Getting More Out of Information-rich Kepler Multis that Show Transit Timing Variations

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Kepler Science Conference V
Getting More Out of Information-rich Kepler Multis that Show Transit Timing Variations
Outline

• Introduction
• Transit Timing Variations
• Photodynamical Modeling
• Future Plans
Multi-transiting systems are the most information-rich exoplanetary systems, combining the value of physical characterization with orbital architecture.

Ragozzine & Holman 2010
Multi-Transiting Systems in 2008

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Kepler Multi-Transiting Systems
Planet-Planet Interactions → Masses

- Star+Planet 2-body model = perfectly periodic transits
- Gravitational interactions between planets cause planets to transit early or late → masses → composition, habitability
- Fit transit times for each transit, measure deviation from periodic: *Transit Timing Variations (TTVs)*
Review of TTV results

- Kepler-9
- RV and TTV mass comparisons make sense, no fundamental issue with either method
- TTVs on individual stars: masses of small planets around faint stars
- Series of TTV Catalogs, ending with Holczer et al. 2016
- Dynamical fits of
- Kane, Ragozzine et al. 2019 out on arXiv today (1903.02336) did a visual inspection of all TTVs and discussed results
**Kepler-9**

The First System of Multiple Transiting Planets, Confirmed by Timing Variations

**Kepler-9c**
- 38.9-day period

**Kepler-9b**
- 19.2-day period

Super-Earth Candidate
- 1.6-day period

Image: NASA/Kepler/Darin Ragozzine
No fundamental tension between RV and TTV

Borsato et al. 2019
TTV Results

- Series of TTV Catalogs starting with Ford et al. 2010 and most recent is Holczer et al. 2016
- Tons of fits to individual planets
- Some ensemble TTV fits like Hadden & Lithwick 2017
Kane, Ragozzine et al. 2019 (arXiv)

- Visual inspection of all TTV curves
- Computer missed a few interesting cases
- TTV Demographics
Visual inspection of all TTV curves

Computer missed a few interesting cases

TTV Demographics

Some TTVs in multis are caused by non-transiting planets

Lots of weak TTV systems

All TTV plots available at haumea.byu.edu/kanettv

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>TTVs</th>
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<tbody>
<tr>
<td>1</td>
<td>Very Strong</td>
</tr>
<tr>
<td>2</td>
<td>Strong</td>
</tr>
<tr>
<td>3-4</td>
<td>Mild</td>
</tr>
<tr>
<td>5-7</td>
<td>None</td>
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Kane, Ragozzine et al. 2019 (arXiv)

- Distribution of TTVs
- All TTV plots available at haumea.byu.edu/kanettv
The Exoplanet Mass-Radius Diagram

• At a given mass/radius, you CANNOT predict a specific planet property
  - There is no “Main Sequence” for planets

• Smaller planets are rocky/iron, larger planets often have H/He
Areas of Improvement (1/3)

1) TTVs add an intermediate step, fits are not self-consistent
Areas of Improvement (2/3)

2) If the planet is small, can’t measure individual times!

Carter & Agol 2012

IF THERE’S NO TRANSIT TIME

IS THE TRANSIT ON TIME?
Areas of Improvement (3/3)

3) Use Short Cadence data
   • Kepler had a 1-minute “Short Cadence” mode, but could only use it on 500 stars
   • Kepler-19 by Ballard et al. 2011
Areas of Improvement (3/3)

- Price & Rogers 2014, SC improvement independent of transit SNR
Areas of Improvement (3/3)

• Kepler TTV SC Czar worked hard to get best ~200 TTV cases every quarter

3) Use SC data... but no catalog!
Photodynamical Modeling

- Issues: 1) not self-consistent, 2) no TTVs for small planets, 3) no SC TTV Catalog
- Solution: photodynamical modeling, including SC data
Photodynamical Modeling

- Has been used for some individual interesting systems, e.g., Kepler-444 by Mills & Fabrycky 2017
- New public tool: PhoDyMM (PhotoDynamical Multi-planet Model)
- Github: https://github.com/dragozzine/PhoDyMM
PhoDyMM

Example: Kepler-18

Similar to prior
Ensemble Studies

- No homogeneous mass measurement catalog from powerful TTVs
  - Basically no information on upper limits and non-detections
- Can’t understanding the underlying mass-radius relationship without homogeneous catalog
<table>
<thead>
<tr>
<th>Principal Investigator</th>
<th>E-mail Address</th>
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<tbody>
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<td></td>
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**PHODYMM ALL THE MULTIS!**

**THANKS NASA ADAP**
Future Work

- Apply PhoDyMM to all 700+ Kepler multi-planet systems!
- Homogeneous catalog of posterior distributions for ensemble studies
- Best-data catalog of posterior distributions for individual systems
- Anticipate meaningful mass improvements for ~50 small planets
Conclusions
Darin Ragozzine

- Planet-planet interactions cause TTVs which allow us to measure masses → compositions, habitability
- New photodynamical model (PhoDyMM) overcomes limitations of TTV method
- Working on applying photodynamical model to all 700 Kepler multis to get many more small planet densities