Stellar Jitter

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Workshop on Astronomy of Exoplanets with Precise Radial Velocities

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Velocity and velocity variations correlate with chromospheric activity

TOWARDS AN ESTIMATE OF THE FRACTION OF STARS WITH PLANETS FROM VELOCITIES OF HIGH PRECISION

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Paper Presented by B. Campbell

Summary

We have been measuring precise radial velocities for 20 solar-like stars in an attempt to detect reflex motion due to low mass, possibly planetary companions. This project is currently in its tenth year at the Canada-France-Hawaii telescope. The hydrogen fluoride technique that we utilize is now a proven method for obtaining velocities over long periods with a precision of order 10 meters per second.

We now believe that we understand what factors limit the precision attainable. We have also discovered a new phenomenon: stars with extreme levels of chromospheric activity show correlated velocity variations. This phenomenon does not interfere with our ability to detect long-term modulation. We have tested for such modulation, and have found a number of low-level variables. We will discuss the implication of these variations vis-a-vis planetary companions. We will also consider how such data might ultimately help to distinguish between low mass brown dwarfs and planets.

Campbell et al. (1991)

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Campbell et al. (1991)

Jitter is short-term, non-COM variation in measured radial velocity

Jitter increases with:

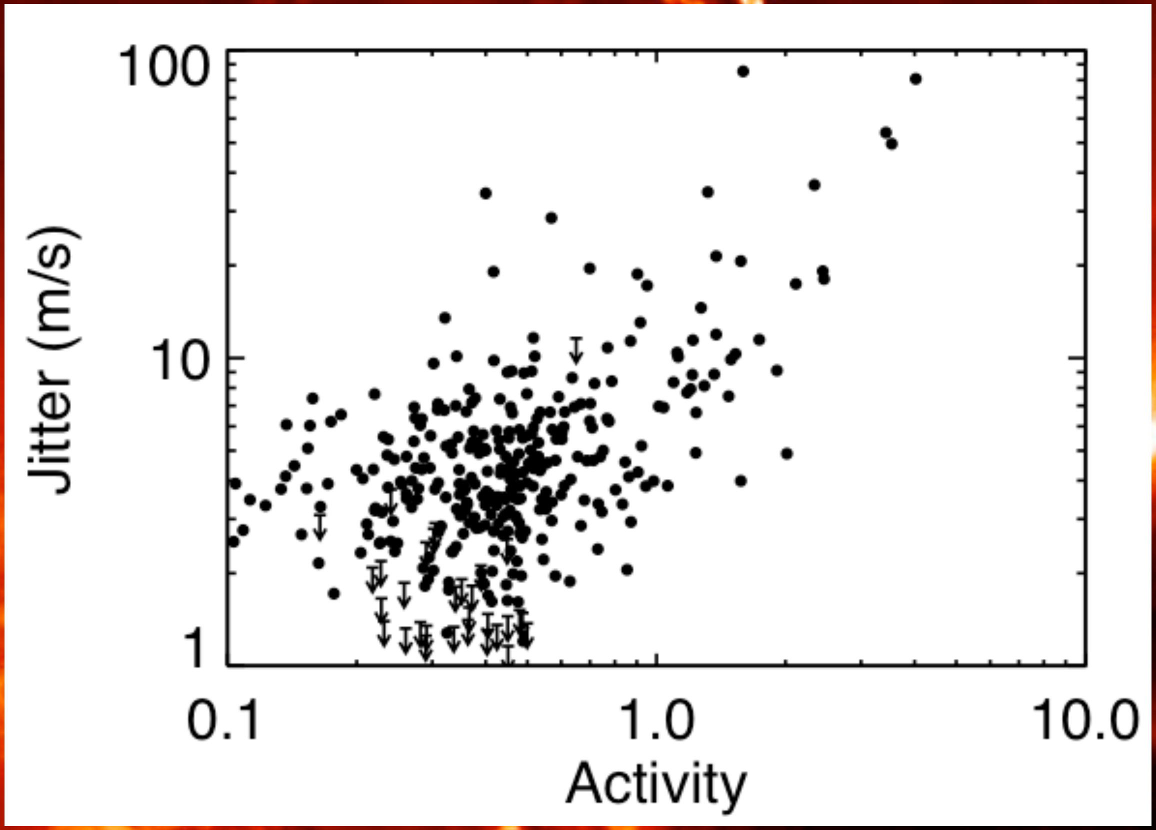
- Instrument systematics (non-astrophysical)
- Chromospheric activity
- Rotation
- Stellar mass
- Post-main sequence evolution

(Chromospheric activity, Rotation, Stellar mass } Stellar Youth)

Some options for dealing with jitter

- Avoidance: Focus on old, inactive late-G and K dwarfs
- Mitigation: treat the asteroseismology (see Gilliland)
- Mitigation: correlate with photometry (see Walkowicz)
- Beat it down: Many observations (if possible)
- “Direct detection”: bisectors (see Boisse)
- See also: Santos, Dumusque

Jitter increases strongly with stellar activity



After Wright (2005)

Jitter increases with evolutionary state

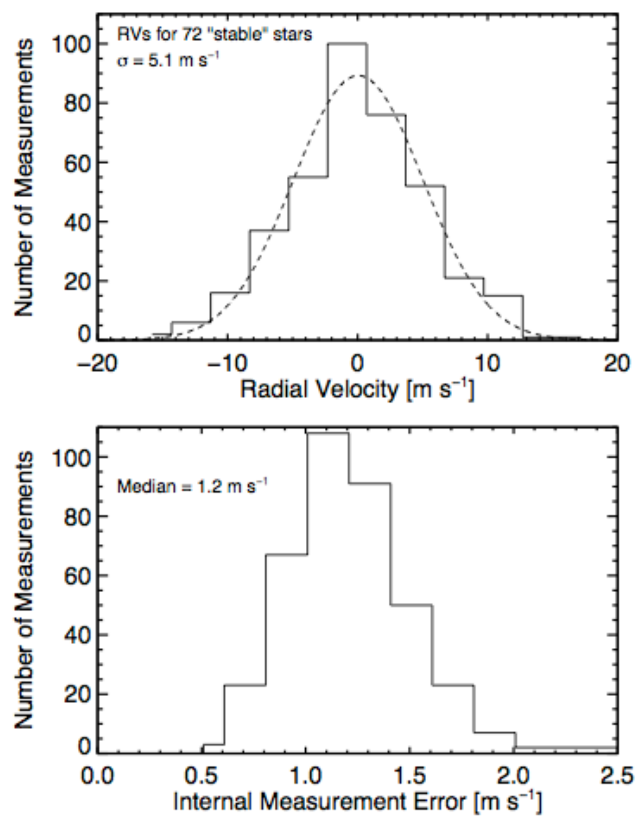
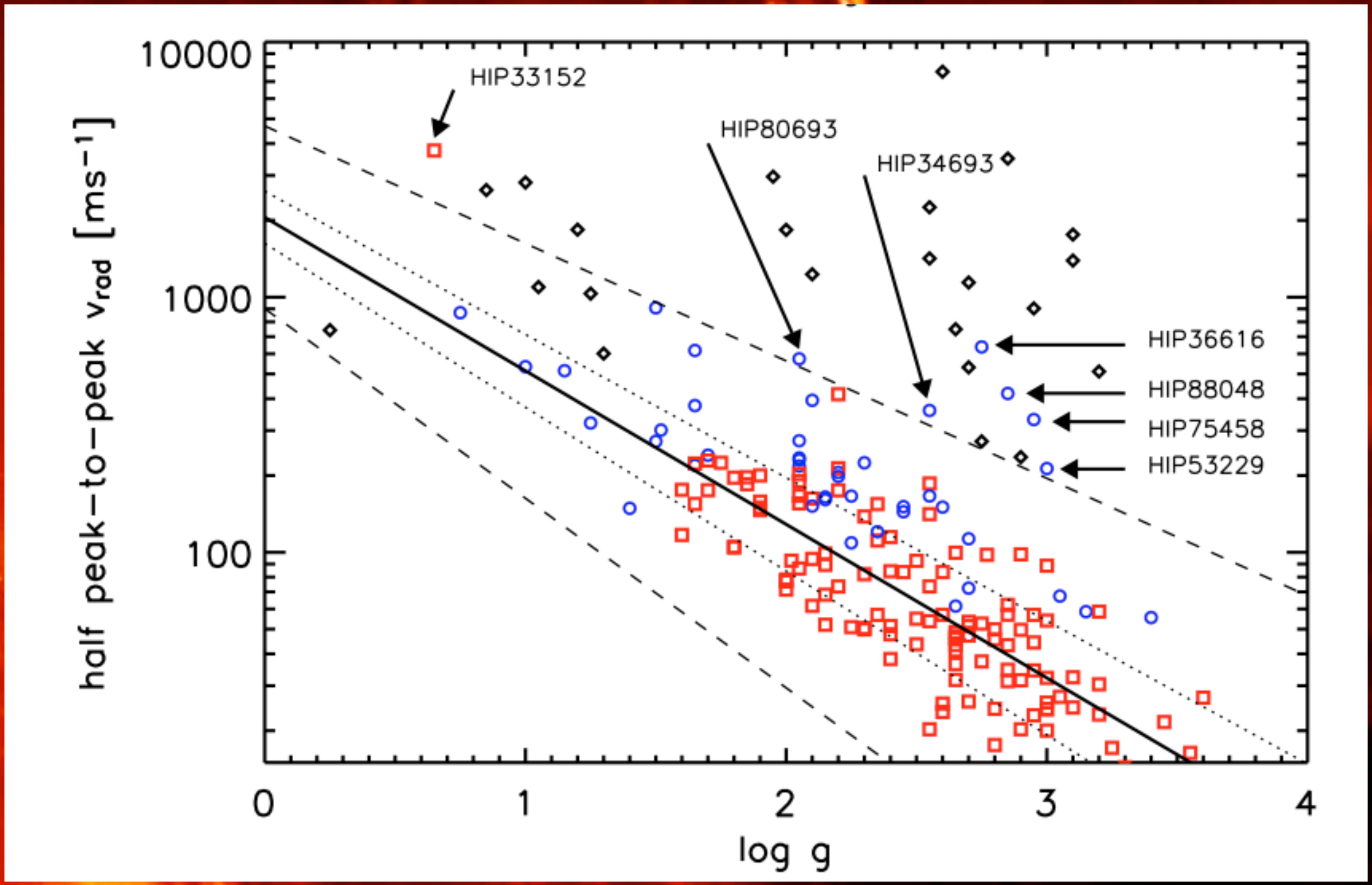


FIG. 1.— *Top*—Distribution of RVs for 72 standard stars, comprising a total of 382 measurements. The dashed line shows the best-fitting Gaussian with a width $\sigma = 5.1$ m s^{-1}. *Bottom* – Distribution of internal measurement uncertainties for 382 RV measurements. The median is 1.2 m s^{-1}. Together with the distribution of RVs in the top panel, this provides us with a jitter estimate of 5 m s^{-1}, which we apply to all of the stars presented herein.

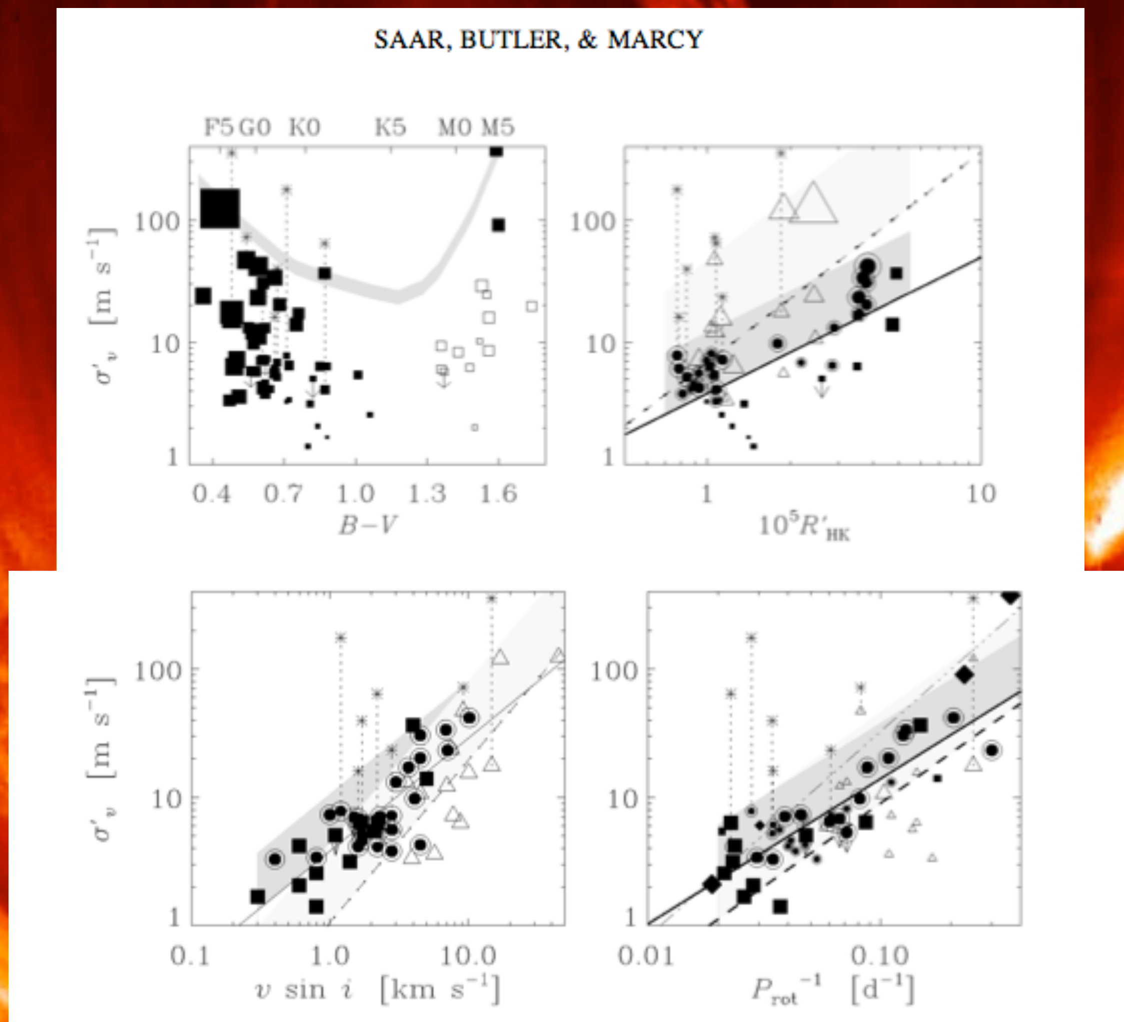
Johnson et al. (2010)

Jitter increases with evolutionary state



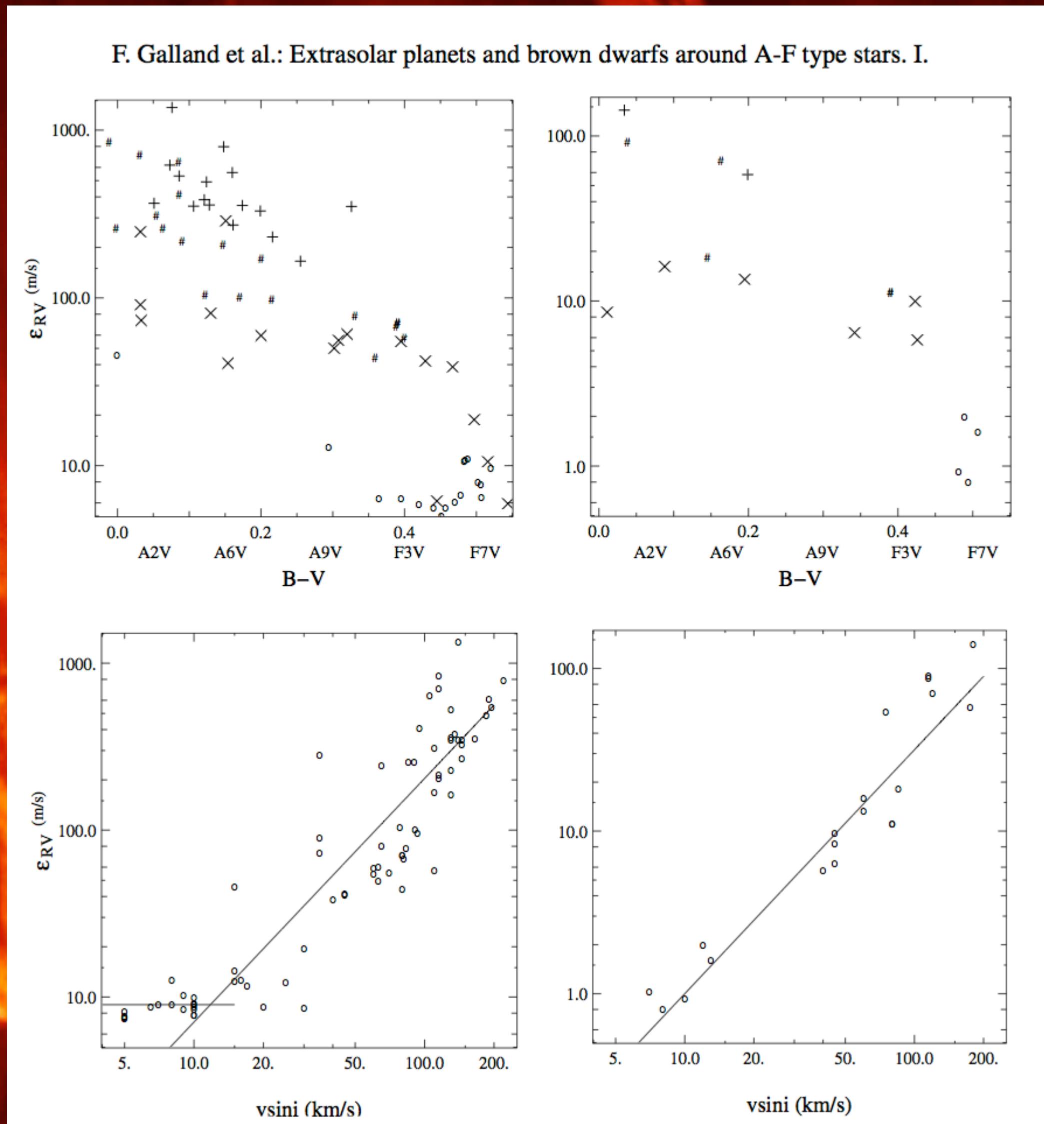
Hekker et al. (2008)

Jitter increases with stellar mass and rotation speed



Saar, Butler, & Marcy (1998)

Jitter increases with stellar mass and rotation speed



Galland et al. (2005)

Jitter can be incoherent and has many timescales

- Rotationally modulated spots (days-weeks)
- Other rotationally modulated features (days-weeks)
- Flares, CMEs, and other violent events (minutes-days)
- p-modes (asteroseismology)
- active longitudes (years)

Rotationally modulated spots can masquerade as planets

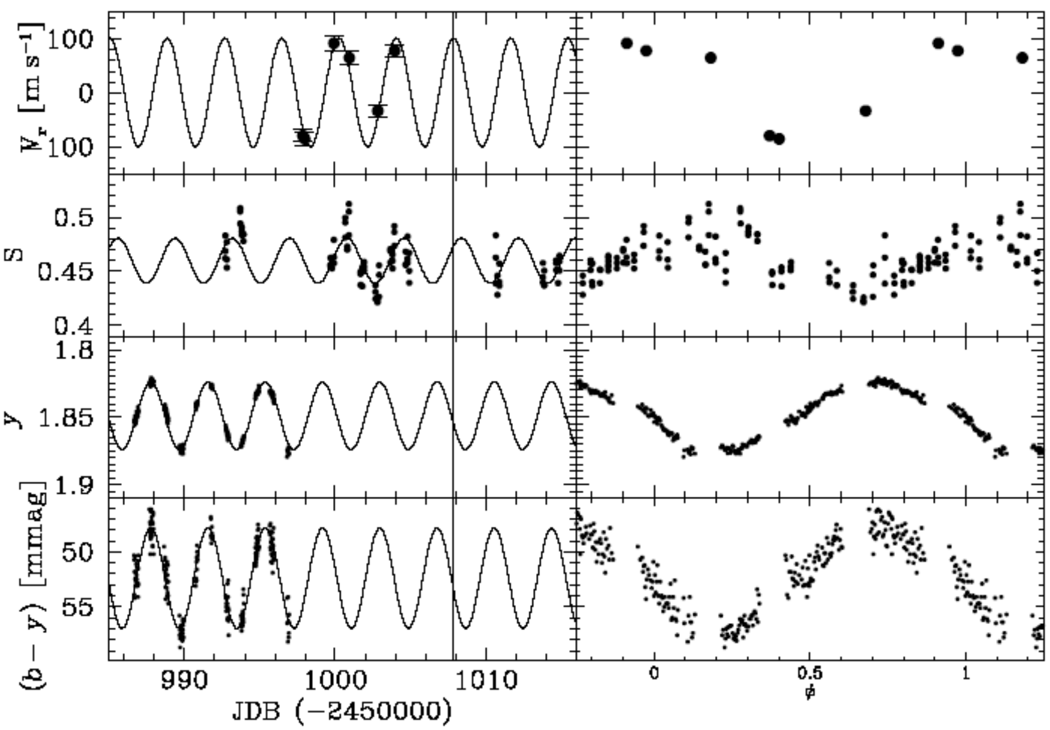
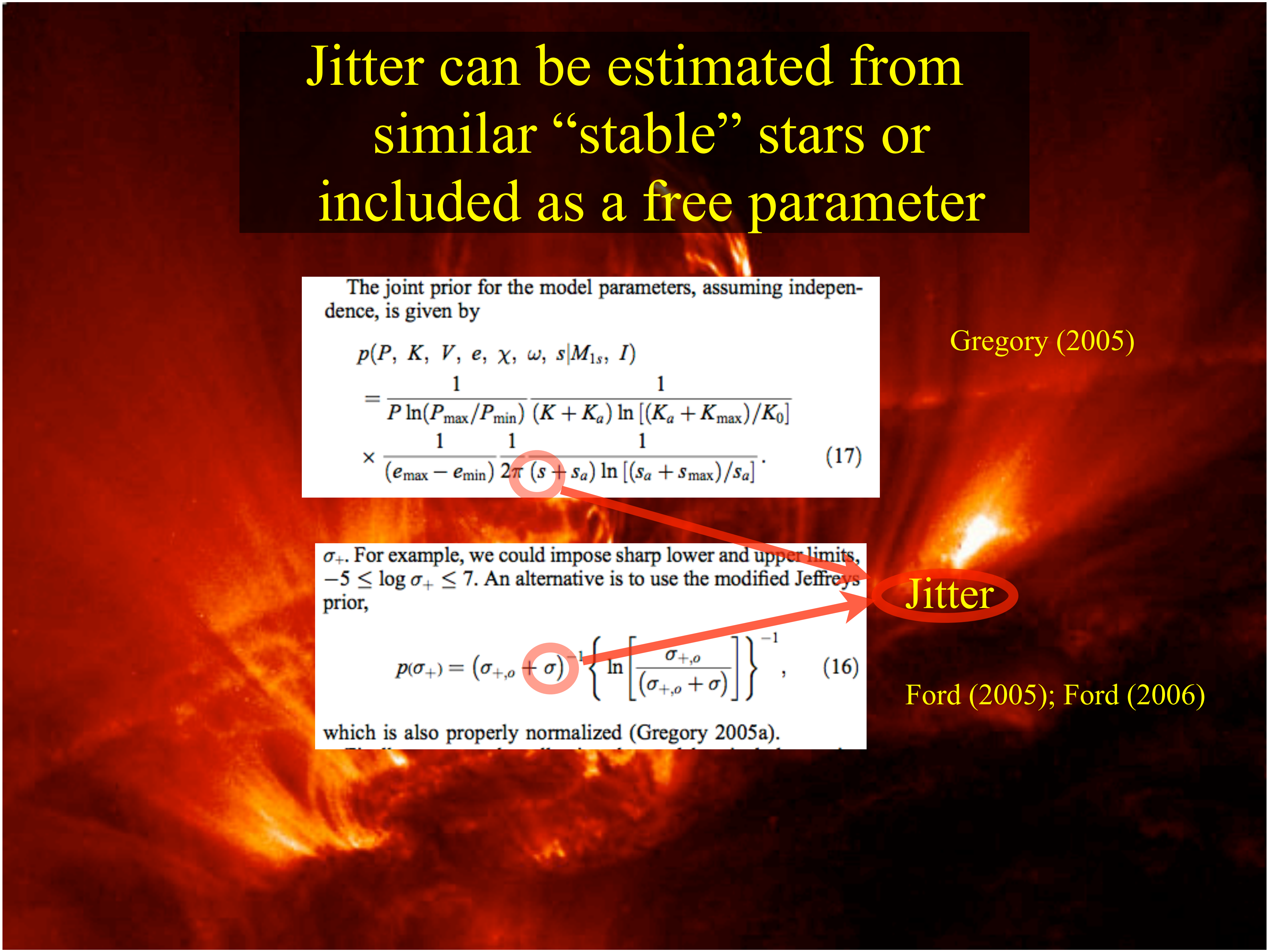


Fig. 8. Left: simultaneous observations of (from the top) radial velocity, S index, delta y magnitude, and delta $(b-y)$ color, of HD 166435 over a time span of 30 days. A best-fit sine-curve with a period fixed at 3.798 days is shown. A vertical line is drawn at an epoch of maximum radial velocity to help visualize the phase offsets between data sets. Right: same data but phase folded with $P = 3.798$ d and $T_0 = 2\,450\,996.5$.

HD 166435; Queloz et al. (2001)



Jitter can be estimated from similar "stable" stars or included as a free parameter

The joint prior for the model parameters, assuming independence, is given by

$$p(P,\ K,\ V,\ e,\ \chi,\ \omega,\ s|M_{1s},\ I) = \frac{1}{P\ln(P_{\rm max}/P_{\rm min})}\frac{1}{(K+K_a)\ln[(K_a+K_{\rm max})/K_0]} \times \frac{1}{(e_{\rm max}-e_{\rm min})}\frac{1}{2\pi}\frac{1}{(s+s_a)\ln[(s_a+s_{\rm max})/s_a]}. \quad (17)$$

Gregory (2005)

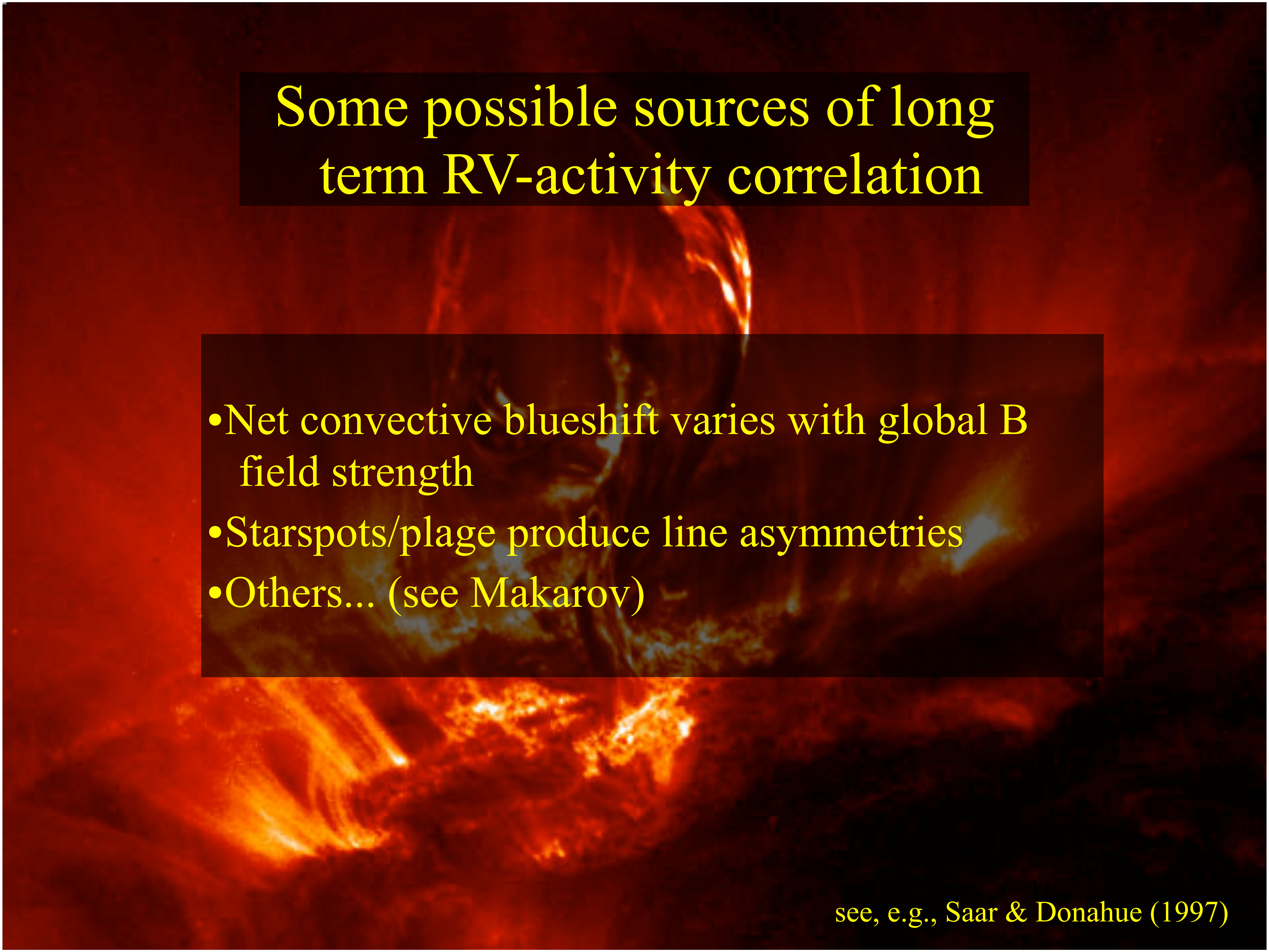
σ_+. For example, we could impose sharp lower and upper limits, $-5 \leq \log\sigma_+ \leq 7$. An alternative is to use the modified Jeffreys prior,

$$p(\sigma_+) = (\sigma_{+,o}+\sigma)^{-1}\left\{\ln\left[\frac{\sigma_{+,o}}{(\sigma_{+,o}+\sigma)}\right]\right\}^{-1}, \quad (16)$$

which is also properly normalized (Gregory 2005a).

Jitter

Ford (2005); Ford (2006)



Some possible sources of long term RV-activity correlation

- Net convective blueshift varies with global B field strength
- Starspots/plage produce line asymmetries
- Others... (see Makarov)

see, e.g., Saar & Donahue (1997)

Long-term velocity-activity correlations have been predicted

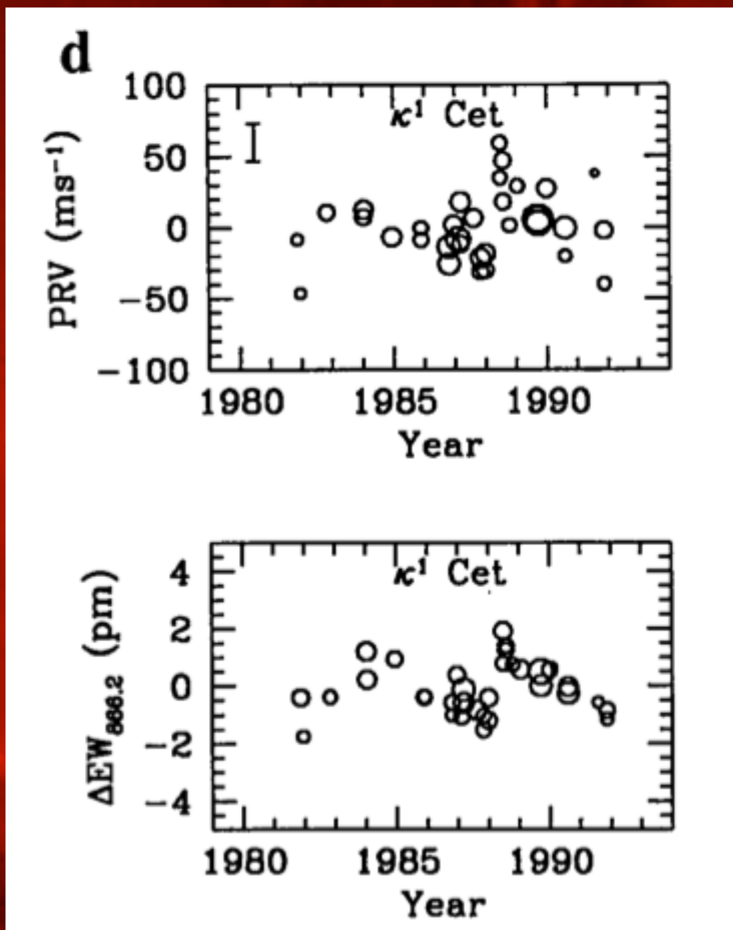
Title:	Stellar lineshifts induced by photospheric convection.
Authors:	Dravins, D.
Publication:	Stellar Radial Velocities, Proceedings of IAU Colloquium No. 88, held in Schenectady, N.Y., October 24-27, 1984. Edited by A. G. D. Philip and David W. Latham. Schenectady: L. Davis Press, 1985, p. 311 - 320
Publication Date:	00/1985
Origin:	ARI
ARI Keywords:	Convection:Stellar Atmospheres, Line Formation:Stellar Atmospheres, Radial Velocities:Stellar Spectra, Stellar Atmospheres:Convection, Stellar Atmospheres:Line Formation, Stellar Spectra:Radial Velocities
Bibliographic Code:	1985srv..conf..311D

Abstract

Effects of stellar atmospheres on measured radial velocities are examined. Surface convection ("stellar granulation") causes photospheric line asymmetries and wavelength shifts of ≅ 100 - 500 m/s. Cyclic changes in the convection patterns, such as observed during the solar 11-year cycle, may mimic radial velocity variations of perhaps 30 m/s. The study of stellar atmospheres would benefit from accurate (< 100 m/s) differential radial velocity measurements among lines of different parameters (strength, excitation potential, wavelength region) in the same star.

ADS

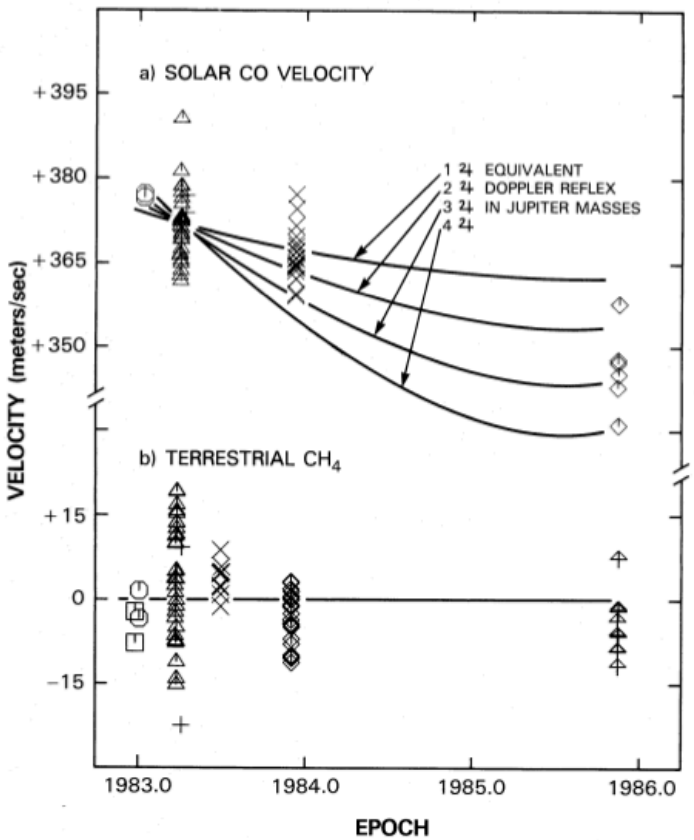
Long-term velocity-activity correlations may be seen



Because convective and chromospheric activity are related for dwarf stars, there might be some correlation between our velocity trends and chromospheric activity but we have found none. Only in the case of κ^1 Cet does chromospheric activity seem to coincide with a short-term velocity change (Fig. 2). Given the variety of chromospheric behaviour of the stars and the limited time coverage and precision of our observations, we are not in a position to distinguish a planetary perturbation from other plausible explanations for such long-term trends. Here we simply caution that there could be planetary perturbations below the upper limits set in the next section.

Walker et al. (1995)

Long-term velocity-activity correlations may be seen



ON THE APPARENT VELOCITY OF INTEGRATED SUNLIGHT. I. 1983–1985

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Planetary Systems Branch, Goddard Space Flight Center
AND
James W. Brault and Jeremy Wagner
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Received 1985 August 23; accepted 1986 October 29

ABSTRACT

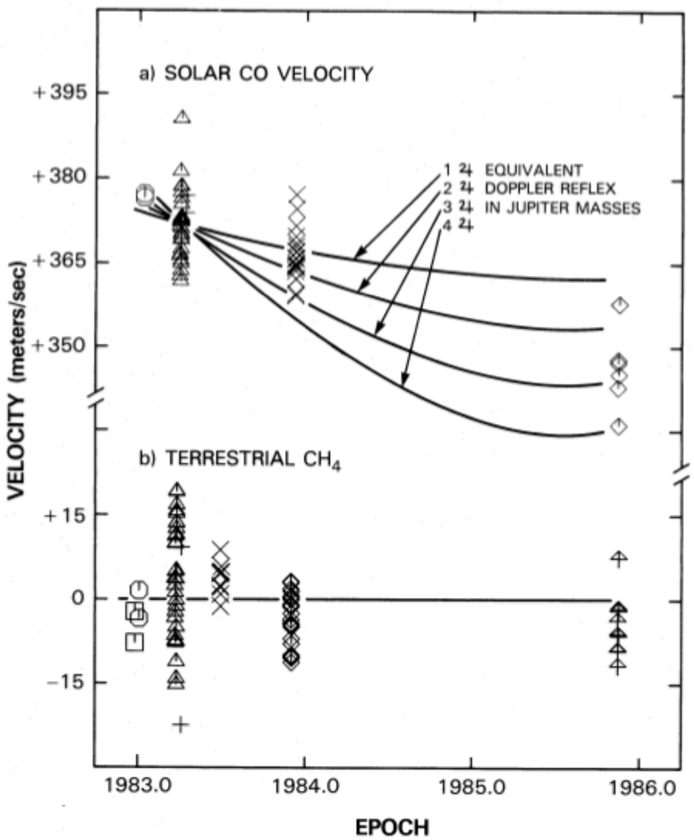
We have measured absolute frequencies for the $\Delta V = 2$ transitions of $^{12}C^{16}O$ in the 2.3 μm spectrum of integrated sunlight. The data consist of 78 interferograms taken over a 3 yr period with the McMath Fourier transform spectrometer on Kitt Peak. The spectra cover the 4000–4800 cm^{-1} region with 0.012 cm^{-1} resolution (FWHM) and with signal-to-noise ratios of order 3×10^3. We measure 16 lines of $^{12}C^{16}O$ and five weak atomic lines, obtaining frequency calibration using the 00°0–00°2 band of N_2O formed in a low-pressure gas absorption cell. The frequency calibrations are stable at the 1 m s^{-1} level, relegating instrumental drift to a negligible source of error. As a check, we also measure eight lines due to CH_4 in the terrestrial atmosphere. These lines show diurnal displacements of order ± 20 m s^{-1} due to the prevailing westerly winds over Kitt Peak, but are otherwise stable. The principal source of error in our solar measurements is imperfect optical integration over the solar disk due to vignetting by the telescope optics and, at low declinations, differential transmission of the terrestrial atmosphere. These effects are identified and removed by observing and modeling the hour angle dependence of the integrated light velocity, and by monitoring their effect on the rotationally broadened solar line profiles. At a given epoch, we obtain the absolute velocity of integrated sunlight with an uncertainty of $\lesssim 5$ m s^{-1}.

We find that the integrated light velocity varies by $\lesssim 3$ m s^{-1} over a 1 day period, consistent with expectations based on the properties of supergranulation. Over the long term, our data indicate an increasing blueshift in these weak infrared lines, amounting to 30 m s^{-1} from 1983 through 1985. The sense of the drift is consistent with a lessening in the magnetic inhibition of granular convection at solar minimum. Such an effect will have implications for the spectroscopic detectability of planetary-mass companions to solar-type stars, because it may mimic the Doppler reflex due to a planetary system. On this basis we find the spectroscopic planetary detection limit for a one solar mass star to be $0.055r^2/\sin i$ Jupiter masses, where r is the planetary orbital radius in astronomical units.

Subject headings: interferometry — radial velocities — Sun: spectra

Deming et al. (1997)

Long-term velocity-activity correlations may be seen



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Most stars do NOT show activity CYCLE correlations with velocity

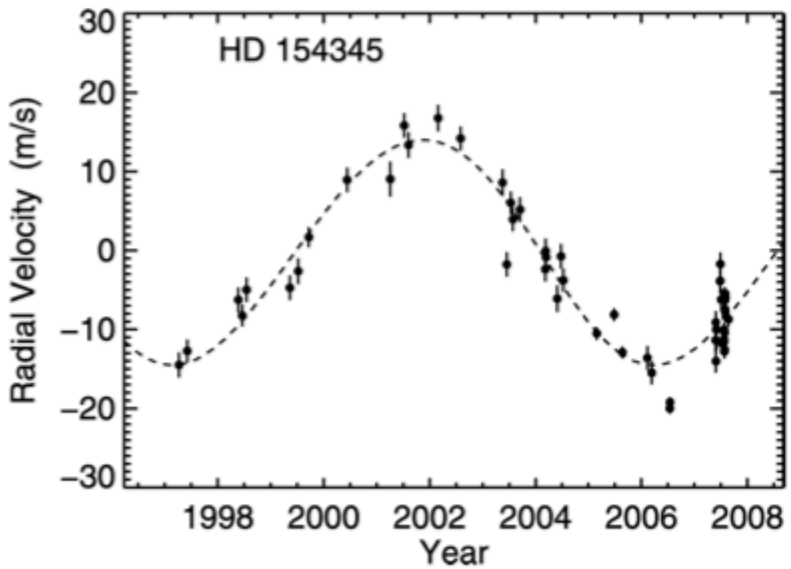

FIG. 1.—Radial velocity vs. time for HD 154345.

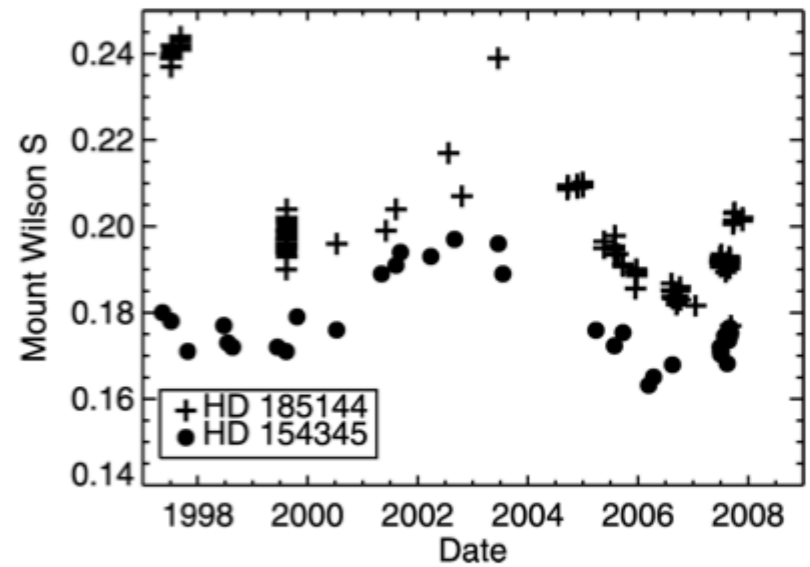

FIG. 2.—Mount Wilson activity index measured from RV science spectra taken at Keck Observatory. Except for a few small discrepancies, the temporal coverage of these data is the same as that of the RV data for both of these stars. Data from prior to 2004 are taken from the "differential" measurements in Wright et al. (2004); subsequent data have been extracted in a similar manner (H. Isaacson, in preparation). Both HD 154345 and the RV-stable star HD 185144 show strong evidence of activity cycles, although the cycle strength and overall activity level in HD 185144 is considerably larger. Cycles such as these are not uncommon in old G dwarfs, typically have ~10 year periods, and are not observed to have an effect on long-term RV stability. Data for the two stars are plotted on the same scale.

sufficiently strong cycles that we can confirm their continued coherence since the end of the published Mount Wilson data from our own activity measurements.

None of these four stars shows RV variations similar to HD 154345, or any correlation of *S*-index with RV. In fact, all of these stars show rms RV variations of less[14] than 5 m s^{-1}, and one, HD 185144, is among the most RV-stable stars in our entire sample.

Wright et al. (2009)

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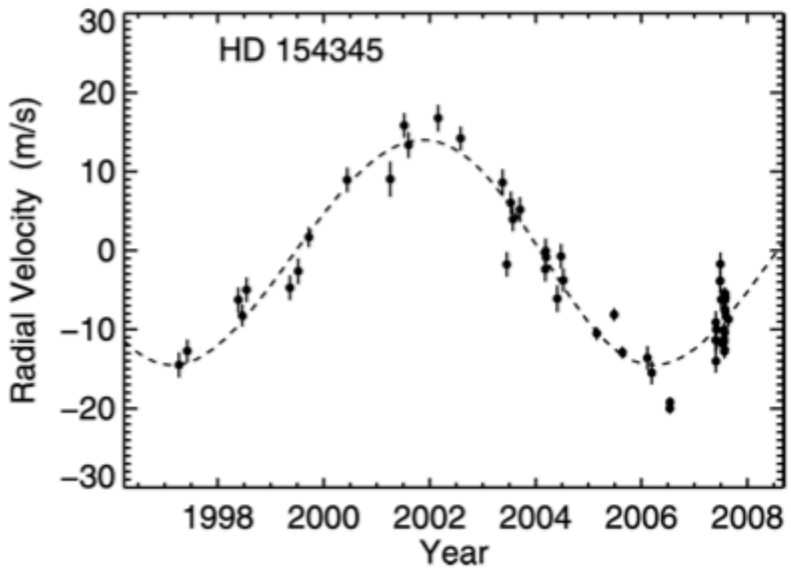

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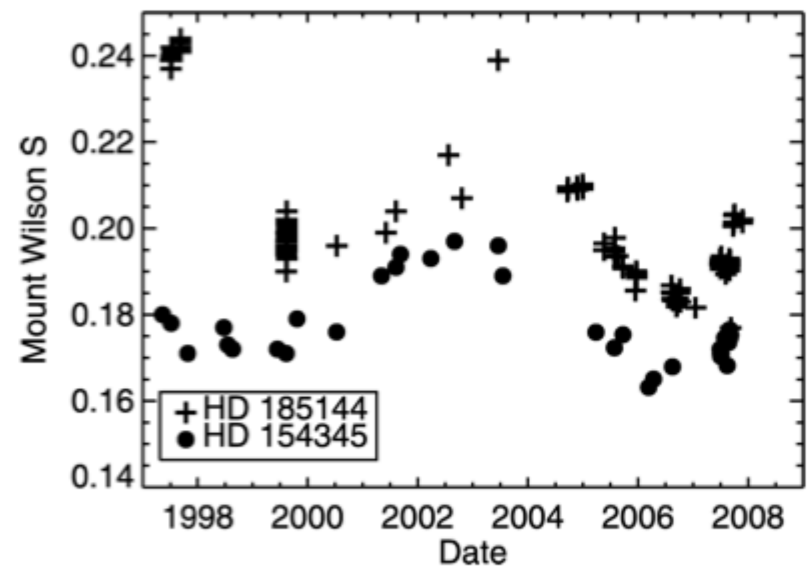

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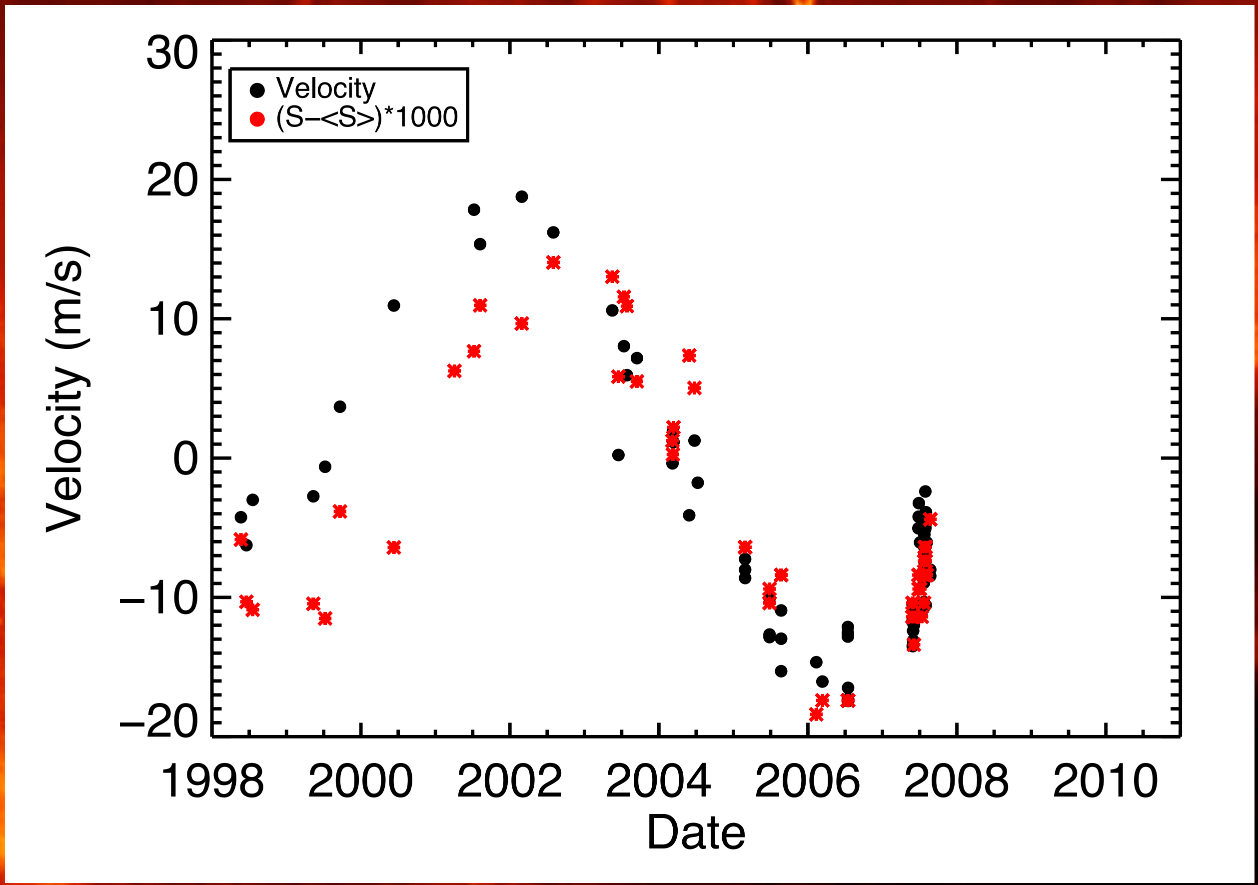
HD 154345 -- conspiracy of periods



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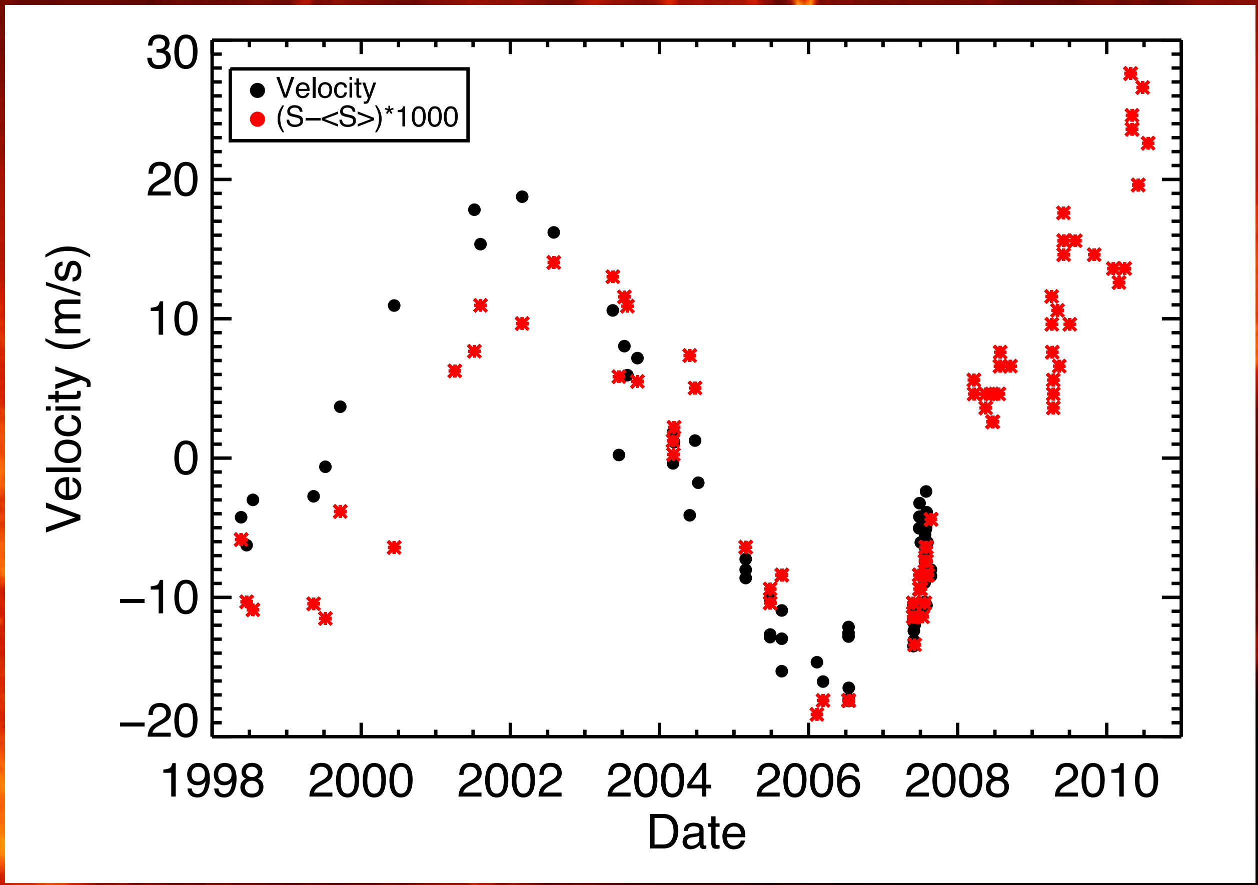
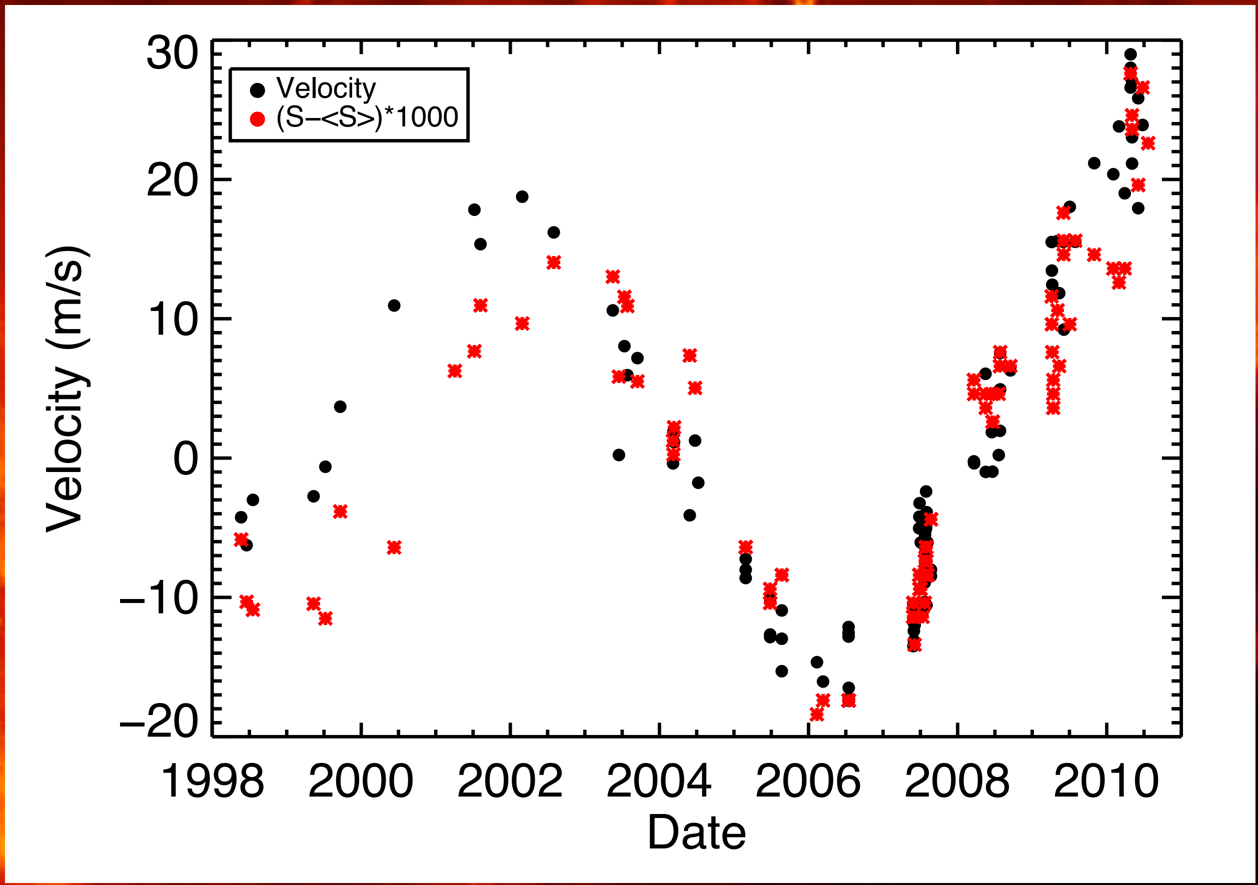
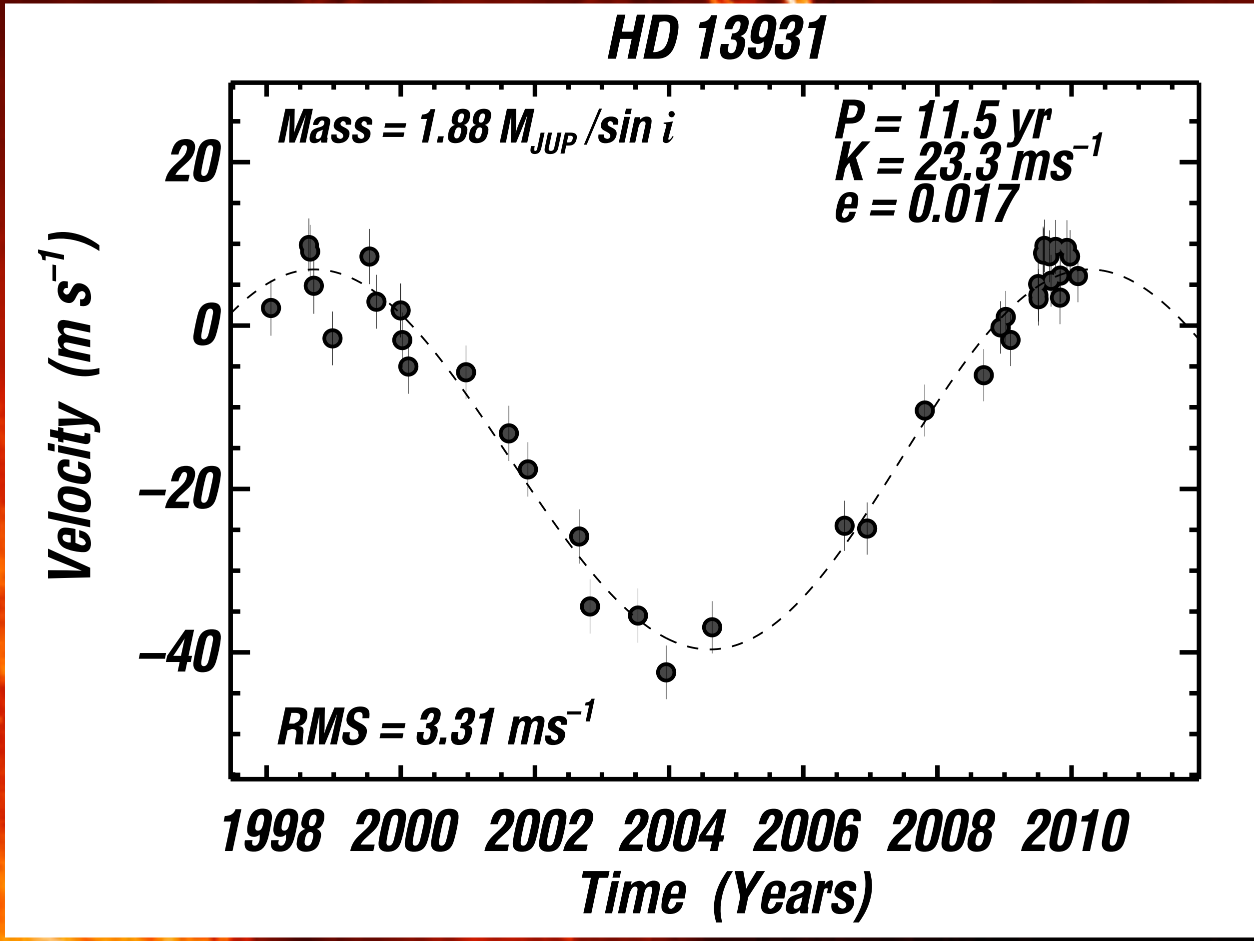


HD 154345 -- conspiracy of periods?!?



Jupiter-analogs WITHOUT cycles



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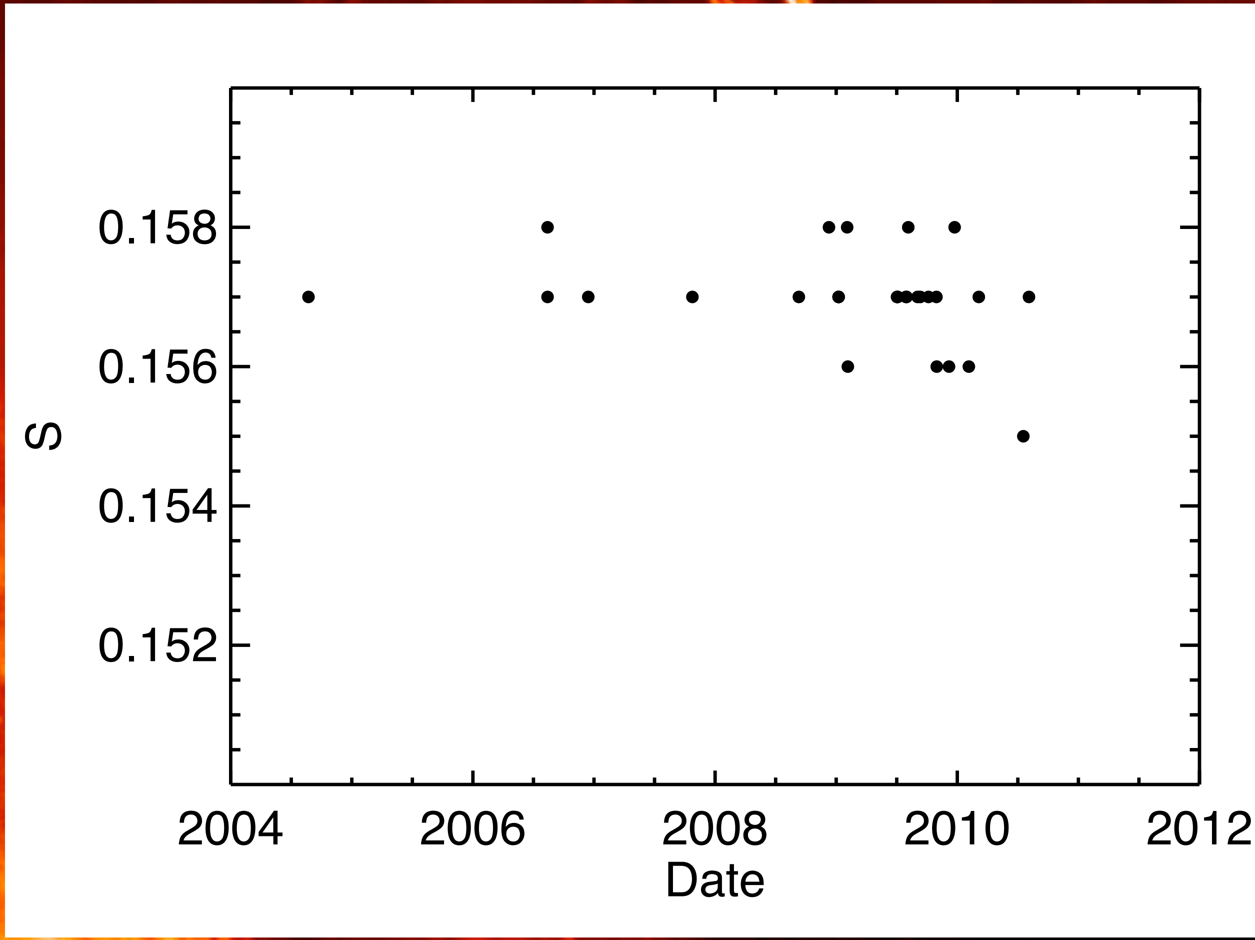

Activity cycles masquerading as planets

- Long-term S-RV correlations rare, but not unknown
- Difficult, but not impossible to distinguish
- A few other examples known, but not as clear
- Contemporaneous activity meas./photometry essential!
- Implications for:
  - K-giant planets? (e.g. Hekker (2008))
  - eps Eridani?

Summary

- Jitter is short-term, non-COM variation in measured radial velocity
- Jitter increases strongly with stellar activity, stellar mass, evolution, and rotation speed
- Jitter can be incoherent and has many timescales
- Rotationally modulated spots can masquerade as planets
- Jitter can be estimated from similar “stable” stars to a factor of ~2 or included as a free parameter in orbital fits
- Long-term velocity-activity correlations have been predicted and seen, but are rare among quiet stars