# Astrophysical Noise
# Long Term Effects

Valeri Makarov

US Naval Observatory

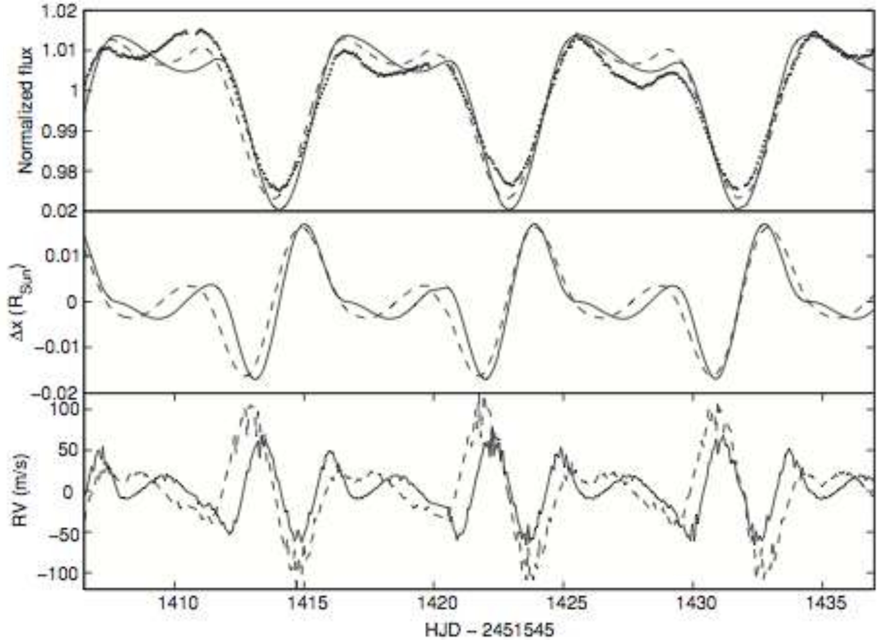
# Short Term Perturbations

- Star spots produce quasi-periodical variations
  - Random phase, unless active longitudes are present (not on the Sun)
  - RV curve modulated with rotation period, usually less than 40 days
  - Bisector lines twist – a useful diagnostics
  - Accompanied by correlated photometric variation
- Projected rotation velocity is odd function of longitude, hence, does not change the integral RV
- Any other flows that are not anti-symmetric around the central meridian will change the net RV

# Two kinds of RV perturbation from small-scale magnetic features

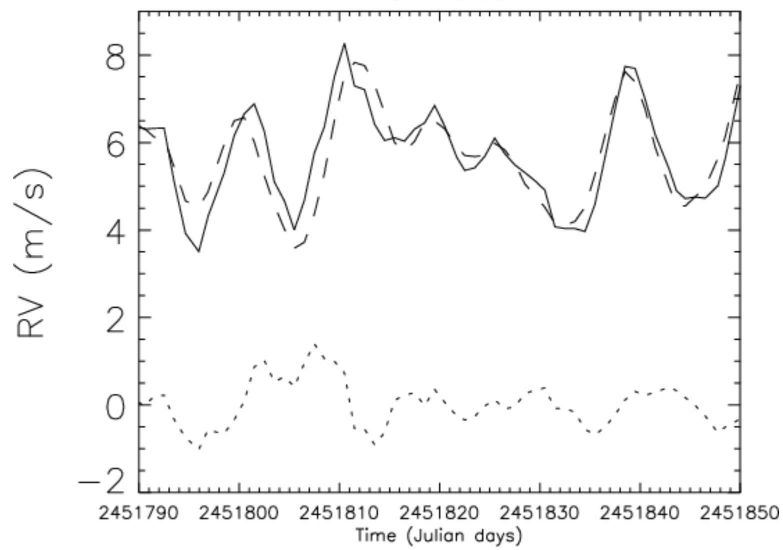
- Photometric variation of integrated RV due to the appearance of dark spots or bright plages

  *Normalized flux, photocenter and RV variations of the active, rapidly rotating star κ[1] Ceti: full line from Makarov et al. 2009, dashed line from Walker et al. 2007 simulations, dotted line from MOST data*



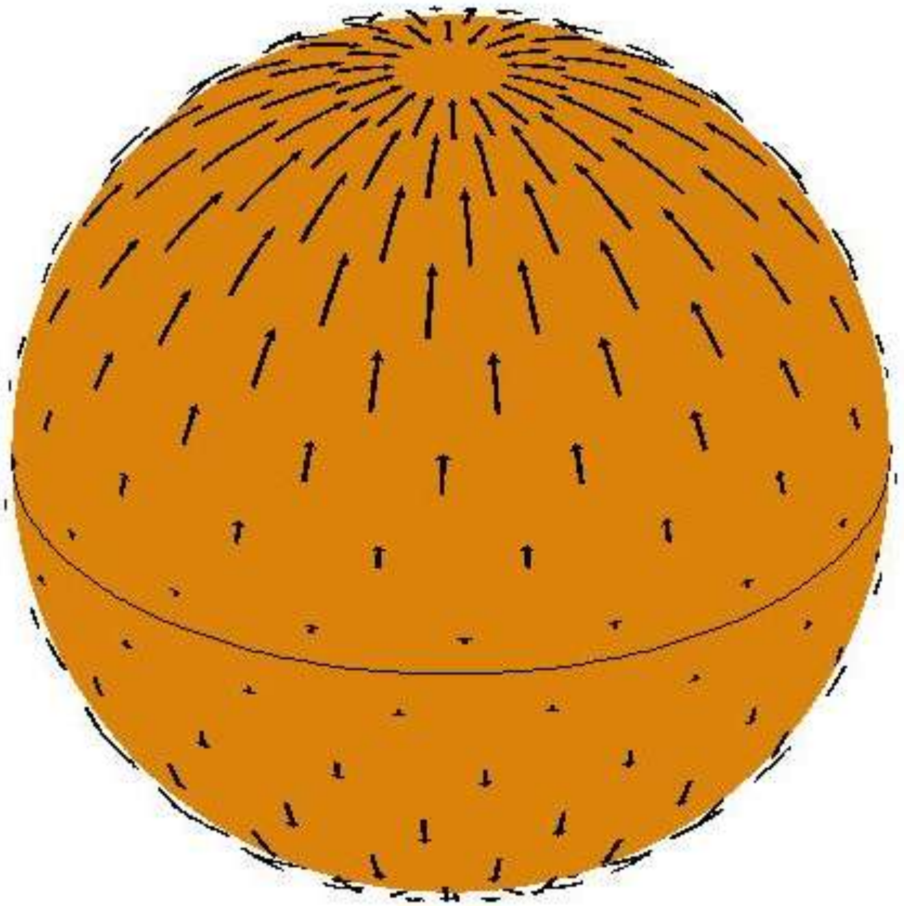

- Attenuation of convective blueshift in areas of magnetic activity, e.g. the blueshift in plages is only 1/3 of that of the quiet photosphere (Brandt & Solanki 1990)

  *Reconstructed RV curve of the Sun from spots and plages (dotted), convective blueshift inhibition (dashed) and total (full), from Meunier et al. 2010*



# Meridional flow on the Sun

- Is symmetric around equator ⏩ net nonzero contribution to observed RV
- Directed from the equator toward the poles – most of the time!
- Of order 20 m/s in amplitude



# Mount Wilson magnetograms

- Daily Doppler velocity measurements covering 1967--1982
- Fe I line 5250.2 Å
- Discovered variations in the solar velocity field of tens of m/s
- Data fitted to model (Howard et al. 1982)

$$\begin{aligned} V \;=\; & (A + B\sin^2\phi + C\sin^4\phi)\sin\lambda\cos\phi\cos b_0 + \\ & (D + E\sin^2\phi + F\sin^4\phi)\sin^2\lambda\cos\phi\cos b_0 + G \end{aligned}$$

With $\lambda$ the heliocentric longitude, $\varphi$ the latitude and $b_0$ the latitude of disk center

## Integrated solar RV

- The net solar RV can be reconstructed from observations by integration over the visible disk:

$$\bar{V} = \frac{1}{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\lambda \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} (\alpha_0 + \alpha_1 \cos\phi \cos\lambda + \alpha_2 \cos^2\phi \cos^2\lambda)\, V \cos\phi \cos\lambda \cos\phi \, d\phi.$$

- LaBonte & Howard (1982) explained the symmetric velocity field as a combination of
  - Meridional flow $$V_{\rm M} = \mu_2 P_2^1(\sin\phi) + \mu_4 P_4^1(\sin\phi),$$
  - Axisymmetric convective blueshift (limb shift)

$$V_{\rm B} = \sum_{k=1}^{3} \beta_i P_k^*(1 - \cos\rho),$$

## Refitting the data

Problem: $[\mathbf{\Lambda}\ \mathbf{\Phi}]\ \tilde{\mathbf{x}} = [\mathbf{\Lambda}\ \mathbf{T}]\ \bar{\mathbf{x}} + \epsilon$

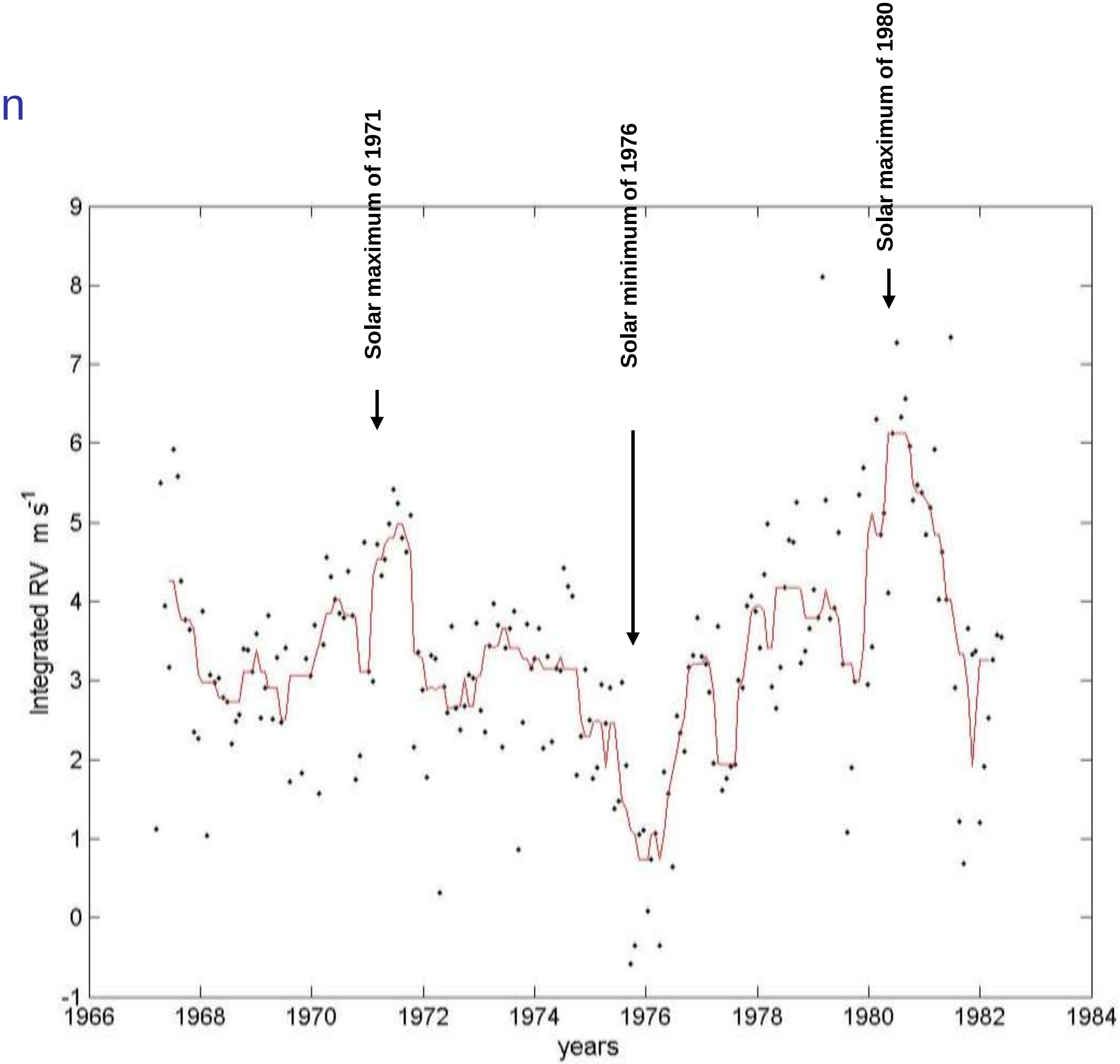
Solution:

$$\bar{\mathbf{x}} = \mathbf{T}^{\dagger}\, [\mathbf{\Lambda}\ \mathbf{\Phi}]\ \tilde{\mathbf{x}}$$

Reconstructed solar RV variation

$$\bar{V} = -0.157\,\mu_2 + 0.025\,\mu_4 - 0.295\,\beta_1 + 0.044\,\beta_2 + 0.004\,\beta_3$$

# RV of the Sun



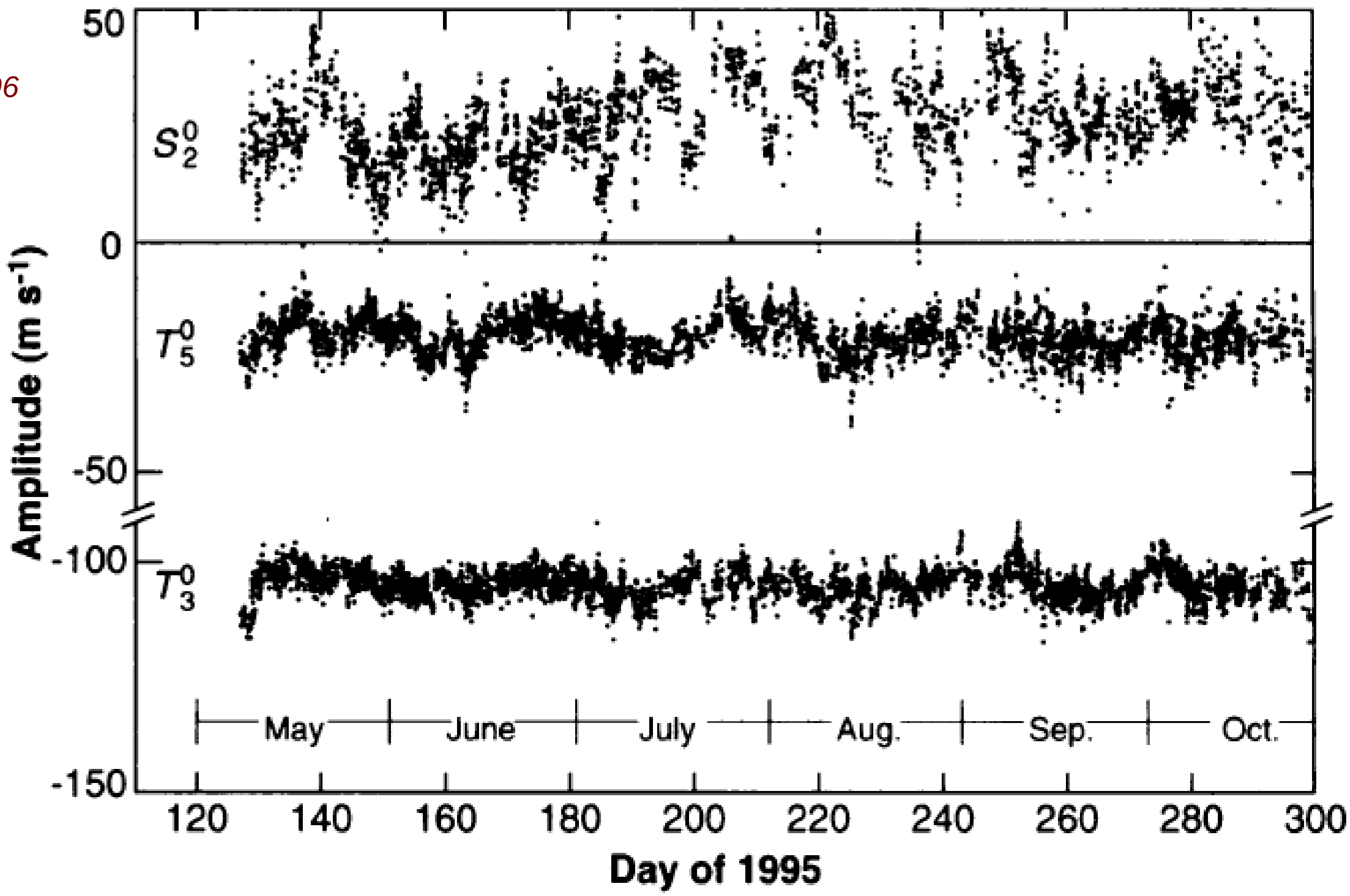

σ = 1.4 m/s

# GONG observations of surface flows

*From*
*Hathaway et al. 1996*
*Science 272, 1306*

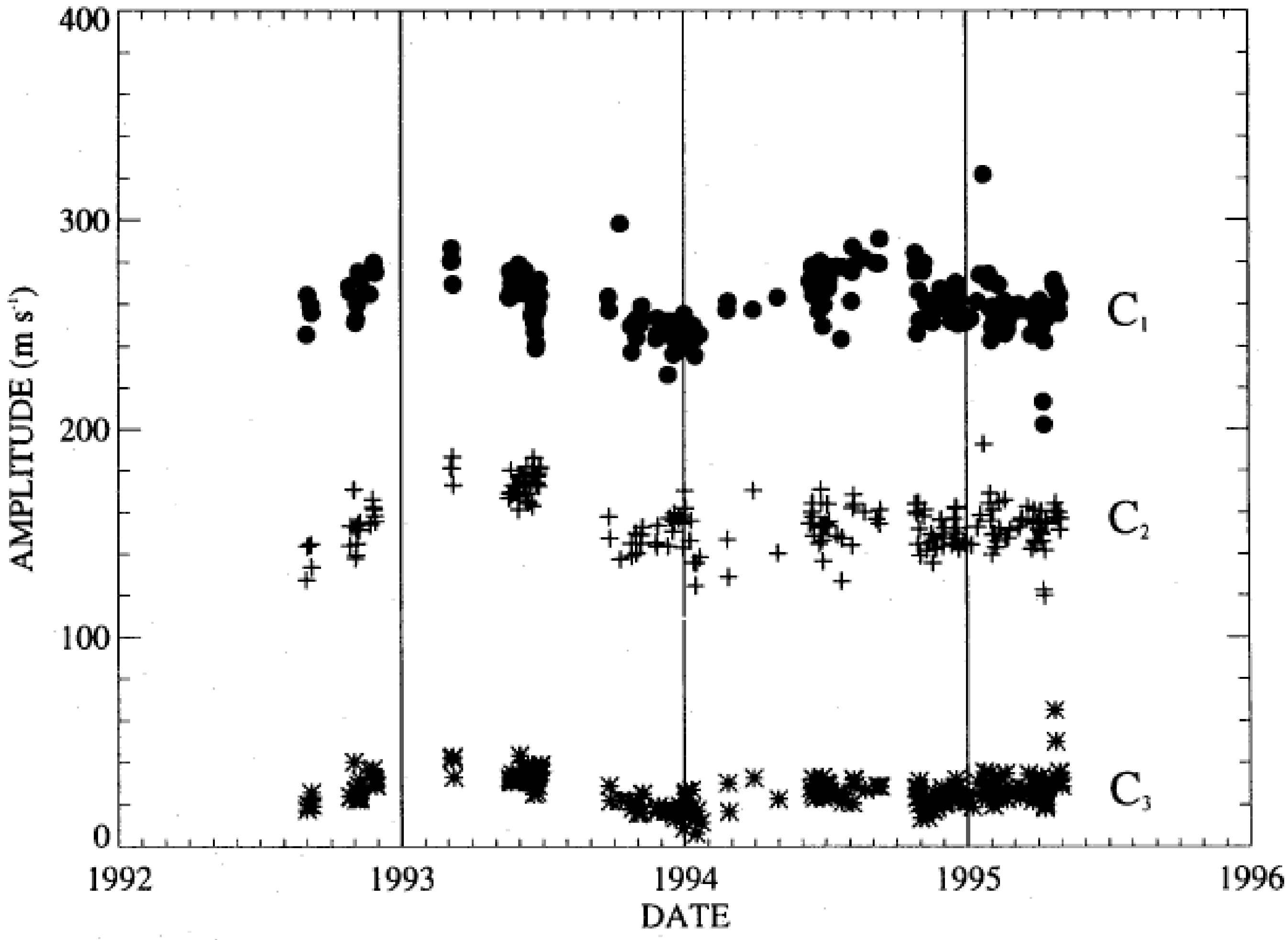
$S_2^0$

Is the main term of meridional flow



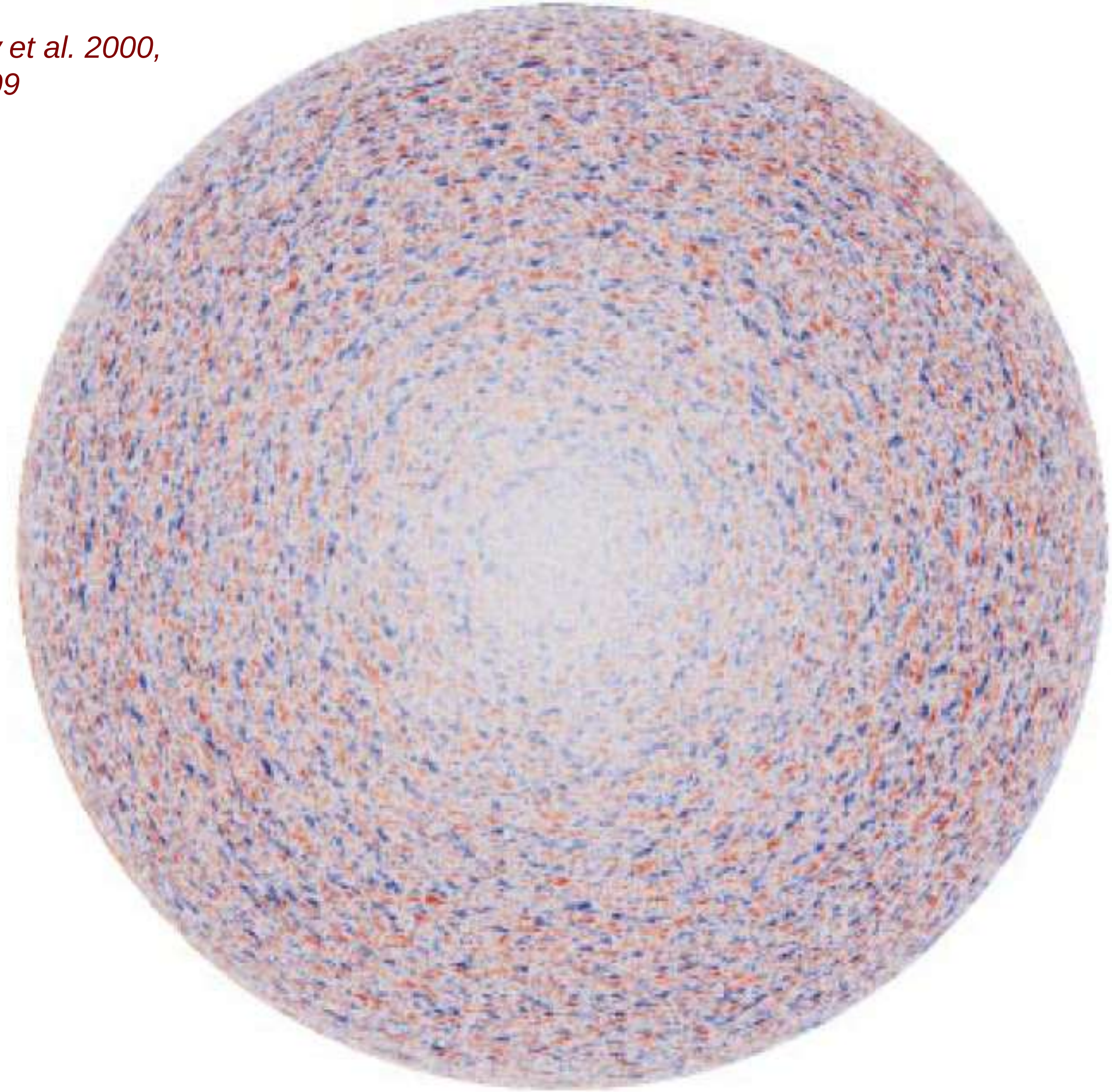
# Variability of limb shift from GONG data

*From Hathaway 1996, ApJ 460, 1027*



# Velocity field with MDI (SOHO)

*From Hathaway et al. 2000, Sol.Ph., 193, 209*



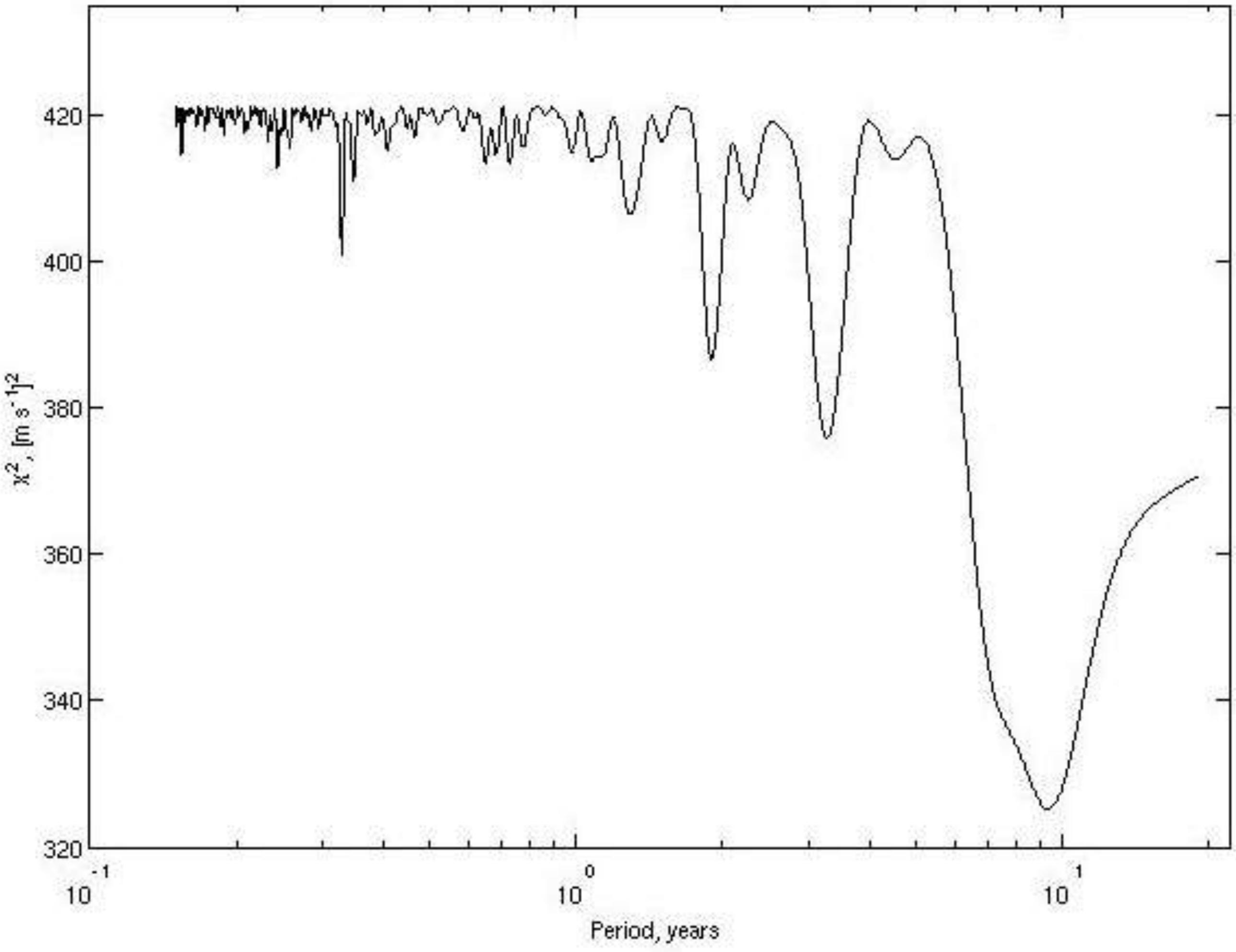
24 May 1996

Typical horizontal velocities
In supergranules
300 – 400 m/s

Modulation of RV on time scales of a several hours

# $\chi^2$ periodogram of solar RV

A generic planet detection algorithm detects two bogus planets at >99% confidence with $P_1$=9.35 yr, $M_1$=26 $M_E$ and $P_1$=6.35 yr, $M_2$=15 $M_E$



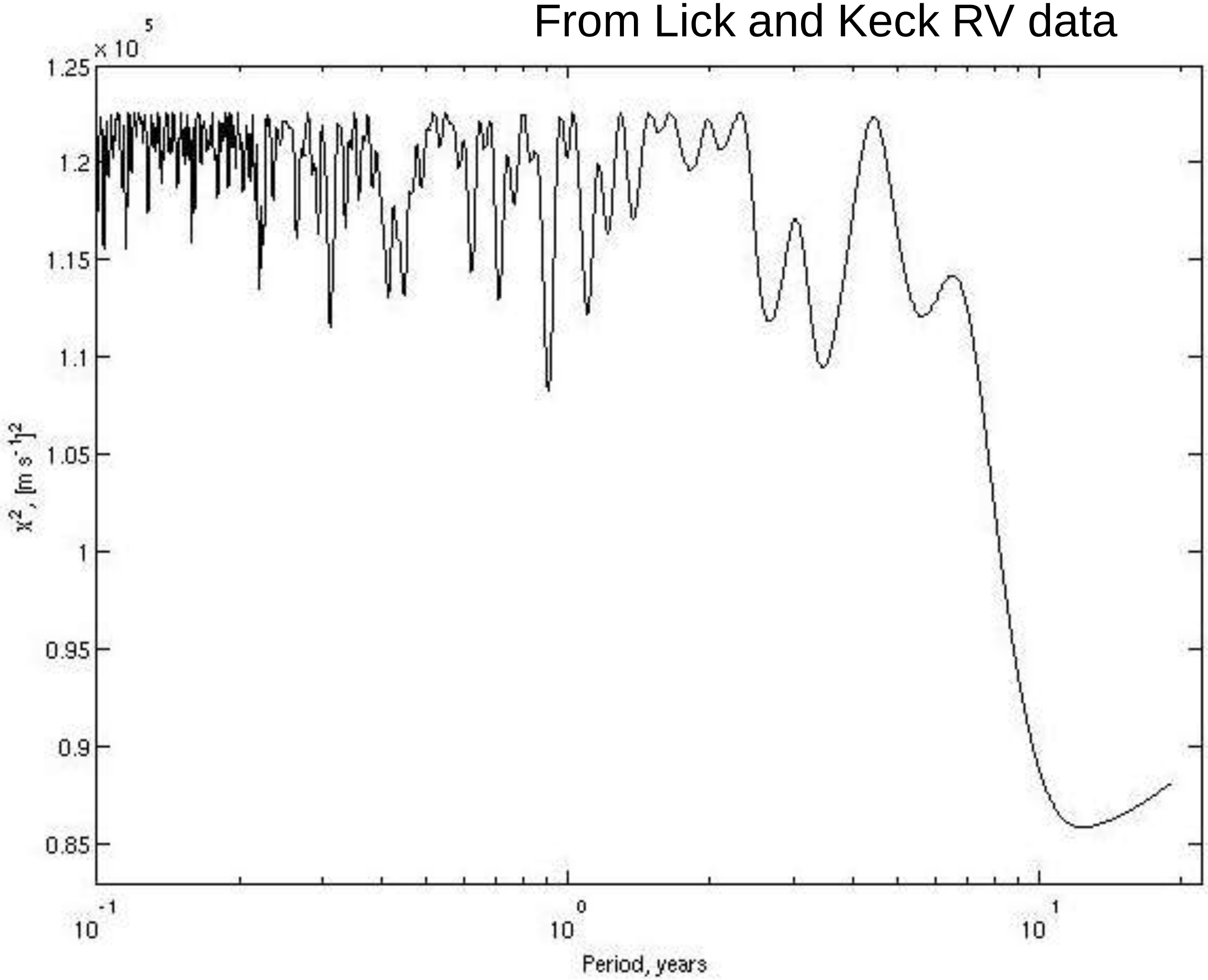
# Planets and RV jitter of 55 Cnc

K0/G8 V star
$T_{eff}$ = 5234 K
Fe/H = +0.31
Log $R'_{HK}$=-4.84
Age > 2 Gyr
v sin i = 2.4±0.5 km/s
*M* = 0.94 $M_{sun}$
$P_{rot}$ = 43 d

Close solar analog except for higher metallicity

*Fischer et al 2008*:
5 planets with periods between 2.8 d and 5220 d
After subtracting all detectable planets, STD(residual RV)=7.5 m/s
⏩ intrinsic scatter 5 m/s

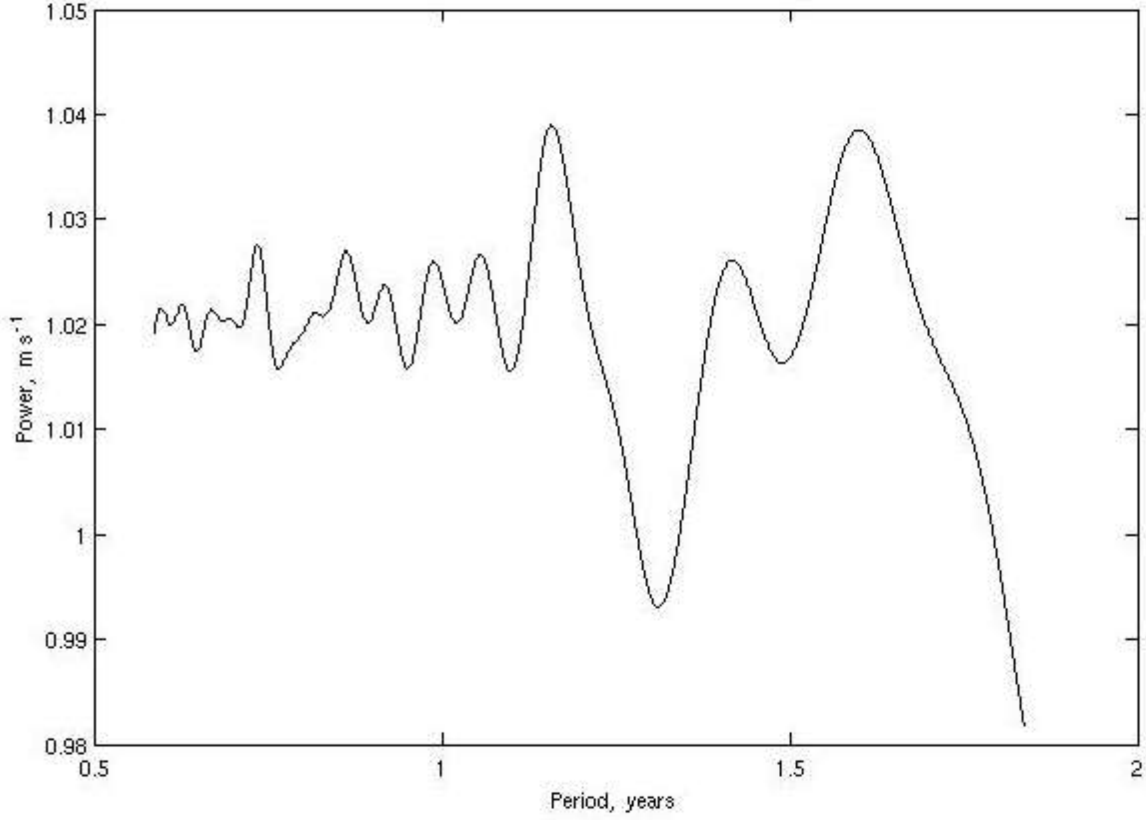
From Lick and Keck RV data



# Spectral density of solar RV in the range of habitable zone

- The impact on detection  of habitable planets around the Sun is defined by the amplitude spectrum of RV perturbations in the corresponding range of periods, which is about 1 m/s

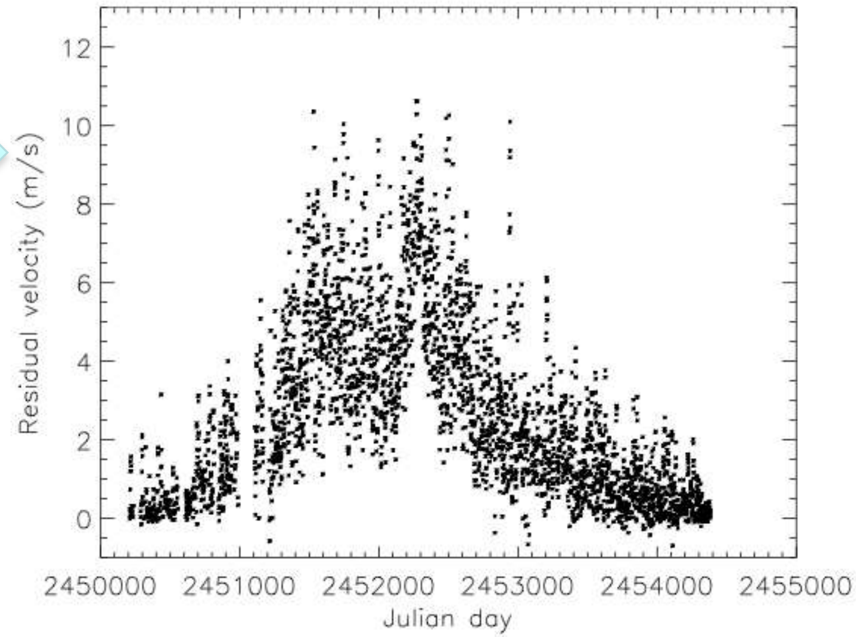
- The signature of Earth is 0.089 m/s

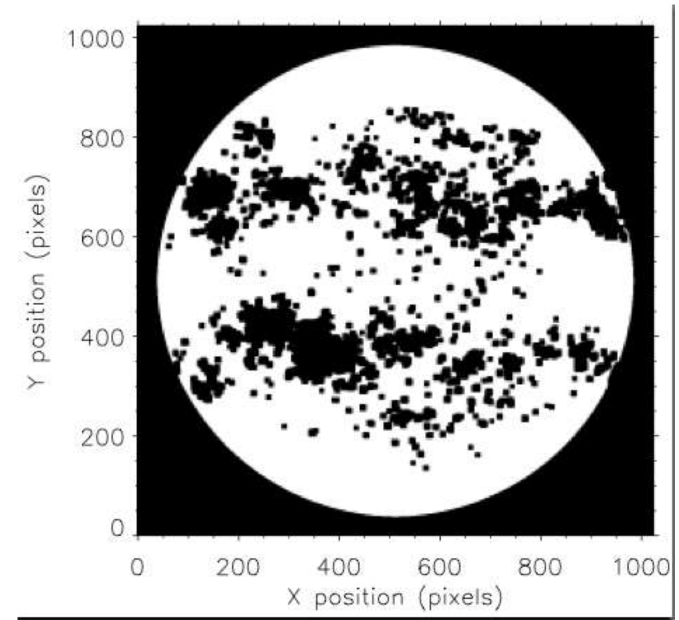


# The interpretation conundrum

- Meunier et al. 2010 obtained a similar reconstructed RV curve for the Sun from MDI/SOHO Dopplergrams, but with a different physical model implying that convective blueshift attenuation in small-scale magnetic features is the only variable part of the velocity field.
- The question is what is actually varying on the Sun,
  - Large-scale tangential flows
  - Small-scale radial convection
  - Or both?

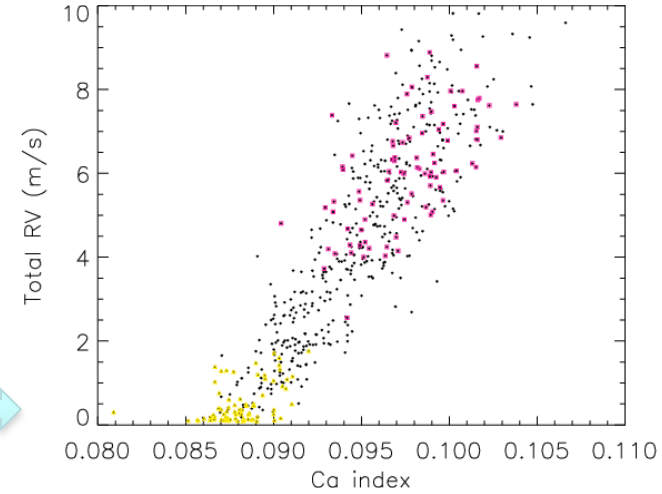
- Surface flows should have been removed by masking out the areas of elevated magnetic strength and extrapolating the background



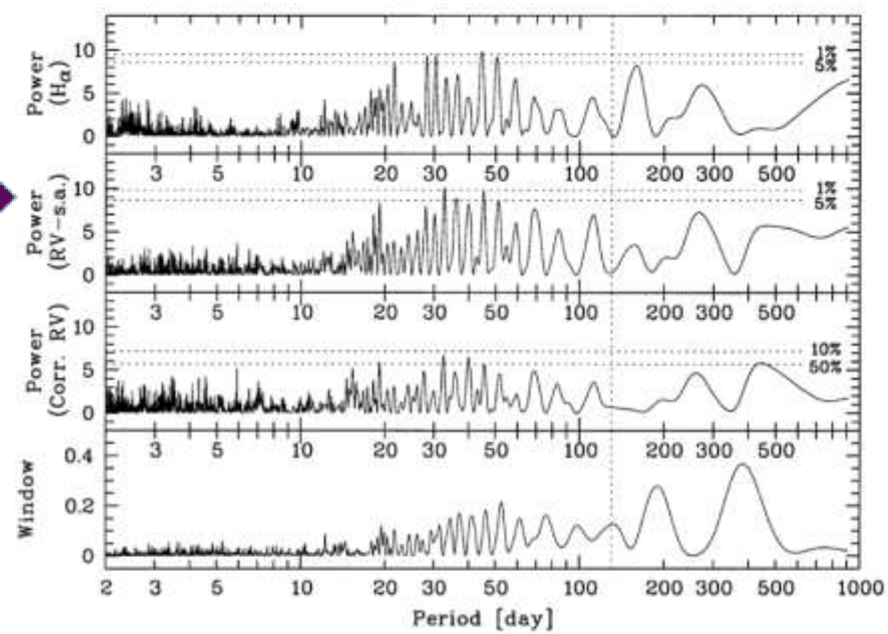
# The importance of correct interpretation

- Convective Doppler shift is correlated with activity indicators (Hα, Ca) and line profiles (bisector, FWHA) leading to useful diagnostics of RV variations origin




*Reconstructed RV of the Sun is strongly correlated with the Ca index at times of elevated activity, from Meunier et al. 2010*

*Empirical correlation of RV and Hα index is used to remove variations related to magnetic activity, leaving no statistically significant signals in the corrected periodogram*




- Meridional flows are likely deep-rooted as parts of global circulation – no acid test for exoplanets

## Conclusions

Variable surface flows on the Sun may be a formidable problem for exoplanet detection of terrestrial planets in habitable zones with the Doppler technique,

But we still need to find out what exactly is going on on the Sun…