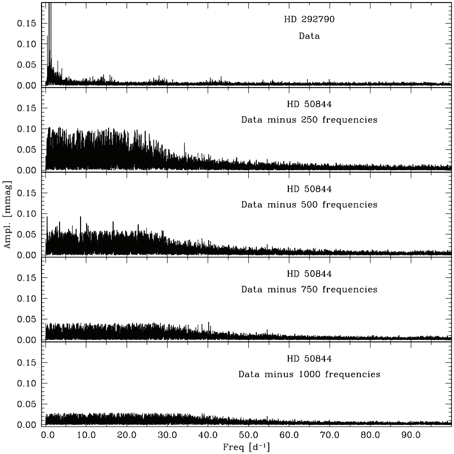
Crab nebula



(Hester et al. 2008)

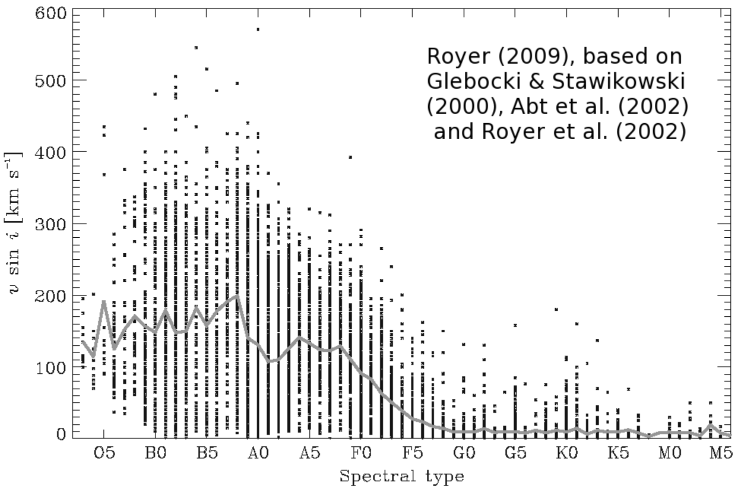
Intermediate mass stars

- do not explode in supernovae
- many of the same physical phenomena
- much more numerous than massive stars
- very rich pulsation spectra



(Poretti et al. 2009)

Rotation



- a significant proportion of these are rapid rotators

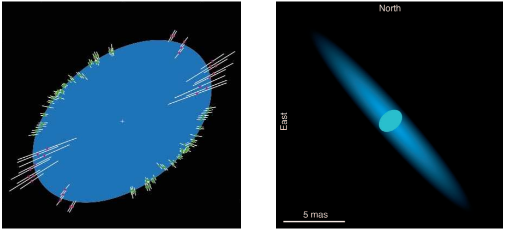
Rotation and its effects

- in order to understand these stars, one needs to understand the impact of rotation on:
  - structure and evolution
  - pulsations

Centrifugal deformation

- the centrifugal acceleration distorts the shape of the star
- recent interferometric observations show very high distortions
- **impact:** such stars can only be modelled with 2D approaches

Achernar (α Eridani)

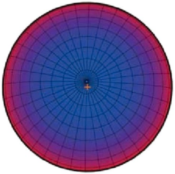


(Domiciano de Souza et al. 2003, 2012, Kervella & Domiciano de Souza 2006)

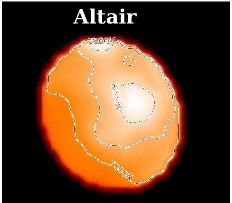
Gravity darkening

- rapid rotation causes the poles to be hotter than the equator
- **impact:** the position of these stars in an HR diagram depends on their inclination
- interferometry confirms this effect and can determine the inclination

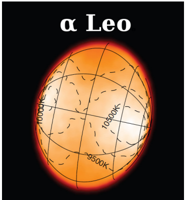
Vega



Peterson et al. 2006



Monnier et al., 2007

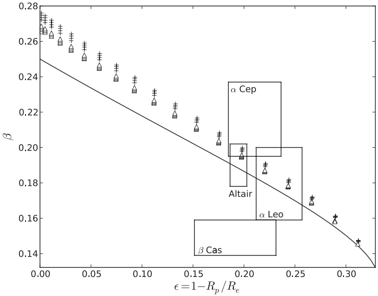


Che et al. 2011

Gravity darkening

Different approaches

- simple power law: $T_{\rm eff} \propto g_{\rm eff}^{\beta}$
  - $\beta = 0.25$ for a radiative envelope (von Zeipel, 1924)
  - $\beta = 0.08$ for a convective envelope (Lucy, 1967)
- Espinosa Lara & Rieutord (2011): $\vec{F} = -f(r,\theta)\vec{g}_{\rm eff}$ and $\nabla \cdot \vec{F} = 0$
  - compares favourably with 2D simulations

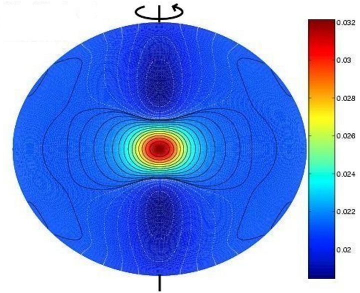


(Espinosa Lara & Rieutord, 2011)

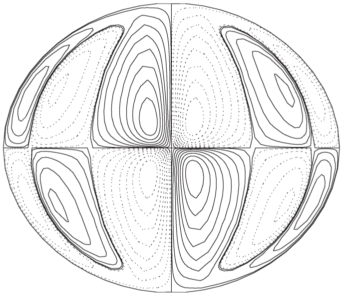
Baroclinic effects

- mismatch between lines of constant P, T, and ρ:
- this causes:
  - meridional circulation
  - differential rotation

Rotation profile

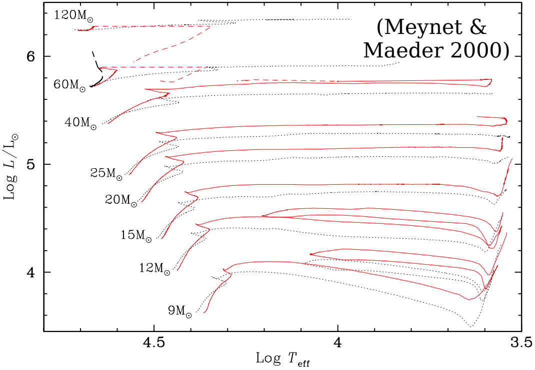


Meridional circulation



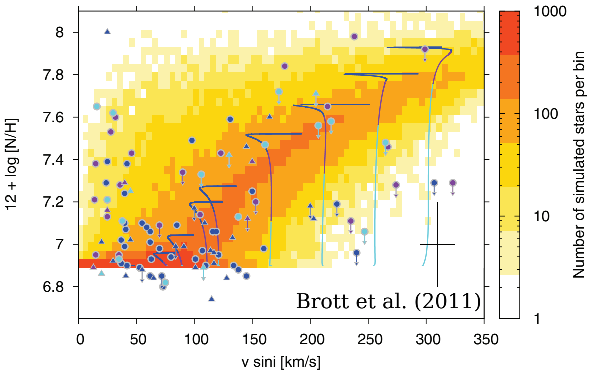
(Rieutord & Espinosa Lara, 2009, Espinosa Lara & Rieutord, 2013)

Baroclinic effects – impact on evolution



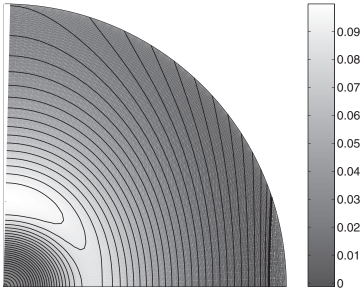
- enhanced transport: modified lifetime and different chemical yields
- improved agreement with observations (Meynet & Maeder 2005 and references therein)

Baroclinic effects – impact on evolution

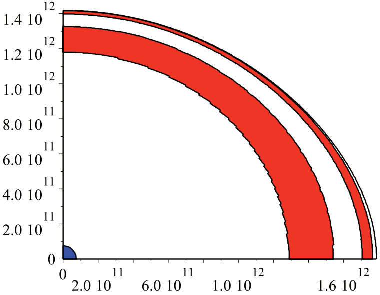


- mismatch on N enrichment in some stars (Hunter et al. 2009, Brott et al. 2011)
- mismatch on core rotation rate of red giants (Eggenberger et al. 2012, Marques et al. 2013, Ceillier et al. 2013)

Impact on convection zones



(Espinosa Lara & Rieutord 2007)

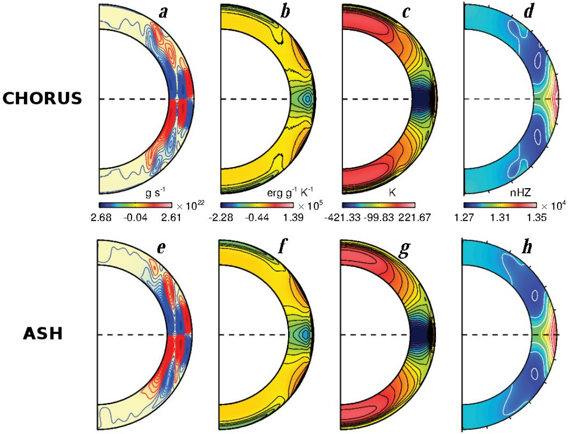


(Maeder et al. 2008)

- Espinosa Lara & Rieutord (2007): convective equatorial belts may exist
- Maeder et al. (2008): rotation favours convection in stellar envelopes, especially at the equator

Impact on convection zones

- open question: 2D prescription for convection in rotation models?
- answer may come from the CHORUS code (Wang et al., in prep.)

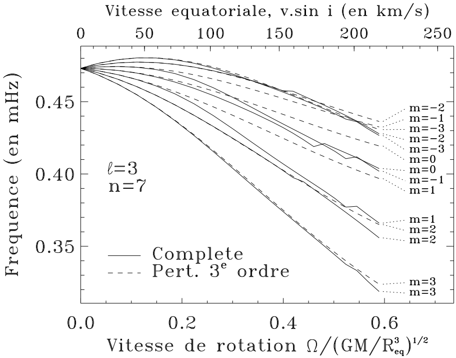


Wang et al., in preparation

Summary

- rotation causes many new phenomena which affect stellar structure, transport processes, mixing, and evolution
- although there has been much progress, there are still large uncertainties
  - need for observational constraints on internal structure
  - asteroseismology is the best way to do this currently

Impact of rotation on stellar pulsations

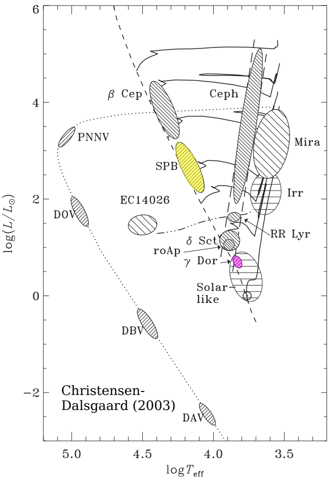


$$\omega = \omega_0 - m(\underbrace{\underbrace{1}_{\text{geometric}}\;\underbrace{-C}_{\text{Coriolis}}}_{\text{D. Kurtz' talk}})\,\Omega + \underbrace{\omega_2\Omega^2}_{\text{centrifugal \& Coriolis}} \quad \ldots$$

Gravito-inertial modes

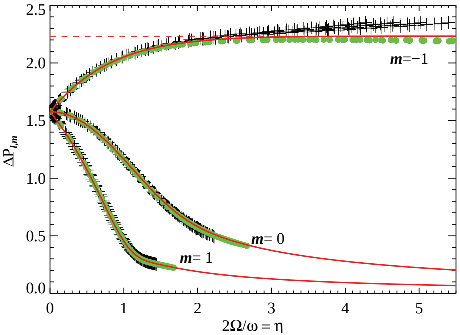
- gravito-inertial modes: restoring force = buoyancy + Coriolis force
  - effect of Coriolis force $\propto 2\Omega/\omega$
- stars with such modes: γ Dor stars, SPBs, Be stars

- extensive literature inertial and singular modes:
  - Papaloizou & Pringle (1978), Lee (2006), Rieutord et al. (2000, 2002), Dintrans & Rieutord (2000), Mirouh et al. (poster)
- in what follows, I will focus on modes that become g-modes in the $\Omega \to 0$ limit



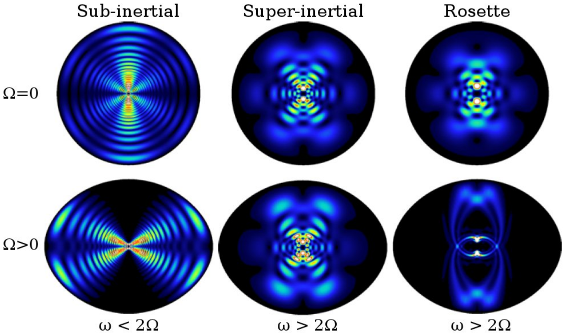
Period spacing

- when $\Omega = 0$, the period spacing depends only on ℓ (Tassoul 1980)
- when $\Omega \neq 0$, the period spacing depends on ℓ, m and $\eta = \frac{2\Omega}{\omega}$
  - first established with traditional approximation (Berthomieu et al. 1978); confirmed with full 2D computations (Ballot et al. 2012)



(Ballot et al. 2012)

Mode geometry

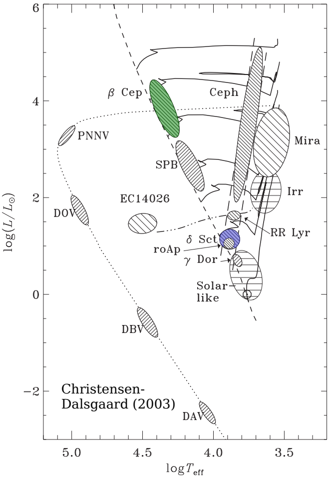


Ballot et al. 2013

- sub-inertial modes – confined by critical surfaces (see Dintrans et al. 1999, Dintrans & Rieutord 2000)
- rosette modes (Ballot et al. 2012, Takata & Saio 2013, 2014, M. Takata's talk)

Acoustic modes

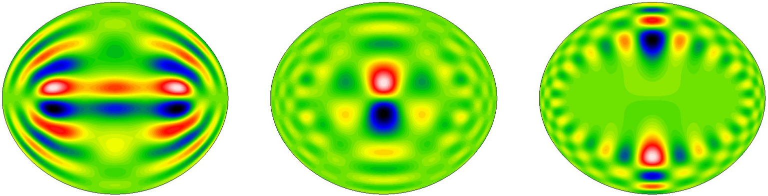
- acoustic modes: restoring force = pressure
  - affected by centrifugal force $\propto \frac{\epsilon}{\lambda} \propto \omega\Omega^2$
- stars with such modes: δ Scuti stars, β Cephei stars



Geometric structure

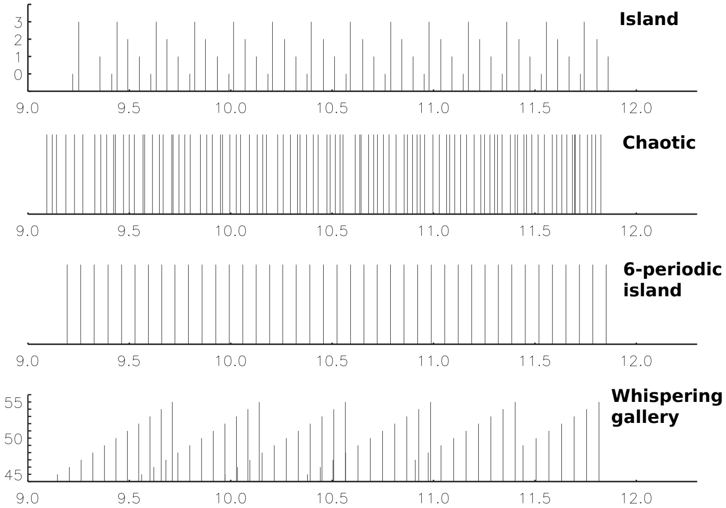
Island | **Chaotic** | **Whispering gallery**

low $\ell - |m|$ | medium $\ell - |m|$ | high $\ell - |m|$



- based on ray dynamics, Lignières & Georgeot (2008, 2009) found different classes of modes:
  - separate geometry
  - separate frequency organisation
- extended to more realistic models (Reese et al. 2009)

Frequency organisation

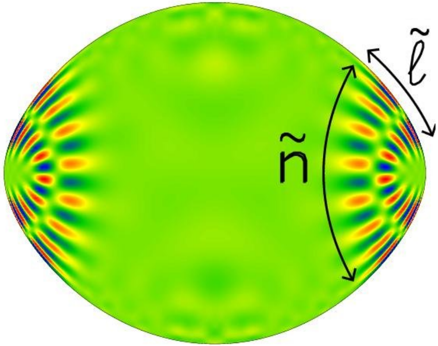


(Lignières & Georgeot, 2009)

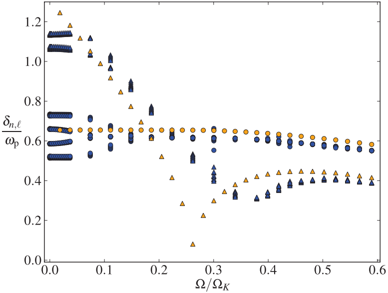
Island modes

- most visible of the regular modes
- rotating counterparts to modes with low $\ell - |m|$ values
- new quantum numbers:

$$\begin{aligned} \tilde{n} &= 2n + \varepsilon \\ \tilde{\ell} &= \frac{\ell - |m| - \varepsilon}{2} \\ \tilde{m} &= m \\ \varepsilon &= \ell + m \text{ modulo } 2 \end{aligned}$$



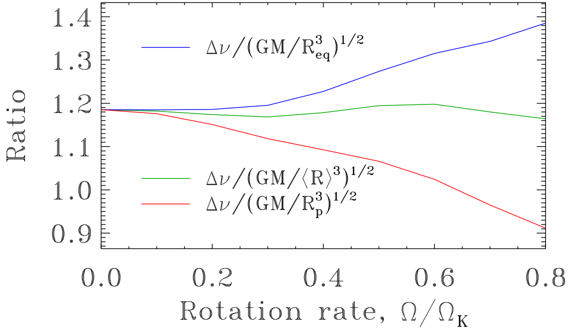
Frequencies of island modes



(Pasek et al. 2012)

- empirical fit (Reese et al. 2009): $\omega \simeq \Delta_{\tilde{n}}\tilde{n} + \Delta_{\tilde{\ell}}\tilde{\ell} + \frac{\Delta_{\tilde{m}}m^2}{\tilde{n}} - m\Omega + \tilde{\alpha}$
- $\Delta_{\tilde{n}}$ = travel time along ray path (Lignières & Georgeot 2008, 2009)
- $\Delta_{\tilde{\ell}}$: semi-analytical formula in Pasek et al. (2011, 2012)

A simple scaling relation

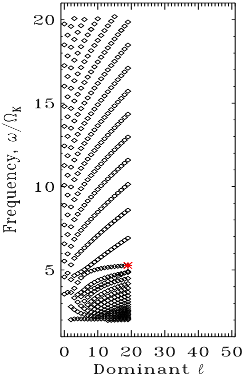


(Reese et al. 2008)

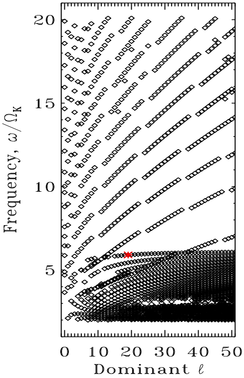
$$\Delta\nu = 2\Delta_{\tilde{n}} \propto \sqrt{G\overline{\rho}}$$

- this can constrain the mean density, even when Ω is large

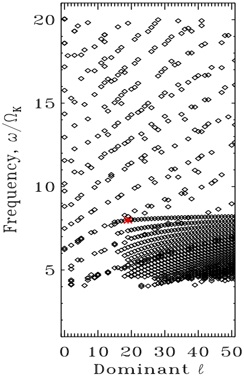
Mixed modes



$\Omega = 0.0\Omega_K$



$\Omega = 0.4\Omega_K$

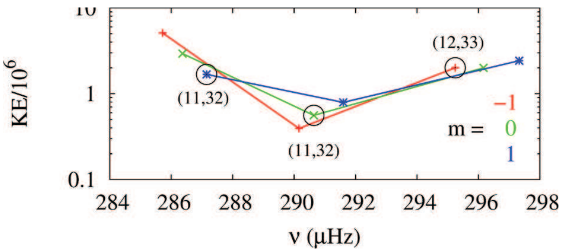


$\Omega = 0.8\Omega_K$

- gravito-inertial modes $\propto \sqrt{GM/R_{\mathrm{pol}}^3}$, acoustic modes $\propto \sqrt{G\bar{\rho}}$
  - rotation increases the overlap between p and g mode domain

Mixed modes

- in evolved stars with mixed modes, rotation affects different members of a multiplet differently (Ouazzani et al. 2013)
  - loss of equidistant spacing even for small Ω

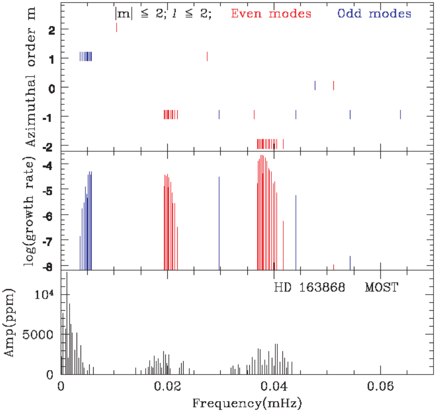


(Ouazzani et al. 2013)

Asteroseismology

- Two approaches:
  - Average/global: focuses on the general characteristics of pulsation spectra rather than on specific modes
  - Detailed/ "boutique": relies on the identification of individual modes

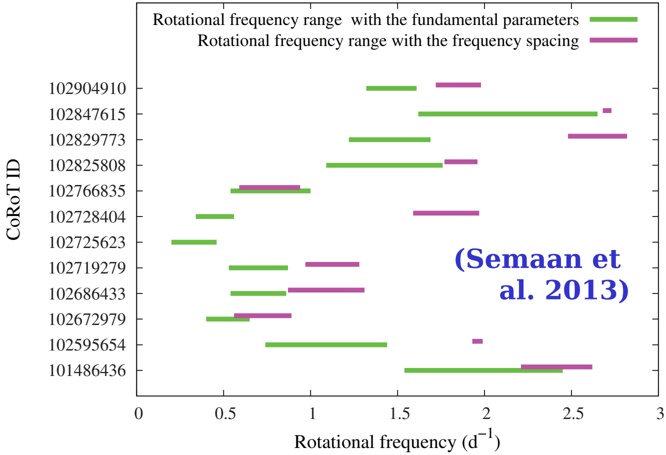
Global asteroseismology – low frequency domain



(Walker et al. 2008)

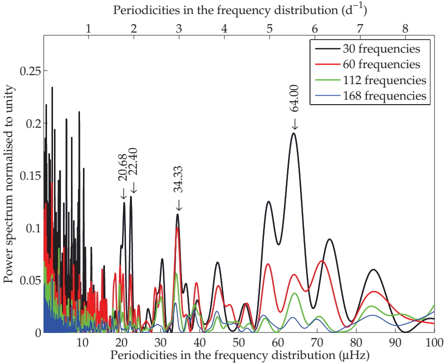
- $\nu_{\text{inert.}} = |\nu_{\text{corot.}} - m\Omega|$
- modes group together in clumps, separated by Ω
- use of non-adiabatic calculations to decide which clumps are excited
- see Savonije (2007), Saio et al. (2007), Dziembowski et al. (2007), Walker et al. (2008), Cameron et al. (2008)

Global asteroseismology – low frequency domain



- discrepancies between seismic and classical values of Ω in Be stars

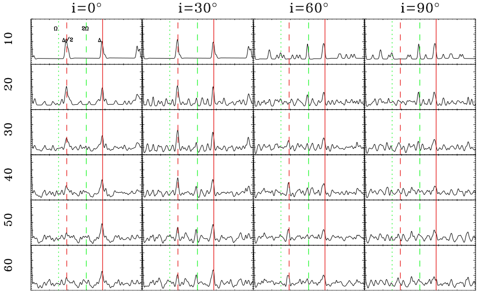
Global asteroseismology – high frequency domain



(García Hernández et al. 2013)

- recurrent spacings in Fourier transform of frequency spectra
- interpreted as $\Delta\nu \Rightarrow$ constraint on mean density

Global asteroseismology – high frequency domain



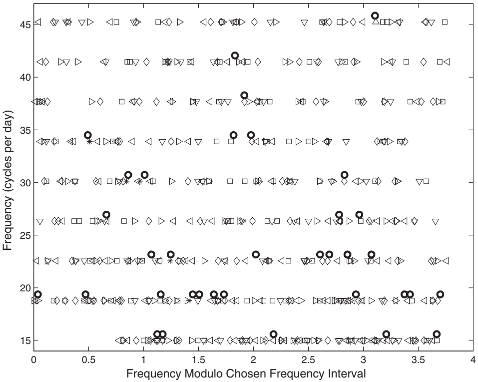
(Reese et al. submitted)

- recurrent spacings found in a number of studies:
  - Breger et al. 2009, García Hernández et al. 2009, 2013, poster, Mantegazza et al. 2012, Suárez et al. 2014
- studies based theoretical spectra:
  - Lignières et al. 2010, Reese et al. submitted

Detailed asteroseismology

Why is it so difficult?

Detailed asteroseismology



(Deupree et al. 2012)

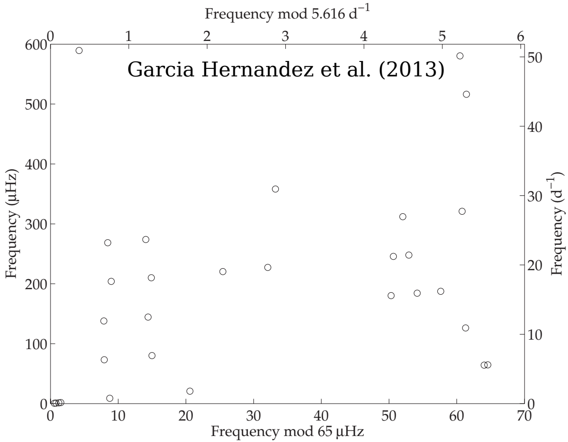
- mode identification is a real challenge

Detailed asteroseismology

Mode identification techniques

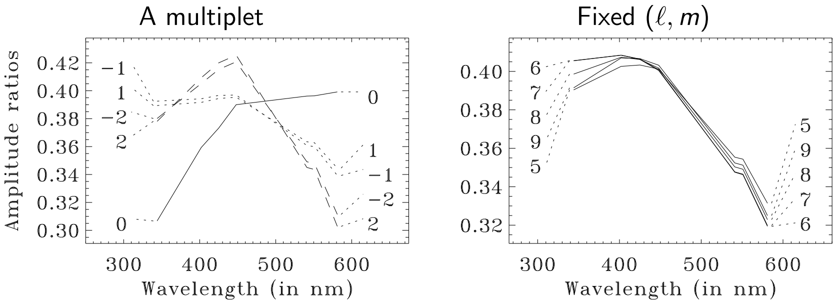
- still try to look for frequency patterns
- multi-colour photometry
  - amplitude ratios, phase differences
  - *advantages:* intrinsic amplitude factors out, simpler observations
- spectroscopy: LPVs
  - *advantage:* more detailed information
- these methods need to be adapted to rapidly rotating stars

Echelle diagrams



- g-modes: Bedding's talk
- p-modes: García Hernández et al. 2013, poster

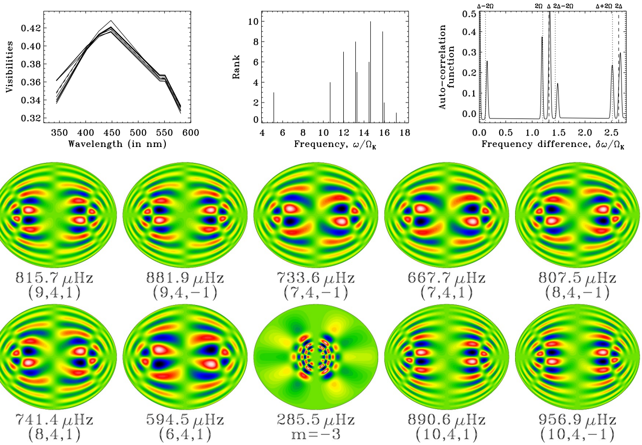
Multi-colour mode identification



(Reese et al. 2013)

- see also Townsend (2003), Daszyńska-Daszkiewicz et al. (2002, 2007), Lignières et al. (2006), Lignières & Georgeot (2009)
- the amplitude ratios for a given multiplet depend on m, *unlike for spherical stars*
- the amplitude ratios remain similar for fixed (ℓ, m) values

Multi-colour mode identification

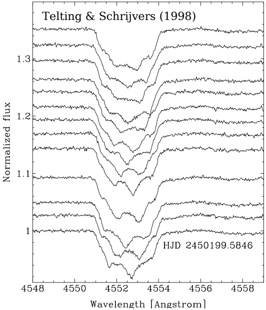


(Reese et al. submitted)

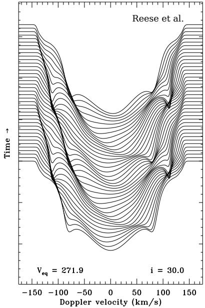
- compare observed amplitude ratios between each other
  - $\Rightarrow$ group modes with similar (ℓ, m) values

Spectroscopic signatures

Observations



Theory



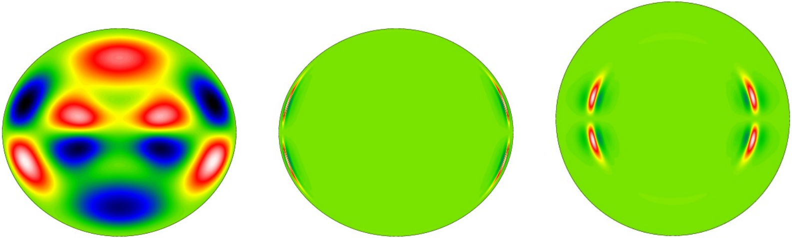
- theory: Lee & Saio (1990), Clement (1994), Townsend (1997), R+
- observations: Telting & Schrijvers (1998), Poretti et al. (2009), poster by Themeßl et al.
- mode identification tools such as FAMIAS (Zima 2008) need to be adapted to rapid rotation

Non-adiabatic calculations

- these mode identification techniques need $\delta T_{\text{eff}} / T_{\text{eff}}$
  - only non-adiabatic calculations yields this accurately
- mode excitation only from non-adiabatic calculations

- previous studies: Lee & Baraffe (1995) + subsequent papers
  - models based on Chandrasekhar expansion
- current work: based on rapidly rotating ESTER models
  - only 2D models in which the energy equation is solved self-consistently

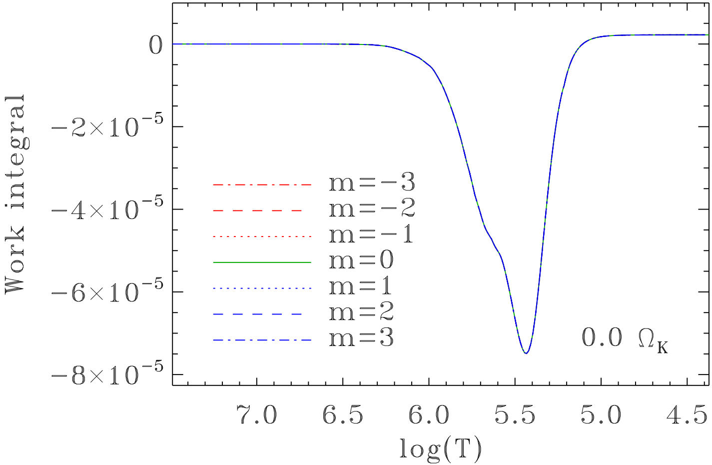
Non-adiabatic calculations



Acoustic | Work | Work (vs. log T)

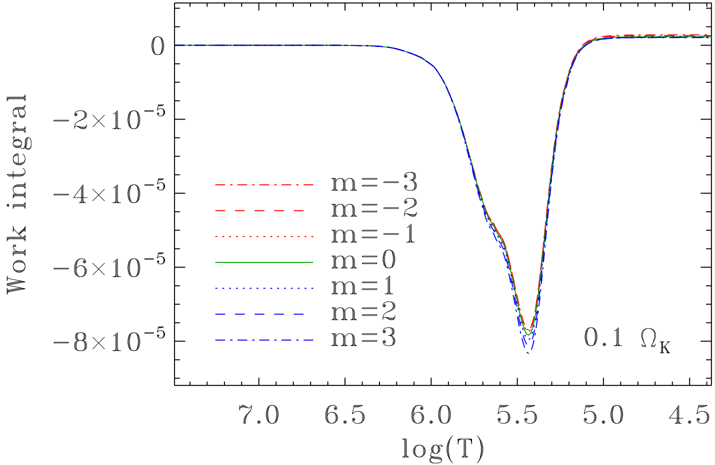
- a given pulsation mode (stabilised by rotation)

Non-adiabatic calculations



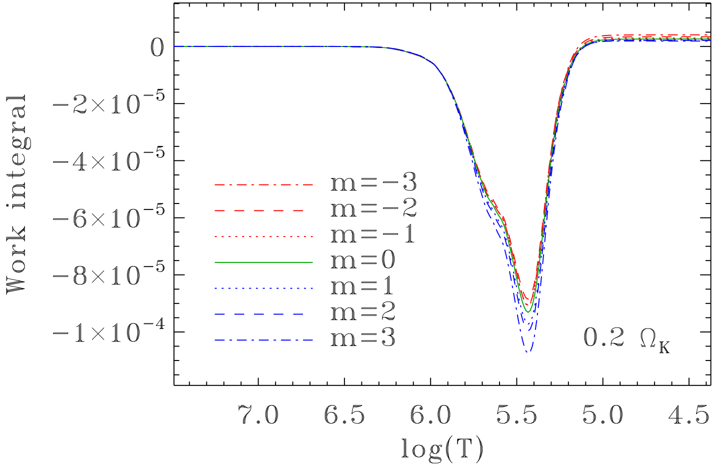
- a multiplet (the retrograde modes are stabilised first)

Non-adiabatic calculations



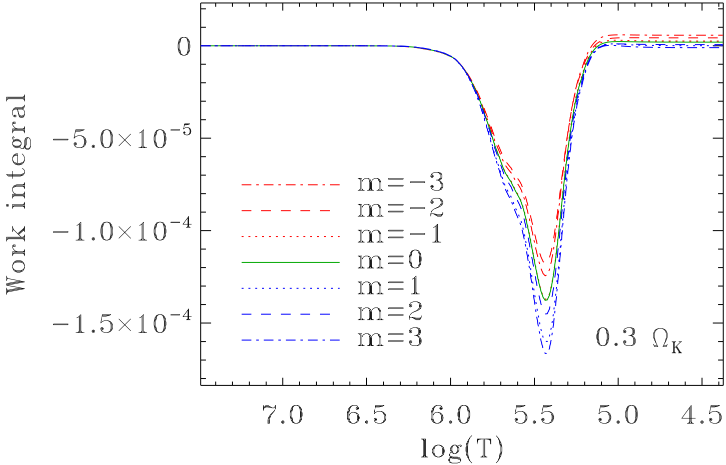
- a multiplet (the retrograde modes are stabilised first)

Non-adiabatic calculations



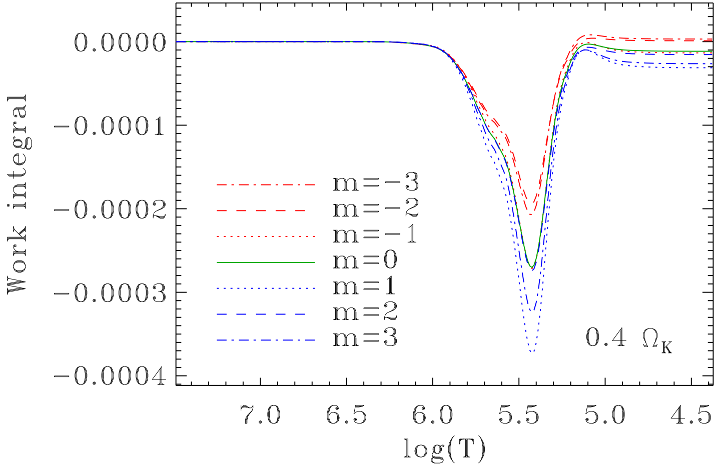
- a multiplet (the retrograde modes are stabilised first)

Non-adiabatic calculations



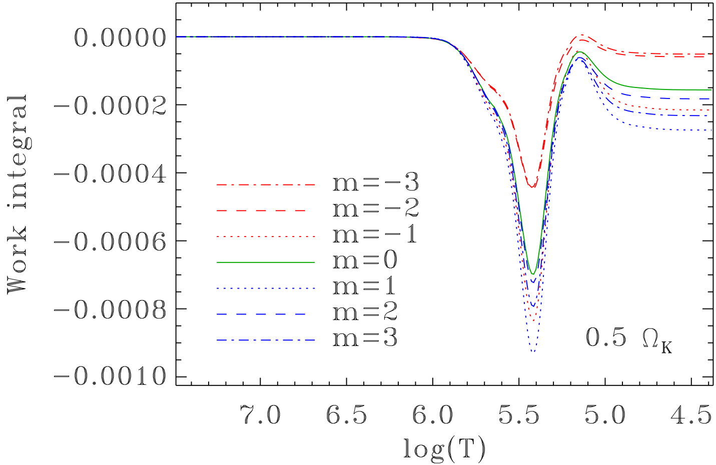
- a multiplet (the retrograde modes are stabilised first)

Non-adiabatic calculations



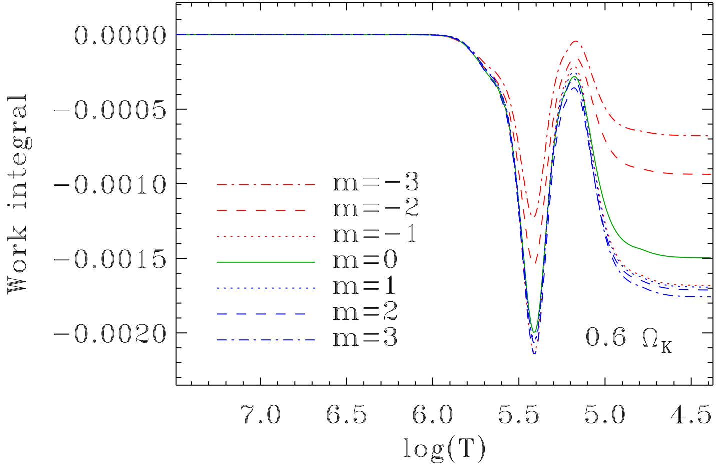
- a multiplet (the retrograde modes are stabilised first)

Non-adiabatic calculations



- a multiplet (the retrograde modes are stabilised first)

Non-adiabatic calculations



- a multiplet (the retrograde modes are stabilised first)

Conclusion

- rapid rotation plays a major role in massive and intermediate mass stars
  - these stars are important for many domains in astrophysics
- multiple effects both on structure and evolution
  - better understanding of these effects
  - many unanswered questions remain
- impact on stellar pulsations
  - progress on understanding these effects and interpreting seismic data
  - more work needed, especially with current (MOST, CoRoT, Kepler, BRITE) and future data (PLATO)