Multiplicity and properties of
Kepler planet candidates:
High spatial imaging and RV studies at Calar Alto

Andres Moya
on behalf of
David Barrado, Jorge Lillo-Box
2nd & 3rd Release
(2321 planets around 1790 stars)

Phases:
- Phase I: AstraLux
  - 124 KOIs
    - 77 isolated KOIs
    - 33 KOIs w/ companions at 3”-6”
    - 20 KOIs w/ companions at <3”
- Phase II: CAFOS
  - 29 KOIs
    - 15 isolated KOIs
    - 14 KOIs w/ companions at <3”
- Phase III: CAFE
  - 23 KOIs
    - 23 isolated KOIs

False positives
Stellar properties

A three phases study: from high spatial resolution imaging, to reject false positives and study multiplicity of the host star, to high-spectral resolution for RV (and planet properties)
**IMAGING: False positives**

**False positives**

- Low-mass EB
- Low-mass EB + backgr. object
- Grazing eclipse

- Background EB
- Background (larger) planet
- Real (larger) planet with a background object
IMAGING: False positives

Configurations already rejected by other techniques such as long-term photometric surveys, photo-centroid motion, etc.
IMAGING: False positives

Configurations that can be rejected with our high-spatial resolution imaging
Phases of our follow-up

<table>
<thead>
<tr>
<th>PHASE</th>
<th>Objective</th>
<th>Instrument</th>
<th>Tipo de datos</th>
</tr>
</thead>
</table>
| 1     | - To detect isolated host  
       |   - To detect multiple systems (2 or more stars) | AstraLux (Lucky Imaging) | High-resolution imaging |
| 2     | - Characterization host.  
       |   - Characterization stellar companion: physical association? | CAFOS | Low-resolution spectroscopy |
| 3     | - Characterization star-planet and planet properties | CAFE | Stable, high-spectral resolution spectroscopy |
AstraLux is a Lucky-Imaging camera installed at the 2.2m telescope at Calar Alto. With a FOV of 24x24 arcsec, it obtains thousands of images of short-exposure time (tens of milliseconds, below the typical timescale of the atmosphere changes) to achieve diffraction-limited images of 0.1 arcsec.
Our Astralux image with the Kepler psf overimposed. Each kepler
pixel is 4x4 arcsec large and several pixels are used in the
aperture. As in this image, several objects could lie inside the
aperture, affecting photometry and eventually making planet
smaller than they are.
Results: many visual companions

We have found 111 companions near the 98 observed hosts (closer than 10").
Results: many visual companions

SDSS photometry can be recovered for most of it (no in the Kepler catalog)
Completeness and detectability limits

Detectability limits for our survey. We obtained deep images with the same exposure times as the scientific images to measure the number of detected stars on each magnitude bin.

$m_{i,\text{complete}} = 18.4 \text{ mag}$

$m_{i,\text{detect}} = 22.0 \text{ mag}$
Our sensibility plots show that we reach 5.5-6.0 magnitudes for SNR=3 detections within 1 arcsec from the target and magnitude differences of 3.0 mag for an object located at 0.4 arcsec.
RESULTS: visual companion

At least one object detected within 3 arcsec.

Close (17 KOIs)

Medium (27 KOIs)

Isolated (57 KOIs)

Isolated (no objects within 6 arcsec)

At least one object detected within 3-6 arcsec

Three objects are found to have both objects within 3 arcsec and 3-6 arcsec
RESULTS: physical companion

17 KOIs (hosts)

19 companions

22 planet candidates
Characteristics of the companions

This spectral typing were only possible for objects with i-z > 0.21. Earlier-type objects do not present large differences in these color so that can not be classified. We have found 7 M-type companions and 2 late-K stars around our KOIs.
Characteristics of the companions

Possible bounded companions
Planet parameter need to be recomputed if visual companion is present

\[
\Delta F = \frac{F_{nt} - F_t}{F_{nt}}
\]

**Transit depth:**

\[
\Delta F_{new} = (1 - 10^{-0.4\Delta m_z}) \Delta F
\]

**New depth:**

**Planet radius:**

\[
\frac{R_p}{R_*} = \sqrt{\Delta F}
\]

<table>
<thead>
<tr>
<th>Planet ID</th>
<th>Cat. Depth (ppm)</th>
<th>NewDepth (ppm)</th>
<th>New ( \frac{R_p}{R_*} ) (10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>641.01</td>
<td>1080</td>
<td>1386 ± 113</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>703.01</td>
<td>124</td>
<td>125 ± 1</td>
<td>1.1 ± 0.003</td>
</tr>
<tr>
<td>298.01</td>
<td>239</td>
<td>412 ± 59</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>658.01</td>
<td>460</td>
<td>471 ± 8</td>
<td>2.2 ± 0.0</td>
</tr>
<tr>
<td>658.02</td>
<td>439</td>
<td>449 ± 7</td>
<td>2.1 ± 0.0</td>
</tr>
<tr>
<td>387.01</td>
<td>941</td>
<td>988 ± 83</td>
<td>3.1 ± 0.1</td>
</tr>
<tr>
<td>626.01</td>
<td>316</td>
<td>319 ± 3</td>
<td>1.8 ± 0.008</td>
</tr>
<tr>
<td>628.01</td>
<td>380</td>
<td>402 ± 17</td>
<td>2.0 ± 0.0</td>
</tr>
<tr>
<td>644.01</td>
<td>22486</td>
<td>28510 ± 555</td>
<td>16.9 ± 0.2</td>
</tr>
<tr>
<td>401.01</td>
<td>1986</td>
<td>2231 ± 124</td>
<td>4.7 ± 0.1</td>
</tr>
<tr>
<td>401.02</td>
<td>1411</td>
<td>1585 ± 88</td>
<td>4.0 ± 0.1</td>
</tr>
<tr>
<td>704.01</td>
<td>459</td>
<td>459 ± 0.0</td>
<td>2.1 ± 0.025</td>
</tr>
<tr>
<td>1375.01</td>
<td>2369</td>
<td>2527 ± 178</td>
<td>5.0 ± 0.2</td>
</tr>
<tr>
<td>592.01</td>
<td>440</td>
<td>440 ± 0.0</td>
<td>2.1 ± 0.024</td>
</tr>
<tr>
<td>379.01</td>
<td>251</td>
<td>363 ± 21</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td>645.01</td>
<td>169</td>
<td>201 ± 4</td>
<td>1.4 ± 0.0</td>
</tr>
<tr>
<td>645.02</td>
<td>193</td>
<td>229 ± 5</td>
<td>1.5 ± 0.0</td>
</tr>
<tr>
<td>721.01</td>
<td>190</td>
<td>196 ± 2</td>
<td>1.4 ± 0.059</td>
</tr>
<tr>
<td>433.01</td>
<td>2730</td>
<td>2905 ± 73</td>
<td>5.4 ± 0.1</td>
</tr>
<tr>
<td>433.02</td>
<td>12016</td>
<td>12788 ± 320</td>
<td>11.3 ± 0.1</td>
</tr>
<tr>
<td>841.01</td>
<td>2885</td>
<td>2986 ± 44</td>
<td>5.5 ± 0.0</td>
</tr>
<tr>
<td>841.02</td>
<td>4056</td>
<td>4198 ± 62</td>
<td>6.5 ± 0.0</td>
</tr>
</tbody>
</table>
High spatial resolution imaging is neede to validate the planet candidate.

Isolated host: 58%.

More than 40 % have stellar visual companions

17% of the host have companions closer than 3”.

8 possible bounded KIOs
<table>
<thead>
<tr>
<th>PHASE</th>
<th>Objective</th>
<th>Instrument</th>
<th>Tipo de datos</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>- To detect isolated host&lt;br&gt;- To detect multiple systems (2 or more stars)</td>
<td>AstraLux (Lucky Imaging)</td>
<td>High-spatial Resolution imaging</td>
</tr>
<tr>
<td>2</td>
<td>- Characterization host.&lt;br&gt;- Characterization stellar companion: physical association?</td>
<td>CAFOS</td>
<td>Low-resolution spectroscopy</td>
</tr>
<tr>
<td>3</td>
<td>- Characterization star-planet and planet properties</td>
<td>CAFE</td>
<td>Stable, high-spectral resolution spectroscopy</td>
</tr>
</tbody>
</table>
CAFÉ: the planetary system properties

- New spectrogram at Calar Alto.
- Commissioning in May-June 20111 (Aceituno et al. 2012)
- Since then, we have been using the Spanish GTO and open time

Calar Alto statistics

Distribution of Seeing
Median: 0.80 arcsec
(639364 data points)

Distribution of V-Extinction
Median: 0.169 mag/AM
(408820 data points)

Fig. 15.— Radial velocity curves for two well-known extra-solar planets, TrES-2b (left-panel), and TrES-3b (right-panel), derived from the early measurements taken during the CAFE commissioning run. Red circles represent the derived values for the radial velocity. The black solid line represents the theoretical curve assuming the simple expression: $v_r = \frac{2\pi a}{P} \sin(i) \frac{M_p}{M_p + M_s} \sin(\phi)$ where $a$ is the semi-major axis, $P$ is the orbital period, $i$ is the orbital inclination and $\phi$ is the orbital phase. The shaded region has been calculated by error propagation of the published values in the previous expression. The lower panel shows the residuals for the fit.

Aceituno et al. (2012), in press
Beyond our expectations: the RV accuracy

We are getting close to the optimal values: 10/s
First result: a multiple system

**Planet #1**
- $M\sin(i) = 1.535 \pm 0.099 \text{ Mj}$
- $e = 0.293 \pm 0.045$

**Planet #2**
- $M\sin(i) = 0.501 \pm 0.091 \text{ Mj}$
- $e = 0.531 \pm 0.089$
Thanks!!!

And stay tuned