Gaussian processes regression networks for the analysis of RV data

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Contents

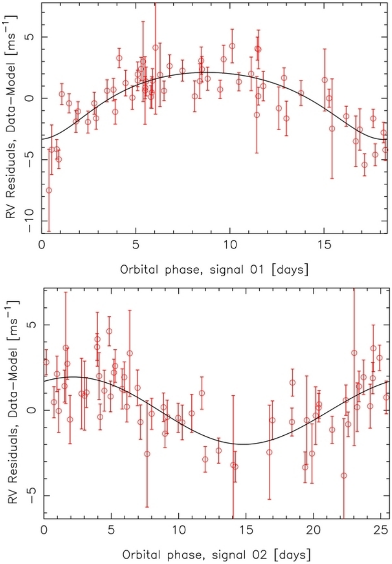
Stellar noise problem

HD 41248

- Jenkins et al. (2013); ApJ, 771, 41
- Santos et al. (2014); A&A 566, A35

Stellar activity can induce RV signals:

- Periodicity from stellar rotation
- Aperiodicity from active region evolution



Jenkins et al. (2013)

Gaussian Processes[1]

A Gaussian process (GP) is a generalization of the multivariate Gaussian distribution.

$$f(\mathbf{x}) \sim \mathcal{GP}\left(m(\mathbf{x}), k(\mathbf{x}, \mathbf{x'})\right)$$

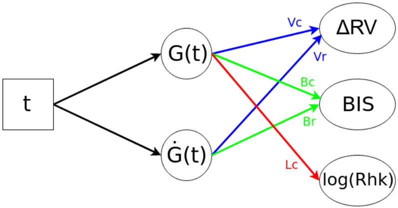
Has been used for exoplanet detection:

- Haywood et al. (2014) → CoRoT-7
- Grunblatt et al. (2015) → Kepler-78
- Rajpaul et al. (2015) → Gliese 15 and Alpha Centauri B
- Faria et al. (2016) → CoRoT-7
- Cloutier et al. (2018) → K2-18
- etc...

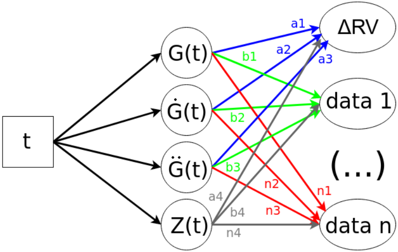
[1] Rasmussen and Williams (2006)

Some existing multi-output Gaussian processes frameworks

Before explaining my work there are two important GP frameworks to mention.



Rajpaul et al. (2015)



Jones et al. (2017)

Rajpaul et al. (2015) framework

$$\begin{cases} \Delta RV = V_c G(t) + V_r \dot{G}(t) \\ BIS = B_c G(t) + B_r \dot{G}(t) \\ \log(R'_{HK}) = L_c G(t) \end{cases}$$

$$G(t) \equiv F^2(t),$$

$F(t)$ is the fraction of the visible hemisphere covered in spots. (Aigrain et al. 2012).

- It is a physically-motivated GP framework capable of modelling RV-induced by stellar activity jointly with activity indicators, by assuming the same GP is responsible for all stellar activity signals.

Jones et al. (2017) framework

$$\begin{cases} \Delta RV = a_1 G(t) + a_2 \dot{G}(t) + a_3 \ddot{G}(t) + a_4 Z_0(t) \\ data_1 = b_1 G(t) + b_2 \dot{G}(t) + b_3 \ddot{G}(t) + b_4 Z_1(t) \\ \qquad (...) \\ data_n = n_1 G(t) + n_2 \dot{G}(t) + n_3 \ddot{G}(t) + n_4 Z_l(t) \end{cases}$$

- Extends the Rajpaul et al. (2015) framework to a larger class of models.
- Other stellar activity indicators can carry similar information to the BIS and $\log(R'_{HK})$, and thus help further characterize the RV-induced by stellar activity.

Gaussian processes regression network (GPRN)[2]

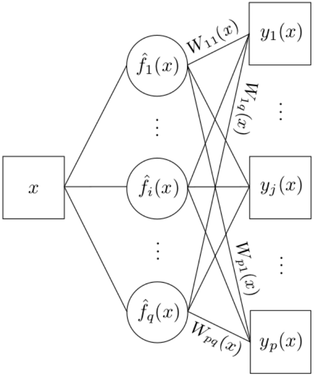
A general GP framework capable of taking into account multiples inputs and outputs

- Combines a Bayesian neural network with the flexibility of GPs

$$\boxed{\mathbf{y}(\mathbf{x}) = \mathbf{W}(\mathbf{x})\left[\mathbf{f}(\mathbf{x}) + \sigma_f \boldsymbol{\epsilon}\right] + \sigma_y \mathbf{z}}$$

$$f_i(x) \sim \mathcal{GP}(0, k_f)$$

$$W_{ij} \sim \mathcal{GP}(0, k_w)$$



Wilson (2014)

A GPRN is in effect an adaptive mixture of GPs, that accommodates input dependent signal and noise correlations between multiple output variables.

[2]Wilson et al. (2012)

Our GPRN implementation

- **gprn**[3] → eventually I'll give it a prettier name.
  - ▷ Python implementation that uses either **emcee** (affine-invariant ensemble sampler) or **dynesty** (dynamic nested sampling).
  - ▷ Since I'm currently developing this package, it is possible that I'll mess up something as I work on it and break everything!
  - ▷ To be used in a future GPRN implementation in **kima**[4], a package for the analysis of radial velocity (RV) data (Faria et al. 2018).

[3] `https://github.com/jdavidrcamacho/gprn`
[4] `https://github.com/j-faria/kima`

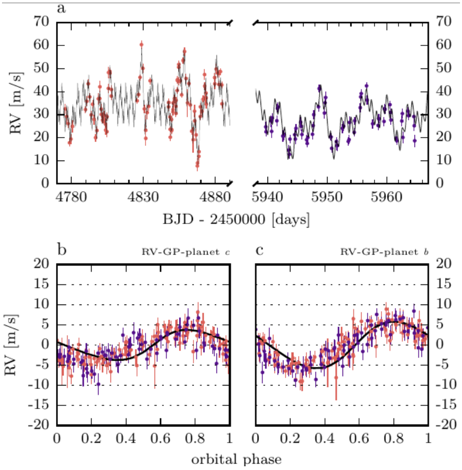
CoRoT-7 - previous works

A G9V type star, with an average temperature ~ 5250 K, and age ~ 1.2 – 2.3 Gyr (Léger et al. 2009).

- Queloz et al. (2009)
- Haywood et al. (2014)
- Faria et al. (2016)

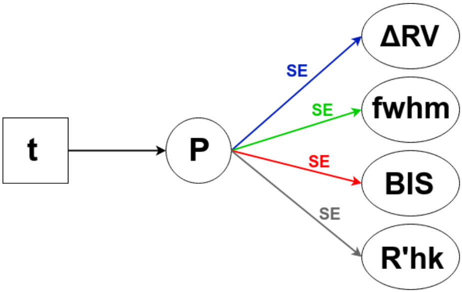
Very active star with two confirmed planets.

- CoRoT-7b
  P ~ 0.85 days and K ~ 3.97 m/s
- CoRoT-7c
  P ~ 3.70 days and K ~ 5.55 m/s



Faria et al. (2016)

CoRoT-7 - GPRN



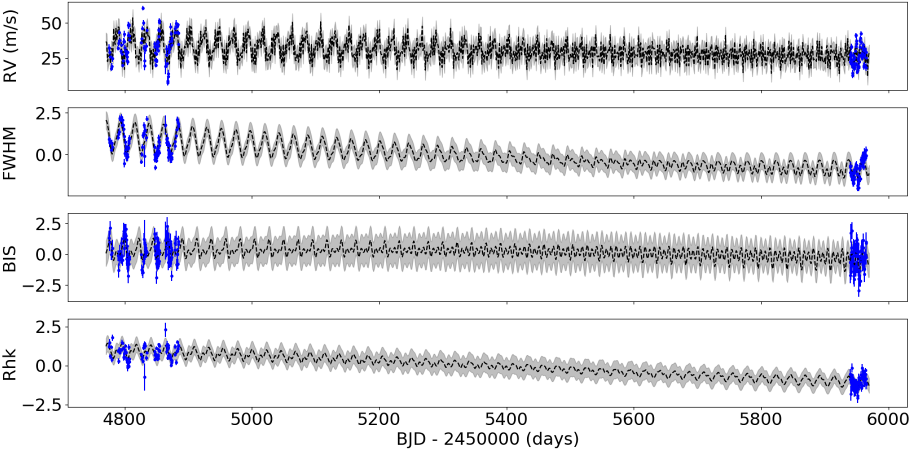
P → periodic kernel

$$P(x,x') = \theta_P^2 \left[-\frac{2}{l_P^2} sin^2 \left(\frac{\pi}{P} |x - x'| \right) \right]$$

SE → squared exponential kernel

$$SE(x,x') = \theta_{SE}^2 exp \left(-\frac{(x - x')^2}{2 l_{SE}^2} \right)$$

CoRoT-7 - results

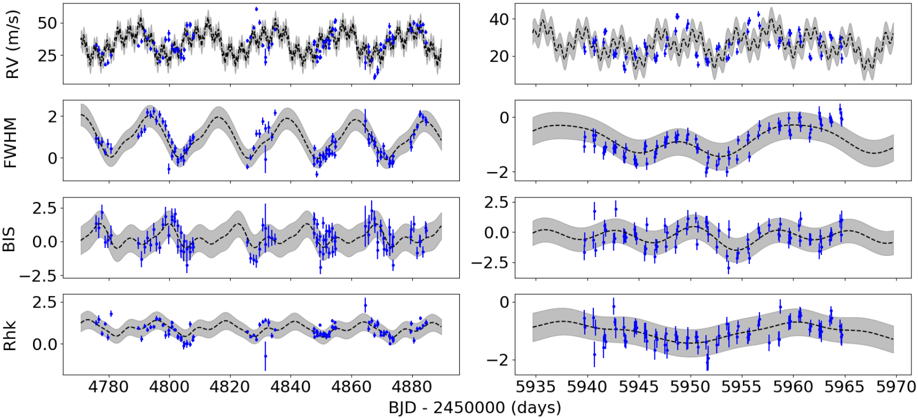


CoRoT-7 - results

Period (days) = $22.704^{+0.228}_{-0.168}$
Periodic scale = $1.197^{+0.171}_{-0.151}$
Decay timescale (days) = $1100.187^{+744.159}_{-670.123}$

	Our work	**Faria et al.(2016)**	**Haywood et al.(2014)**
P_b $(days)$	$0.85358^{+0.00030}_{-0.00009}$	$0.85424^{+0.0071}_{-0.00126}$	$0.085359165 \pm 5 \times 10^{-8}$
K_b (m/s)	$3.58^{+0.17}_{-0.21}$	$3.97^{+0.62}_{-0.55}$	3.42 ± 0.66
e_b	$0.046^{+0.005}_{-0.005}$	$0.045^{+0.053}_{-0.027}$	0.12 ± 0.07
P_c $(days)$	$3.6957^{+0.0024}_{-0.0233}$	$3.69686^{+0.00036}_{-0.00026}$	3.70 ± 0.02
K_c (m/s)	$5.58^{+0.78}_{-1.02}$	$5.55^{+0.34}_{-0.31}$	6.01 ± 0.47
e_c	$0.020^{+0.007}_{-0.005}$	$0.026^{+0.033}_{-0.017}$	0.12 ± 0.06

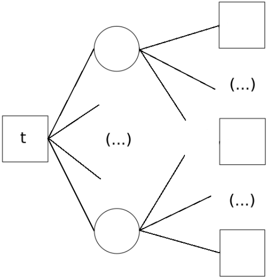
CoRoT-7 - results



Final thoughts

- A "true" GPRN will not be as simplistic as the example shown today.

  Different nodes should (in theory) be capable of dealing with other processes that might be affecting our data.



- How to interpret the GPRN parameters?
  - ▷ SE timescale ~ 1100 days?
    It's not the average lifespan of the active regions.
  - ▷ If one of the datasets has no relation with the others should we see its weight $\theta \to 0$ for a given node?

Thank you!

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CoRoT-7 - priors

Periodic kernel

Period $\rightarrow \mathcal{U}(10, 40)$
Periodic scale $\rightarrow \mathcal{U}(0, 2)$

Squared Exponential kernel

Timescale $\rightarrow \mathcal{U}(\sim 7, \sim 2378)$
RV "θ" $\rightarrow \mathcal{U}(0, \sim 105.4)$
FWHM "θ" $\rightarrow \mathcal{U}(0, \sim 8.5)$
BIS "θ" $\rightarrow \mathcal{U}(0, \sim 10.4)$
$log(R'_{hk})$ "θ" $\rightarrow \mathcal{U}(0, \sim 8.8)$

Jitters $\rightarrow \mathcal{U}(0, 2\sigma)$

Keplerians

$P_b = \rightarrow \mathcal{N}(0.85359165, 0.001)$
$K_b = \rightarrow \mathcal{U}(3, 4)$
$e_b = \rightarrow \mathcal{N}(0.04, 0.01)$[5]
$\omega_b = \rightarrow \mathcal{U}(0, 2\pi)$
$\phi_b = \rightarrow \mathcal{U}(0, 2\pi)$

$P_c = \rightarrow \mathcal{N}(3.70, 0.1)$
$K_c = \rightarrow \mathcal{U}(5, 6)$
$e_c = \rightarrow \mathcal{N}(0.03, 0.01)$[5]
$\omega_c = \rightarrow \mathcal{U}(0, 2\pi)$
$\phi_c = \rightarrow \mathcal{U}(0, 2\pi)$

Offsets $\rightarrow \mathcal{U}(min, max)$

[5] Truncated between 0 and 1