Planetary System Architectures & Formation

Science Conference V: A Decade of Kepler

Lauren Weiss
Parrent Fellow
University of Hawaii
Architecture of the Solar System

Inclinations < 7 degrees
Eccentricities ~ 0

Terrestrial planets close to the star

Gas giants beyond the “snow-line”
How did the solar system form?

Inclinations < 7 degrees
Eccentricities ~ 0

Terrestrial planets close to the star
Gas giants beyond the “snow-line”
Before Kepler, we thought...

Protoplanets formed by core accretion

- Dust grains
- Pebbles
- Planetesimals
- Protoplanets
Before Kepler, we thought...

The giant planets formed by core accretion in a gas disk
Before Kepler, we thought...

Terrestrial planets formed by oligarchic growth + giant impacts

a) A few $10^5$ yrs

b) A few $10^6$ yrs
Gas disk depleted
Small planetesimals accreted

c) Orbit crossing and giant impact stage

d) A few $10^7$ yrs
Final state
Kepler has changed how we think about planetary system architectures and planet formation.
Circumbinary planets

misaligned planetary systems

Compact multi-planet systems

Doyle+11
Welsh+12
Huber+13
Lissauer+11
Kepler discovered that multi-planet systems are common
Kepler’s compact multis inspired new* theories of planet formation

Type I Migration: gas torques the planet and moves its orbit radially

Pebble formation: Seeds of small planets aggregate beyond the snow line & migrate inward

Protoplanetary disk

Snow line

Liquid water

Icy zone

Armitage

Drazkowska & Alibert (2017)
We can test planet formation theories by finding patterns in planetary architectures.

Patterns in the host stars?

Patterns in system-wide distributions (e.g., $e$ dispersion, mutual $i$ dispersion)?

Planet-to-planet patterns (e.g., radius ratio, period ratio)?
We can test planet formation theories by finding patterns in planetary architectures.
The California Kepler Survey:

Precise stellar & planet properties of 2025 Kepler planets transiting 1305 F, G, K stars

Petigura+17, Johnson+17 (Keck-HIRES spectra only)
Fulton+18 (Keck-HIRES + Gaia)

Also: LAMOST survey (Xie+16), asteroseismology (e.g., Huber+14), Gaia (Berger+18)
Nomenclature:

“Multi” = system with multiple observed, transiting planets

“Single” = system with only one observed, transiting planet
  (non-transiting planets could be present!)
(Anti)-Pattern 1: Host star masses, metallicities, vsini, log(g) are indistinguishable for singles vs. multis.

- **CKS**: Singles vs. Multis
  - Mass (M$_\odot$): $p = 0.47$
  - [Fe/H]: $p = 0.29$
  - vsini [km/s]: $p = 0.83$

- **Weiss+18b (CKS)**: Singles vs. Multis
  - Log(g): $p = 0.145$

- **Xie+16 (LAMOST)**: Singles vs. Multis
  - Mass (M$_\odot$): KS: $p = 0.353$
  - [Fe/H]: KS: $p = 0.452$
Do M dwarfs have too many singles?

Ballard & Johnson '16: yes

Gaidos+16: no

See poster by Jon Zink for FGK stars! (Zink+18)
We can test planet formation theories by finding patterns in planetary architectures.

Patterns in system-wide distributions (e.g., eccentricities, inclinations)?
Kepler Singles & Multis have similar distributions in \((R_p, P)\)

also: Steffen & Coughlin (2016)
Pattern 2: Both singles and multis have a gap in the planet radius distribution at ~1.8 $R_e$.

Conclusion: most of the “singles” and “multis” likely had a common origin & arrived in their present locations in the first ~100 Myr.
Dynamical information from transit durations

$T_0 = f(\rho_\star, P)$

Transit near periapse:
$V > V_{\text{circ}}$
$T < T_0$

Transit near apoapse:
$V < V_{\text{circ}}$
$T > T_0$

Orbital plane of planet b

Dawson & Johnson (2012)
Kipping (2013)
Pattern 3: Apparent “singles” have higher eccentricities than multis

Also: Van Eylen+19 (asteroseismology)
Pattern 4: The singles with the highest eccentricities are around high-metallicity stars
Pattern 5: The majority of the Kepler multis are nearly coplanar

If coplanar: Projected chord length shortens as orbital period increases

Fang & Margot 2012:
85% of Kepler exoplanet systems have mutual inclinations of < 3 degrees
Pattern 6: The shortest-period planets have the highest mutual inclinations

The diagram shows a scatter plot with the x-axis representing the semi-major axis ratio $a/R_\star$ of the innermost planet and the y-axis representing the inclination difference $\Delta I$ in degrees. The plot includes data points from different models (power-law and two-zone) and observations from LC and SC. The text indicates that the inclinations span a possible region, with the transits possible and more coplanar than necessary for detection.
There is an excess of short-period singles with $P < 3$ days ($p=0.001$)

also: Steffen & Coughlin (2016)
Systems with ultra-short period planets likely had dynamically exciting lives

**Theory papers:**
- Petrovich+18 — secular chaos (high-eccentricity migration)
- Pu+18 — low eccentricity migration via planet-planet scattering
We can test planet formation theories by finding patterns in planetary architectures

Planet-to-planet patterns (e.g., radius, period)
California Kepler Survey
Systems with 4 or more transiting planets
(Grad students only): Do you see any patterns?
Do you see any patterns?

Planets in the same system often have:

- **Similar Sizes**
- **Regular Spacing**

_Similar Sizes & Regular Spacing_

*Weiss+18a*

- $1 \ R_\odot$
- $3 \ R_\odot$
- $10 \ R_\odot$

_Also: Lissauer+11, Titius & Bode_
Do you see any patterns?

Pattern 7: Planets in the same system often have Similar Sizes

Weiss+18a
The sizes of planets in the same system are correlated (504 adjacent pairs).
Do you see any patterns?

Pattern 8: Planets in the same system often have

Regular Spacing

Weiss+18a
The orbital period ratios of planets in the same system are correlated (165 triples)
(Anti)-Pattern 9: Kepler multis are not preferentially in mean motion resonance

See Jack Lissauer's talk!
See Sarah Millholland's Talk!
Is there a connection between planet size and spacing?

Do you see any patterns?
Pattern 10: The spacing and size of a pair of planets are correlated
Did most Kepler planetary systems start as peas in a pod?
Clues from oligarchic growth

Lissauer & Stewart (1993):

The self-limiting nature of runaway growth strongly implies that massive protoplanets form at regular intervals in semimajor axis.

Kokuba & Ida (1998):

We have shown the oligarchic growth of protoplanets in the post-runaway stage. Protoplanets with the same order masses with the orbital separation larger than about $5r_H$ is the inevitable outcome of planetary accretion in the post-

Kepler multis = aged oligarchs with few/gentle giant impacts?
Similar Planet Masses in 37 Multis with Transit Timing Variations (TTVs)

TTV dynamics are powerful!
See Darrin Ragozzine’s talk
TESS multis so far: peas in a pod prevail!

Thanks to TESS exofop!

<table>
<thead>
<tr>
<th>STAR</th>
<th>$M_{Tess}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOI 402</td>
<td>8.3</td>
</tr>
<tr>
<td>TOI 174</td>
<td>8.7</td>
</tr>
<tr>
<td>TOI 119</td>
<td>9.2</td>
</tr>
<tr>
<td>TOI 175</td>
<td>9.4</td>
</tr>
<tr>
<td>TOI 125</td>
<td>10.1</td>
</tr>
<tr>
<td>TOI 178</td>
<td>10.4</td>
</tr>
<tr>
<td>TOI 270</td>
<td>10.4</td>
</tr>
<tr>
<td>TOI 256</td>
<td>11.2</td>
</tr>
<tr>
<td>TOI 216</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Period (days)
Patterns in planetary architectures:

Patterns in system-wide distributions:
- All planet multiplicities consistent with a gap at 1.8 Re
- Singles have higher average eccentricities than multis
  - The highest-eccentricity singles are around metal-rich stars
- Multi-planet systems are mostly dynamically cool
  - The shortest-period planets have the highest mutual inclinations

Patterns in the host stars?
- No/Inconclusive

Planet-to-planet patterns:
- Similar sizes in the same system—maybe masses & compositions too?
- Regular, non-resonant spacing
- Spacing is related to size — fossil of oligarchic growth?

We can test planet formation theories by finding patterns in planetary architectures.