Intermediate mass star: magnetic field, rapid rotation and seismology

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Motivations

Stellar evolution with magnetic field and rotation

- $M > 1.5 \, M_\odot$ stars: a laboratory with great potential but ...
- magnetism and rotation remain poorly constrained/understood as compared to solar-type stars

Two old problems prevent direct constraints on internal rotation and magnetism

- rapid rotation prevents detailed seismic diagnostic: a modelling issue
- the magnetic field in the vast majority of the stars is unconstrained: an observational issue
Stellar rotation across the main-sequence

The hot/cool star dichotomy

(from Royer et al. 2007 and Peterson et al. 2006)
Computing oscillation modes in rotating stars

\( \Omega = 0 \Rightarrow \text{spherical symmetry} \)

The solutions are fully separable \( g(\vec{x}) = f(r)P^m_\ell(\theta)\exp(im\phi) \)

\( \Rightarrow \) solve a 1D linear boundary value problem (for each \( \ell \) and \( m \))

\( \Omega \neq 0 \Rightarrow \text{axial symmetry + equatorial symmetry} \)

The solutions are only partially separable \( g(\vec{x}) = f(\vec{x}_M)\exp(im\phi) \)

\( \Rightarrow \) solve a 2D linear boundary value problems for each \( m \pm \)

A significantly more difficult problem

- construct a complex code with accuracy constraints from spatial photometry
- explore a dense frequency spectrum
- no simple physical classification of the modes
Computing oscillation modes in rotating stars

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No simple physical classification of the modes

\[ \Omega = 0 \]

\[ \Omega \neq 0 \]

- \( n \) radial nodes, \( \ell \) latitude nodes
- complex node pattern
Summary of recent progress with 2D models

- 2D codes are available: TOP (Reese et al., 2006, 2009), NRO (Lovekin et al., 2008), ACCOR (Ouazzani et al, submitted)

- Significant numerical explorations of the p-mode and g-mode spectra have been performed (Lignières et al. 2006, Reese et al., 2006, 2008, 2009, Lovekin et al. 2008, Ballot et al. 2012)

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- An asymptotic theory provides a framework to understand p-modes properties (Lignières & Georgeot, 2008, 2009, Pasek et al., 2011, 2012)

Some results

- Limit of validity of approximate approaches
- p-mode classification
- New regular spacings at high rotation rates
Testing approximate treatments of the rotation

- Perturbative methods \( \omega = \omega_0 + \omega_1 \Omega + \omega_2 \Omega^2 \ldots \)

\[ \delta \nu = 0.1 \mu \text{Hz} \]

- \( 1^{\text{st}} \) order
- \( 2^{\text{nd}} \) order
- \( 3^{\text{rd}} \) order

- low degree \( \ell \leq 3 \)
- \( M = 3 \, M_\odot, \, R = 2 \, R_\odot \)

from Reese et al. (2006) and Ballot et al. (2010), see also Lovekin et al. 2008, Suárez et al. 2010, Burke et al. 2011
Acoustic rays

\[ \Omega = 0 \]
Acoustic rays

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\[ \Omega = 0.6\Omega_K \]
Acoustic dynamics phase space

\[ \Omega = 0 \]

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Classification and spectrum structure from a ray based asymptotic theory

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The spectrum is a superposition of sub-spectra with specific properties

Lignières & Georgeot 2008, 2009
From low degree modes to island modes

Centrifugal volume growth $\Rightarrow$ global spectrum contraction

$\ell = \begin{array}{cccc}
1 & 0 & 1 & 0 \\
\hline
\end{array}$

$\Omega/\Omega_k = 0$

$\Omega/\Omega_k = 0.18$

$\Omega/\Omega_k = 0.40$

$\Omega/\Omega_k = 0.59$

$\omega/(GM/R^3)^{1/2}$
From low degree modes to island modes
The asymptotic view

Rescaling of the spectrum

\[ \ell = 1 \quad 0 \quad 1 \quad 0 \]

\[ \Omega / \Omega_k = 0 \]

\[ \Omega / \Omega_k = 0.18 \]

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\[ \Omega / \Omega_k = 0.59 \]

\[ \omega / \omega_1(\Omega) \]
From low degree modes to island modes

### Evolution of the small separation

<table>
<thead>
<tr>
<th>$\ell$</th>
<th>1</th>
<th>20</th>
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<th>20</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
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- The small separation $(\ell, n + 1, 0) - (\ell + 2, n, 0)$ is no longer small
From low degree modes to island modes

Evolution of the $\ell = 1, m = \pm 1$ multiplet: in the rotating frame

$\ell = 1 \quad 0 \quad 1 \quad 0$

$\Omega/\Omega_k = 0$

$\Omega/\Omega_k = 0.18$

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$\omega(m) \sim \omega(-m)$ because the Coriolis force is negligible

$(\ell + 1, n, m = \pm 1)$: from $(\ell + 1, n, m = 0)$ to $(\ell, n, m = 0)$
From low degree modes to island modes

Evolution of the $\ell = 1, m = \pm 1$ multiplet: in the observer’s frame

- $\ell = 1, 0, 1, 0$
- $\Omega / \Omega_K = 0$
- $\Omega / \Omega_K = 0.18$
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- $\Omega \sim 0$: equidistant multiplet $\omega_0 + m\Omega$
- Intermediate $\Omega$: no equidistant multiplet
- High $\Omega > \sim 0.4\Omega_K$: new equidistant multiplet $\omega_0 + m\Omega$ if $m$ not too large
From low degree modes to island modes

Evolution of the $\ell = 2, m = \pm 2$ multiplet: in the observer frame

- Even the $\ell = 0$ mode has a multiplet!!

\[ \Delta \omega_I = m\Omega \text{ at low rotation to } \Delta \omega_I = \Omega \text{ at high rotation} \]
Intermediate-mass star magnetism

Some years ago ...

- All magnetic stars have Ap type abundance anomalies
- Fields are nearly dipolar, strong ($\sim 1$ kG), stable in time
- If all Ap/Bp stars are magnetic, 5 to 10 percents of intermediate mass stars are magnetic

Open questions

- A fossil origin of the field?
- Why only 5 percents should be magnetic?
- Stellar evolution of normal A stars with or without magnetic field?
Progress with spectropolarimeters Narval@TBL, Espadons@CFHT

- Ap/Bp magnetic field lower bound: $\sim 300$ Gauss (Auriere et al. 2007)
- No detection of magnetic fields between 100 G and 1 G (Auriere et al. 2010)
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Two magnetisms and a magnetic desert

- Are all intermediate-mass stars magnetic?
- Properties of Vega-like magnetism?
- Origin of the Ap/Bp magnetic lower bound and of the magnetic desert?
A scenario for the Ap magnetic lower bound and the magnetic desert


\( \mathbf{\vec{B}} \) stability in a differentially rotating star (e.g. Spruit 1999)

- Strong \( B \) suppress differential rotation and reaches stable configurations
- Weak poloidal field \( B_p \) ⇒ strong azimuthal field \( B_\phi \) ⇒ Tayler instability

Order of magnitude of the critical field (Auriere et al. 2007)

magnetic forces react just on time to avoid \( B_\phi > B_{pol} \)

\( \Rightarrow \quad B_c = \left(4\pi \rho\right)^{1/2} r\Omega \)
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- The gap opens due to strong polarity cancellation of the destabilized field
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Conclusions

Seismology of rapidly rotating stars

- p-modes are relatively well understood
- space photometry data flux
- amplitudes are basically unknown
- rotation is poorly constrained ($v \sin i$)

Intermediate-mass star magnetism

- a new observational view
- renew interest in modelling
- Vega-like magnetism hard to study
- magnetic fields are hard to model

Magnetism vs seismology

- Vega magnetic field has been found looking for Vega pulsations
- rotational modulation of the lightcurve (Balona 2011, 2012)

Progress towards the study of typical i.e. rapidly rotating, non-strongly chemically peculiar intermediate-mass stars