Towards the detection of optical reflected light from other worlds

Nuno C. Santos
(Centro de Astrofísica, Univ. do Porto)

With the collaboration of P. Figueira, J. H. Martins
Why to detect reflected light spectrum

- Represents a direct detection of an exoplanet
  - Complementary to IR observations (yesterday’s talk by I. Snellen)
- Allows to probe planetary atmosphere
  - Geometric albedo
  - Atmosphere physics (e.g. winds - e.g. Snellen et al. 2010)
- Allows to derive the velocity of the planet
  - Derive its real (dynamical) mass (e.g. Brogi et al. 2012)
- Complementary physics: planet rotation (e.g. Kawahara 2012)
- Important: can be applied even for non transiting planets
The difficulties

- Reflected light (even broad band) is not easy to detect
  - Recently possible using CoRoT and Kepler
    (e.g. Alonso et al. 2009; Borucki et al. 2009; Kipping et al. 2011)

- Jovian planet with $P=3$ days, $A_g=0.3$
  - Expected $F_p/F_*=4.2 \times 10^{-5}$ (maximum value)

- Hot Jupiters: former results suggest low geometric albedos?
  (e.g. Collier Cameron et al. 2002, Rowe et al. 2008, Langford et al. 2010)

- Though $A_g$ values around 0.3 or higher have been found
  (e.g. Santerne et al. 2011; Cowan et al. 2011)
Using the power of the Cross-Correlation Function

- By construction, the Cross-Correlation Function (CCF) represents an average spectral line

\[ CCF(v) = \sum_i A[\lambda(i)] \cdot M[\lambda(i) (1 + v/c)] \]

Stellar spectrum  Binary mask
Using the power of the Cross-Correlation Function

- All lines in the CCF mask/spectrum are “stacked”
- The S/N in each corresponding “resolution element” (pixel on the CCD) of the CCF is given, as a good approximation, by:

\[
\frac{S}{N_{\text{CCF}}} = \frac{S}{N_{\text{spe}}} \times \sqrt{N_{\text{lines}}}
\]

**Example:**
- Spectrum with \(\frac{S}{N_{\text{spe}}} = 1000\)
- \(N_{\text{lines}} \sim 3600\) (HARPS G2 mask)
- Expected \(\frac{S}{N_{\text{CCF}}} = 60\,000\)
Simulations: testing the concept with real data

1. Initial set of high S/N HARPS data
   - Built from random stack of 20 spectra taken same night
   - Average S/N ~1000
   - Compute CCF

2. Add another spectrum/CCF (taken in a different night) to simulate planetary signal:
   - Multiplied by factor of $6 \times 10^{-5}$ (1/15 000)
   - Vary its velocity: simulate planetary motion

3. Subtract stellar contribution with template CCF

   Expected S/N$_{CCF}$ ~ 60 000 (residuals of ~$2 \times 10^{-5}$)
   - i.e., we expect a 3-sigma detection
Simulations: results

Flux ratio: 1/15000

CCF number

Velocity [km/s]
Simulations: results

- Example of resulting CCF (one single phase)
- 3-sigma detection as expected!
Jupiter, A=0.3, P=3 days, S/N\textsubscript{spec} = 2000 / 10 min.
Jupiter, $A=0.3$, $P=3\text{ days}$, $S/N_{\text{spec}} = 2000 / 10 \text{ min.}$
Jupiter, $A=0.3$, $P=3\text{ days}$, $S/N_{\text{spec}} = 2000 / 10 \text{ min.}$
Neptune, $A=0.3$, $P=2\text{days}$, $S/N_{\text{spec}} = 2000 / 10 \text{min.}$

Fit Coefficients:
- $A = -2.43571565362e-08$
- $a = 0.0310682747547$
- $B = 0.0153846192869$
- max flux ratio = $9.01929467117e-06$
- $I = 1.57079632679$
- $K = 168.988251953$
- $A/\text{Continuum SD} = 3.79662894255$
- $t_0 = 0.0$
- $P = 2.0$
- $\text{FWHM} = 9.78210160386$
- $\text{Mean} = 0.303278975634$

4-sigma detection
Super-Earth, $A=0.3$, $P=2$ days, $S/N_{\text{spec}} = 3000 / 10$ min.
### Estimates for 2-sigma detections

<table>
<thead>
<tr>
<th>Planet</th>
<th>Ag *</th>
<th>Needed S/N_{spe}</th>
</tr>
</thead>
<tbody>
<tr>
<td>P=3 days, R=1 R_{jup}</td>
<td>0.3</td>
<td>800</td>
</tr>
<tr>
<td>P=3 days, R=1 R_{Nept}</td>
<td>0.3</td>
<td>6000</td>
</tr>
<tr>
<td>P=1 day, R=1 R_{Nept}</td>
<td>0.3</td>
<td>1700</td>
</tr>
<tr>
<td>P=1 day, R=2 R_{Earth}</td>
<td>0.3</td>
<td>6000</td>
</tr>
<tr>
<td>P=1 day, R=1 R_{Earth}</td>
<td>0.67 (Venus)</td>
<td>10 000</td>
</tr>
</tbody>
</table>

*0.3 is reasonable value according to Cowan & Agol (2011) and Santerne et al. (2011)*
HIRES@ELT

• From a simple extrapolation from UVES@VLT:

  • HIRES@ELT: G2V, mv~7, T_{exp}=900s => S/N~5000

  • Many available targets!!!
The challenges

- **Flux**: detect signals that are of the order of $10^{-5}$
  - ELT collecting power critical
  - Relatively short exposure times (due to planetary motion)

- **Spectral fidelity**
  - Very good FF correction (stable detector/well characterized)
  - PSF stability needed

- **High resolution ($\sim 10^5$)**: keep line contrast

In brief: we need a stable spectrograph and a large telescope! HIRES@ELT will be the right instrument.
Thank you!

Questions?