Modeling the Vertical Velocity Gradient

to disentangle stellar activity from exoplanet signals

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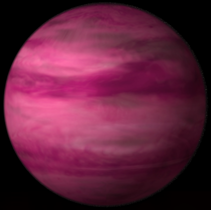
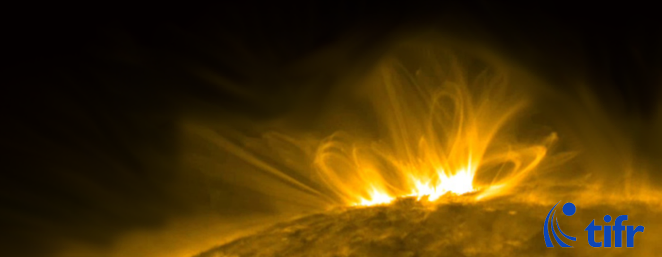
Long Running Problem in Exoplanet Detection

- Are the observed signals really due to planet or . . . ?
  - Stellar activity can minmic planetary signal.





Long Running Problem in Exoplanet Detection

- Are the observed signals really due to planet or . . . ?
    - Stellar activity can minmic planetary signal.
- High precision ⇒ Discovery of earth-like exoplanet (?).
    - Stellar activity dominates over planetary singal..

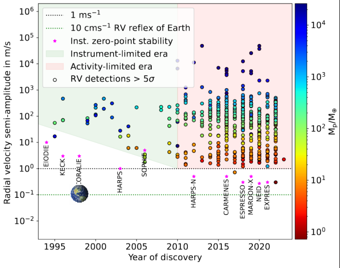
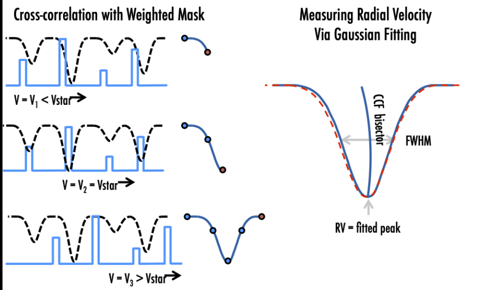
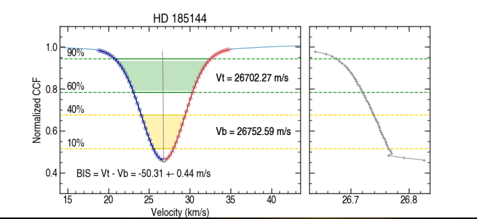


Figure: The radial velocity semi-amplitudes of planets vs discovery year (A. A. John et. al. 2023)

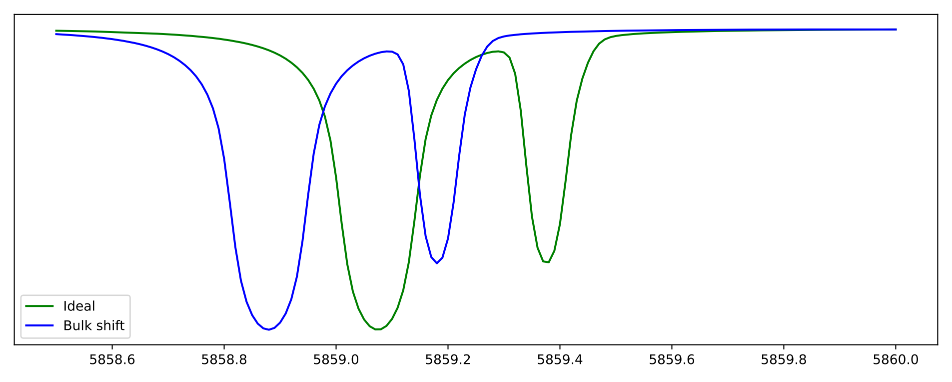
CCF-based activity indicators





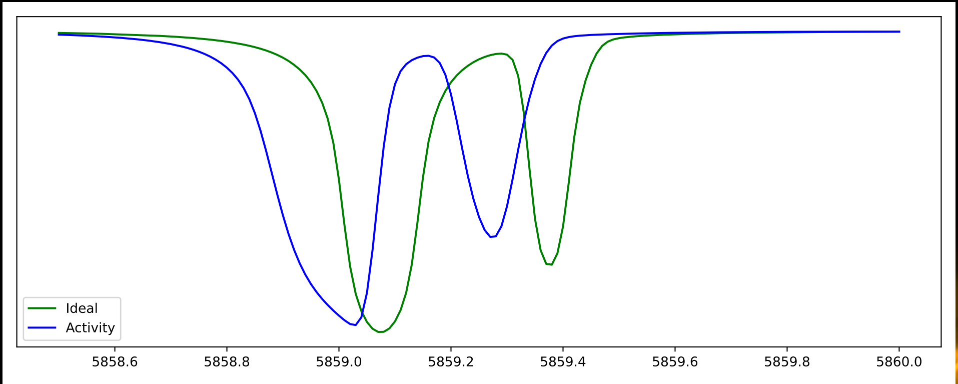
Velocities on stellar spectra: Bulk motion

- If the star is moving in bulk, doppler shift will be uniform across the spectrum.



Velocities on stellar spectra: Velocity profile

- Stellar activity causes different velocities in the photospheric layers. $\rightarrow$ Line shape changes.

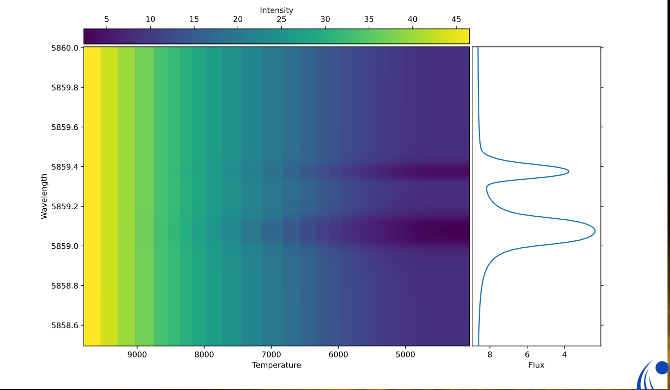


Radiative transfer in stellar photosphere

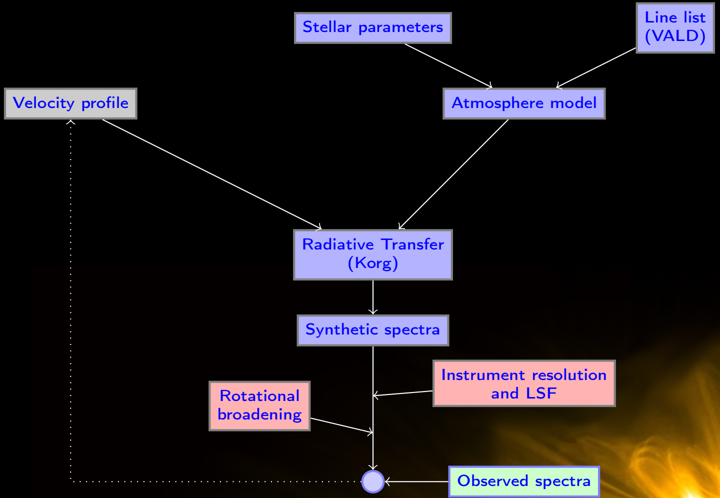
Change in intensity = -Absorption + Emission

$$dI_\lambda = -\kappa_\lambda \rho I_\lambda ds + j_\lambda \rho ds$$

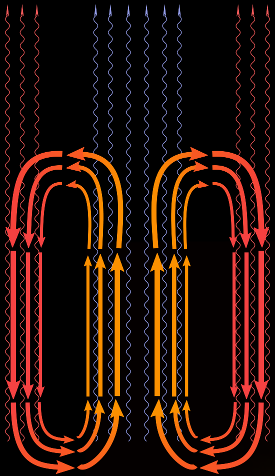
- I_λ : Intensity
- κ_λ : absorption coefficient
- ρ : Density
- ds : Layer thickness
- j_λ : Emission Coefficient



Synthesize spectra with Korg



Convective Blueshift



- The rising lane is hotter, so the emitted light is blueshifted.
- The falling lane is cooler, so the emitted light is redshifted.

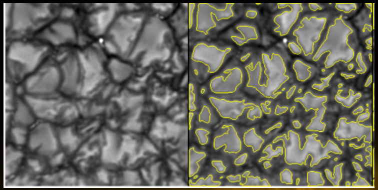
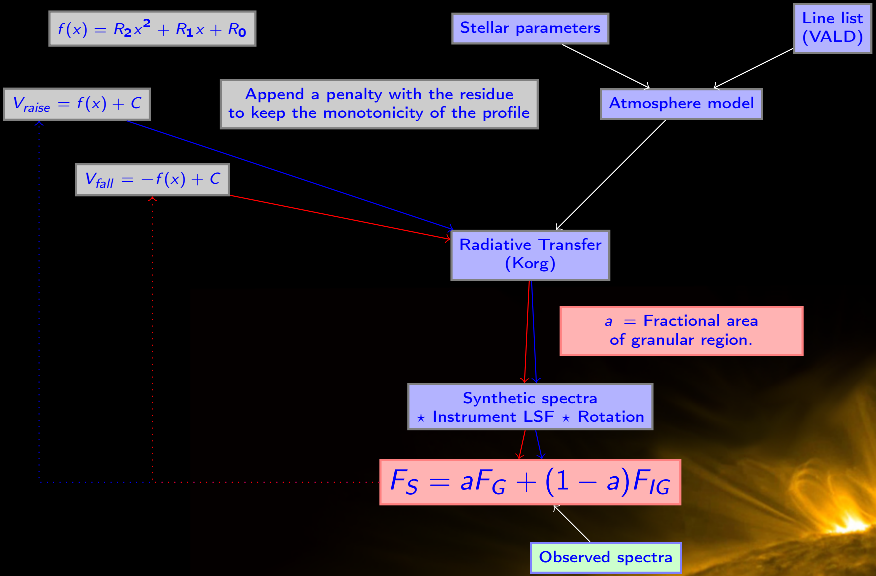


Figure: Quiet-sun granulation observed with BBSO/NST, 705 nm broadband filter.(V. I. Abramenko et al 2012 ApJL 756 L27) .

Bi-lane Model



Spectra from Falling lane

- Use the Granulation Contrast

$$G = \left(\frac{\sum (I - I_0)}{N I_0^2} \right)^{\frac{1}{2}}$$

(Abramenko et. al 2012)

- Assume equal areas for both lanes on the solar disk. $\Rightarrow$

$$I_F = \frac{1 - G}{1 + G} I_R$$

- For Rising lane, generate spectrum with $T = 5770K$.
- $I_R \to I_F \to T_F$.
- $G = 15\%$ at 705 nm.

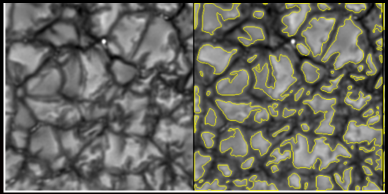


Figure: Quiet-Sun granulation observed on 2010 August 3 (Abramenko et al. 2012).

Data from NEID

- Mounted on 3.5 m WIYN Telescope, Kitt Peak National Observatory, Arizona, USA.
- $R \sim 117000$
- Range: 360-930 nm

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- Mounted on 3.5 m WIYN Telescope, Kitt Peak National Observatory, Arizona, USA.
- $R \sim 117000$
- Range: 360-930 nm
- Observe the Sun as a star during the daytime.

Figure: NEID solar feed assembly (Lin et al 2022).

Advantages and Challenges

Advantages

- Applicable on full spectra.
- Separates the motion of rising and falling plasma.
- Applicable to all spectral types of stars.

Challenges

- Imperfections in the atmospheric model.
- Disagreements between the depth of observed and synthetic lines.
- Disagreements between the position of observed and synthetic lines.
- Computationally expensive.

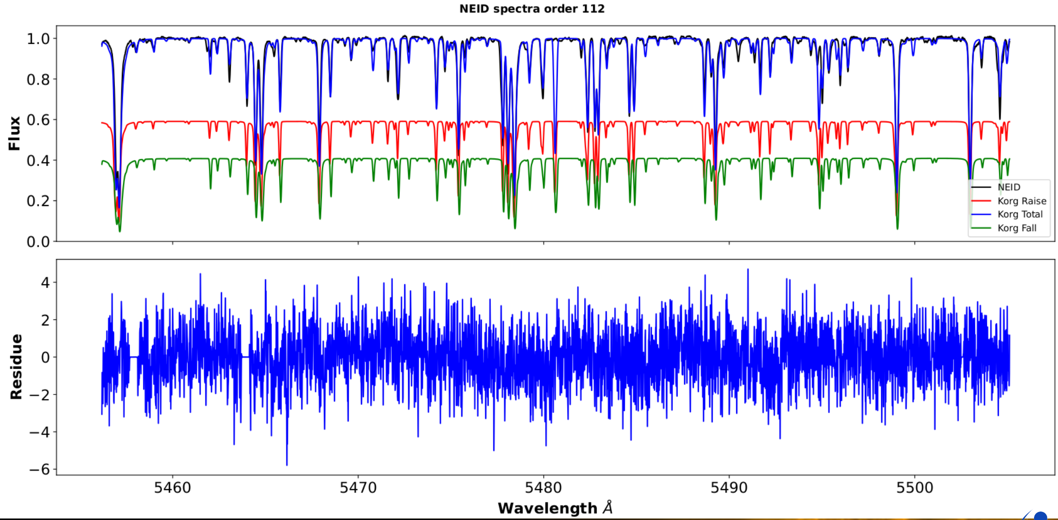
Overcoming the Chellanges

- Imperfections in model spectrum cause large cost.
- Penalty to keep the profile monotonic cause the termination of process.
- Since we are looking for variability of parameters, we can just subtract one spectrum from other. We can model that.
- Residue:

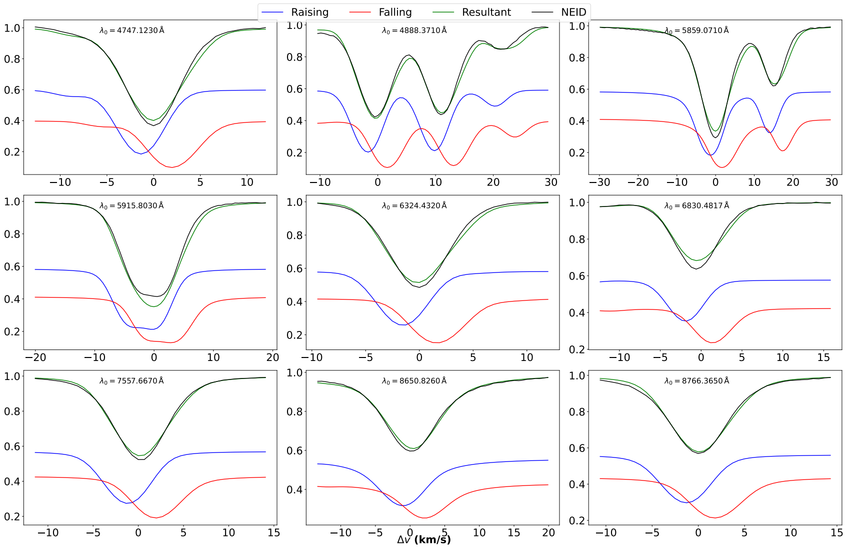
$$Z = \frac{(F_S - F_S^0) - (F_N - F_N^0)}{\sqrt{\sigma^2 + \sigma_0^2}}$$

- F_S^0: Reference Synthesised spectra
- F_N^0: Reference Observed spectra

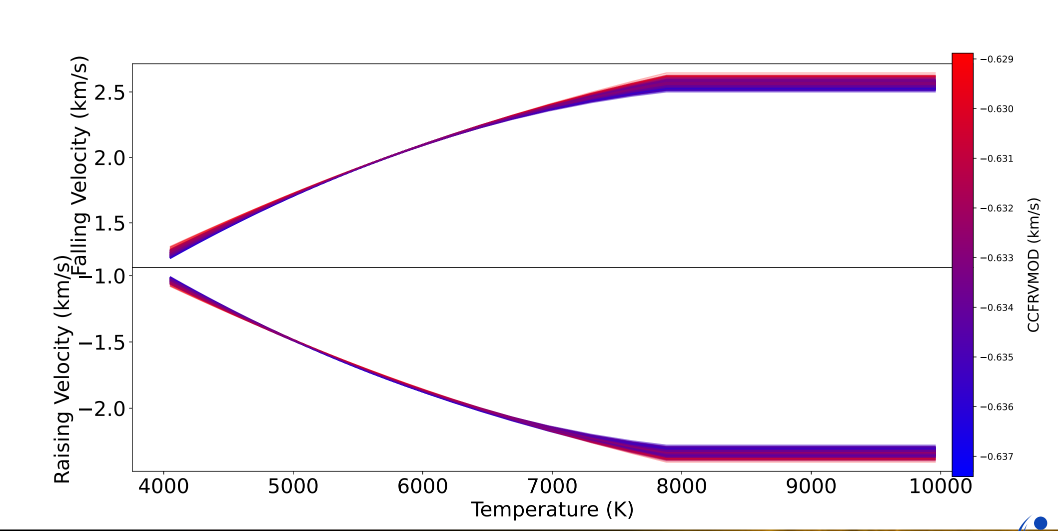
Fitted spectra



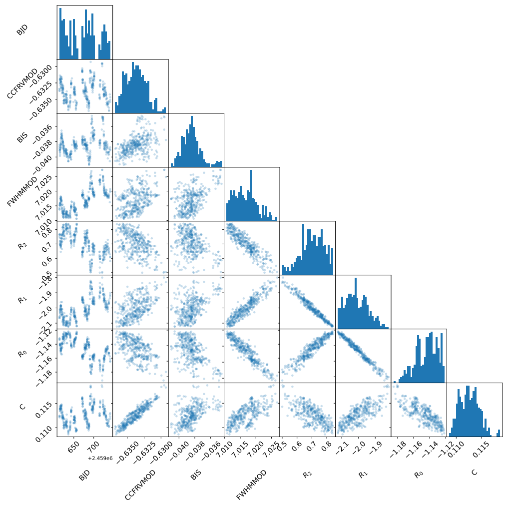
Fitted spectra - Lines



Velocity Profile

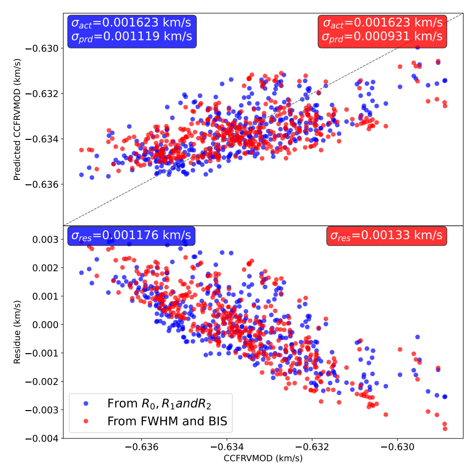


Parameters



- The model parameters are highly correlated.
- Can the model parameters predict CCF parameters?

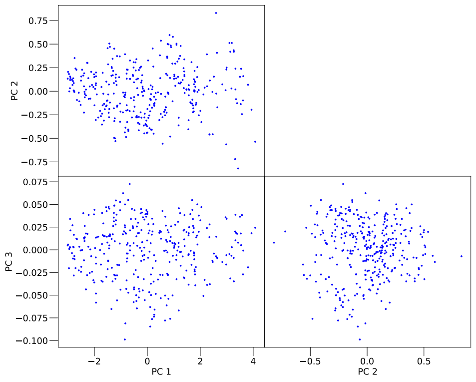
CCF parameters vs Model parameters



- Profile parameters (R_2, R_1 R_0) could reduce the stellar activity better than CCF parameters.
- Scatter in CCF RVMOD: $\sim$ 1.62 **m/s**.
- Reduction in scatter by FWHM and BIS: $\sim$ 1.33 **m/s**.
- Reduction in scatter by profile parameters: $\sim$ 1.18 **m/s**.
  - Improvement in quadrature is $\sim$ 1.12 **m/s**.

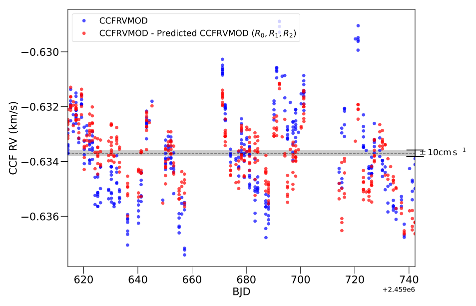
Ongoing

- Since the profile parameters (R_2, R_1, R_0, C) are correlated to each other, we applied PCA on the parameter space.
- PCA orthogonalization revealed a partial degeneracy between Doppler shifts and stellar activity. We are exploring prior selections to reduce this degeneracy.



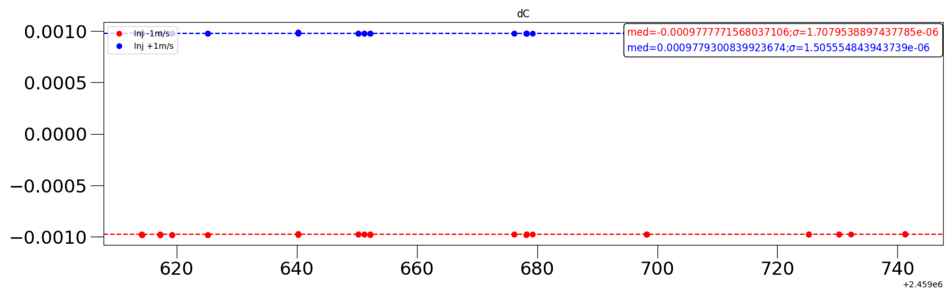
Summary

- This novel method measures the variability of raising and falling regions of the photosphere.
- The model separates the photospheric velocity field from the planetary motion of the star.
- The model parameters can reduce the scatter of CCFRV to ~ 1.18 m/s.



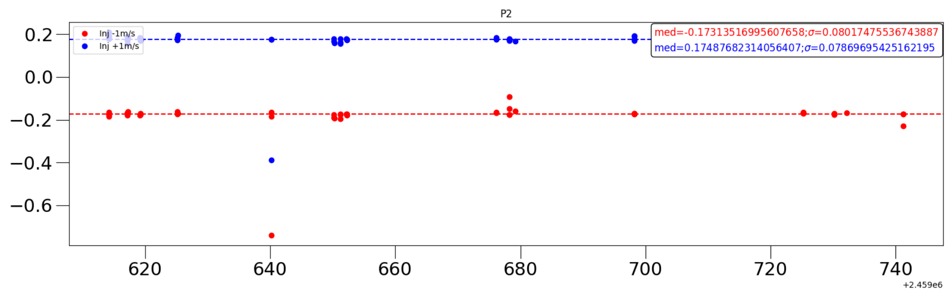
Difference on dC

- dC absorbed the injected velocity (here, 1 m/s). Scatter is $\sim$ 1 mm/s.



Difference in P_2

- P_2 also changed wrt the injected velocity. Shift is $\sim 174 \pm 0.08$ m/s.



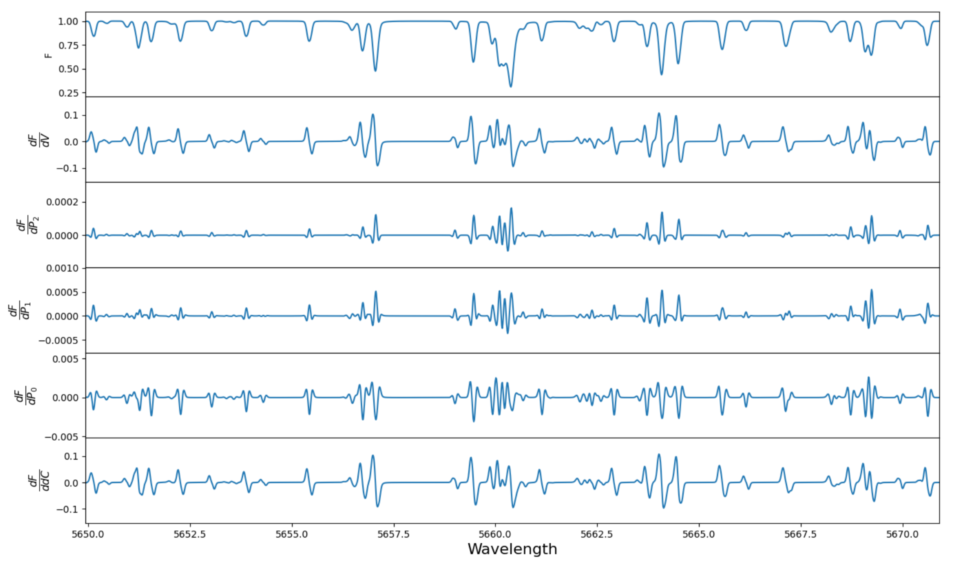
Dot product test

- Why the Profile parameters are changing while inject the velocity?

($h=10^{-6}$)

- $\langle \frac{dF}{dv}, \frac{dF}{ddC} \rangle = 310.484895126288$
- With PCs
  - $\langle \frac{dF}{dv}, \frac{dF}{dP_2} \rangle = -0.07090215794848242$
  - $\langle \frac{dF}{dv}, \frac{dF}{dP_1} \rangle = -0.29370020034043076$
  - $\langle \frac{dF}{dv}, \frac{dF}{dP_0} \rangle = 2.5071555998743777$
- With Rs
  - $\langle \frac{dF}{dv}, \frac{dF}{dR_2} \rangle = 10.555977701240572$
  - $\langle \frac{dF}{dv}, \frac{dF}{dR_1} \rangle = 30.011363774143437$
  - $\langle \frac{dF}{dv}, \frac{dF}{dR_0} \rangle = 99.80239699275697$
- This shows that even if there is a pure doppler shift due to bulk motion, the activity indicators will absorb some portion of it.

Derivatives wrt PCs



Derivatives wrt Rs