Sagan Summer School

Stars as homes for habitable planets

The Effects of Stellar Variability on the Detection and Characterization of Exoplanets

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Astrophysical noise sources: p-modes, granulation, meridional flows

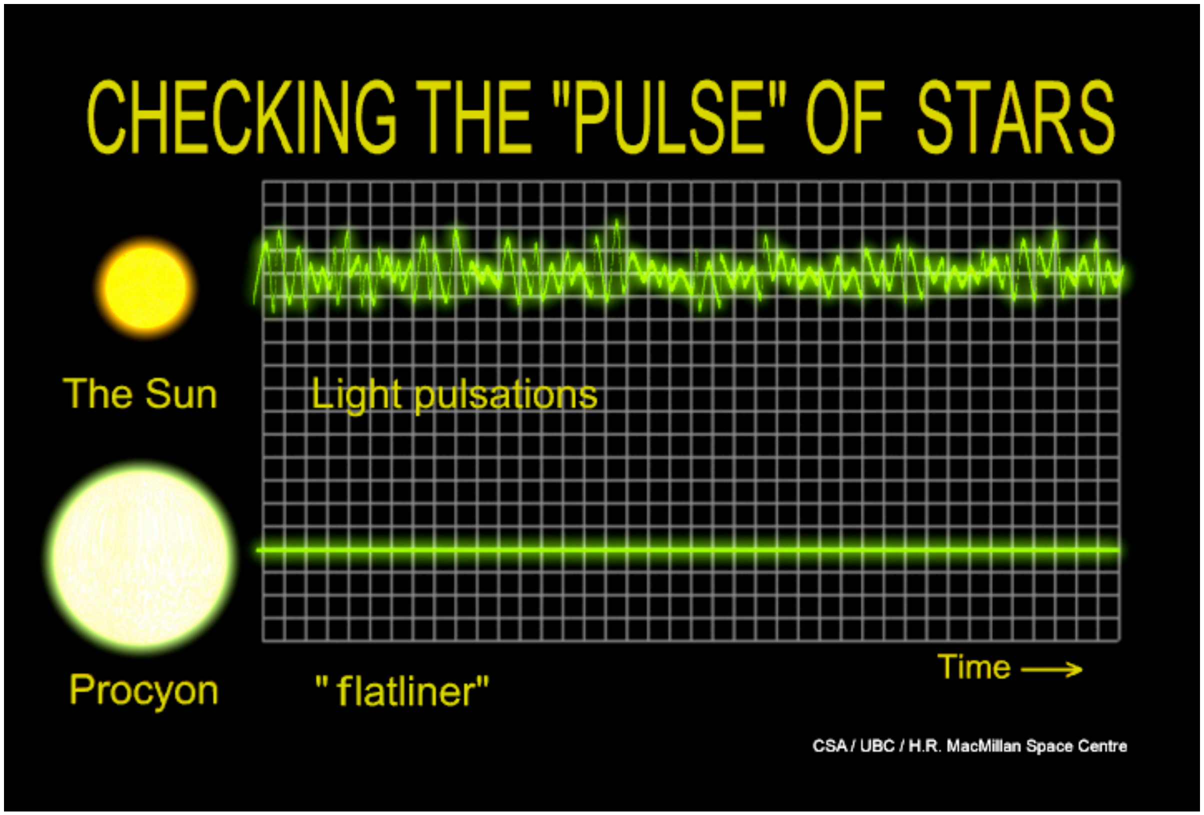
Diagnostics: Svalues, log R'HK, photometry, bisector analysis

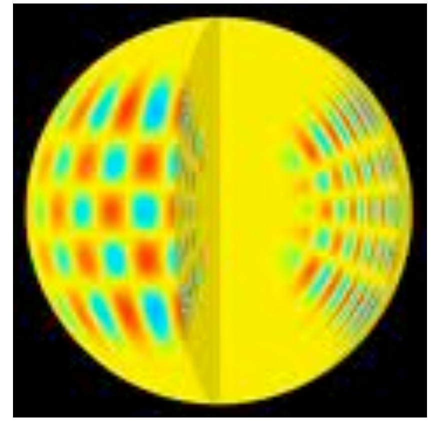
Impact on RV technique

Measuring line shifts of 1/3000 of a pixel already. As we reduce this further (e.g., with laser frequency combs) what will we measure: dynamical motions or astrophysical flows? The latter might be less interesting.

Impact on photometry and astrometric observations

Noise sources: P-mode oscillations





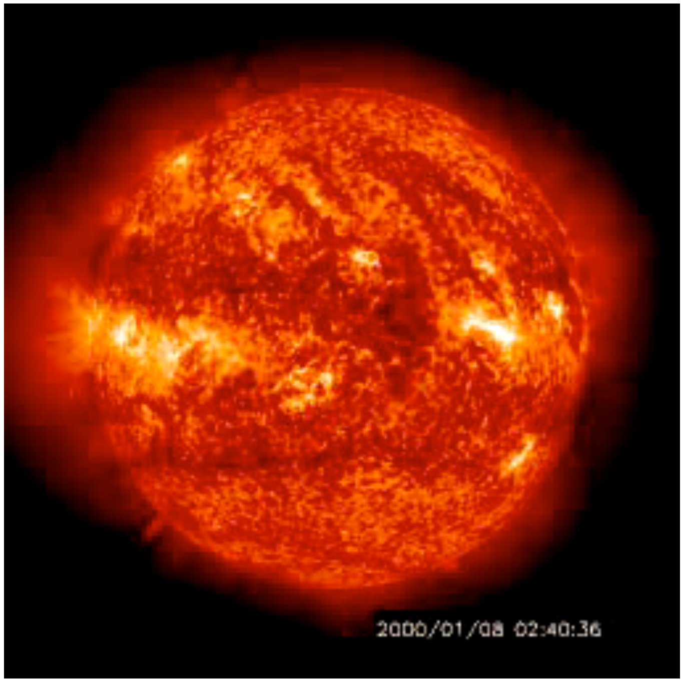
Noise sources: p-modes

Millions of seismic eigenmodes driven by non-adiabatic granular pressure fluctuations are excited to low amplitudes with a frequency spectrum that grows as f^4 until it reaches a narrow maximum at 3 mHz, then drops off again toward higher frequencies.

5 minute oscillations in the Sun.

Pressure modes move in and out of resonance - probably no way to correct for them. Instead, we average over them by taking longer or multiple exposures.

Noise sources: Spots and flares

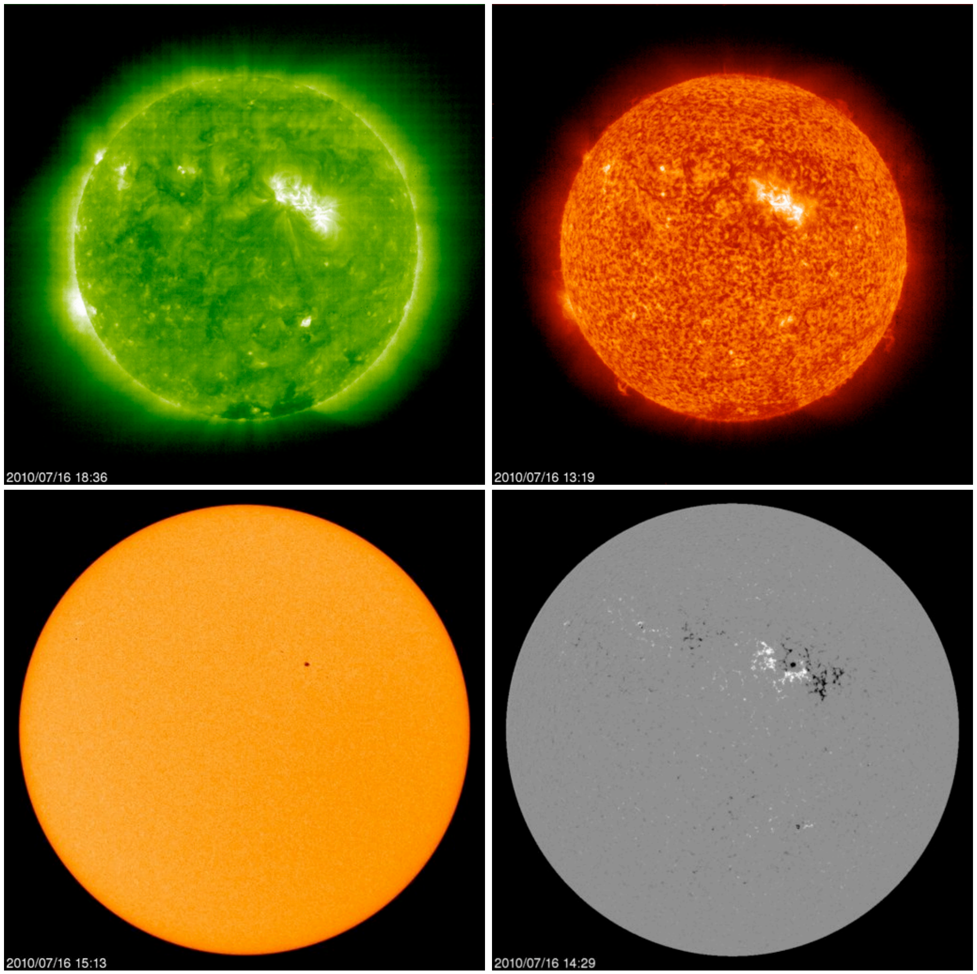


This is the quiet, steady old Sun!

Convective dynamos spawn magnetic fields and result in spots and flares with km s^{-1} outflows producing convective blue shifts in spectral line profiles.

These arise from the photosphere and are not dynamical Doppler shifts, but how to tell the difference?

Example: The Sun: July 16, 2010

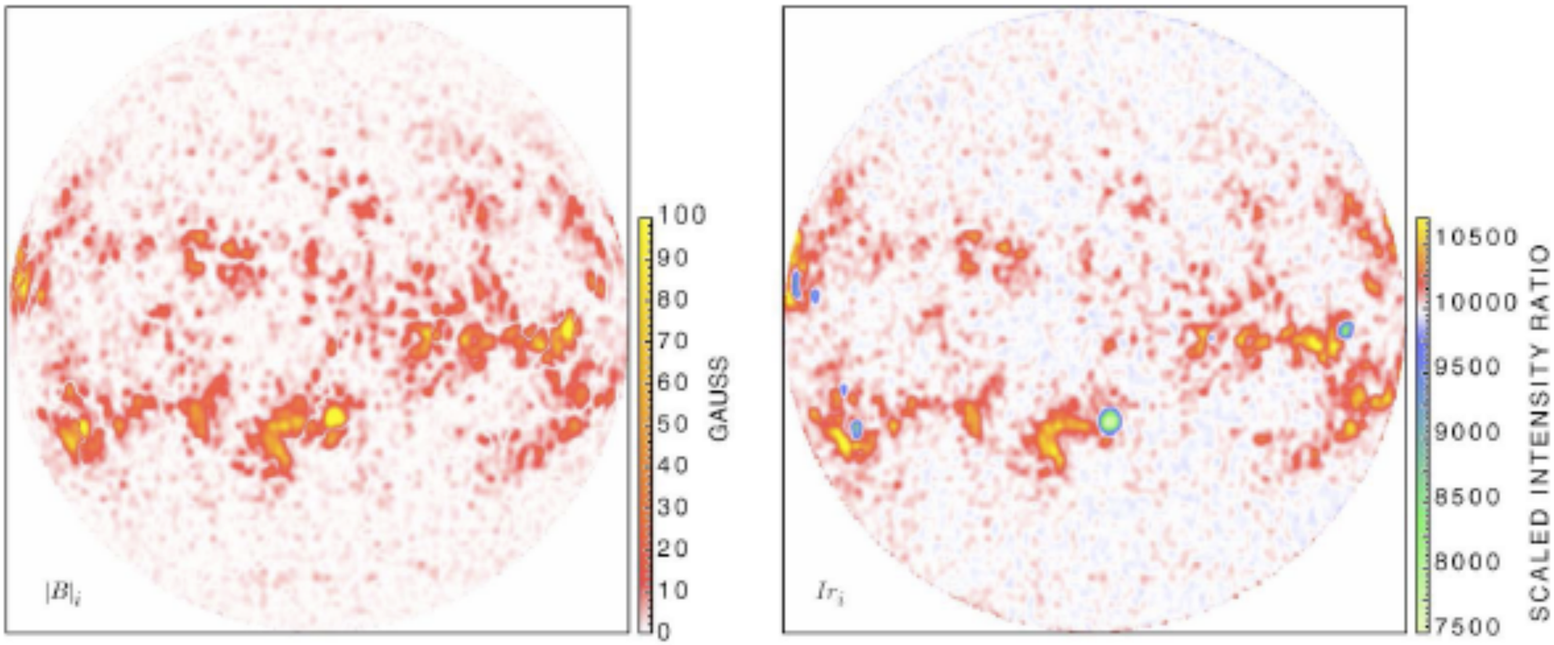


EIT images: 195A 1.5M K
304A 70,000K

(Which of these images higher layers in the solar atmosphere?)

MDI images: 6768A (continuum)
Magnetogram
(black and white show opposite polarity)

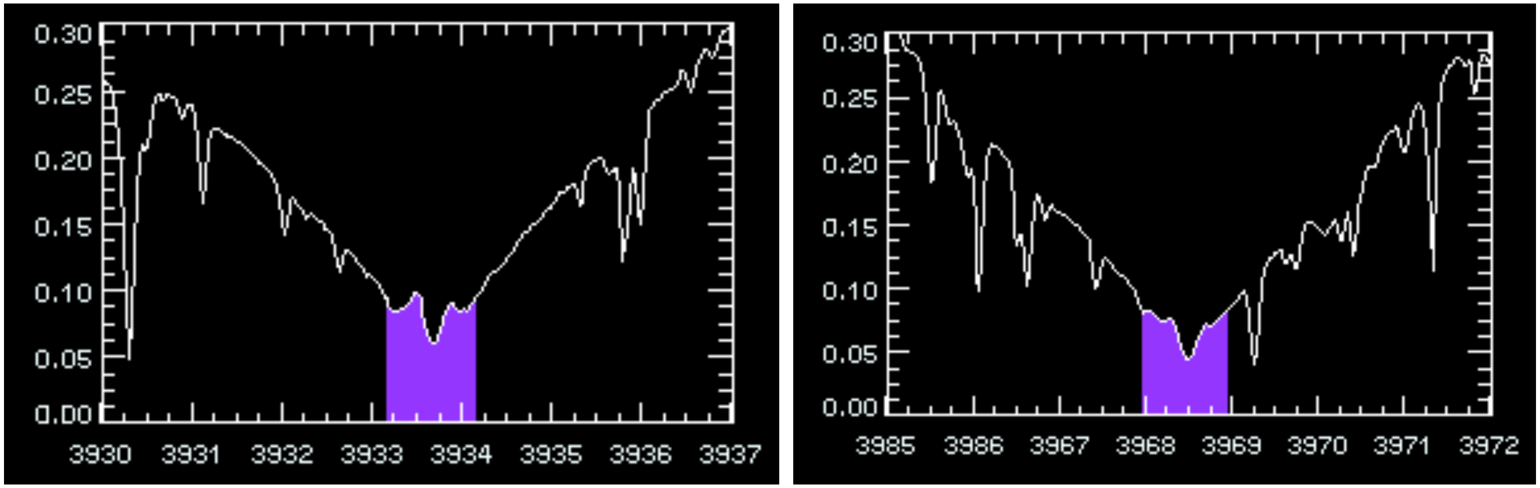
Diagnostic tool: Ca II H&K



Ulrich *et al*. (2010) map magnetic field intensity (using the l 5250 flux strength_ from MWO (1997 – 2007) to the total solar irradiance (using line ratio 5250A/ 5237A (upper photosphere / lower chromosphere).

Evidence that magnetic fields in the photosphere are casually related to chromospheric emission.

Diagnostic tool: Ca II H&K

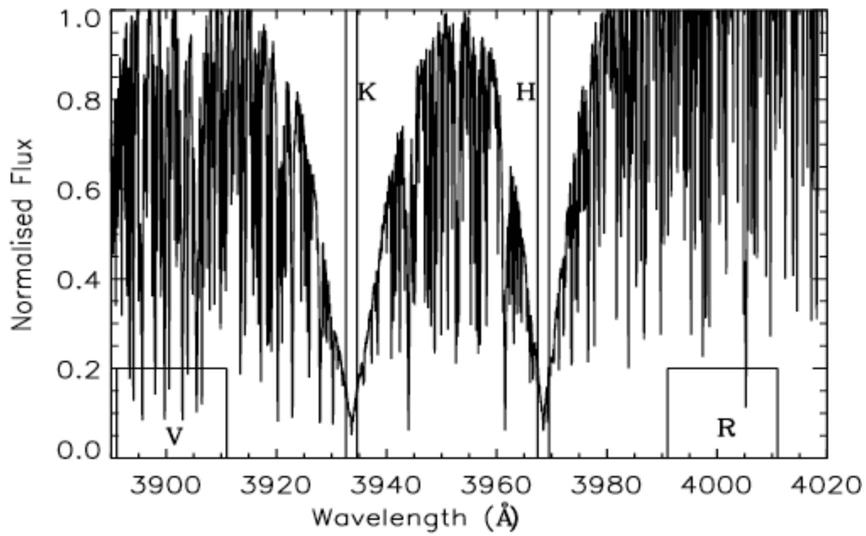


Singly ionized calcium produces broad absorption features in the solar spectrum, the Ca II H&K lines, formed in the lower chromosphere.

Direct relation b/t magnetic field strength and emission in the Ca II lines (Skumanich et al . 1975). Energy from stellar magnetic fields is transferred into the upper chromosphere where it fills in the line cores with emission. ***Ca II H&K core emission lines are a signature of magnetic activity (chromospheric activity) in stars***.

The Mt Wilson H&K project obtains time series measurements of H&K line core emission for hundreds of stars: S_{HK} metric.

Diagnostic tool: S_{HK} and log R'_{HK}

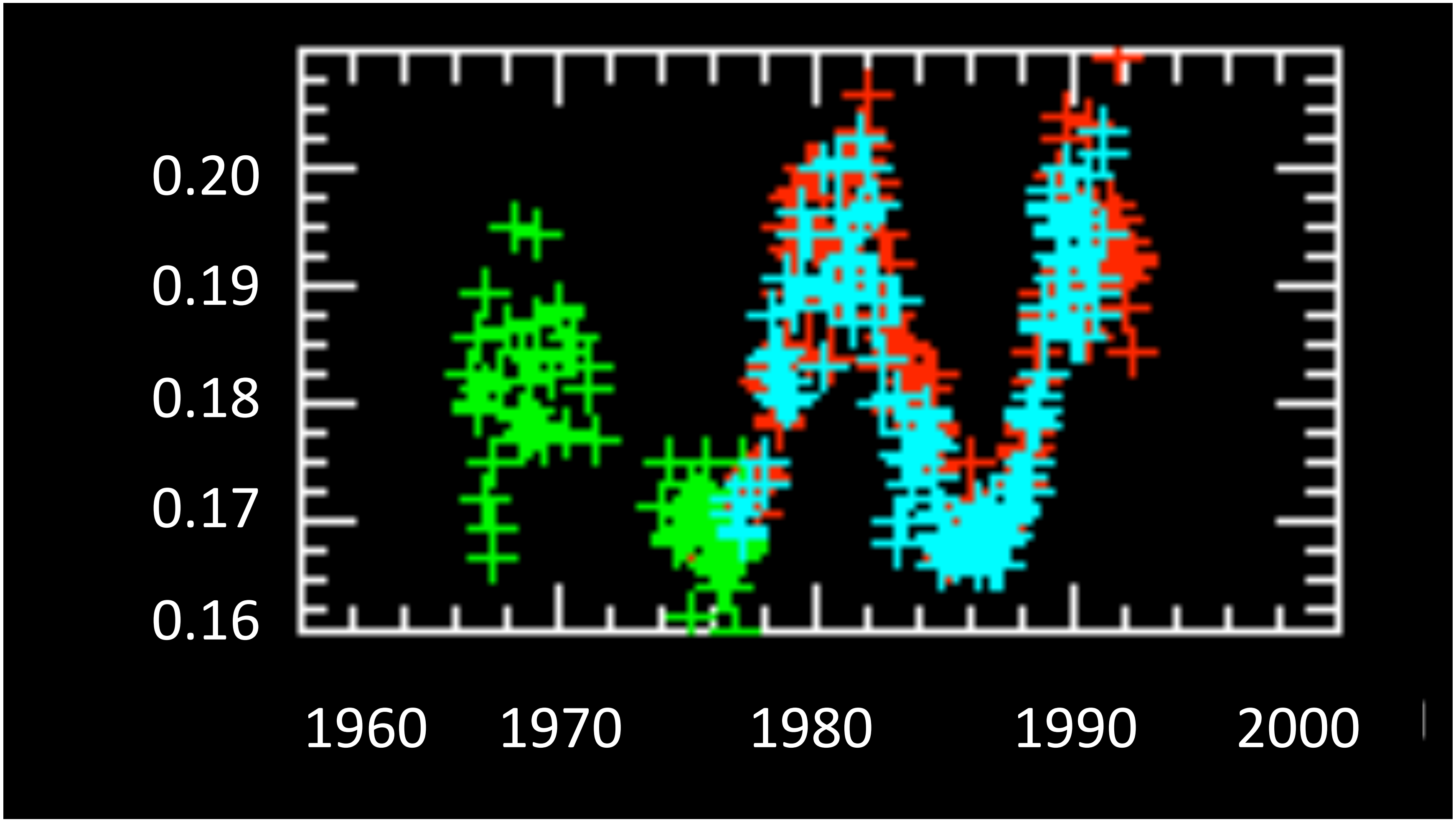


S_{HK} is the ratio of emission in the Ca II line cores (relative to continuum windows).

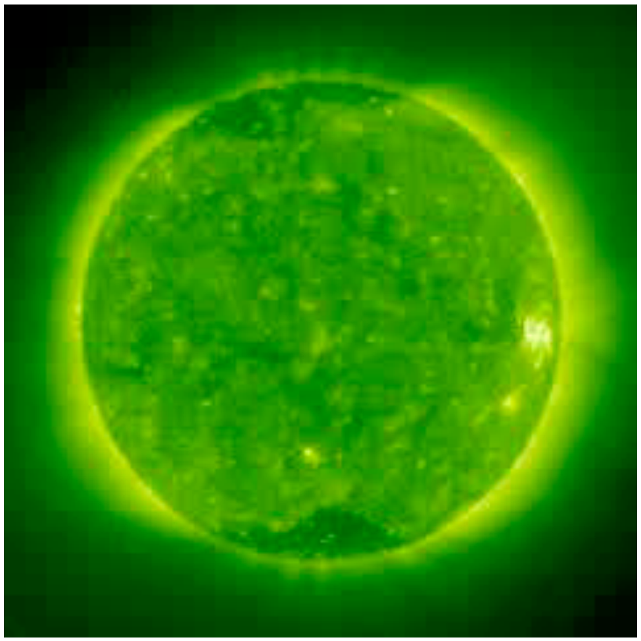
The continuum at 3900A is extremely low in red stars; S_{HK} can increase either because more energy is being dumped into the upper chromosphere or because continuum flux is decreasing.

log R'_{HK} was defined, essentially as a ratio of S_{HK} to photospheric flux. Puts all stars on a common "activity" scale.

Example: Time series solar Ca H&K cycle



Noise sources: Meridional Flows

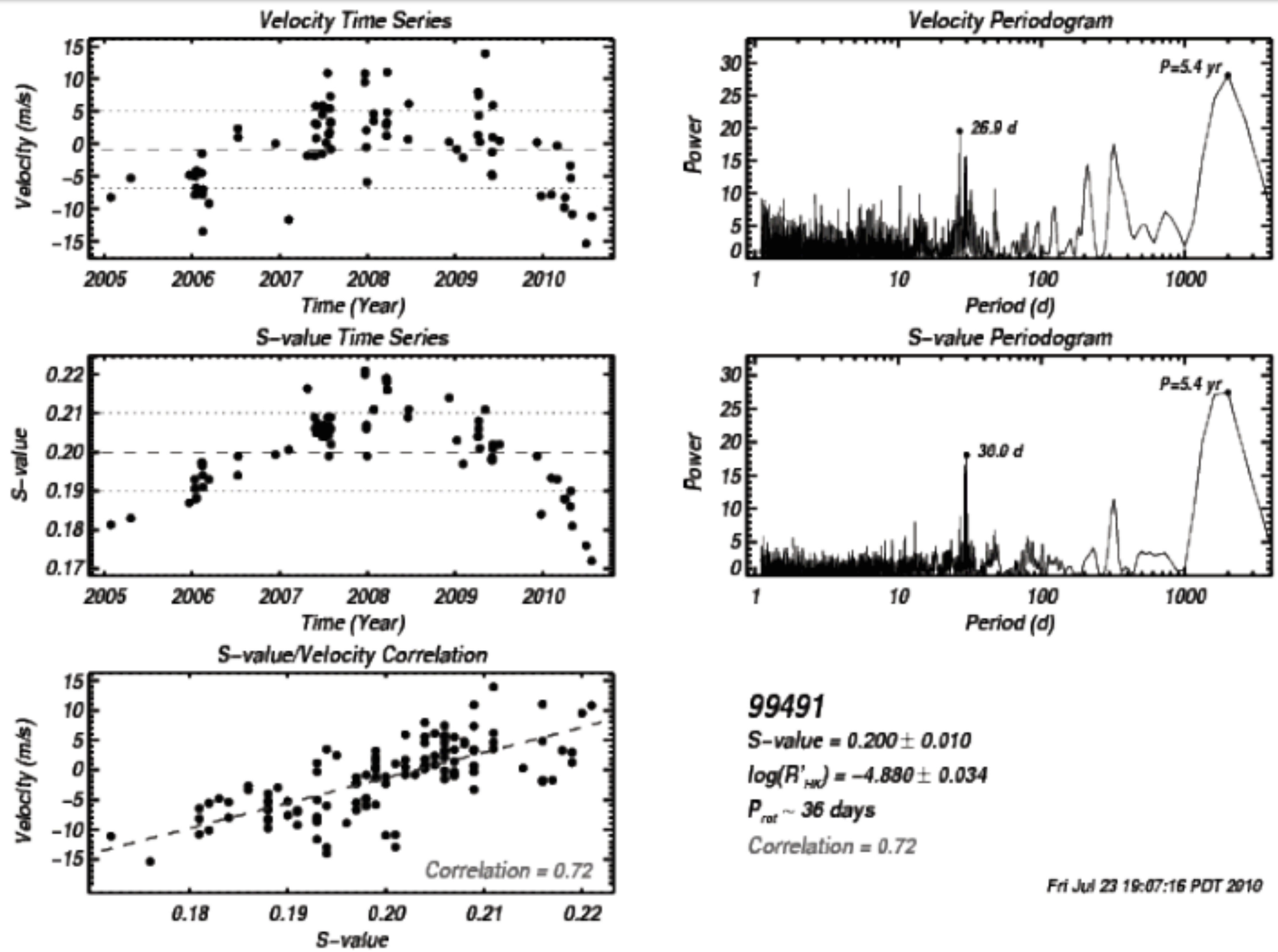


Long term cycles in the magnetic fields may also be associated with cycles in photospheric velocities - a non-dynamical source of RV variation.

Modeling Ca H&K line emission can at least serve to warn you - but we don't have a good correction yet.

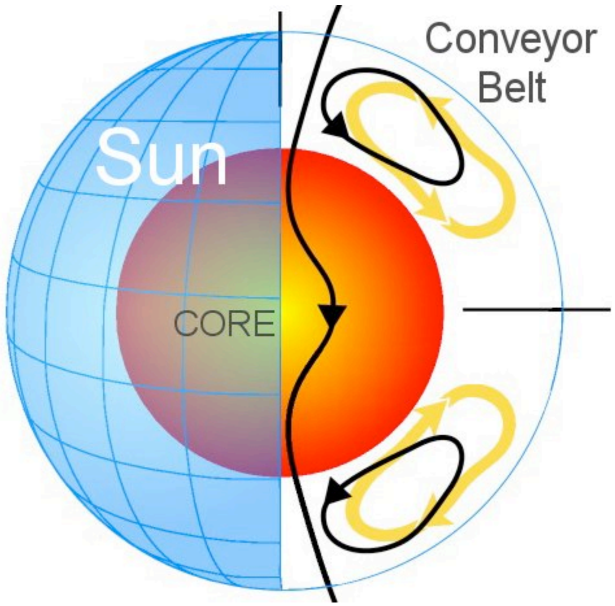
This is the quiet, steady old Sun!

Noise sources: Meridional Flows



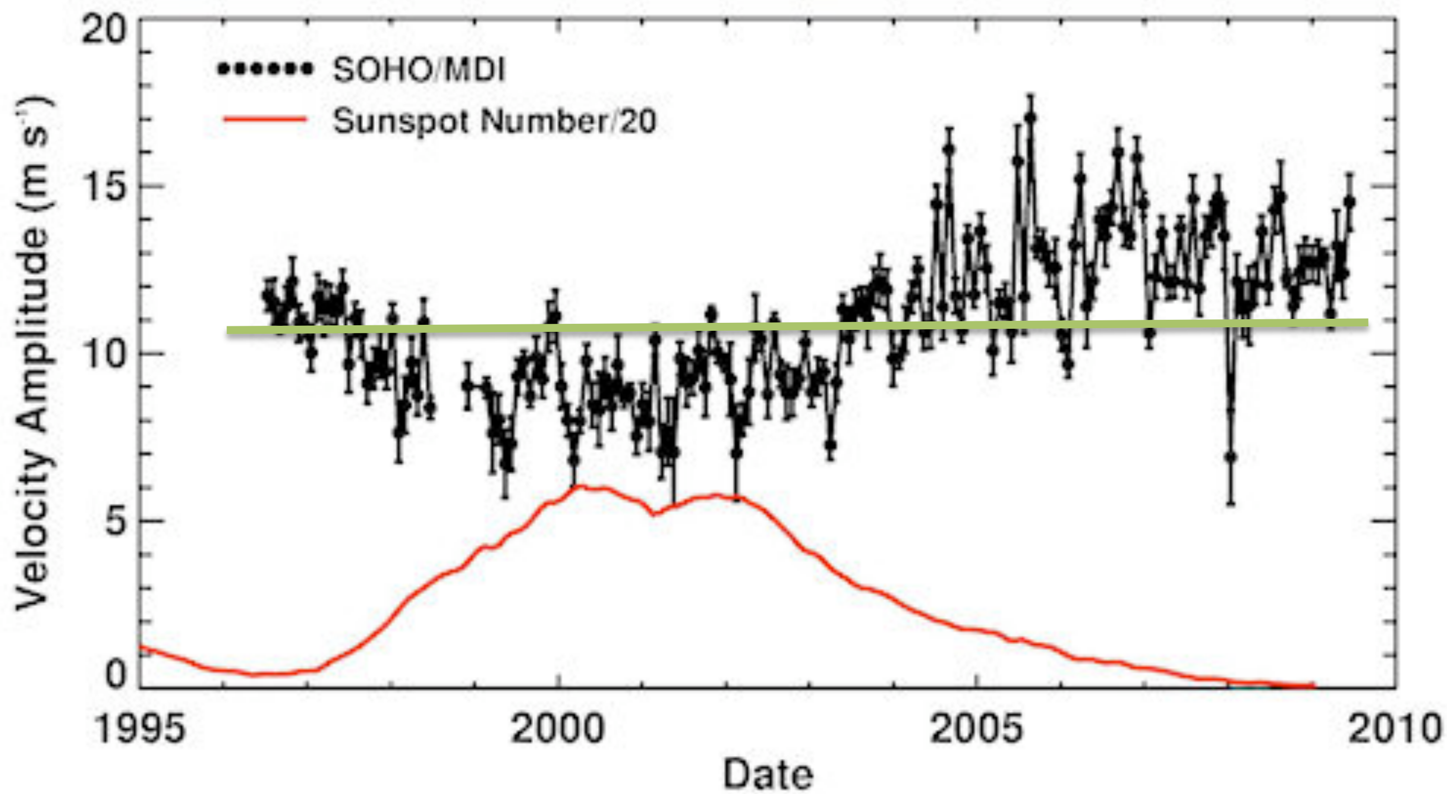
From Andrew Howard's talk

Example: Solar meridional flow



Meridional Circulation: massive flow pattern that transports hot plasma to the poles and deeper CZ layers. Flows are thought to be ~10 m s^{-1} (slow, relative to the outflows from plages or spot rotation). Meridional flow may govern the strength of the polar magnetic field and strength of sunspots.

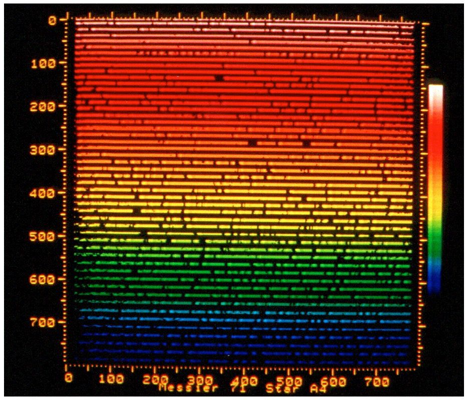
Example: solar meridional flow



Meridional Flow variation 1996 – 2009 measured by SOHO/MDI. The scaled sunspot number in red indicates the phase of the solar activity cycle (Hathaway & Rightmire: 2010, *Science* 327, 1350).

One take-away message: RV variations may be out of phase with activity cycles.

Impact on RV technique



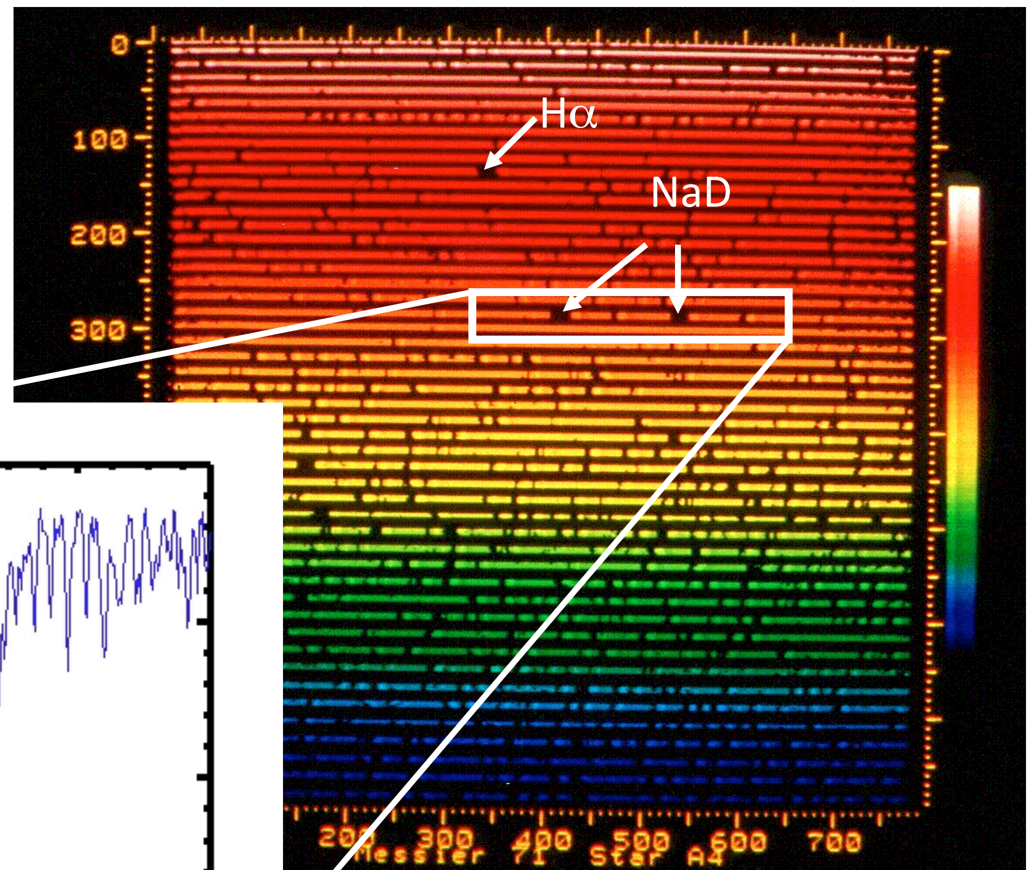
1) the intensity of spectral lines is determined by the optical depth of the absorbing species, regulated by temperature and element abundance.

2) Exploiting the Doppler effect, the relative velocity between the telescope and the star can be measured by measuring shifts in spectral lines:

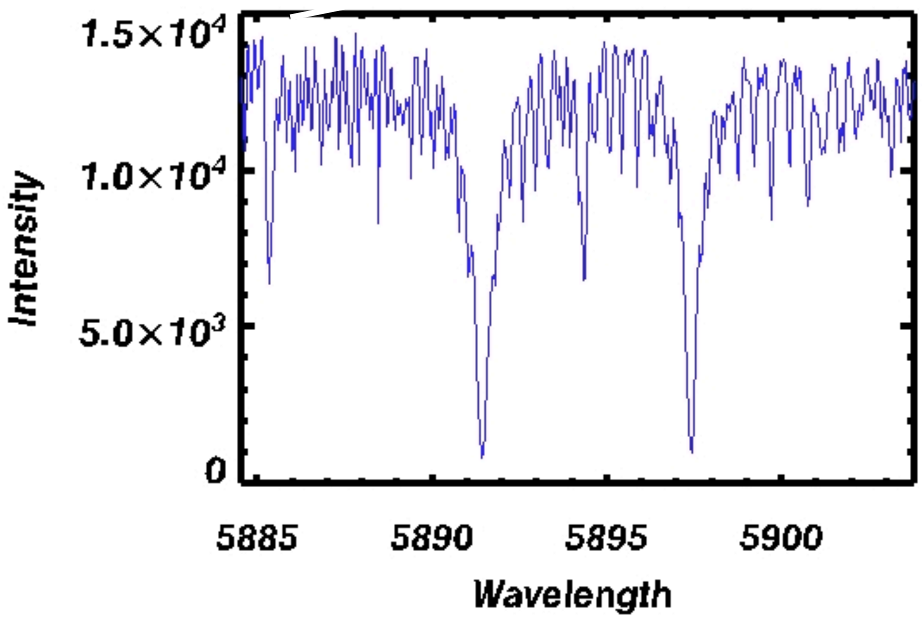
   DI/I = v/c

Impact on RV technique

Echelle spectrum



The spectrum is extracted from the 2-D echelle image, to give an array of intensity *vs* wavelength for each spectral order.



Impact on RV technique

The detection of extrasolar planets requires the highest precision Doppler measurements possible.

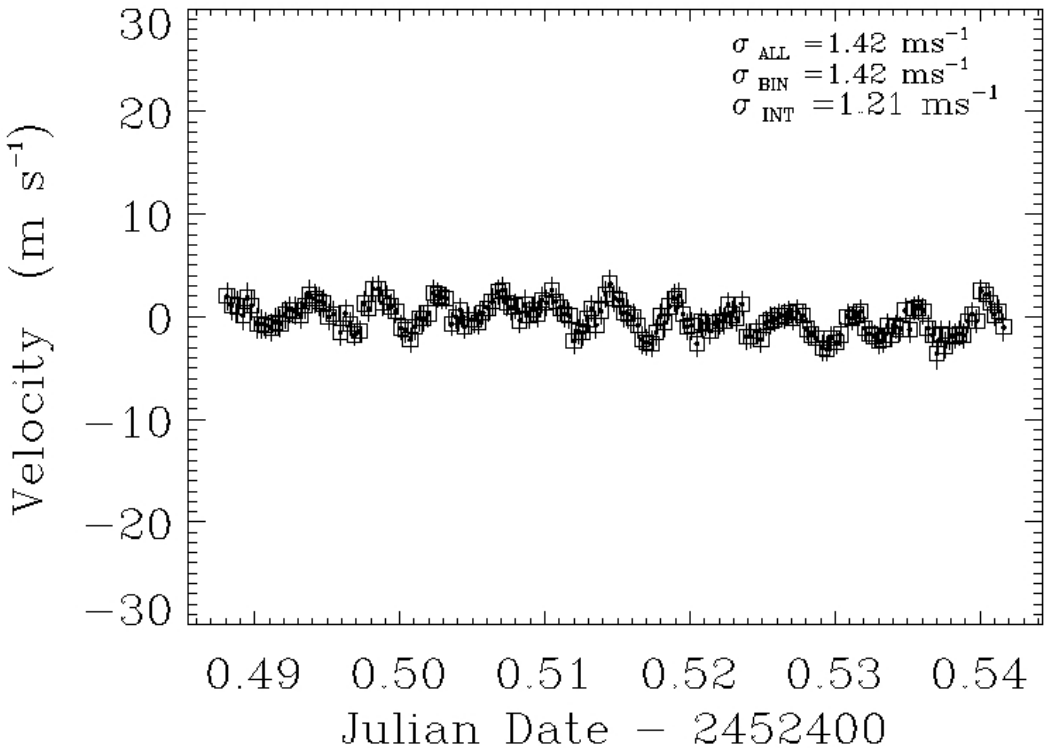
- Jupiter: induces a reflex velocity of ~12 m/s in the Sun.
- Earth: induces a reflex velocity of ~0.1 m/s in the Sun

For $RV_{STAR} = 12$ *m/s,* $\delta\lambda \sim 0.0002$ *Angstroms*

Impact on RV technique

Example: p-modes

R. P. Butler: observations of αCen, a chromospherically inactive, old, slowly rotating, sunlike star

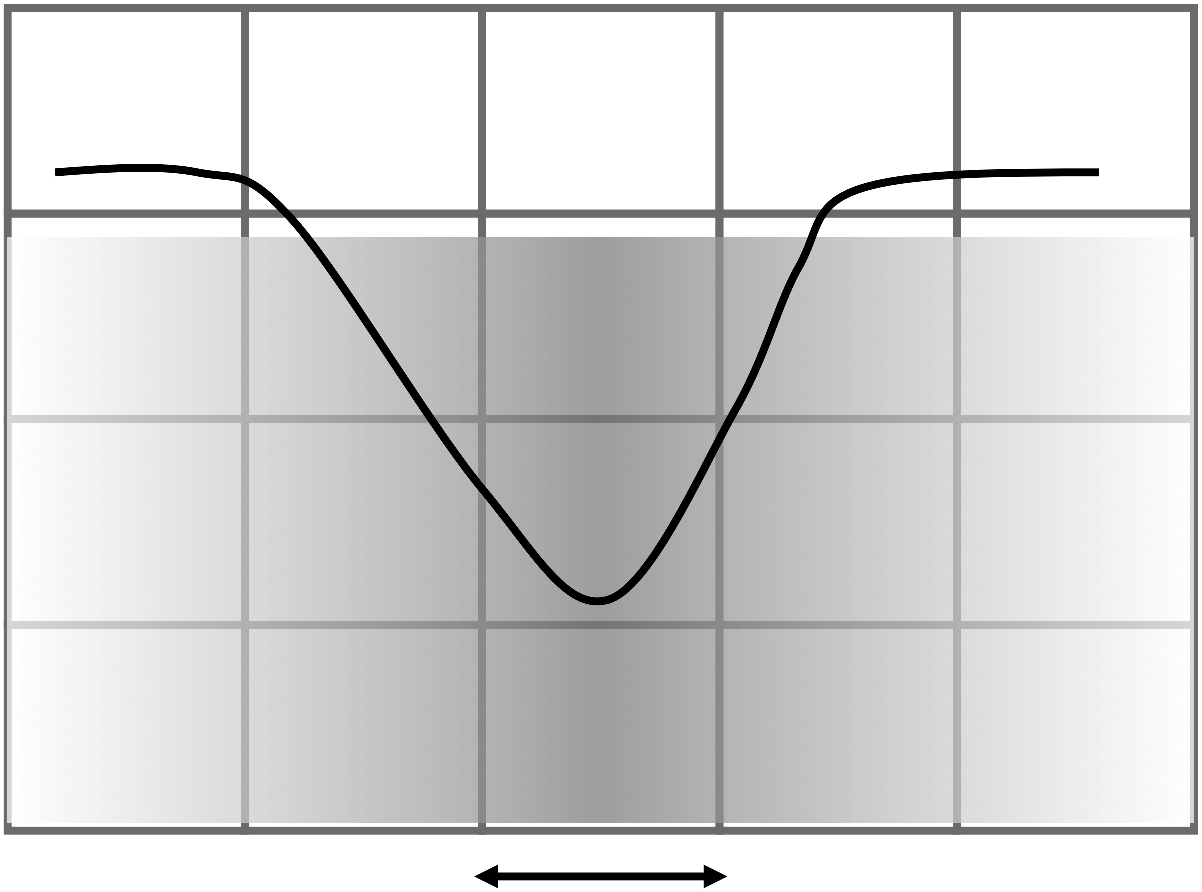


P-mode oscillations

5 minute periodicity, amplitude of about 3 m/s

Short exposure times would register snapshots of this RV variablility

Impact on RV technique



One pixel

Physical dimension: 15 μ

Dispersion λ: 0.05 A

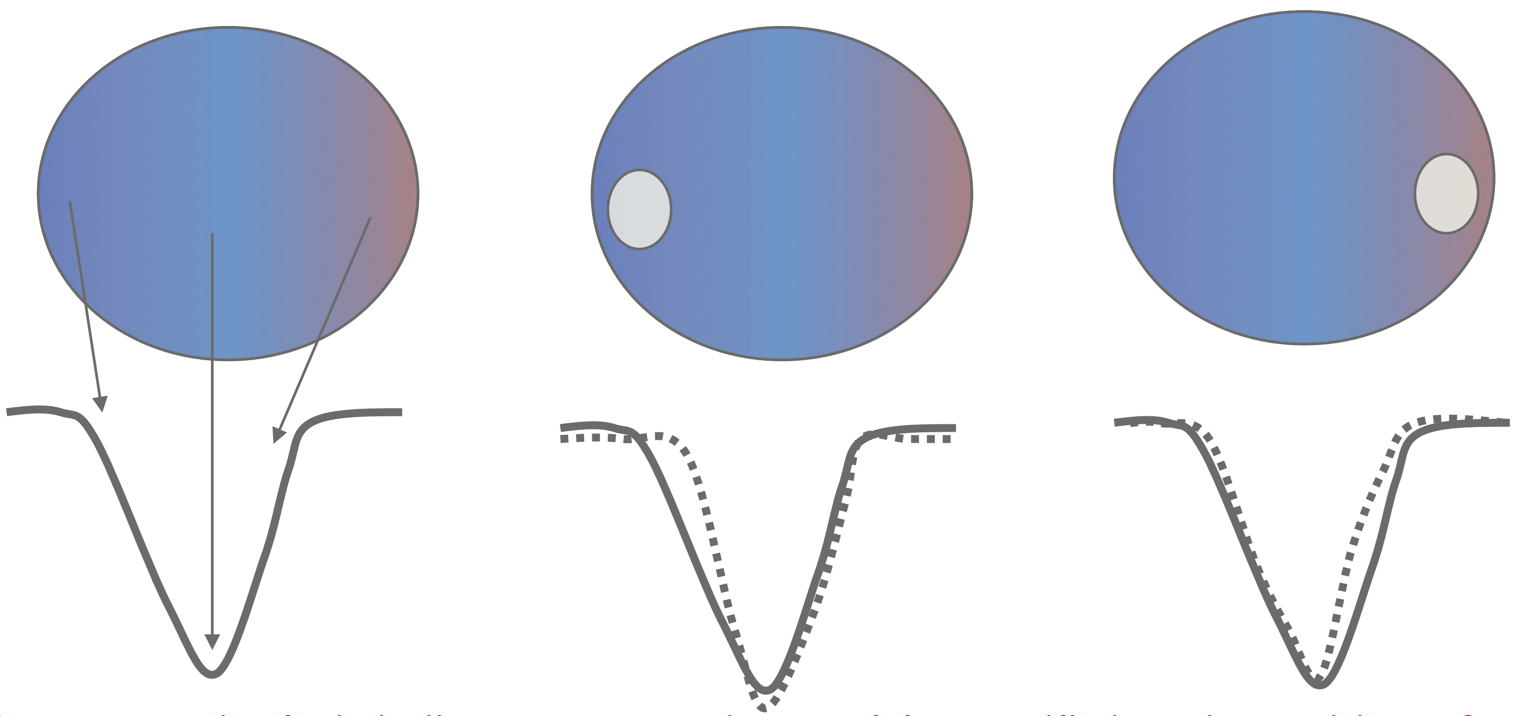
Velocity: 3000 m/s

For typical high resolution spectrographs with 15 μicron pixel CCD detectors (e.g. HDS on Subaru or HIRES on Keck), dl = 0.0002 A corresponds to 0.004 pixel shift. To measure this signal, you need a precision that is many times better.

Note: typical spectral lines are a few CCD pixels (or more) in width, so we need to detect shifts better than 1/1000 the width of the lines we model.

Impact on RV technique

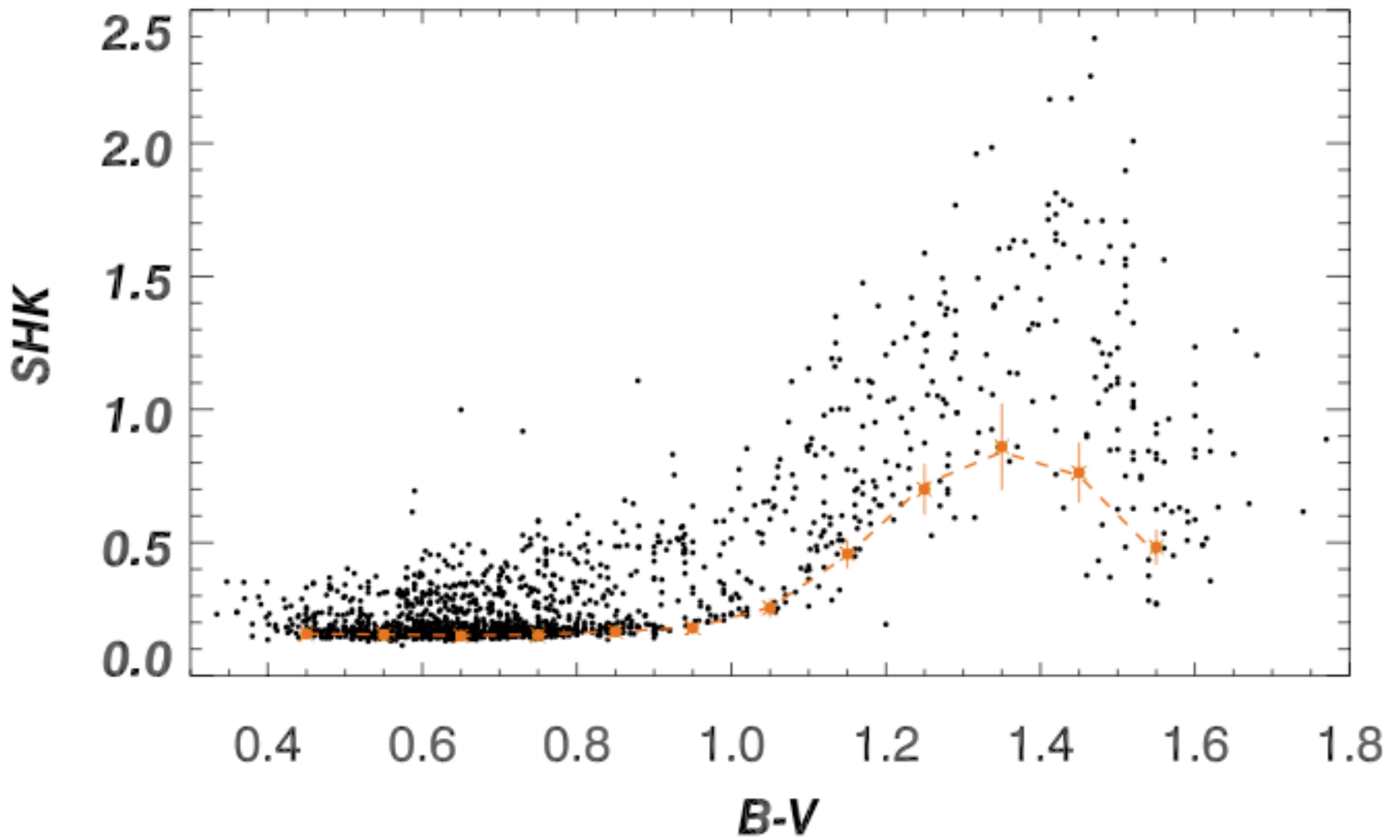
High rotational velocities are associated with chromospheric activity and starspots. As starspots rotate across the star, the line centroid shifts.



These astrophysical challenges to Doppler precision are likely to be problems for other detection techniques, too.

Diagnostic tool: S_{HK} and log R'_{HK}

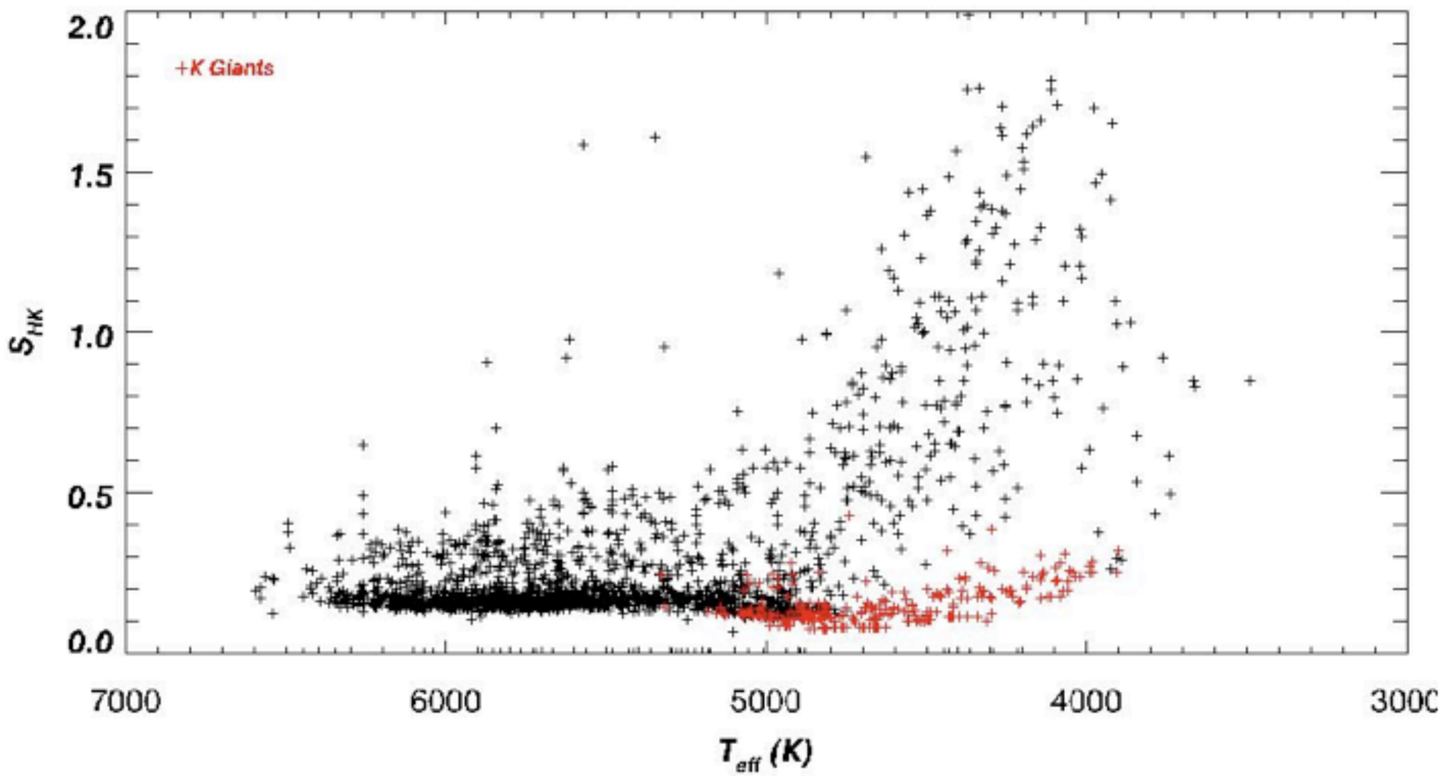
Isaacson & Fischer 2010 (ApJ in press)



Slipper diagram: lower SHK for hotter stars and smaller range. Turn-over in minimum SHK for cool stars.

Diagnostic tool: S_{HK} and log R'_{HK}

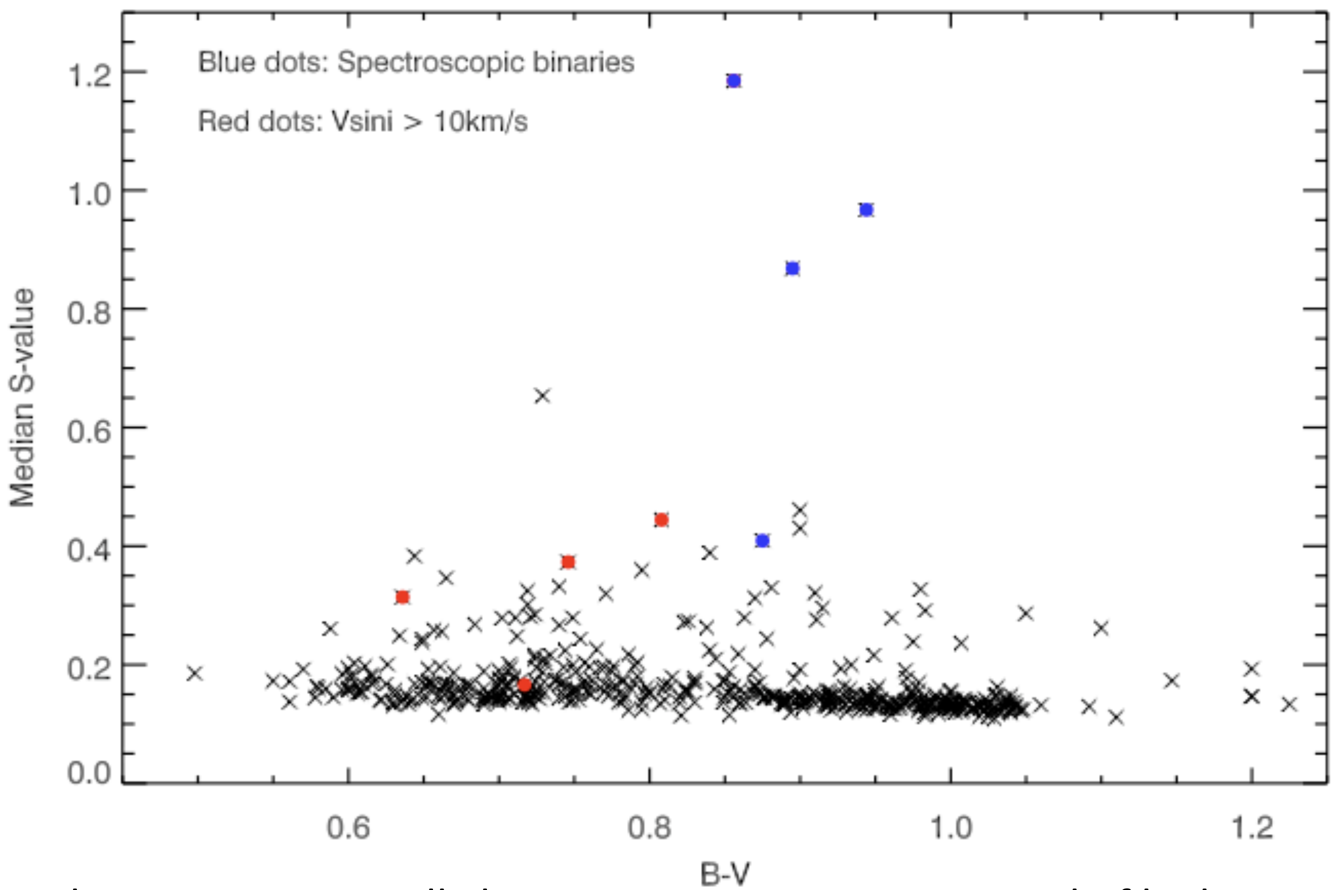
Fittingoff, Fischer et al. 2010 (ApJ in prep)



Low activity indicators for Kgiants, yet the RV jitter is substantially greater than for MS or subgiants.

Diagnostic tool: S_{HK} and log R'_{HK}

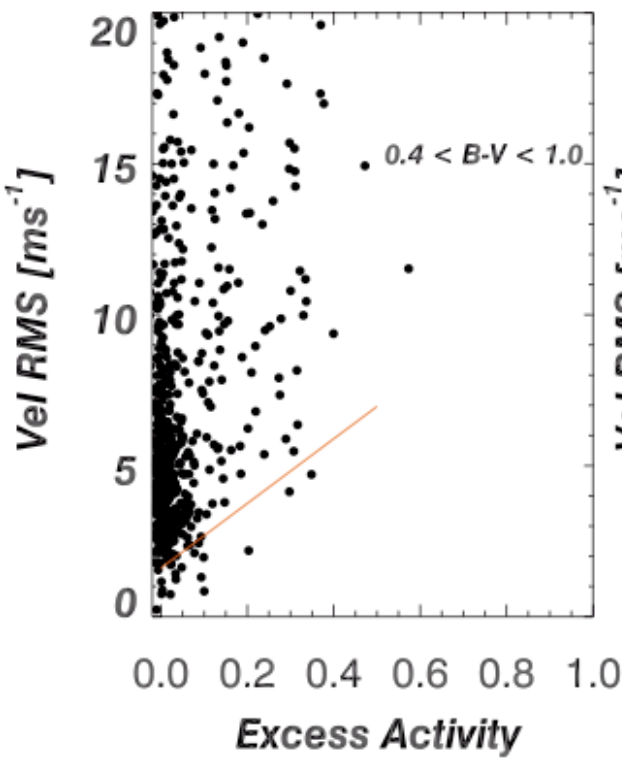
Isaacson & Fischer 2010 (ApJ in press)

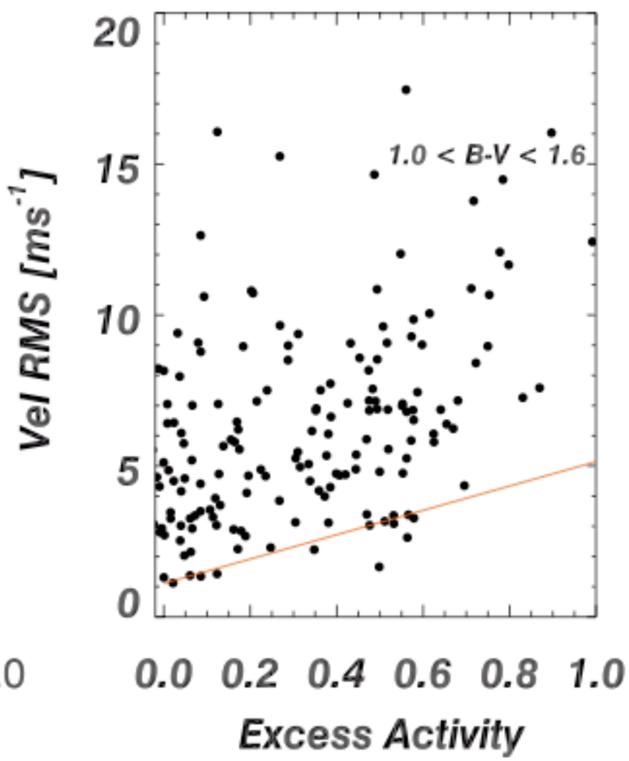


Subgiants are generally low activity. Exceptions: arrival of high angular momentum stars on the MS or binary stars.

Diagnostic tool: S_{HK} and log R'_{HK}

Isaacson & Fischer 2010 (ApJ in press)



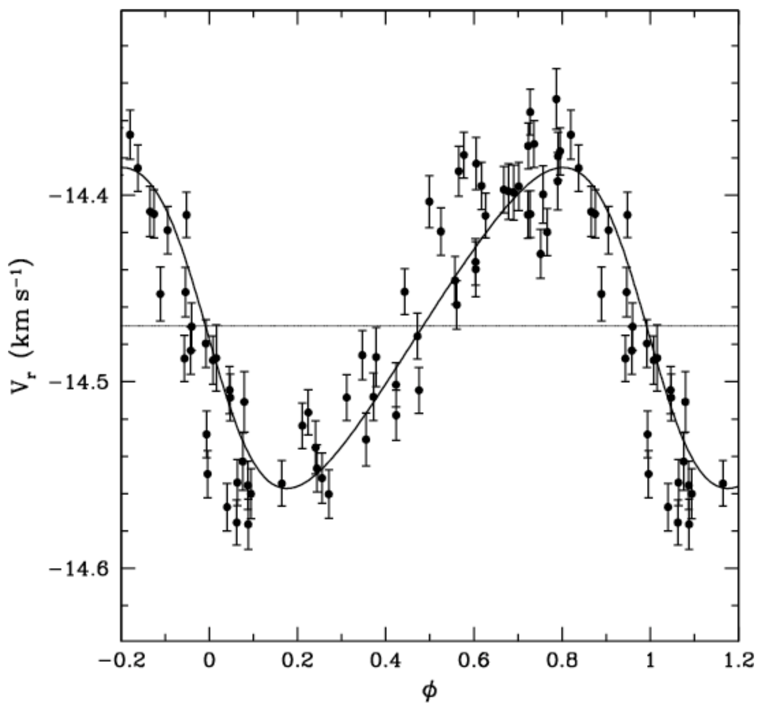


The minimum RMS sets a "floor" in activity (intrinsic to star?) Includes instrumental and analysis errors. Low activity stars have less jitter.

Impact on RV technique

Example: Spots

HD166435 (Queloz et al. A&A 2001)

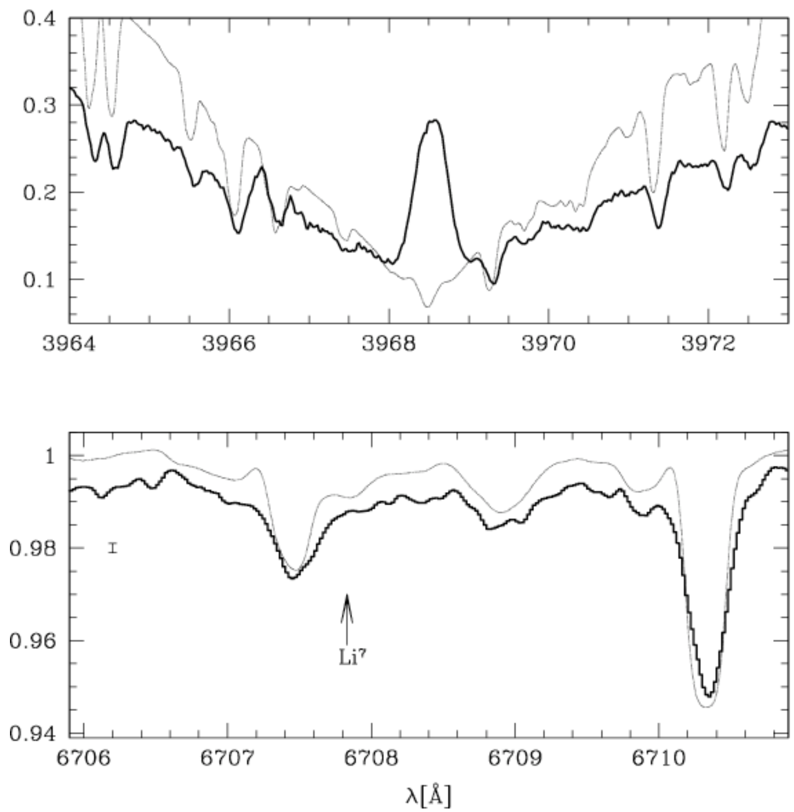


Phase diagram of radial velocities with a 3.7987-d period, amplitude of ~100 m s^{-1} in a two year data set. HD166435 is a G0V star, vsini = 7.6 km s^{-1}. Age (X-ray) ~ 200 Myr.

Impact on RV technique

Example: Spots

HD166435 (Queloz et al. A&A 2001)

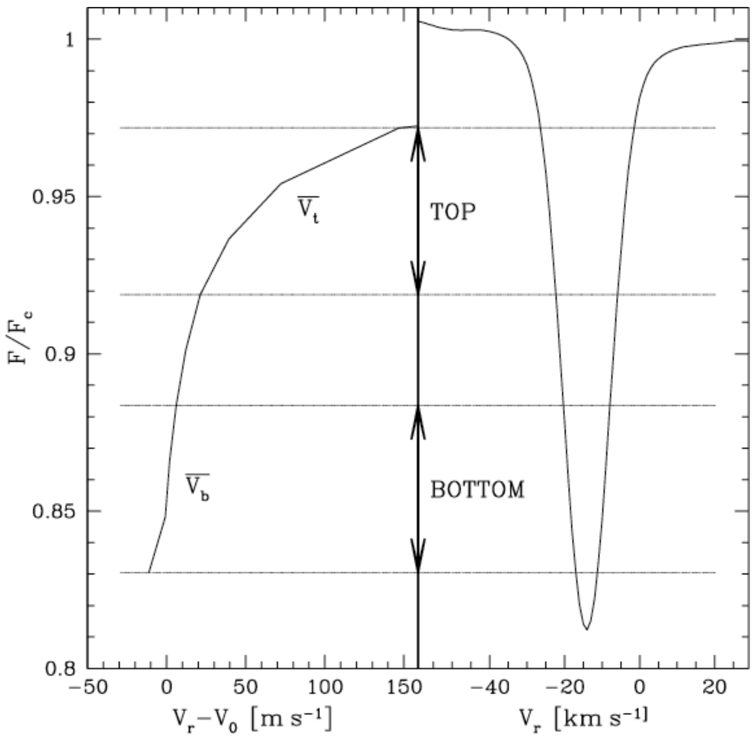


Top: Ca H&K emission for HD 166435 (relative to the Sun – light gray) and lithium line strength (youth indicator).

Impact on RV technique

Example: Spots

HD166435 (Queloz et al. A&A 2001)

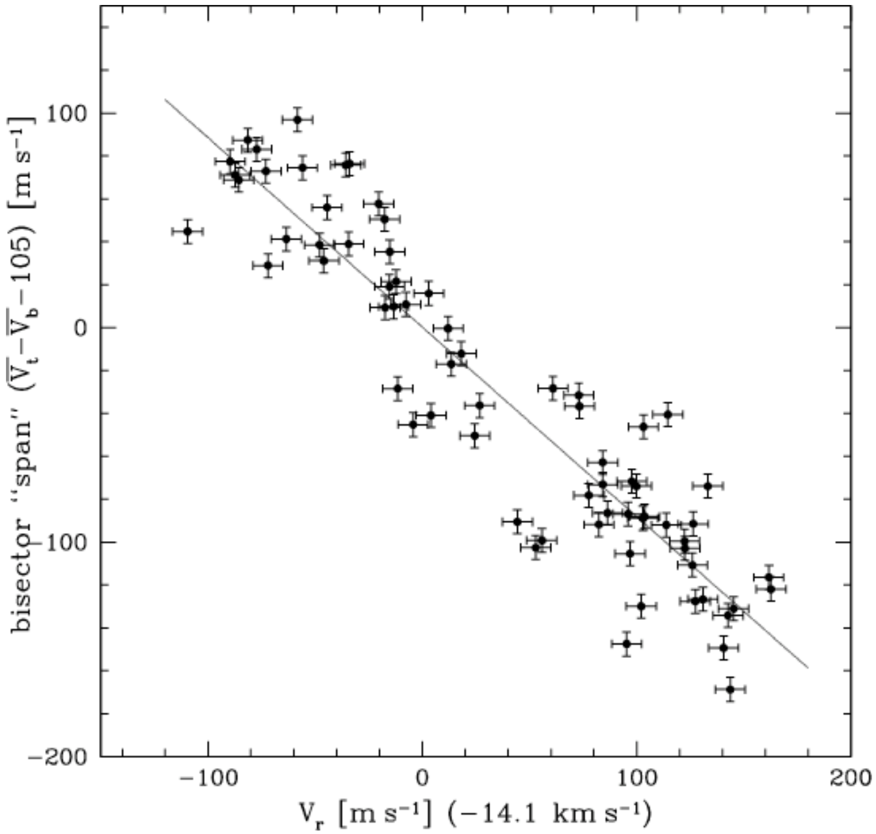


Bisector analysis (Vt – Vb) is a measure of the slope of the bisector

Impact on RV technique

Example: Spots

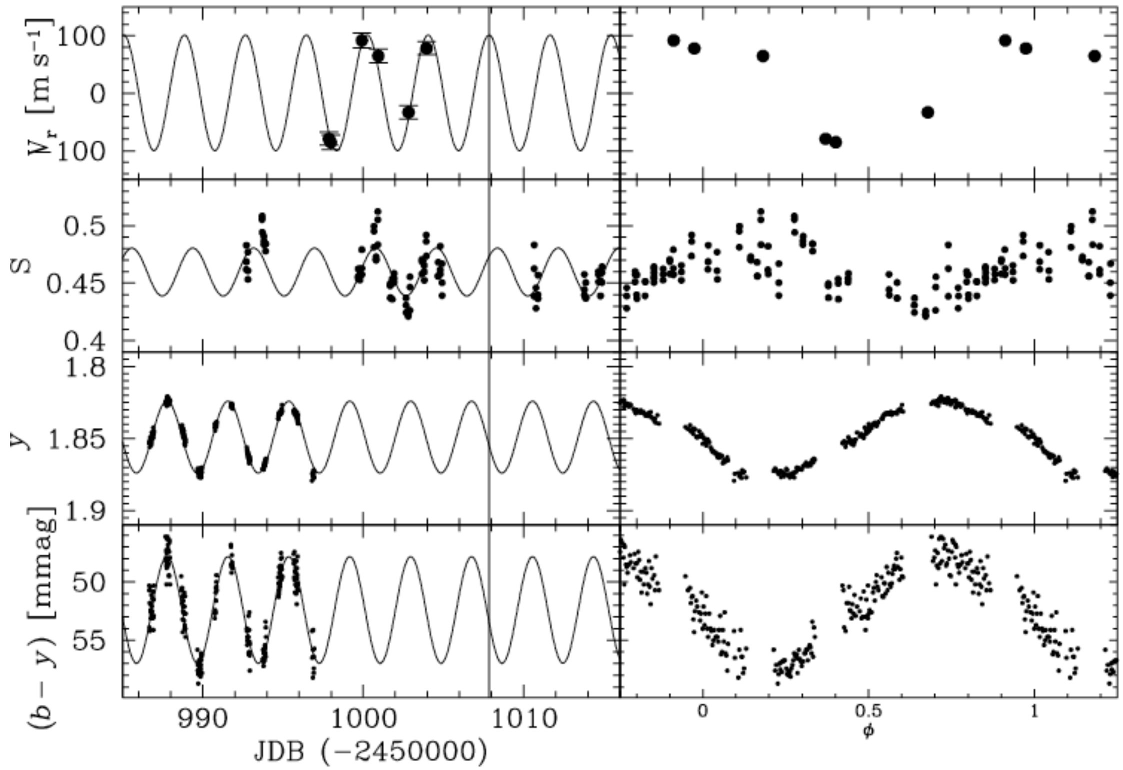
HD166435 (Queloz et al. A&A 2001)



Radial velocity vs bisector span ($V_t - V_b$) of the CCF profile

Impact on RV technique

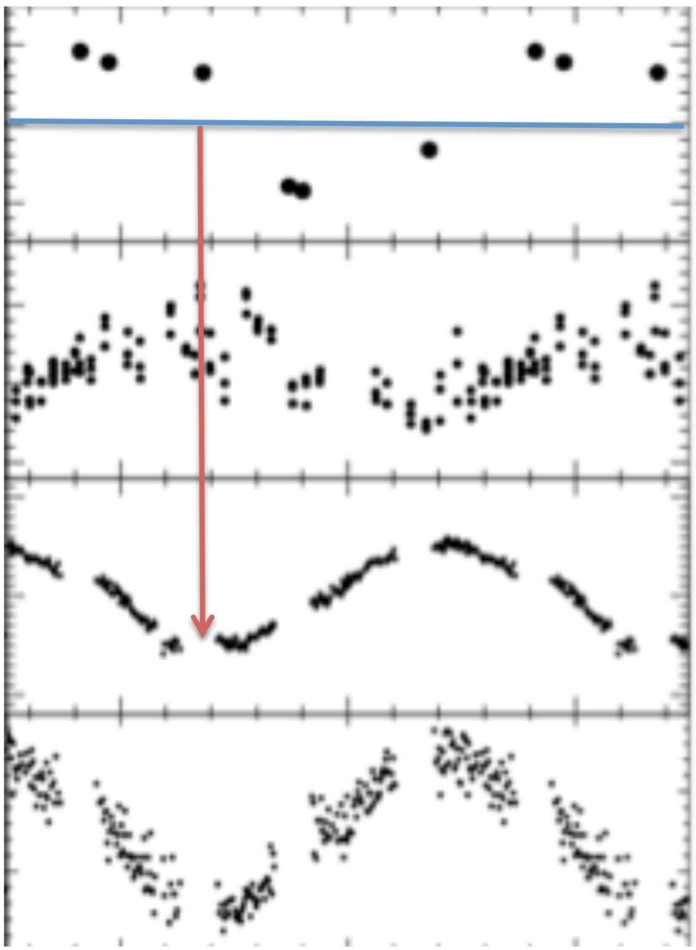
HD166435 (Queloz et al. A&A 2001)



Coherence in radial velocities (3.7987-d period), S-values and photometery. Quasi-coherence maintained for nearly two years: unusual stability in the chromosphere of an active star. The S-values (Mt Wilson) spanned 30 days and were out of phase with RV's by 1/8 phase; the photometry was out of phase with RV's by ¼ phase.

Impact on RV technique

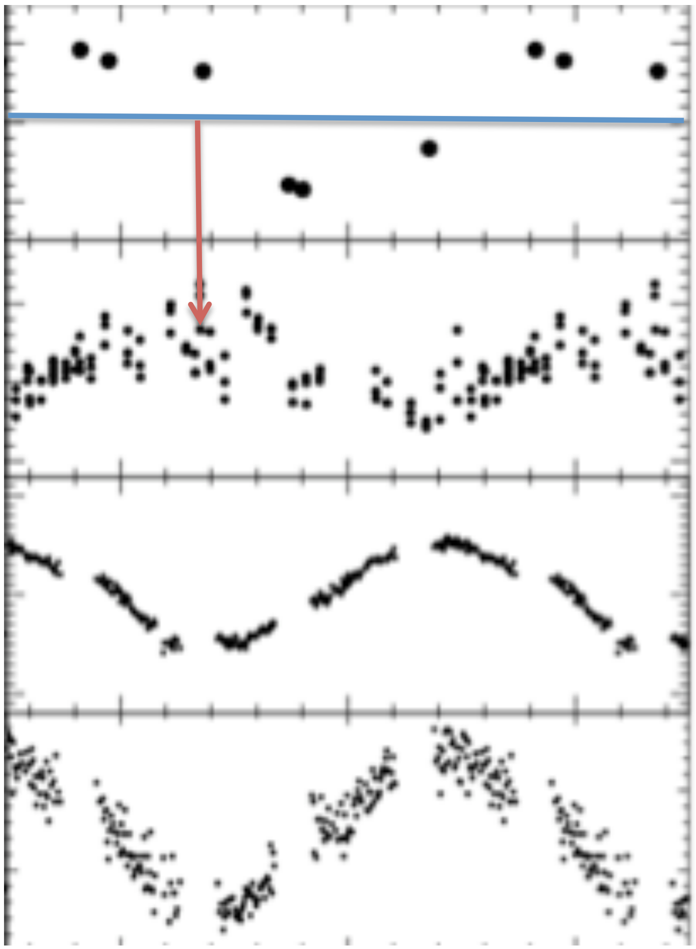
HD166435 (Queloz et al. A&A 2001)



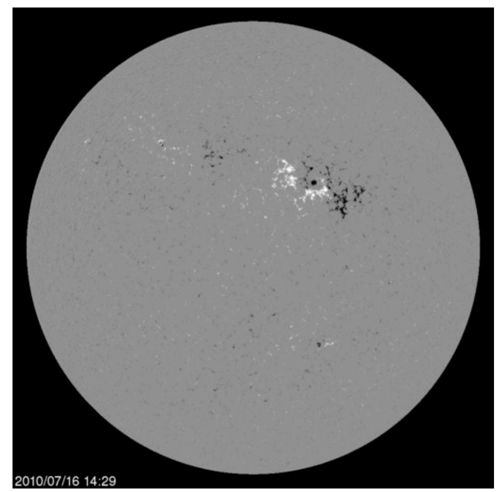
Brightness and RV are out of phase by ¼ phase.
When the spot is in center of star, the RV signal is zero, but the brightness is maximally suppressed.

Coherence for 21 days shows that the spot lifetimes are of order one rotation period. Quasi-coherence over two years, shows that spots are regenerated at about the same longitude. Stable spot cycles can persist for years in young stars by reforming at same latitude.

Example: Spots
HD166435 (Queloz et al. A&A 2001)



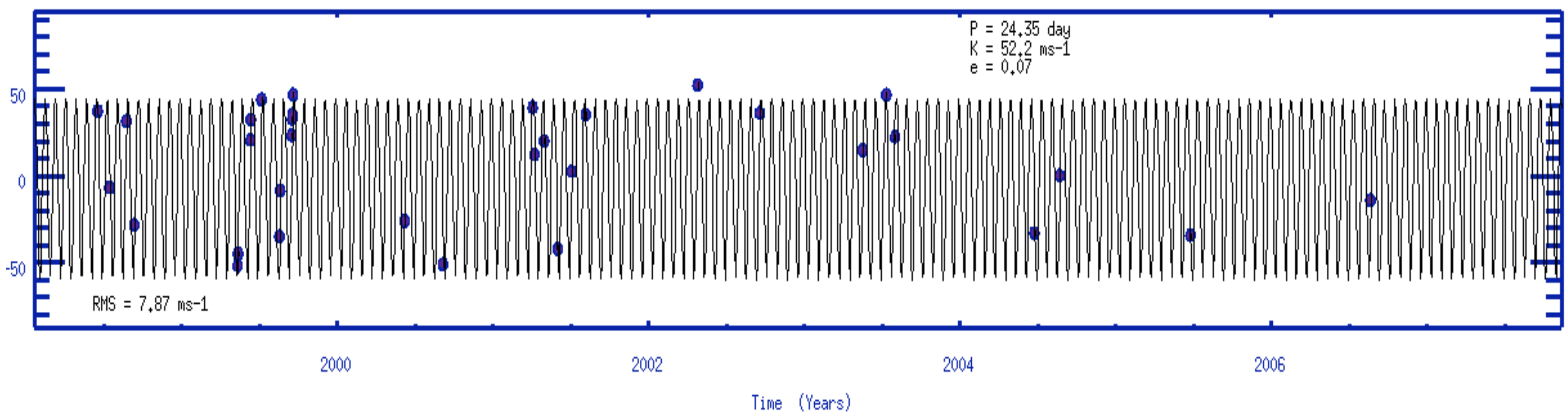
Brightness and S-values are out of phase by 1/8 phase.
Suggests that the photocenter of dark spot distribution is offset from the plage. In the Sun, leading spots tend to be larger and live longer than trailng spots.



Impact on RV technique

Example: HD192263

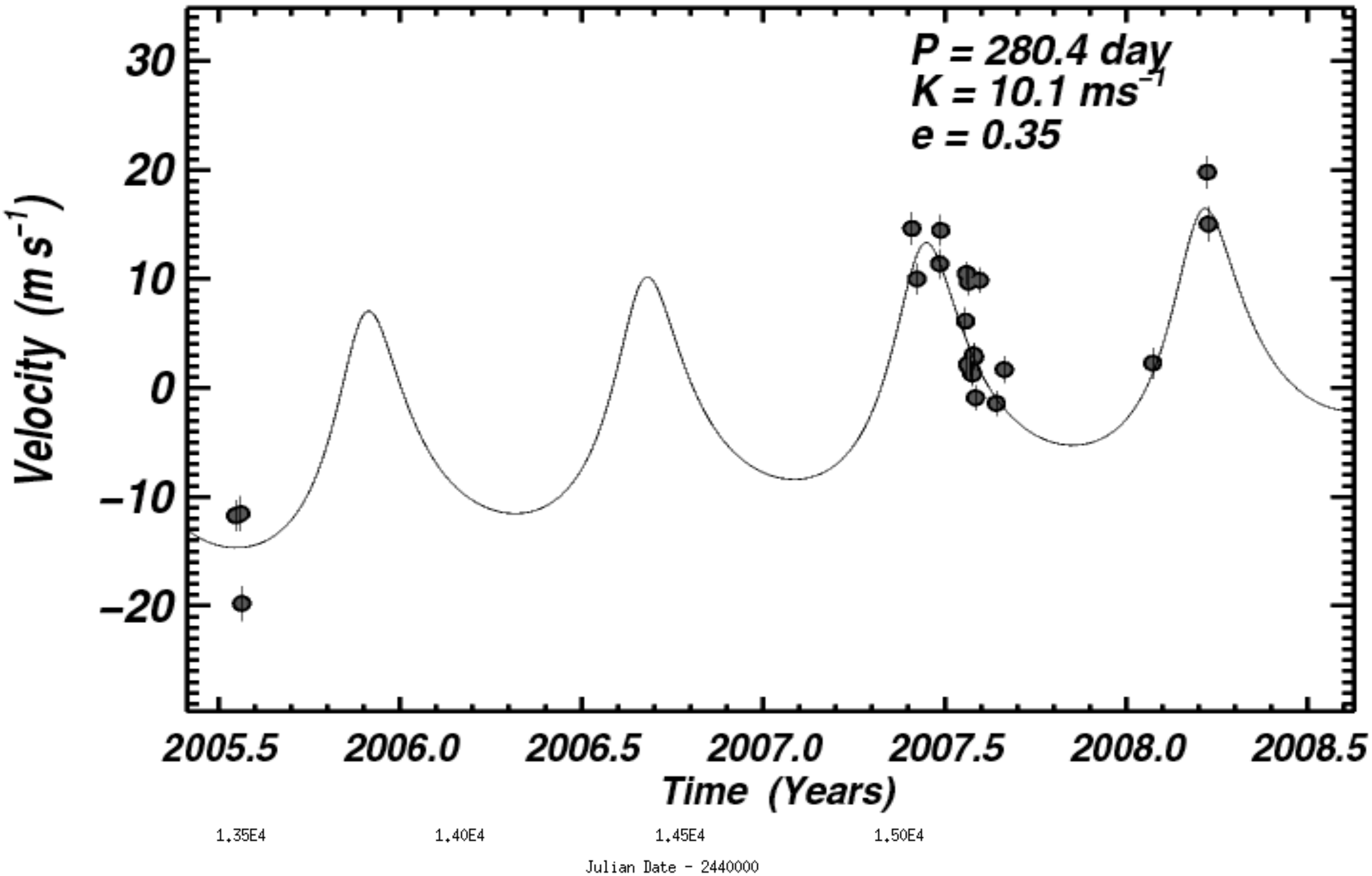
(Santos et al. A&A 2000. Vogt et al. ApJ 2000)



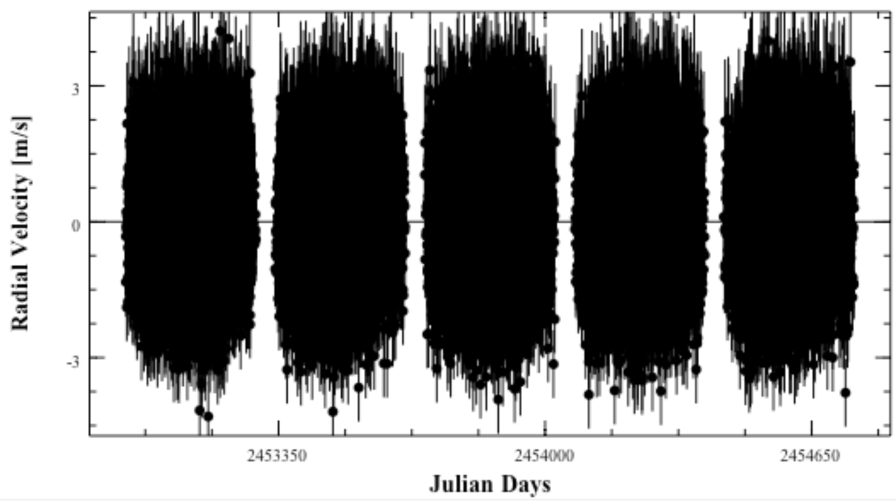
K5V, log R'HK = -4.37. The Keplerian model has continued to yield a good fit for years.
Why no 164335 disease? The answer is almost certainly related to the spectral type (mass, magnetic fields).

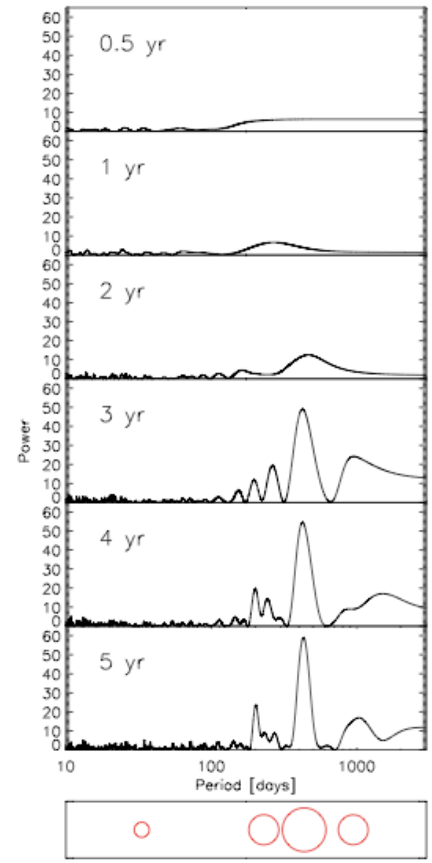
Impact on RV technique

Example: HD14xxxx G0V



Impact on RV technique
Low amplitude systems

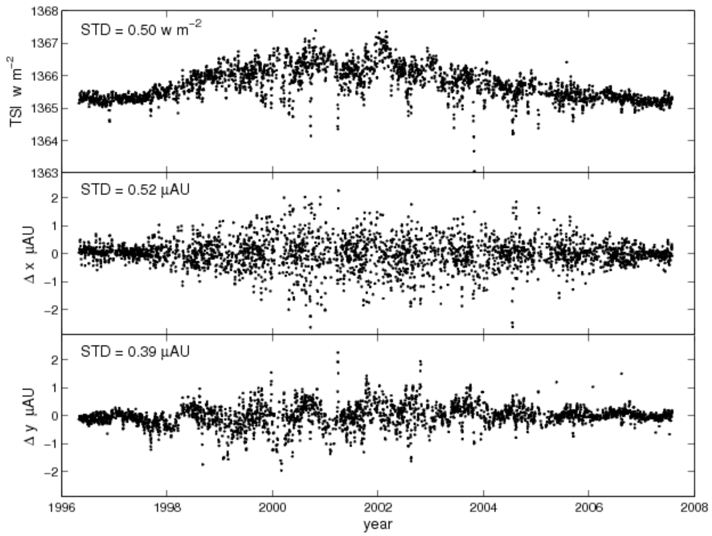




If noise sources average down on chromospherically quiet stars, then just take many observations to beat down single measurement precision.

Question for the Kepler team: what fraction of stars are at least as quiet as the Sun?

Impact on Astrometry



Using the total solar irradiance models (Ulrich et al. 2010), Makarov et al. 2010 synthesize astrometric measurements to estimate the impact of photospheric variability on astrometric (SIM) measurements.

$$\log A_s = 12.468 + 1.75 \log R'_{HK}$$

For quiet stars like the Sun: Earths are detectable. However, jitter increases with chromospheric activity:

$$\log R'_{HK} = -4.96 \rightarrow solar\ jitter$$

$$\log R'_{HK} = -4.6 \rightarrow 5 \times\ jitter$$

$$\log R'_{HK} = -4.2 \rightarrow 25 \times\ jitter$$

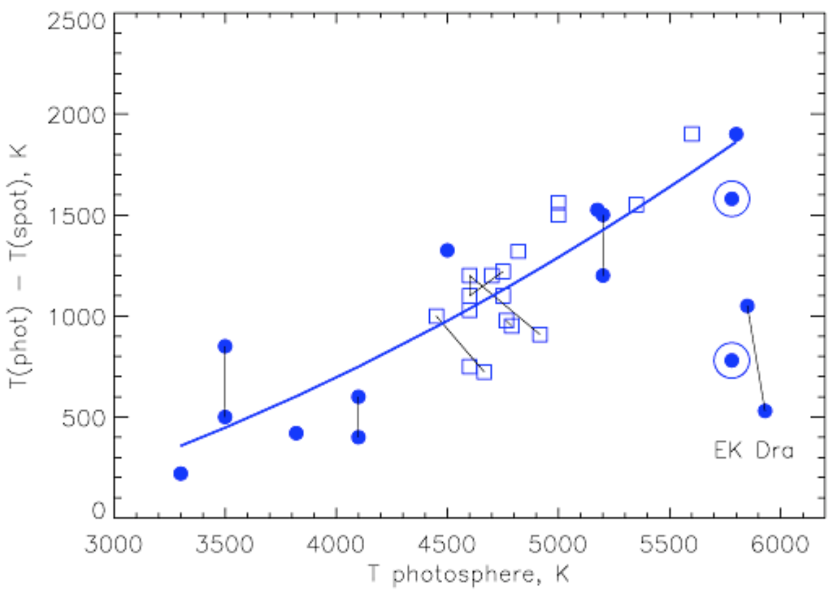
If spots are randomly distributed, the amplitude of jitter is minimized. If magnetic activity is confined to particular "active longitudes," jitter is worse.

Comparison of Impact on RV and Astrometry

Makarov et al. 2010 compared the impact of simulated models of magnetic activity (star spots) on astrometric and RV data.

Star type	Sun	F5V	K5V
Rotation period, d	25.4	18	30
Astrometric signal, μas	0.30	0.23	0.45
RV signal, m s^{-1}	0.089	0.078	0.109
Astrometric jitter, μas	0.087	0.113	0.063
RV jitter, m s^{-1}	0.38	0.69	0.23
Astrometric SNR	3.4	2.0	7.1
RV SNR	0.23	0.11	0.47

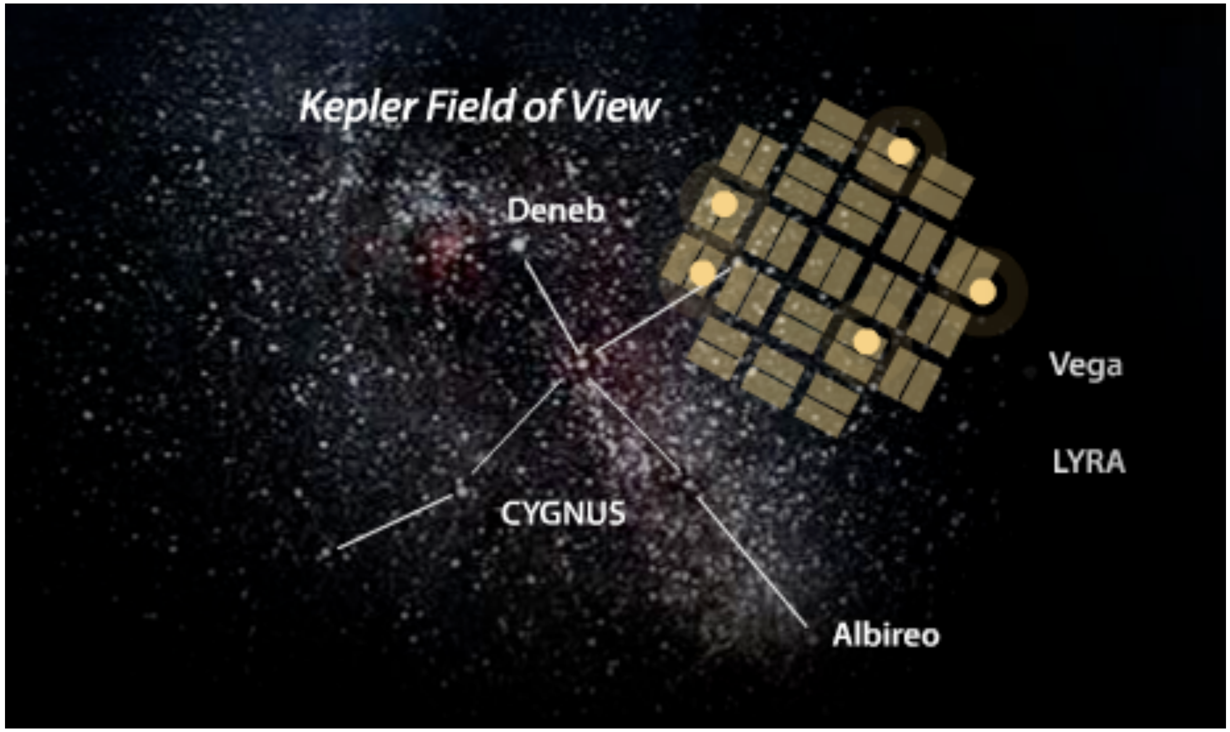
Impact on RV and Astrometry



Contrast between magnetic features and the photosphere is less at redder wavelengths (i.e., cooler temperatures).

TW Hyadra showed RV variations (similar to HD166435) at optical wavelengths, but IR observations were less impacted .

Doppler measurements at redder wavelengths? Iodine reference spectrum spans 500 – 600 nm; laser frequency combs have arbitrary wavelength ranges.



The Kepler project will tell us more than statistical occurrence rates for exoplanets; we will also learn about star spot distributions in chromospherically inactive stars.

Ultimately, this will reveal whether RV and astrometric planet surveys will be successful in the search for large numbers of Earth-like planets.

Conclude

P-mode noise is the most “treatable” noise source: many observations can average over the few-minute-long signal.

Astrophysical noise sources (magnetic origin) operate on timescales similar to planets. Spots or meridional flow can impact RV and astrometric sensitivity to “habitable” planets. Space-based astrometry should still be able to detect Earthlike planets for favorable targets.

Individual spots generally persist for one or two stellar rotation periods, however the global distribution can persist and multiple spots are the rule, forming at different latitudes with differential rotation.

Sometimes active stars have RV’s correlated with activity, sometimes they don’t. Sometimes the noise seems to phase with the RV’s, sometimes it is out of phase. There is not a reliable diagnostic that correlates astrophysical noise and RV or astrometric signatures: i.e., can’t cleanly decorrelate this noise souce from RV’s.

REFERENCES

Baliunas, S. L., et al. 1995, "Chromospheric variations in main-sequence stars" ApJ, 438, 269

Duncan, D. K., et al. 1991, "CA II H and K measurements made at Mount Wilson Observatory, 1966-1983" ApJS, 76, 383

Isaacson & Fischer 2010, ApJ (in press)

Living Reviews in Solar Physics: http://solarphysics.livingreviews.org/

Makarov, V. V., Beichman, C. A., Catanzarite, J. A., Fischer, D. A., Lebreton, J., Malbet, F. , Shao, M. 2009, "Starspot Jitter in Photometry, Astrometry, and Radial Velocity Measurements" ApJL 707, 73

Makarov, V. V., Parker, D., Ulrich, R, K. 2010, "Astrometric Jitter of the Sun as a Star" ApJ 717, 1202

Noyes, R. W., Hartmann, L., Baliunas, S. L., Duncan, D. K., & Vaughan, A.H. 1984, "The relation between stellar rotation rate and activity cycle periods" ApJ, 279, 763

Saar, S. H. & Donahue, R. A. 1997, "Activity-related Radial Velocity Variation in Cool Stars" AJ 485, 319

Soderblom, D. R., Duncan, D.K., Johnson, D. R. H. 1991, "The chromospheric emission-age relation for stars of the lower main sequence and its implications for the star formation rate" ApJ 375, 722

SOHO project: http://sohowww.nascom.nasa.gov

Ulrich, R., Parker, D. Bertello, L., Boyden, J. 2010, "Modeling Total Solar Irradiance Variations Using Automated Classification Software On Mount Wilson Data" Solar Phys 261, 11

Wright, J. T. 2005, "Radial Velocity Jitter in Stars from the California and Carnegie Planet Search at Keck Observatory" PASP, 17, 675