On Using The Rossiter-McLaughlin Effect To Detect Terrestrial Planets

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and
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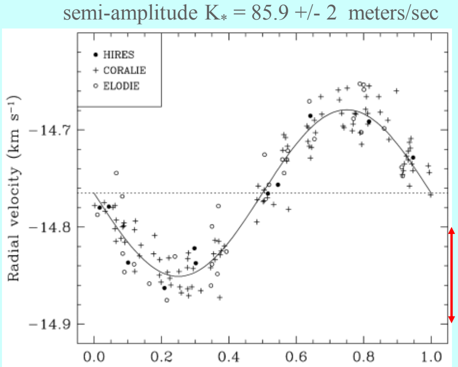
2004 transit of Venus

transit of Mercury (in X-rays)

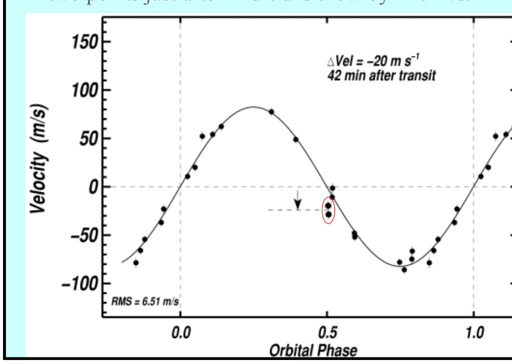
Rossiter-McLaughlin Effect

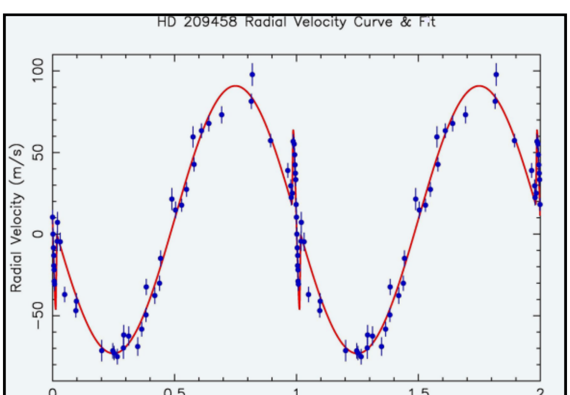
1. What is it?
2. What use is it?
3. Can we use it to find an Earth-size planet?

Mazeh et al. (2000) HD 209458 orbital radial velocity semi-amplitude $K_* = 85.9 \pm 2$ meters/sec

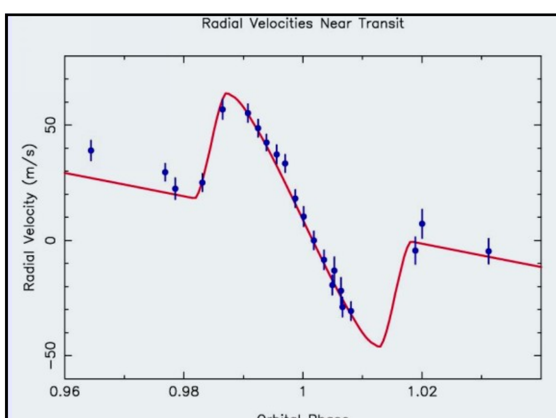


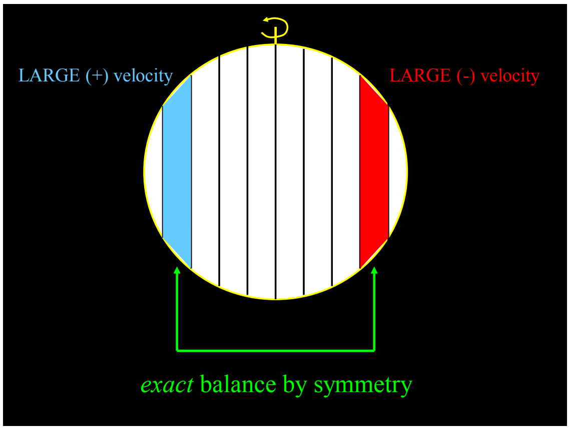
Bundy & Marcy (2000) noticed something peculiar: two points just after mid-transit low by ~20 m/s.

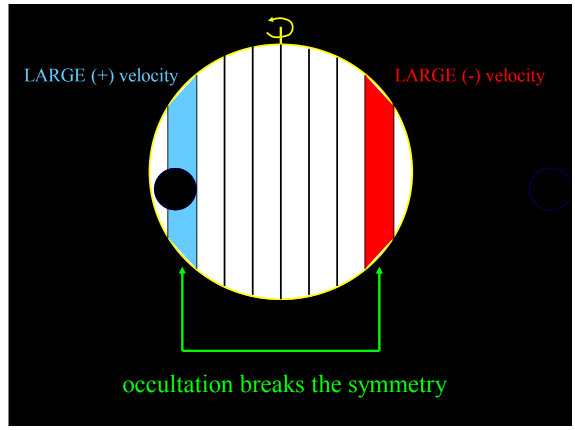




Wittenmyer, Welsh, Orosz, Schultz, Henry, Marcy, et al. (2005)







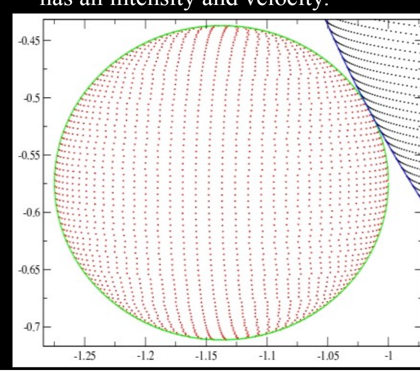
Rossiter-McLaughlin Effect:

Effect is large because stellar rotation $V_{rot} \sin i$ is *very* large compared to reflex orbital velocity:
km/s vs. m/s

Stationary star has zero net velocity due to exquisite balance of large (+) and (-) velocity elements.

In a sense, the transit is *removing absorption.*

Cover the star with a fine grid ("tiles"). Each tile has an intensity and velocity.

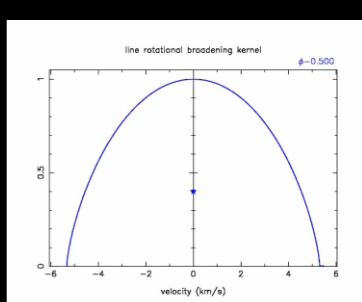


ELC numerical simulation for a hot Jupiter.

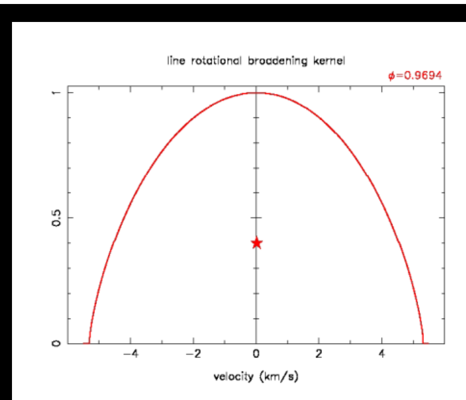
first contact point of ingress

grid points "tiles" =
star: 400 x 600
planet: 80 x 80

Sum of intensity-weighted velocities
➔ rotational broadening kernel "G".
Observed absorption line = (*intrinsic sharp line* H * G)



"G" for HD 209458 computed by ELC using Gimenez (2006) formulation with V_{rot} = 5.3 km/s



Rossiter-McLaughlin Effect

2. What use is it?

Stellar Characteristics

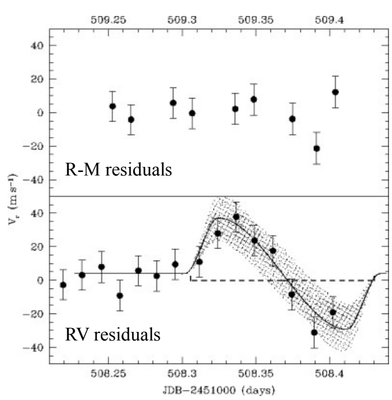
- R-M effect very sensitive to stellar rotation
- R-M effect sensitive to stellar limb darkening
- Measure the obliquity (mis-alignment of the spin-orbit axes)

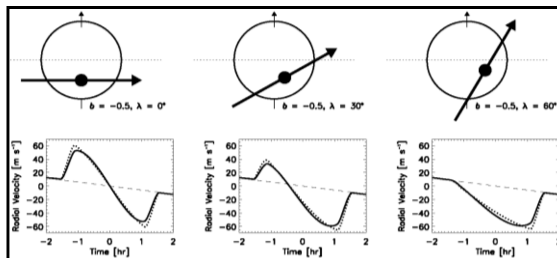
Assist in discovering planets

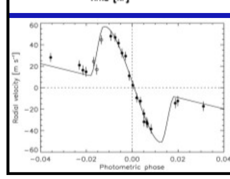
- HD 189733 (Bouchy et al. 2005) first transit discovered spectroscopically before photometrically

Queloz, Eggenberger, et al. (2000)

Used Rossiter effect to show star spin axis aligned with orbital axis





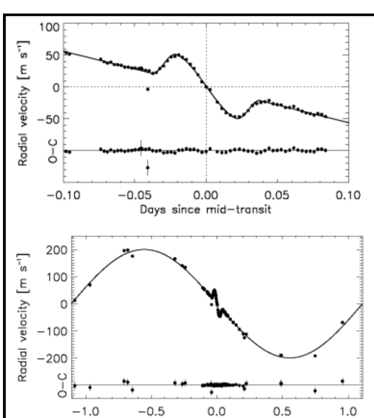


HD 209458

Spin-orbit alignment

Gaudi & Winn (2006)

Winn et al. (2005)



HD 189733

Winn et al. (2006)

Measure star/planet spin/orbit alignment

- HD 209458: 4.4 +/- 1.4 degrees (Winn et al. 2005)
- HD 149026: 11 +/- 14 degrees (Wolf et al. 2006)
- HD 147506: 1.2 +/- 13.4 degrees (Winn et al. 2007)
- TrES-1: 30 +/- 21 degrees (Narita et al. 2007)
- HD 189733: -1.4 +/- 1.1 degrees (Winn et al. 2006)

Planet orbit evolution

- expect alignment if steady migration, tidal forces at play
- expect mis-alignment if collision or scattered into orbit

→ **the former seems more likely**

Probe of planet atmosphere

- λ-dependent effective star radius → λ-dependent R-M shift

e.g. Na D amplitude is 1.7 +/- 1.1 m/s larger than other lines

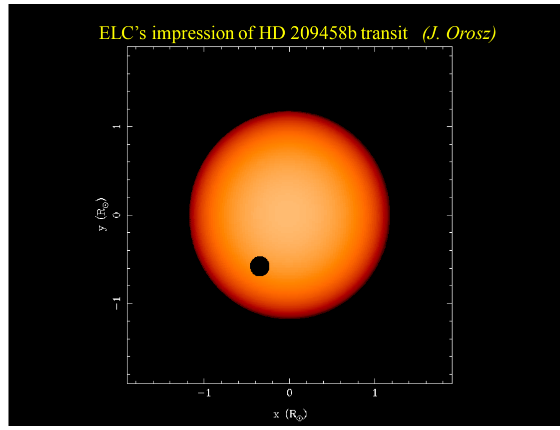
(Snellen 2004)

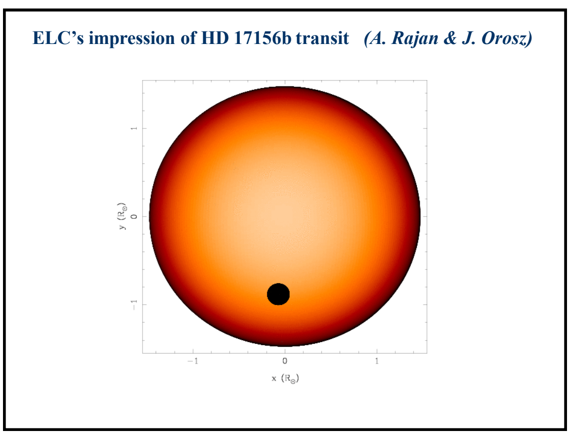
Q: Can an Earth-size planet be detected via the RM effect?

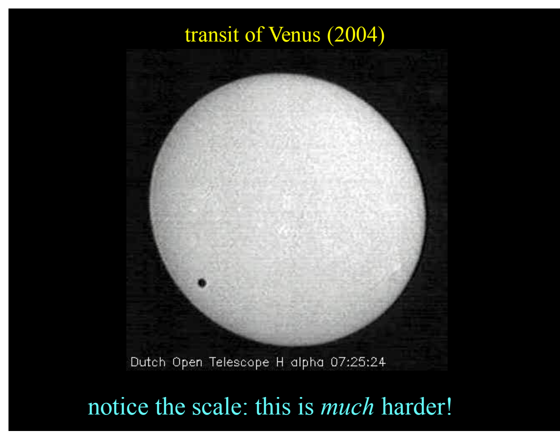
Consider: $R_*=R_\odot$ $M_*=M_\odot$ a=1AU i=90° $M_p=M_{Earth}$
$V_{rot} \sin i$= 3-5 km/s and R_p~1-2 R_{Earth}

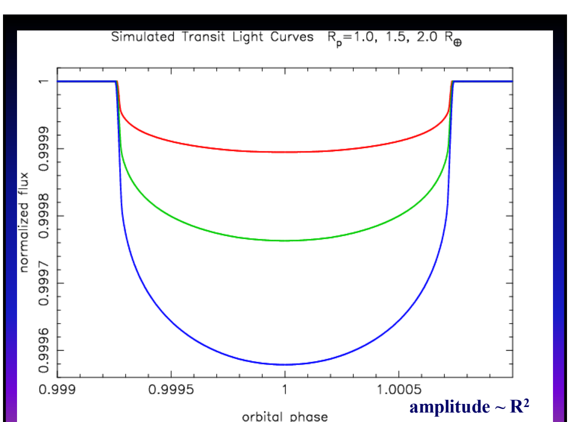
photometric signal:	8×10^{-5}	need space obs.
star orbital radial vel:	0.09 m/s	tiny!
RM amplitude:	0.1-1.0 m/s	interesting!

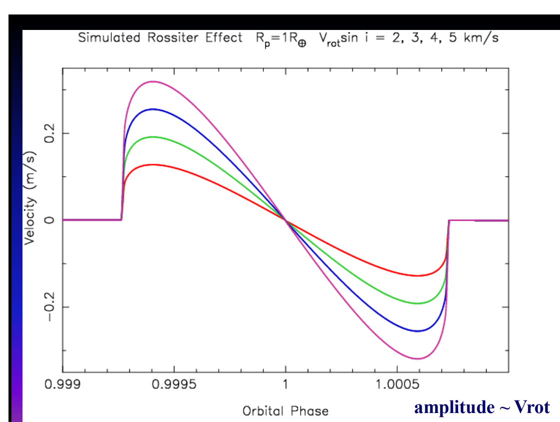
Worthy of a realistic simulation…

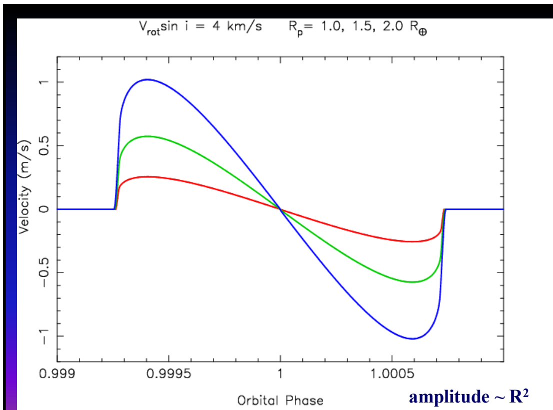


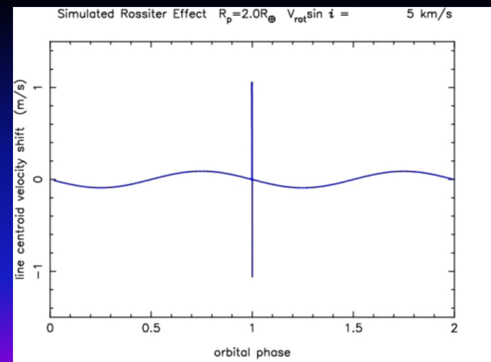






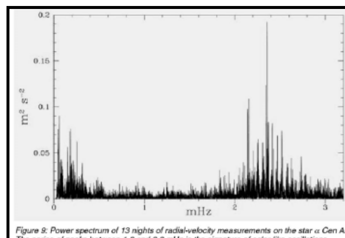


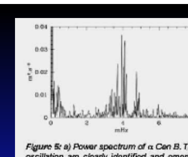




Simulation

- Stellar variability is the dominant noise, not observational Poisson (photon) noise
  - I. Stellar pulsations (periodic)
    - p-mode oscillations; period ~few min; amp ~0.1 m/s
  - II. Stellar random "burbling" (red noise)
    - random walk-like ($1/f$ to $1/f^2$ power spectrum)
    - due to convection, granulation, microflares, spots, etc. → "weather"

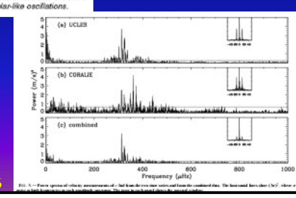




HARPS: Mayor et al. (2003)

HARPS: Queloz et al. (2001)

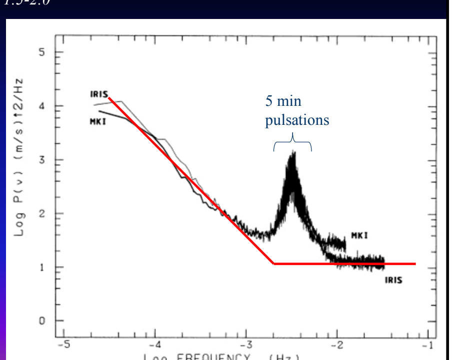
Examples of stellar pulsation



Bedding et al. 2006

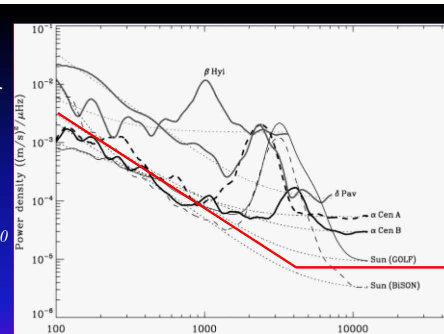
Solar power spectrum shows intrinsic red noise

$P(f) \sim 1/f^{1.5-2.0}$



Palle et al. (1992)

α Cen B and other stars also show intrinsic red noise $\sim 1/f^{1.5-2.0}$



Kjeldsen et al. (2005)

→ more power at longer timescales

Simulation Details: I. Oscillations

- p-mode oscillations: (n,ℓ = integer radial, angular modes)
  frequency of sinusoids =

  $$\nu_{n,\ell} = \Delta\nu(n + \ell/2 + \varepsilon) - \ell(\ell+1)D_0$$

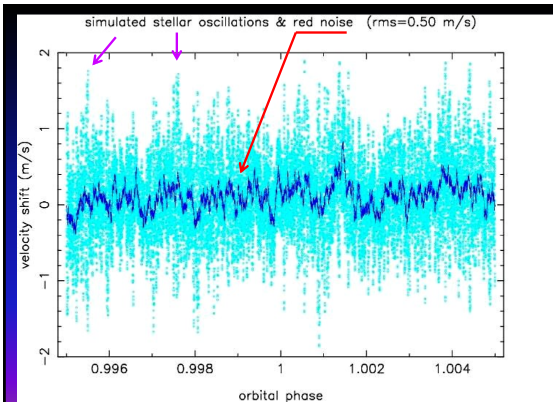
  $\Delta\nu \rightarrow$ mean density $D_0 \rightarrow$ sound speed near core $\varepsilon \rightarrow$ surface layers

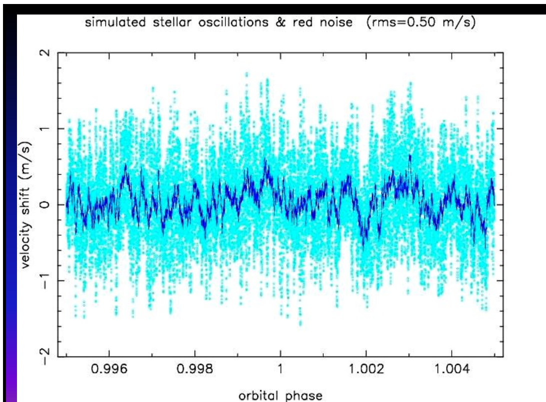
- n = 17-32 ℓ = 0,1,2,3 ➔ total of 60 sinusoids
- strongest amplitude ν_{peak} = 0.2 m/s
- individual amplitudes = 0.0-0.2 m/s (random) x Gaussian drop-off away from ν_{peak}
- mode lifetime= 3 (ν / ν_{peak}) days
- phase drift = random walk $\Delta\phi = 2\pi$ in lifetime
- compute with Δt=12 s

Simulation Details: II. "Burbling"

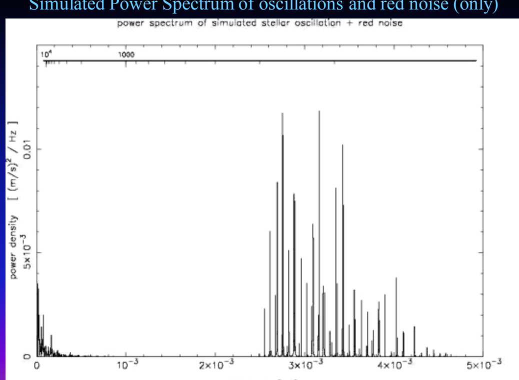
- Random walk generated using first order auto-regressive (AR) process: $v(t_i) = \alpha\, v(t_{i-1}) + \varepsilon_i$
  - ε_i = white noise
  - filter coefficient α = 0.995
- gives red power spectrum with $P(f) \sim f^{-1.5 \text{ to } -2}$

Then normalize RMS of oscillations + red noise = 0.5 m/s





Simulated Power Spectrum of oscillations and red noise (only)



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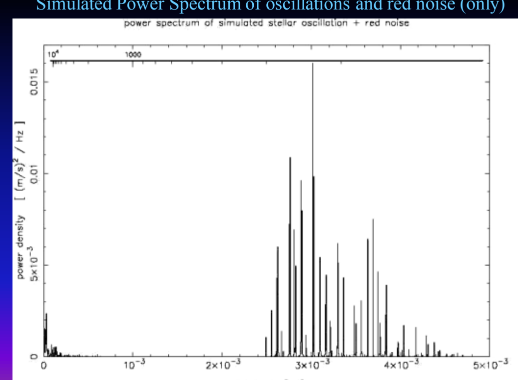
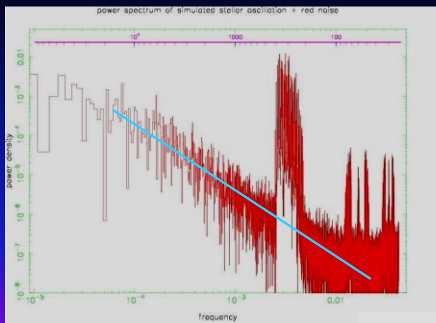


simulation power spectrum showing $1/f^2$ –like red noise



Simulation Details: Observations

- Match stability predictions of *HARPS,* but on a 10-m telescope
- V=9 mag
- bin to Δt= 60 min
- add observational noise per bin = **0.25 m/s**
  - **insanely optimistic??**

Note: transit duration ~ 13 hours

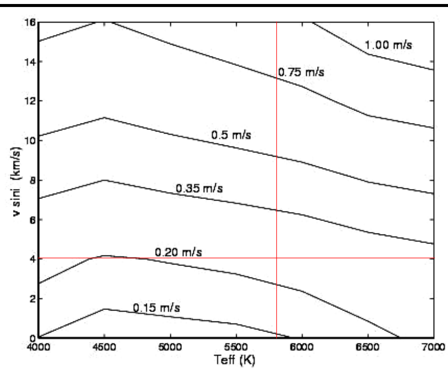


Fig. 8. Radial velocity uncertainty predictions for HARPS (t_{exp} $(s) = 2.512^{m_V}$). → 66 min for 9th mag

Bouchy et al. (2002)

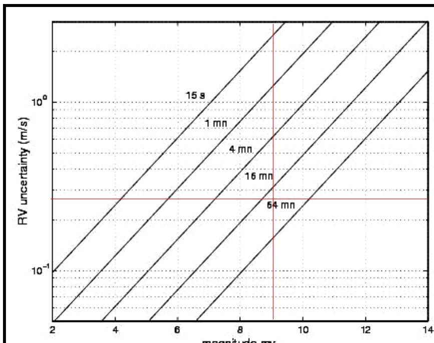


Fig. 9. Radial velocity uncertainty predictions for HARPS versus magnitude for a star spectrum with $T_{\rm eff}$ = 4500 K and $v \sin i = 0$ km s^{-1}.

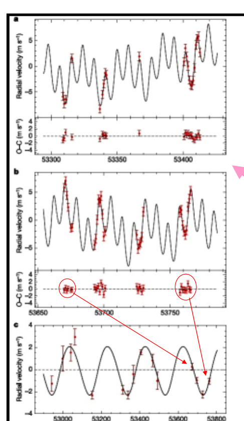
Bouchy et al. (2002)

The HARPS search for southern extra-solar planets. I. HD 33075 b: a new "Hot Jupiter"

- Pepe et al. 2004 A&A 423, 385

The short-term precision performance of HARPS has been characterized on the sky by intensive asteroseismology observations carried out during the instrument commissioning phase (Mayor et al. 2003). The observations proved that on short time-scales (one night) the precision is better than 0.2 m s^{-1} *rms* and mainly limited by photon noise and, in particular, by the intrinsic stability of the star itself. Besides tracking the in-

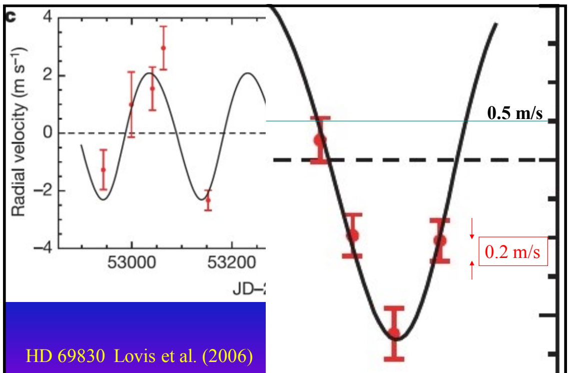
* night-to-night wavelength calibration stability is a problem of ~0.8 m/s



HARPS in action:

1. μ Arae V=5.12 mag G5V
Santos et al. (2004)
residuals ~0.43 m/s in average of 15 spectra taken in 20 min

2. HD 69830 V=5.95 mag K0V
Lovis et al. (2006)
uncertainty ~ 0.7 m/s in 15 min



HD 69830 Lovis et al. (2006)

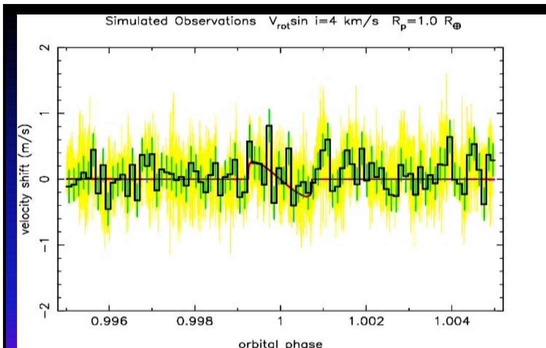
uncertainty ~ 0.2 m/s when 6-9 observations binned together

Simulation Details: Observations

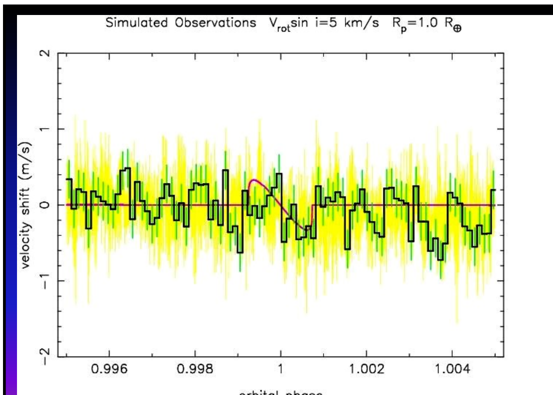
- Match stability predictions of *HARPS*, but on a 10-m telescope
- V=9 mag
- bin to Δt= 60 min
- add observational noise per bin = **0.25 m/s**
  - only slighly crazy!
  - not out of the question for a *"super HARPS"*

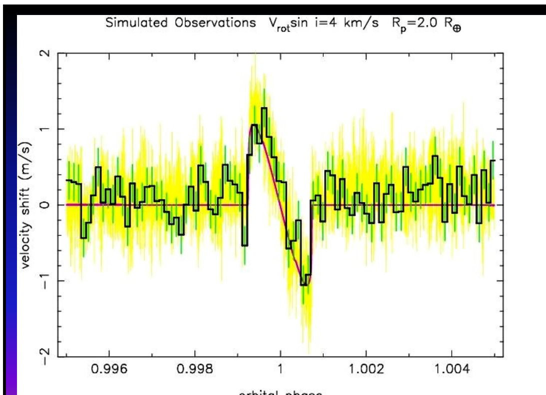
Note: transit duration ~ 13 hours

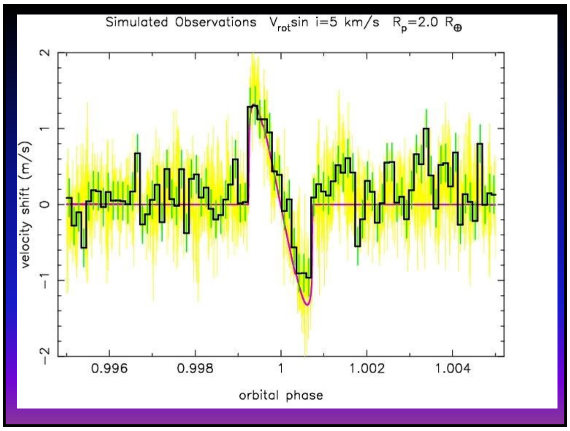
Simulation Results

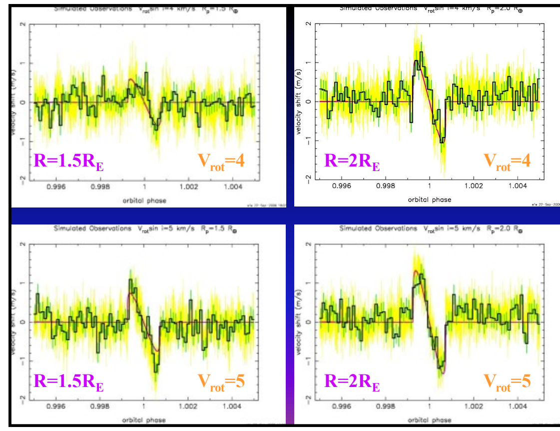


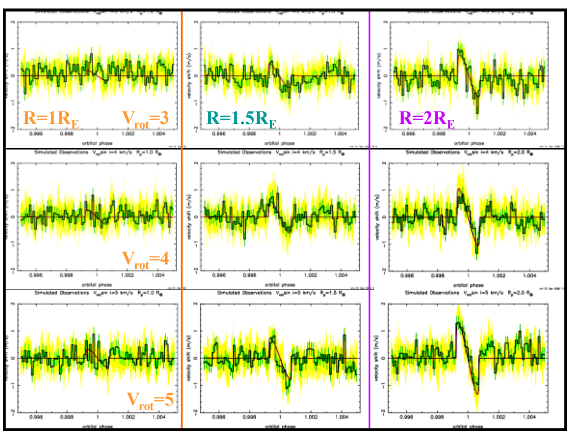
yellow = "true" (unobserved) signal at 2-min without noise
black = simulated 60-min observations with noise











Results

Vrot sin i	R_{planet} / R_{Earth} 1	1.5	2
3 km/s	No	No	~
4 km/s	No	~	Y
5 km/s	No	Y	Y

Results

A terrestrial-size planet transit is (barely) detectable with current technology.

- Stellar pulsations average out.
- Low freq red noise does NOT average away; special filtering may help.
- Would be *easy* for a Jupiter-size planet (a "warm Jupiter")

Results

Not a way to find planets, but a valuable method to confirm terrestrial-size planets at 1AU found other ways, e.g. Kepler

The only method??

Other Considerations

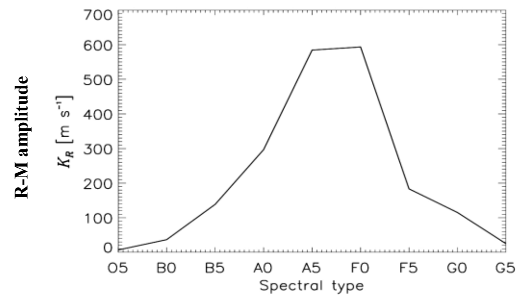
+ easier for A+F type stars (Gaudi & Winn 2006)

- more difficult if power spectrum is redder
 (i.e. if A-R α is closer to 1.000)

+ RM velocity shift of *line profile* is larger than centroid shift of *rotation kernel*; observed amplitude will be larger than these simulations
 (helps offset the overly optimistic i=90^0)

R-M amplitude: Jupiter-size planet vs. spectral type

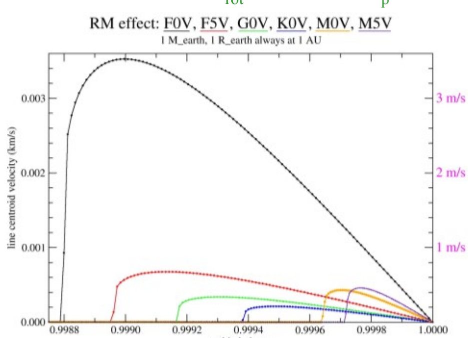
hot massive stars: V_{rot} ↑ but R_p/R_* ↓



Gaudi & Winn (2006)

R-M amplitude: Earth-size planet vs. spectral type

cool low-mass stars: V_{rot} ↓ but R_p/R_* ↑



Conclusion

The Rossiter-McLaughlin effect can help confirm suspected Earth analog planets.

- Motivation for a 30-m telescope!
- Gas-giant planets are easy!
- Still some puzzles to solve

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Using the Rossiter-McLaughlin effect to measure stellar obliquities

Tells us about planet formation & migration history:

- Aligned is what we expect if planets formed in a co-planar disk.
- Mis-aligned if there is planet scattering.

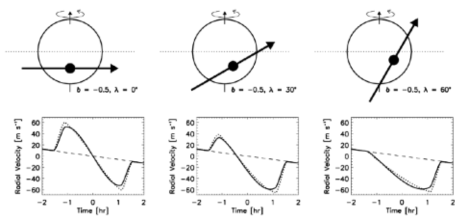


Figure 1. The RM effect as an anomalous Doppler shift. Top: three transit geometries that produce identical light curves, but differ in spin-orbit alignment. Bottom: corresponding radial velocity signals. Good spin-orbit alignment (left) produces a symmetric "red-shift-then-blueshift" signal, a 30° tilt (middle) produces an asymmetric signal, and a 60° tilt (right) produces a blueshift throughout the transit. From Gaudi & Winn (2007).

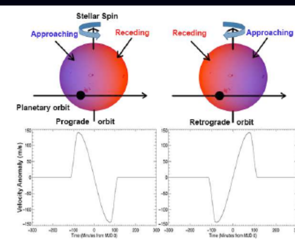
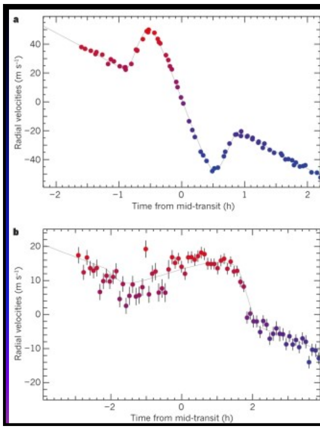


Fig. 1: Top: Artist's impression of a transiting planet on a prograde and a retrograde orbit (for clarity, the motion of the planet across its host star is the same for both prograde and retrograde orbits while the rotation direction of the star is reversed for the retrograde orbit). The stellar hemisphere shaded blue represents the side rotating towards the observer with its light blue-shifted. The stellar hemisphere shaded red represents the side rotating away from the observer with its light red-shifted.
Bottom: The modeled radial velocities for the two orbits showing the differing Rossiter-McLaughlin effect as a planet transits across the disk of its host star.



HD198733

and

WASP 8

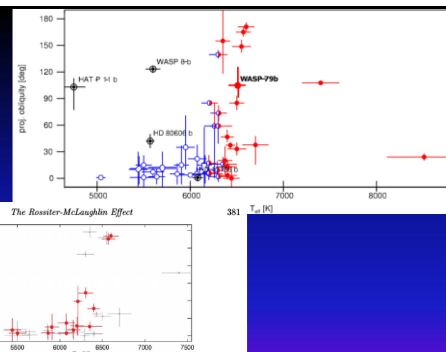
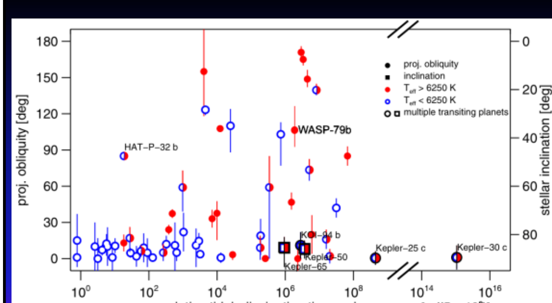


Figure 1. Hotter stars have oblique rotation. The projected obliquity of Hot Jupiter ($M_{planet} > 0.2\ M_{Jupiter}$; Period < 6 days) systems is plotted as function of the effective temperature of the host star. Using the measurements available 2010 (Winn *et al.* 2010a) noticed that systems with cool stars are aligned, while the obliquities of hot stars tends to be higher (gray small circles). Since then 16 new RM measurements have been reported (red large circles). The systems Kepler-8, CoRoT-1/11, have been omitted (see section 3.2) and the values for WASP-1/2 have been taken from Albrecht *et al.* (2011)



RESULTS:

Several dozen systems investigated.

- **Many are aligned, but many are not**
  → scattering is important

- **Tendency for the planets around hotter stars to be less aligned with the stellar rotation axis**
  → less convection in stellar envelope
  → less efficient tidal torques