The Legacy of Kepler and K2: The Follow-up Observation Programs

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415 Known Exoplanets Prior to Kepler
58 Transiting Exoplanets Prior to Kepler
[Transit + RV Detection]
Kepler Opened Up a New Parameter Space
As We Push to Smaller Planets In Longer Orbits, Direct Confirmation becomes harder

~90% have K-amplitudes < 2 m/s

(~10% of Kepler Planets have mass estimates)
Astrophysical False Positives Abound

“Validate” by statistical elimination of Astrophysical False Positives

Kepler-9: Torres et al. 2011

Talk by T. Morton
Light Curves are but the First Step

• Follow-up was no longer about direct RV detections and mass determinations of the transiting object
• Ground-based follow-up programs
  • Characterize the star
  • Vet Astrophysical False Positives
  • Validate Kepler’s Planetary Candidates
• Contributions from the world-wide community
  • Imaging, Spectroscopy – all contributed to the effort!
Follow-up was no longer about direct RV detections and mass determinations of the transiting object.

Ground-based follow-up programs:
- Characterize the star
- Vet Astrophysical False Positives
- Validate Kepler’s Planetary Candidates

Contributions from the world-wide community:
- Imaging, Spectroscopy – all contributed to the effort!

Light Curves are but the First Step.
A Tale of Two Follow-Up Programs

- Project produced light curves and planetary candidates
- Small, dedicated project funded follow-up program
- Community contributions

- Community-only light curves and planetary candidates
- No funded project follow-up program
- Only community driven observations
Planet Radii From Transit Depths

\[ \delta_o = \left( \frac{R_p}{R_{t\star}} \right)^2 \]
Good Stellar Spectroscopy is Crucial

Teff, [M/H], log(g) $\rightarrow$ R$_{\star}$ $\rightarrow$ R$_p$

Kepler-21

Howell et al. 2012

KIC R$_{\star}$ = 1.1 R$_{\odot}$ $\rightarrow$ R$_p$ = 1.0 Re

True R$_{\star}$ = 1.8 R$_{\odot}$ $\rightarrow$ R$_p$ = 1.6 Re

Howell et al. 2011
Spectroscopic Parameters

- Kepler FOP had dedicated effort to observe as many of the KOIs as possible in a uniform manner
- >2700 KOIs were observed with many more done by the general community
- 615 common set of “standards” with parameters from seismology to connect the different facilities
- Characterized differences and limitations of different datasets

KeplerSciConV
Furlan, Ciardi, et al. 2018
Combined FOP Data with Community Efforts

Mathur et al. 2017
Gaia Taking It to the Next Level

Berger et al. 2018
But, It’s More Complicated ...

\[ \delta_o = \left( \frac{F_t}{F_{total}} \right) \left( \frac{R_p}{R_{t*}} \right)^2 \]
Underestimate Planet Radius From Blends

\[ X_R \equiv \frac{R_p(\text{true})}{R_p(\text{observed})} = \sqrt{\frac{F_{\text{total}}}{F_1}} \]

Ciardi et al. 2015
If the planet orbits the companion?

\[ X_R = \frac{R_p(\text{true})}{R_p(\text{observed})} = \left( \frac{R_{1*}}{R_{1*}} \right) \sqrt{\frac{F_{\text{total}}}{F_t}} \]

- Planet Orbits Secondary Star
- Planet Orbits Primary Star

Ciardi et al. 2015

Primary - Secondary Brightness Difference [Δmag]
## KOI2626: HZ Earth-sized Planet

<table>
<thead>
<tr>
<th>KOI List: Single Star</th>
<th>Stellar Temperature and Radius</th>
<th>Planet Radius</th>
<th>Equilibrium Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3480 K 0.35 R_{Sun}</td>
<td>1.12+/−0.16 Re</td>
<td>229 K (0.7 S_{0})</td>
</tr>
</tbody>
</table>

*Cartier, (Ciardi), et al. 2015*
KOI2626: HZ Earth-sized Planet ... TO NOT

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<td>3480 K 0.35 $R_{\text{Sun}}$</td>
<td>1.12+/-0.16 Re</td>
<td>229 K (0.7 $S_0$)</td>
</tr>
<tr>
<td>Component A</td>
<td>3650 K 0.48 $R_{\text{sun}}$</td>
<td>2.04+/-0.33 Re</td>
<td>265 K (1.17 $S_0$)</td>
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<tr>
<td>Component B</td>
<td>3520 K 0.42 $R_{\text{sun}}$</td>
<td>2.37+/-0.44 Re</td>
<td>244 K (0.84 $S_0$)</td>
</tr>
<tr>
<td>Component C</td>
<td>3400 K 0.32 $R_{\text{Sun}}$</td>
<td>2.58+/-0.62 Re</td>
<td>217 K (0.52 $S_0$)</td>
</tr>
</tbody>
</table>

*Cartier, (Ciardi), et al. 2015*
Imaging to Find Companions

- Kepler FOP had dedicated optical and NIR high resolution imaging programs
- Direct contributions from outside non-funded community members
- ~100% of the KOIs were observed with at least one technique

Plenty Of Community contributions

• Unfunded Community Members who just did stuff (too many to list!)
  • Spectroscopy
  • Radial velocity
  • Imaging
  • Asteroseismology
  • TTVs
  • Etc ...

• Groups contributed their data to the effort and often worked with the funded team

• This was all enabled because the candidates were made available to the public!
A Tale of Two Follow-Up Programs

- **Kepler**
  - Project produced light curves and planetary candidates
  - Small, dedicated project funded follow-up program
  - Community contributions

- **K2**
  - Community-only light curves and planetary candidates
  - No funded project follow-up program
  - Only community driven observations
K2: The Wild West ...

- Community self-organized into loose collaborations with some overlap
- Individual groups were competing for the same resources and duplicating effort
- After the first year, competitive groups started to merge and work together
- Groups began to share data and work collaboratively
Community Shared Their Data

### ExoFOP-Kepler Statistics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Number of uploaded files</td>
<td>110,466</td>
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<tr>
<td>Number of stellar parameters</td>
<td>25,763</td>
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<tr>
<td>Number of planet parameters</td>
<td>127</td>
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<tr>
<td>Number of observing notes</td>
<td>14,986</td>
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<tr>
<td>Number of spectroscopy observations</td>
<td>8,253</td>
</tr>
<tr>
<td>Number of imaging observations</td>
<td>7,884</td>
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### K2FOP Statistics

<table>
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<tr>
<th>Metric</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
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<td>580,133</td>
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<tr>
<td>Number of stellar parameters</td>
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<tr>
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<td>Number of observing notes</td>
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<tr>
<td>Number of spectroscopy observations</td>
<td>1,710</td>
</tr>
<tr>
<td>Number of imaging observations</td>
<td>2,201</td>
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</tbody>
</table>

[Go to ExoFOP-Kepler >>] [Go to ExoFOP-K2 >>]
A True Legacy of the Kepler/K2 FOP: Social Change

- TESS Follow-Up Observation Program has engaged the community from the beginning → Open to Everyone
- Almost 300 community members
- Organized into sub-groups
  - Time Series Photometry
  - Spectroscopy
  - Imaging
  - Radial Velocity
  - Characterization (RV, Atmospheres)

### TESSFOP Statistics

<table>
<thead>
<tr>
<th>Observations</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of uploaded files</td>
<td>9,607</td>
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<tr>
<td>Number of stellar parameters (including mags)</td>
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<tr>
<td>Number of planet parameters</td>
<td>0</td>
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<tr>
<td>Number of observing notes</td>
<td>151</td>
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<tr>
<td>Number of spectroscopy observations</td>
<td>412</td>
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<tr>
<td>Number of imaging observations</td>
<td>251</td>
</tr>
<tr>
<td>Number of time series observations</td>
<td>812</td>
</tr>
</tbody>
</table>

### TOIs/CTOIs

<table>
<thead>
<tr>
<th>TOIs/CTOIs</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of all TOIs</td>
<td>408</td>
</tr>
<tr>
<td>List of all CTOIs</td>
<td>9</td>
</tr>
</tbody>
</table>