Study Analysis Group 8: Requirements & Limits of Future Precise Radial Velocity Measurements

Co-Chairs:
Peter Plavchan, NASA Exoplanet Science Institute
Dave Latham, Harvard-Smithsonian

ExoPAG 10 – 6 June 2014
SAG 8 Charter

This group will evaluate the future role of RV measurements in the exoplanet field, both scientific and programmatic, and will attempt to analyze the resources required to fulfill this goal.

See our ExoPAG 6 presentation for the full charter
SAG 8 Sermon

• The demands on telescope time for NASA mission support, especially for systems of small planets, will exceed the number of nights available using instruments now in operation by a factor of at least several for TESS alone. Pushing down towards true Earth twins will require more photons (i.e. larger telescopes), more stable spectrographs than are currently available, better calibration, and better correction for stellar jitter.
## Summary of PRV support for NASA mission science objectives

<table>
<thead>
<tr>
<th>Mission</th>
<th>Target identification for mission science yield optimization</th>
<th>Follow-up validation &amp; characterization of low mass transiting exoplanets</th>
<th>Exoplanet mass &amp; orbit determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TESS</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>JWST</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>AFTA/Coronagraph/probe direct imaging</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Future Flagship direct imaging</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
**Mass vs Radius Diagram for Small Planets**

Orbital Period: 0.87d

CoRoT-7b: The First Rocky Planet
CoRoT-7 is an active star with velocity jitter

Pre-whitening for rotation (Dumusque et al. 2012; Boisse et al. 2011; Queloz et al. 2009), correlation with activity (Boisse et al. 2009), velocity differences (Hatzes et al. 2010), correlation with photometry (Aigrain et al. 2012), jitter as correlated noise (Feroz & Hobson 2013, Haywood et al. 2014)
Kepler 11 – six transiting planets

Periods 10 to 118 days
Kepler-10b (rocky) and the puzzle of Kepler-11 (puffy)

Periods:
- 10b: 0.84d
- 11b: 10.3d
- 11c: 13.0d
- 11f: 46.6d
- 18b: 3.5d
- 20b: 3.7d
- 20c: 10.9d
- 1214: 1.6d

Kepler-36b and c in 6:7 MMR, masses from TTVs
Densities differ by a factor of 8

Periods:
36b: 13.8d
36c: 16.2d
55 Cnc: 0.73d

55 Cancri planetary system found first by RVs: V=6th mag
The HARPS-N Collaboration
Geneva Observatory, Harvard-Smithsonian, INAF-TNG, St. Andrews & Queens Univ. Belfast

Francesco Pepe, Andrew Collier Cameron, David W. Latham, Emilio Molinari, Stéphane Udry; David Charbonneau, Mercedes Lopez-Morales, Christophe Lovis, Michel Mayor, Giusi Micela, David Phillips, Giampaolo Piotto, Didier Queloz, Ken Rice, Dimitar Sasselov, Damien Ségransan, Alessandro Sozzetti, Andrew Szentgyorgyi, Chris A. Watson, and many collaborators...
80 nights per year for 5 years:
1. Masses of small Kepler planets
2. Rocky Planet Search
Kepler-78b: Observed Independently by HIRES & HARPS-N
Results Agreed, Papers Submitted Simultaneously

Periods
78b: 8.5hr
10b: 20hr

Kepler-10b: four times as many HARPS-N observations
Mass error half as big (15%), now closer to Earth-like density
Kepler-10b Orbits

Mass K00072b ($M_\oplus$) = 3.33 +/- 0.49 (HARPN), 4.56 +/- 1.17 (HIRES)

Credit: Xavier Dumusque
Kepler-10b: $P = 0.84\, \text{d}$

$R = 1.47\, R_E$
$M = 3.33\, M_E$ (15%)
$\rho = 5.8\, \text{g/cc}$

Kepler-10c: $P = 45\, \text{d}$

$R = 2.35\, R_E$
$M = 17.2\, M_E$ (11%)
$\rho = 7.1\, \text{g/cc}$

Kepler-10c: a rocky planet as massive as Neptune

17.2±1.9 \( M_\text{E} \) (11%)

2.35±0.03 \( R_\text{E} \)

Are there more of these?
Mass vs. Radius for 30 planets followed up with HIRES on Keck1 over four seasons
16 have masses better than 2 sigma, 14 better than 1 sigma
Role of the transit ephemeris is critical
The TESS Advantage

• Planet candidates will be 30 to 100 times brighter
TESS targets are 30 to 100 x brighter than Kepler targets.
The TESS Advantage

- Planet candidates will be 30 to 100 times brighter
- Commitments from both HARPS & HARPS-N
  - HARPS time contingent on ESO TAC
  - HARPS-N contingent on renewed International Agreement
  - Nominally 90 nights per year dedicated to TESS follow-up
    - Only sufficient to follow up some of easiest rocky candidates
- New infrared spectrometers promise to help
  - TPF (Hobby-Eberly), Carmenes (Calar Alto), SPIRou (CFHT), etc
### TFOP PRV Assets

<table>
<thead>
<tr>
<th>MASS: Measuring Instrument</th>
<th>Telescope</th>
<th>Band</th>
<th>PRV [m s(^{-1})]</th>
<th>Available</th>
<th>Leads</th>
<th>Observing Time [hr]</th>
<th>Commitment</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARPS-N</td>
<td>TNG 3.6m N</td>
<td>Opt</td>
<td>0.7</td>
<td>Now</td>
<td>Latham, Sasselov</td>
<td>960</td>
<td>Collaboration</td>
<td>Partial</td>
</tr>
<tr>
<td>HARPS</td>
<td>ESO 3.6m S</td>
<td>Opt</td>
<td>0.7</td>
<td>Now</td>
<td>Udry, Pepe</td>
<td>720</td>
<td>TACs</td>
<td>Collab</td>
</tr>
<tr>
<td>SOPHIE</td>
<td>OHP 2m N</td>
<td>Opt</td>
<td>3</td>
<td>Now</td>
<td>Bouchy</td>
<td>1500</td>
<td>TACs</td>
<td>Collab</td>
</tr>
<tr>
<td>LCOGT</td>
<td>1-m network S</td>
<td>Opt</td>
<td>3</td>
<td>2015</td>
<td>Brown</td>
<td>720</td>
<td>Committed</td>
<td>Partial</td>
</tr>
<tr>
<td>HDS</td>
<td>Subaru 8.2m N</td>
<td>Opt</td>
<td>3</td>
<td>Now</td>
<td>Narita</td>
<td>100</td>
<td>TACs</td>
<td>Collab</td>
</tr>
<tr>
<td>IRD</td>
<td>Subaru 8.2m N</td>
<td>IR</td>
<td>1-3</td>
<td>2015</td>
<td>Narita</td>
<td>100</td>
<td>TACs</td>
<td>Collab</td>
</tr>
<tr>
<td>HRS</td>
<td>HET 9.2m N</td>
<td>Opt</td>
<td>3</td>
<td>2014</td>
<td>Cochran</td>
<td>200</td>
<td>TACs</td>
<td>Collab</td>
</tr>
<tr>
<td>CARMINES</td>
<td>Calar Alto 3.5m N</td>
<td>OPT/IR</td>
<td>1-3</td>
<td>2015</td>
<td>Quirrenbach</td>
<td>200</td>
<td>TAC</td>
<td>Collab</td>
</tr>
<tr>
<td>ESPRESSO</td>
<td>VLT 8.2m S</td>
<td>OPT</td>
<td>0.1</td>
<td>2016</td>
<td>Pepe, Udry</td>
<td>?</td>
<td>TACs</td>
<td>Collab</td>
</tr>
<tr>
<td>SPIRou</td>
<td>CFHT 3.6m N</td>
<td>OPT/IR</td>
<td>1-3</td>
<td>2017</td>
<td>Doyon</td>
<td>?</td>
<td>TACs</td>
<td>Collab</td>
</tr>
<tr>
<td>SPIRou</td>
<td>NTT 3.6m S</td>
<td>Opt/IR</td>
<td>1-3</td>
<td>2017</td>
<td>Hebrard</td>
<td>?</td>
<td>TACs</td>
<td>Collab</td>
</tr>
</tbody>
</table>

**Total Hours \( \approx \) 4500**
Three Hypothetical Scenarios
To support NASA missions with PRVs

• Dedicated 4-m with optical HARPS-like 50 cm/s
  – Masses and densities for TESS transiting planets
  – PRV survey of candidates for AFTA-type mission

• Access to 10-m with 5 cm/s performance
  – Push towards orbits for true Earth twins
  – Requires much better correction of stellar jitter

• Access to 4-m with infrared 50 cm/s
  – Masses for habitable planets around M dwarfs
“The first task on the ground is to improve the precision radial velocity method by which the majority of the close to 500 known exoplanets have been discovered. ... Using existing large ground-based or new dedicated mid-size ground-based telescopes equipped with a new generation of high-resolution spectrometers in the optical and near-infrared, a velocity goal of 10 to 20 centimeters per second is realistic.” – page 7-8

To prepare for direct imaging, “NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates” - page 1-8
AFTA-type Coronograph Mission

• PRV survey of nearest stars for best targets
  – DRM studies underway in SAG 9
    • For known RV planets

• Long-term PRV monitoring required
  – Very high precision and stability needed
  – Volunteers from the community unlikely
    – Many potential targets have been observed, but not published
    – Can those results be harvested?
    – How to merge results from different instruments?
SAG 8 Status

• Slow progress this spring
• Draft executive summary
• Detailed outline
• Lots of draft text, but many place holders
  – Peter has enlisted “volunteer” experts
    • Asks for 30 June submission deadline
• It’s already too long