FourIER phase SpecTrum Analysis (ΦESTA / FIESTA)

Parametrising Stellar Variability in Fourier Space

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Challenge

Intrinsic shift (orbiting companions)

Apparent shift (stellar variability)
Challenge

Bisector (Queloz et al. 2001)

FWHM (Queloz et al. 2009)

$V_{\text{span}}$ (Boisse et al. 2011)

$\Delta V, V_{\text{asy}}$ (Figueira et al. 2013)

Skew Normal density (Simola et al. 2019)
Challenge

Bisector (Queloz et al. 2001)

FWHM (Queloz et al. 2009)

$V_{\text{span}}$ (Boisse et al. 2011)

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Skew Normal density (Simola et al. 2019)

$\Phi\text{ESTA (Zhao & Tinney, submitted)}$
Entrée

Signal shifted

Sum
Component 1
Component 2
Component 3

Signal deformed

Sum
Component 1
Component 2
Component 3
Translation Property – Line Shift

- If $h(x) = f(x - x_0)$, then $\hat{h}(\xi) = e^{-2\pi i x_0 \xi} \hat{f}(\xi)$
- Phase shift $\Delta \phi(\xi) = -(2\pi x_0)\xi$
Translation Property – Line Deformation

- Phase shift $\Delta \phi(\xi) = -[2\pi x_0(\xi)]\xi$
Line Shift – Velocity Domain

SOAP simulator (Boisse et al. 2012; Dumusque et al. 2014)
Line Shift – Inverse Velocity Domain
Line Shift – ΦESTA Measurements

$\text{rms} = 0.08 \text{ m/s}$

$\text{rms}_L = 0.19 \text{ m/s}$  
$\text{rms}_H = 0.21 \text{ m/s}$
Line Deformation – Velocity Domain

SOAP simulation (3 starspots)
Line Deformation – Inverse Velocity Domain
Line Deformation – ΨESTA Measurements

\[ \text{RV}_{\text{FT}} = \text{RV}_{\text{Gaussian}} = \text{RV}_{\text{jitter}} \]

\[ \text{RV}_{\text{FT,L}} = k_L \, \text{RV}_{\text{jitter}} \quad (k_L < 1) \]

\[ \text{RV}_{\text{FT,H}} = k_H \, \text{RV}_{\text{jitter}} \quad (k_H > 1) \]
Line Deformation – ΦESTA Measurements

\[ RV_{FT} = RV_{Gaussian} = RV_{jitter} \]
\[ RV_{FT,L} = k_L \cdot RV_{jitter} \quad (k_L < 1) \text{ less sensitive to jitter} \]
\[ RV_{FT,H} = k_H \cdot RV_{jitter} \quad (k_H > 1) \text{ more sensitive to jitter} \]
\[ RV_{\text{Gaussian}} - RV_{\text{FT, L}} \propto RV_{\text{jitter}} \]

\[ RV_{\text{FT, H}} - RV_{\text{Gaussian}} \propto RV_{\text{jitter}} \]
ΦESTA Jitter Metrics

\[
\begin{align*}
\Delta RV_L &= RV_{\text{Gaussian}} - RV_{\text{FT, L}} \propto RV_{\text{jitter}} \\
\Delta RV_H &= RV_{\text{FT, H}} - RV_{\text{Gaussian}} \propto RV_{\text{jitter}}
\end{align*}
\]
ΦESTA Jitter Model

- $\Delta RV_L = RV_{\text{Gaussian}} - RV_{\text{FT, L}} \propto RV_{\text{jitter}}$
- $\Delta RV_H = RV_{\text{FT, H}} - RV_{\text{Gaussian}} \propto RV_{\text{jitter}}$
- Linear combination of $\Delta RV_L$ and $\Delta RV_H \propto RV_{\text{jitter}}$
ΦESTA Jitter Model

- $\Delta RV_L = RV_{\text{Gaussian}} - RV_{\text{FT},L} \propto RV_{\text{jitter}}$

- $\Delta RV_H = RV_{\text{FT},H} - RV_{\text{Gaussian}} \propto RV_{\text{jitter}}$

- Linear combination of $\Delta RV_L$ and $\Delta RV_H \propto RV_{\text{jitter}}$

$rms_{\text{jitter}} \approx 1.2 \text{ m/s}$

$rms_{\text{residual}} \approx 0.6 \text{ m/s}$
Application
Periodogram Analysis

- Stellar jitter: 3 spots
- Input $\nu_{\text{orb}} = 0.7 \nu_{\text{rot}}$
- CCF S/N = 2,000 (SNR ~ 50/pixel)
Application Classifications

- Jitter amplitude $\approx 2$ m/s
- $RV_{\text{Planet}}$ amplitude = 0, 2, 10 m/s
- CCF S/N = 10,000
Application Classifications

- Jitter amplitude $\approx 2$ m/s
- $RV_{\text{Planet}}$ amplitude = 0, 2, 10 m/s
- CCF S/N = 10,000
ΦESTA on HARPS
An Active Star

- Log $R'_{HK} = -4.46$ (Figueira et al. 2013)
- Jitter amplitude $\sim 30$ m/s
- CCF S/N $\sim 4000$; HARPS SNR = 106/pixel
- Median $RV_{noise} = 0.63$ m/s
ΦESTA on HARPS
An Active Star

• Log $R'_{HK} = -4.46$ (Figueira et al. 2013)
• Jitter amplitude $\sim 30$ m/s
• CCF S/N $\sim 4000$; HARPS SNR = 106/pixel
• Median $RV_{\text{noise}} = 0.63$ m/s

Strong correlation due to stellar jitter
ΦESTA on HARPS
An Active Planet-host Star

- \( \log R'_{\text{HK}} = -4.46 \) (Figueira et al. 2013)
- Planetary orbital amplitude \( \sim 80 \text{ m/s} \); jitter amplitude \( \sim 9 \text{ m/s} \) (Moutou et al. 2015)
- CCF S/N \( \sim 1400 \); HARPS SNR = 35/pixel
- Median \( \text{RV}_{\text{noise}} = 2 \text{ m/s} \)
ΦESTA on HARPS
An Active Planet-host Star

- Log $R'_{\text{HK}} = -4.46$ (Figueira et al. 2013)
- Planetary orbital amplitude $\sim 80$ m/s; jitter amplitude $\sim 9$ m/s (Moutou et al. 2015)
- CCF S/N $\sim 1400$; HARPS SNR = 35/pixel
- Median RV$_{\text{noise}} = 2$ m/s
• Linear trend: binary (HD 189733 B) + exoplanet (HD 189733 b)
• Rossiter-McLaughlin velocity anomaly amplitude $\sim$ 40 m/s
• $\Phi$ESTA jitter model constructed with $\Delta RV_H$
• Residual amplitude $\sim$ 10 m/s
ΦESTA on HARPS α Centauri B

The $\Delta RV$ in this slide was computed using an older version of ΦESTA; the scale can be slightly different but the trends of jitter metrics remain consistent with the latest version.

Epoch 1: 2009-02-15..2009-05-06

$P_{\text{rot}} = 35.7$ d

Gaussian processes regression model; George package (Ambikasaran et al. 2014)

Epoch 2: 2010-03-23..2010-06-12

ΦESTA on HARPS α Centauri B

- \( P_{\text{rot}} = 35.7 \, \text{d} \)
- Gaussian processes regression model; George package (Ambikasaran et al. 2014)

The \( \Delta \text{RV} \) in this slide was computed using an older version of ΦESTA; the scale can be slightly different but the trends of jitter metrics remain consistent with the latest version.

- > 2400 observations
- CCF S/N \( \sim 10,000 \); HARPS SNR = 250/pixel
- Median \( \text{RV}_{\text{noise}} = 0.2 \, \text{m/s} \)
ΦESTA on 
HARPS
α Centauri B

- Binary removed (2^{nd} order polynomial, Dumusque et al. 2012)
- Linear trend corrected
ΦESTA on HARPS α Centauri B

- Planet candidate orbiting α Centauri B?
- Binary not corrected removed / systematics?
- Correlation between ΦESTA jitter metrics and stellar jitter can be non-linear?
Summary

• \( \Phi \)ESTA measurement of line deformation \( x_0(\xi) \)
  • \( RV_{FT, L} = k_L \cdot RV_{\text{jitter}} \) (\( k_L < 1 \))
  • \( RV_{FT, H} = k_H \cdot RV_{\text{jitter}} \) (\( k_H > 1 \))

• \( \Phi \)ESTA jitter metrics
  • \( \Delta RV_L = RV_{\text{Gaussian}} - RV_{FT, L} \propto (1/4) \cdot RV_{\text{jitter}} \)
  • \( \Delta RV_H = RV_{FT, H} - RV_{\text{Gaussian}} \propto (1/2) \cdot RV_{\text{jitter}} \)

• Application
  • Periodogram analysis (activity indicator)
  • Classifications (linearity)
    • Active star (HD 224789)
    • Active planet-host star (HD 103720)
    • Rossiter-McLaughlin effect (HD 189733)
    • \( \alpha \) Centauri B – remain unsolved

• Collaborations?
• Postdoc positions?
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Supplementary Material
Jitter Correction

$$\text{RV} = \Phi_{\text{ESTA jitter Model}} + \text{Keplerian Orbits}$$

Triples the percentage of planets recovered to within 10% of input orbital parameters (Zhao & Tinney, submitted).
• CCF S/N ~ 2600; HARPS SNR = 85/pixel
• Median RV\textsubscript{noise} = 0.83 m/s
• k underrepresented
• k dependency on spot temperature (Zhao & Tinney, submitted)