High-frequency δ Scuti stars with TESS

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http://xkcd.com/26/
δ Scuti pulsators are common among A-type stars
δ Scuti stars are very good clocks!

Murphy et al. (2014, 2016a, 2016b, 2018)
A PLANET IN AN 840 DAY ORBIT AROUND A **KEPLER** MAIN-SEQUENCE A STAR FOUND FROM PHASE MODULATION OF ITS PULSATIONS

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A $12 M_{\text{Jup}}$ planet orbiting in or near the habitable zone of a main-sequence
Aims of asteroseismology:

1. fundamental properties of stars (masses, radii, ages)
2. probe stellar interiors in exquisite detail (convective overshoot, nuclear burning, internal rotation, magnetic fields)
solar-like oscillations: 16 Cyg A (*Kepler*)

labels are $\ell$ values (angular degree)

Garcia & Ballot (2019)
$\ell = 0$ (radial modes)

\[a) \ell = 1 \quad d) \ell = 2\]
p-mode oscillations are standing sound waves

$n = 1$

$n = 2$

$n = 3$

$n$ is the radial order of the overtone

$n = 20$
astroseismology needs mode identification for comparison with theoretical models

16 Cyg A: Metcalfe et al. (2016)

Garcia & Ballot (2019)
Why is mode identification so difficult in δ Scuti stars?

- not all modes excited
- rotation (+ ellipsoidal shape) spoil regular patterns
- (so do avoided crossings of mixed modes)
A typical Sun-like star

White et al. (2012)

\[ \ell = 2 \]
\[ \ell = 0 \]
\[ \ell = 1 \]

\[ n = 16 \]
\[ n = 17 \]
\[ n = 18 \]
\[ n = 19 \]
\[ n = 20 \]

KIC 6933899 ("Fred")

\textit{Échelle} diagram using \textit{lightkurve}

\[ \ell = 1 \]
\[ \ell = 0 \]
\[ \ell = 1 \]
TESS short-cadence data (Sector 5)
High-frequency A-type pulsators discovered using SuperWASP


about 1/3 observed with TESS 2-minute cadence
TESS 2-minute data

HD 28548

TESS 2-minute data

HD 44726
KIC 6933899 ("Fred")
Sun-like star

$\ell = 2$
$\ell = 0$
$\ell = 1$

$\ell = 2$
$\ell = 0$
$\ell = 1$

MESA model mass = 1.56

we can assign $n$ and $l$ to the modes 😊

HD 28548
$\delta$ Scuti star

$n = 22$
$n = 21$
$n = 20$
$n = 19$
$n = 18$
$n = 17$
$n = 16$
$n = 15$
$n = 14$
$n = 13$

$n = 10$
$n = 9$
$n = 8$
$n = 7$
$n = 6$
$n = 5$
$n = 4$
$n = 3$
$n = 2$
$n = 1$
radial fundamental ($\ell=0$, $n=1$)
weak high-frequency peaks excited by turbulent pressure? (Antoci et al 2014)

Nyquist frequency (30 minutes)
Finding more stars

- downloaded all TESS short-cadence data (Sectors 1 to 9; PDC-MAP)
- computed amplitude spectrum
- considered distribution of peak heights above 30 c/d; measure skewness (3rd moment; Murphy et al 2019)
- inspected échelle diagrams
- also looked at Kepler δ Scutis with short-cadence data
- total 60 stars so far
Finding $\Delta v$

<table>
<thead>
<tr>
<th>Frequency (d$^{-1}$)</th>
<th>Frequency mod $\Delta v$ (d$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
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<td>6</td>
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</tbody>
</table>

OH, HEY, YOU ORGANIZED OUR PHOTO ARCHIVE!

YEAH, I TRAINED A NEURAL NET TO SORT THE UNLABELED PHOTOS INTO CATEGORIES.

WHOA! NICE WORK!

ENGINEERING TIP: WHEN YOU DO A TASK BY HAND, YOU CAN TECHNICALLY SAY YOU TRAINED A NEURAL NET TO DO IT.
Finding $\Delta v$

- **Finding $\Delta v$**

- **Diagram**

- **Comic**

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  "YEAH, I TRAINED A NEURAL NET TO SORT THE UNLABELED PHOTOS INTO CATEGORIES."

  "WHOA! NICE WORK!"

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OH, HEY, YOU ORGANIZED OUR PHOTO ARCHIVE!

Yeah, I trained a neural net to sort the unlabeled photos into categories.

Whoa! Nice work!

Engineering tip: When you do a task by hand, you can technically say you trained a neural net to do it.
Δν varies with frequency
TESS short-cadence data (Sector 5)
HR diagram (Gaia DR2) – these are young stars
some more complex patterns:
some more complex patterns:
some more complex patterns:

rotation
Young associations

• used *Gaia* DR2 space motions
• cross-matched with known moving groups, clusters and stellar streams:
  – 5 in associations: Octans (3), Carina
  – 1 in moving group: β Pic
  – 1 in stellar stream: Pisces-Eridanae (HD 31901)
Pisces-Eridanae stellar stream
What next?

- can finally do detailed asteroseismology of (some) δ Scuti stars
- compare with models: ages and internal rotation
- TESS is observing many at 2-minute cadence - and even more when FFI long cadence is shortened to 10 minutes
Asteroseismology of $\delta$ Scuti pulsators is difficult!

Breger et al. (2005)

Murphy et al. (2014)
Some δ Scutis are simple

- both radial ($\ell=0$)
- fundamental ($n=1$) & 1st overtone ($n=2$)

Petersen Diagram:
OGLE data for the LMC
(Poleski et al. 2010)

Antoci et al. (2019)
TESS - SX Phe
V435 Car

V349 Pup & V435 Car

\[ \ell = 0 \quad \ell = 1 \]
These are *not* solar-like oscillations:
- much higher amplitude
- much lower $n$ (do not obey the same $\nu_{\text{max}}$ scaling relation)
Δν varies with frequency

Pairwise differences (μHz)
\[ \Delta v \propto 0.85 \rho^{0.5} \]

\[ \Delta v \propto \rho^{0.5} \]
Rotation

• obtained high-resolution spectra of 14 stars with Keck/HIRES and LCO/NRES
• plus published $v \sin i$ for 5 stars
• more than half $v \sin i$ values below 70 km/s
• implies some (but not all) are seen close to pole-on
• also lots are $\lambda$ Boo stars