The Importance of Stellar Properties to Estimating Planet Characteristics

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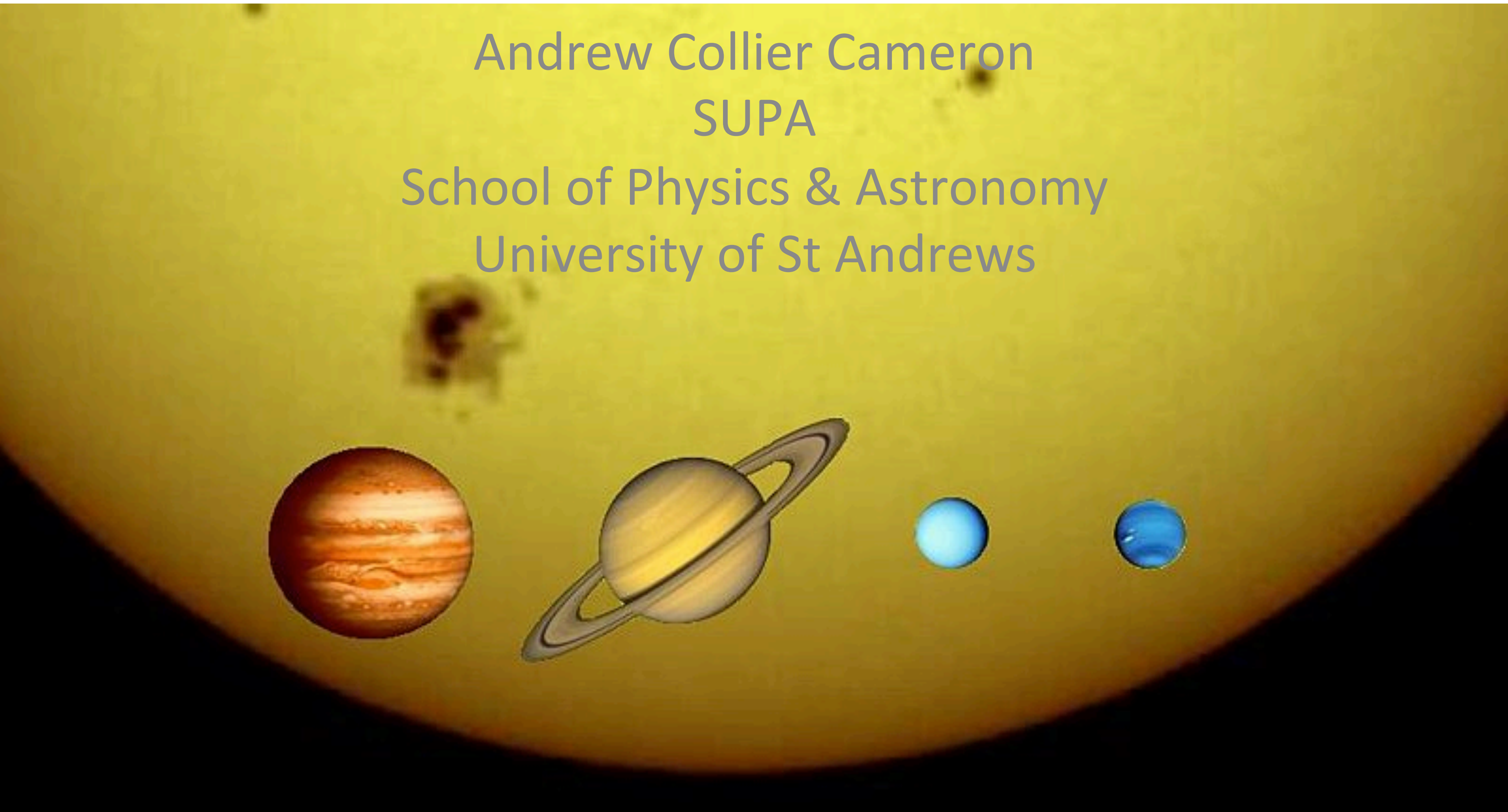
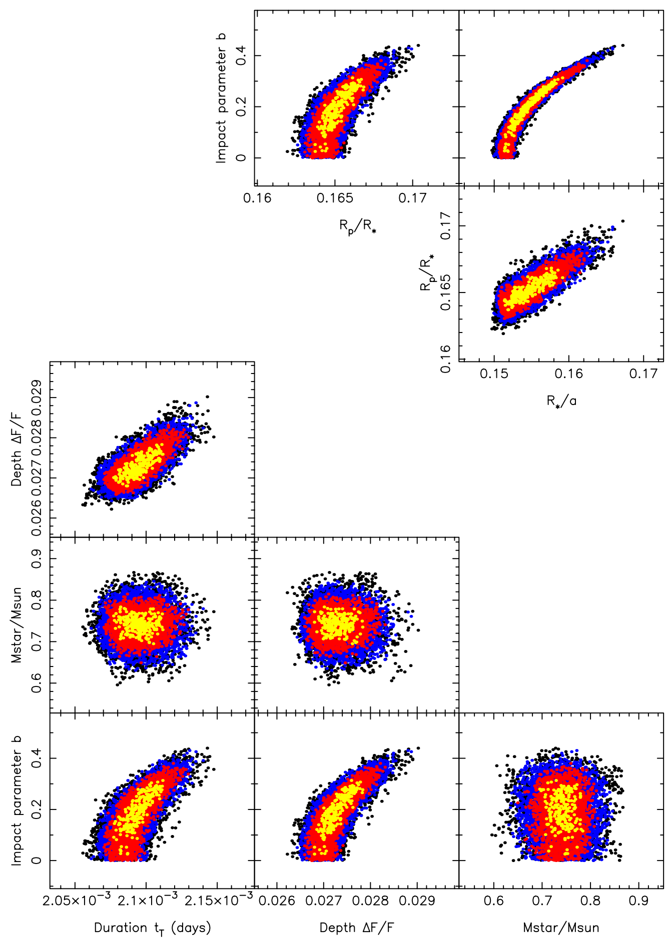


Fundamental observables - transits



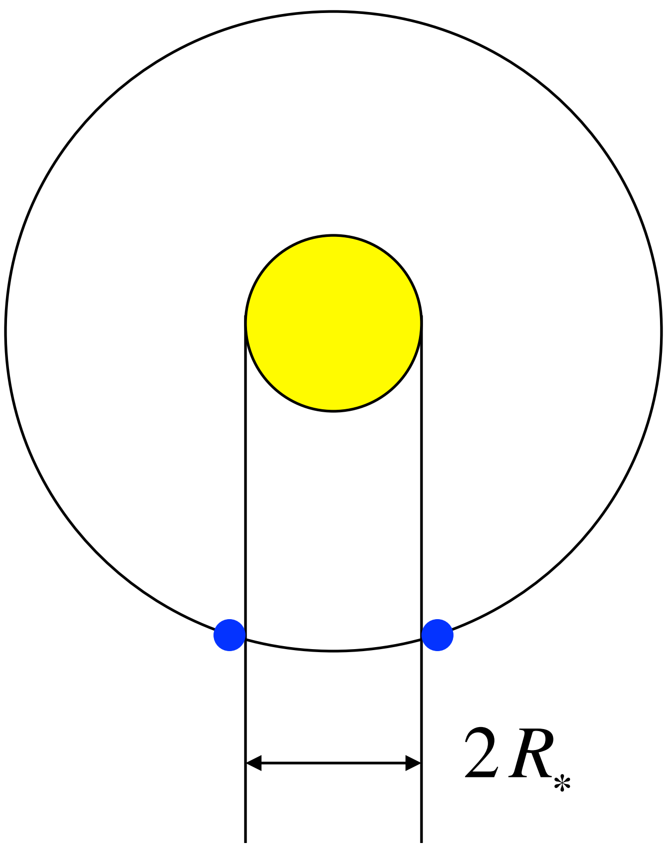
Bryan et al 2012 (Qatar-2b)

- Fundamental observables:
  - transit depth
  - transit duration
  - impact parameter
- Derived quantities:
  - R_p/R_*
  - R_*/a
- Need to know:
  - M_*
  - Limb darkening
  - cf. Jason Eastman's & Eric Agol's talks yesterday

Transit Duration ($i = 90^o$)

Consider **circular edge-on orbit:**

$$\text{circumference} = 2\pi\, a$$



$$\frac{\Delta t}{P} \approx \frac{2(R_* + r_p)}{2\pi\, a} \approx \frac{R_*}{\pi\, a}$$

$$\text{Kepler's law :} \quad a^3 = G\, M_* \left(\frac{P}{2\pi}\right)^2$$

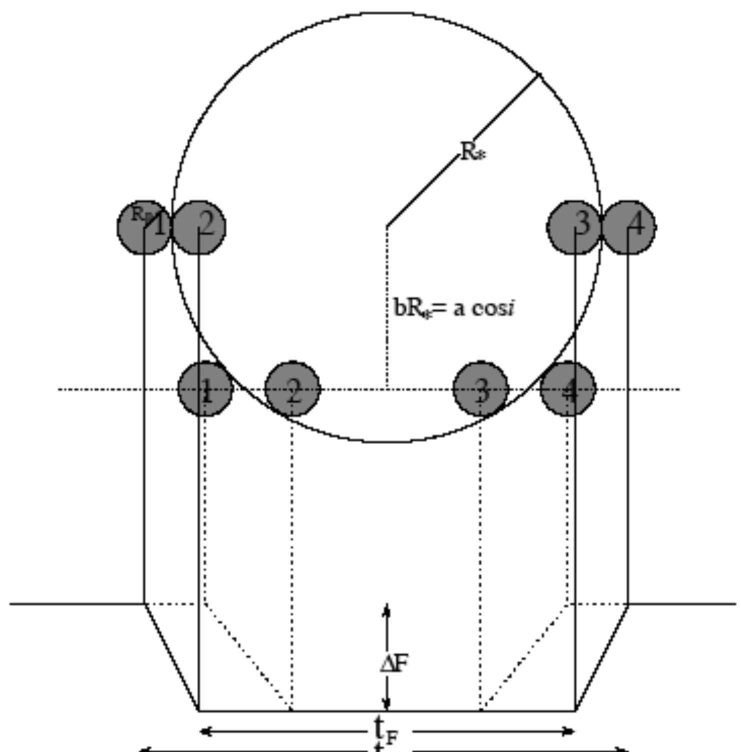
$$\Delta t \approx \frac{P\, R_*}{\pi\, a} = \frac{P\, R_*}{\pi}\left(\frac{4\pi^2}{GMP^2}\right)^{1/3}$$

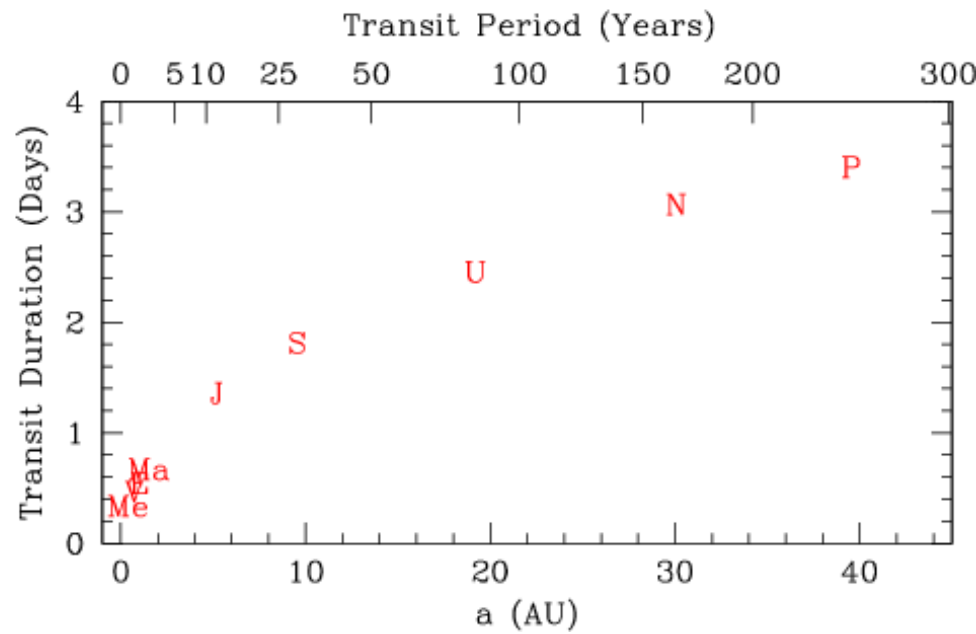
$$= 3\text{h} \left(\frac{P}{4\text{d}}\right)^{1/3} \left(\frac{R_*}{R_{Sun}}\right)\left(\frac{M_*}{M_{Sun}}\right)^{-1/3}$$

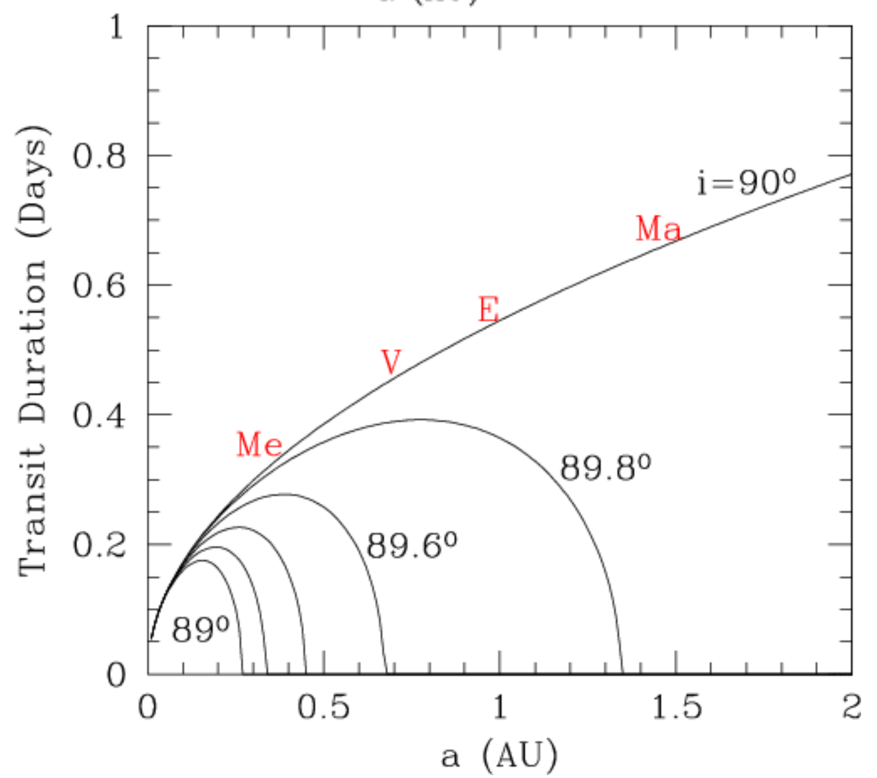
Transit Duration

$$t_T = \frac{P R_*}{\pi a}\sqrt{\left(1+\frac{R_p}{R_*}\right)^2 - \left(\frac{a}{R_*}\cos i\right)^2}\;.$$

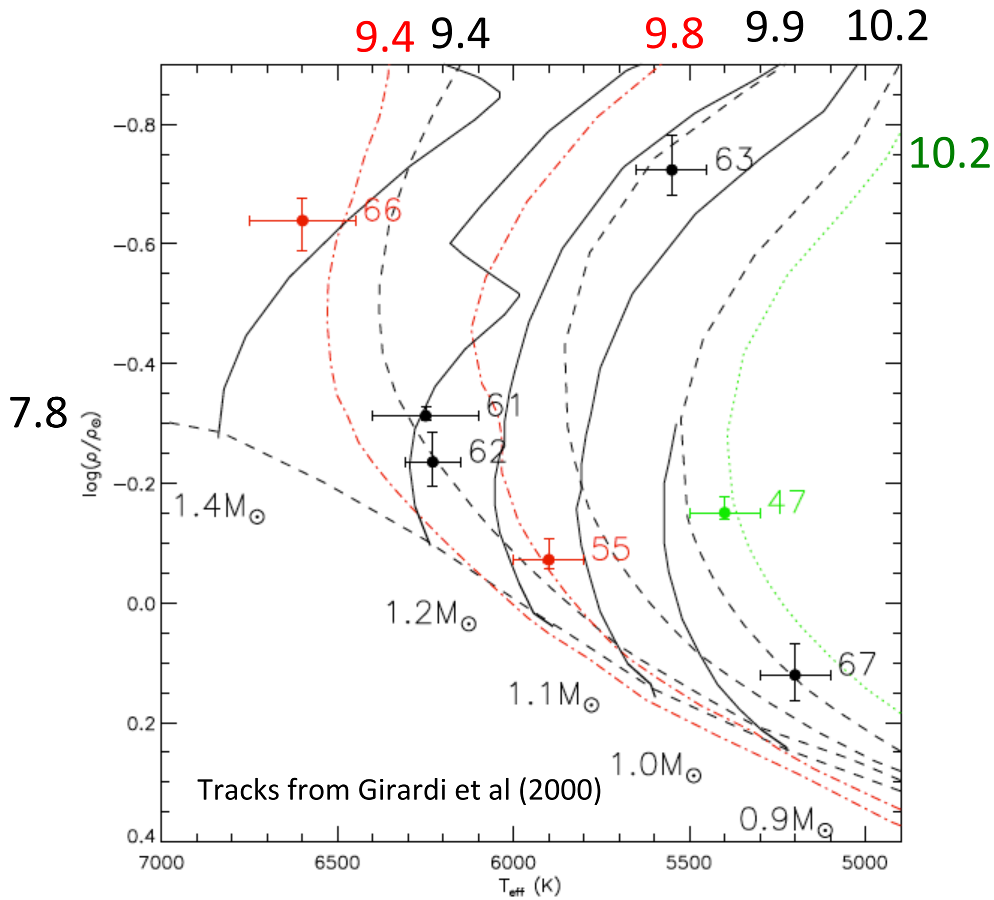
Shape of lightcurve determines impact parameter, $b = a \cos i / R_*$ hence inclination.







The T_{eff} vs $\rho^{-1/3}$ HR diagram



[Fe/H]=+0.18, 0.0, -0.2

Hellier et al 2012, arXiv/1204.5095

- R_*/a is a direct measure of stellar density:

$$\left(\frac{R_*}{a}\right)^3 = \frac{3\pi}{GP^2}\frac{4\pi R_*^3}{3M_*}$$

$$\Rightarrow \frac{R_*}{a} = \left(\frac{3\pi}{G}\right)^{1/3} P^{-2/3}\rho_*^{-1/3}$$

- Stellar mass estimates are as good as the models that produce the tracks and isochrones!

Empirical mass-radius relation: 94 EBs

$$\log M = a_1 + a_2 X + a_3 X^2 + a_4 X^3 + a_5 (\log g)^2 + a_6 (\log g)^3 + a_7 [\mathrm{Fe/H}]$$

$$\log R = b_1 + b_2 X + b_3 X^2 + b_4 X^3 + b_5 (\log g)^2 + b_6 (\log g)^3 + b_7 [\mathrm{Fe/H}] \text{ , where } X = \log T_{\mathrm{eff}} - 4.1.$$

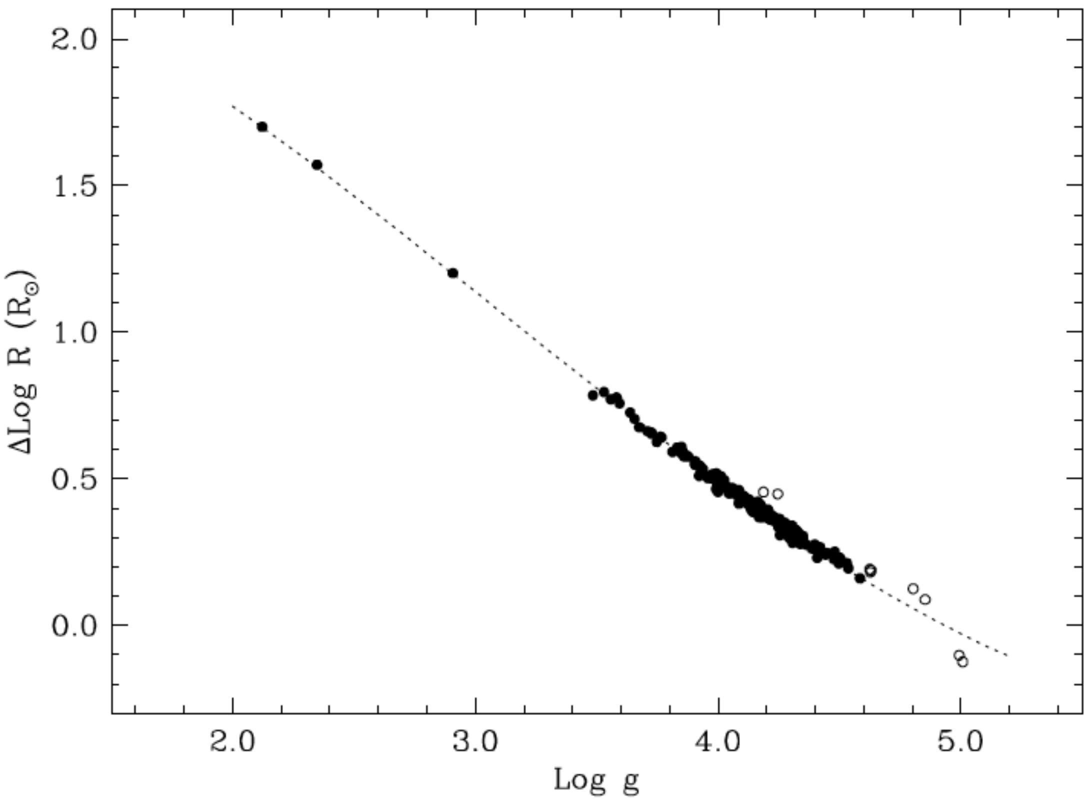


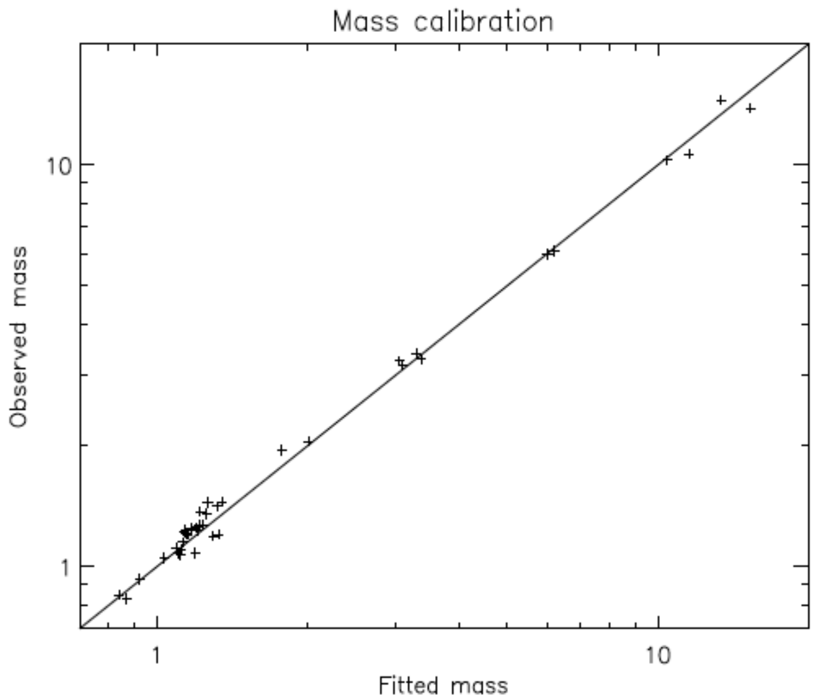
Fig. 14 Deviation of the observed radii from a polynomial ZAMS relation in T_{eff} and [Fe/H], $\Delta \log R$ vs. $\log g$. Open symbols denote stars below 0.6 $M_{\odot}$ and pre-main-sequence stars. The dotted line represents the remaining fitted dependence on $\log g$.

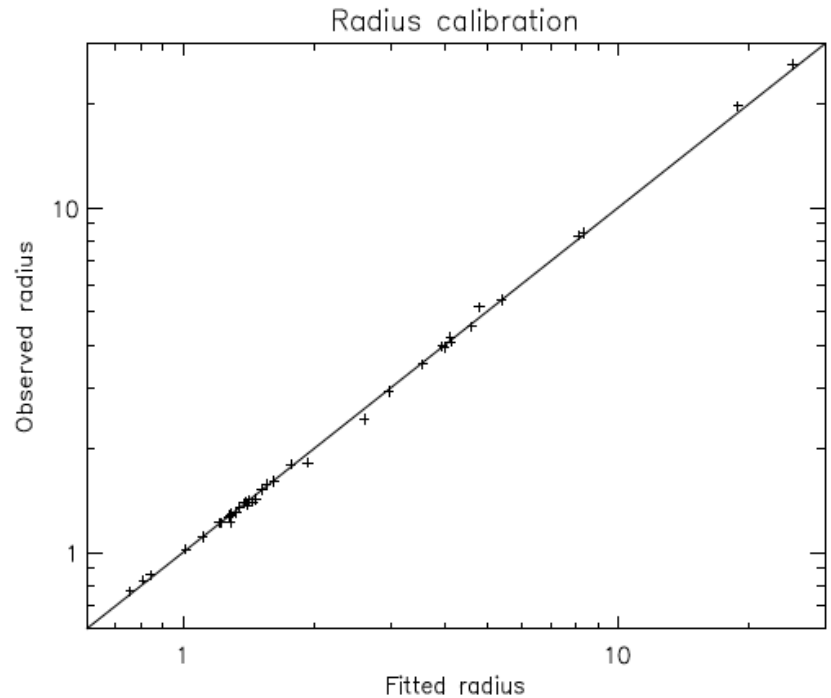
Torres, Andersen & Giménez 2010, A&ARv, 18, 67

Empirical mass-radius-relation 2

$$\log M = a_1 + a_2 X + a_3 X^2 + a_4 \log\rho + a_5 \log\rho^2 + a_6 \log\rho^3 + a_7[\mathrm{Fe/H}]$$

$$\log R = b_1 + b_2 X + b_3 \log\rho + b_4[\mathrm{Fe/H}].$$



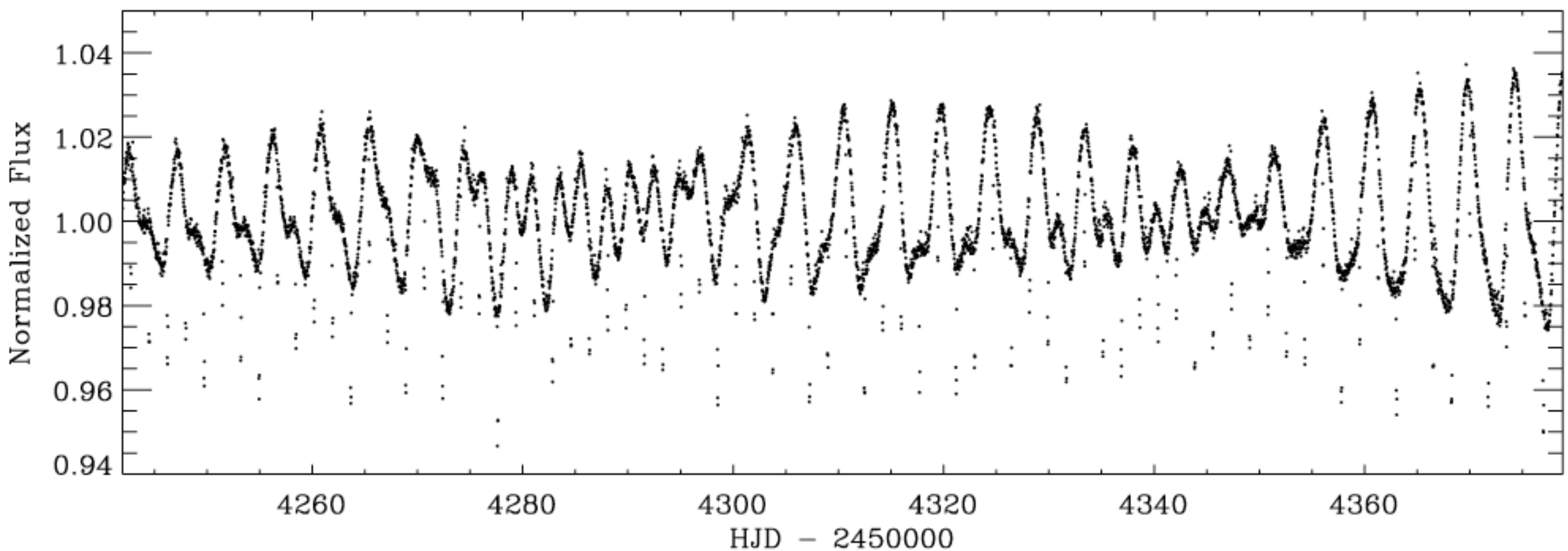


38 binary components with well-determined [Fe/H] from Torres et al 2010.

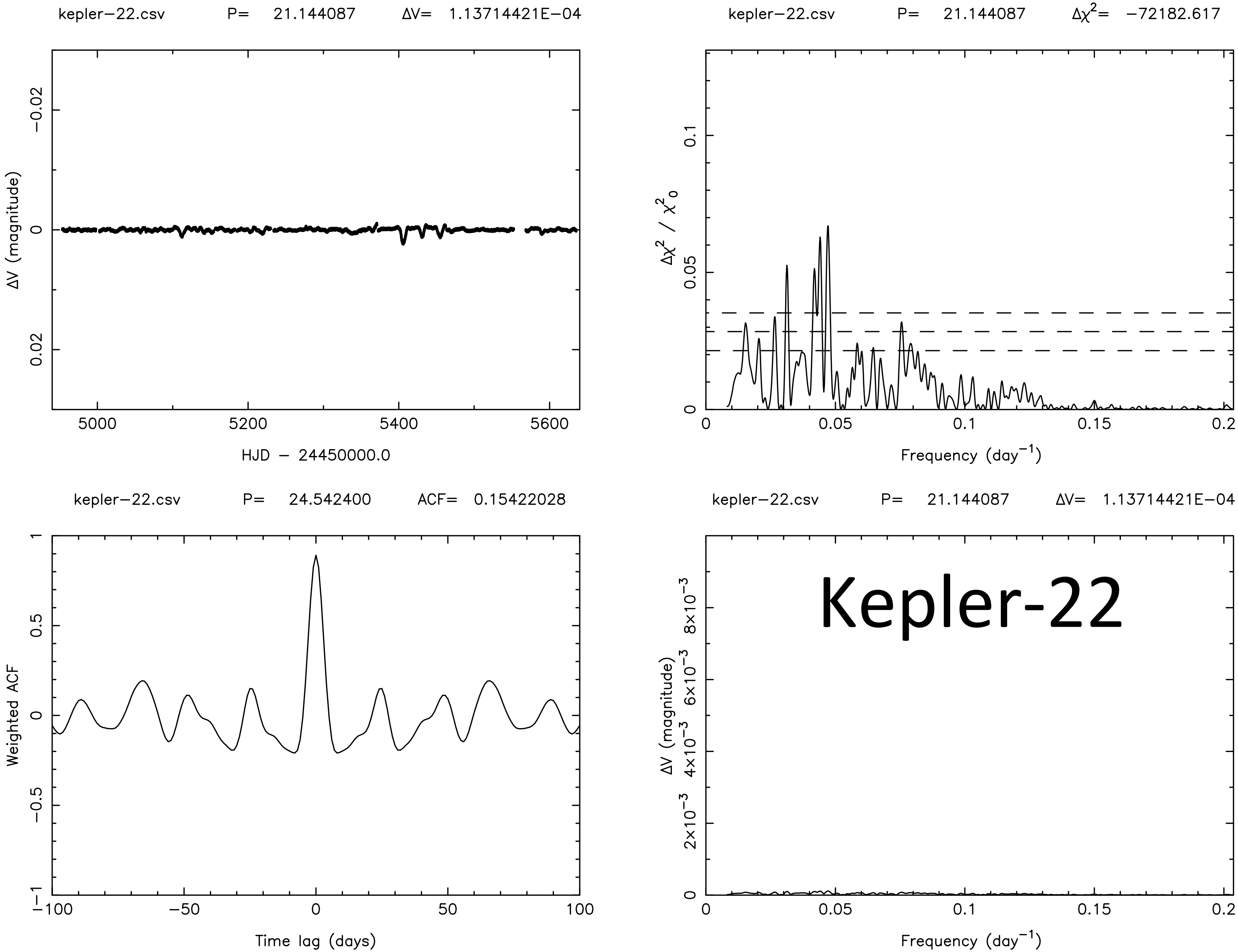
Enoch et al 2010, A&A 516, A33

Benign uses for starspots

R. Alonso et al.: CoRoT-Exo-2b

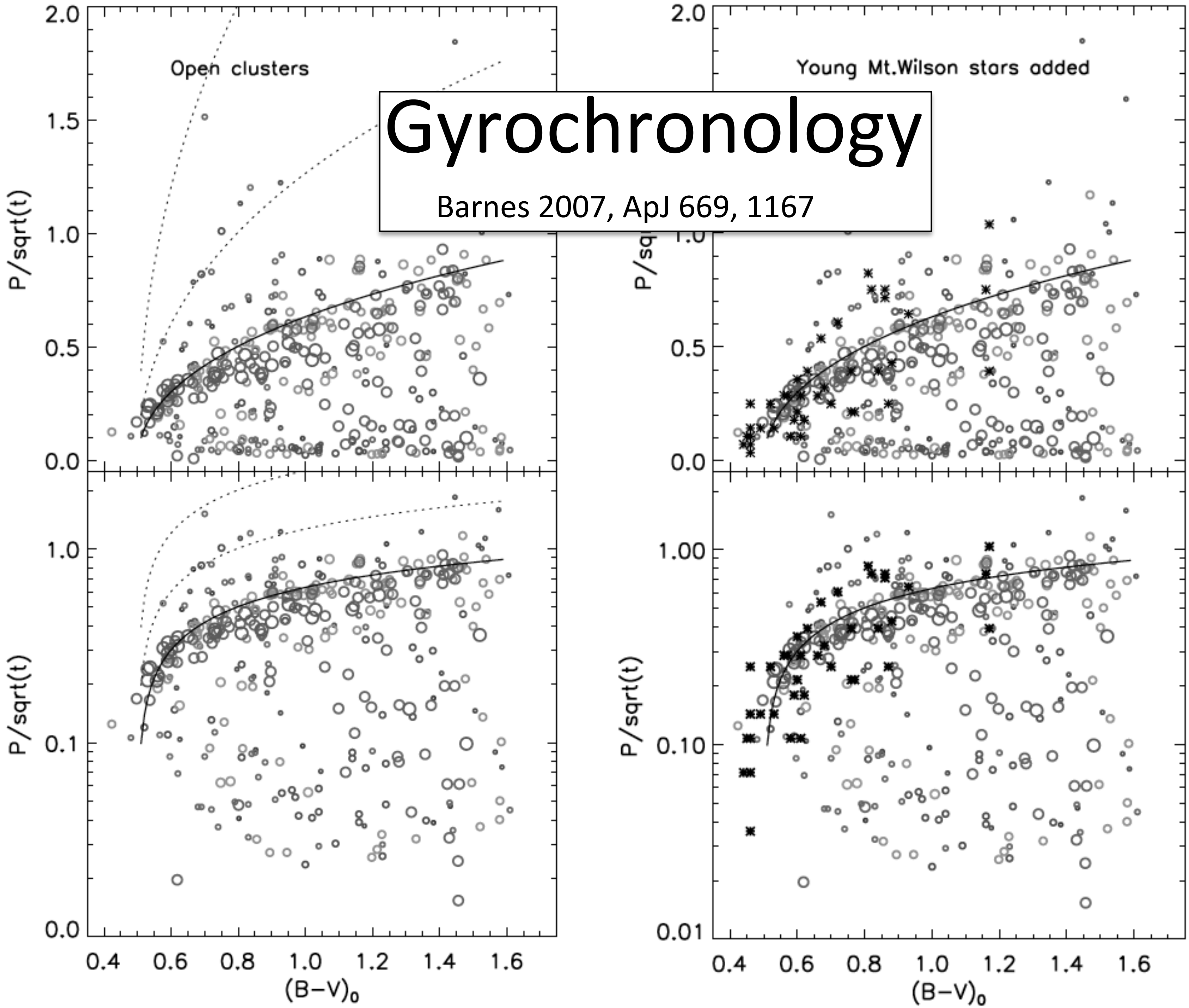


Alonso et al 2008, A&A 482, L21: CoRoT-2
Nutzman et al 2011, ApJ 740, 10

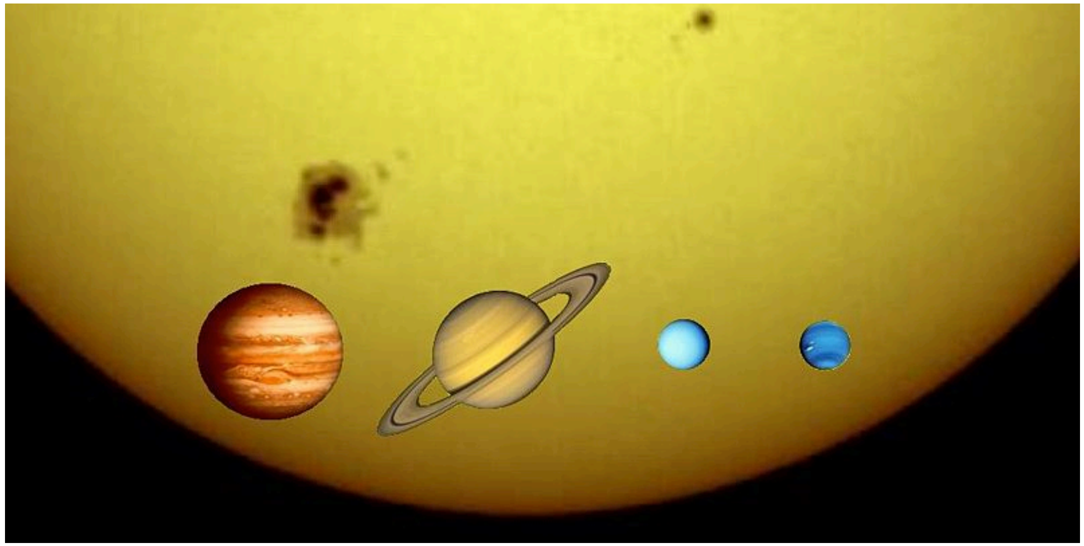

kepler−22.csv P= 21.144087 ΔV= 1.13714421E−04
ΔV (magnitude)
HJD − 24450000.0
kepler−22.csv P= 21.144087 Δχ2= −72182.617
Δχ2 / χ2o
Frequency (day−1)
kepler−22.csv P= 24.542400 ACF= 0.15422028
Weighted ACF
Time lag (days)
kepler−22.csv P= 21.144087 ΔV= 1.13714421E−04
ΔV (magnitude)
Frequency (day−1)
Kepler-22

Gyrochronology

Barnes 2007, ApJ 669, 1167



Transit Depth



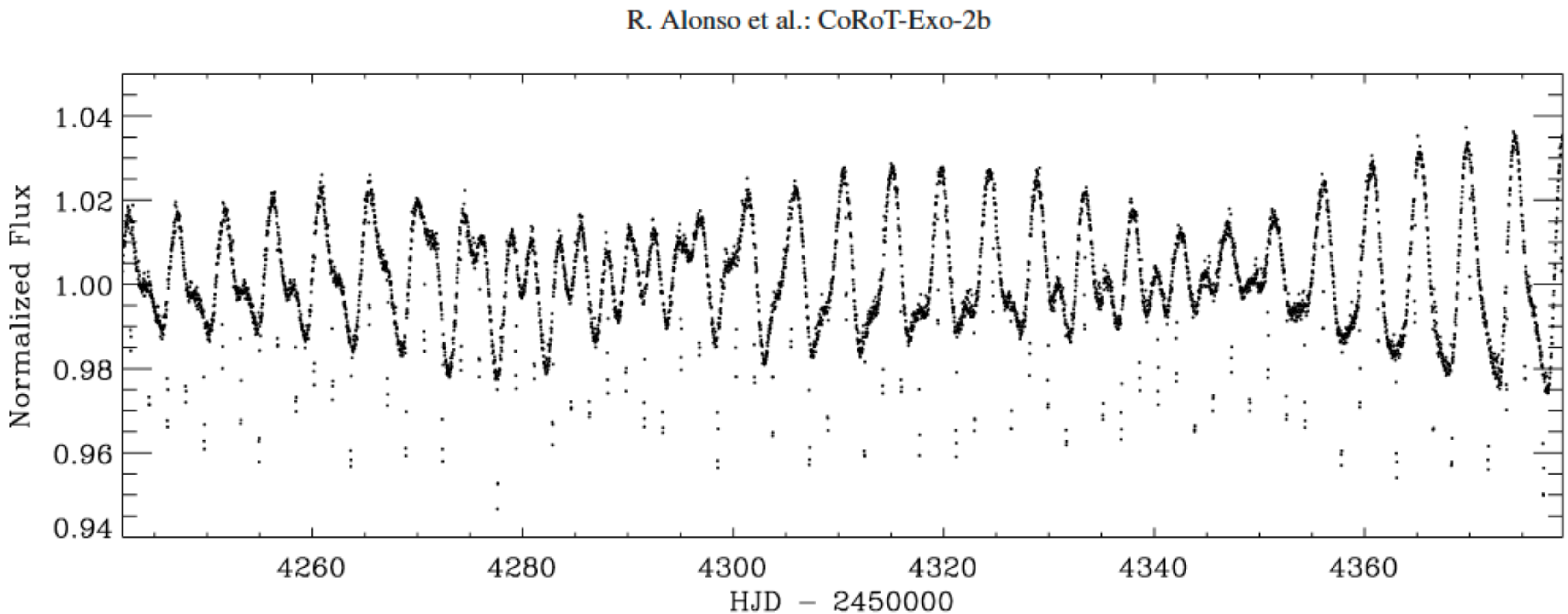
What fraction of the star's disk does the planet cover?

$$\frac{\Delta f}{f} \approx \left(\frac{r_p}{R_*}\right)^2 = 0.01\left(\frac{r_p}{r_{Jup}}\right)^2\left(\frac{R_*}{R_{sun}}\right)^{-2}$$

Find star radius from its spectral type.

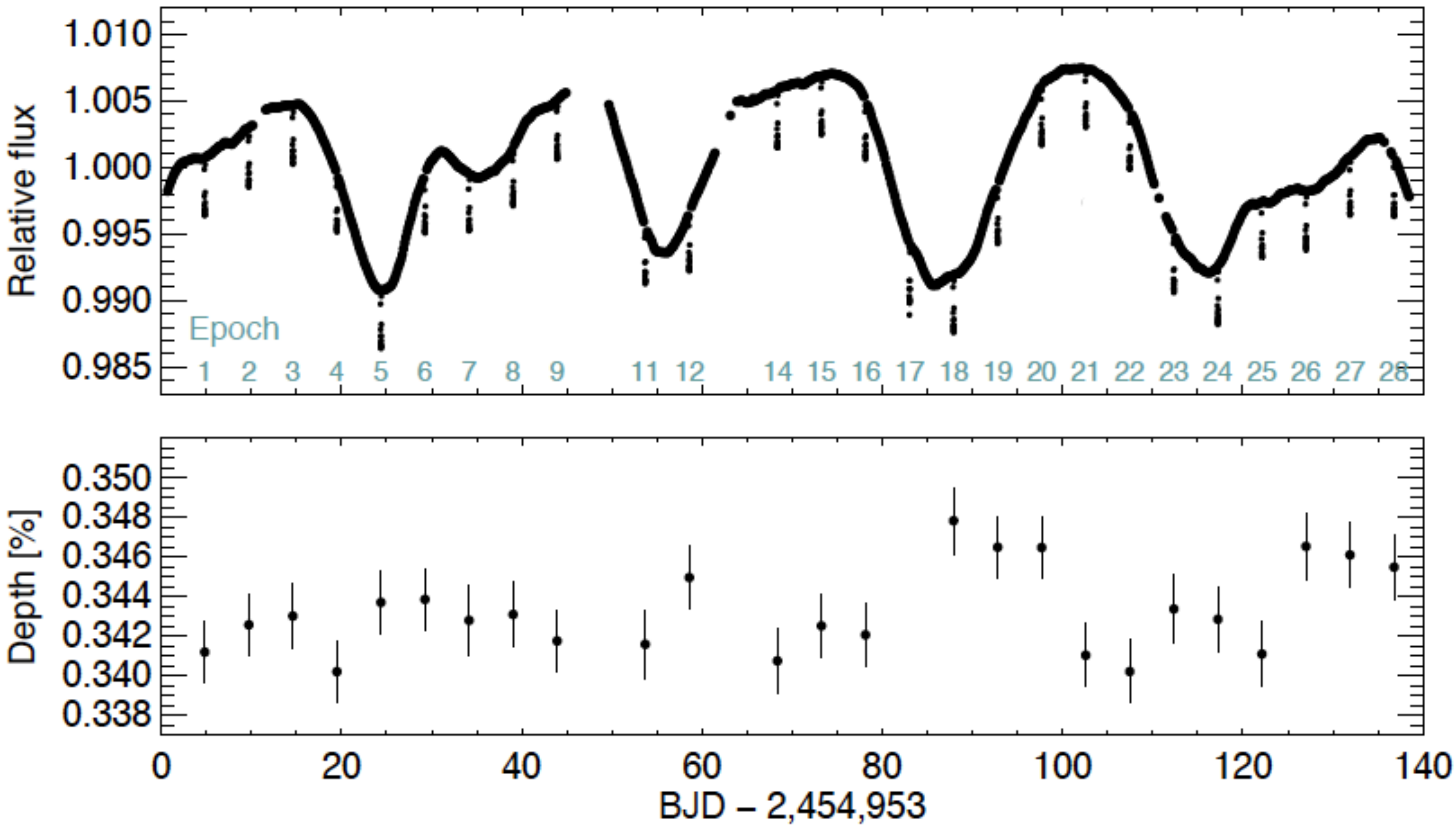
Observed depth tells us planet's radius.

Starspots as vermin



Alonso et al 2008, A&A 482, L21: CoRoT-2
Nutzman et al 2011, ApJ 740, 10

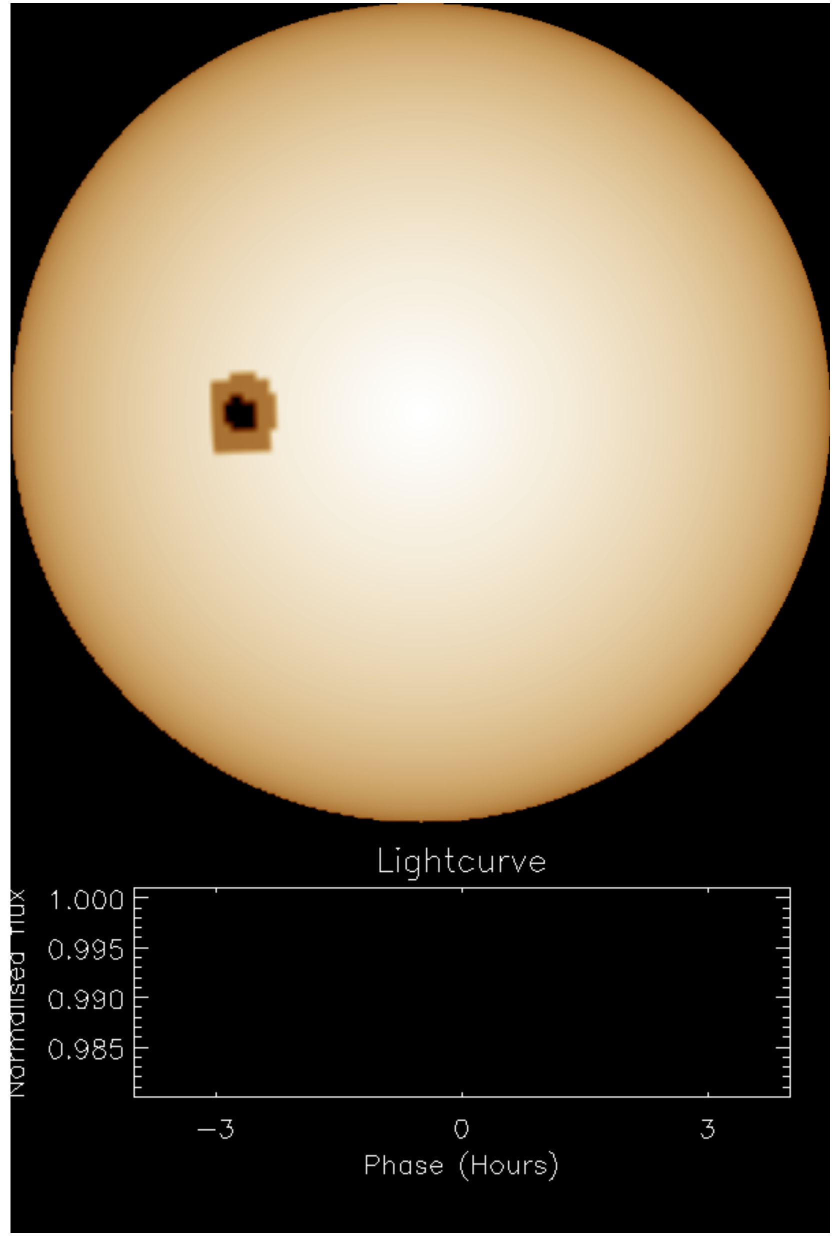
Constant flux deficit? HAT-P-11



Sanchis-Ojeda & Winn 2011, ApJ 743, 61

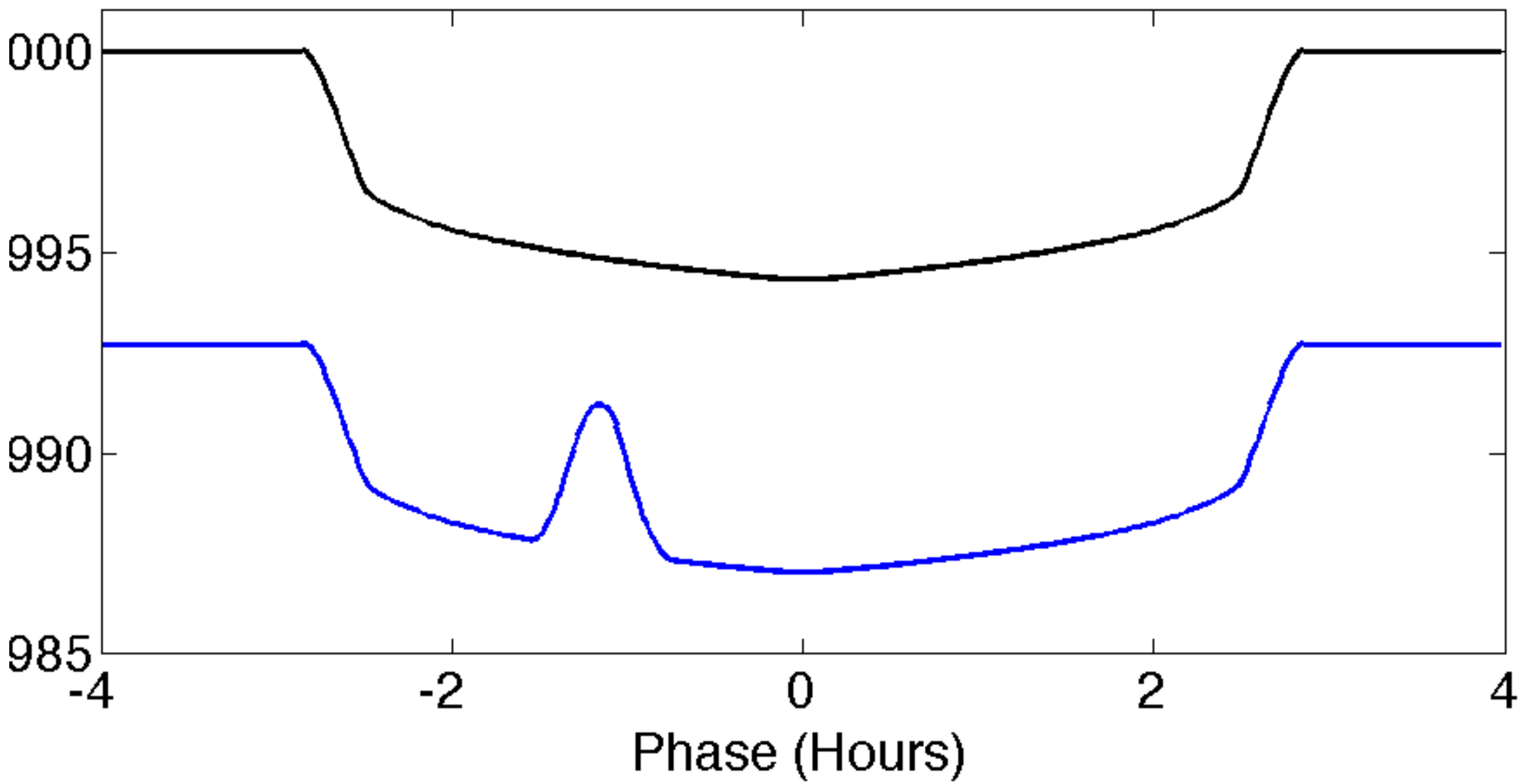
Transit depth amplification by uneclipsed starspots

Constant flux deficit at all times except when planet occults a spot.



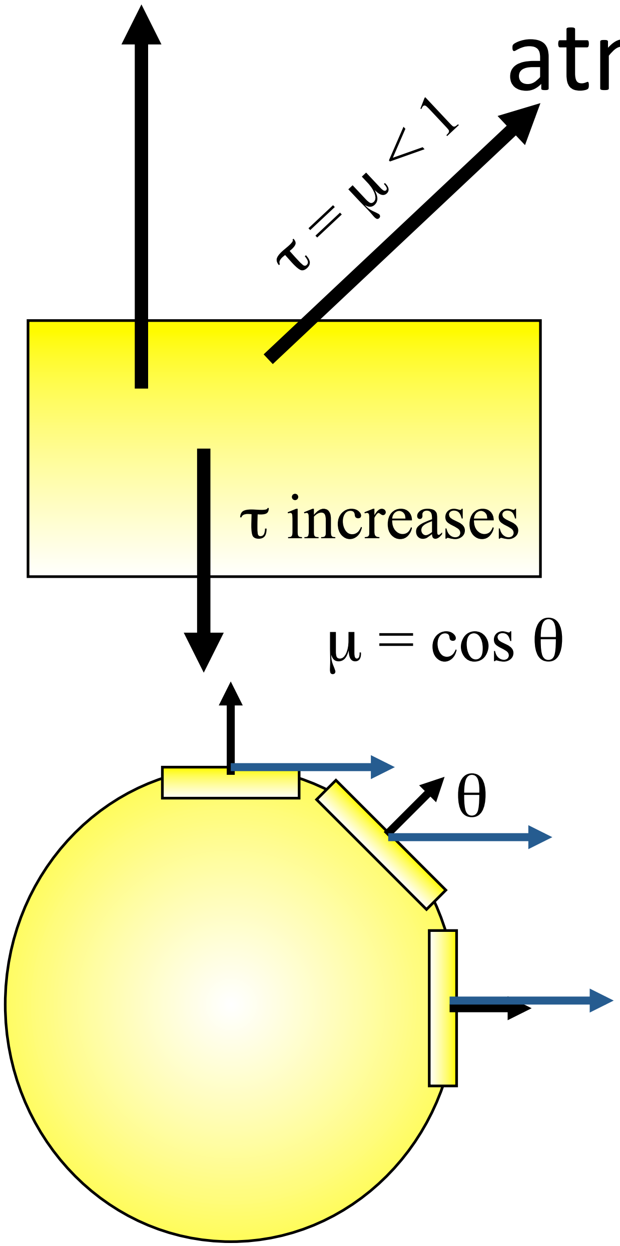
Animation courtesy of Joe Llama, St Andrews

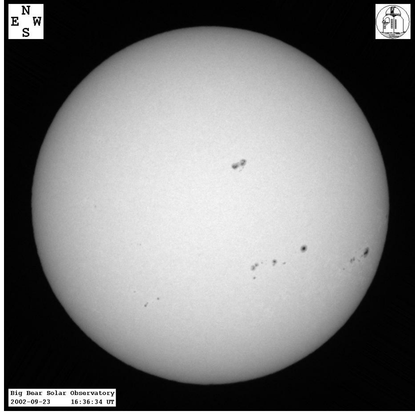
Transit depth amplification



Plot courtesy of Joe Llama, St Andrews

Limb darkening and atmospheric structure



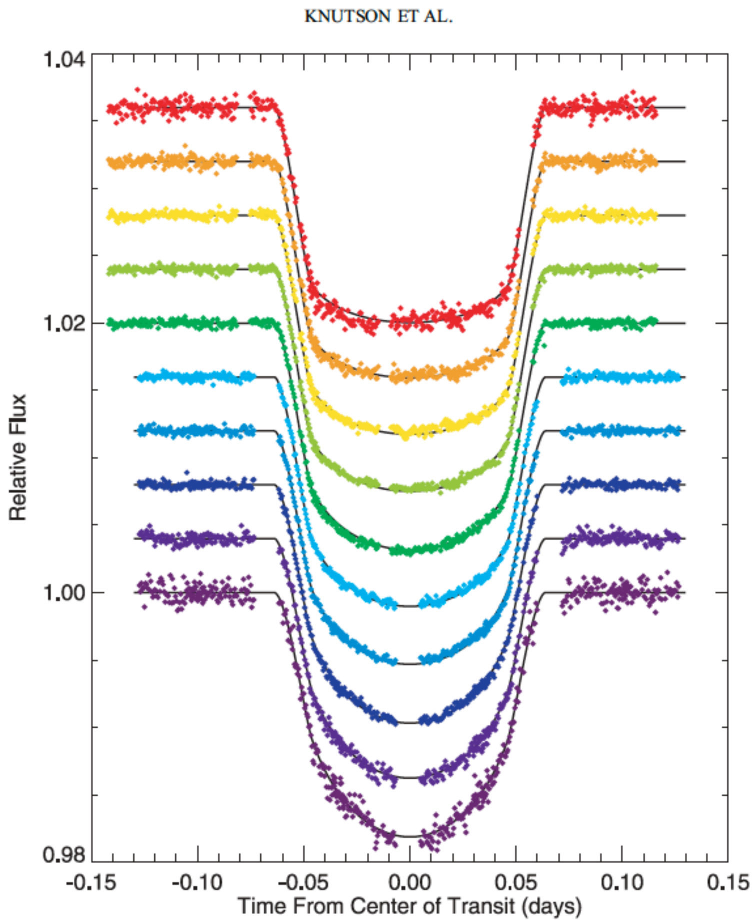


- Depth dependence of source function maps on to angular dependence of emergent specific intensity via Laplace transform:

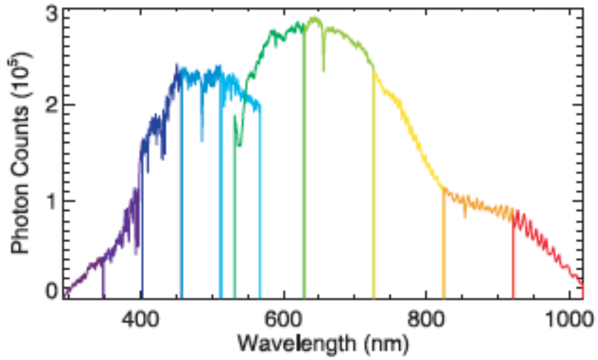
$$S_\nu(\tau_\nu) = \sum_{n=0}^{\infty} a_n \tau_\nu^n$$

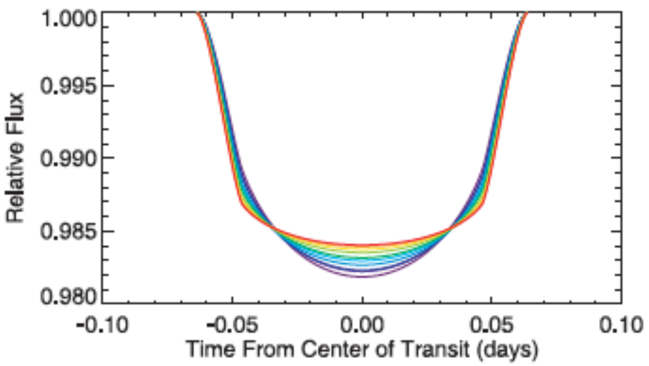
$$I_\nu^+(0,\mu) = \mathcal{L}_{1/\mu}\{S_\nu(\tau_\nu)\} = \sum_{n=0}^{\infty} n!\, a_n\, \mu^n$$

Wavelength dependence

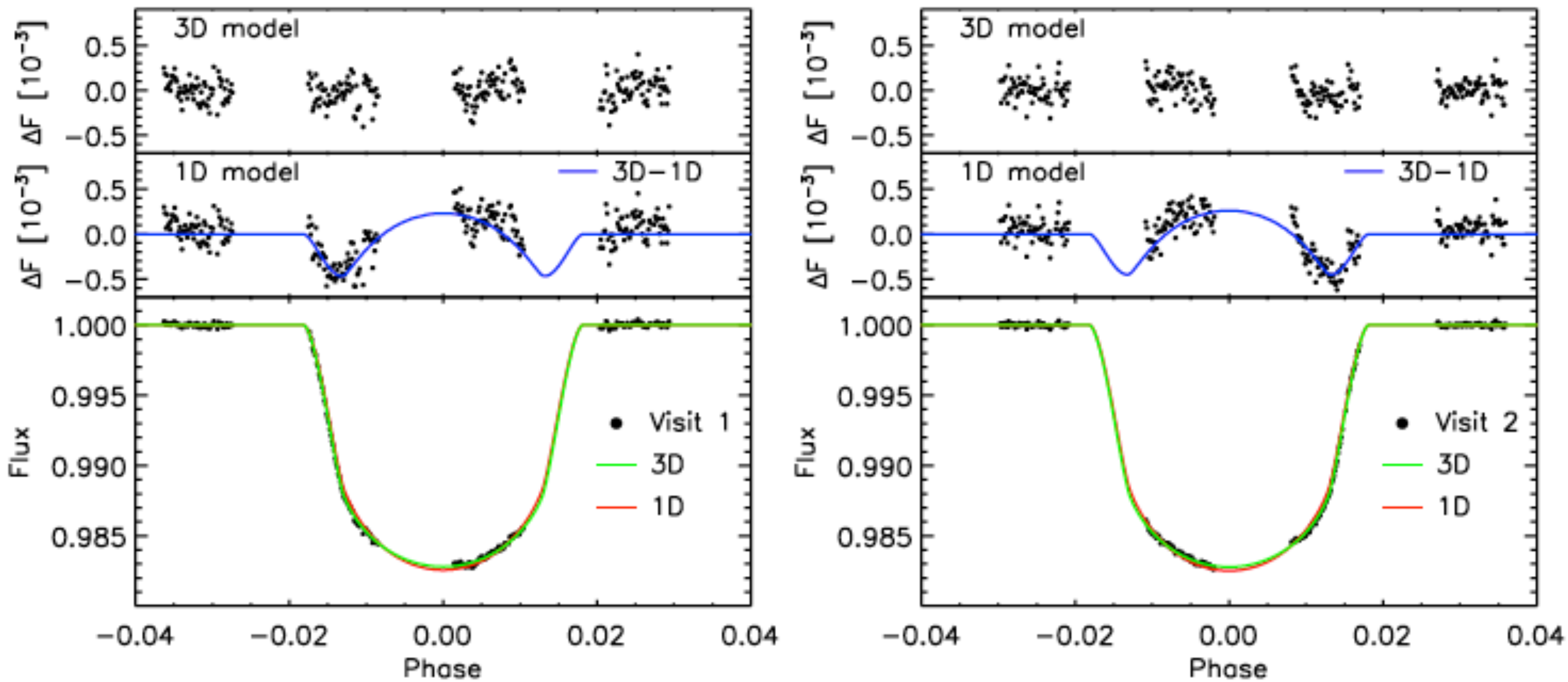


- Knutson et al 2007
- STIS spectrophotometry of HD 209458b transit





1D versus 3D atmosphere models



Hayek et al 2012, A&A 539, A102: 3D hydrodynamical atmosphere models including granulation vs 1D MARCS model atmosphere.

Transit depth reduction by eclipsed spots

Which effect wins?
Depends on spot coverage and active-belt location.

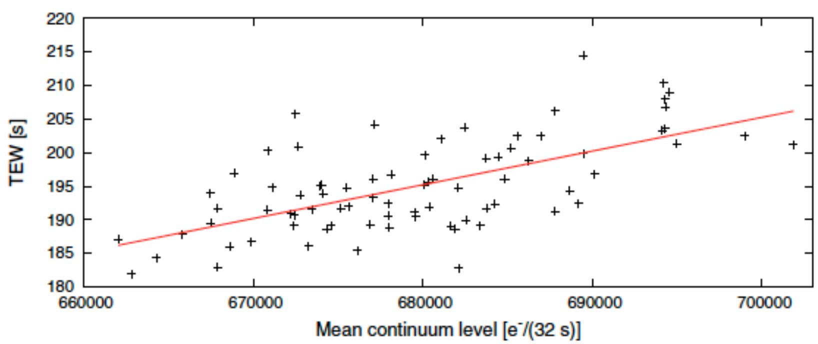


Fig. 1. Transit equivalent width (TEW) versus transit continuum level as well as the best-fit linear model.

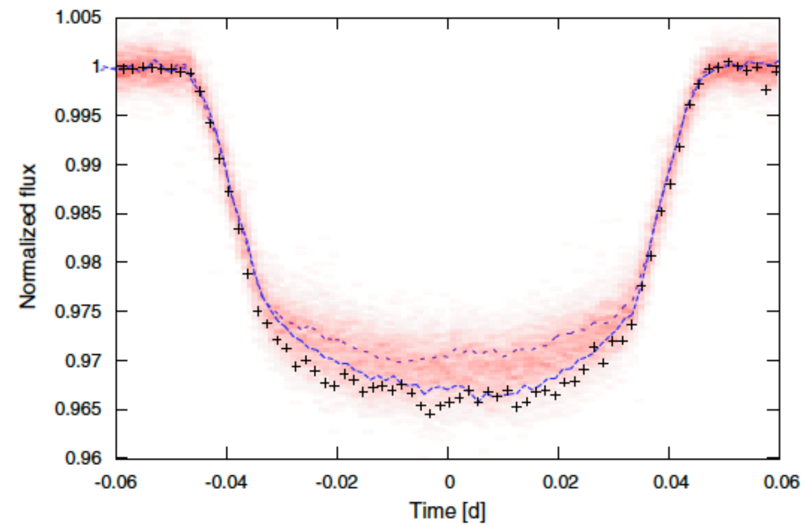
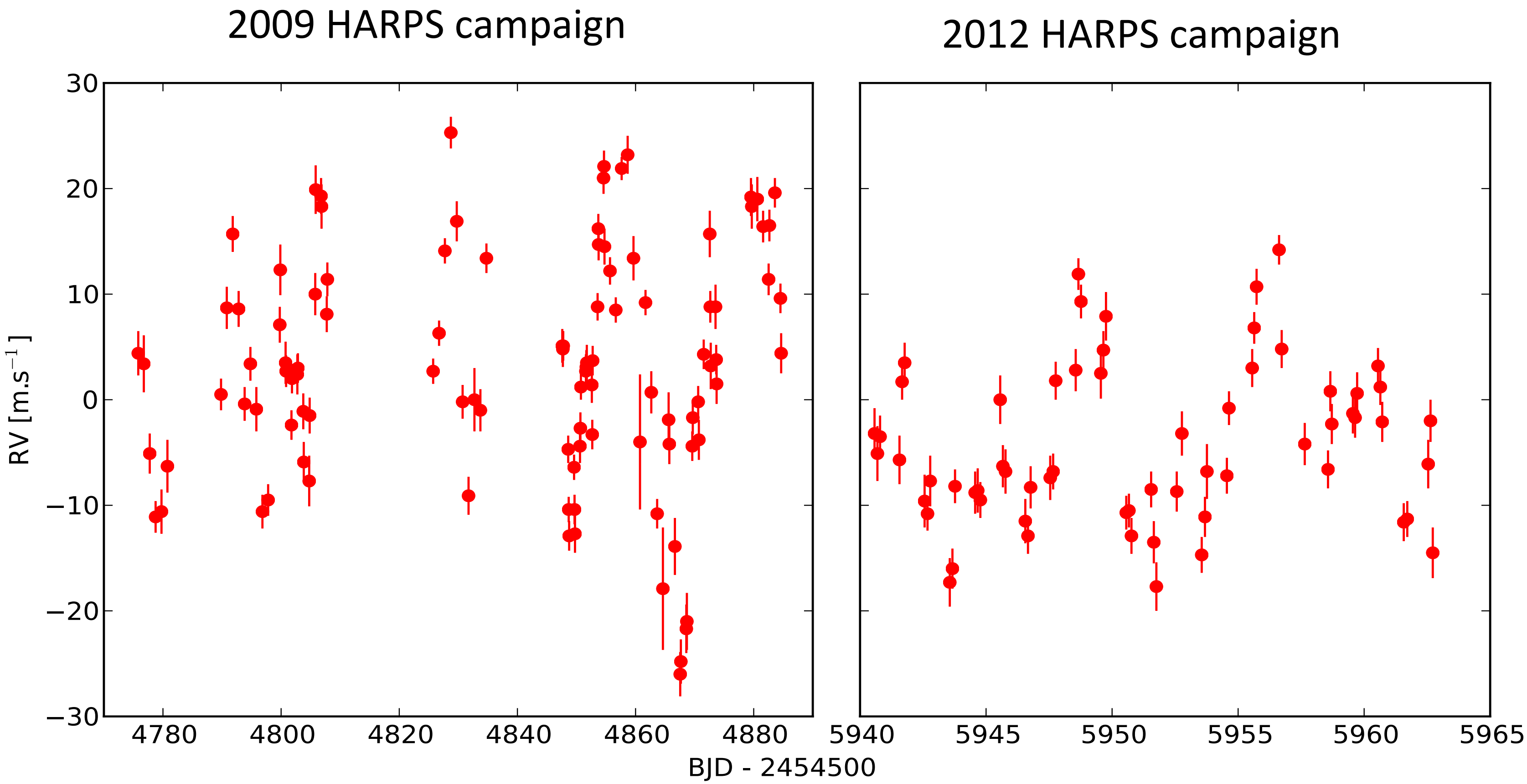


Fig. 2. Average transit light curves obtained by combining the ten profiles exhibiting the highest (thick dashes) and lowest (thin dashes) continuum levels. The crosses indicate our lower envelope estimate and the color gradient (red) illustrates the distribution of data points for all available transits.

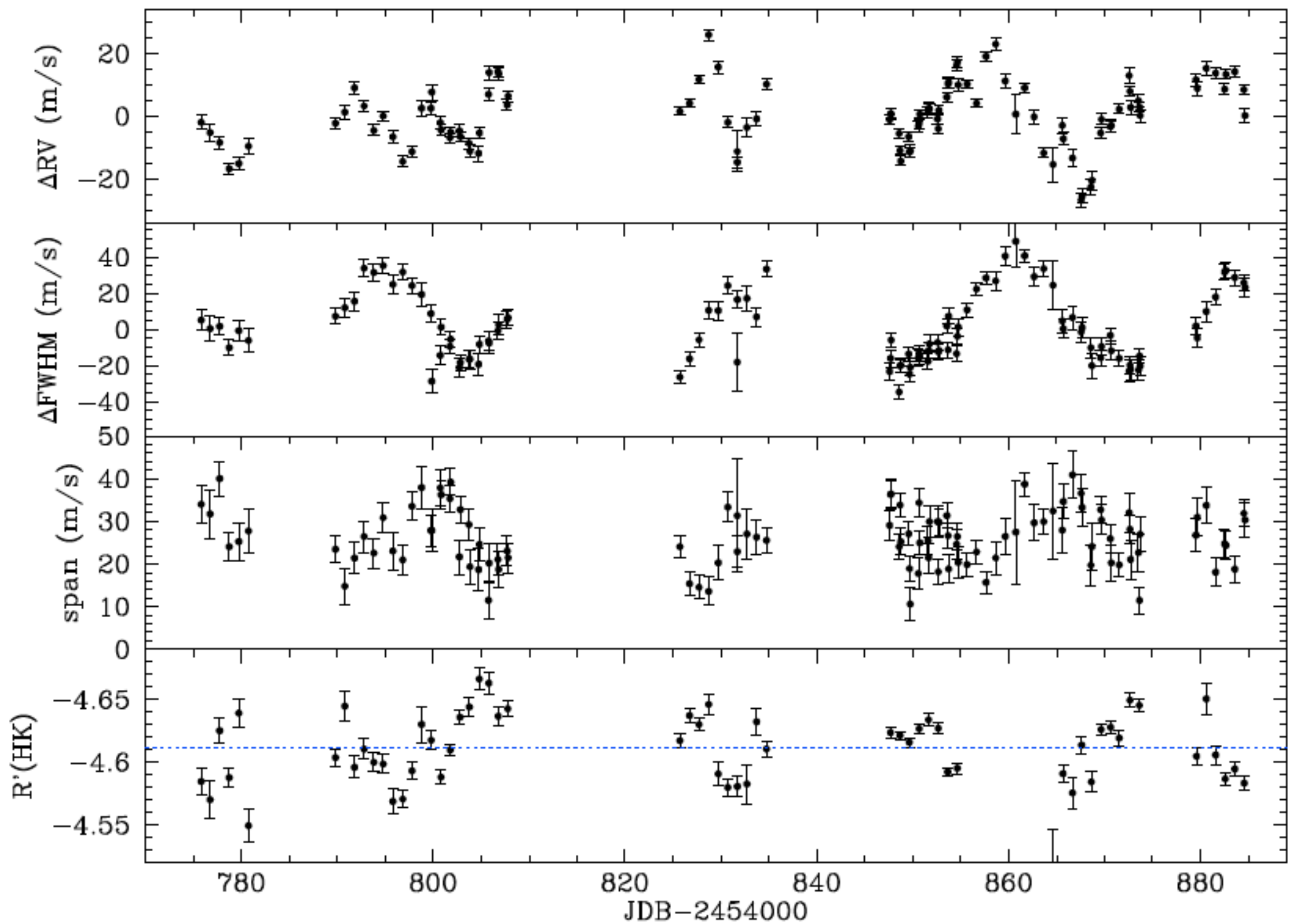
Czesla et al 2009, A&A 505, 1277: CoRoT-2

CoRoT-7: Spot-induced RV jitter



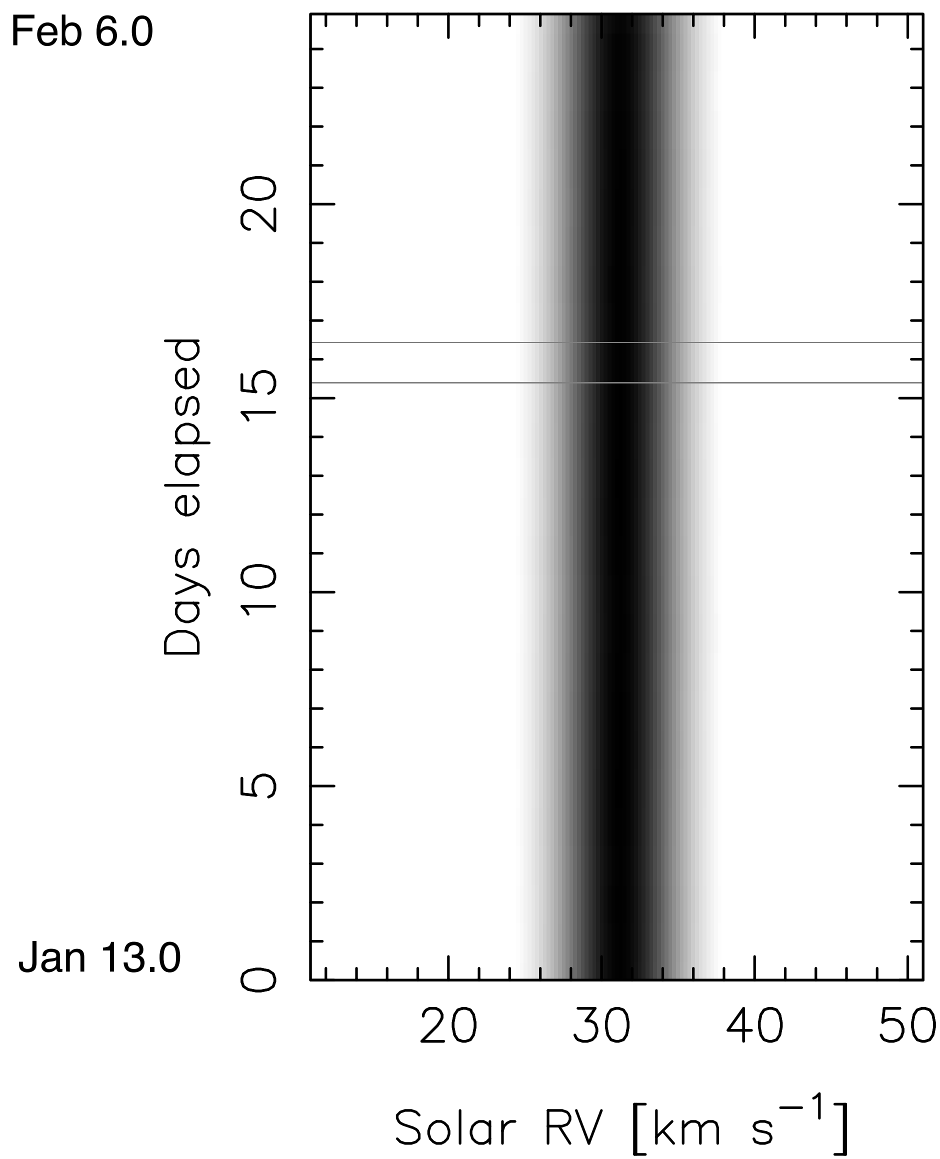
Decorrelation against activity proxies

CoRoT-7 2009 HARPS campaign

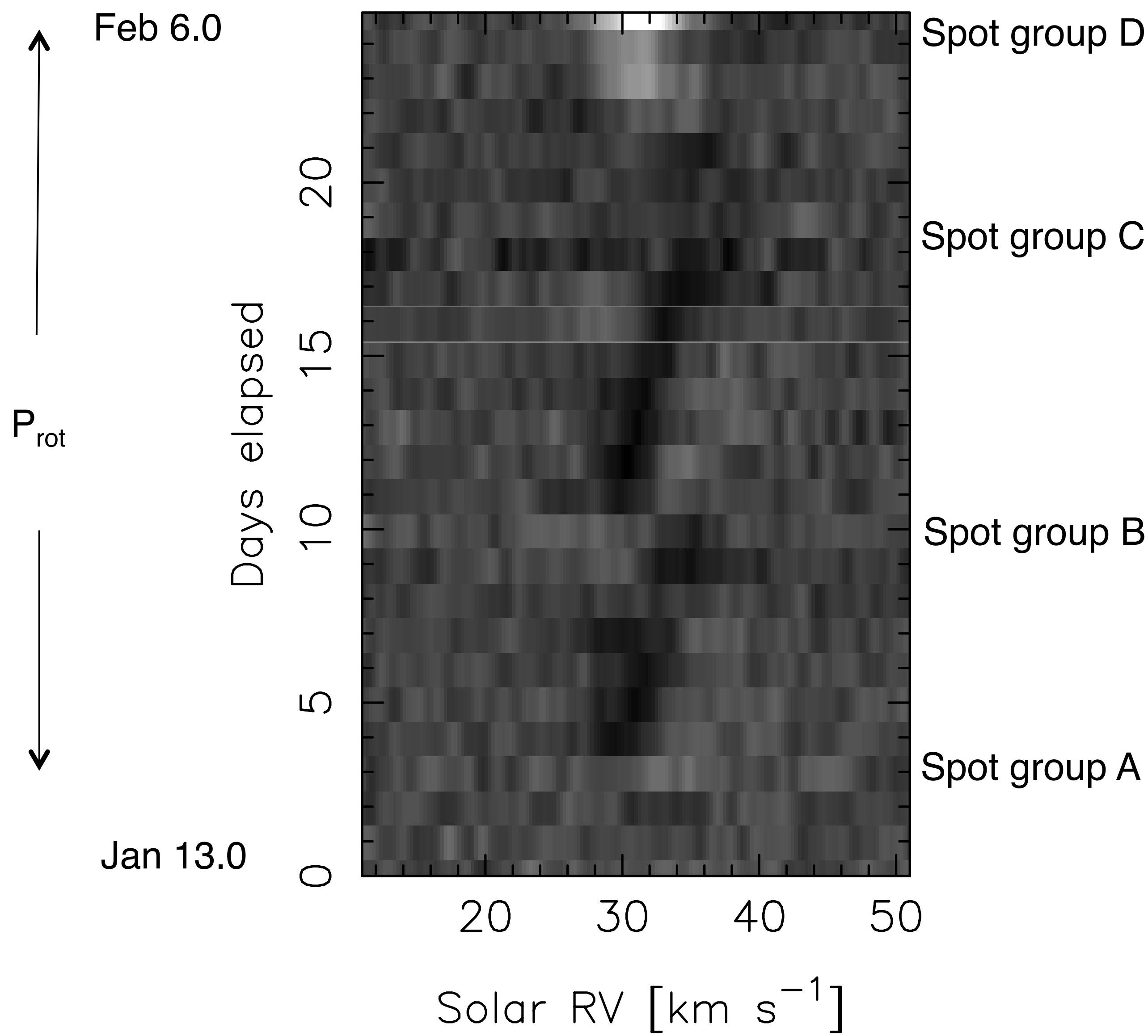


Queloz et al 2009, A&A 506, 303

CoRoT-7: HARPS CCF

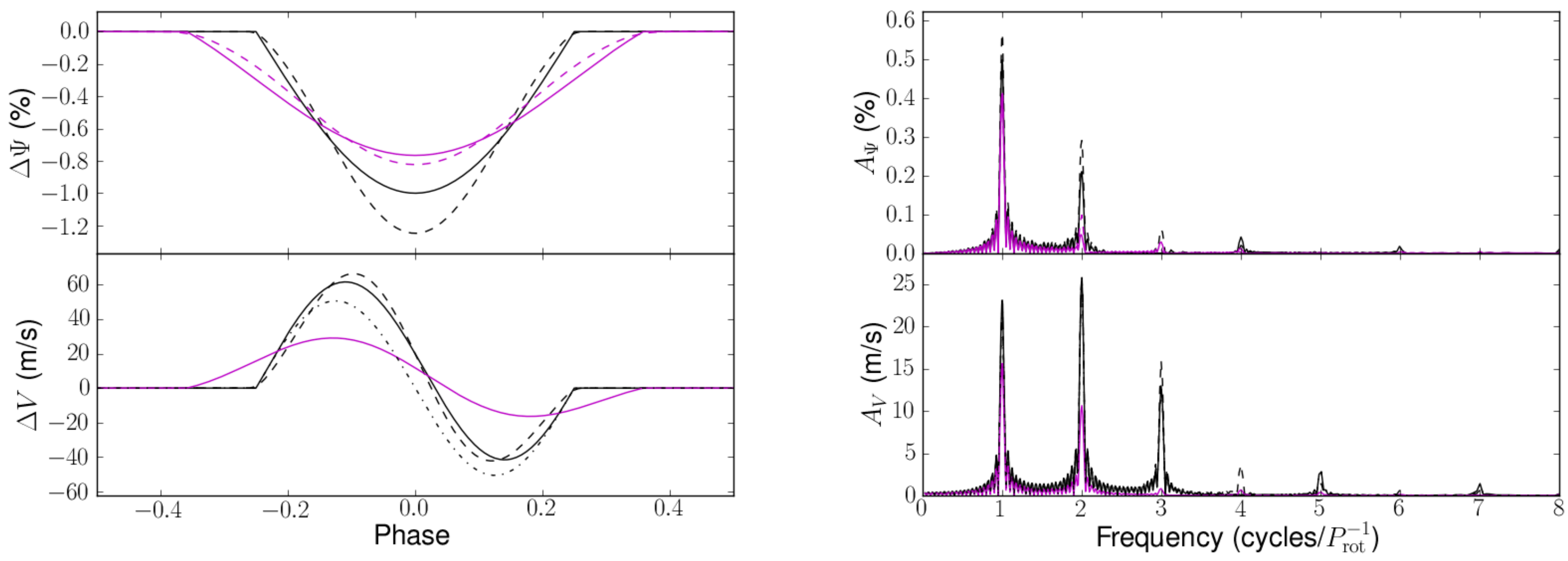


CoRoT-7: HARPS CCF



Flux and RV variations: isolated spot

RV variation is closely approximated by product of light curve and its first derivative



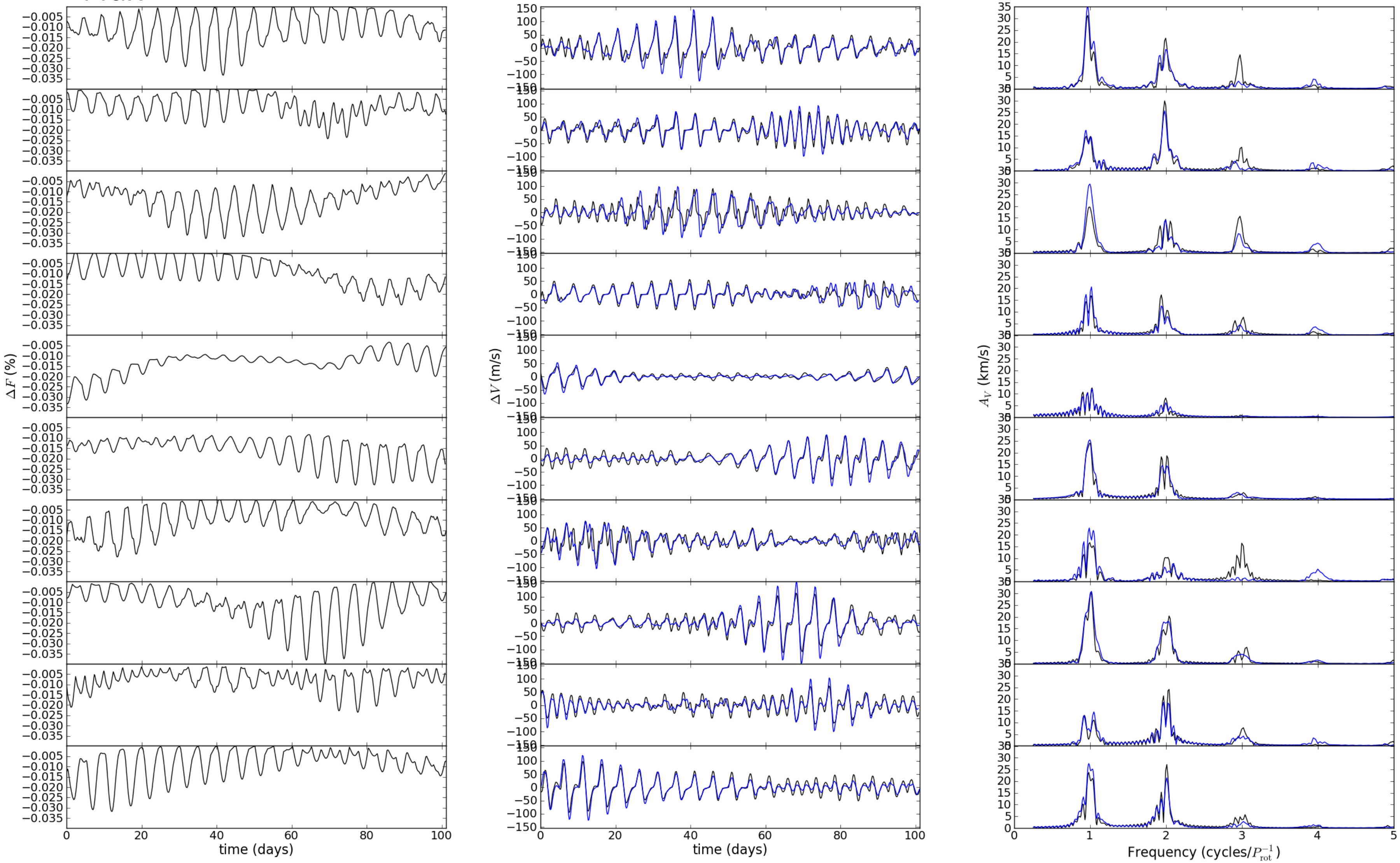
Aigrain, Pont & Zucker 2012, MNRAS 419, 3147

RV variations from photometry

Flux

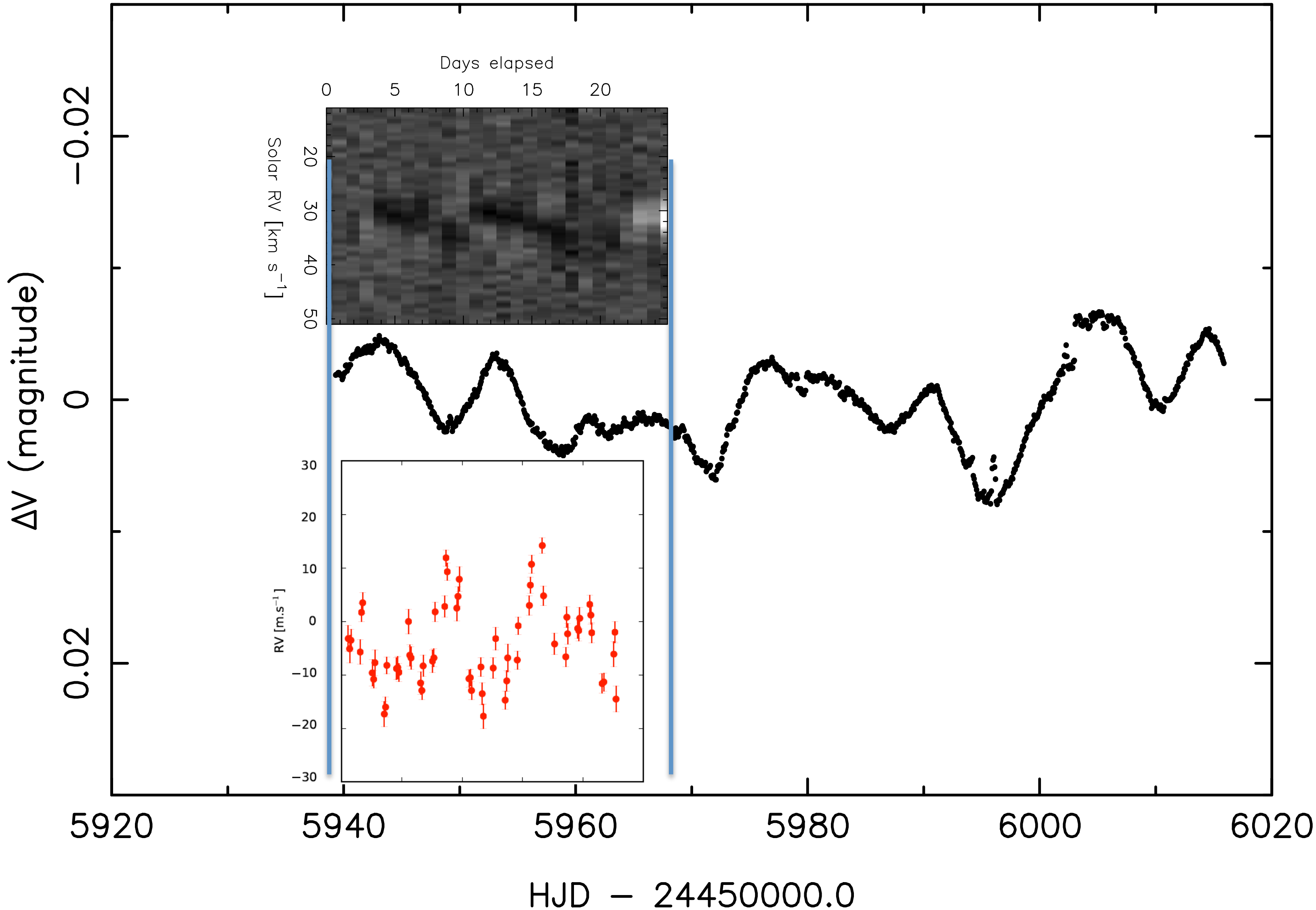
RV and FF' model

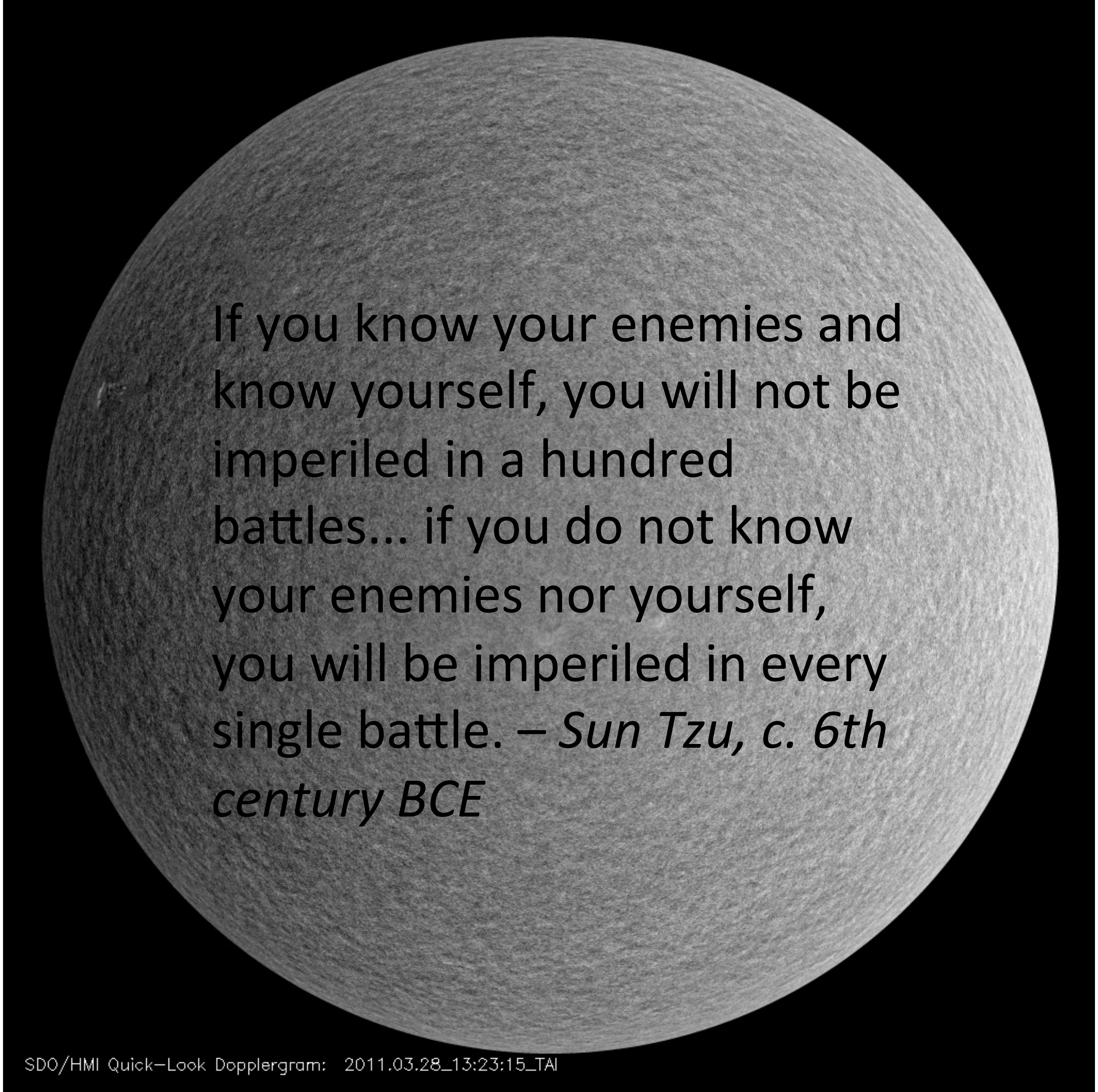
Periodogram



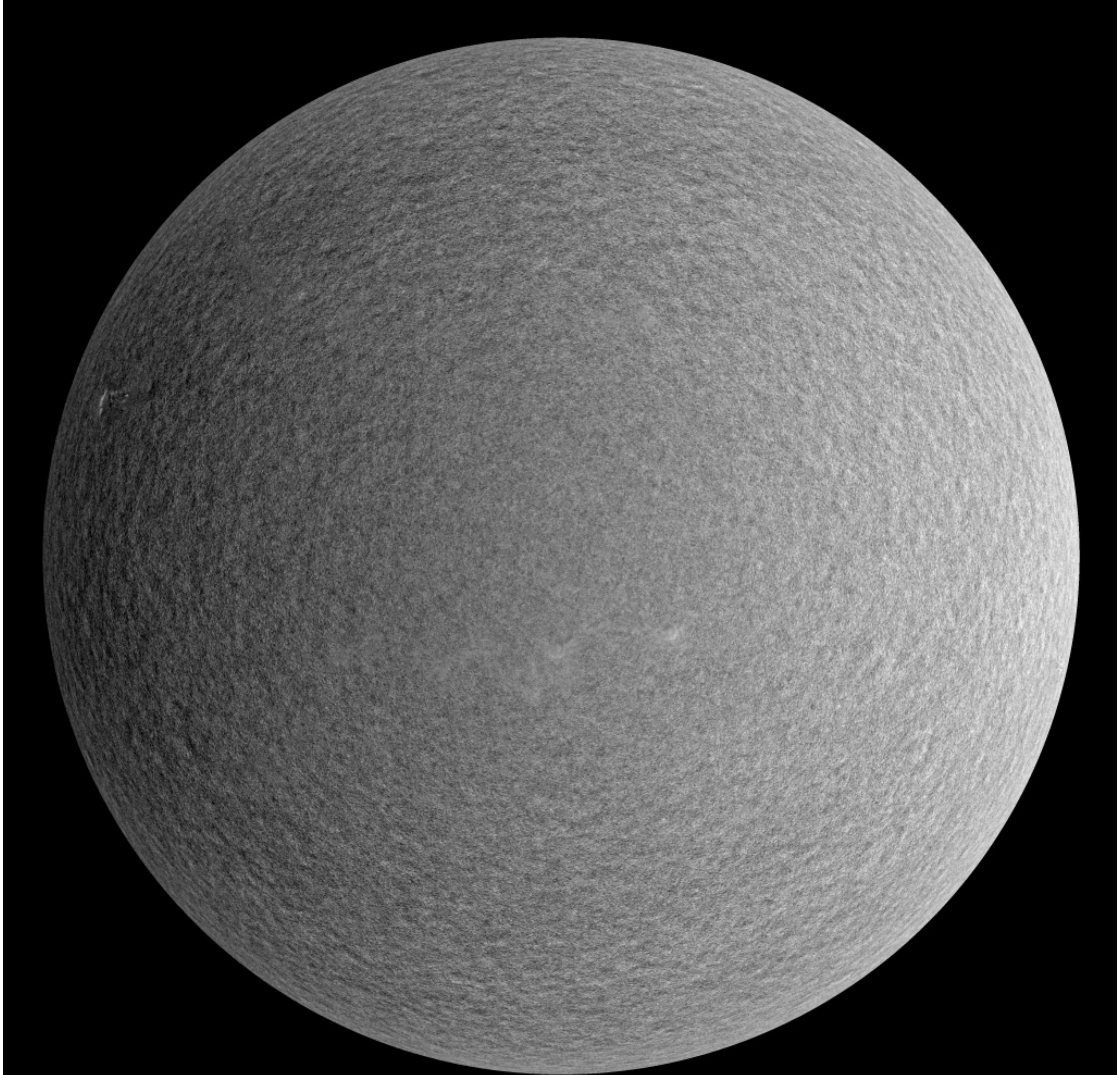
Aigrain, Pont & Zucker 2012, MNRAS 419, 3147

How are flux, CCF and RV jitter related?

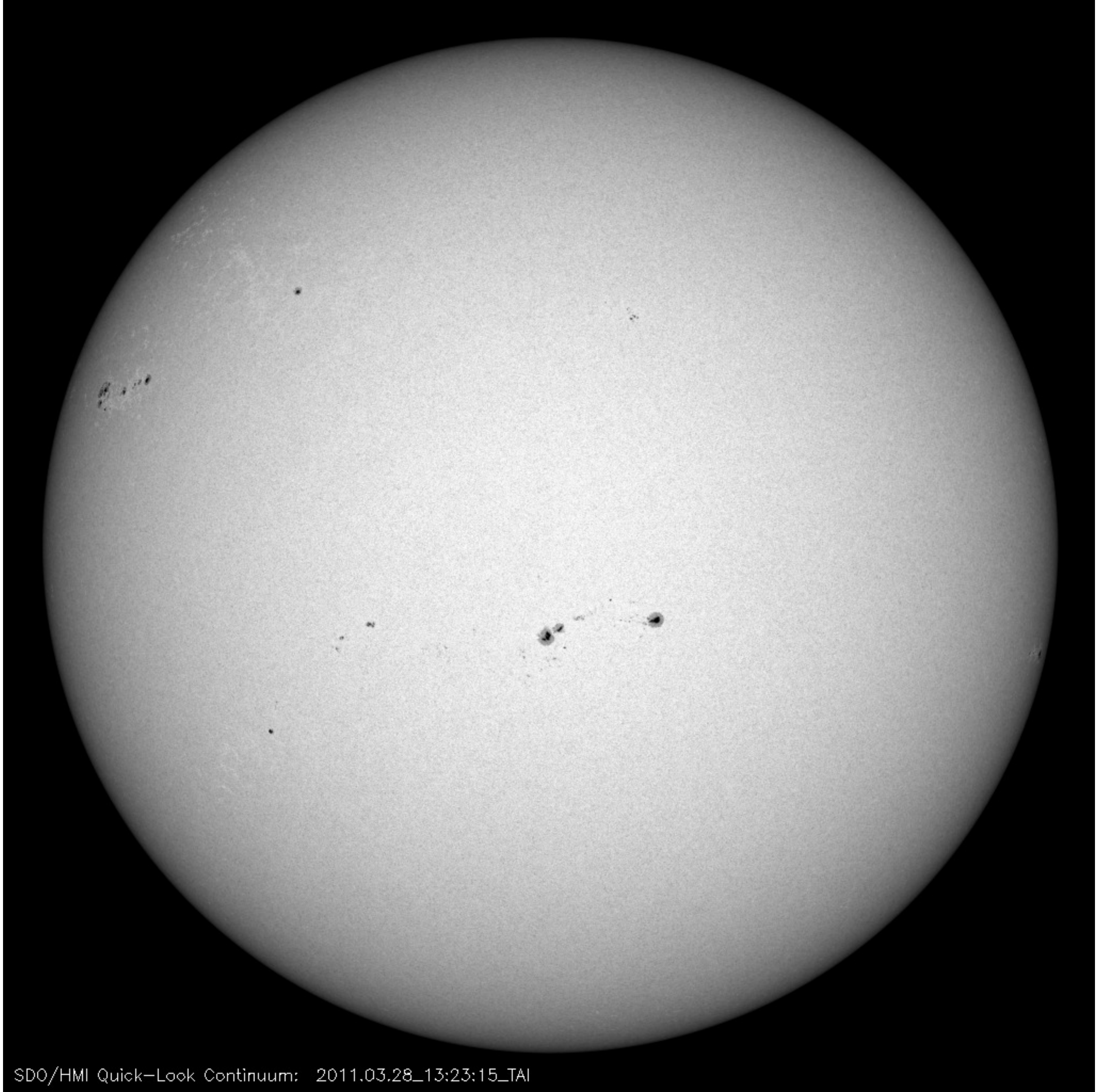


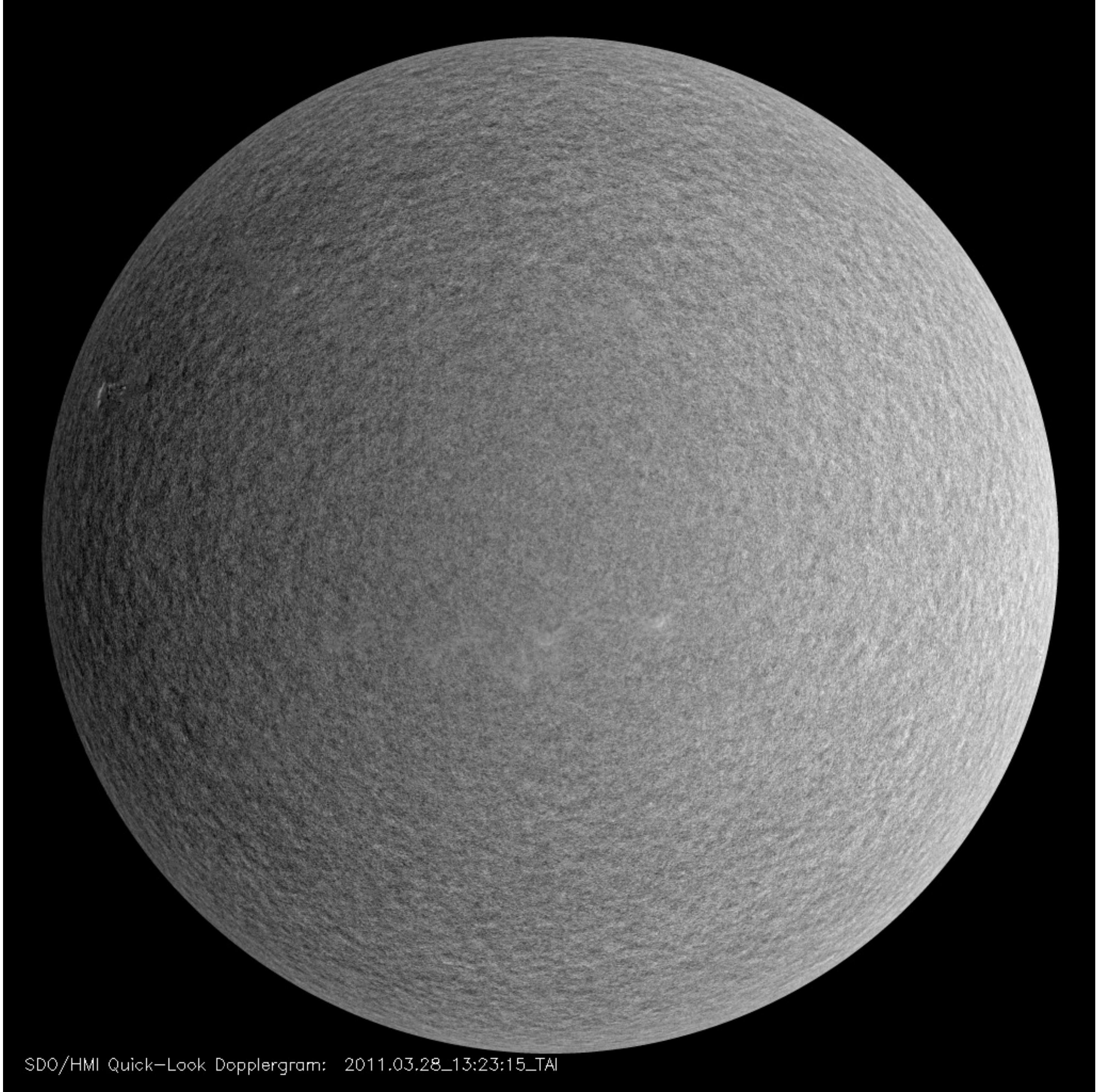


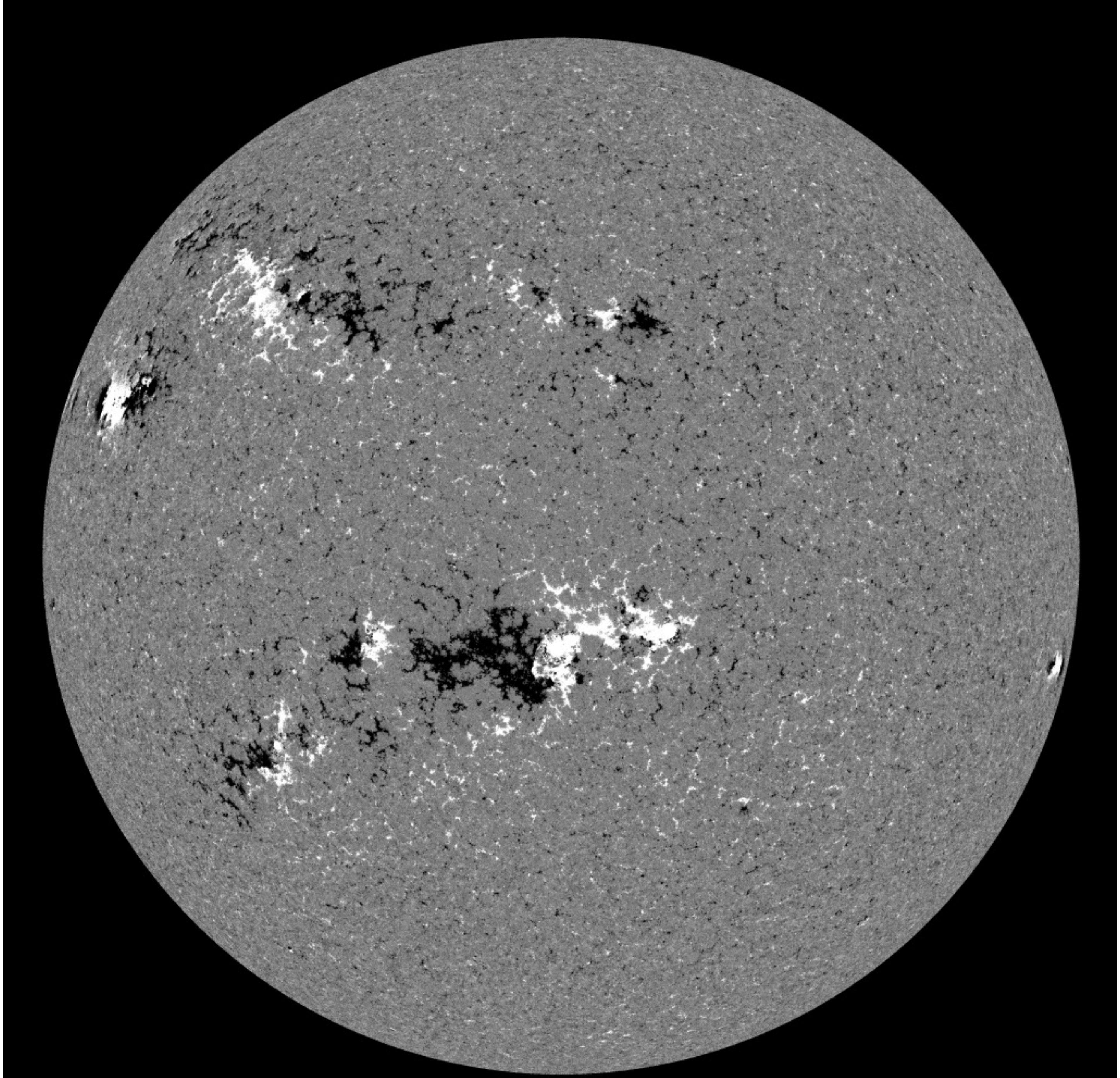
If you know your enemies and know yourself, you will not be imperiled in a hundred battles... if you do not know your enemies nor yourself, you will be imperiled in every single battle. – *Sun Tzu, c. 6th century BCE*



SDO/HMI Quick-Look Dopplergram: 2011.03.28_13:23:15_TAI

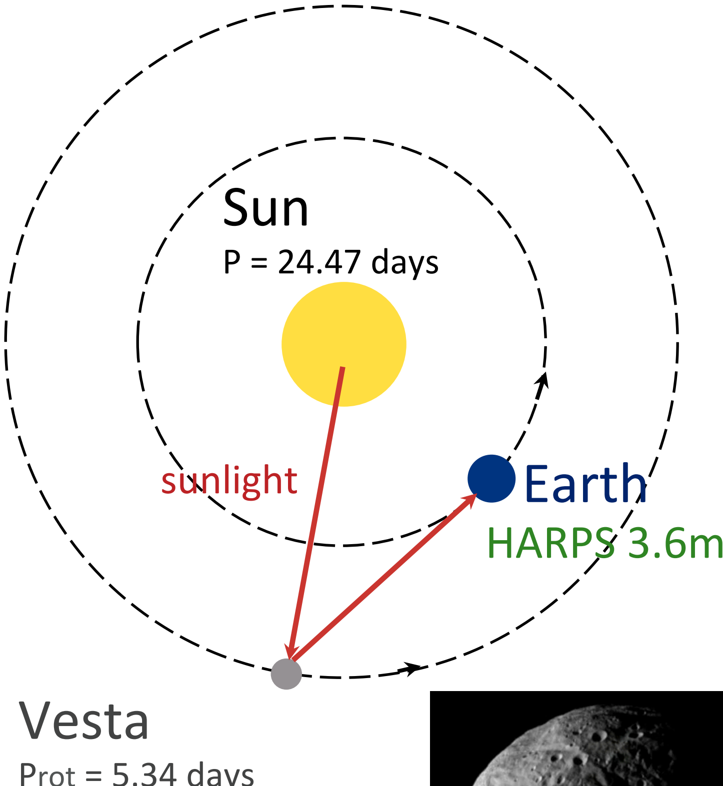

SDO/HMI Quick-Look Continuum: 2011.03.28_13:23:15_TAI

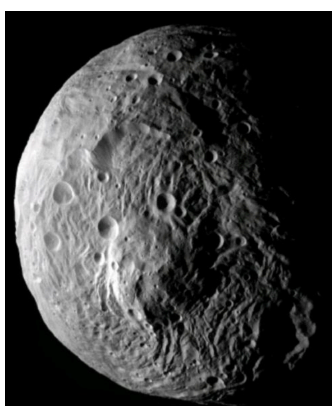

SDO/HMI Quick-Look Dopplergram: 2011.03.28_13:23:15_TAI



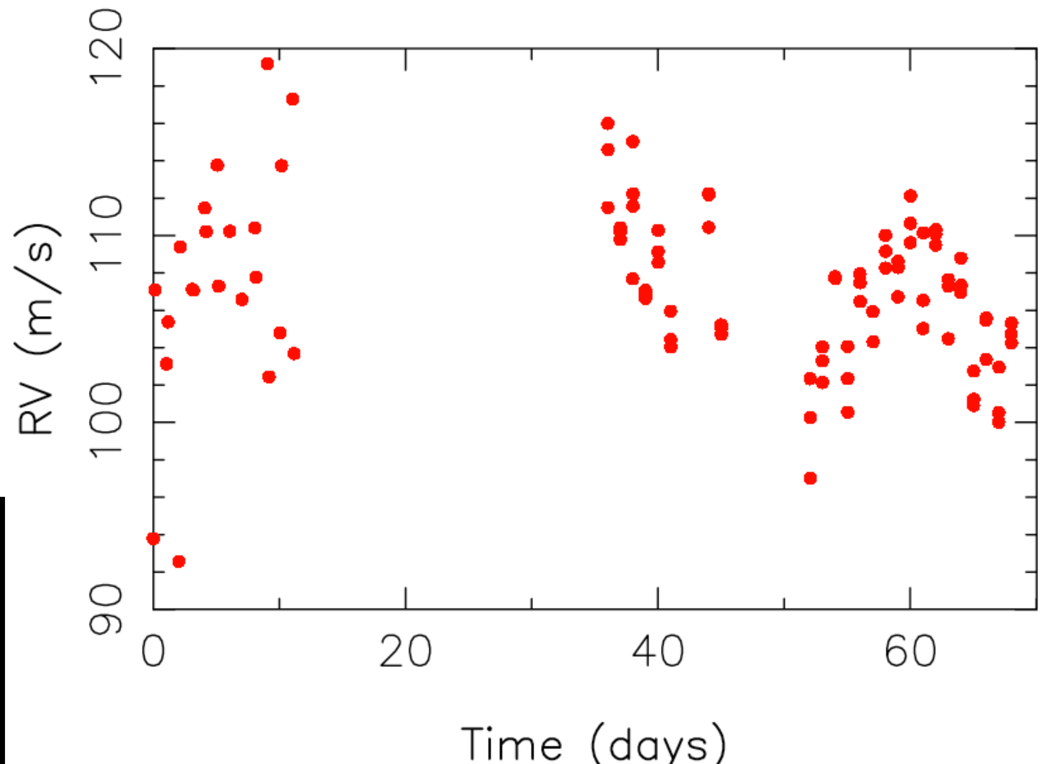
SDO/HMI Quick-Look Magnetogram: 2011.03.28_13:23:15_TAI

Using asteroid 4/Vesta to obtain the Sun's radial velocity variations

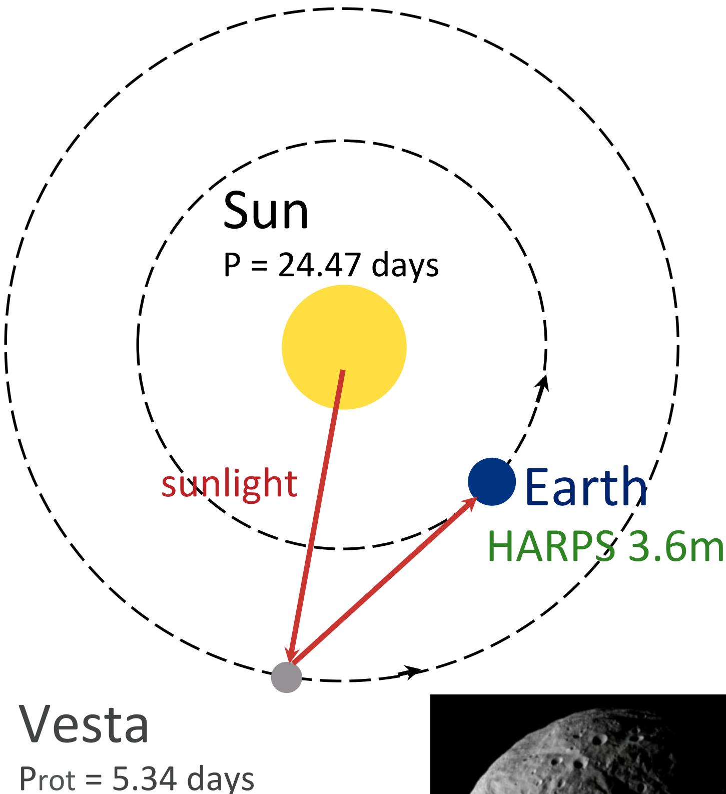


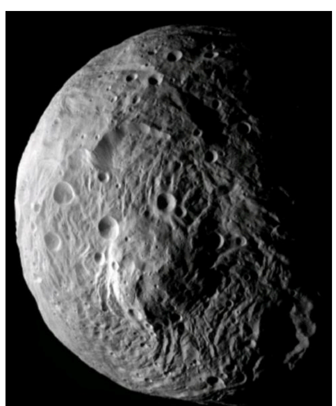


HARPS observations: 29 Sept. - 7 Dec. 2011

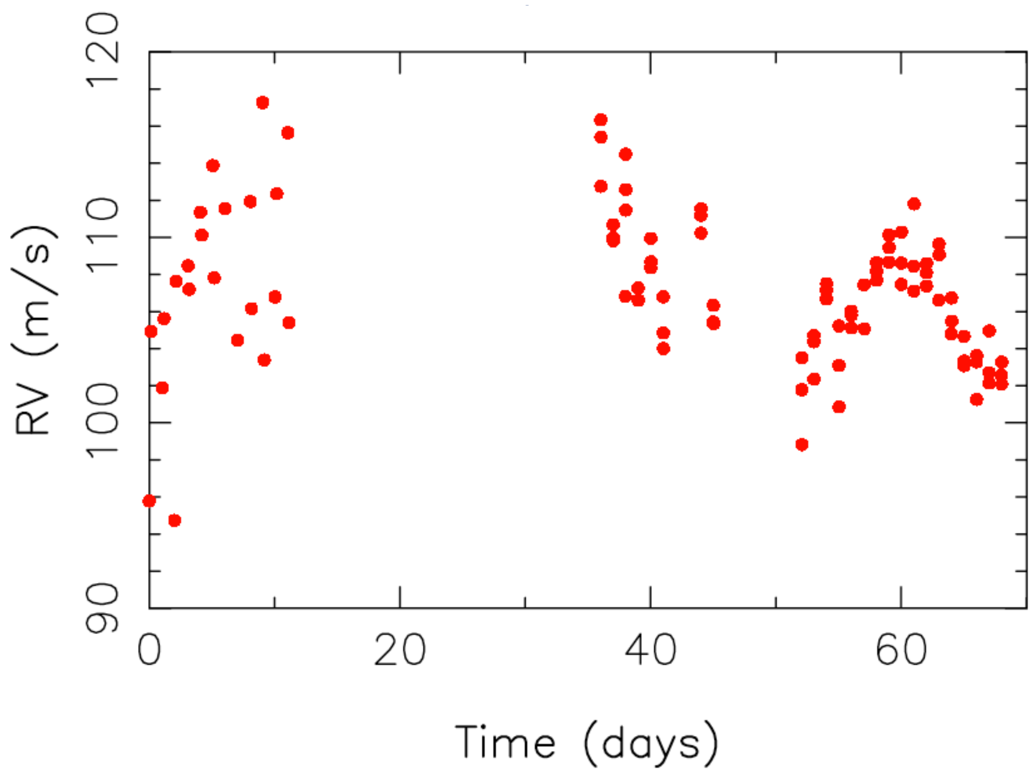


Using asteroid 4/Vesta to obtain the Sun's radial velocity variations





HARPS observations: 29 Sept. - 7 Dec. 2011
(Vesta rotation signal removed)

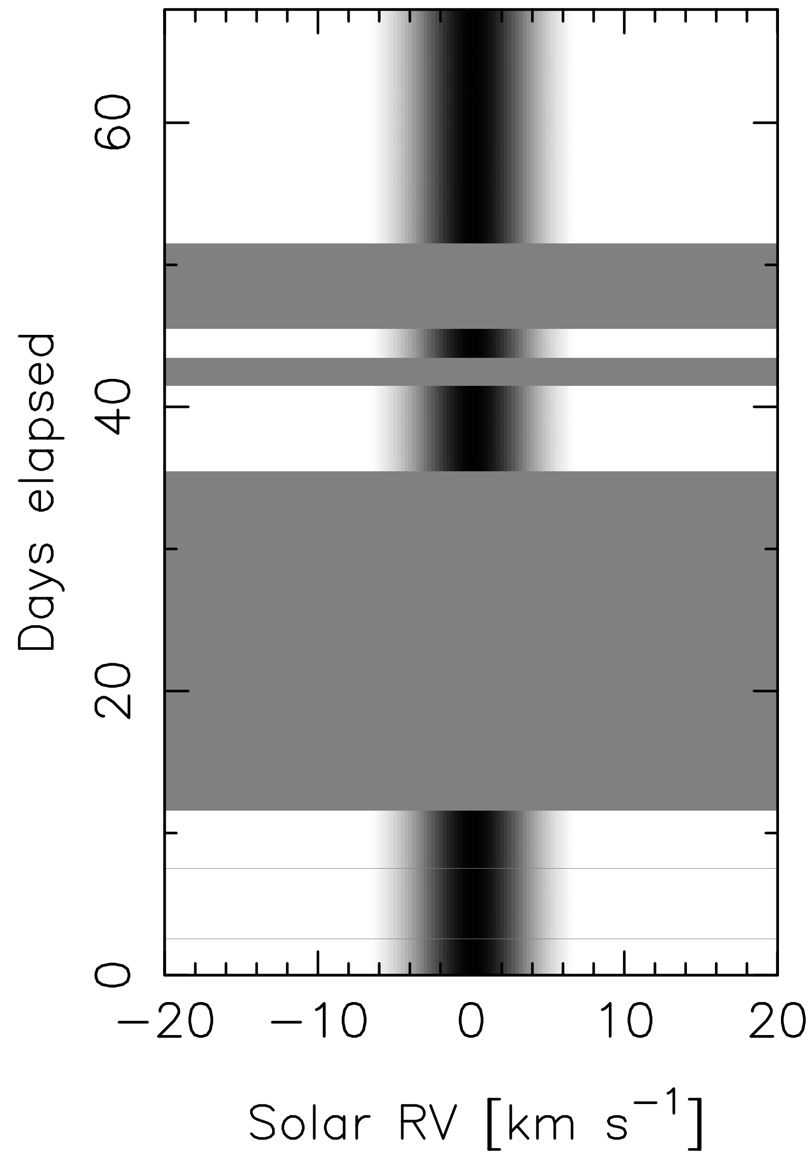


HARPS detects … spots on the Sun!

HARPS CCF of asteroid 4 Vesta

2011 September 29 – December 7

(R Haywood et al, in prep.)



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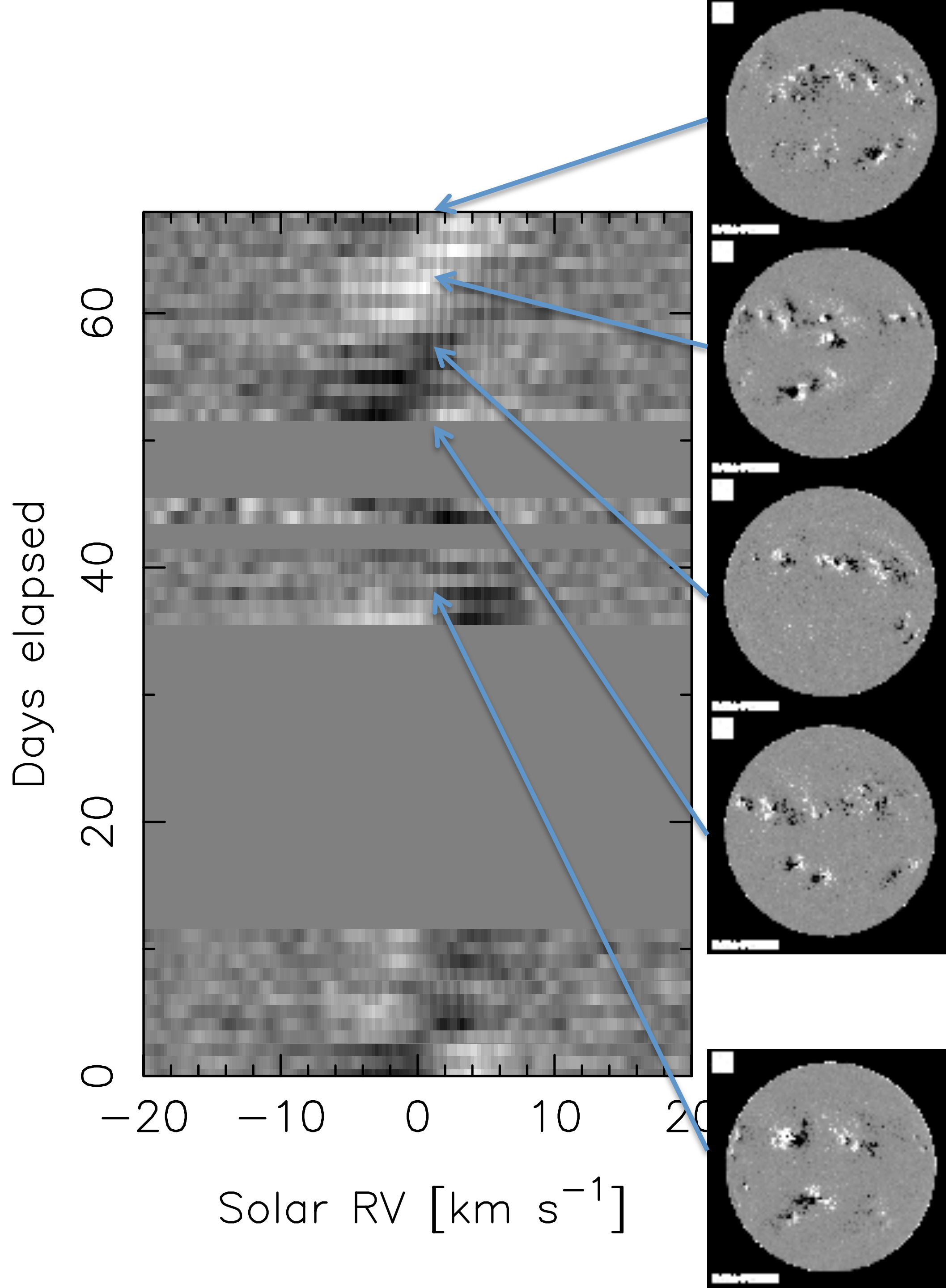
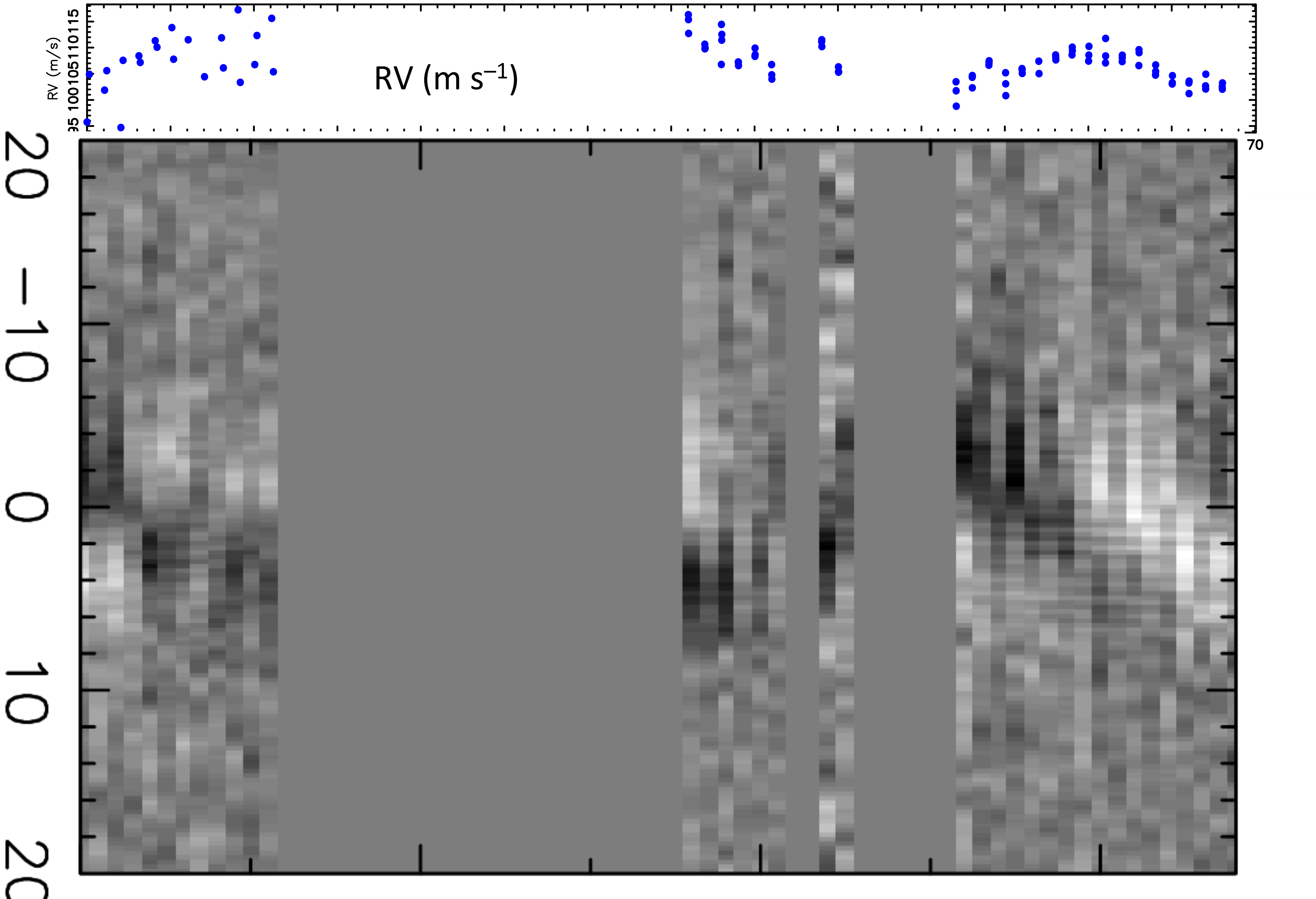
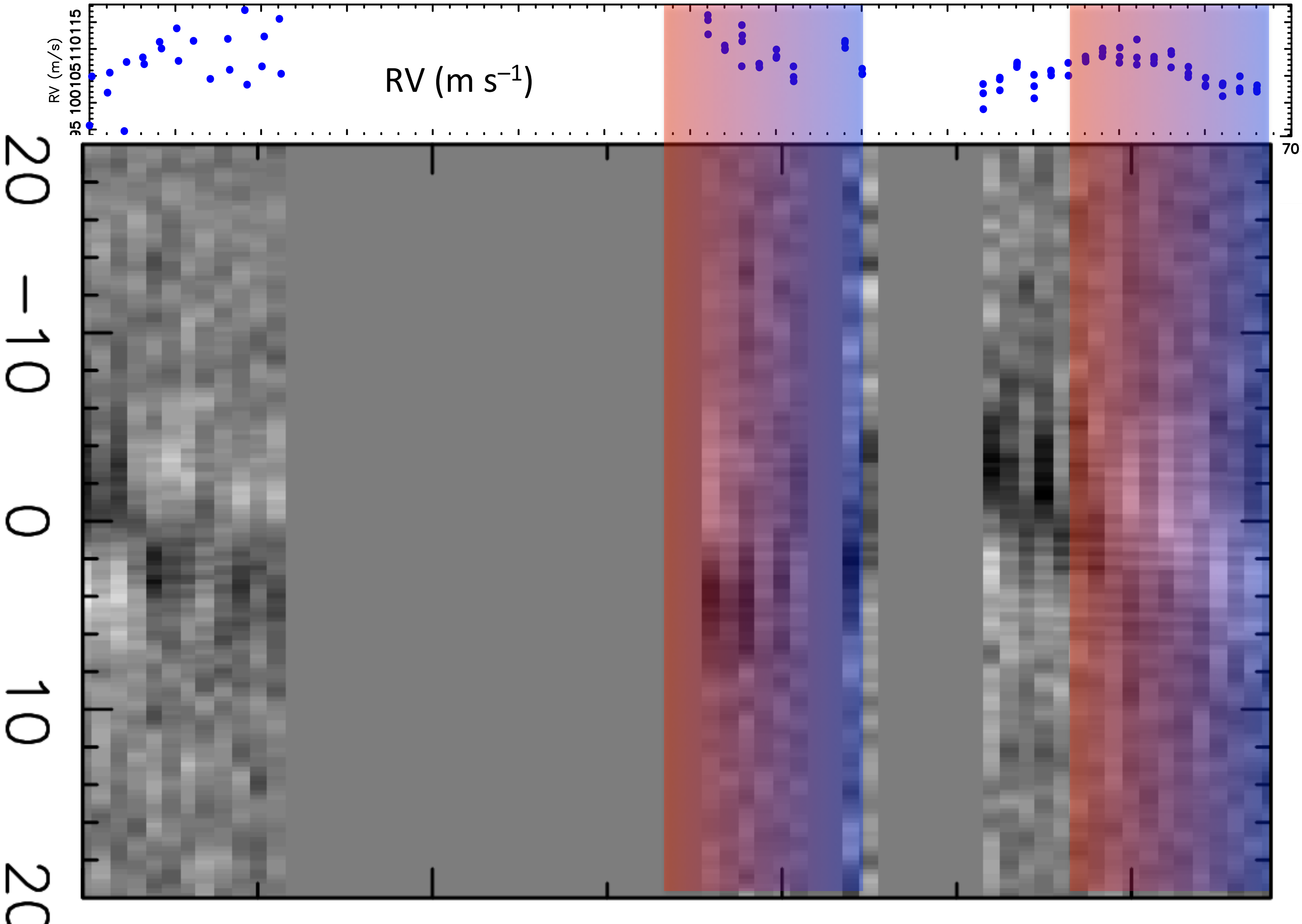


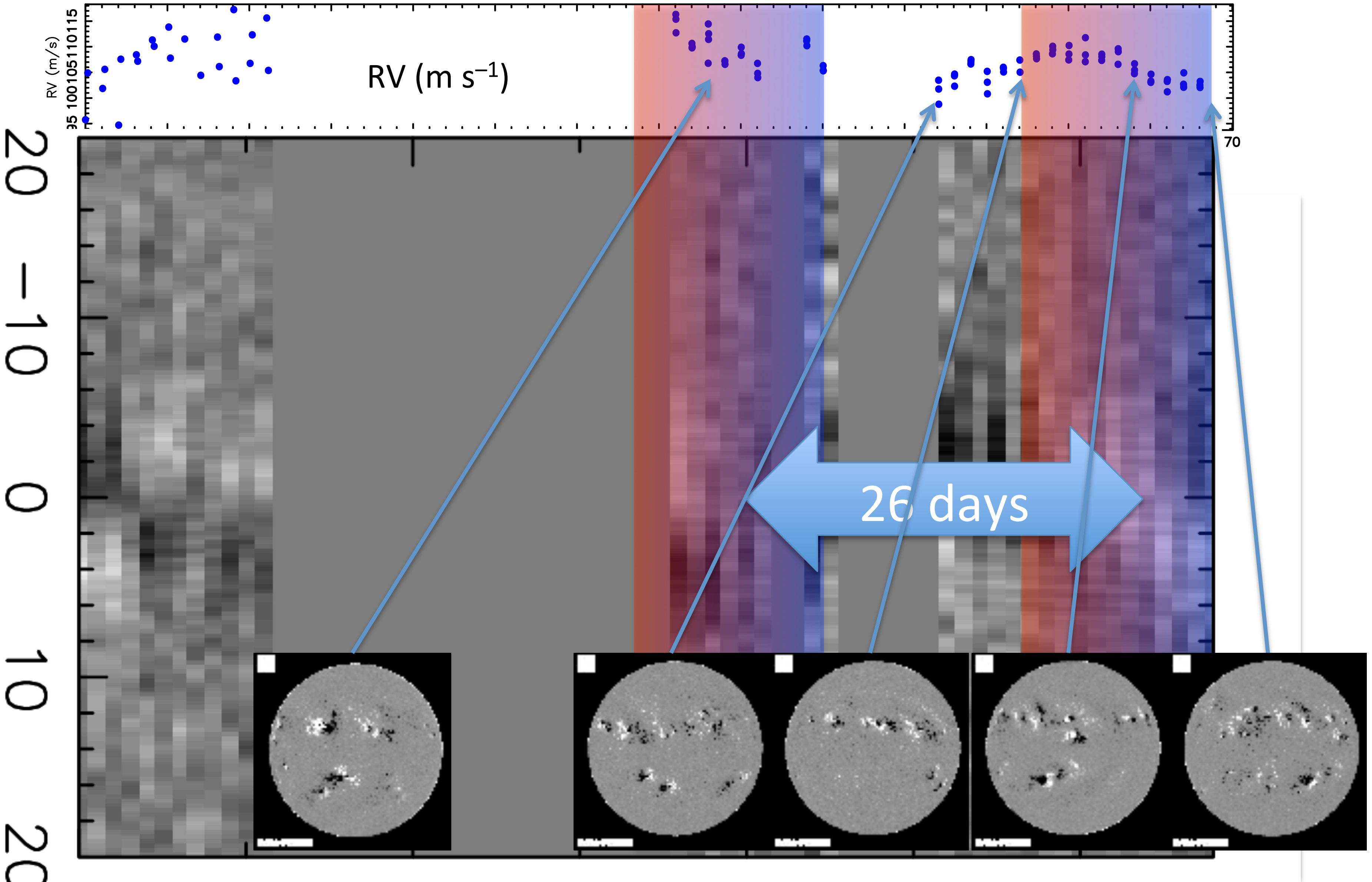
The Sun's radial-velocity jitter



The Sun’s radial-velocity jitter

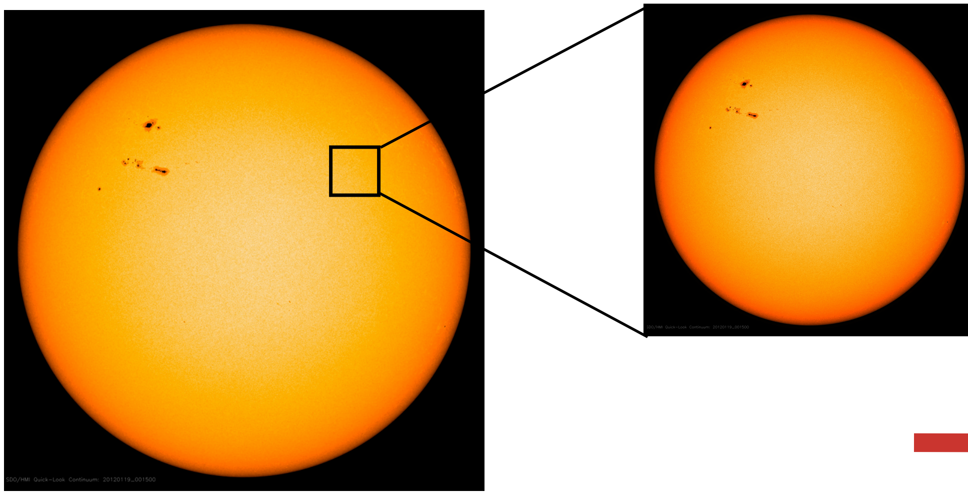


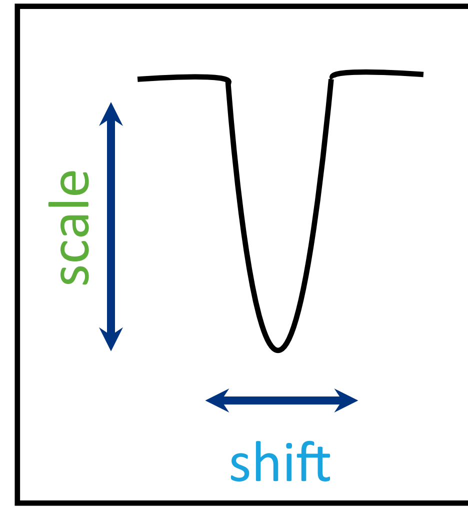
The Sun's radial-velocity jitter



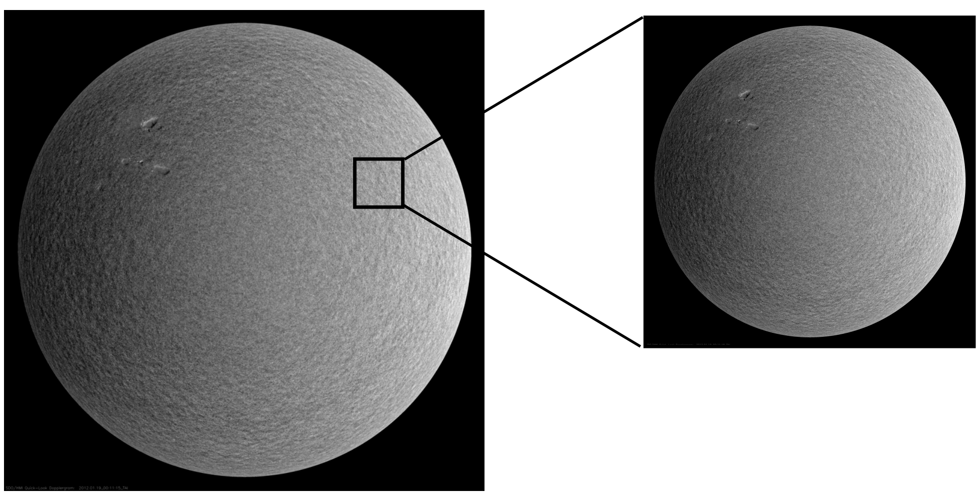
Next step: model line-profile distortions caused by sunspots, granulation, faculae,...

Continuum image
(scale)



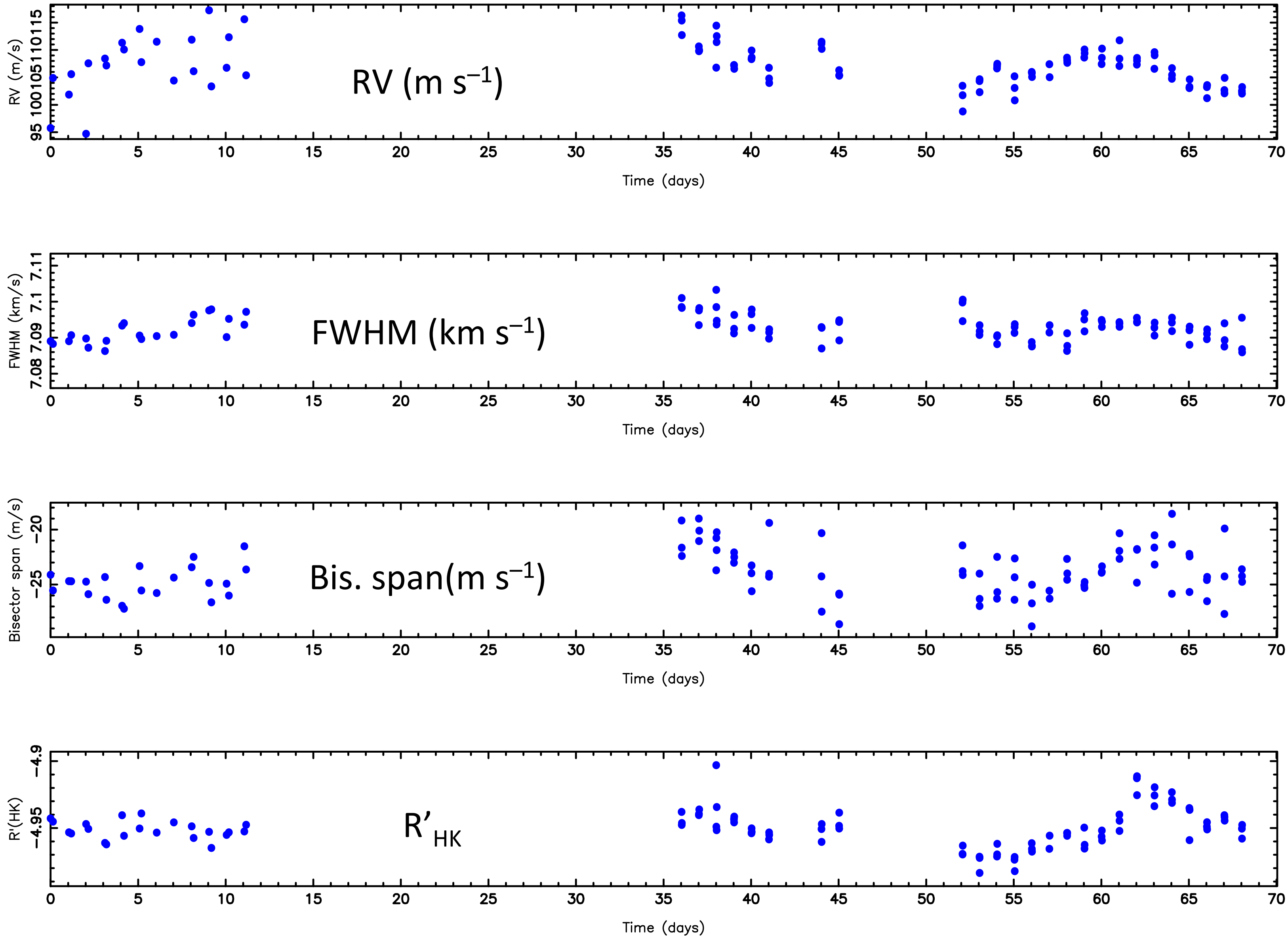


Doppler image
(shift)

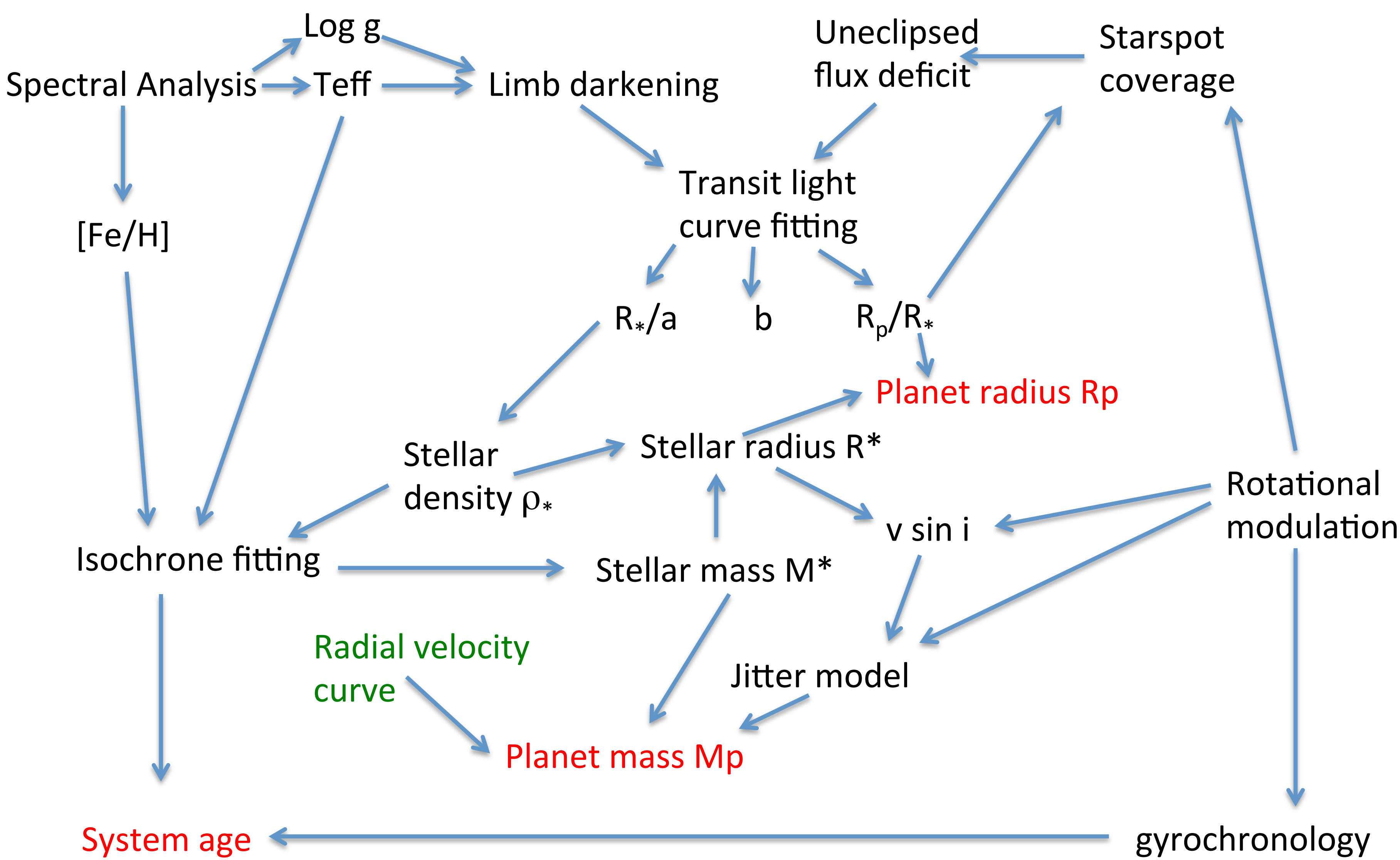


Identify proxies to remove stellar jitter from exoplanet RV curves

The Sun’s radial-velocity jitter

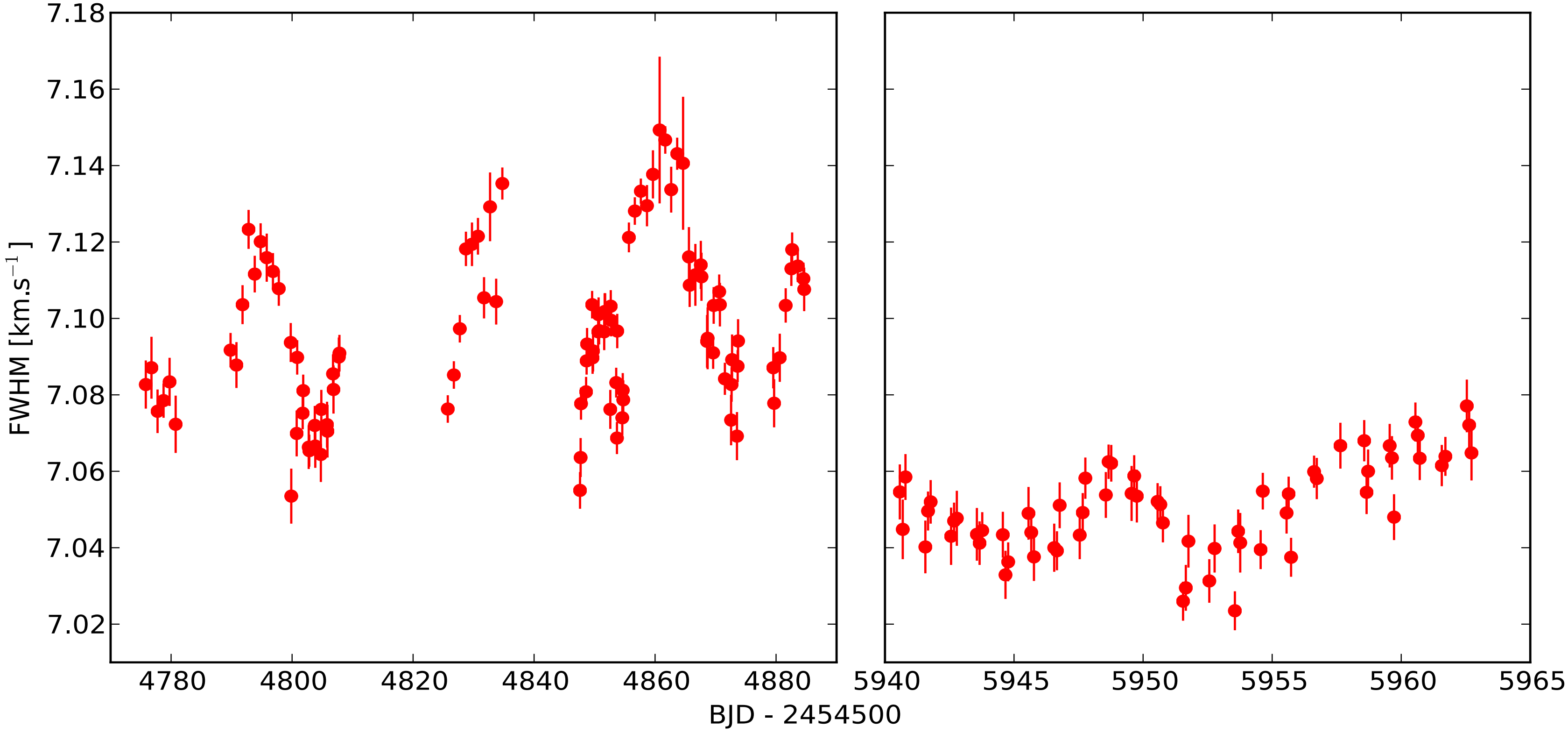


Summary – this was meant to be easy?

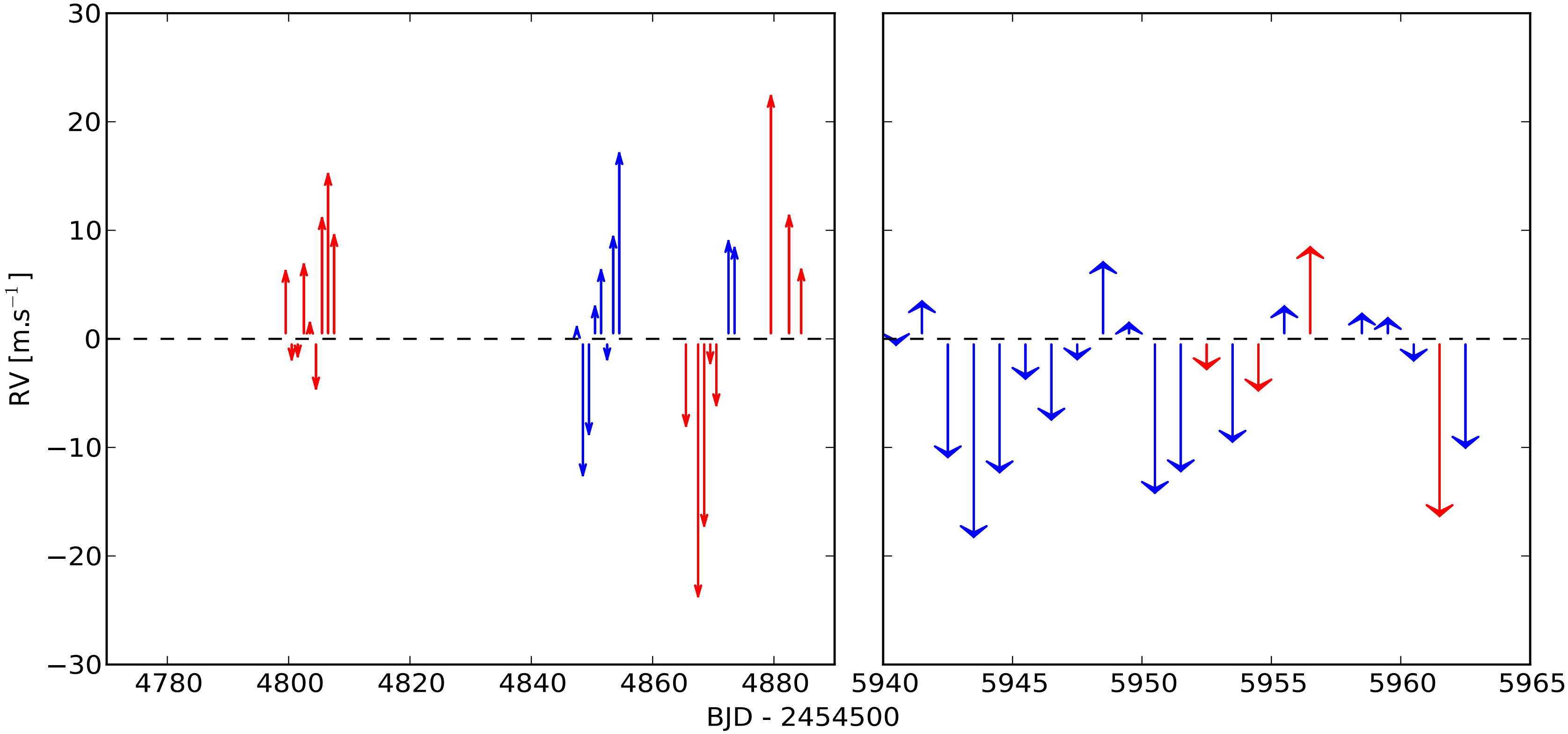


The Last Word (courtesy Stephen Kane)

CoRoT-7: FWHM of CCF dip



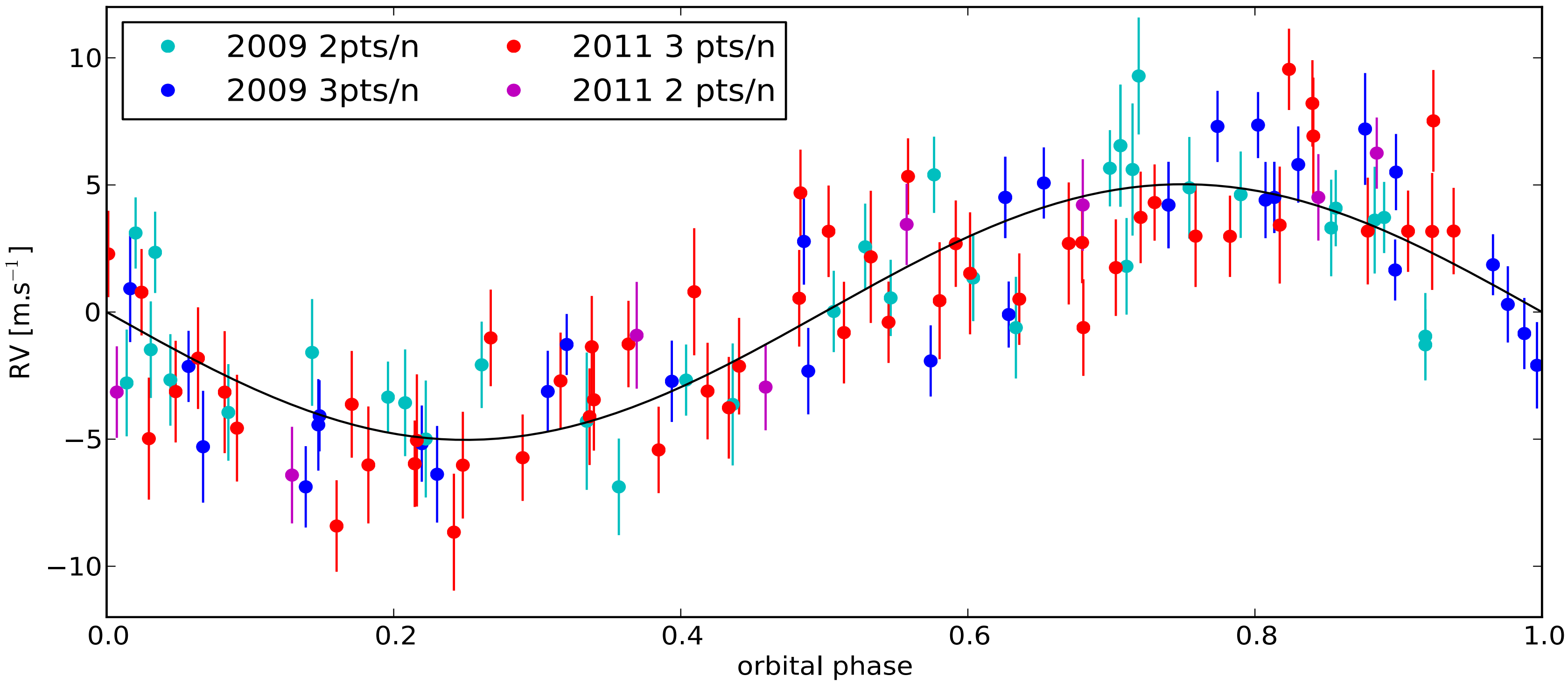
CoRoT-7: Nightly RV zero-point



Using technique of Hatzes et al (2010)

Red: 2 points/night; Blue = 3 points/night

Phased RV curve of CoRoT-7b



Gyrochronology

Asteroseismology

- See Bill Chaplin’s talk on Friday!