Galax and asteroseismology

Dennis Stello
The asteroseismic revolution
pre-2007

~10 dwarfs & subgiants
~8 giants

Ground-based radial velocity.
WIRE star tracker.
MOST spacecraft.

figure by Daniel Huber
Kepler 2010-13
~ 600 dwarfs & subgiants
~ 20000 giants

Surface Gravity (dex)

Effective Temperature (K)

figure by Daniel Huber
Photometry

APOGEE Red Giants/original Kepler field

Pinsonneault et al. 2016
Early results from Kepler

Snapping into focus

Pinsonneault et al. 2016

Photometry  Spectroscopy

APOGEE Red Giants/original Kepler field
Early results from Kepler

Snapping into focus

Pinsonneault et al. 2016

Photometry Spectroscopy Spectroscopy + asteroseismology

APOGEE Red Giants/original Kepler field
A short introduction to cool-star asteroseismology
Asteroseismology of cool stars
Excitation of solar-like oscillations
Excitation of solar-like oscillations
Excitation of solar-like oscillations

Standing sound waves (p modes)
### Observing oscillation modes

<table>
<thead>
<tr>
<th></th>
<th>Velocity (cm/s)</th>
<th>Brightness (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Red giant</td>
<td>1-100</td>
<td>30-300</td>
</tr>
</tbody>
</table>

- **Frequency**: Sound speed
- **Interior properties**
Virgo data of the Sun

Overtone determined by number of nodes (shells) radially.

Spherical degree determined by number of `surface' nodal lines.
How we do it!

Virgo data of the Sun

Overtone determined by number of nodes (shells) radially.

Spherical degree determined by number of `surface' nodal lines.

\[ \delta f/f \sim 10^{-4} - 10^{-6} \]
What can we measure?

Age of star
Ages of main sequence stars

H → He

Radial modes ($\ell = 0$)

Quadrupole modes ($\ell = 2$)
But there is more

\[ \nu_{\text{max}} \sim g/(T_{\text{eff}})^{0.5} \]

\[ \Delta \nu \sim \rho^{1/2} \]

Age of star
Age precisions

• **Individual mode fitting (or frequency ratios):**
  - **Main sequence:** ~3% (best, Metcalfe 2015),
    5-15% (typical, Metcalfe 2014, Silva Aguirre 2015).
  - **Subgiants:** ~1% (best, Metcalfe 2010),
    ~3% (typical, Deheuvels & Michel 2011).
  - **Red giants:** < 15%(?) (very time consuming)

• $\Delta \nu + \nu_{\text{max}}$ (**at least one scaling relation**):
  - **Main sequence:** ~15% – 25% (Chaplin 2014).
  - **Subgiants:** ~15% – 25% (Chaplin 2014).
  - **Red giants:** ~15 – 30% (Casagrande 2014).
Ages of red giants

Spectroscopic-only constraints

Seismic-included constraints

Silva Aguirre & Serenelli 2016
Back to the revolution...what have we learned so far!
Evolution of frequency spectra

Paxton et al. (2013)
Evolution of frequency spectra

- He-core burn (red clump)
- p-mode cavity (envelope)
- g-mode cavity (core)
- evanescent zone

Paxton et al. (2013)
Red Clump (He-core burning)

RGB (non He-core burning)

Problem!!!
Gravity modes as a way to distinguish between hydrogen- and helium-burning red giant stars

Timothy R. Bedding\textsuperscript{1}, Benoit Mosser\textsuperscript{2}, Daniel Huber\textsuperscript{1}, Josefina Montalbán\textsuperscript{3}, Paul Beck\textsuperscript{4}, Jørgen Christensen-Dalsgaard\textsuperscript{5}, Yvonne P. Elsworth\textsuperscript{6}, Rafael A. García\textsuperscript{7}, Andrea Miglio\textsuperscript{3,6}, Dennis Stello\textsuperscript{1}, Timothy R. White\textsuperscript{1}, Joris De Ridder\textsuperscript{4}, Saskia Hekker\textsuperscript{6,8}.

[Graph showing frequency versus power density for KIC 6779699 with $\Delta P_{\text{obs}} = 53 \text{ s}$, $\Delta \nu = 8.00 \mu\text{Hz}$, $\nu_{\text{max}} = 87 \mu\text{Hz}$ and another graph for KIC 4902641 with $\Delta P_{\text{obs}} = 96 \text{ s}$, $\Delta \nu = 7.89 \mu\text{Hz}$, $\nu_{\text{max}} = 100 \mu\text{Hz}$]
RGB/RC stars: seismically different

RGB (H-shell burning)

RC (He-core burning)
Red Clump (He-core burning)

RGB (non He-core burning)
Ages of red giants

Silva Aguirre & Serenelli 2016
Other breakthroughs!!!

**Magnetic green house effect**
Fuller et al. 2015 (Science)

**Stellar inclinations: Do cluster stars’ spin align?**
Corsaro et al. 2017 (NatureCom)

**Radial differential rotation and angular momentum transport**

**A prevalence of convective core dynamos**
Stello et al. 2016 (Nature)

Beck et al. 2012 (Nature)
Mosser et al. 2012 (A&A)
Ensemble seismology: Probing the structure and evolution of the Milky Way
Our Galaxy

Stellar halo

Bulge

Stellar disk(s)

Hippoarcos + Copenhagen-Geneva Survey
Probes of the Galaxy

Asteroseismic probes of the Galaxy

Credit: Miglio

Mathur et al. 2016
Ensemble seismology: $M$, $R$, $L$

**Power location:**

\[
\nu_{\text{max}} \approx \frac{M / M_*}{(R / R_*)^2} \sqrt{T_{\text{eff}} / T_{\text{eff,*}}} \times 3.1 \text{mHz}
\]

**Frequency spacing:**

\[
\Delta \nu \approx \frac{(M / M_*)^{1/2}}{(R / R_*)^{3/2}} \times 135 \mu\text{Hz}
\]
Ensemble seismology: M, R, L

Power location:

\[ \nu_{\text{max}} \approx \frac{M / M_*}{(R / R_*)^2 \sqrt{T_{\text{eff}} / T_{\text{eff},*}}} \times 3.1 \text{mHz} \]

Frequency spacing:

\[ \Delta \nu \approx \left( \frac{M / M_*}{(R / R_*)^{1/2}} \right) \times 135 \mu\text{Hz} \]

Distance:

\[ R, T_{\text{eff}} \rightarrow L \]
Ensemble seismology: M, R, L

Power location:
\[ \nu_{\max} \approx \frac{M}{M_\odot} \left( \frac{R}{R_\odot} \right)^2 \sqrt{T_{\text{eff}}} \]

Frequency spacing:
\[ \Delta \nu \approx \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{R}{R_\odot} \right)^{3/2} \times \nu_{\max, \odot} \]

Distance:
\[ R, T_{\text{eff}} \rightarrow L \]
Ensemble seismology: M, R, L

Whole-sale seismology!

Power index:

\[ V_{\text{max}} \approx \frac{1}{(R / R_*)^2} \sqrt{T_{\text{eff}}} \]

Frequency spacing:

\[ \Delta \nu \approx \frac{(M / M_*)^{1/2}}{(R / R_*)^{3/2}} \times \nu_{\text{max}} \]

Distance:

\[ R, T_{\text{eff}} \rightarrow L \]

\[ \frac{M}{M_\odot} \sim \left( \frac{\nu_{\text{max}}}{\nu_{\text{max}, \odot}} \right)^3 \left( \frac{\Delta \nu}{\Delta \nu_{\odot}} \right)^{-4} \left( \frac{T_{\text{eff}}}{T_{\text{eff}, \odot}} \right)^{3/2} \]

\[ \frac{R}{R_\odot} \sim \left( \frac{\nu_{\text{max}}}{\nu_{\text{max}, \odot}} \right) \left( \frac{\Delta \nu}{\Delta \nu_{\odot}} \right)^{-2} \left( \frac{T_{\text{eff}}}{T_{\text{eff}, \odot}} \right)^{1/2} \]
Ensemble seismology: M, R, L

Whole-sale seismology!

Typical precisions:

- $\Delta \nu \approx 0.1-1\%$
- $\nu_{\text{max}} \approx 0.5-2\%$

Log(g) 0.01-0.03 dex
Radius 2-3%
Mass 6-10%
Age 15-30%
Distance 3-5%

Power law

$\nu_{\text{max}} \approx \frac{(R / R_*)^2}{\sqrt{T_{\text{eff}}} }$

Frequency spacing:

$\Delta \nu \approx \frac{(M / M_*)^{1/2}}{(R / R_*)^{3/2}}$
Early results from Kepler and CoRoT

Population synthesis of red giant stars

Differential comparison between two fields/populations

Miglio, Chiappini, Morel et al. 2013
Early results from Kepler and CoRoT

Sharma, Stello, Bland-Hawthorn et al. (2016)

Direct comparison with Galaxy model
Early results from Kepler and CoRoT

Not a good match in mass!

Is this mismatch because of unknown selection effects
OR because our galactic model is inadequate?

Extremely important to understand. Otherwise we can not expect to make useful comparisons!
K2: The concept

Kepler's Second Light: How K2 Will Work

1. Photons of sunlight exert pressure on the spacecraft. If properly positioned, the spacecraft can be balanced against the pressure much as a pencil can be balanced on your finger.

2. When the spacecraft is balanced, the telescope is stable enough to monitor distant stars in search of transiting planets. A specific portion of the sky is studied for approximately 83 days, until it is necessary to rotate the spacecraft to prevent sunlight from entering the telescope. There are approximately 4.5 viewing periods or campaigns per orbit or year.
K2: A new opportunity for Galactic Archaeology

Each campaign field: 10-30K stars observed for ~80 days
The K2 Galactic Archaeology Program (GAP)

**The thrust:** Use seismology of red giants (K2) combined with \( T_{\text{eff}} \) and \([\text{Fe}/\text{H}]\) (ground-based) to probe the structure of the Milky Way.
# K2 GAP targets so far

<table>
<thead>
<tr>
<th>Campaign</th>
<th>( N_{\text{targets}} )</th>
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<tr>
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<td>15</td>
<td>7625</td>
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<td>16</td>
<td>10672</td>
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\(~30-50\%\) of total K2 capacity

**Data download of seismic results:**
- **MAST:** [https://archive.stsci.edu/prepds/k2gap/](https://archive.stsci.edu/prepds/k2gap/)

**End of mission (C0-C19): \(~30-40k\) giants with seismic results**
# K2 GAP targets so far

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Ground-based spectroscopy/photometry ($T\text{\textit{eff}}$, [Fe/H], Abundances)

- **LAMOST** (no logo?)
- **Strömgren survey for Asteroseismology and Galactic Archaeology**

End of mission (C0-C19): ~30-40k giants with seismic results

~30-50\% of total K2 capacity
HERMES: A multi-object high-resolution spectrograph on the 4-m AAT (Australia). R=28,000, 350 stars per exposure (2 degree field).

K2-HERMES: Aims to obtain spectra of all stars selected by the `K2 GAP’ in the range 9 < V < 15 (within 1 degree of the centres of the K2 CCD modules).
K2-HERMES Status

Jun’17

K2 CCD module

Dense fields

Bright

10<V<13, 38644 stars

Faint

13<V<15, 47207 stars

Dense fields
K2-HERMES Status

Dec'16

K2 CCD module

Dense fields

K2 CCD module

Completeness

10<V<13, K2, 17984 stars

13<V<15, K2, 16315 stars

Jun'17

K2 CCD module

Dense fields

10<V<13, 38644 stars

13<V<15, 47207 stars

Bright

Faint
Reminder: What we want to address!

Not a good match in mass!

Model shows too low masses!

Is this mismatch because of unknown selection effects
OR because our galactic model is inadequate?

Extremely important to understand. Otherwise we cannot expect to make useful comparisons!
K2-HERMES results!

- Campaign 0
- Campaign 1
- Campaign 2
- Campaign 3
- Campaign 4
- Campaign 5
- Campaign 6
- Campaign 7
- Campaign 8
- Campaign 9
- Campaign 10
- Campaign 11
- Campaign 12
- Campaign 13
- Campaign 14
- Campaign 15
- Campaign 16
- Campaign 17
- Campaign 18
- Campaign 19

Fields:
- 2014 Fields
- 2015 Fields
- 2016 Fields
- 2017 Fields
- 2018 Fields
Comparison with Galaxia & K2-HERMES

Sharma, Stello, Bland-Hawthorn et al. in prep

New Galaxia model: Increased thick disk metallicity
Comparison with Galaxia & K2-HERMES

Sharma, Stello, Bland-Hawthorn et al. in prep

\[ \frac{M}{M_\odot} \approx \left( \frac{\nu_{\text{max}}}{\nu_{\text{max,\odot}}} \right)^3 \left( \frac{\Delta \nu}{\Delta \nu_\odot} \right)^{-4} \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{3/2} \]
Comparison with Galaxia & K2-HERMES

Reason for optimism that combining many K2 campaigns can constrain enough free parameters in the models to make meaningful comparisons with the data.

Sharma, Stello, Bland-Hawthorn et al. in prep

\[
\frac{M}{M_\odot} \approx \left( \frac{\nu_{\text{max}}}{\nu_{\text{max,\odot}}} \right)^3 \left( \frac{\Delta \nu}{\Delta \nu_\odot} \right)^{-4} \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{3/2}
\]
Large Area Survey of Bright Stars

- F, G, K stars: +4 to +12 magnitude
- “All sky” observations in 2 years:
  - > 200,000 target stars at <2 min cadence
  - > 20,000,000 stars in full frames at 30 min cadence
  - ~0.5-1.0 mio oscillating red giants

TESS: 2018-2020+
The TESS-HERMES Survey

Oberves all stars in the TESS continuing viewing zone within $10 < V < 13.1$ using the HERMES spectrograph.


MAST: https://archive.stsci.edu/prepds/tess-hermes/

THE TESS-HERMES SURVEY DATA RELEASE 1: HIGH-RESOLUTION SPECTROSCOPY OF THE TESS SOUTHERN CONTINUOUS VIEWING ZONE

SANJIB SHARMA,1 DENNIS STELLO,2,3,1 SVEN BUDER,5,7 JANET KOS,1 JOSS BLAND HAWTHORN,1 MARTIN ASPLUND, JANE LIN,6 KARIN LIND,4,7 MELISSA NESS,5 DANIEL HUBER,8,9,10,11 MARC HON,3 PRAJWAL R. KAHE,12 SHOURYA HAFIZ SADDON,2 BORJA ANGUIANO,13,14 ANDREW R. CASEY,15 KEN FREEMAN,6 SARAH MARTELL,2 GAYANDHI M. JEFFREY D. SIMPSON,16 ROB A. WITTENMYER,17 DANIEL B. ZUCKER,14,18,16 AND TOMAZ ZWITTER19
Deep Learning Classification in Asteroseismology

Marc Hon, 1* Dennis Stello, 1,2,3 and Jie Yu 2

1 School of Physics, The University of New South Wales, Sydney NSW 2052, Australia
2 Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia
3 Institute of Astronomy, Department of Applied Mathematics and Theoretical Physics, University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

<table>
<thead>
<tr>
<th>Dataset</th>
<th>CV (±1 std.)</th>
<th>Test</th>
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</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>0.982 ± 0.005</td>
<td>0.990</td>
</tr>
<tr>
<td>Precision</td>
<td>0.982 ± 0.005</td>
<td>0.990</td>
</tr>
<tr>
<td>Recall</td>
<td>0.982 ± 0.005</td>
<td>0.991</td>
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<tr>
<td>F1 Score</td>
<td>0.982 ± 0.005</td>
<td>0.991</td>
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<tr>
<td>ROC AUC</td>
<td>0.998 ± 0.002</td>
<td>0.996</td>
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<tr>
<td>Log Loss</td>
<td>0.055 ± 0.020</td>
<td>0.044</td>
</tr>
</tbody>
</table>

**Image Descriptions:**
- Binning input data for classification.
- Convolution and pooling layers for feature extraction.
- Fully-connected layers for prediction.
- Scatter plot of Δν vs. ΔP with predictions.
- Probability density distribution for age vs. Gyr.
- Confusion matrix comparing RGB predictions with real data.
AI-based classification on K2/TESS

- Kepler (4yr)
- TESS (1yr, best)
- K2/TESS (82days)
- TESS (27days, worst)

Changing length of time series

Deep Learning Classification in Asteroseismology: An Improved Neural Network, and Applications to K2 and TESS Data

Marc Hon,1* Dennis Stello,1,2,3 and Jie Yu2

1School of Physics, The University of New South Wales, Sydney NSW 2052, Australia
2Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia
3Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark
Next up: Detection or not?

Input 2D image

Activation layers
Summary

Can we make meaningful comparisons between data and Galaxy models?

It seems K2/Galah can show a path towards meaningful comparisons.

RGB/RC classifications works on TESS data; an important step for obtaining precise masses and ages!
A gala(h) of results expected from asteroseismic Galactic archaeology

Thank you!