Surface Flows on the Sun
and
Implications for Detection of Habitable Exoplanets

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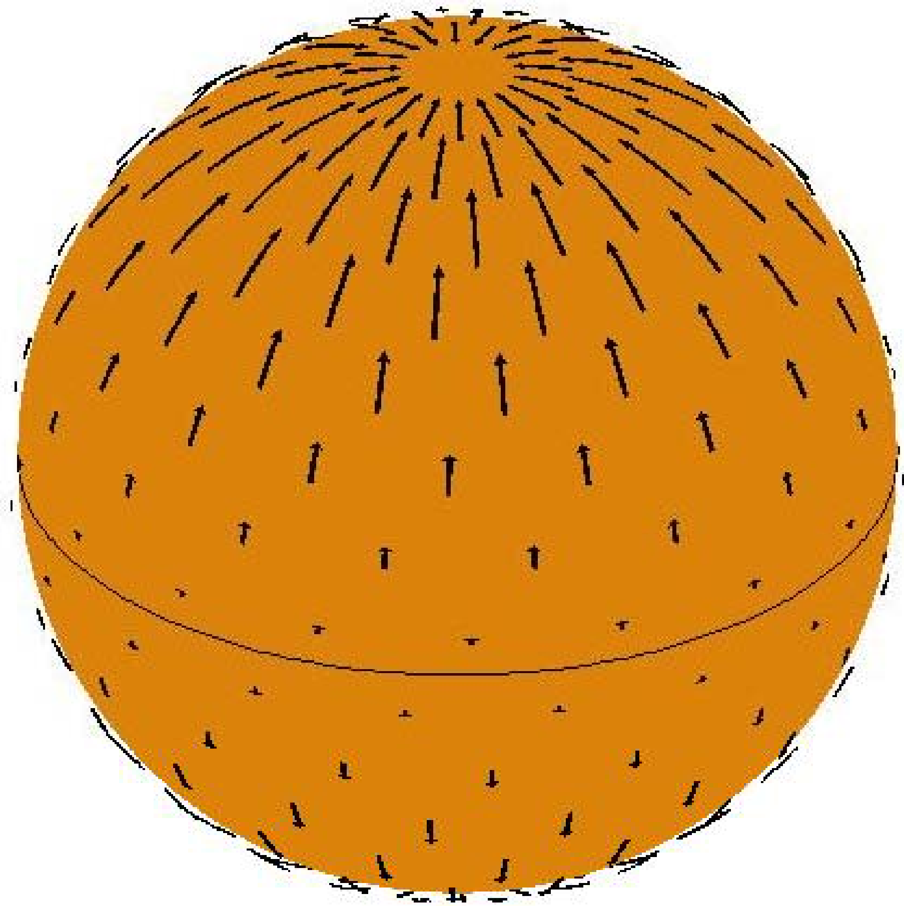
The restless solar surface

- Sun does not rotate as a solid body
  - Differential rotation – faster at the equator
  - Equatorial rotation velocity 2 km/s
  - The rate of surface rotation is variable
  - Torsional jet-like streams correlated with the solar cycle
- 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

Meridional flow

- 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)

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

With λ the heliocentric longitude, φ 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:

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

- The symmetric DEF terms produce a non-zero contribution to the integral
- LaBonte & Howard (1982) explained the symmetric velocity field as a combination of
  - Meridional flow

$$V_{\mathrm{M}} = \mu_2 P_2^1(\sin\,\phi) + \mu_4 P_4^1(\sin\,\phi),$$

  - Axisymmetric convective blueshift (limb shift)

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

Refitting the data

Problem:

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

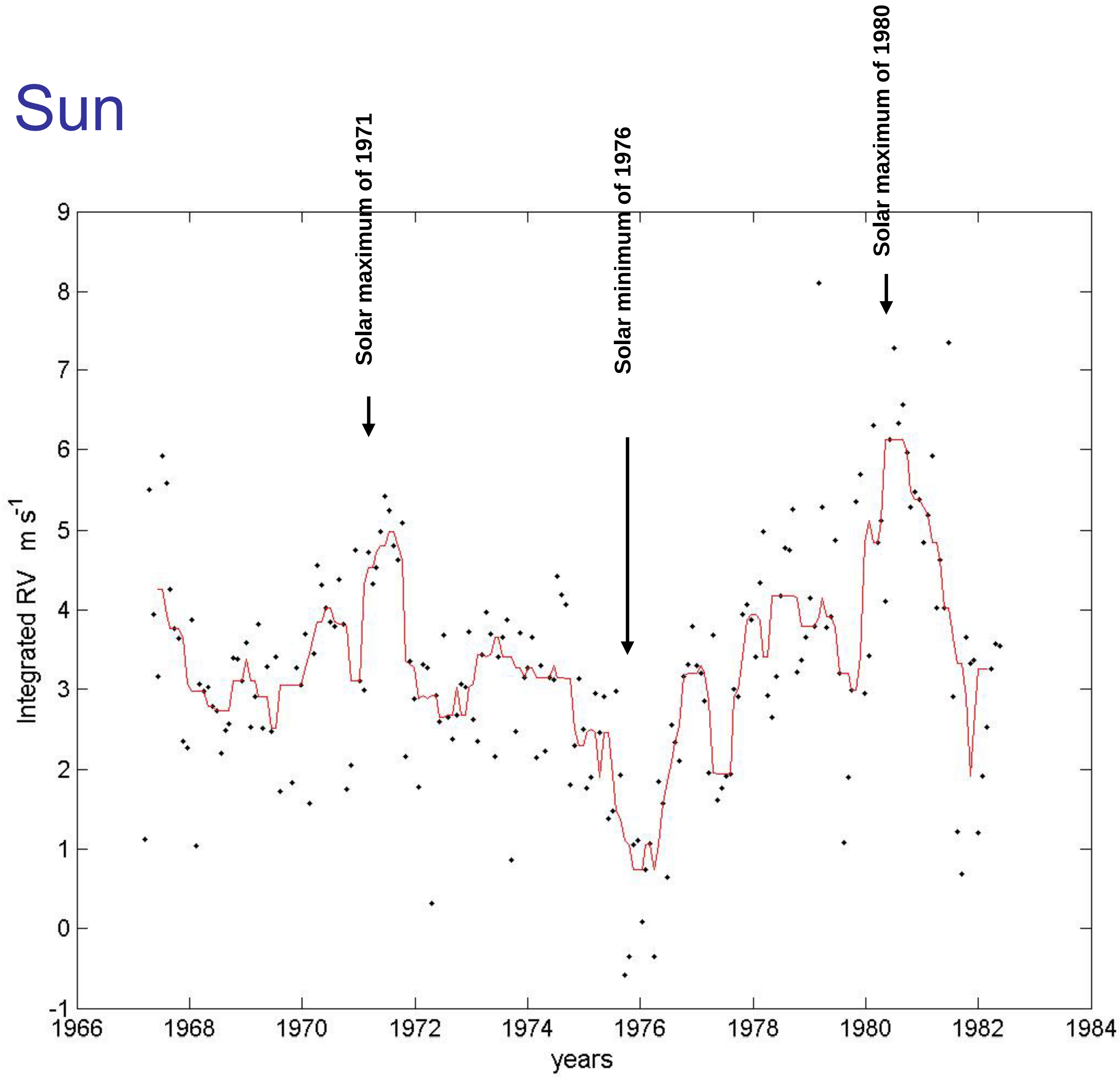
Solution:

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

Reconstructed solar RV variation

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

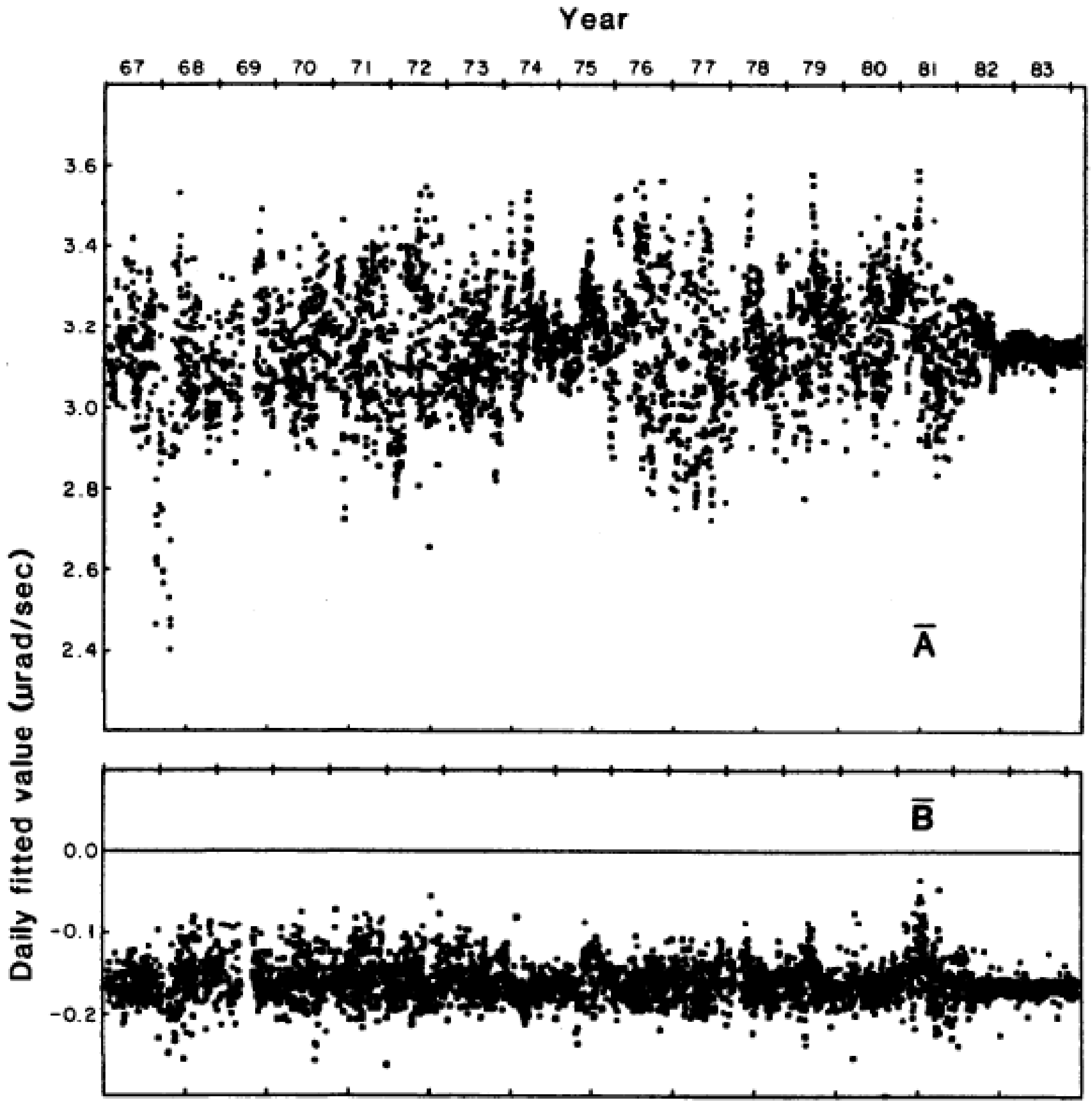
RV of the Sun



σ = 1.4 m/s

Daily changes in solar rotation

From
Snodgrass & Howard,
1985, Science 228, 4802

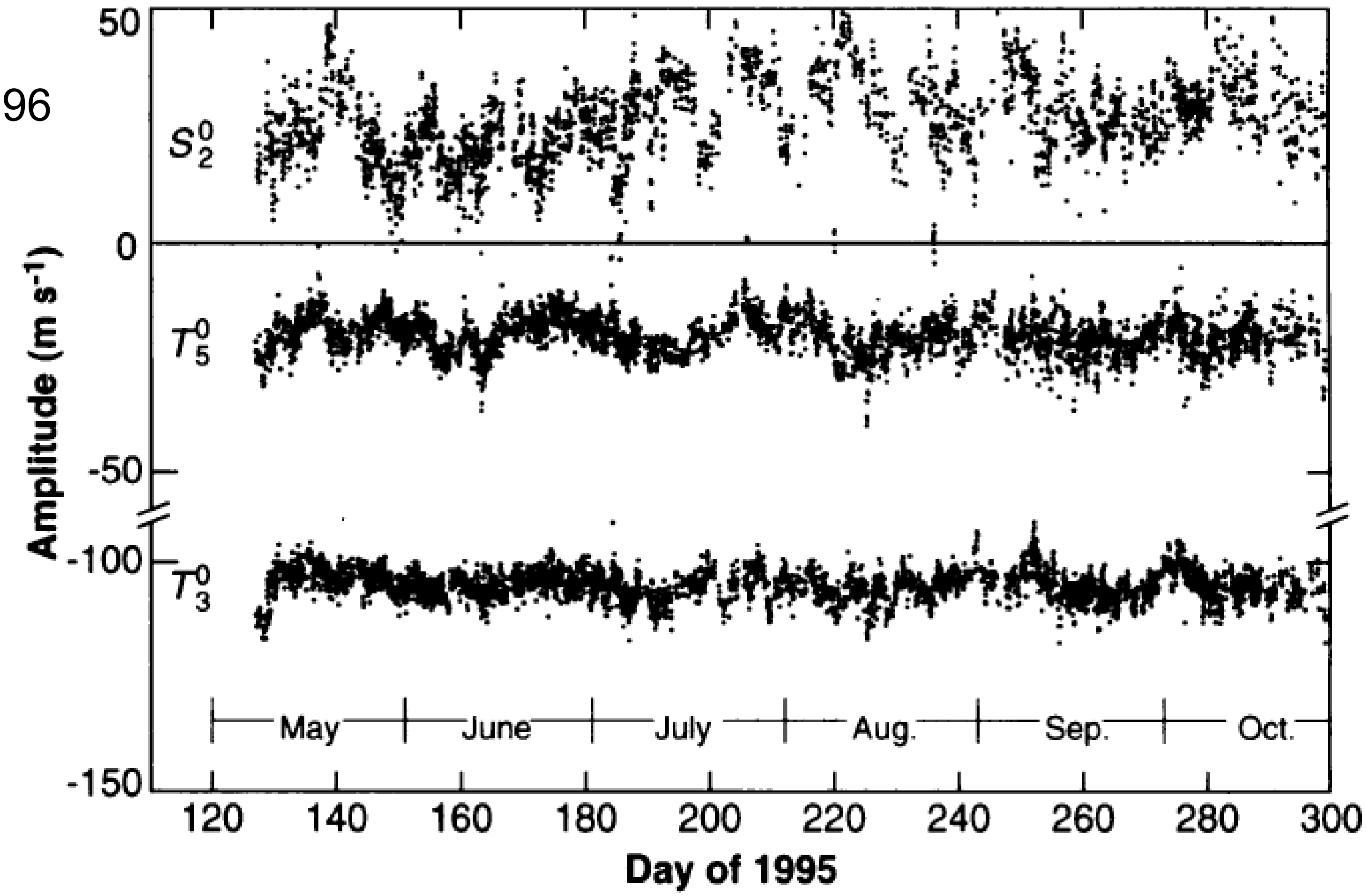


GONG observations of surface flows

From
Hathaway et al. 1996
Science 272, 1306

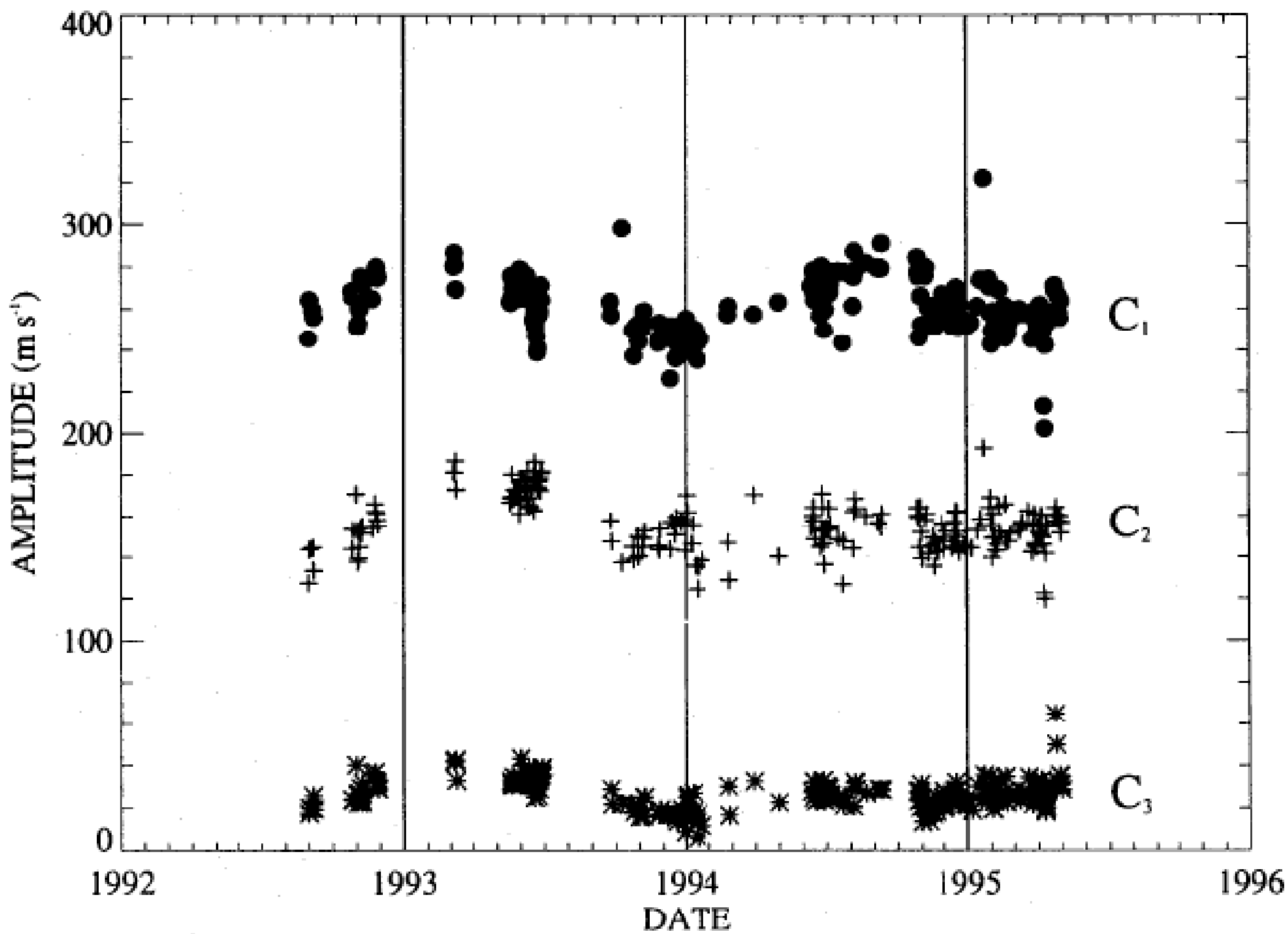
S_2^0

Is the main term of meridional flow



Variability of limb shift from GONG data

From
Hathaway 1996,
ApJ 460, 1027

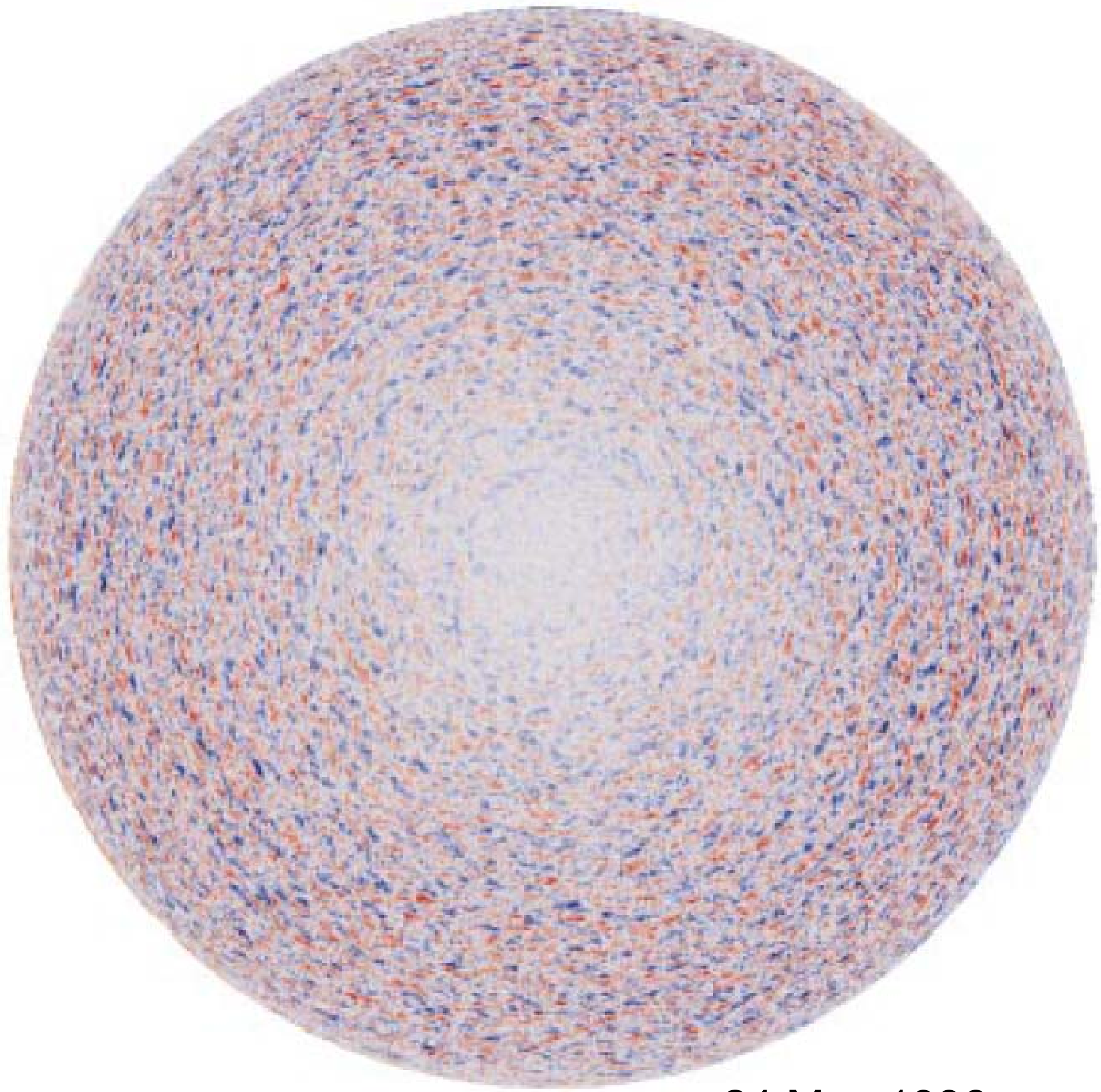


Velocity field snapshot with MDI (SOHO)

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

Typical horizontal velocities
In supergranules
300 – 400 m/s

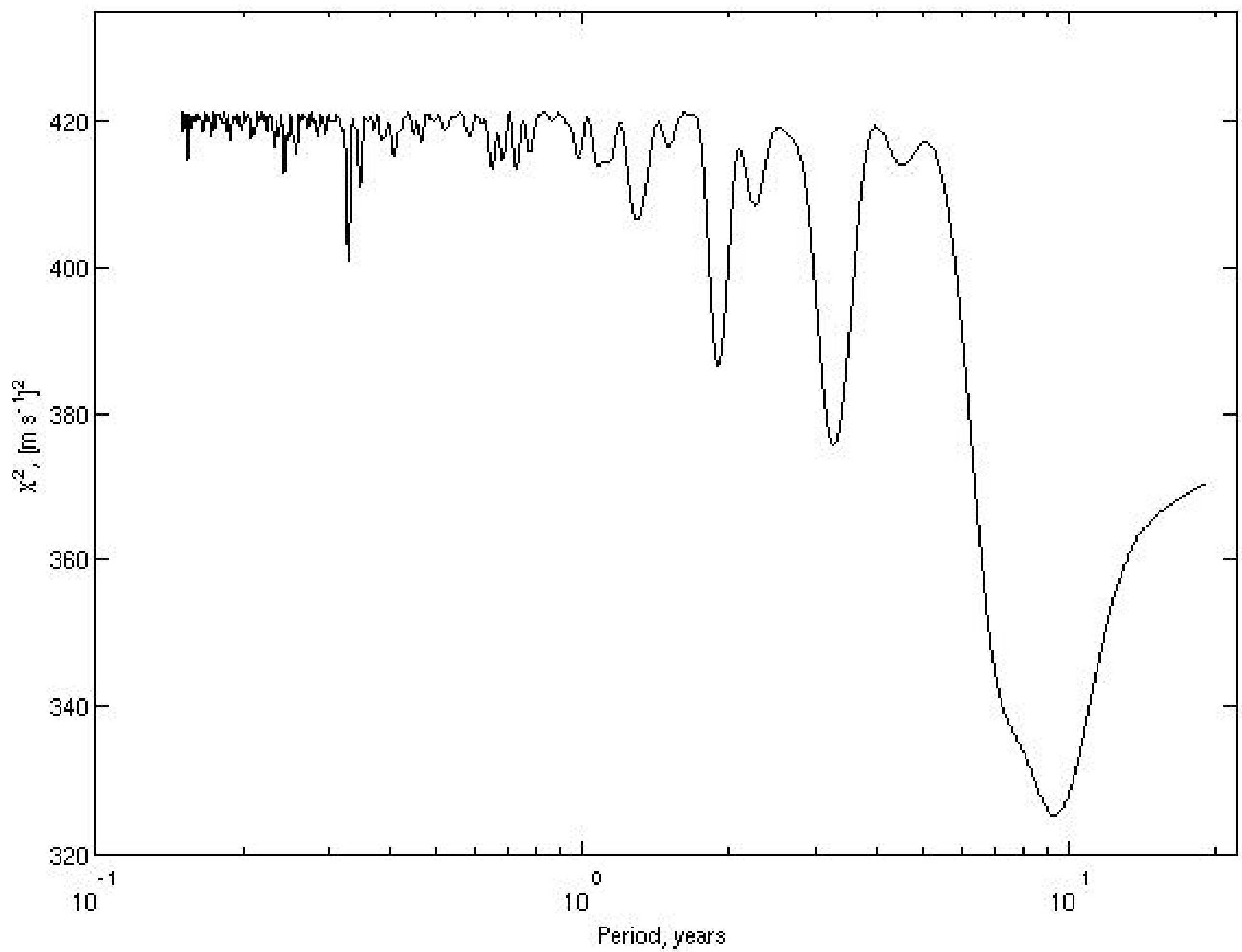
Modulation of RV on time
Scales of a several hours



24 May 1996

χ^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



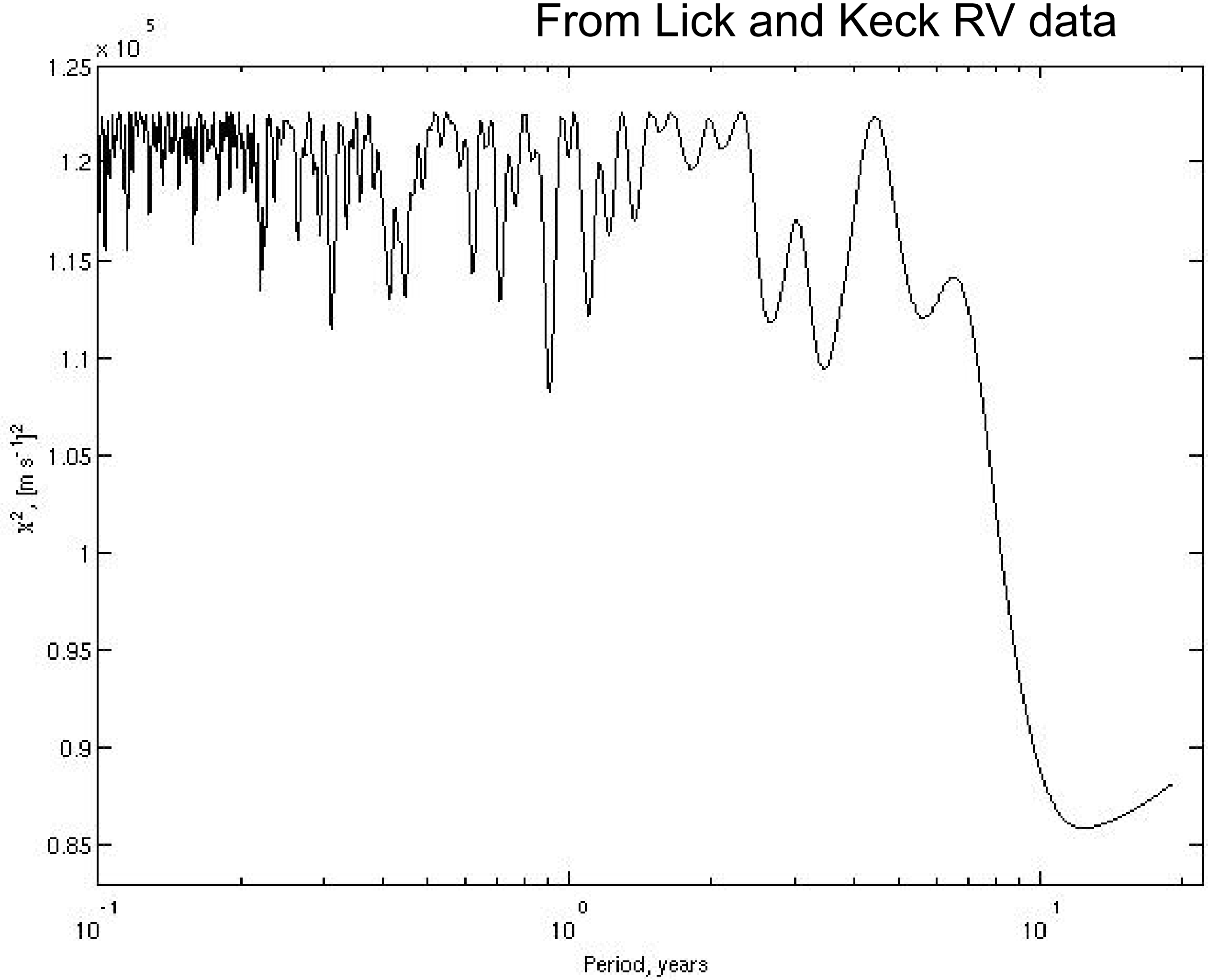
Planets and RV jitter of 55 Cnc

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

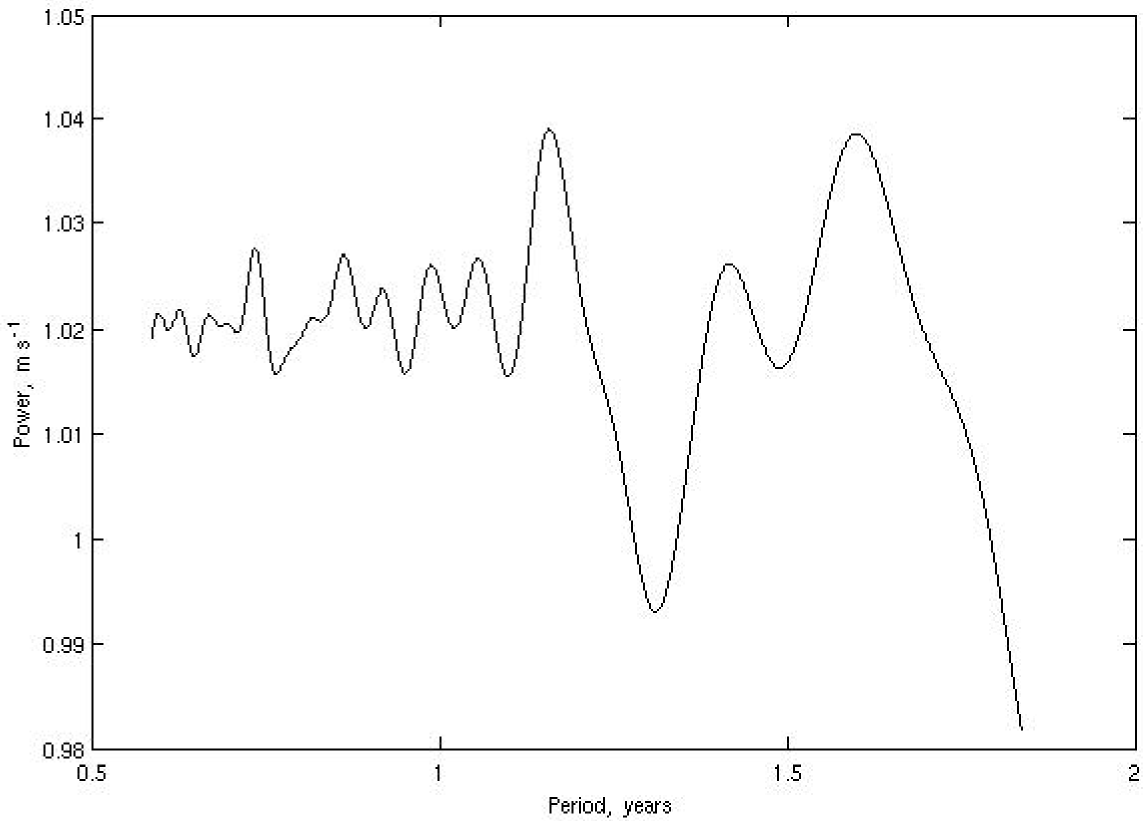
Fischer et al 2008:
5 planets with periods between 2.8 d and 5220 d
After subtracting all detectable planets, STD(residual RV)=7.5 m/s
⏩ intrinsic scatter 5 m/s

From Lick and Keck RV data



Spectral power of solar RV in the range of habitable zone

- The impact on detection of habitable planets around the Sun is defined by the spectral power of RV perturbations in the corresponding range of periods, which is about 1 m/s
- The signature of Earth is 0.089 m/s



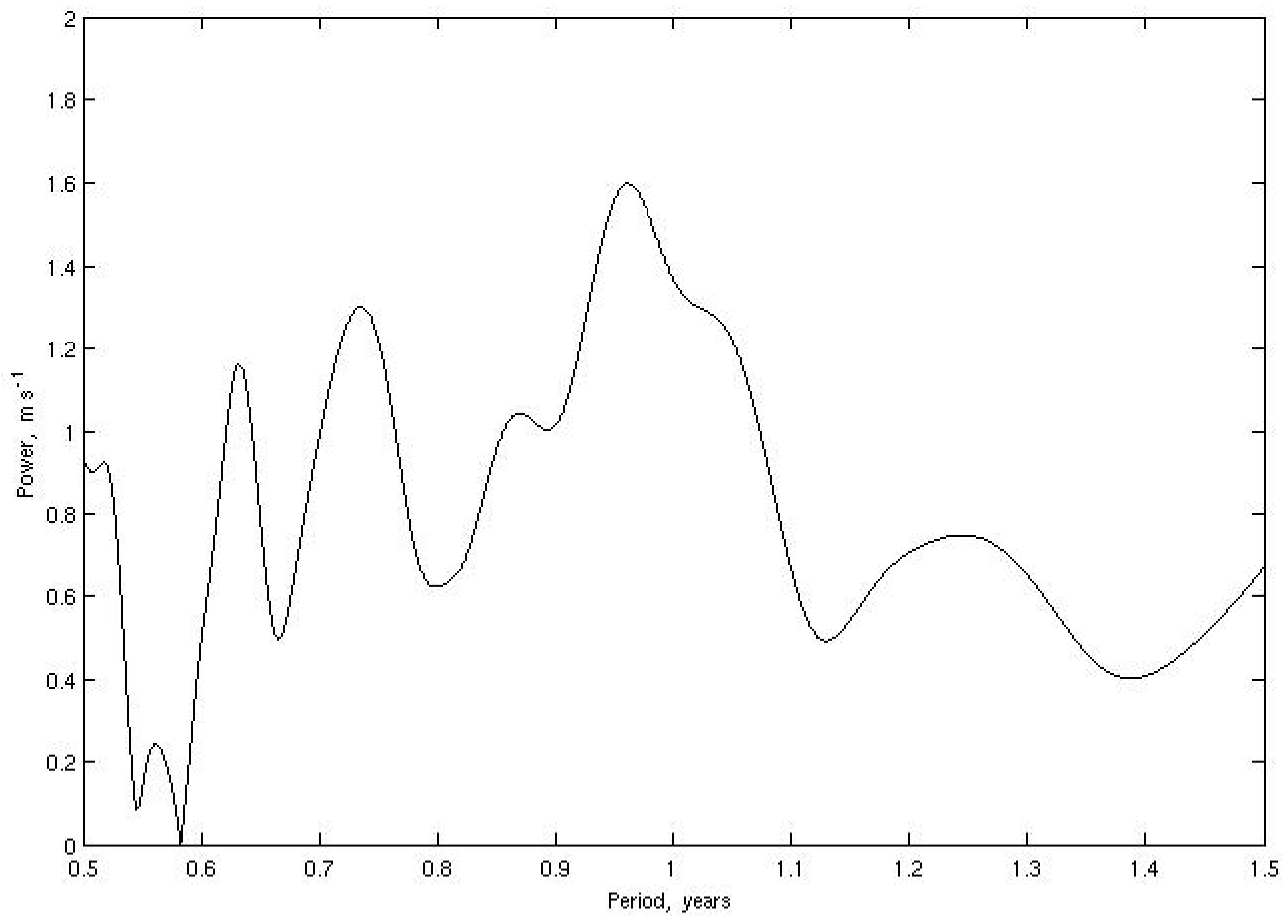
HD 40307 and its three super-earths

K2 V star
T_{eff} = 4977 K
Fe/H = -0.31
Log R'_{HK}=-4.99
v sin i = < 1 km/s
M = 0.77 M_{sun}
P_{rot} = 48 d

Exceptionally low activity

Mayor et al. 2009:
3 super-earths with
periods 4.3
9.6, 20.5 d

After subtracting all
detectable planets,
$r\chi^2$ = 3.2 indicating
intrinsic scatter ~ 1 m/s



Conclusions

Variable surface flows on the Sun is a showstopper for exoplanet detection of terrestrial planets in habitable zones with the Doppler technique