Asteroseismology

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FAMIAS software package (W. Zima)
At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe.
Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers?
What appliance can pierce through the outer layers of a star and test the conditions within?
Large variation of internal structure

We need to do much better than this!
Motivation: the crucial rôle of stars

- Stars are the sources of the chemical evolution of the Universe:
  - Massive stars synthesize elements $H \rightarrow Fe$
  - Stars with moderate masses form C, N, O
  - Chemical evolution strongly dependent on internal mixing processes
- Stars are local memory of history of Universe and allow to estimate its age
Present unknowns in stellar modelling

- Effect of (differential) internal rotation?
- Effect of convective overshooting? => how does mixing occur inside the stars?
- Preamble of supernova explosion?
- Evolution of close binary systems?

Asteroseismology will imply major steps forward in answering these questions
History of the research topic

With your naked eye: 3% of the stars is variable
History of the research topic

- Periodic large-amplitude variables known since long, e.g. Cepheids, RR Lyraes
- Multiperiodicity at low amplitude found in many different kinds of variables
- Cause: non-radial oscillations
- Idea: every body 'sounds' according to its internal structure => the different oscillation frequencies learn us something about the stellar interior
- Between 1900 - 1990: mainly inventories of variables
- Since 1990: use frequency content to derive internal structure parameters
通过分析恒星的脉动，我们想要研究恒星的内部。

aster: star
seismos: oscillation
logos: discours, reasoning

Through the analysis of stellar oscillations we want to study the stellar interior
1-dimensional oscillations

- Fundamental
- First overtone
- Second overtone

Nodes

Modes
pressure modes

- More frequent collisions = faster sound speed
  - Higher temperature = faster sound speed
  - Higher density = faster sound speed
  - Lighter gases = faster sound speed
Why do stars oscillate?

- Because they have convective outer layers which cause stochastic excitation of oscillations (cf. gong)

- Because some outer layers act as a heat engine: partial ionisation zones absorb and accumulate energy generated in the stellar interior (opacity mechanism)

- Forced oscillations may occur due to tidal effects in close binaries
Pulsating stars are everywhere.
Characterization of non-radial modes

\((l,m) = (3,0)\) axisymmetric
\((l,m) = (3,2)\) tesseral
\((l,m) = (3,3)\) sectoral

Blue : Moving towards Observer
Red : Moving away from Observer
Internal behaviour of the oscillations

The oscillation pattern at the surface propagates in a continuous way towards the stellar centre.

Study of the surface patterns hence allows to characterize the oscillation throughout the star.
Theoretical description of oscillations

- Perturbation of mass, momentum and energy conservation

- Solutions ~ $\exp(2\pi i t f)$ can be found, with $f$ the oscillation frequency of one mode

- Velocity vector ~ spherical harmonic, consisting of Legendre polynomial with wavenumbers $(l,m)$

- Limit of large or small frequency: pressure and gravity modes
The oscillations are standing sound waves that are reflected within a cavity.

Different oscillations penetrate to different depths and hence probe different layers.
Modes with almost equal frequency

Green and yellow oscillations probe almost same region

Such oscillations allow to map the mixing processes layer by layer
Solar frequency spectrum from ESA/NASA satellite SoHO: systematics!
Musical Intermezzo: Symphony of the Sun
Frequencies of a red giant star

1 month RV data of Xi Hya (2002, 1.2m Euler)
Musical Intermezzo:
Symphony of a red giant
Frequencies of an sdB star

6 nights of data of PG0014+067 (2004, 4.2m WHT)
Musical Intermezzo: Symphony of PG0014+067
Dopplermap of the Sun

The Sun oscillates in thousands of non-radial modes with periods of ~5 minutes.

The Dopplermap shows velocities of the order of some cm/s.
The sun as a star - BiSON

![Graph showing power versus frequency for the sun.](image)
Result: internal sound speed and internal rotation could be determined very accurately by means of helioseismic data (SoHO, BiSON, GONG)
Asteroseismic HR (JCD) diagram

Large frequency separation: measure of sound speed
Small frequency separation: measure of discontinuities in the sound speed

\[ \delta \nu (\mu \text{Hz}) \]

\[ \Delta \nu (\mu \text{Hz}) \]

- : mass
- : \( X_e \)
- \( 2.0 M_\odot \)
- \( 0.9 M_\odot \)
- \( 0.7 M_\odot \)
- \( 0.40 \)
- \( 9.5 \text{ Gyr} \)
- \( 14.4 \text{ Gyr} \)
- \( \sigma(\delta \nu) \)

\[ 0.05 \]
Internal rotation law?

- Rotational splitting of the non-radial modes:

\[ \sigma_{n,l,m} = \sigma_{n,l} - m \int_0^R \Omega(r)K_{n,l}(r)dr + \Theta(\Omega^2) \]

- Needed to solve this set of equations:
  - Several observed frequency splittings
  - Mode identification \((l,m,n)\)

- At present: we are able to treat only slow rotation
Internal rotation of the Sun

Solar interior has rigid rotation

Beginning of outer convection zone
But the Sun is just one simple star...

- She does not have a large convective core
- She is a slow rotator
- She is relatively unevolved

How do all these results/techniques change for other types of stars?
Solar-like Oscillations in α Centauri


- UVES & UCLES
- 42 oscillation frequencies
- $\ell = 1-3$
- Mode lifetimes only
  1-2 days
- Noise level = 2 cm s$^{-1}$!
Results for Alpha Cen A+B (G2V+K1IV)

- 42 & 12 detected frequencies, in range 1.8 - 2.9 & 3.0 - 4.6 milliHertz
- Amplitudes between 2 - 44 & 8 - 14 cm/s
- Large separations = 105.5 & 161.1 micro Hz
- Small separations = 5.6 & 10.2 micro Hz
- α CenA has no convective core, although slightly more massive than the Sun (1.105 & 0.934 solar masses)
- α(A) < α(B) by 5 - 10%

Eggenberger et al. (2004); Miglio & Montalban (2004)
Alpha Cen is more evolved than Sun
Summary of solar-like oscillators

Oscillation frequencies scale as expected

Large (and small) separations derived

Too few frequencies to map interior rotation or tune mixing processes as in the Sun

Need for long-term monitoring of a few selected targets
Frequency spectra of red giants?

Extensive RV campaigns: Frandsen et al. (2002); De Ridder et al. (2006); Hekker et al. (2006): radial modes or NRP?
Fig. 4.—Power spectrum of the complete data set, shown on a scale of $10^{-4}$ vs. frequency in $\mu$Hz. The vertical scale is different for each panel in an attempt to accommodate the dynamic range.
PG 1159-035

- $T_{\text{surf}} = 123,000 - 124,000 \text{ K}; \log g \approx 7$

- $1000 \leq f \leq 2600 \mu\text{Hz}; 385 \leq P \leq 1000 \text{ s}$

- 125 frequencies; >100 modes

- $M = 0.586 \pm 0.003 \text{ solar masses}$

- The star is compositionally stratified
• **DAV**

• $M = 1.09 \, M_\odot$

• $T_{\text{eff}} = 11730 \, K$

• 90% crystallized

**C-O core**

BPM 37093

(a) WET 1998

(b) WET 1999

(c) LCO 2003

Amplitude (mma)

Frequency (µHz)
Pulsating subdwarf B stars: sdBV
Remarkable discoveries of sdBVs

PG 1336 + 018 (Kilkenny et al. 1998, Vuckovic et al. 2007)
Remarkable discoveries of sdBVs

Planet survived Red Giant phase of the sdBV star V391 Pegasi... How??

Planet was discovered in the asteroseismic lightcurve

(Silvotti et al. 2007)
Low-order $p$ & $g$ modes: $\beta$ Cephei stars
Massive star seismology: HD 129929

Waelkens & Aerts: observed this star during 21 years
Phase diagrams for U filter data
First case study: HD 129929
Strategy: forward modelling

- Derive set of frequencies & amplitudes from data
- Compute stellar models thru error box in HR diagram + predict their unstable oscillation modes
  - X, Z (or Y), M, age (or Teff), core overshoot: 5D
- Identify observed modes, either from
  - pattern recognition from theoretical models
  - direct methods (quasi-independent of models)
- Confrontation: does the input physics of the models explain the seismic data?
  - if yes: we get very precise stellar parameters
  - if no: great! Input physics is insufficient and must be upgraded to include additional effects or better descriptions until frequencies can be matched...
HD129929: Position in HR diagram
HD129929: M(Z) relation

HD 129929 BEST MODELS — X=0.70

\[ \text{\textit{M}/M_\odot} \]

\[ \text{Z} \]

\( \alpha_{\text{OV}} = 0 \)
\( \alpha_{\text{OV}} = 0.2 \)
\( \alpha_{\text{OV}} = 0.1 \)
Acceptable range in $M, Z, \text{overshoot}$
Conclusions for HD129929

- We need very small core-overshooting to explain the frequencies of the star using OPAL opacities and standard solar mixture
- FIRST star besides the Sun in which non-rigid rotation is proven: core 3.6 times faster than surface
Results so far for B stars

Compatible with EB & isochrone fitting

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Star</th>
<th>Mass (M☉)</th>
<th>SpT</th>
<th>αov (Hp)</th>
<th>ΩR (km/s)</th>
<th>Ωcore/Ωenv</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>HD 16582</td>
<td>10.2 ± 0.2</td>
<td>B2IV</td>
<td>0.20±0.10</td>
<td>28(14?)</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>HD 29248</td>
<td>9.2 ± 0.6</td>
<td>B2III</td>
<td>0.10±0.05</td>
<td>6±2</td>
<td>~5</td>
</tr>
<tr>
<td>(3)</td>
<td>HD 44743</td>
<td>13.5 ± 0.5</td>
<td>B1III</td>
<td>0.20±0.05</td>
<td>31±5</td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>HD 129929</td>
<td>9.4 ± 0.1</td>
<td>B3V</td>
<td>0.10±0.05</td>
<td>2±1</td>
<td>3.6</td>
</tr>
<tr>
<td>(5)</td>
<td>HD 157056</td>
<td>8.2 ± 0.3</td>
<td>B2IV</td>
<td>0.44±0.07</td>
<td>29±7</td>
<td>~1</td>
</tr>
</tbody>
</table>

(1) Aerts et al. (2006): 20 d MOST photometry + 1 week spectra
(2) Pamyatnykh et al. (2004); Ausseloos et al. (2004):
   5 months multisite photometry + spectroscopy
(3) Mazumdar et al. (2006): 4 years high-resolution spectroscopy
(4) Aerts et al. (2003, 2004); Dupret et al. (2004): 20 years photometry
(5) Briquet et al. (2007): 2 years spectroscopy + few months photometry
Status prior to CoRoT and Kepler

- Solar-like oscillations in some 30 stars:
  - Slightly more massive Suns do not have convective core
  - Oscillation frequencies scale as predicted
  - Insufficient frequencies to derive rotational mixing
  - Mode lifetimes?
- Discoveries of oscillations in 5 red giants since 2001
- First proof of non-rigid rotation inside massive stars since 2003: they live longer!
- Goal: beat the noise level...
Goal 1: better independent constraints

Provide an independent high-precision radius estimate for bright stars
Cunha et al. (2007, A&ARev)

Provide an independent high-precision distance estimate

Dedicated instruments for specific stars attached to private telescopes for mode identification
Goal 2: space asteroseismology

MOST: Canadian mission (15cm) launched in June 2003 max. 6 weeks, extended

CoRoT: French-led European mission (27cm), launched 27/12/2006 max 5 months, extended 2013

Kepler: NASA mission (95cm), launch 7 March 2009, exoplanets 4 (6?) years

PLATO: exoplanet ESA mission with asteroseismic capabilities pre-selected for CV2015-2025 6 years
What appliance can pierce through the outer layers of a star and test the conditions within?

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