COMBINING ASTEROSEISMOLOGY AND EXOPLANETS
PLATO MISSION CONFERENCE 2017
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JAN HENDRIK OORT FELLOW – LEIDEN OBSERVATORY
Exoplanet person surrounded by asteroseismologists...

WHAT ASTEROSEISMOLOGY CAN DO FOR EXOPLANETS: KEPLER-410A b IS A SMALL NEPTUNE AROUND A BRIGHT STAR, IN AN ECCENTRIC ORBIT CONSISTENT WITH LOW OBLIQUITY

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Turns out people were thinking about this for 30 years!

PLAnetary Transits and Oscillations of stars (PLATO) is the third medium-class mission in ESA's Cosmic Vision programme. Its objective is to find and study a large number of extrasolar planetary systems, with emphasis on the properties of terrestrial planets in the habitable zone around solar-like stars. PLATO has also been designed to investigate seismic activity in stars, enabling the precise characterisation of the planet host star, including its age.
What asteroseismology can do for exoplanets

Accurate planet parameters, through accurate stellar parameters (Including planet validation!)

1. Stellar obliquities, through rotational splittings
2. Orbital eccentricities, through mean stellar densities
3. Evolution of planetary systems, through e.g., tides

All have given exciting results with Kepler/K2, and will be order(s) of magnitude better with PLATO.
What asteroseismology can do for exoplanets

Accurate planet parameters, through accurate stellar parameters (Including planet validation!)

But also:

1. Stellar **obliquities**, through rotational splittings
2. Orbital **eccentricities**, through mean stellar densities
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How to explain observed stellar obliquities?

*Courtesy Josh Winn*

Hot Jupiters display a wide range of obliquities, e.g.:
- Winn et al. 2010
- Schlaufman 2010
- Hébrard et al. 2011
- Albrecht et al. 2012
How to explain observed stellar obliquities?

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Hébrard et al. 2011
Albrecht et al. 2012

- Planetary migration?
  (e.g. Rasio & Ford 1996, Matsumura et al. 2010, Fabrycky & Tremaine 2007)

- Primordial star-disk misalignment?
  (e.g. Bate et al. 2010, Thies et al. 2011, Batygin 2012)

x ⇒ Obliquity measurements in multi-(small-)planet systems
Example: multi-planet system Kepler-410
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Time series $\Rightarrow$ power spectrum.
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Time series \implies power spectrum.
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Time series $\Rightarrow$ power spectrum.
Obliquities?

Albrecht et al. 2013
Obliquities?

1. Single-planet systems (grey): a wide range
2. Multi-planet systems (color): flatter obliquity distribution (?)
   Green points from asteroseismology! Waiting for PLATO...

Ensemble studies: e.g. Morton & Winn 2014, Mazeh et al. 2015, Campante et al. 2016

Albrecht et al. 2013, adapted by Huber 2017, including data from Sanchis-Ojeda et al. 2012, Hirano et al. 2012
Chaplin et al. 2013, Huber et al. 2013, Van Eylen et al. 2014, Benomar et al. 2014
Eccentricities from RV detections from exoplanets.org (27 April '15).
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Eccentricities?

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How to observe eccentricity?

![Diagram showing the observation of eccentricity with time and radial velocity](image)

1. Define the time intervals for observation.
2. Measure the radial velocity at specific points in time.

| Time | Radial Velocity [m/s] |
|------|-----------------------|
| 1    | +                     |
| 2    | -                     |
How to observe eccentricity?

| Time | Radial Velocity [m/s] |
|------|-----------------------|
| 1    | +1                   |
| 2    | -2                   |
Small planets: no RV possible. Eccentricity?
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- Occultation timing (Shabram et al. 2015)
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- Occultation timing (Shabram et al. 2015)
- **Transit durations**!

\[ \text{Transit duration} \propto \rho^* \left(1 + e \sin \omega \right) \frac{3}{2} \frac{1 - e^2}{2} \Rightarrow \text{measure the stellar density} \rho^* \text{ (asteroseismology)} \Rightarrow \text{marginalize over unknown orientation} \omega \]
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- Transit timing variations (e.g. Hadden & Lithwick 2014)
- Occultation timing (Shabram et al. 2015)
- **Transit durations!**

Transit duration \( \propto \rho_\star \frac{(1+e \sin \omega)^3}{(1-e^2)^{3/2}} \)

⇒ *measure* the stellar density \( \rho_\star \) (asteroseismology)
⇒ *marginalize* over unknown orientation \( \omega \)
28 multi-planet systems with 74 planets ($\rho_*$ from Huber et al. 2013, Silva Aguirre et al. 2015)
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Rayleigh distribution with $\sigma = 0.049 \pm 0.013$
50 single transiting planets ($\rho_\star$ from Lundkvist et al. 2016)

Rayleigh distribution with $\sigma = 0.36 \pm 0.11$
(Some) single transiting planets have higher eccentricity.

Van Eylen et al. 2017, in prep.

“Two types” of planetary systems (“Kepler dichotomy”)? Non-transiting inclined planets? Perturbing giants?

Waiting for PLATO bright stars...
What about tides?
What about tides? Eccentricity of binary stars!

Van Eylen, Winn & Albrecht 2016
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What about tides? Eccentricity of binary stars!

Van Eylen, Winn & Albrecht 2016, ApJ

Winn et al. 2010, Albrecht et al. 2012
What about tides? Eccentricity of binary stars!

Van Eylen, Winn & Albrecht 2016, ApJ
Winn et al. 2010, Albrecht et al. 2012

Hot (radiative) stars are slow to circularize (binary) or align (planets).

Limitation: evolutionary state of stars? Awaiting PLATO...
Few short-period planets orbit evolved stars
e.g. Bowler et al. 2010, Johnson et al. 2010, Reffert et al. 2015
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1 Tidal destruction: As stars evolve, short-period planets are destroyed.

e.g. Rasio et al. 1996, Villaver & Livio 2009, Schlaufman & Winn 2013
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Spectroscopic mass? ⇒ asteroseismology! see e.g. Hjørringgaard et al. 2017, Stello et al. 2017
K2-39: evolved subgiant with 4.6 day period planet?!

![Graph showing relative flux and O - C values over time.](image-url)
K2-39: evolved subgiant with 4.6 day period planet?!

See also KESPRINT talk by Csizmadia!
If tides destroy planets around evolved stars: closest-in planets least likely to exist/survive

- K2-39b: $t \approx 10,000$ yr
- Period decay: $\dot{P} \approx 40$ sec/yr (Currently: $\dot{P} < 37$ min/yr)

Waiting for PLATO to revisit systems... Waiting for PLATO to detect period decay...

Van Eylen et al. 2016c
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Waiting for PLATO to revisit systems...
Waiting for PLATO to detect period decay...
PLATO Science Goals

Asteroseismology-planet results from Kepler/K2:

1. **Uniqueness of our Solar System**: eccentricities, obliquities, multi-planets
   
   *e.g. Huber et al. 2013, Van Eylen et al. 2014, Lund et al. 2014, Van Eylen & Albrecht 2015, Campante et al. 2016*

2. **Interiors of Terrestrial and Gas Planets**: radius gap
   
   *e.g. Lundkvist et al. 2016, Fulton et al. 2017, Van Eylen, Agentoft et al. submitted*

3. **Evolution of Planetary Systems**: planets on sub(giants), white dwarfs
   
   *e.g. Grunblatt et al. 2016, Van Eylen et al. 2016b, 2016c, van Sluijs & Van Eylen 2017 (in prep.)*

4. **Planetary Atmospheres and Star-Planet Interactions**: tidal alignment, orbit decay, binary stars
   
   *e.g. Lillo-Box et al. 2014, Van Eylen et al. 2016a (binary stars), Van Eylen et al. 2016c*

5. **Structure and Evolution of the Milky Way**: galactic archaeology
   
   *e.g. Miglio et al. 2013, Casagrande et al. 2014, Stello et al. 2017, Silva Aguirre et al. 2017*

We will do order(s) of magnitude better with PLATO!
Extra slides
Photo-evaporation of close-in planets?

Lundkvist et al. 2016
Photo-evaporation of close-in planets?

Fulton et al. 2017
Photo-evaporation of close-in planets?

Van Eylen, Agentoft, Lundkvist et al. 2017, submitted
Photo-evaporation of close-in planets?

Fulton et al. 2017
Photo-evaporation of close-in planets?

Van Eylen, Agentoft, Lundkvist et al. 2017, submitted
Eccentricity of planets without RV

1. $\rho_*$ from transit duration ($T$) 
   \textit{(assuming a circular orbit)}
   - $T \propto R_*/a$
   - $R_*/a \propto \rho_*$ (from Kepler’s law)

2. $\rho_*$ from asteroseismology
   - Directly from large frequency separation: $\Delta \nu \propto \sqrt{\rho_*}$
   - Easiest to determine!

See e.g.: Seager and Mallén-Ortiz 2003, Ford et al. 2008, Dawson & Johnson 2012, Kane et al. 2012, Kipping 2014, Plavchan et al. 2014, Price et al. 2015, Van Eylen & Albrecht 2015
Eccentricity of planets without RV

1. $\rho_\star$ from transit duration ($T$) 
   *(assuming a circular orbit)*
   - $T \propto R_\star/a$:
   - $R_\star/a \propto \rho_\star$ (from Kepler’s law):

2. $\rho_\star$ from asteroseismology
   - Directly from large frequency separation: $\Delta \nu \propto \sqrt{\rho_\star}$
   - Easiest to determine!

IF $1 \neq 2$: eccentric orbit

$\rho_{\star,\text{transit}} \neq \rho_{\star,\text{seismo}} \Rightarrow$ eccentricity, BUT:
   - angle of periastrion $\omega$?
   - impact parameter $b$?
   - transit timing variations?
   - false positives, ...?

See e.g.: Seager and Mallen-Ornélas 2003, Ford et al. 2008, Dawson & Johnson 2012, Kane et al. 2012, Kipping 2014, Plavchan et al. 2014, Price et al. 2015, Van Eylen & Albrecht 2015
Observable: **transit duration** or **density ratio**

\[
\frac{\rho_*}{\rho_{*,\text{transit}}} = \frac{(1-e^2)^{3/2}}{(1+e \sin \omega)^3}
\]

Angle \(\omega\) is unknown.
Changing the impact parameter can also change the duration...
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... but often also affects the shape.
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... but often also affects the shape.

Eccentricity does not.
And transit timing variations (TTV) can complicate this:

| No TTV | TTV |
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No TTV

TTV
And transit timing variations (TTV) can complicate this:

**No TTV**

**TTV**
And transit timing variations (TTV) can complicate this:

No TTV

TTV

Sum:

Sum:
Some ‘singles’ have TTVs or RV companions.

Van Eylen et al. 2017, in prep.
Half have companion stars, but no clear trend.

Companion data from Furlan et al. 2017; Van Eylen et al. 2017, in prep.

See Mann et al. 2017, binary stars higher eccentricity?
A few singles have inclination measurements + eccentricity.

Van Eylen et al. 2017, in prep., with obliquities from Hirano et al. 2012, 2014
Morton et al. 2014, Van Eylen et al. 2014, Quinn et al. 2015, Campante et al. 2016
Temperature detection bias?

![Graph showing the relationship between period (in days) and effective temperature (in K). The x-axis represents Teff [K] ranging from 4900 to 6500, and the y-axis represents period ranging from 10 to 10^2. The graph contains two sets of data points: one set depicted with red triangles representing data points from the first study, and the other set with gray squares representing data points from the second study. The graph shows a positive correlation between the period and Teff, with data points clustering around the line of best fit.]
Temperature detection bias?