Measuring precise planetary masses in the presence of stellar activity in RV surveys

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For low mass planets:
Radial-velocity (RV) signal entangled with stellar activity RV signatures

- Observations suggest that even “quiet” stars have \( \Delta R V_{\text{activity}} \approx 1\text{-}2 \text{ m/s} \) (Isaacson & Fischer 2010)


- HARPS-N is looking for planets with 1-2 m/s amplitude, need to be able to trust results
I. Flux blocked by starspots on a rotating star

Single spot on Sun-like star $\Delta RV \approx 0.38$ m/s (Makarov et al. 2009)
II. Suppression of convective blueshift

Hot & bright outgoing flow $\rightarrow$ blueshift

Cool & dark sinking flow $\rightarrow$ redshift

$\Rightarrow$ Net blueshift

Active regions suppress granulation blueshift $\sim$ few m/s

Found to be dominant contribution to $RV_{activity}$ (Meunier et al. 2010, Haywood et al. submitted)
III. Other potential stellar activity RV signals

- Faculae that are not associated with starspots
- ~ 50 m/s inflows towards active regions in the Sun (Gizon et al. 2001, 2010)
- Other...?
Outline of this work

- Monte Carlo Markov Chain (MCMC) code
- RV model:
  \[ RV_{\text{total}} = RV_{\text{planets}} + RV_{\text{activity}} \]

  Basis functions derived from lightcurve
  \((FF'\) method of Aigrain 2012)\n
  Gaussian process with covariance
  properties of lightcurve
  (Haywood et al., submitted)
Gaussian processes

Flux

Time
Gaussian processes
A Gaussian process is encoded by a covariance function

Quasi-periodic form:

\[ k(t, t') = \theta_1^2 \cdot \exp\left(-\frac{(t - t')^2}{2\theta_2^2} - \frac{2\sin^2\left(\frac{\pi(t - t')}{\theta_3}\right)}{\theta_4^2}\right) \]

- amplitude
- decay timescale
- smoothing factor
- recurrence timescale

See Rasmussen & Williams (2006), Gibson et al. (2011)

Covariance function

Autocorrelation function
Using a Gaussian process to fit data

Lightcurve: naturally has covariance properties of star’s magnetic activity

\( k(t, t') \)

**train GP:** determine \( \theta_1, \theta_2, \theta_3, \theta_4 \) of covariance function through MCMC simulation

**predict GP:** compute covariance matrix using \( k(t, t') \)

RV basis function with covariance properties of lightcurve
Application to CoRoT-7

• G9, V=11.7

• CoRoT transit observations in 2009
  ➡ super-Earth CoRoT-7b (Léger et al. 2009)

• HARPS radial-velocity campaign (2009)
  ➡ another super-Earth CoRoT-7c (Queloz et al. 2009)
  ➡ sub-Neptune mass planet CoRoT-7d at 9 days (Hatzes et al. 2010)

• Many analyses, no agreement

• Jan. 2012: New observations: simultaneous CoRoT photometry & HARPS RV
CoRoT-7 2012 simultaneous RV and photometry

**CoRoT lightcurve (transits of CoRoT-7b removed)**

![CoRoT lightcurve graph](image1)

**HARPS RV data**

![HARPS RV data graph](image2)

\[ \text{RV}_{\text{total}} = \text{RV}_{\text{activity}} + \text{RV}_{\text{planets}} \]
Why the Gaussian process is needed

If model RVs with only method of Aigrain (2012) and 2 planets, get correlated residuals:

Fit Gaussian process to residuals
Outcome of MCMC for CoRoT-7

Haywood et al., submitted
• In case of CoRoT-7:
  - $m_b = 4.62 \pm 0.89 \, M_\oplus$ and $m_c = 13.62 \pm 1.06 \, M_\oplus$
  - signal at 9 days best explained as activity rather than a planet

• Accounting for stellar activity RV signals is key to detecting low-mass planets and determining their masses

• Can account for activity using method of Aigrain et al. (2012) + Gaussian process trained on lightcurve (Haywood et al., submitted)

• Apply to Kepler systems observed with HARPS-N