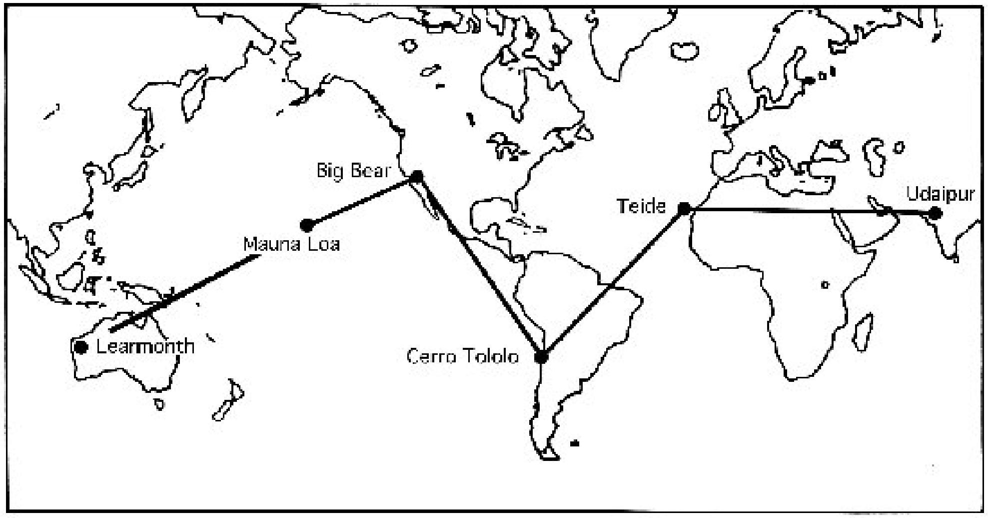
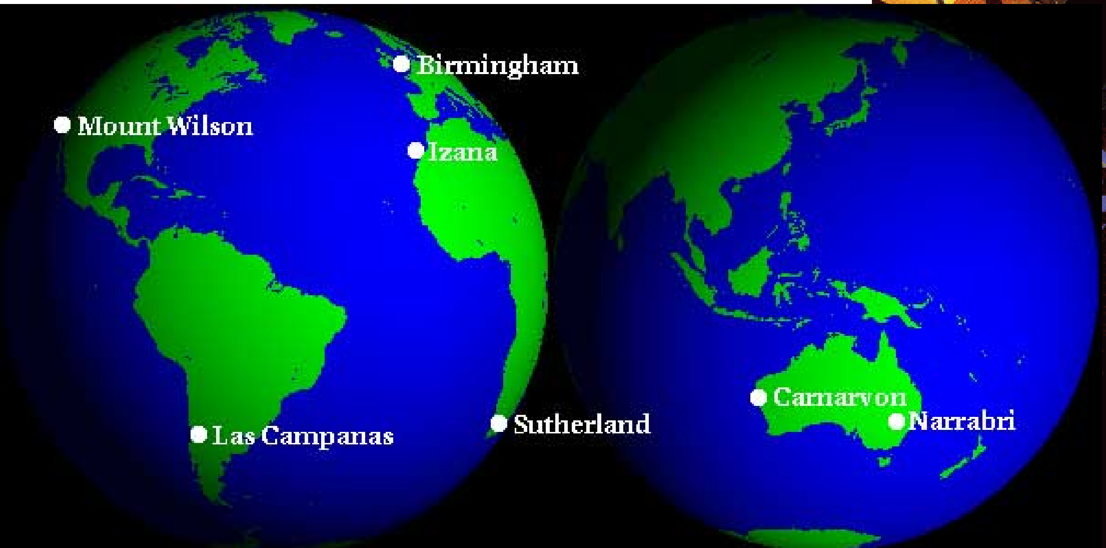
Helioseismology:

GONG/BiSON/SoHO



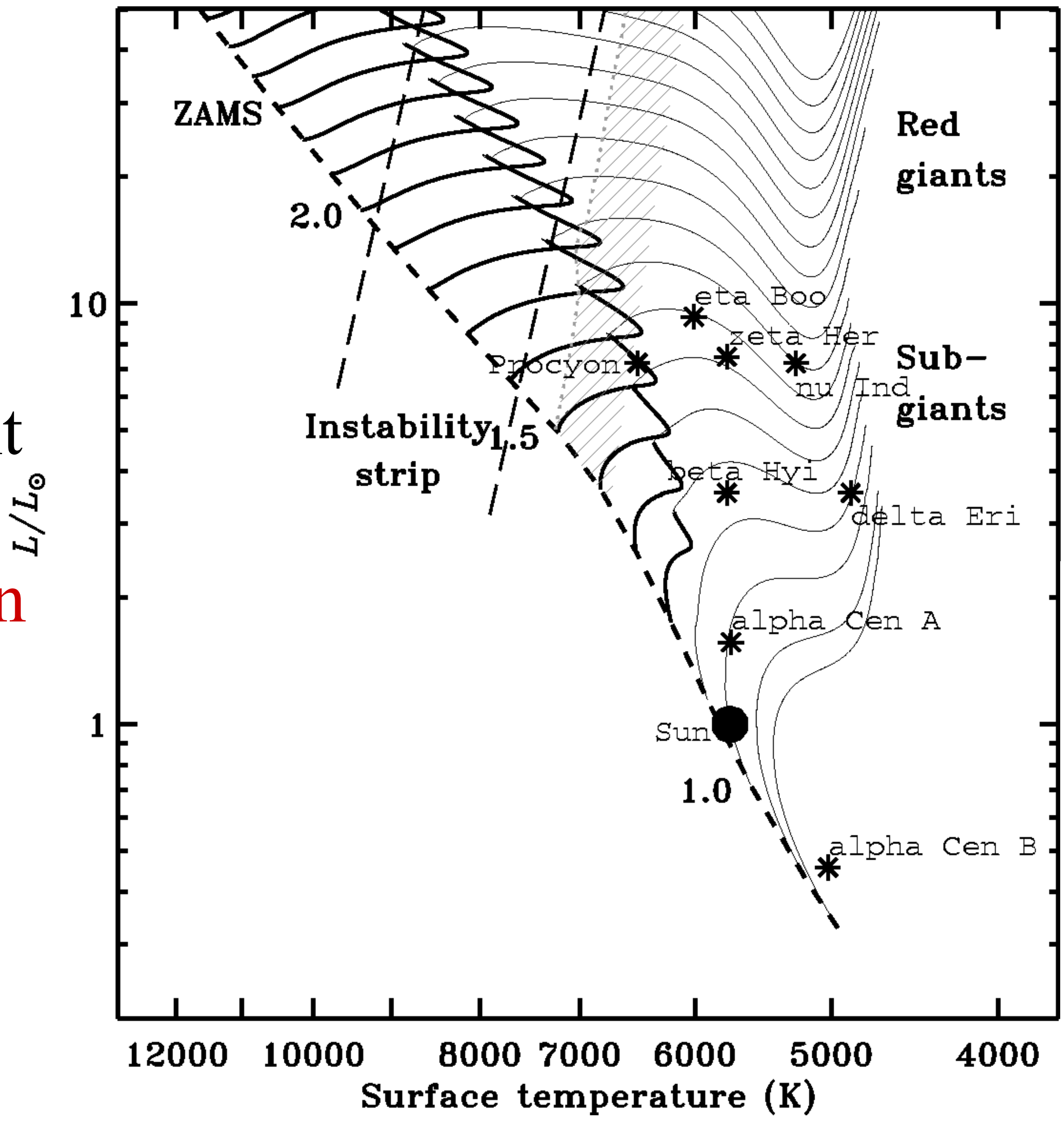


Asteroseismology:

- Solar-like oscillations in other stars

- Study stars of different Masses, Ages and Chemical Composition

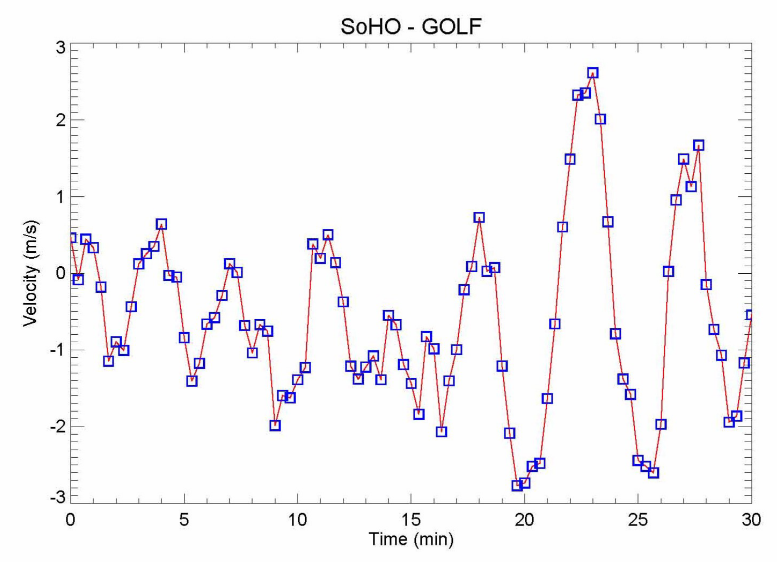
- Stellar Structure *and* Evolution



Solar-like oscillations in other stars

- Amplitudes are very low;

  20 cm/s in velocity, or
  20-30 m in displacement,
  a fraction of a degree in temperature,
  a few ppm in brightness

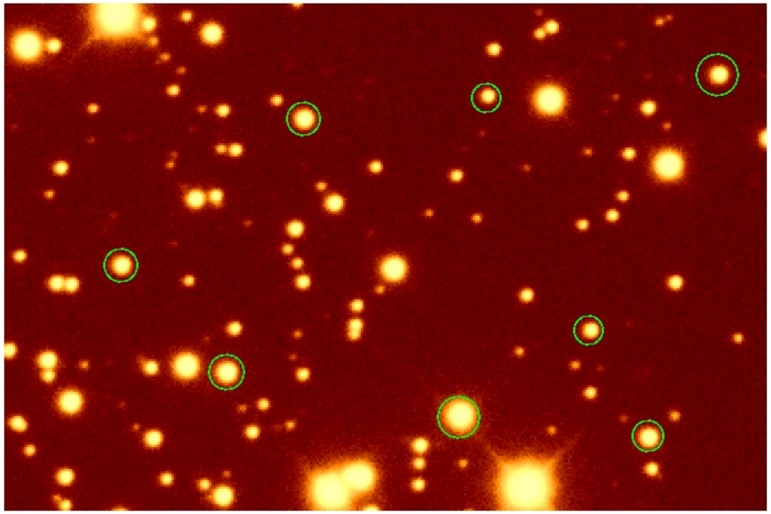


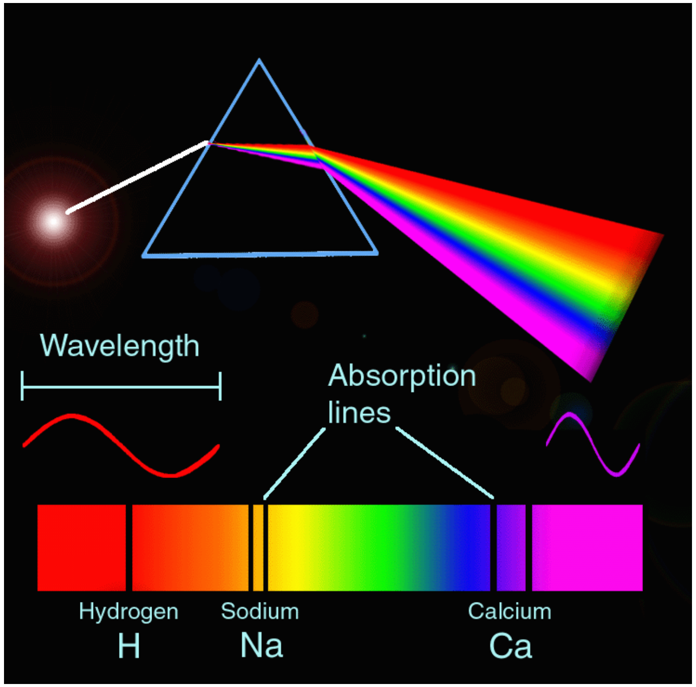
- Only see modes with few node-lines: surface unresolved

- Only possible in the brightest stars using the best telescopes

Observations of Pulsating Stars

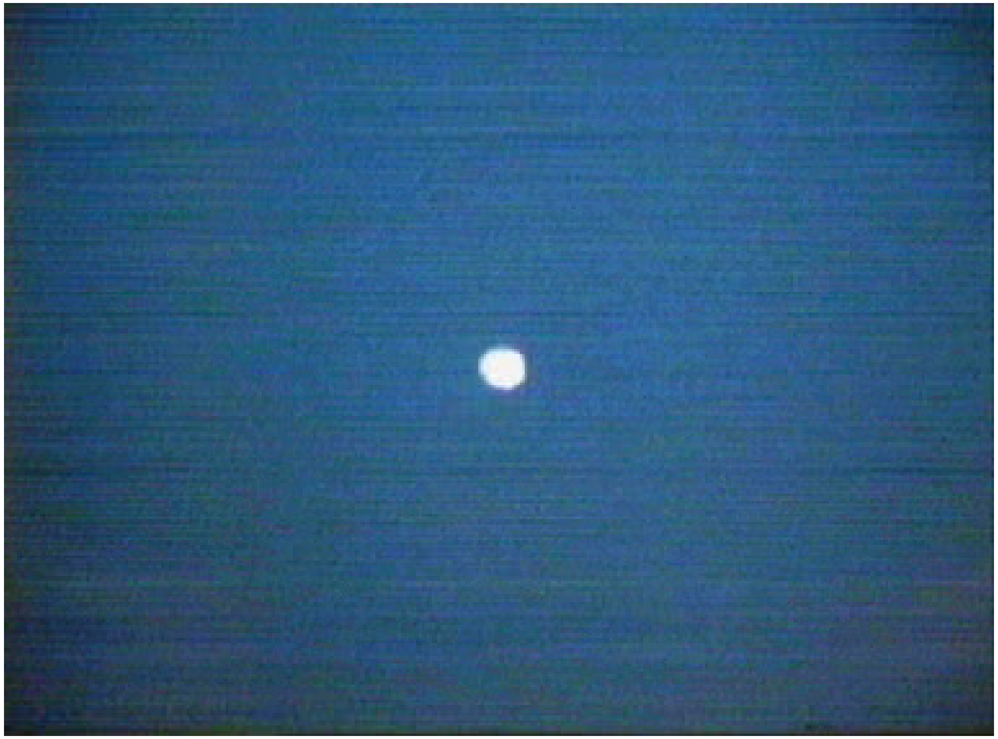
- Time Series Photometry
- Time Series Spectroscopy

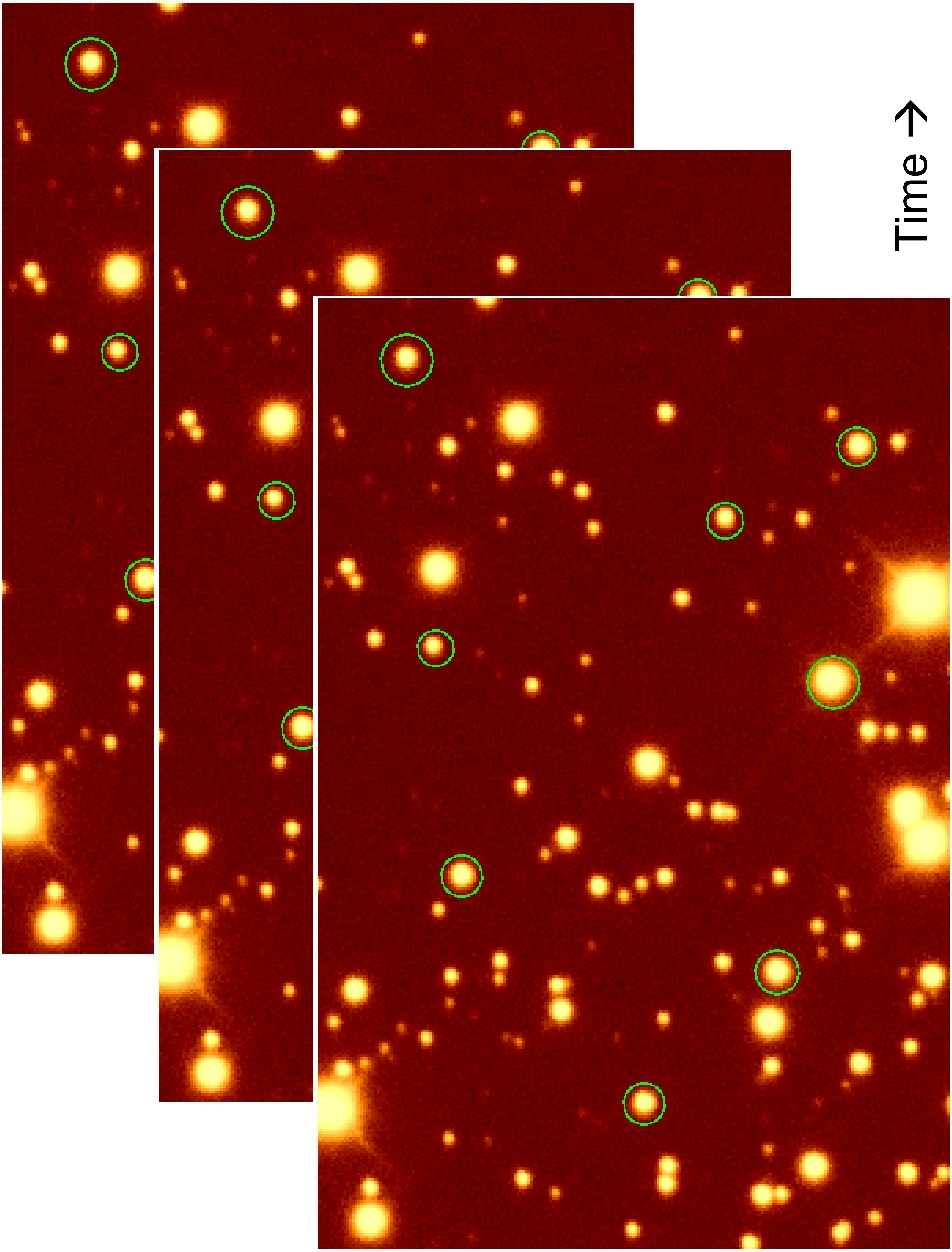




Solar-like oscillations in other stars

- Brightness variations are extremely difficult to observe from ground because of the low amplitudes and the effect of the atmosphere:



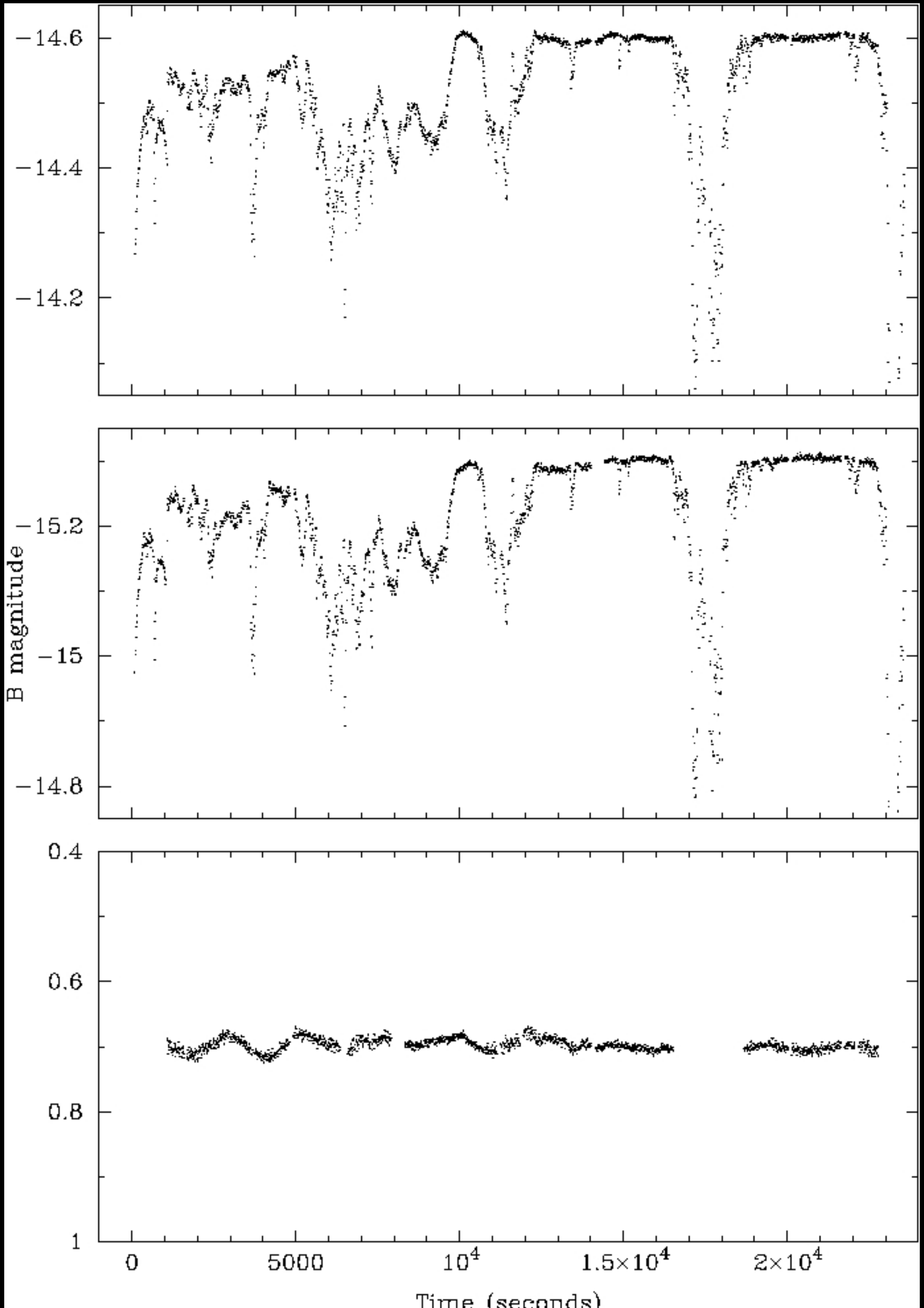

Time →

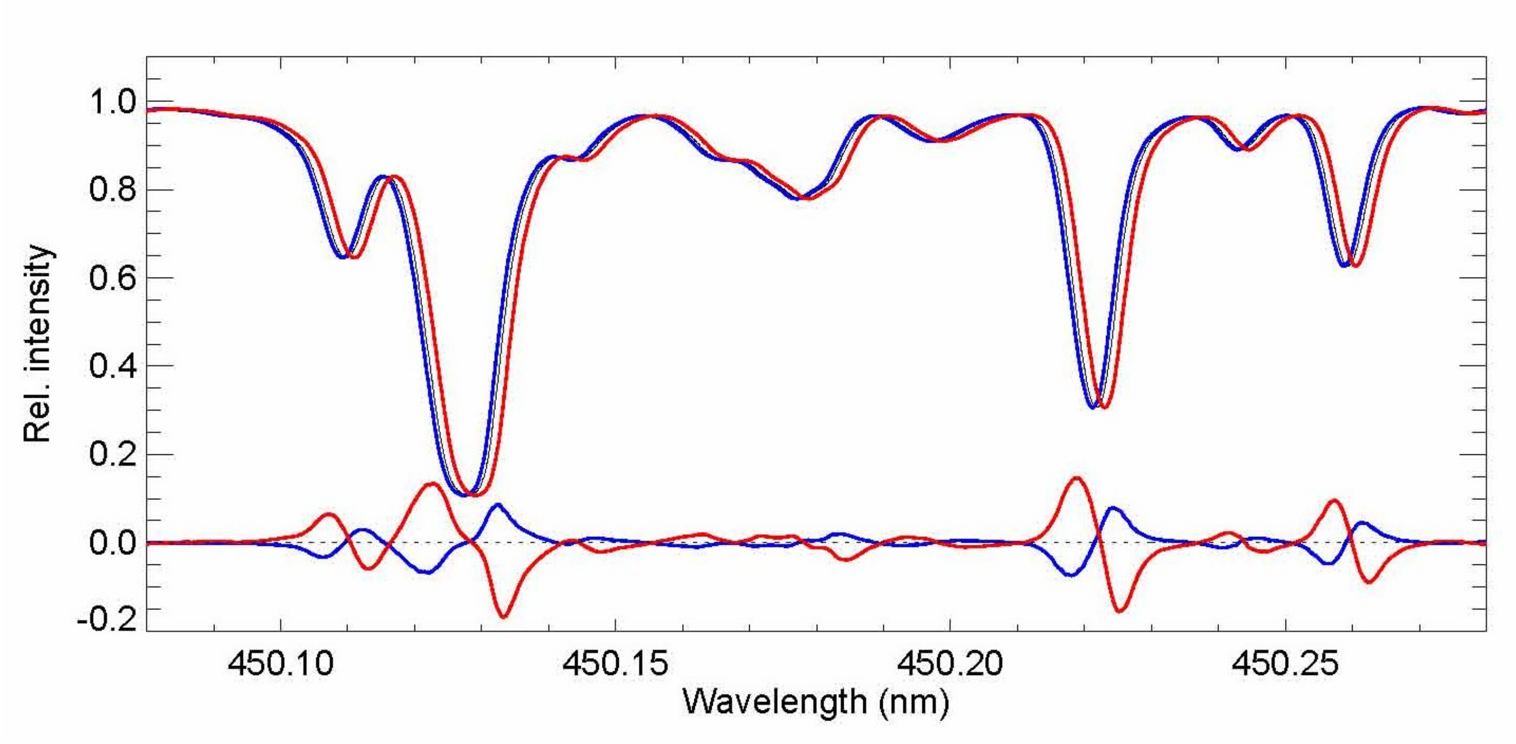
Differential photometry

Variable star:

Constant star:

Variable – constant:

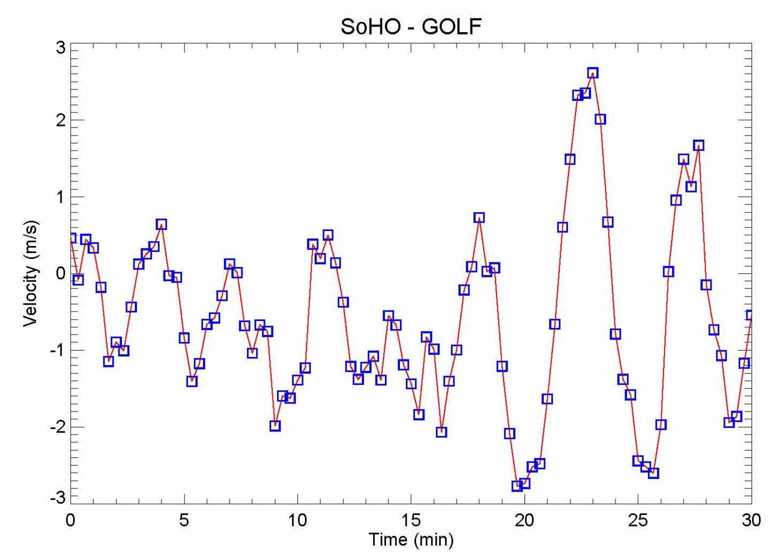




+ 800 m/s: redshifted: 12 mÅ
- 400 m/s: blueshifted: 6 mÅ

Time-series Spectroscopy → Doppler-shifts of Radial Velocities due to the oscillations…

Solar-like oscillations in other stars

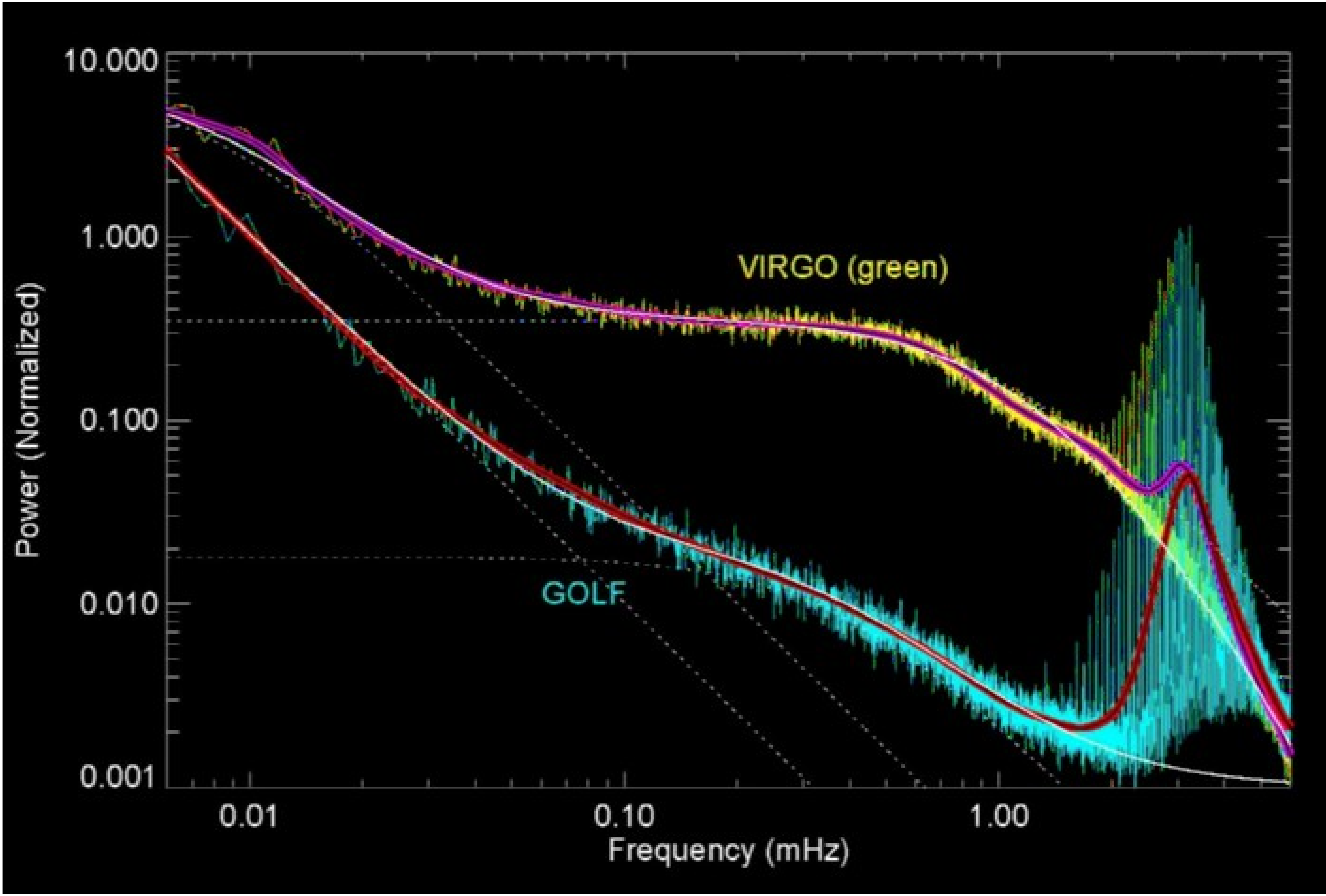


- Amplitudes are very low;

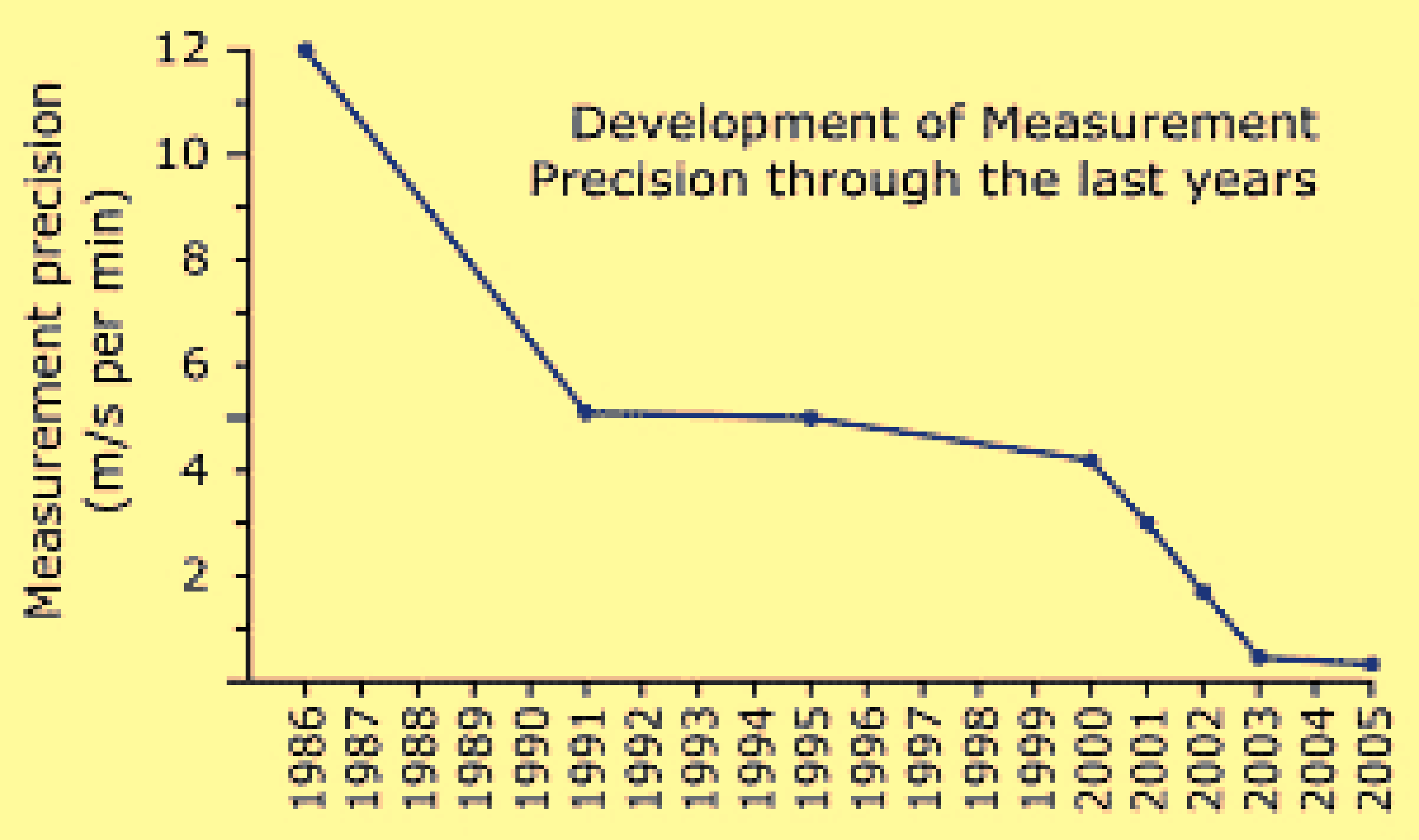
  20 cm/s in velocity, or
  20-30 m in displacement,
  a fraction of a degree in temperature,
  a few ppm in brightness

- From ground: only possible with spectroscopy

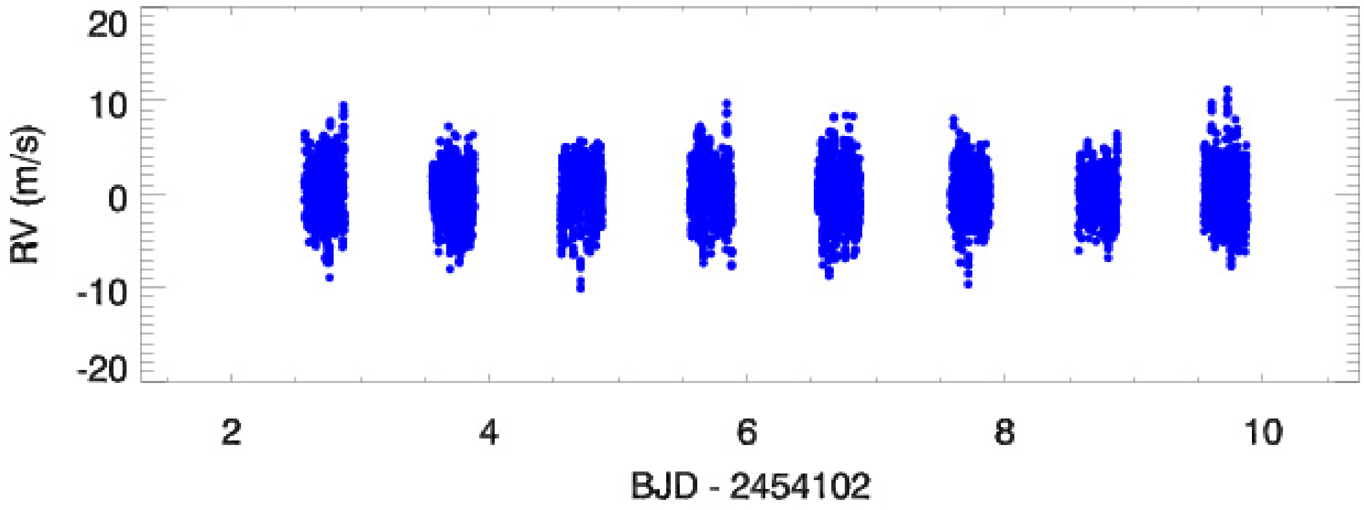
- …but thats anyway much better than photometry because the star itself is much more noisy in photometry

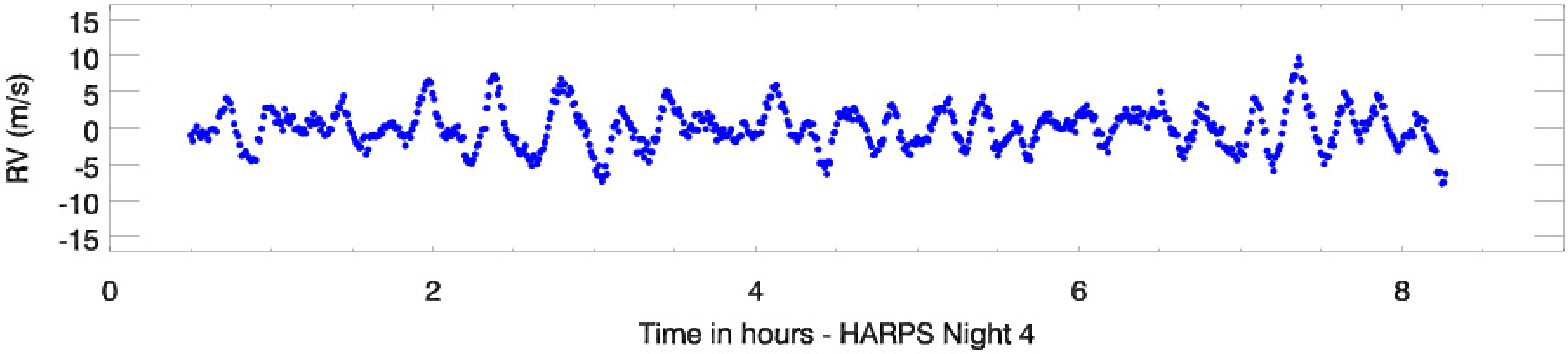

10.000
1.000
0.100
0.010
0.001
Power (Normalized)
0.01
0.10
1.00
Frequency (mHz)
VIRGO (green)
GOLF

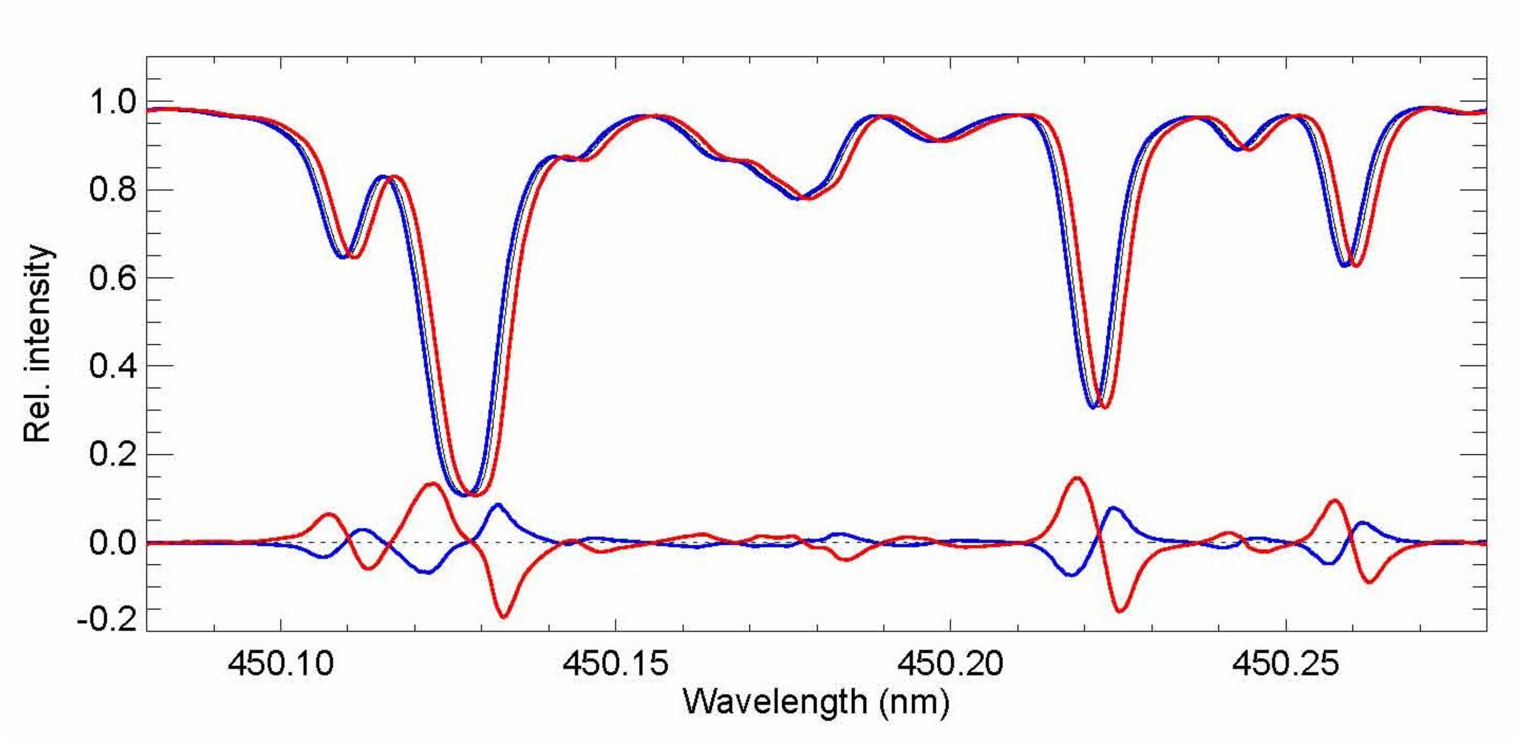
Measurement precision of Radial Velocities now below 1 m/s for a 1 min observation of bright stars:



5700 spectra of Procyon obtained with HARPS in January 2007:





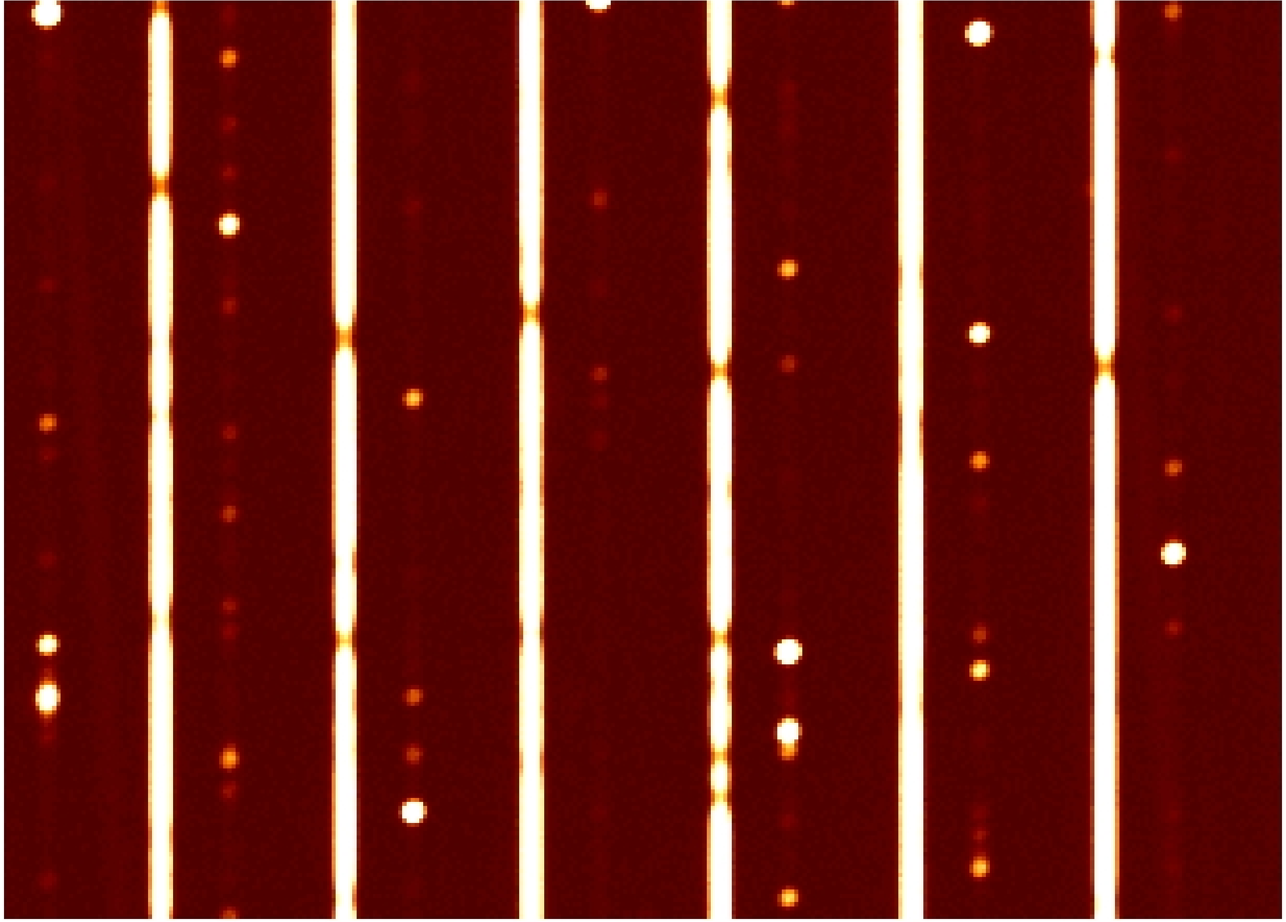


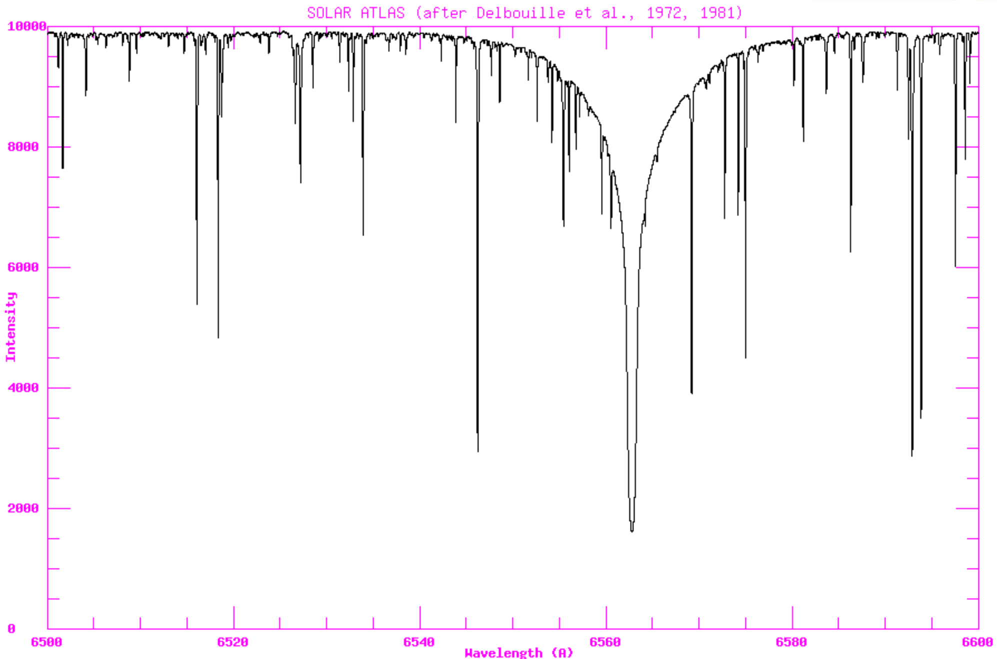
+ 800 m/s: redshifted: 12 mÅ

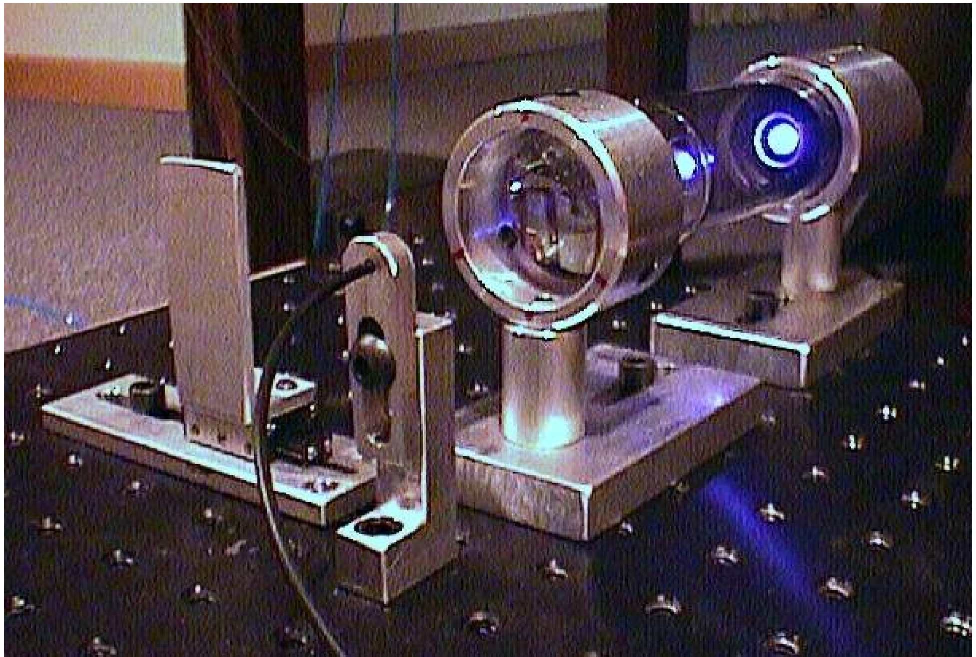
- 400 m/s: blueshifted: 6 mÅ

20 cm/s: 3-6 µÅ (~ 80 Si-atoms on the CCD-detector)

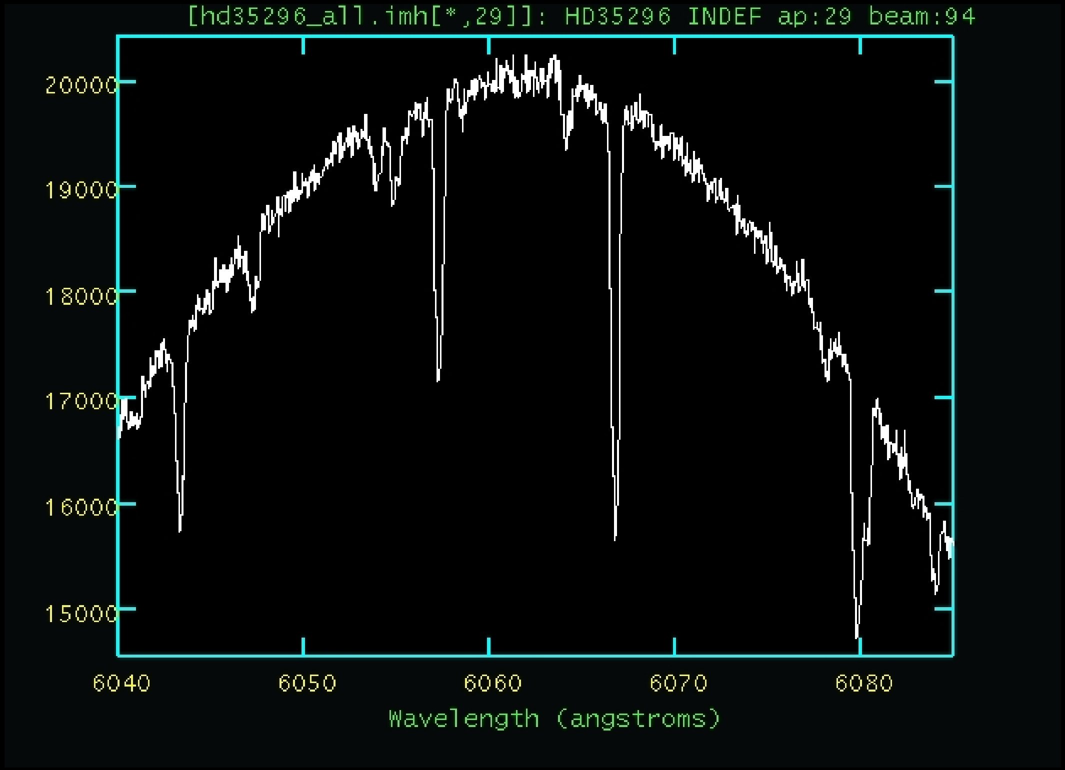
ThAr reference



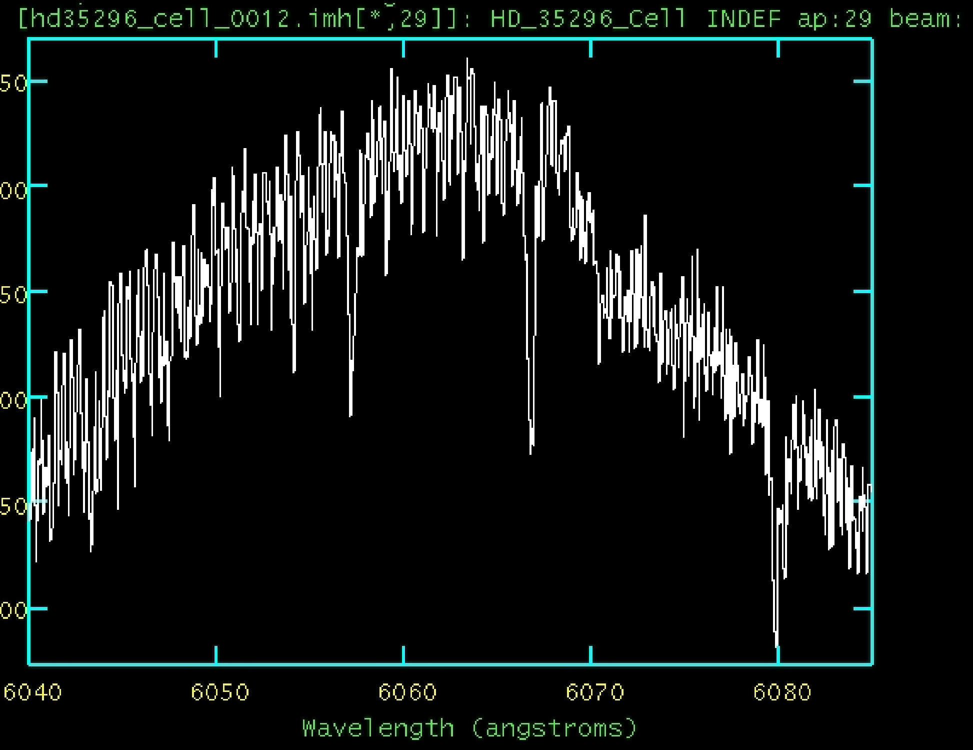




Stellar spectrum
without iodine



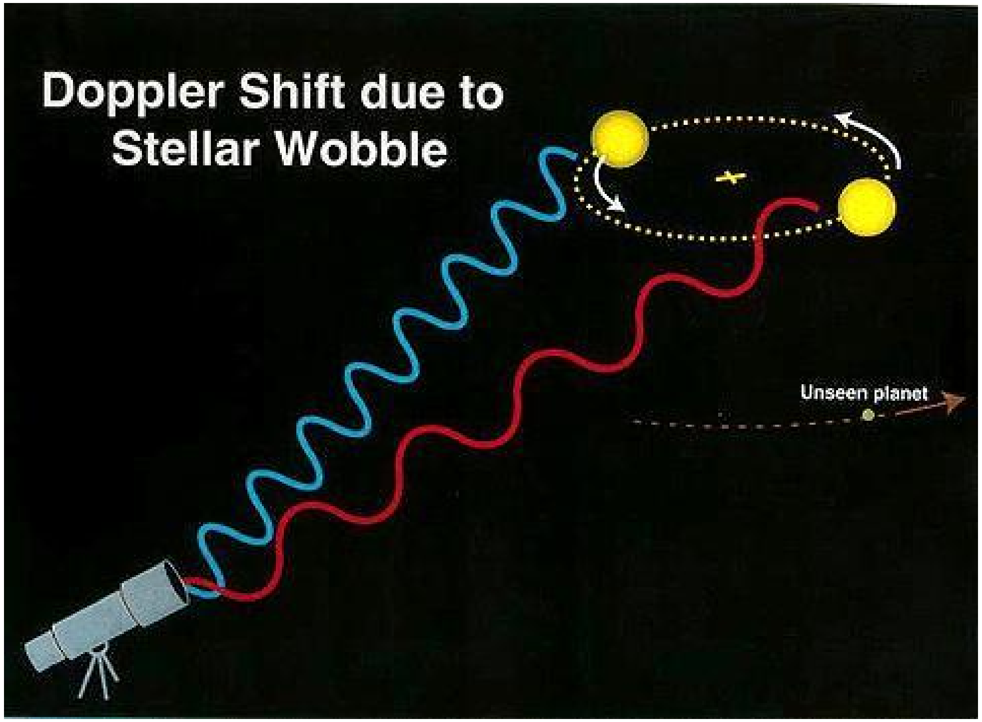
Stellar spectrum
with Iodine



HARPS: High Accuracy Radial-velocity Planet Searcher

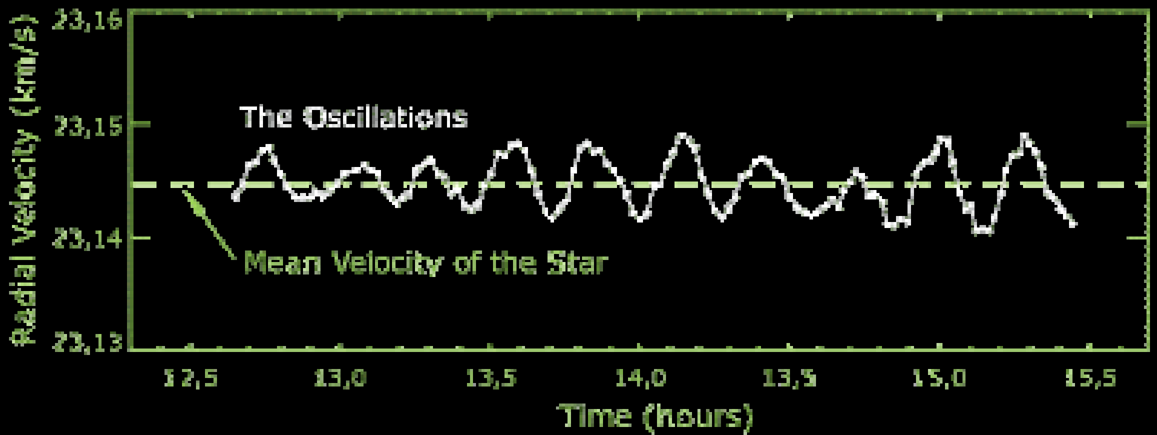
The HARPS Spectrograph and the 3.6m Telescope

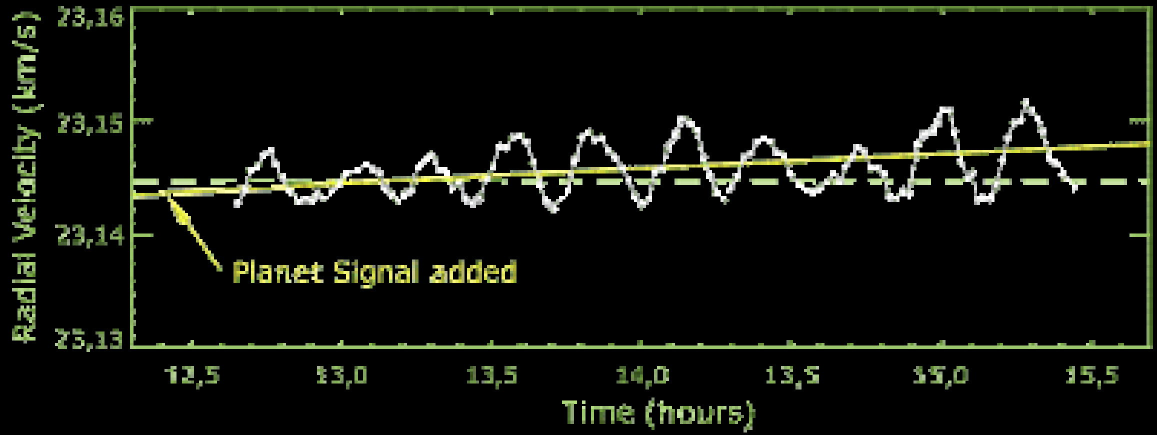
ESO PR Photo 25a/04 (25 August 2004)



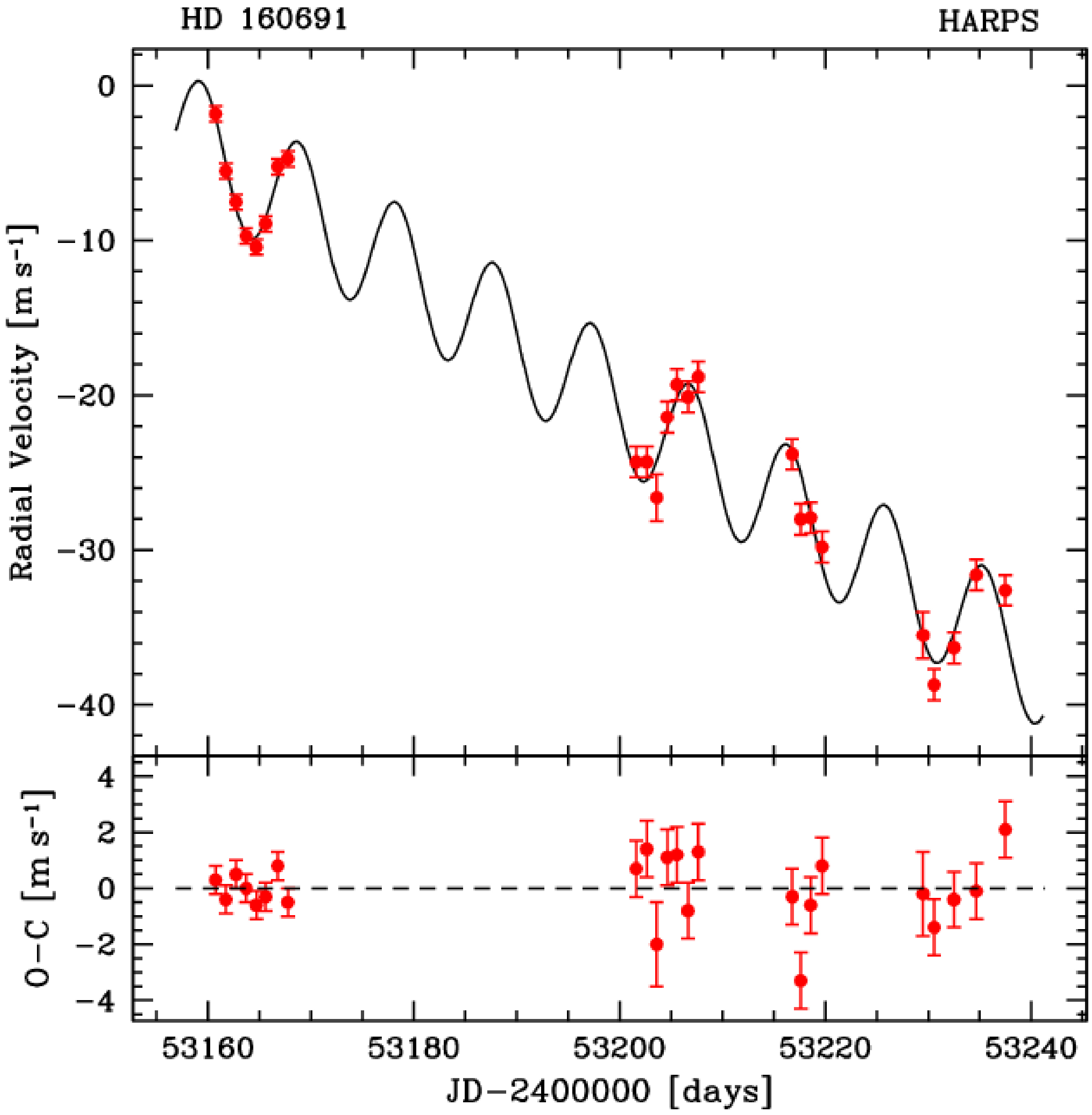
The HARPS Spectrograph and the 3.6m Telescope

ESO PR Photo 25a/04 (25 August 2004)



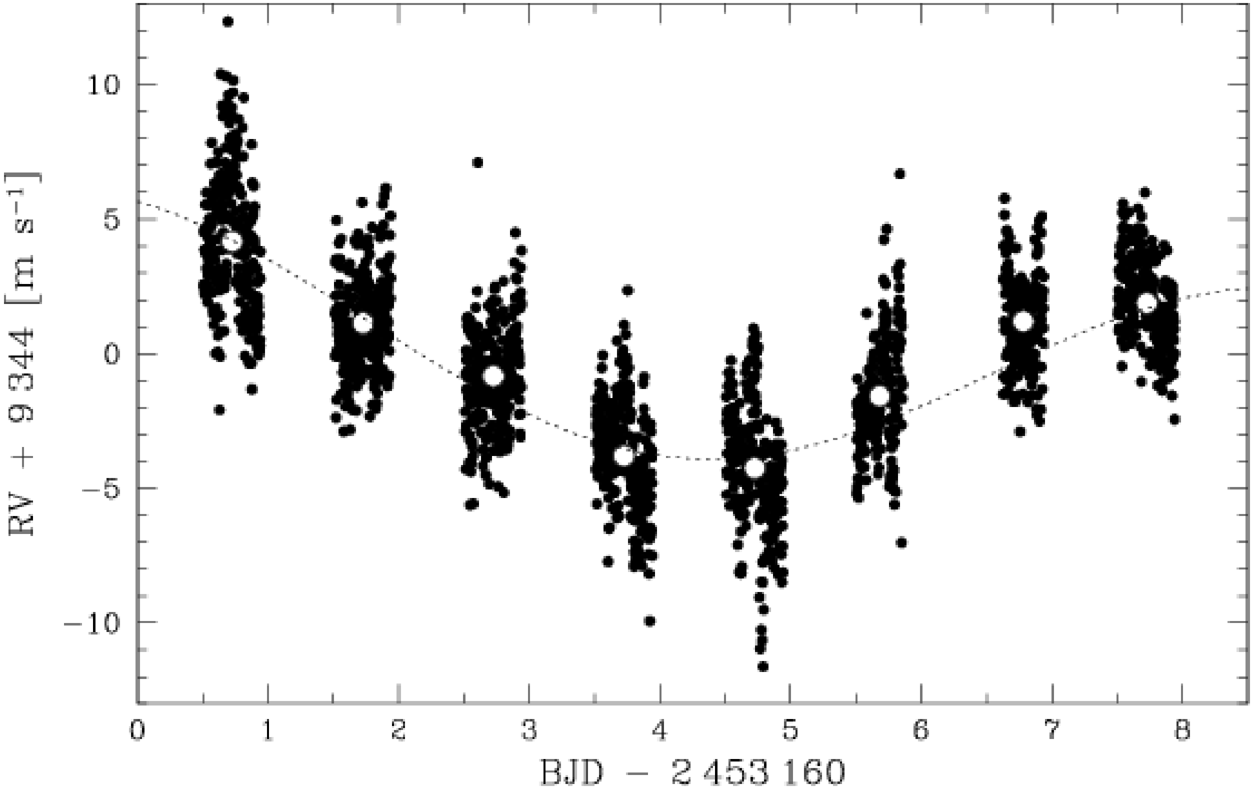


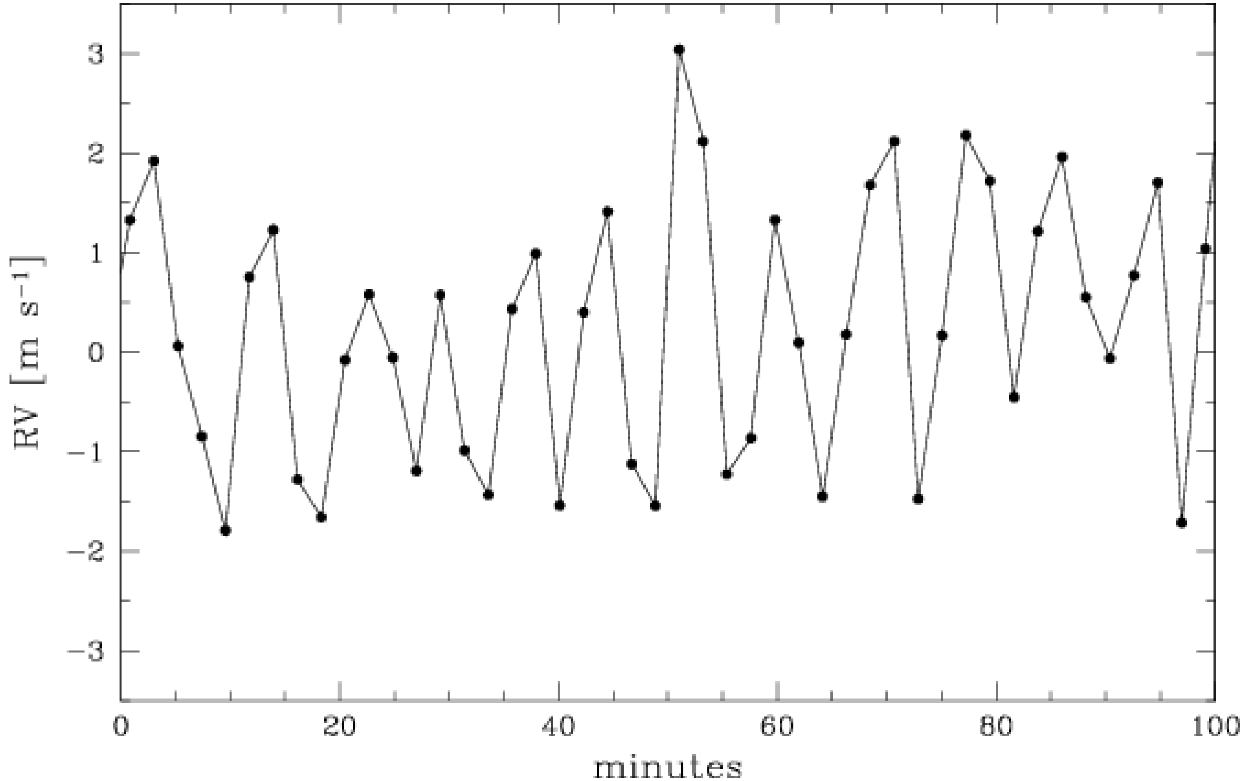
Example: μ Arae – a solar-like star with 3 planets



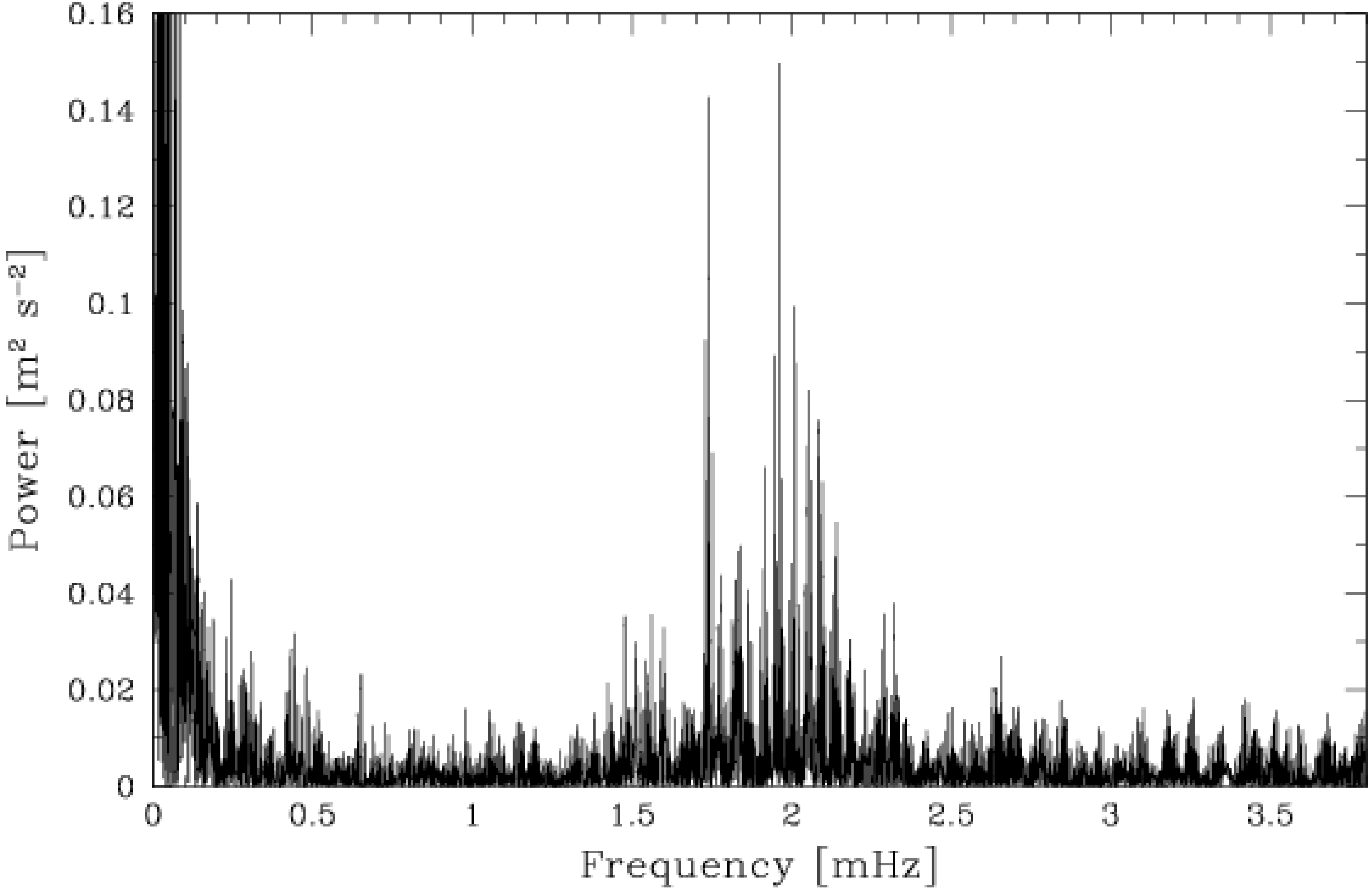
An Exo-planet found from Asteroseismic observations

$$M_{Planet} \sin(i) = 14 M_{Earth}$$

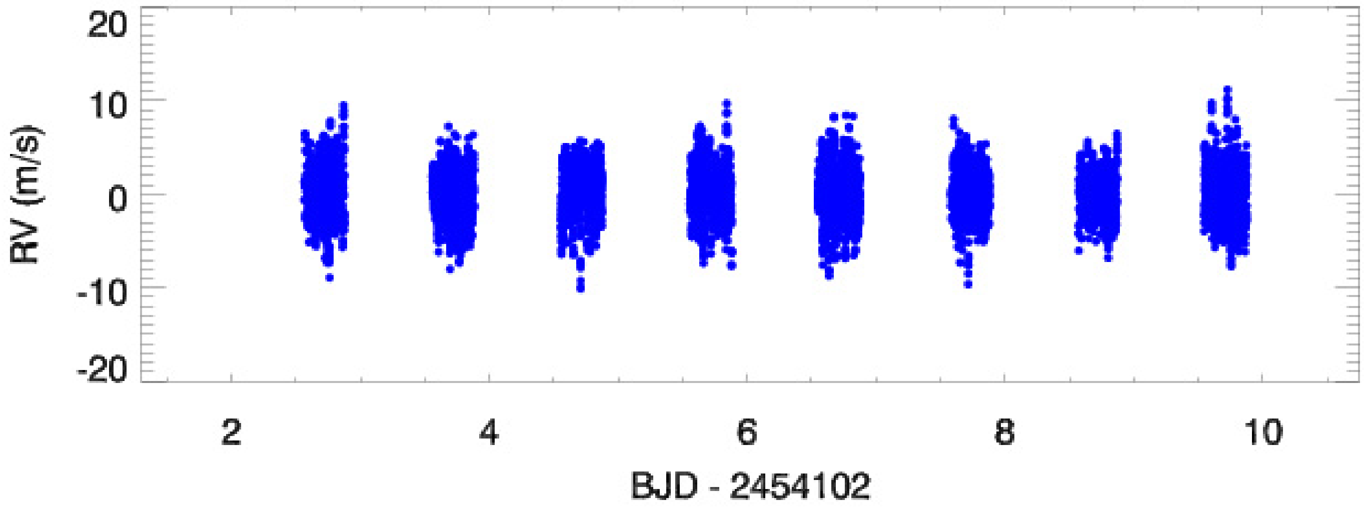


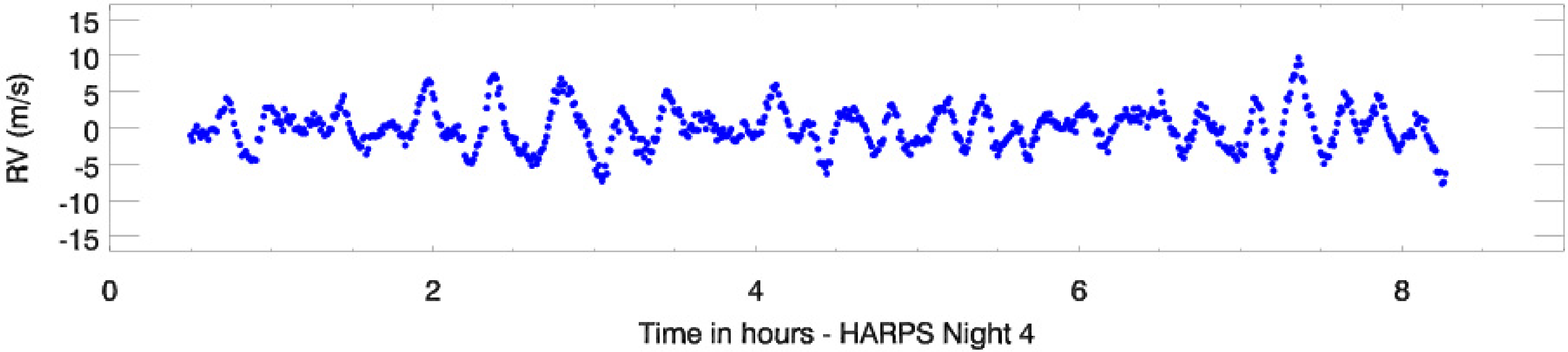


Example: μ Arae – a solar-like star with 3 planets



From Time Series to Frequencies





Calculating the Power Spectrum

- Use Discrete Fourier Transform as our observations are unequally spaced in time + will use statistical weights

- The PS can be calculated as a least-squares fit of

$$A_i \sin(\nu_i t + \varphi_i)$$

to the time-series

- See, e.g., Lomb 1975, Ap&SS 39, 447 or
  Frandsen et al. 1995, A&A 301, 123

Calculating the Power Spectrum

- A set of N observations, $(x_1, t_1), \ldots, (x_N, t_N)$
- Set up a model of the observations at each frequency ν_i

$$x_j = \alpha_i \cdot \cos(\nu_i t_j) + \beta_i \cdot \sin(\nu_i t_j)$$

Calculating the Power Spectrum

- A set of N observations, $(x_1, t_1), \ldots, (x_N, t_N)$
- Set up a model of the observations at each frequency ν_i

$$x_j = \alpha_i \cdot \cos(\nu_i t_j) + \beta_i \cdot \sin(\nu_i t_j)$$

- Minimize the Sum of Squares

$$R(\nu_i) = \sum_{j=1}^{N} \{x_j - [\alpha_i \cdot \cos(\nu_i t_j) + \beta_i \cdot \sin(\nu_i t_j)]\}^2$$

Calculating the Power Spectrum

- Then the Power Spectrum is calculated as

$$P(\nu) = A_i^2 = \alpha(\nu)^2 + \beta(\nu)^2$$

$$\alpha(\nu) = \frac{s \cdot cc - c \cdot sc}{ss \cdot cc - sc^2}$$

$$\beta(\nu) = \frac{c \cdot ss - s \cdot sc}{ss \cdot cc - sc^2}$$

$$s = \sum_{j=1}^{N} x_j \sin(\nu_i t_j)$$

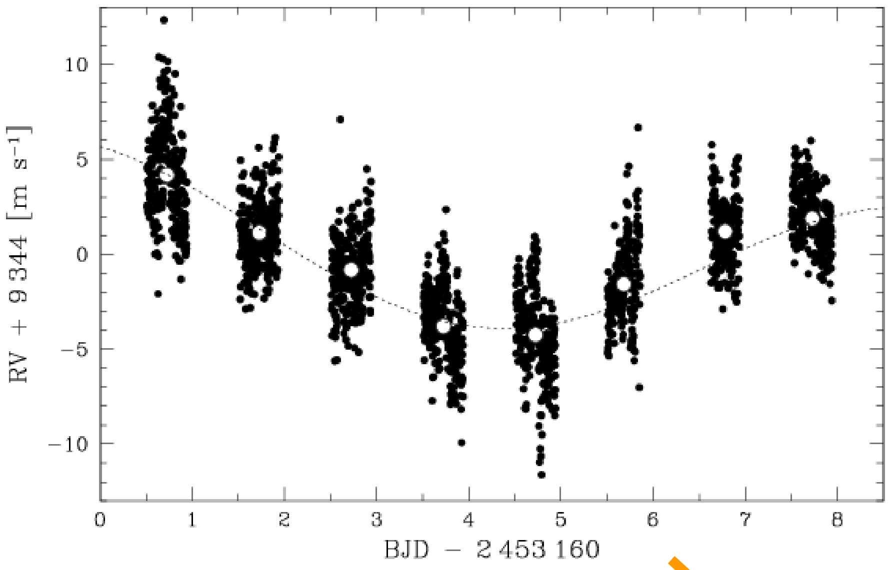
$$c = \sum_{j=1}^{N} x_j \cos(\nu_i t_j)$$

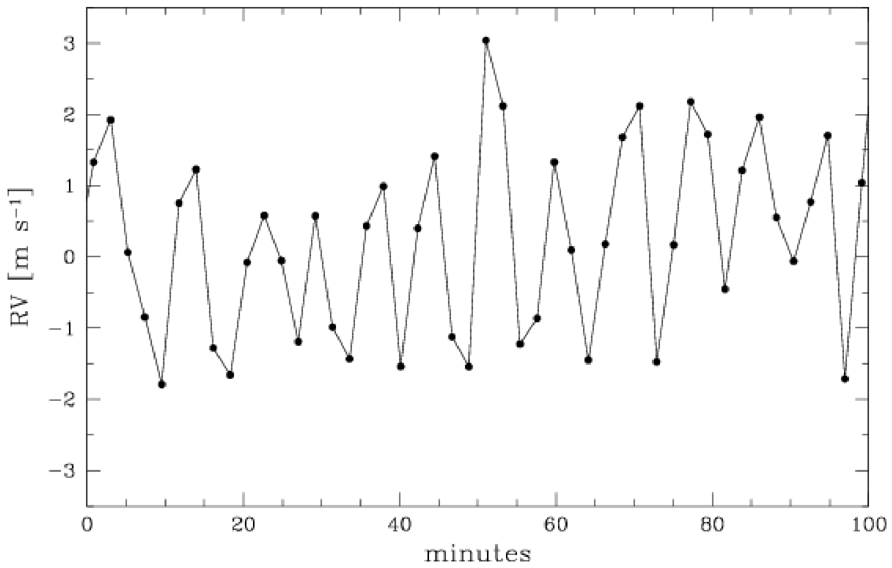
$$ss = \sum_{j=1}^{N} \sin^2(\nu_i t_j)$$

$$cc = \sum_{j=1}^{N} \cos^2(\nu_i t_j)$$

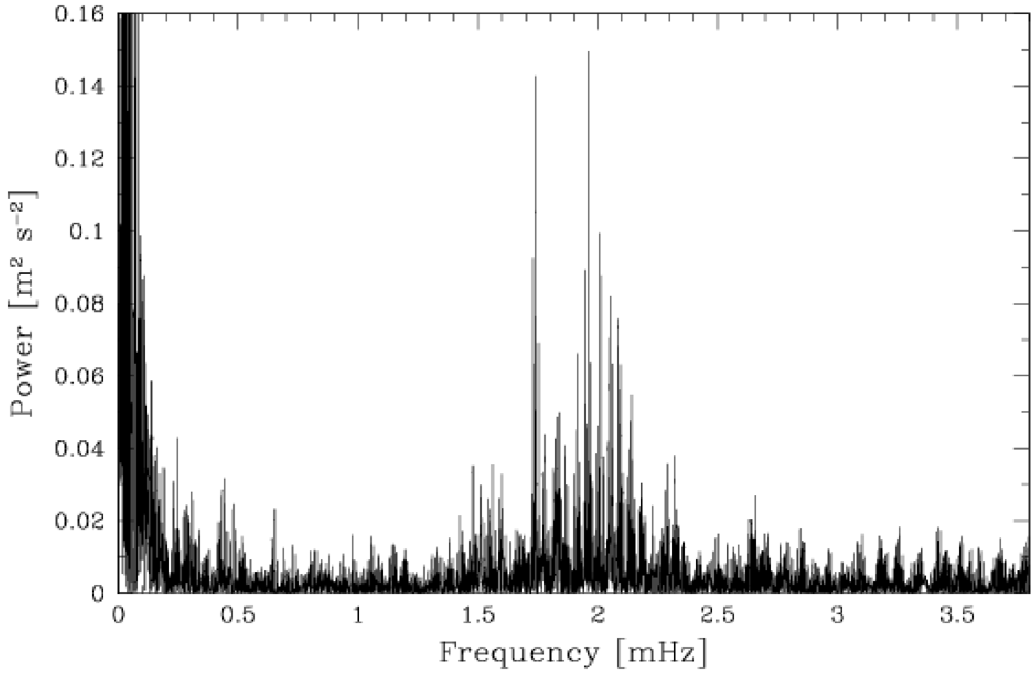
$$sc = \sum_{j=1}^{N} \sin(\nu_i t_j) \cdot \cos(\nu_i t_j)$$

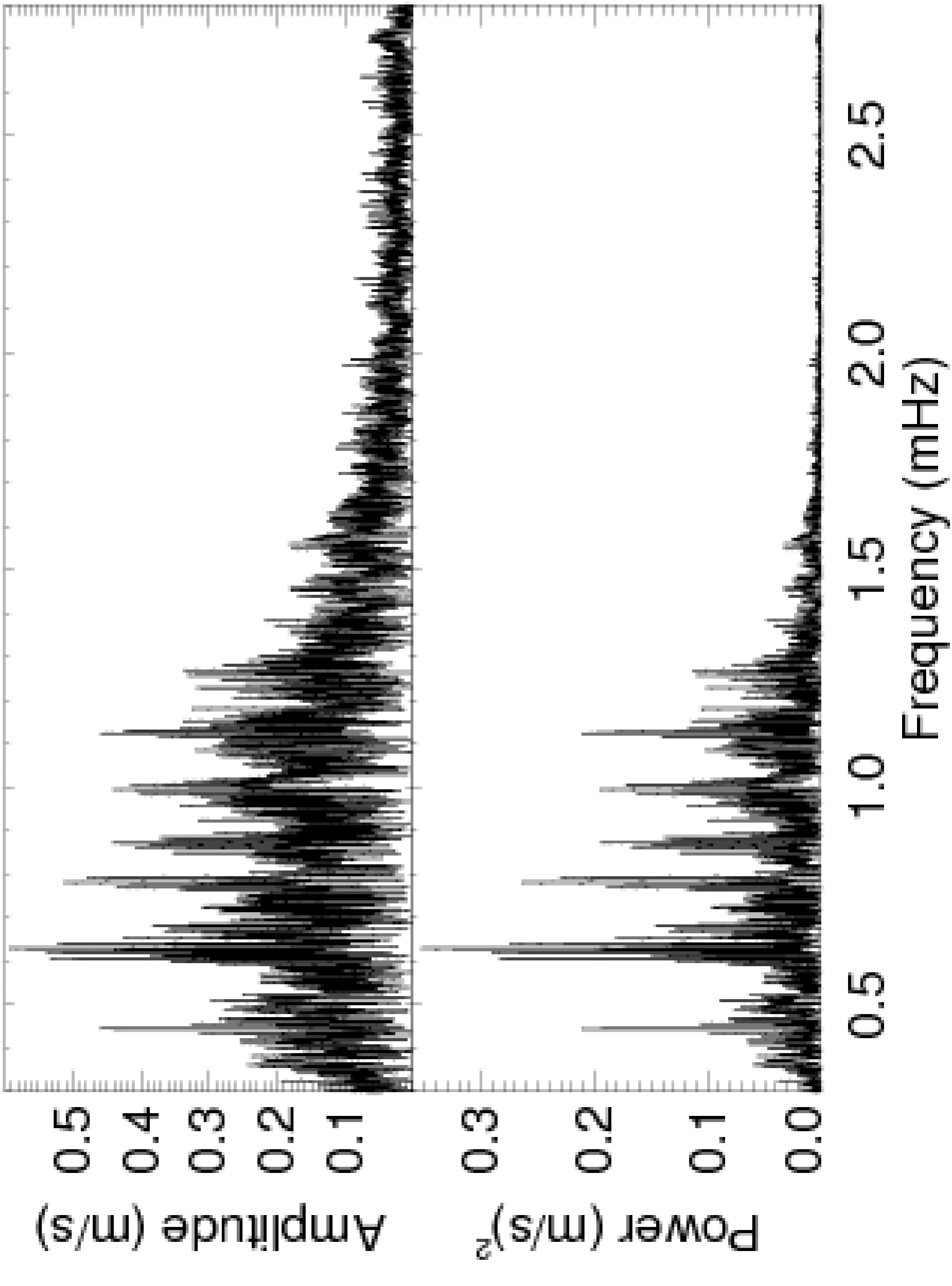
See e.g., Frandsen et al. 1995, A&A 301, 123

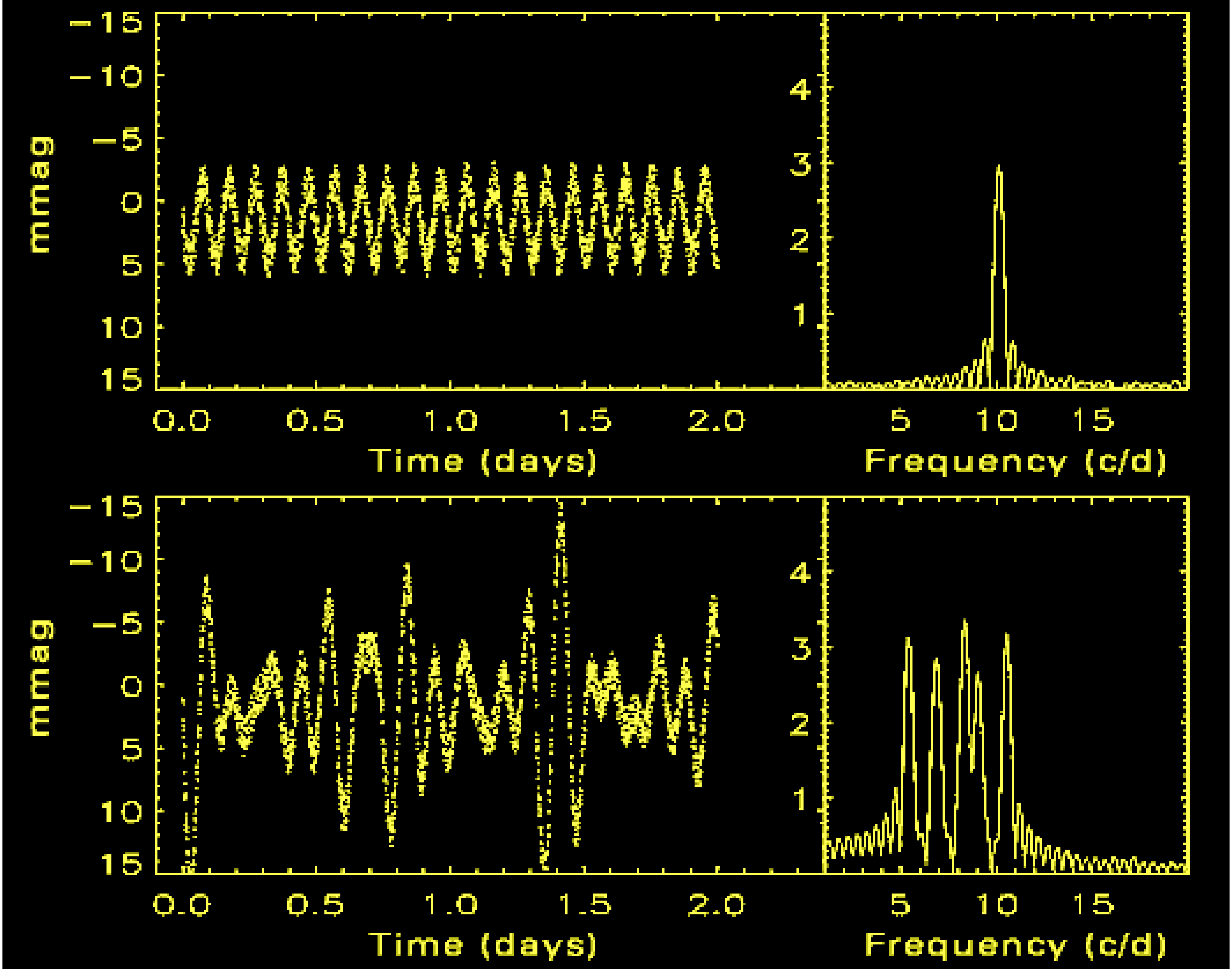

RV + 9 344 [m s^{-1}]
10
5
0
−5
−10
0
1
2
3
4
5
6
7
8
BJD − 2 453 160

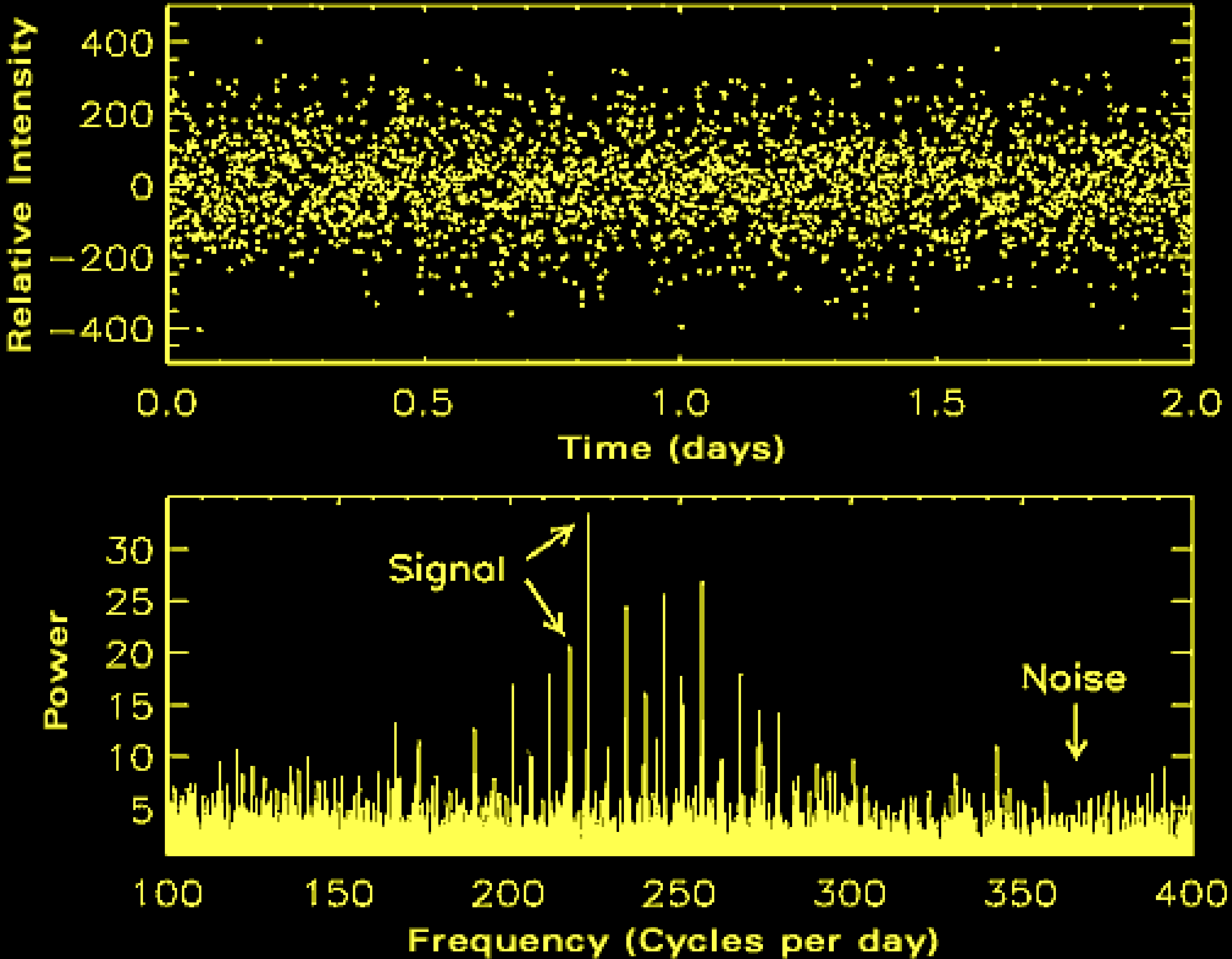

RV [m s^{-1}]
3
2
1
0
−1
−2
−3
0
20
40
60
80
100
minutes

DFT


Power [m² s^{-2}]
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
3.5
Frequency [mHz]


Amplitude (m/s)
0.5
0.4
0.3
0.2
0.1
Power (m/s)^2
0.3
0.2
0.1
0.0
0.5
1.0
1.5
2.0
2.5
Frequency (mHz)


mmag
−15
−10
−5
0
5
10
15
0.0
0.5
1.0
1.5
2.0
Time (days)
4
3
2
1
5
10
15
Frequency (c/d)
mmag
−15
−10
−5
0
5
10
15
0.0
0.5
1.0
1.5
2.0
Time (days)
4
3
2
1
5
10
15
Frequency (c/d)

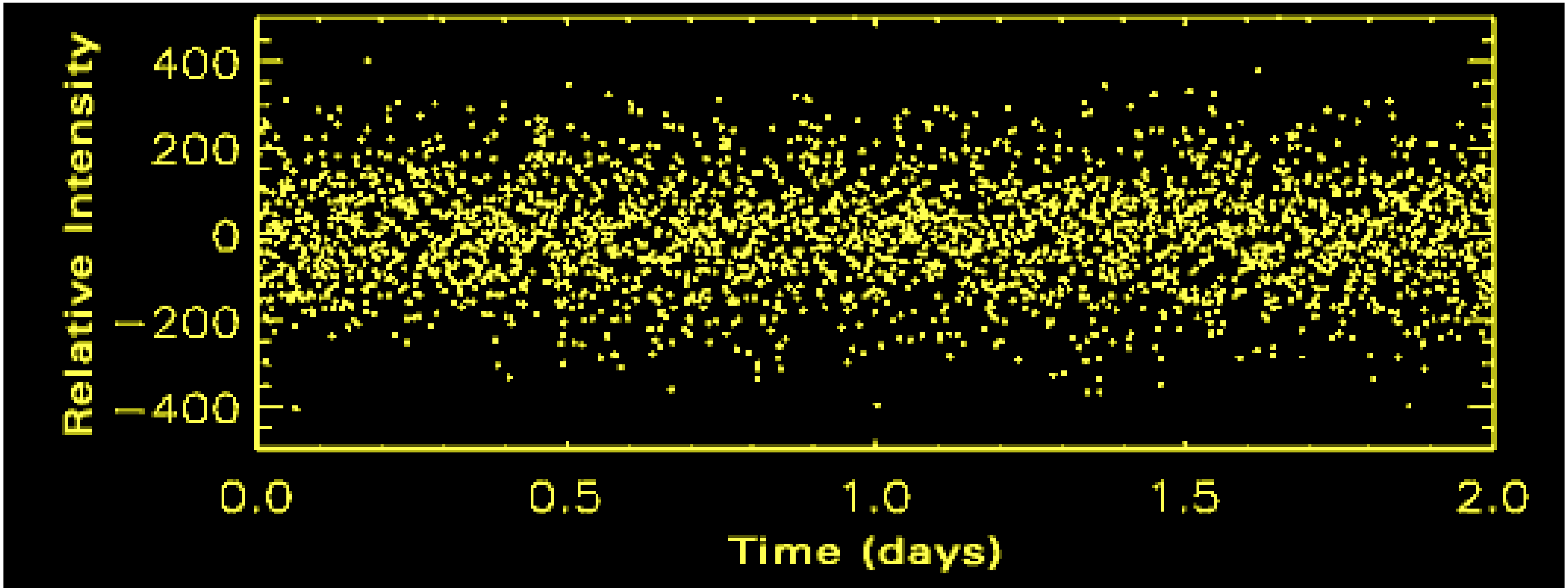

Relative Intensity
400
200
0
−200
−400
0.0
0.5
1.0
1.5
2.0
Time (days)
Power
30
25
20
15
10
5
Signal
Noise
100
150
200
250
300
350
400
Frequency (Cycles per day)

White noise

See, e.g., Kjeldsen & Frandsen
1992, PASP 104, 413

- White noise is frequency independent noise

$$\sigma_{PS} = \frac{4}{N}\sigma_{TimeSeries}^2 \qquad \sigma_{amp} = \sqrt{\frac{\pi}{N}}\cdot\sigma_{TimeSeries}$$

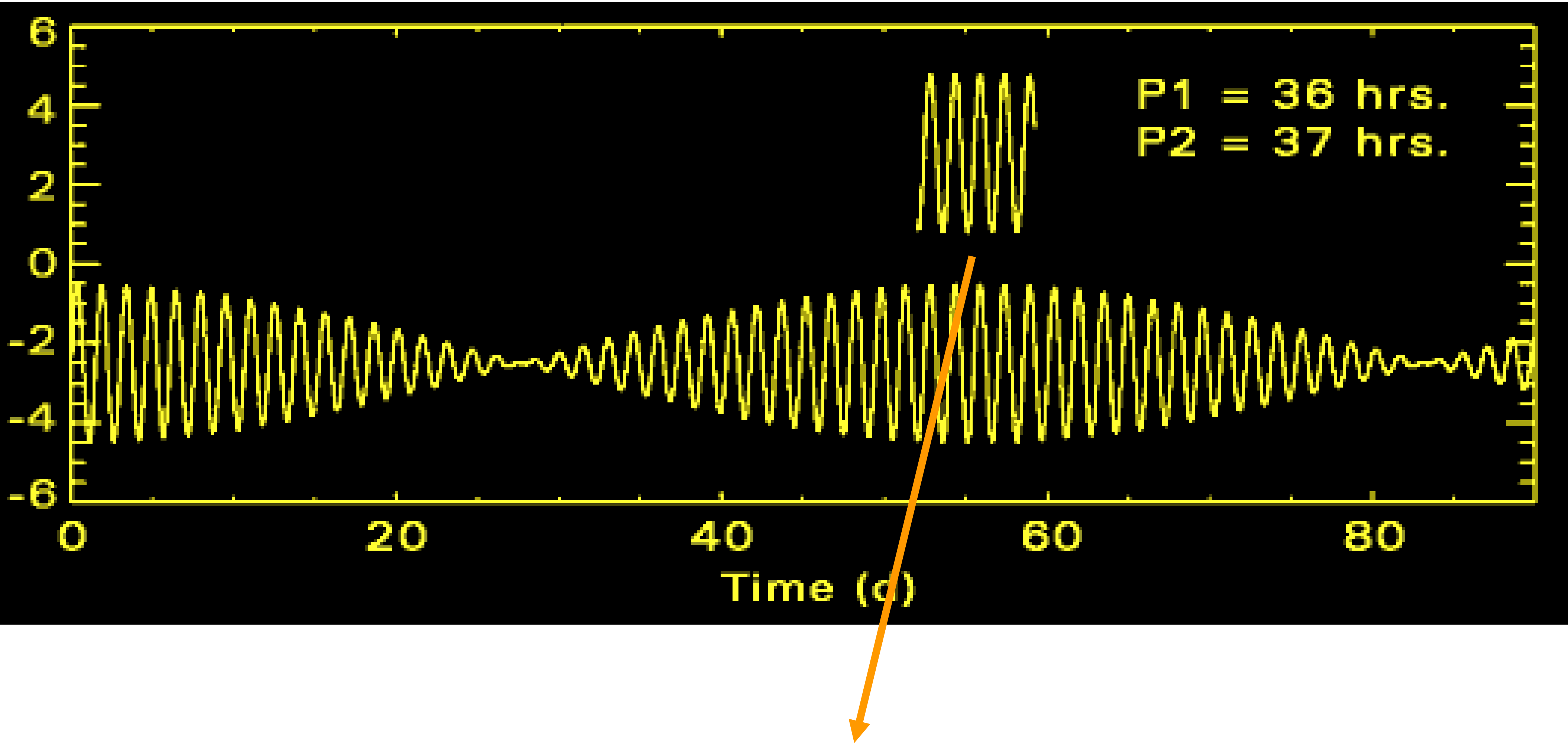


Resolution and The Nykvist Frequency

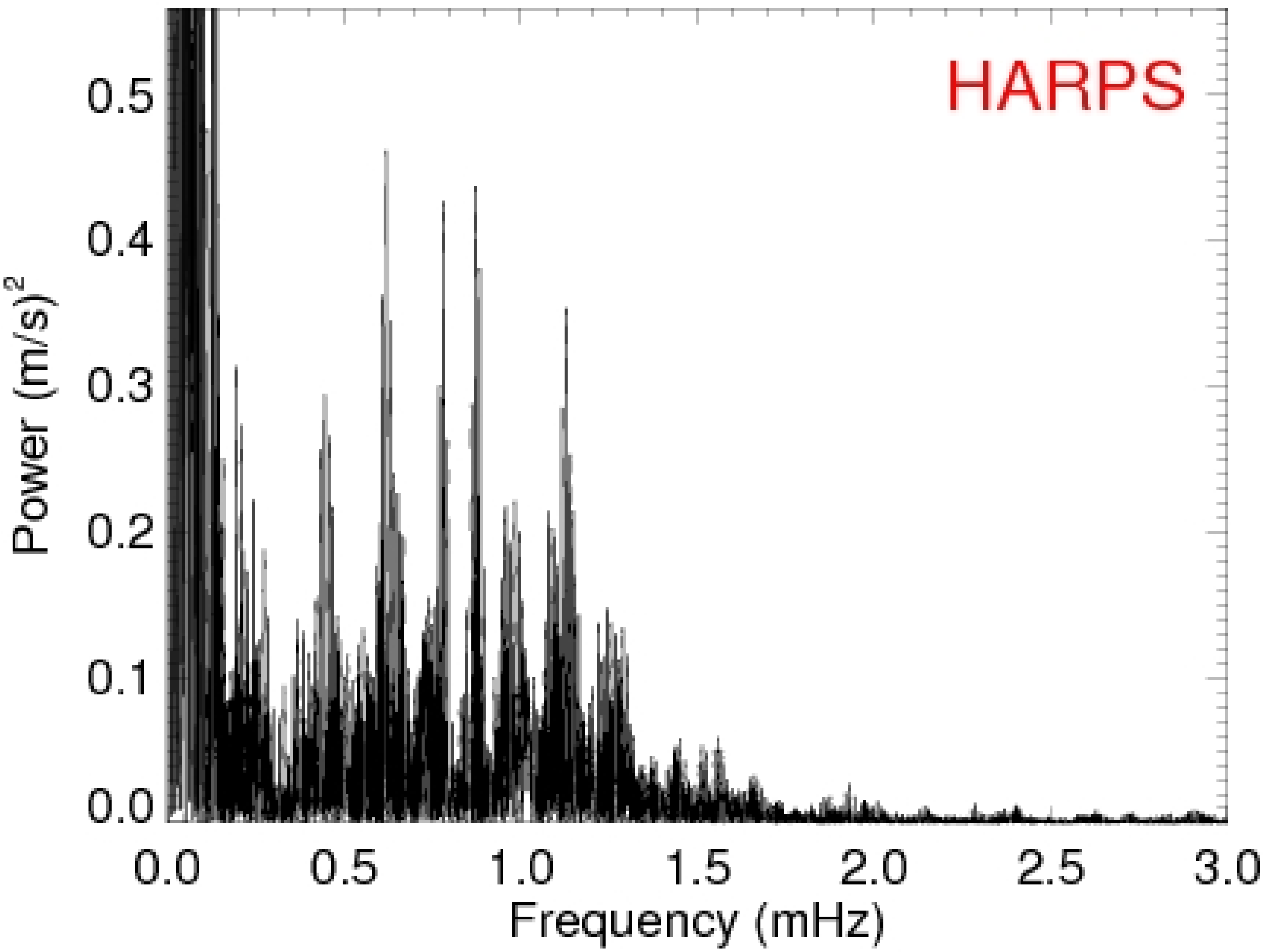
- The Frequency Resoluton: $\Delta f \approx \frac{1.5}{\Delta T}$
  (Loumos and Deeming 1978)

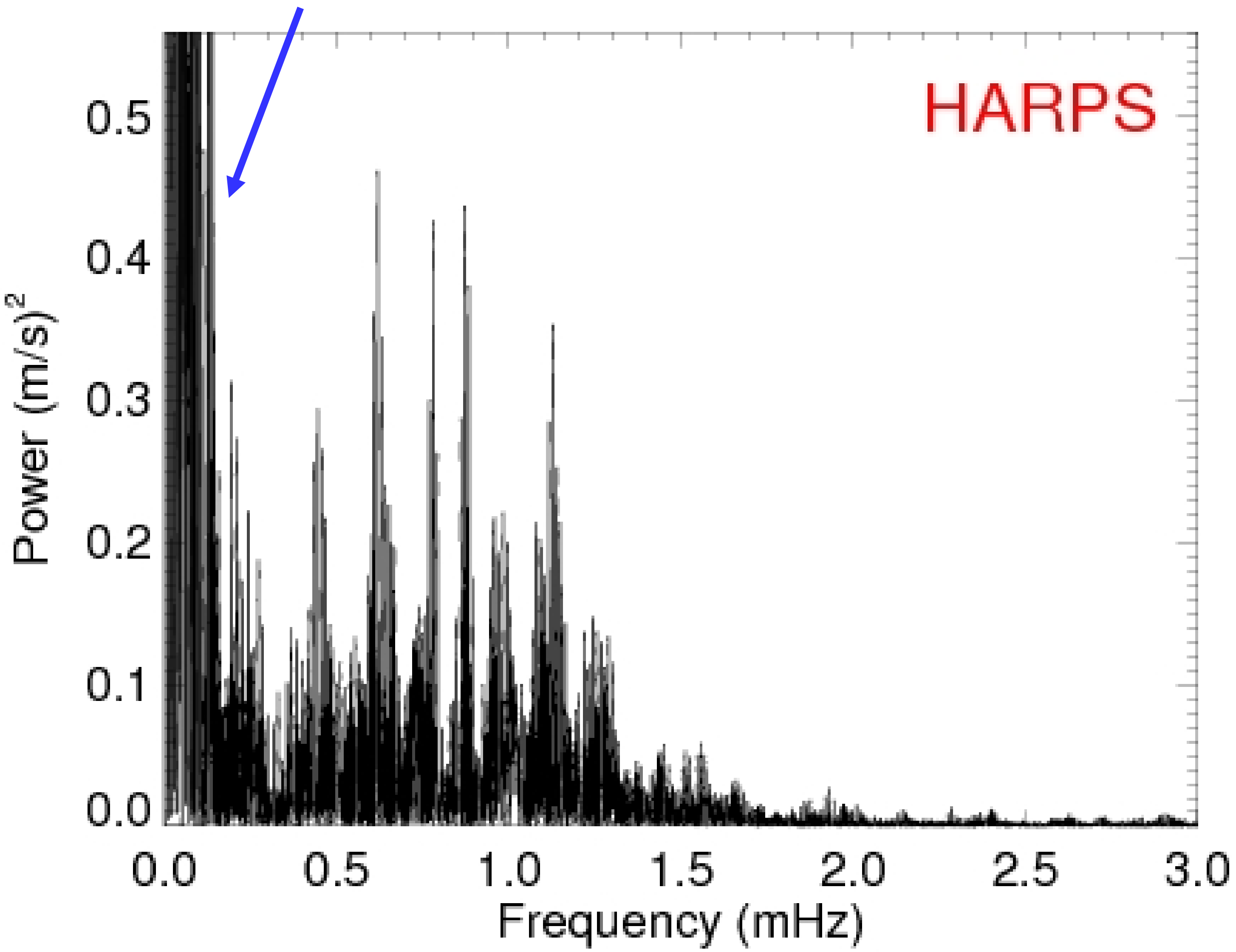
- The Nyquist Frequency: $f_c \approx \frac{1}{2\Delta t}$
  - The upper limit for meaningful frequency detections

The observations have to be sufficiently long in order to cover Beat Periods:

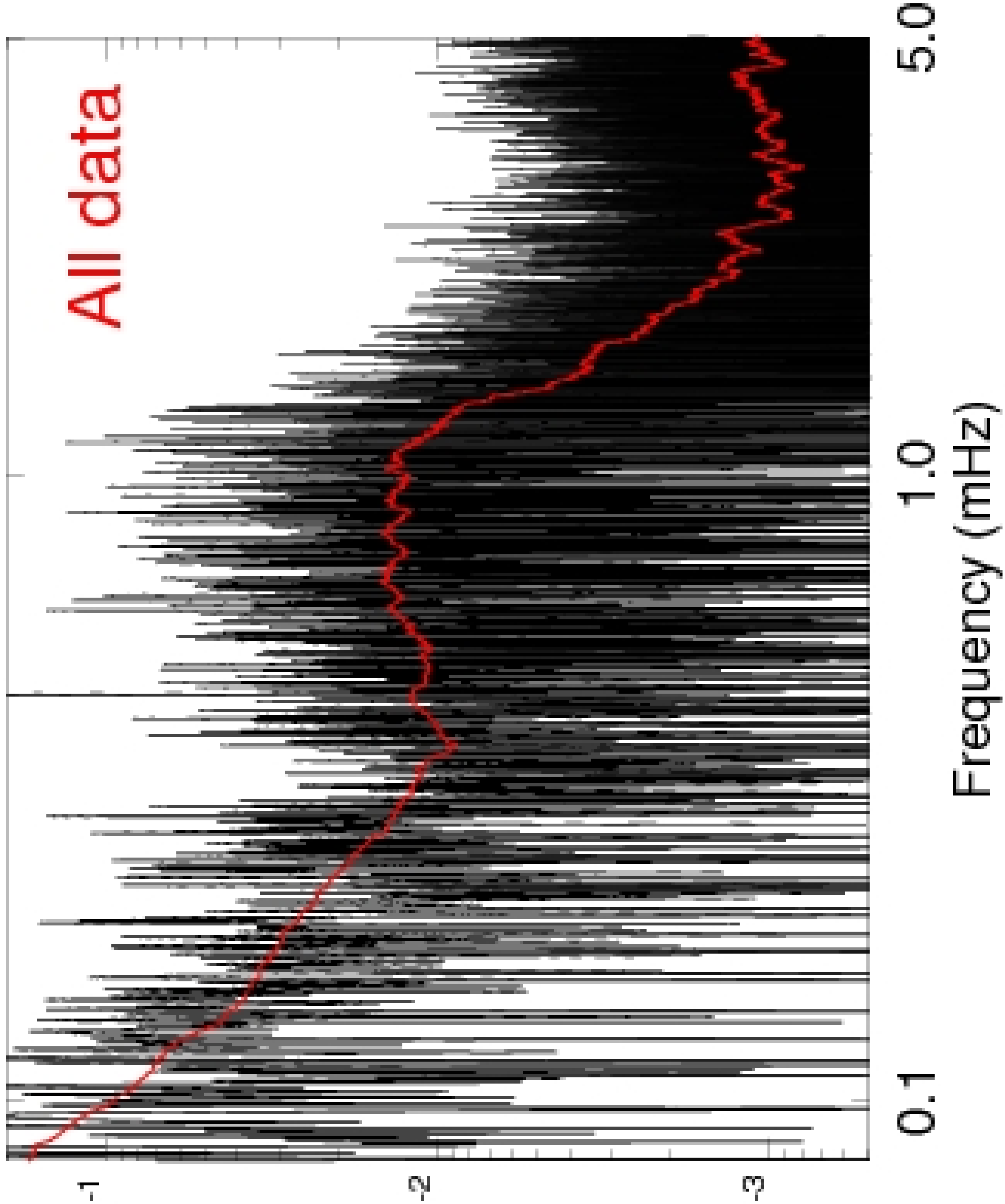


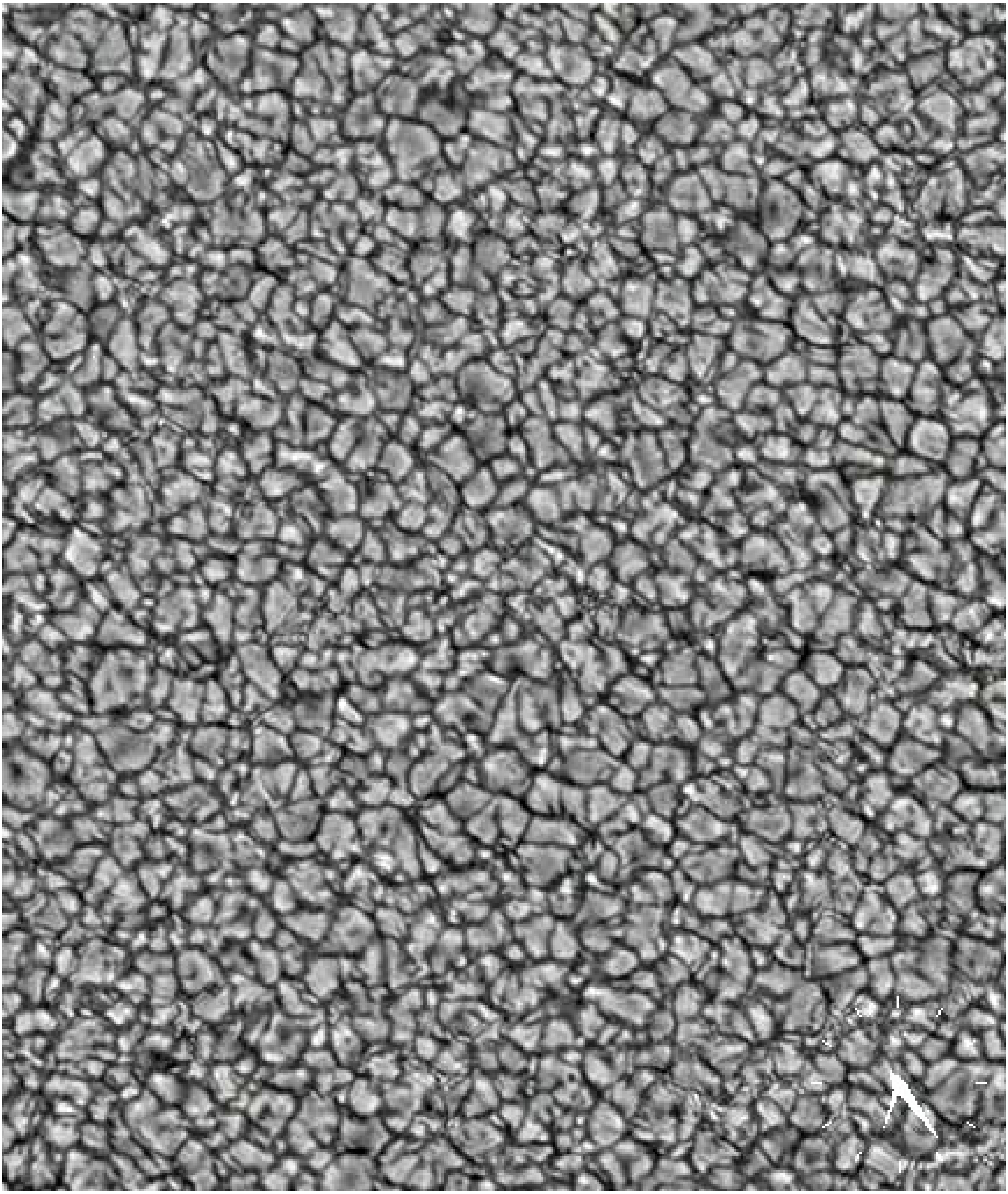
Not even Fourier would help us here…

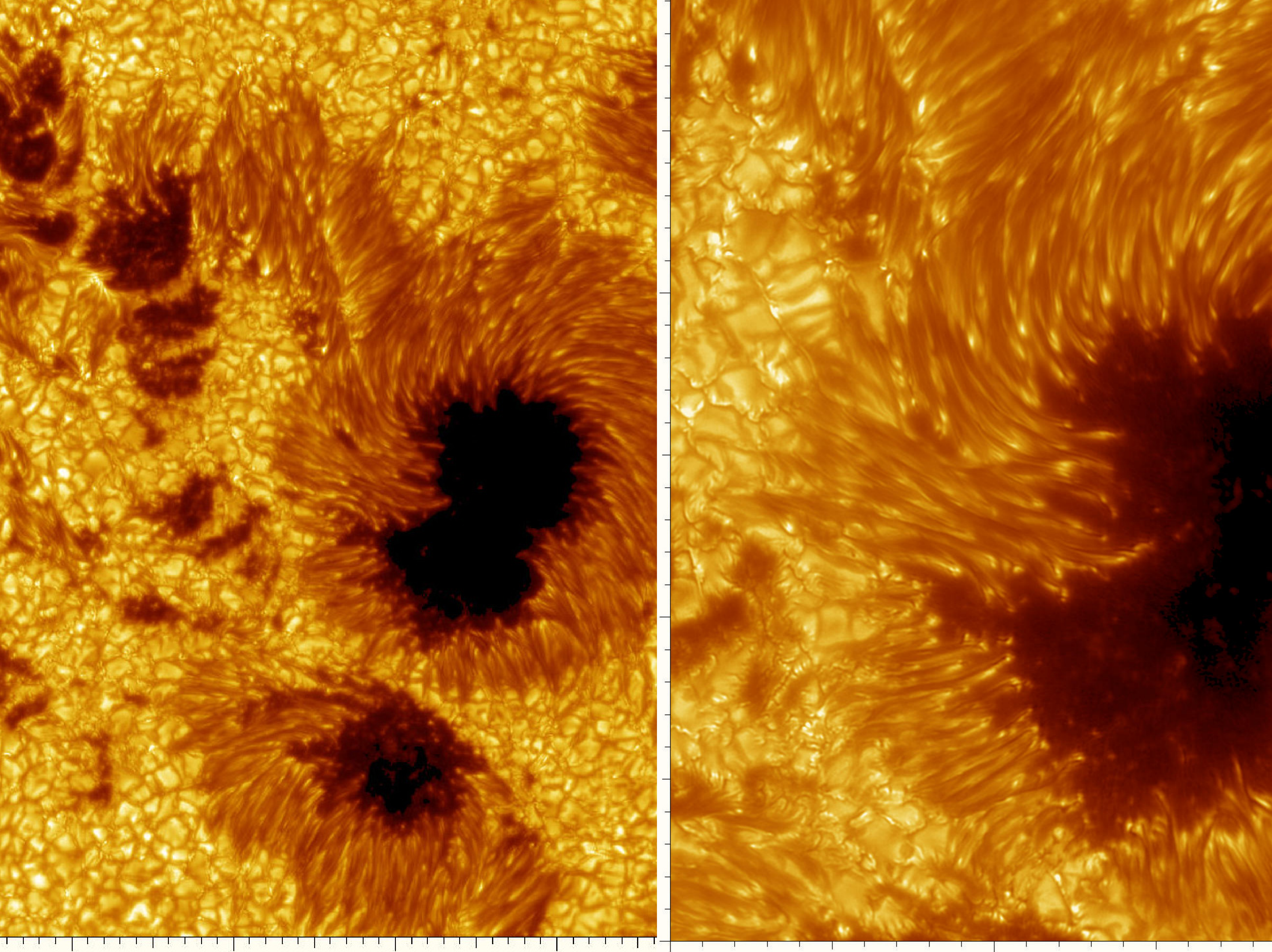

HARPS
Power (m/s)^2
0.0
0.1
0.2
0.3
0.4
0.5
Frequency (mHz)
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Not planets

HARPS
Power (m/s)^2
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Frequency (mHz)

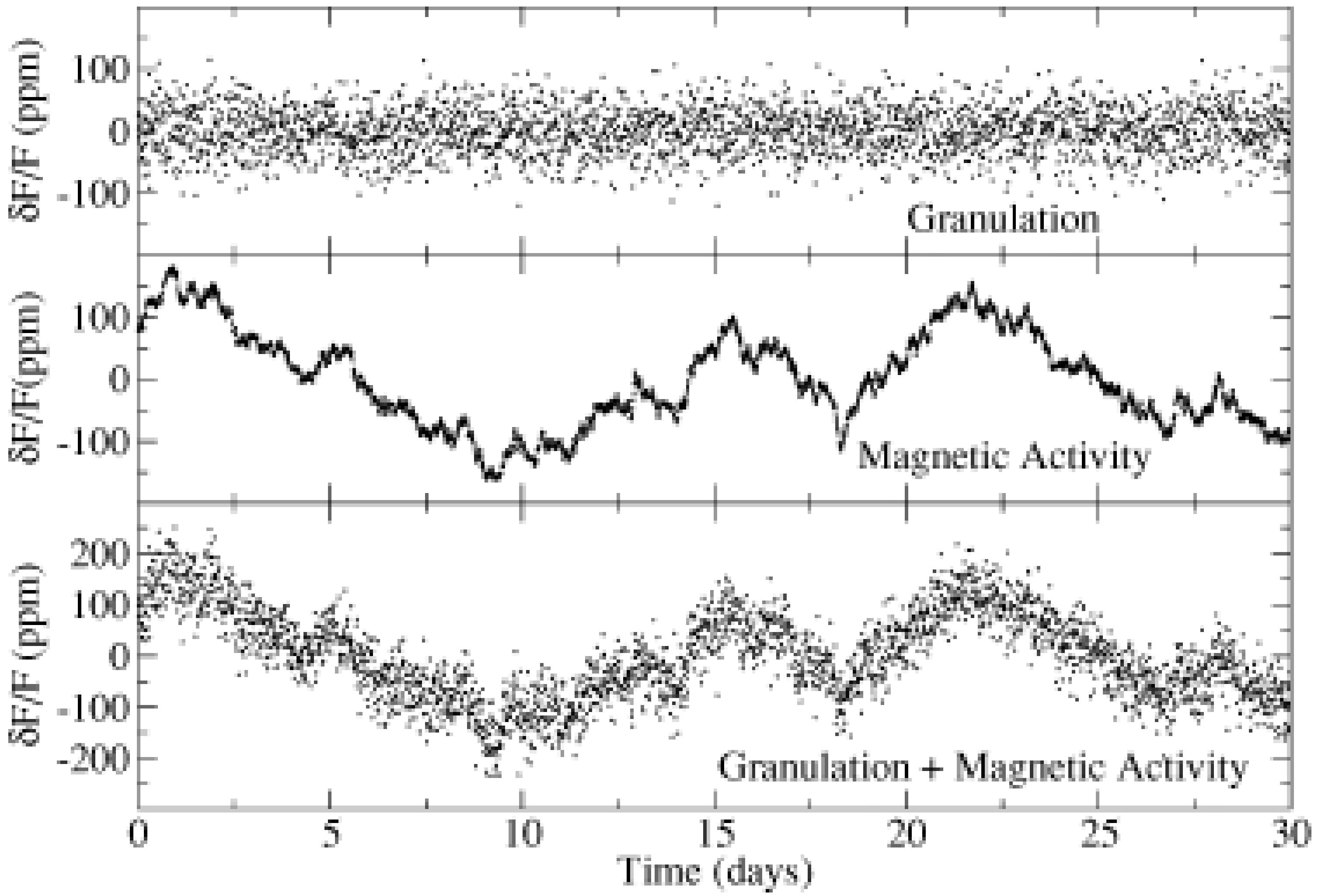

All data
Power (m/s)^2
10^{-1}
10^{-2}
10^{-3}
0.1
1.0
5.0
Frequency (mHz)

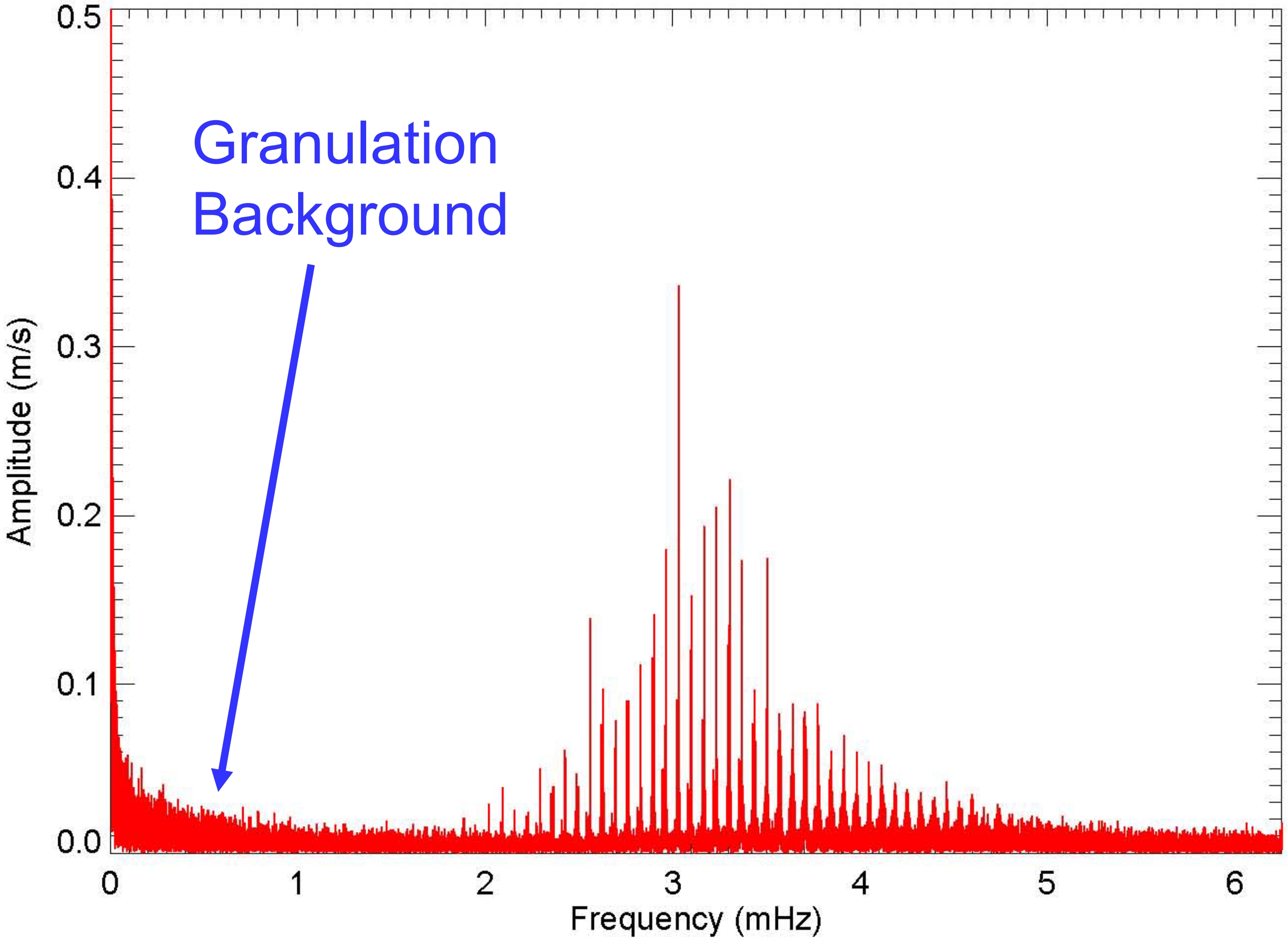


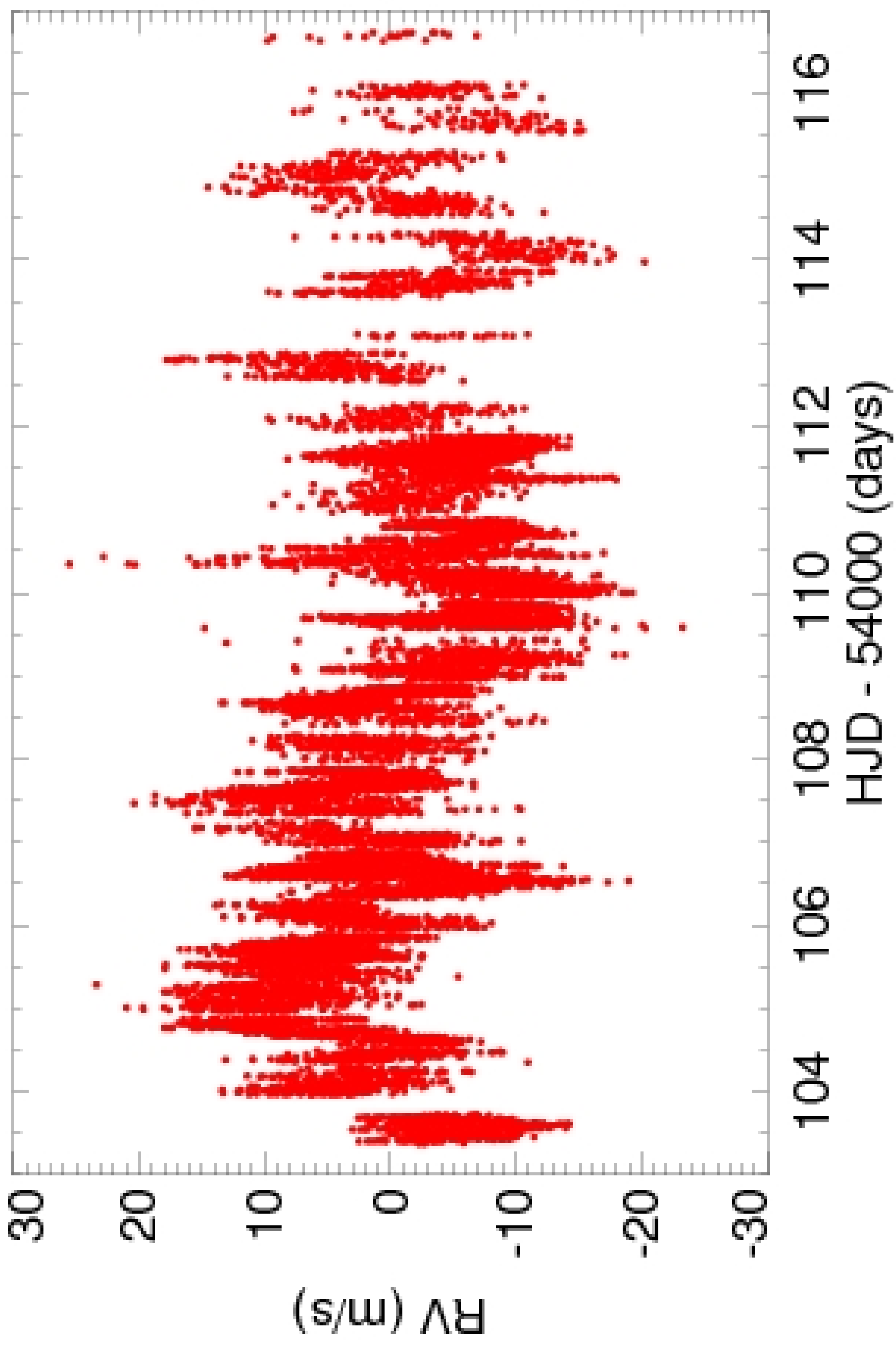


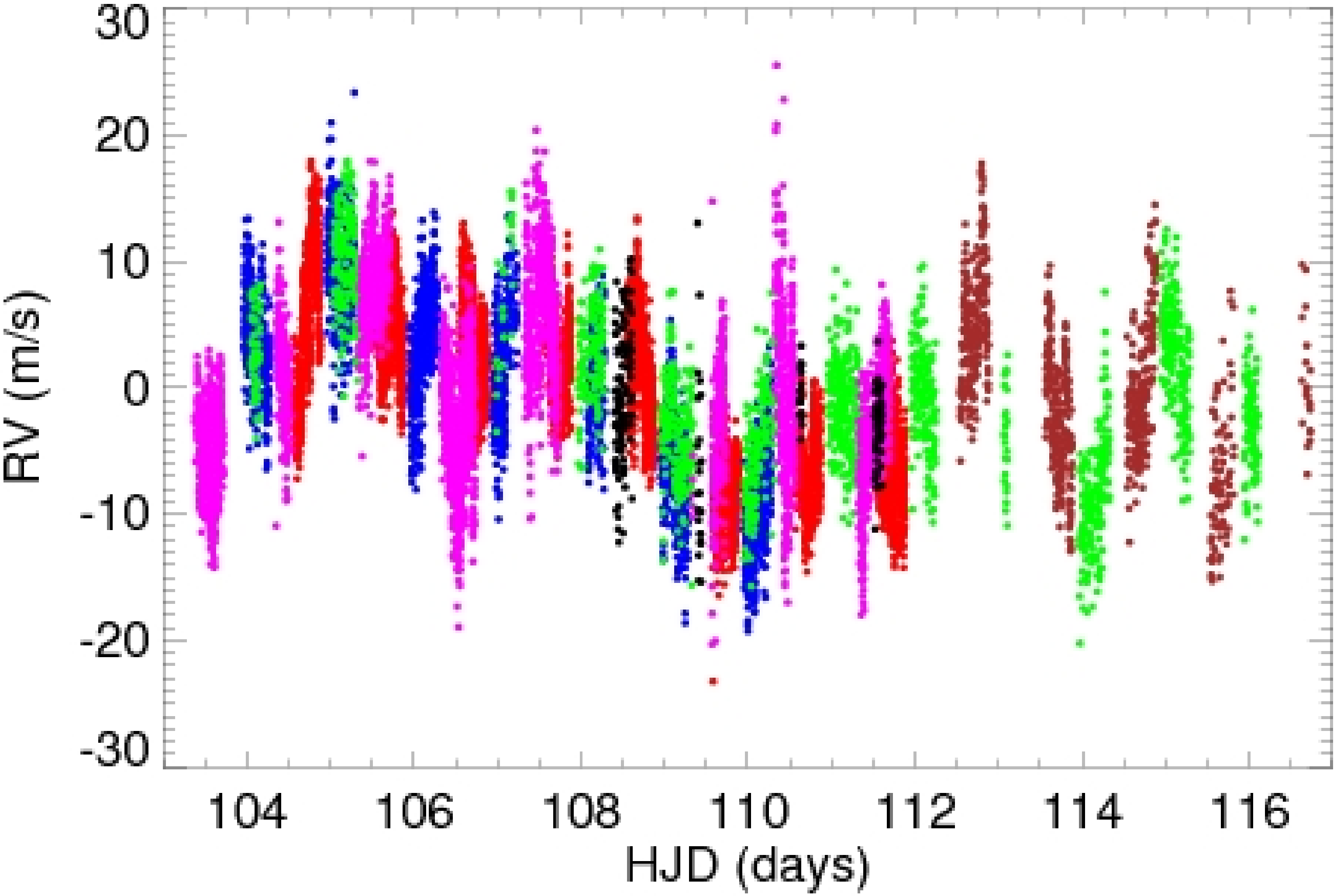
Non-white (red) noise

- Frequency dependent noise: Instrumental + Stellar Noise



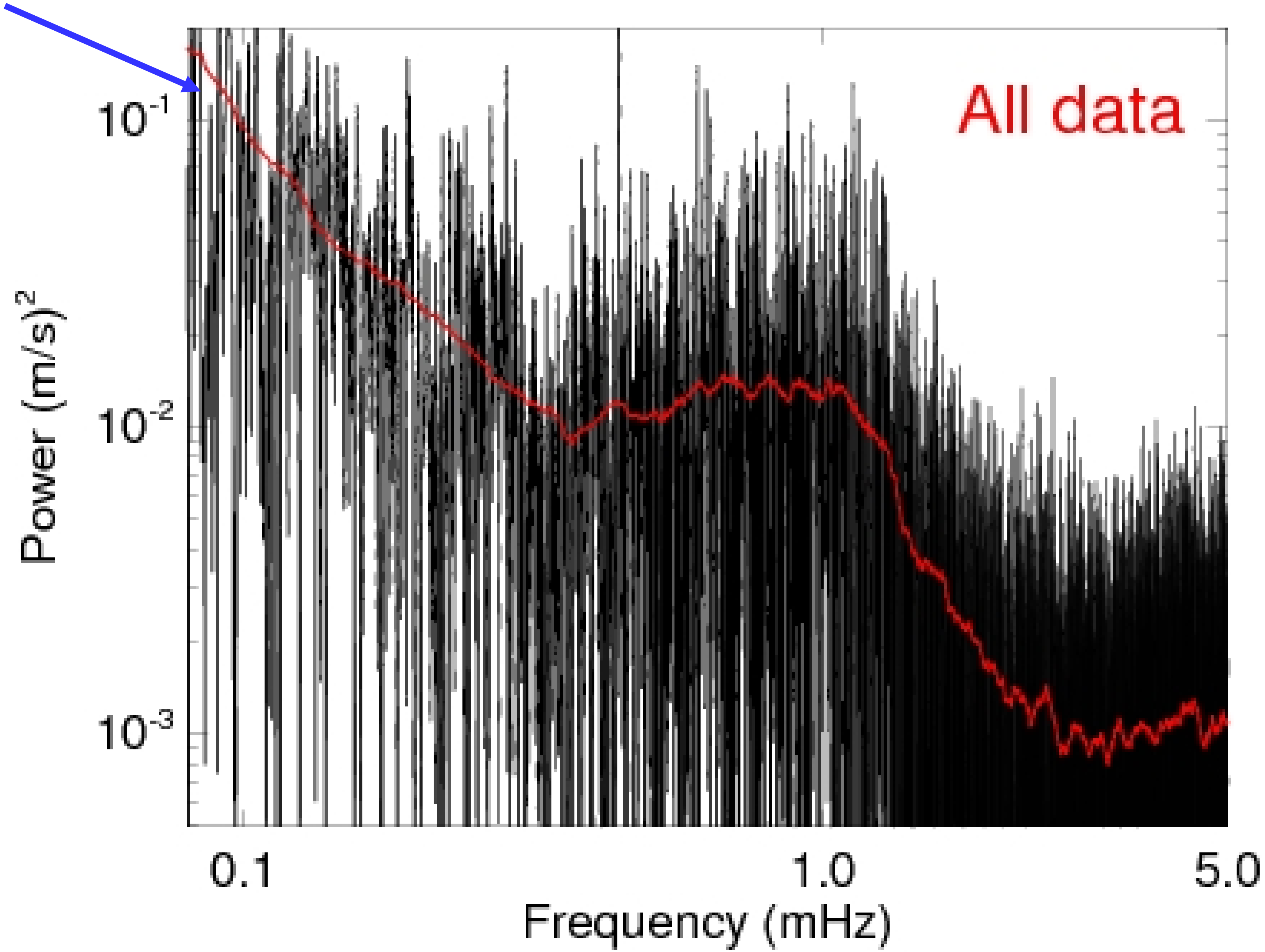

Granulation
Background
0.5
0.4
0.3
0.2
0.1
0.0
Amplitude (m/s)
0
1
2
3
4
5
6
Frequency (mHz)


RV (m/s)
HJD - 54000 (days)
30
20
10
0
-10
-20
-30
104
106
108
110
112
114
116



30
20
10
0
-10
-20
-30
RV (m/s)
104
106
108
110
112
114
116
HJD (days)

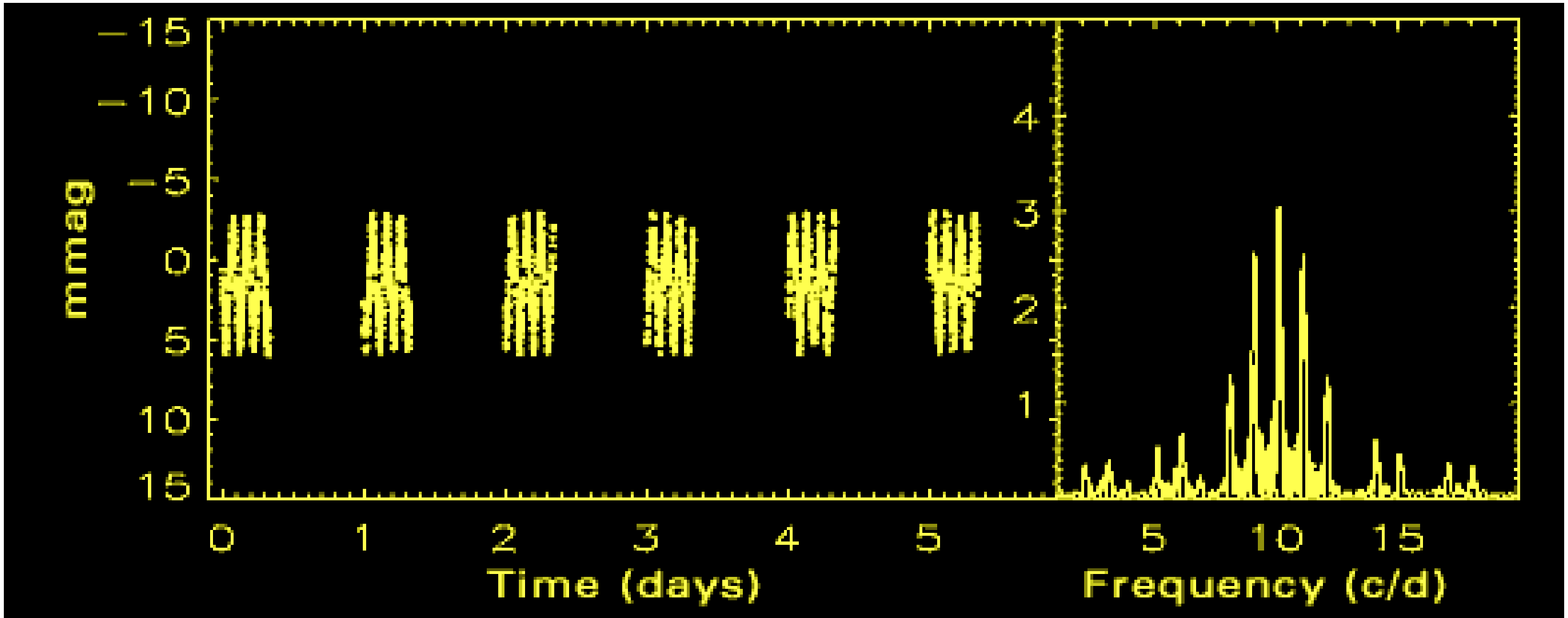
Activity *Noise* – similar to the Sun



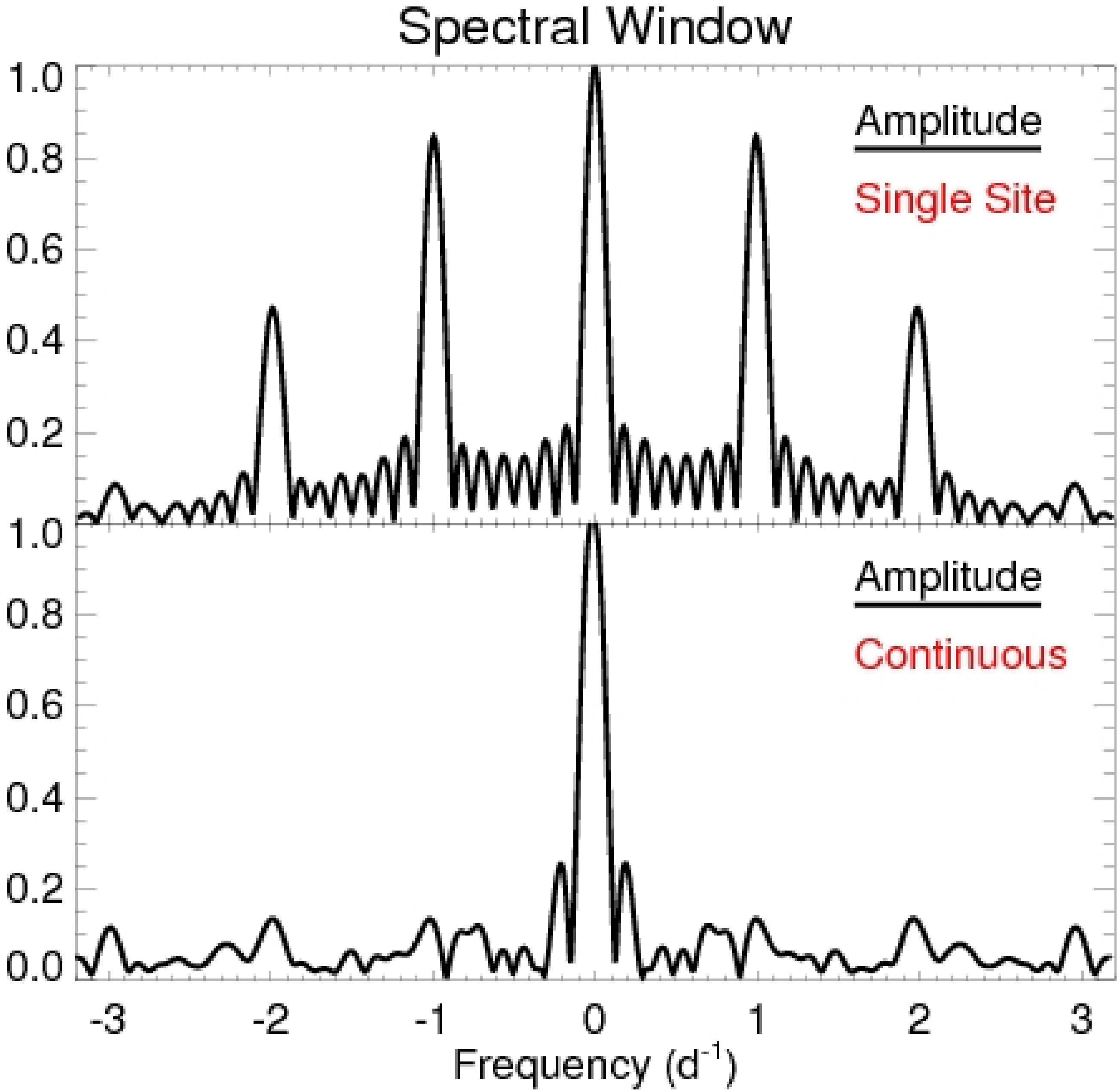
The Spectral Window Function

- Comes into play if the observations are non-continuous (e.g., from a single observing site)

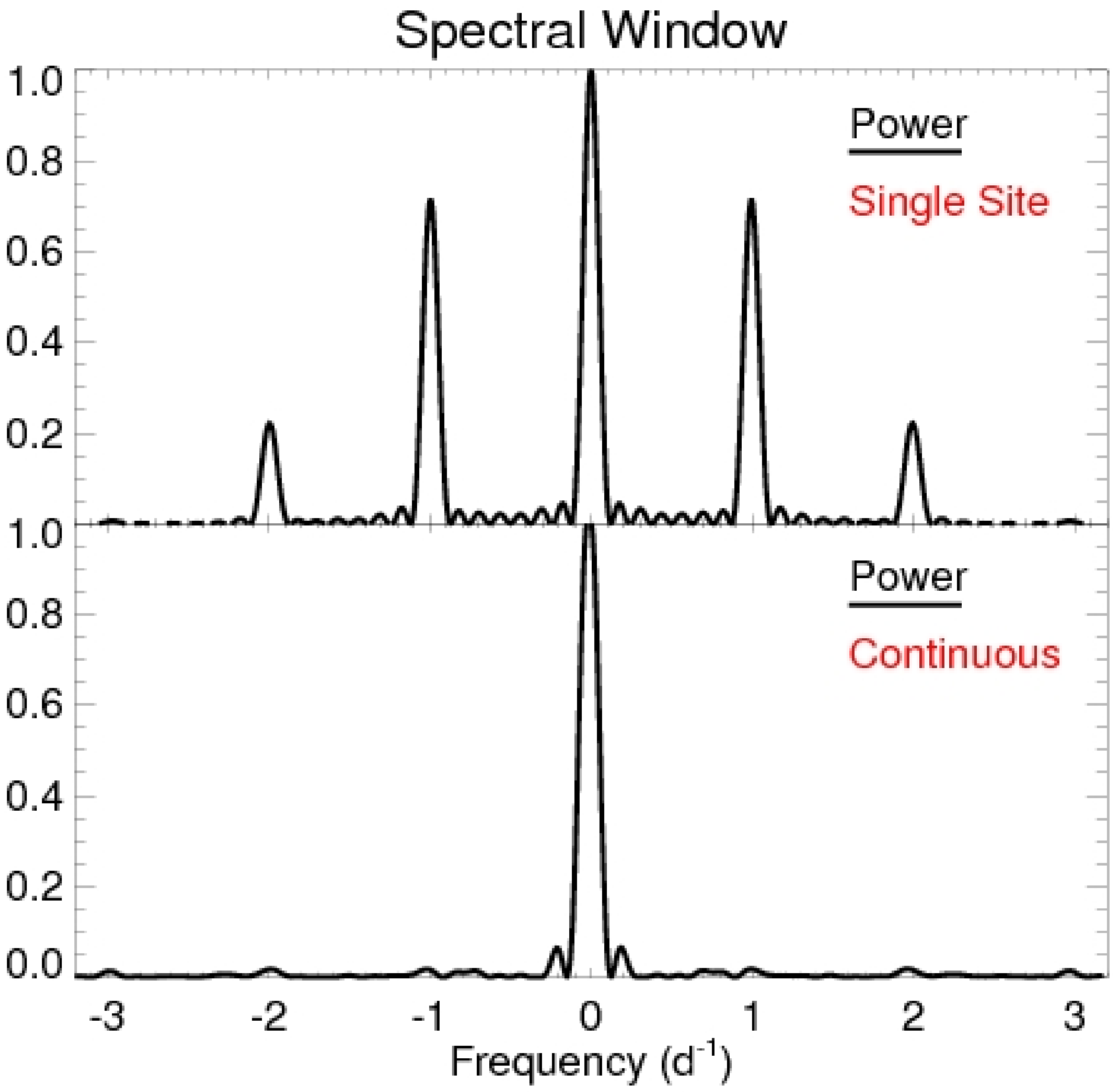
- The representation of a single sinusoid in the Power Spectrum of a given set of observations



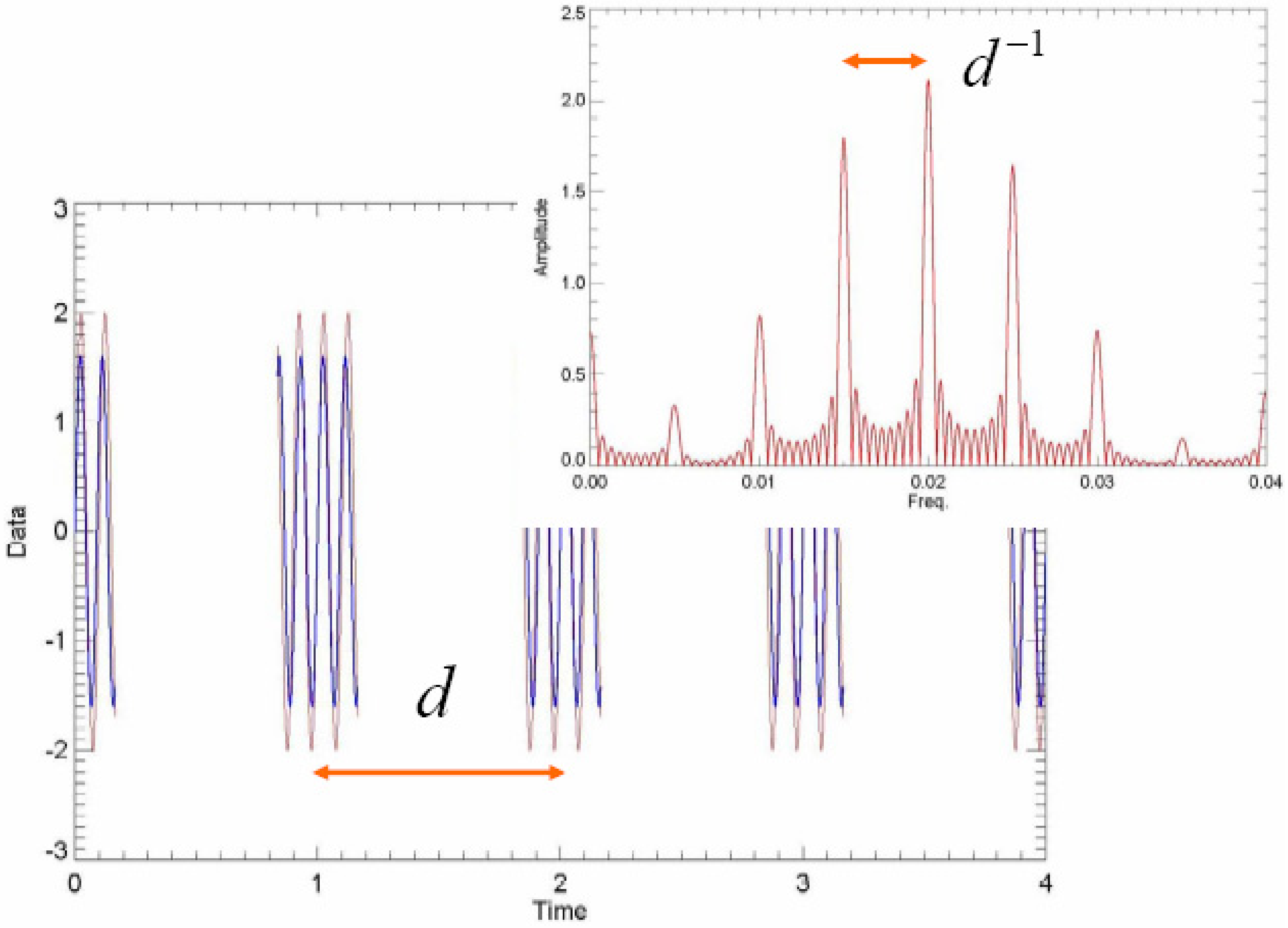
The Spectral Window Function



The Spectral Window Function

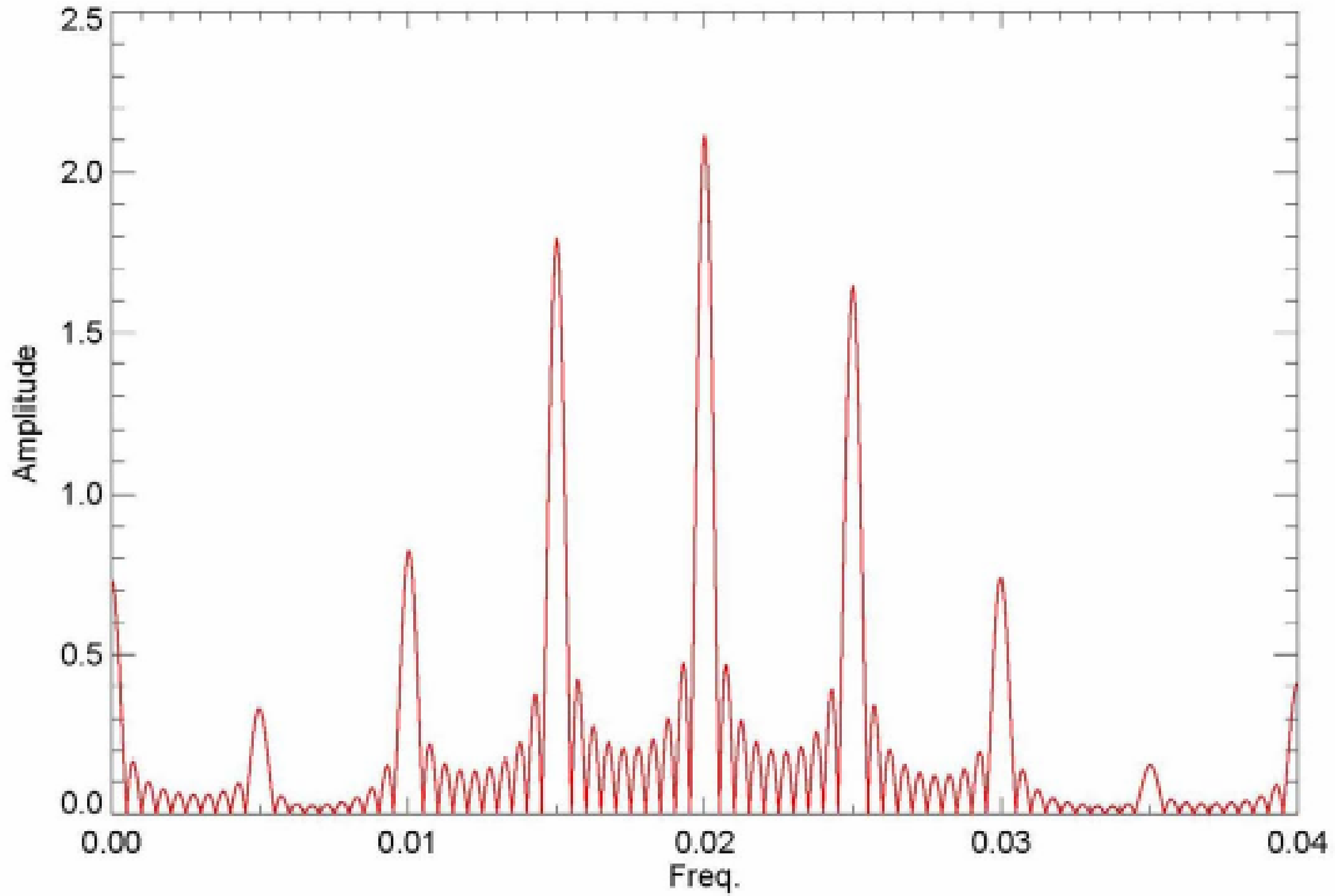


The Spectral Window Function

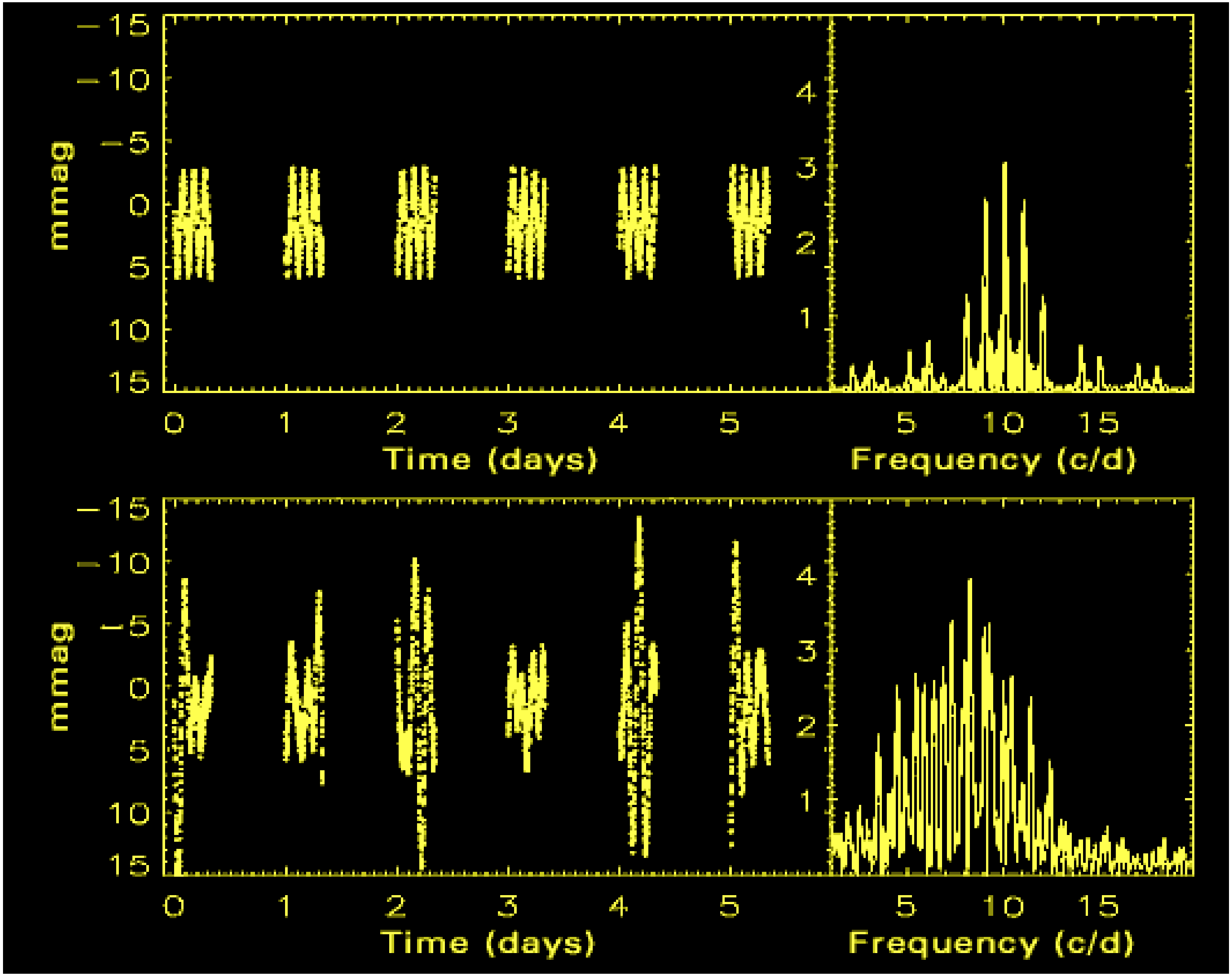


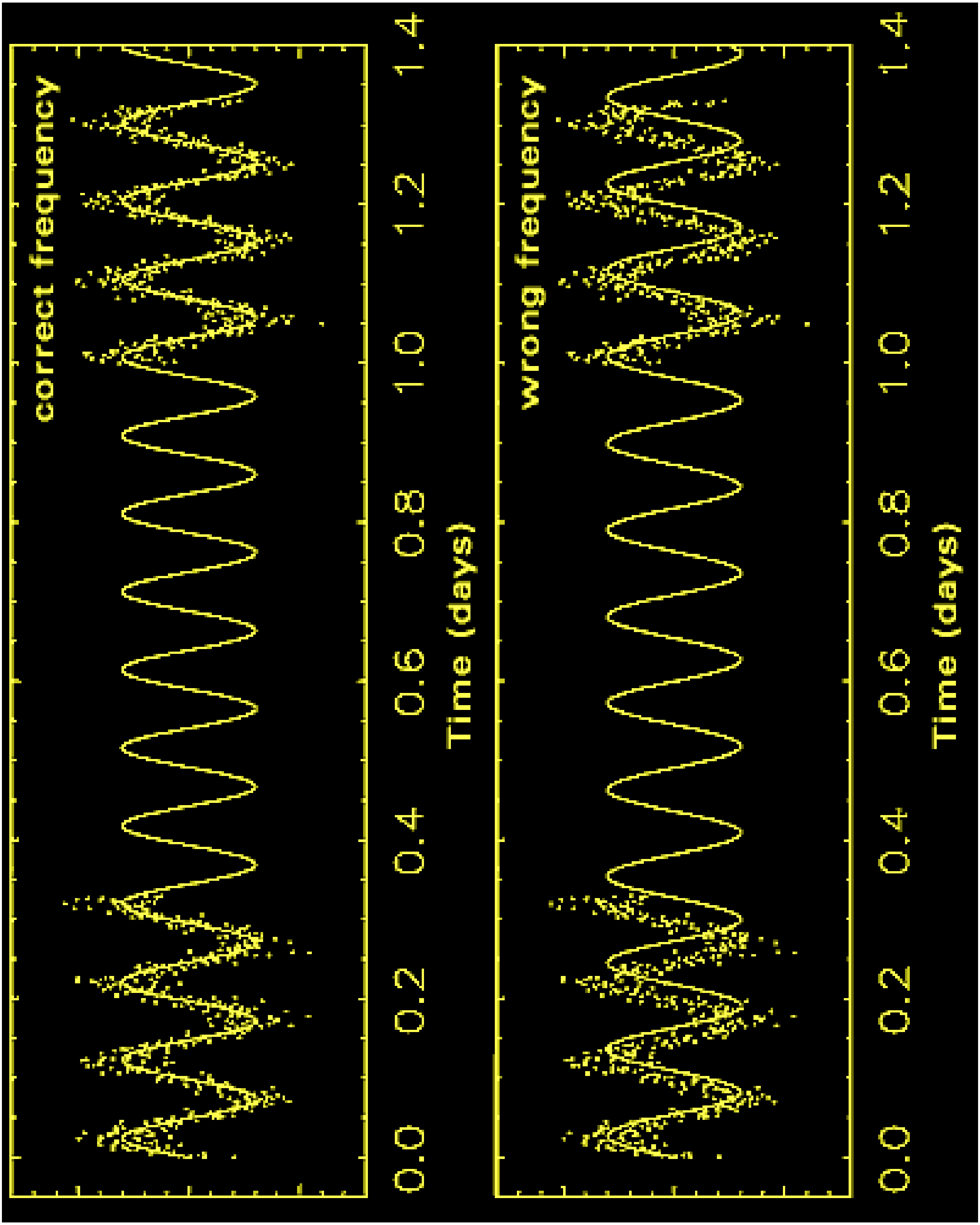
The Spectral Window Function

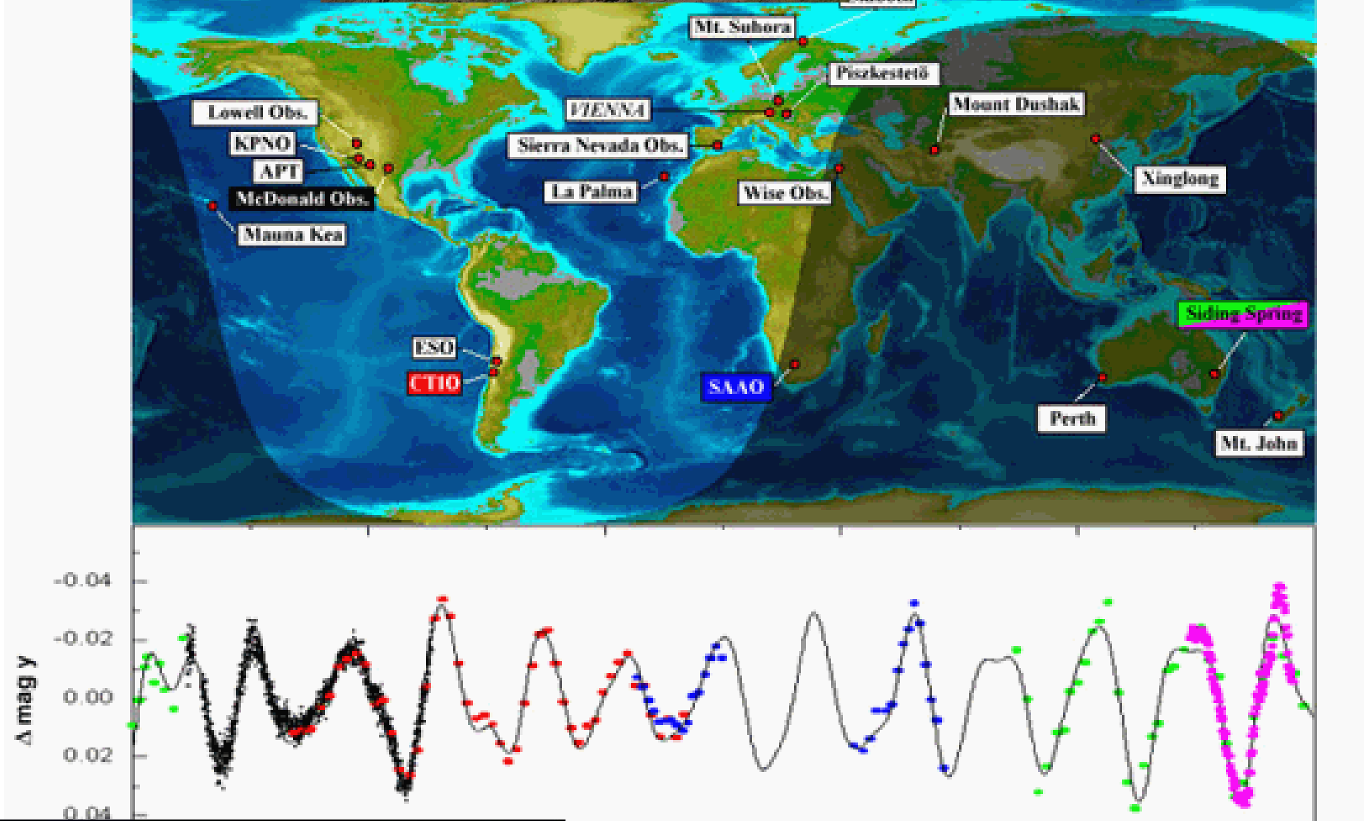
$$d^{-1} = \frac{1}{86400\,\mathrm{s}} = 0{,}01157\,\mathrm{mHz} = 11{,}57\,\mu\mathrm{Hz}$$



The Spectral Window Function

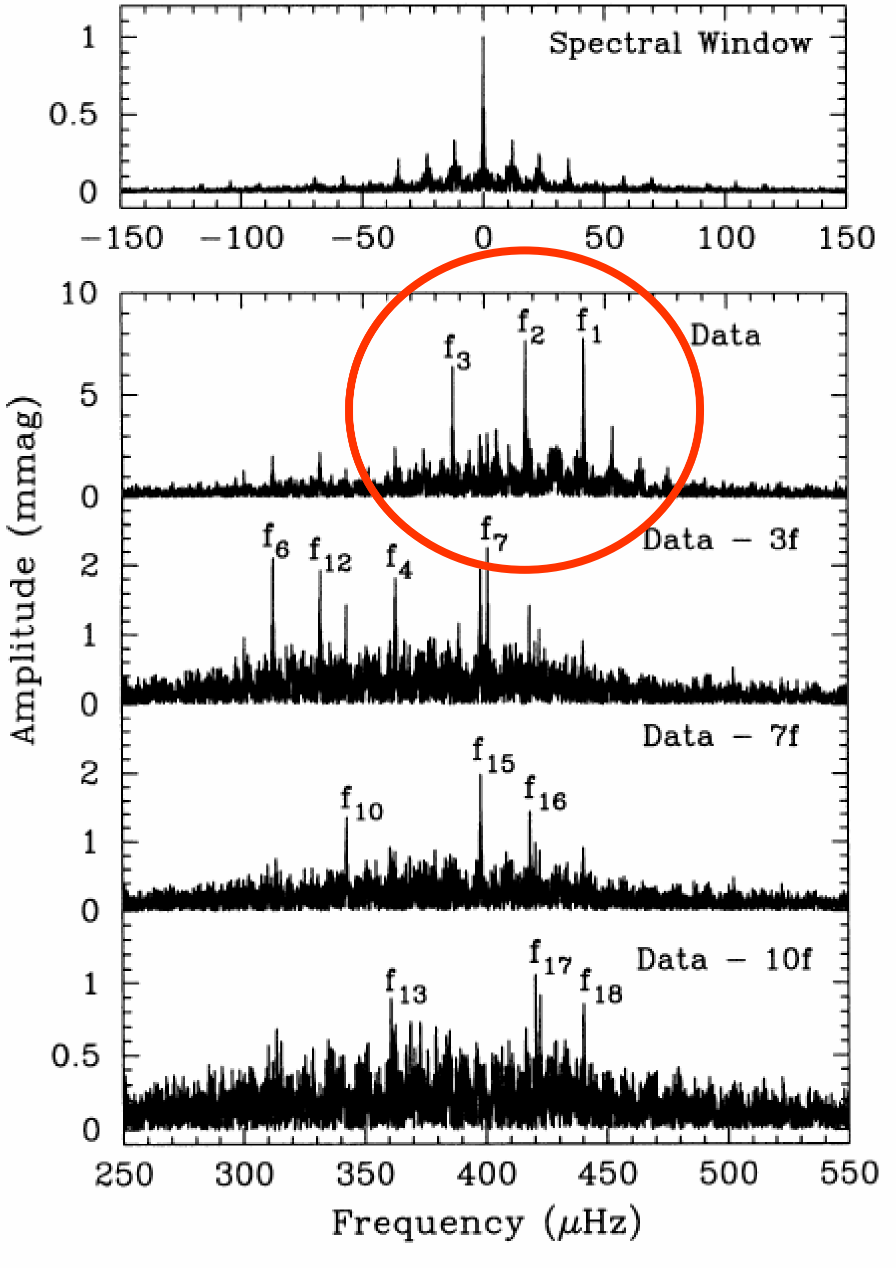



correct frequency
wrong frequency
Time (days)
Time (days)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

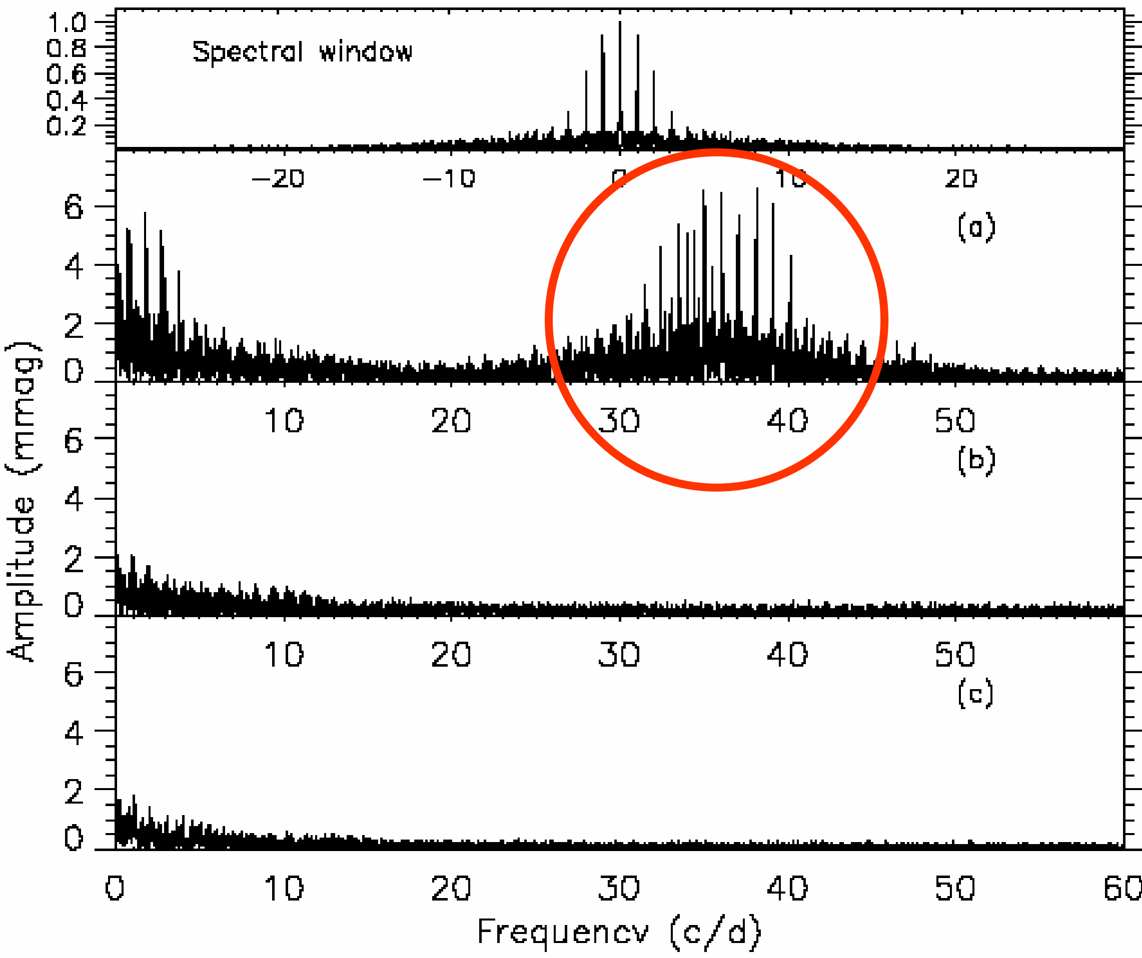

Skibotn
Mt. Suhora
Piszkéstető
VIENNA
Mount Dushak
Lowell Obs.
KPNO
APT
McDonald Obs.
Mauna Kea
Sierra Nevada Obs.
La Palma
Wise Obs.
Xinglong
Siding Spring
ESO
CTIO
SAAO
Perth
Mt. John
Δ mag y
-0.04
-0.02
0.00
0.02
0.04
97
He
9799.0


© Anglo-Australian Observatory

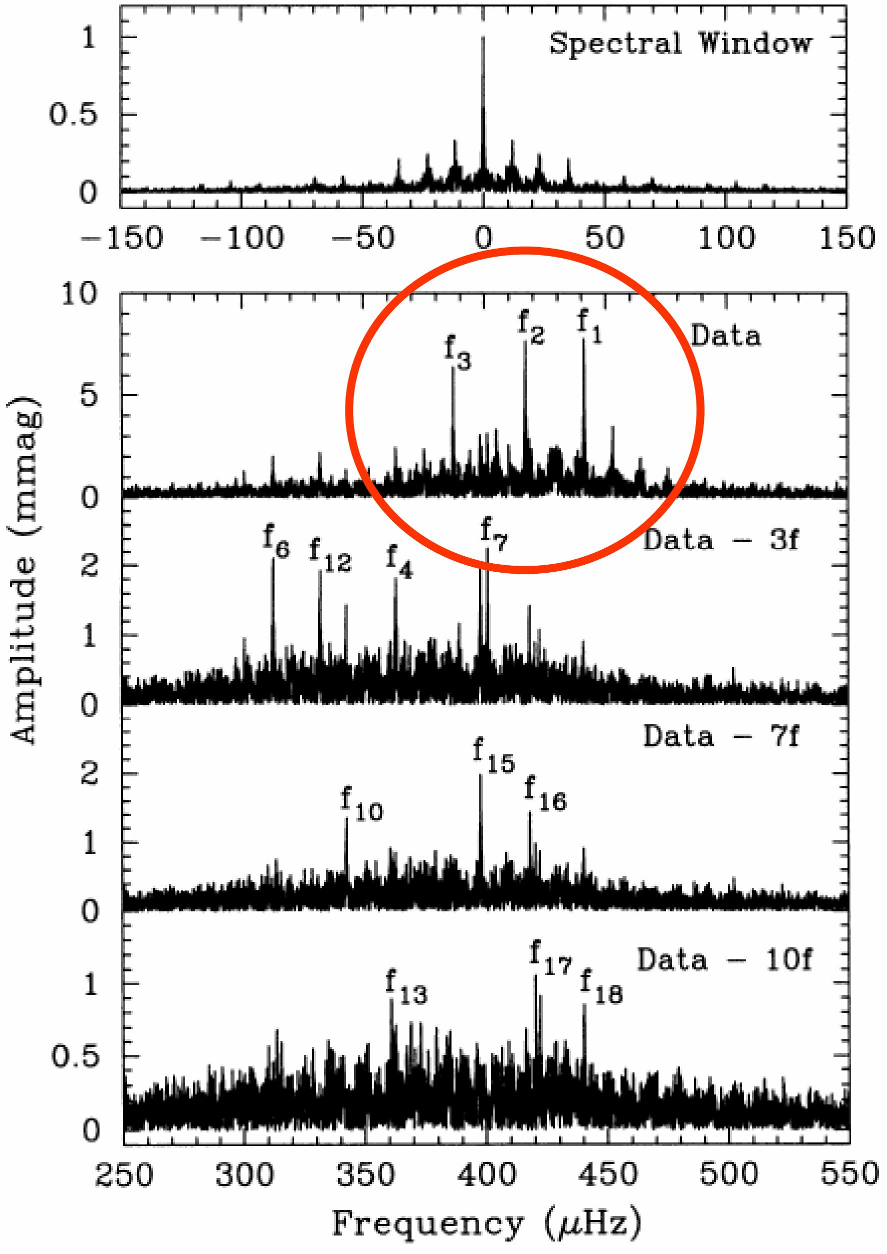
Multi-site



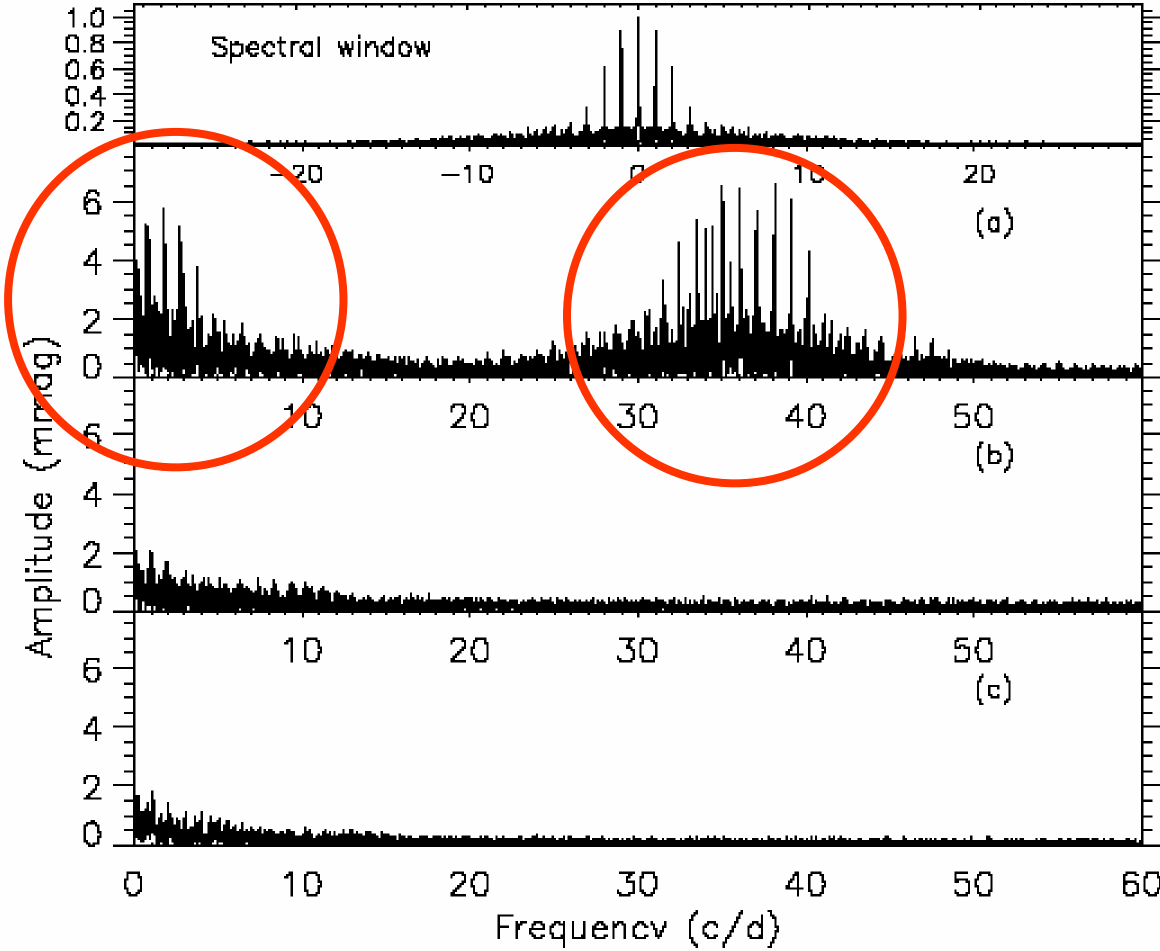
Single-site

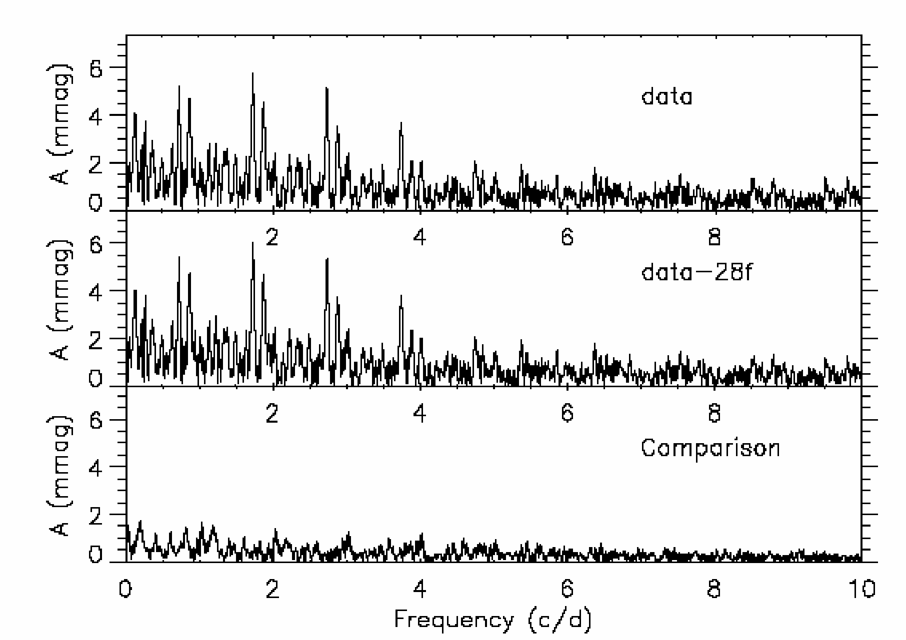


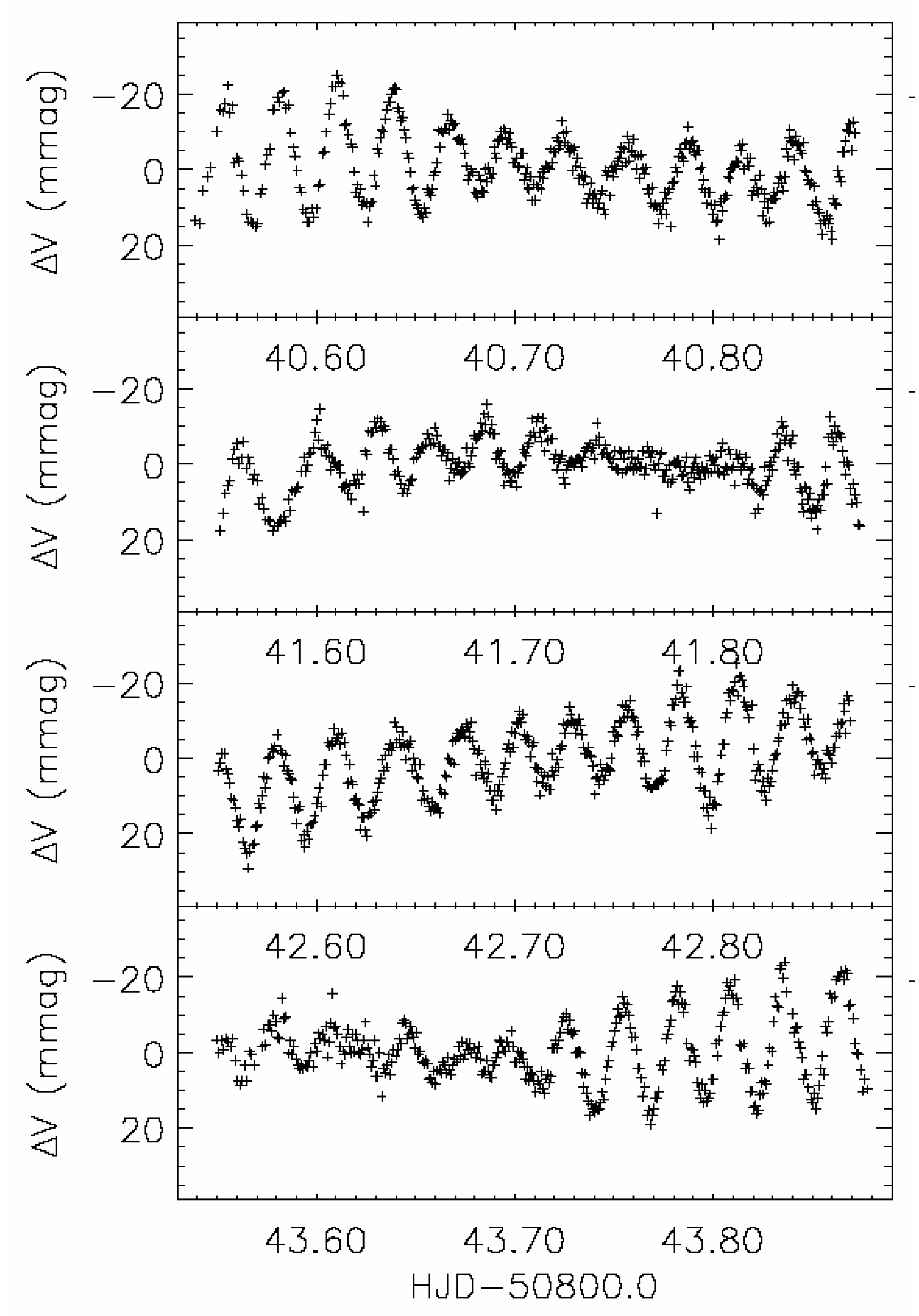
Multi-site



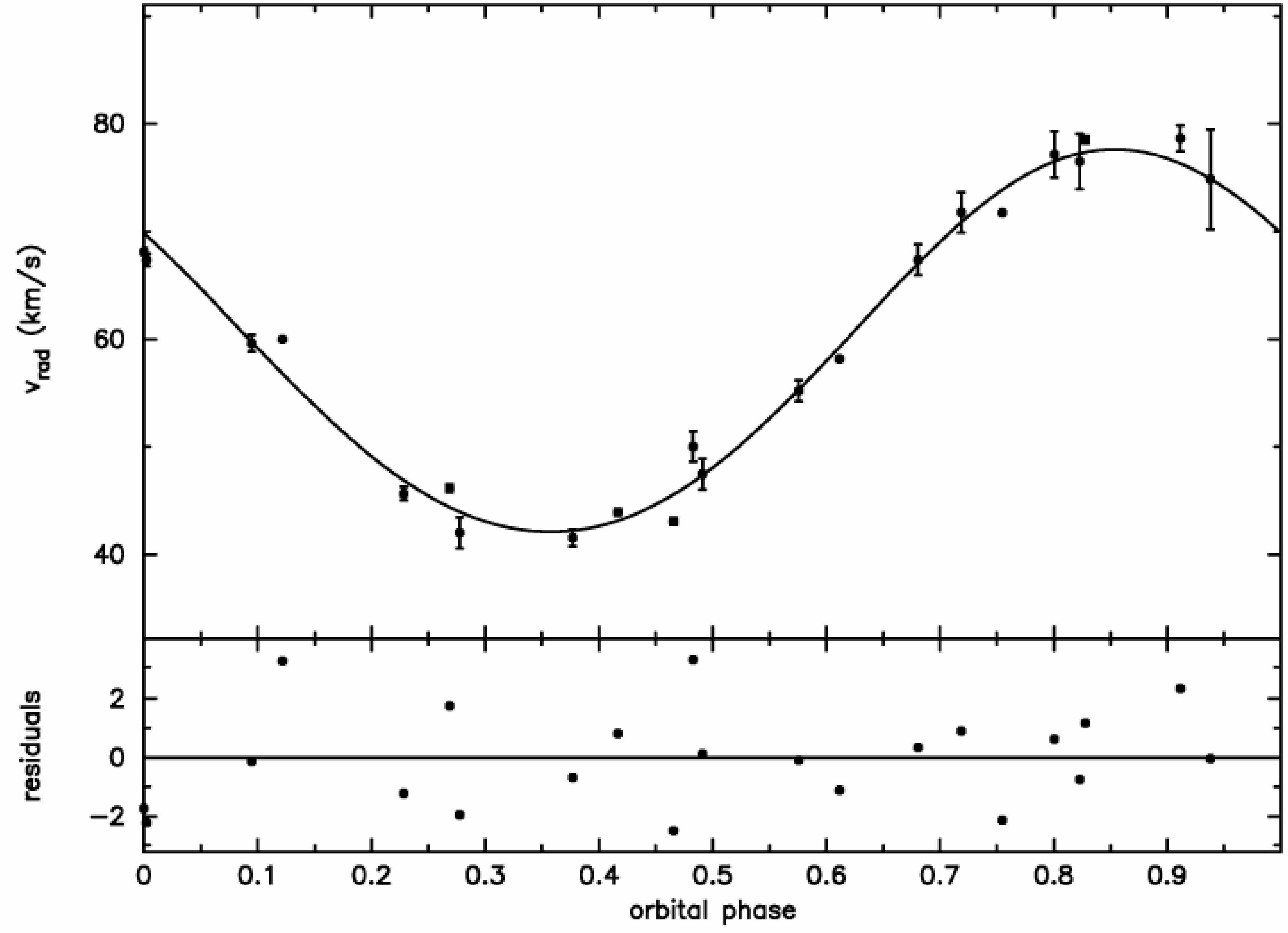
Single-site




A (mmag)
data
data−28f
Comparison
0
2
4
6
8
10
Frequency (c/d)


ΔV (mmag)
−20
0
20
40.60
40.70
40.80
41.60
41.70
41.80
42.60
42.70
42.80
43.60
43.70
43.80
HJD−50800.0

Binary with a period of 1.1 day ☹



Multi-site Campaign on Procyon

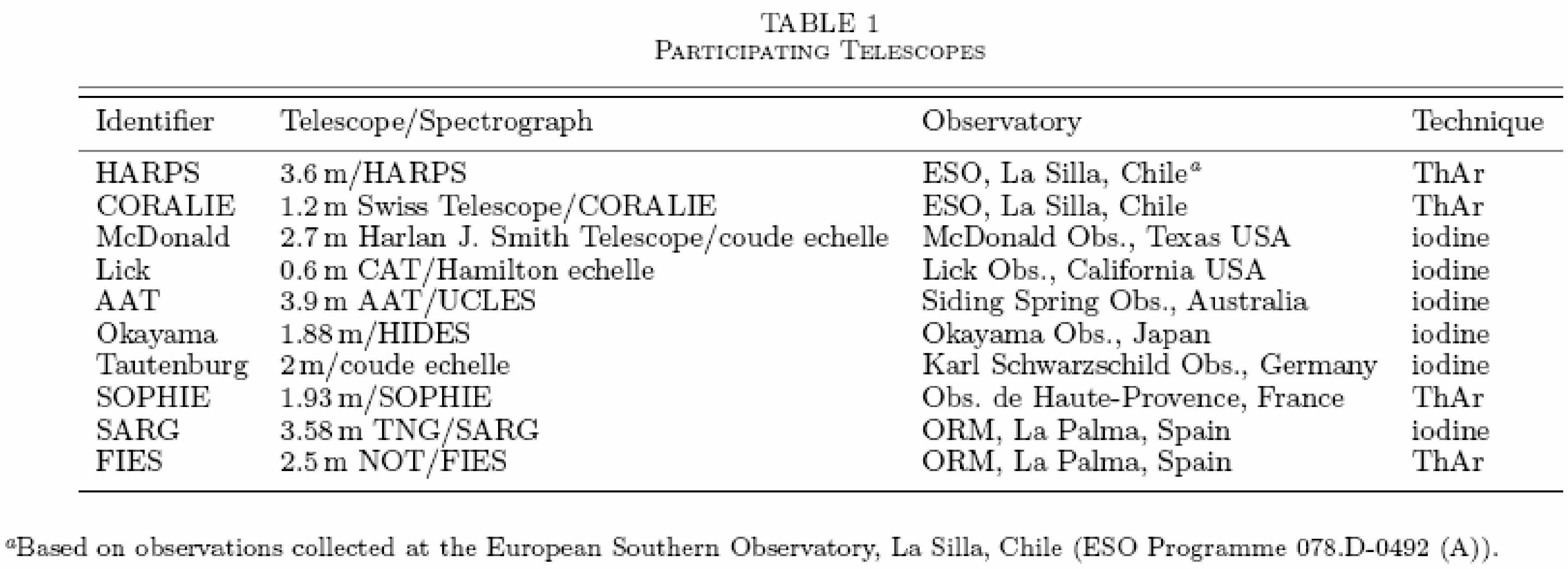
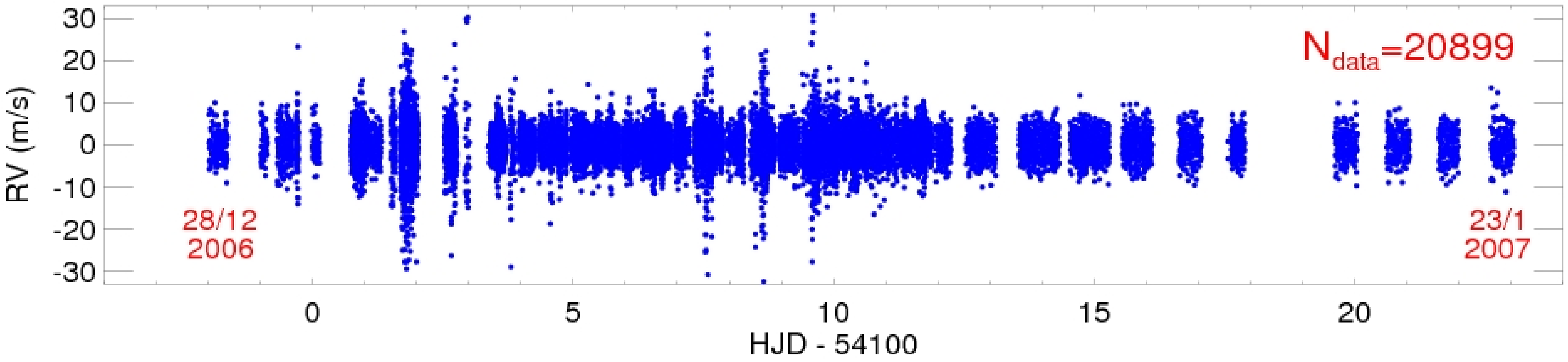


TABLE 1
PARTICIPATING TELESCOPES

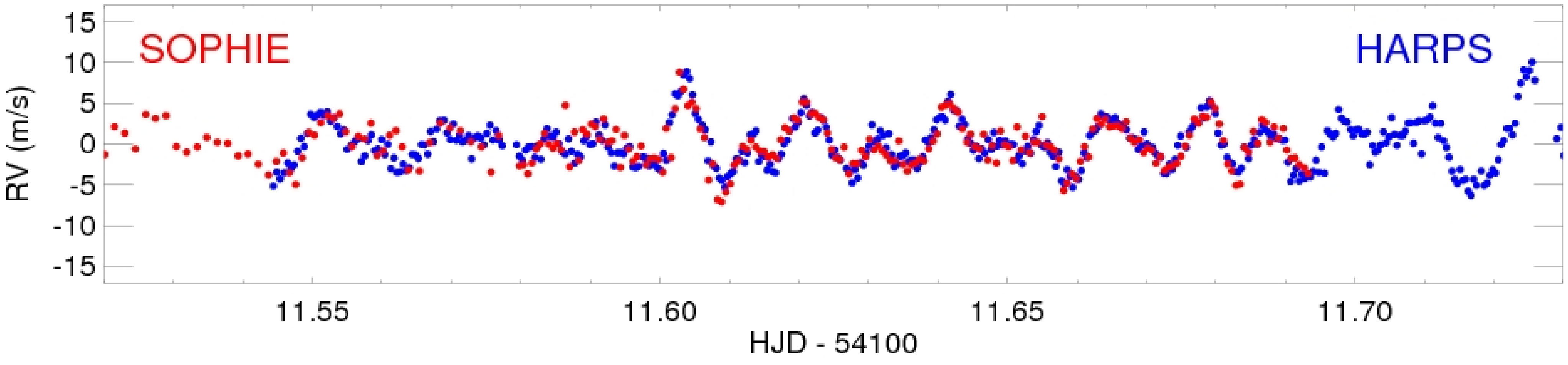
Identifier	Telescope/Spectrograph	Observatory	Technique
HARPS	3.6 m/HARPS	ESO, La Silla, Chile[a]	ThAr
CORALIE	1.2 m Swiss Telescope/CORALIE	ESO, La Silla, Chile	ThAr
McDonald	2.7 m Harlan J. Smith Telescope/coude echelle	McDonald Obs., Texas USA	iodine
Lick	0.6 m CAT/Hamilton echelle	Lick Obs., California USA	iodine
AAT	3.9 m AAT/UCLES	Siding Spring Obs., Australia	iodine
Okayama	1.88 m/HIDES	Okayama Obs., Japan	iodine
Tautenburg	2 m/coude echelle	Karl Schwarzschild Obs., Germany	iodine
SOPHIE	1.93 m/SOPHIE	Obs. de Haute-Provence, France	ThAr
SARG	3.58 m TNG/SARG	ORM, La Palma, Spain	iodine
FIES	2.5 m NOT/FIES	ORM, La Palma, Spain	ThAr

[a] Based on observations collected at the European Southern Observatory, La Silla, Chile (ESO Programme 078.D-0492 (A)).

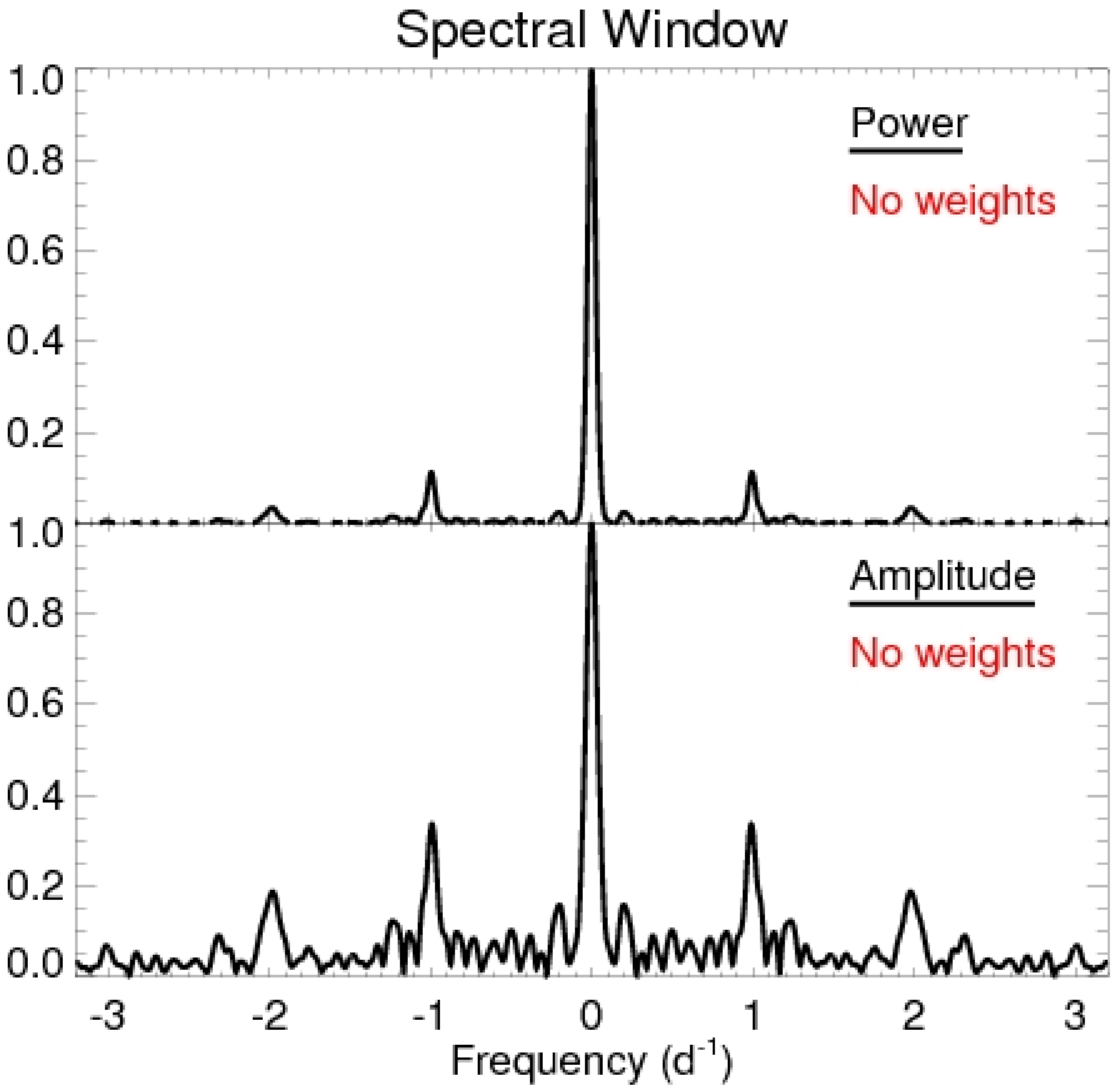
Multi-site Campaign on Procyon



Coverage during central 9 days: 89% (duty cycle)



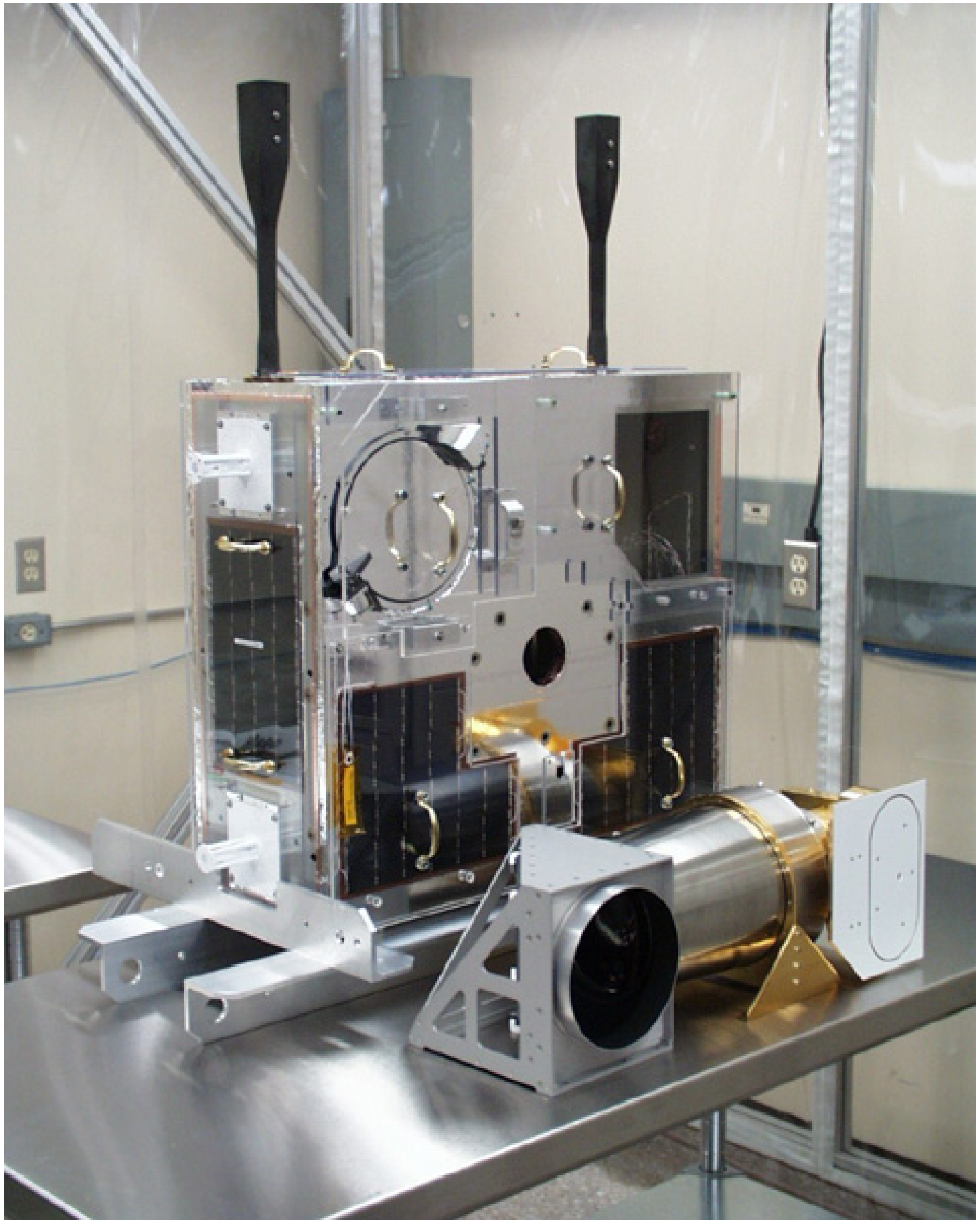
Multi-site Campaign on Procyon

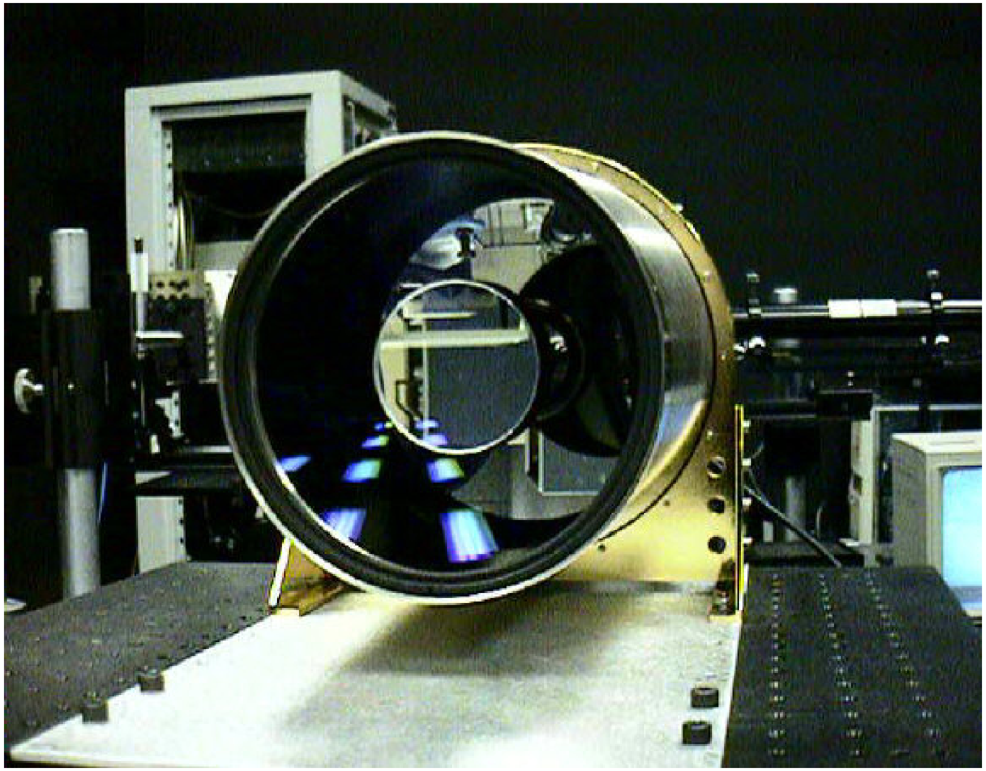


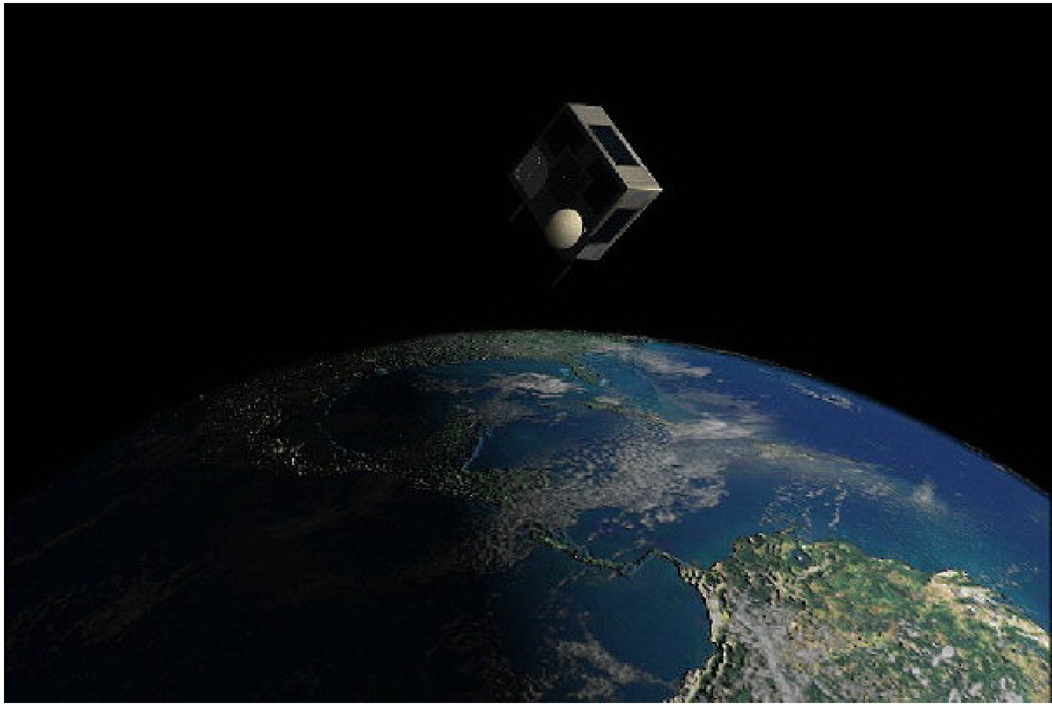
Microvariability & Oscillations of STars

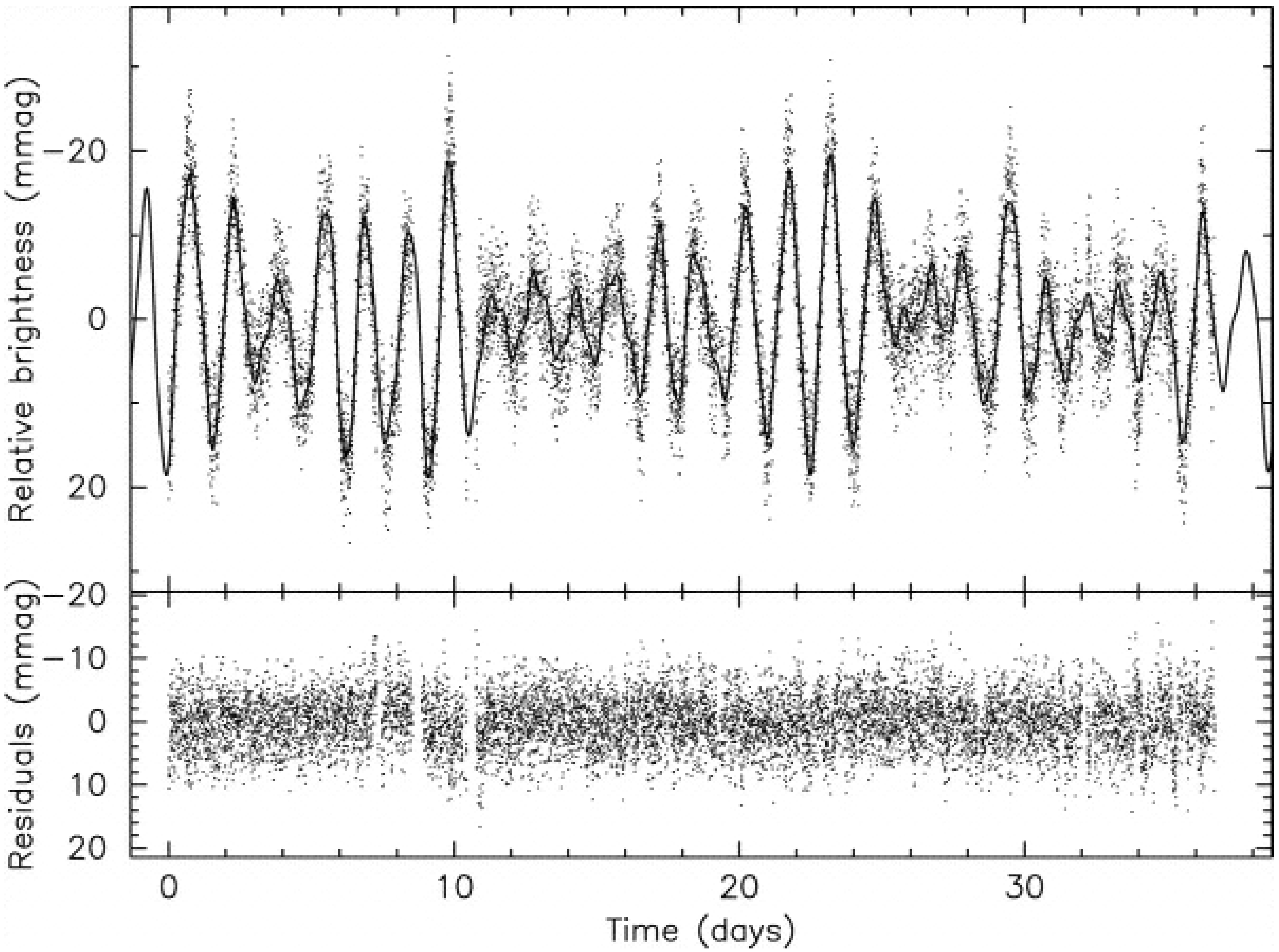
MOST

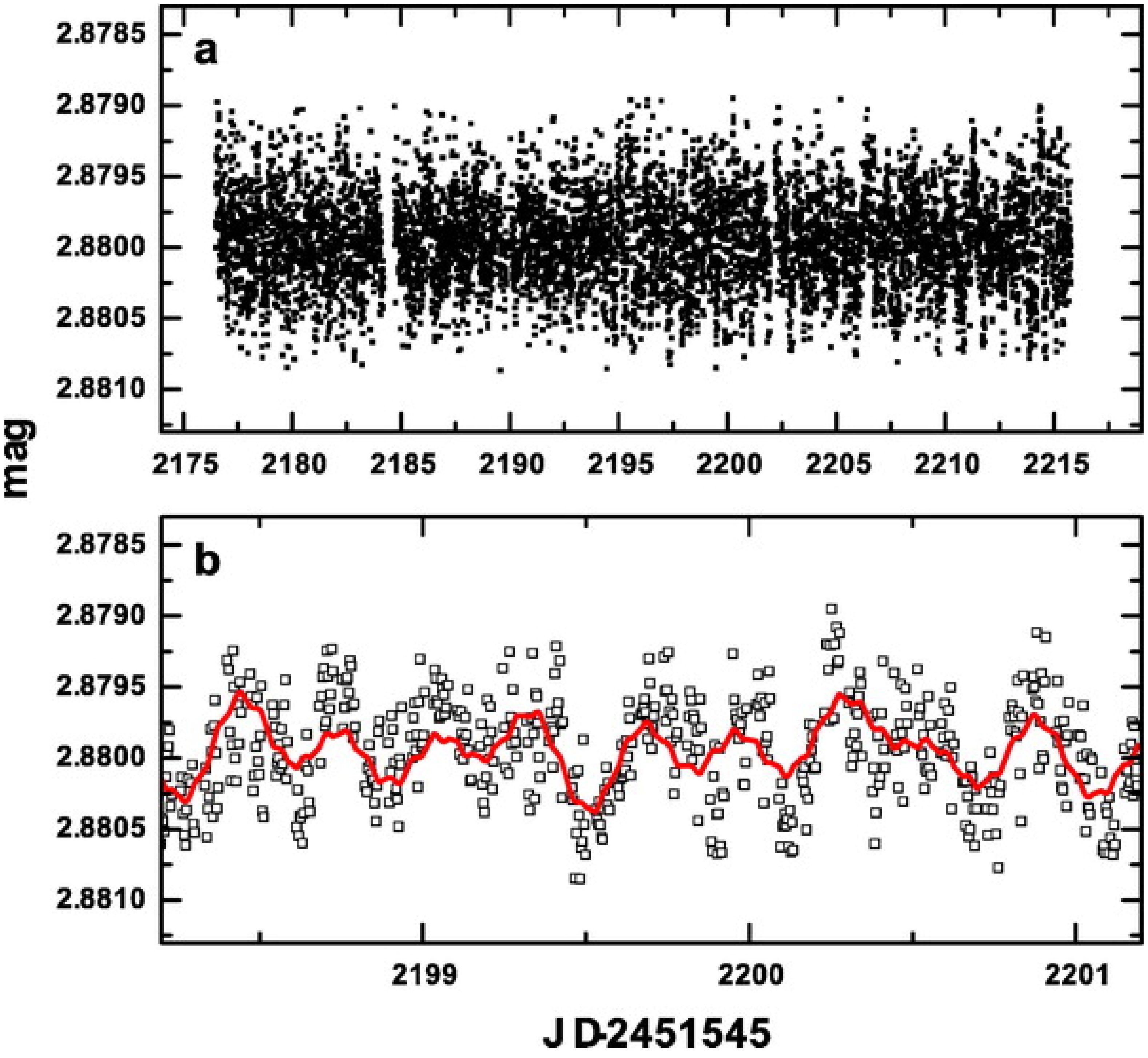
Microvariabilité & Oscillations STellaires

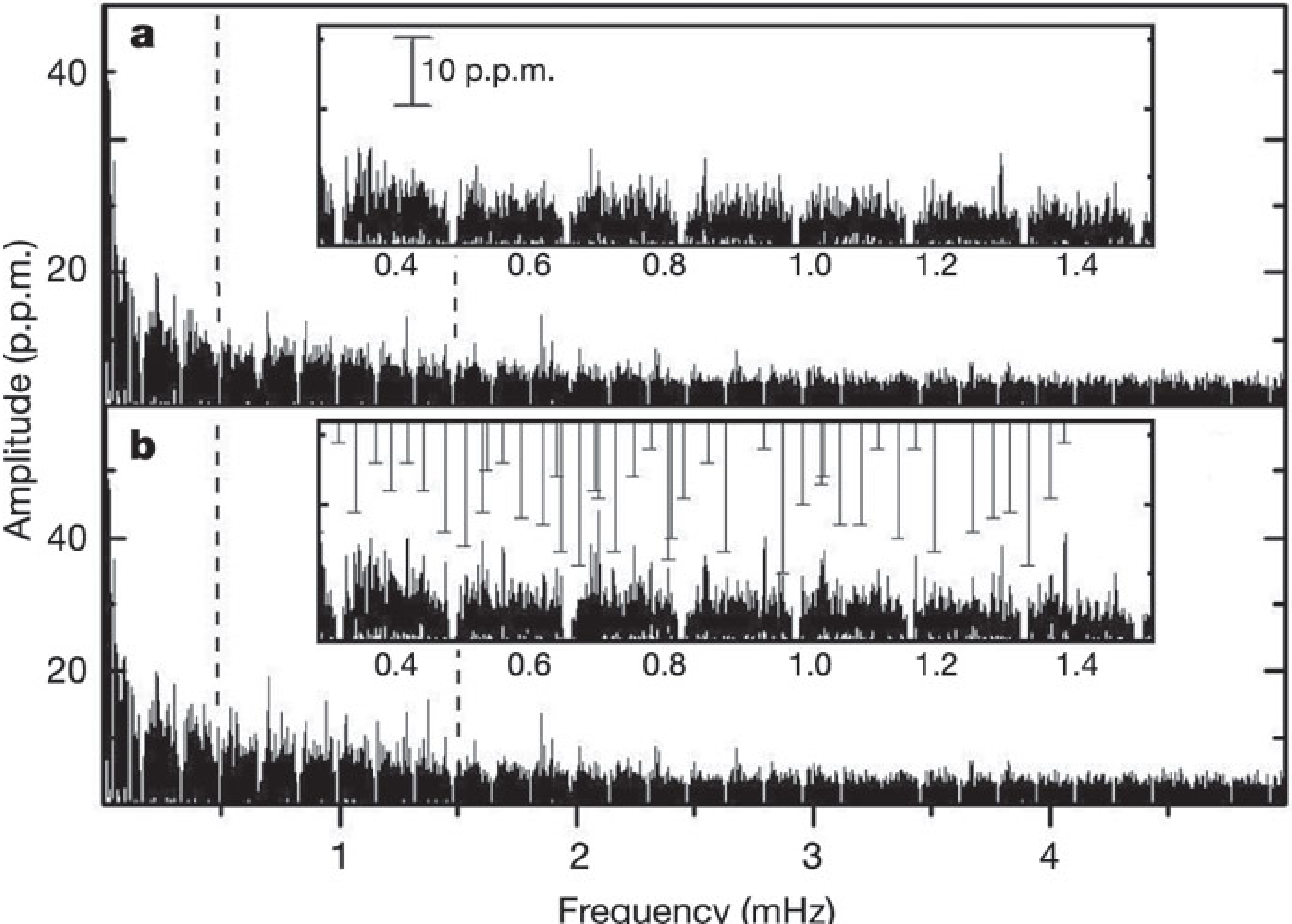







Relative brightness (mmag)
−20
0
20
Residuals (mmag)
−20
−10
0
10
20
0
10
20
30
Time (days)


a
b
mag
2.8785
2.8790
2.8795
2.8800
2.8805
2.8810
2175
2180
2185
2190
2195
2200
2205
2210
2215
2199
2200
2201
J D-2451545


a
10 p.p.m.
0.4
0.6
0.8
1.0
1.2
1.4
b
0.4
0.6
0.8
1.0
1.2
1.4
Amplitude (p.p.m.)
40
20
40
20
1
2
3
4
Frequency (mHz)

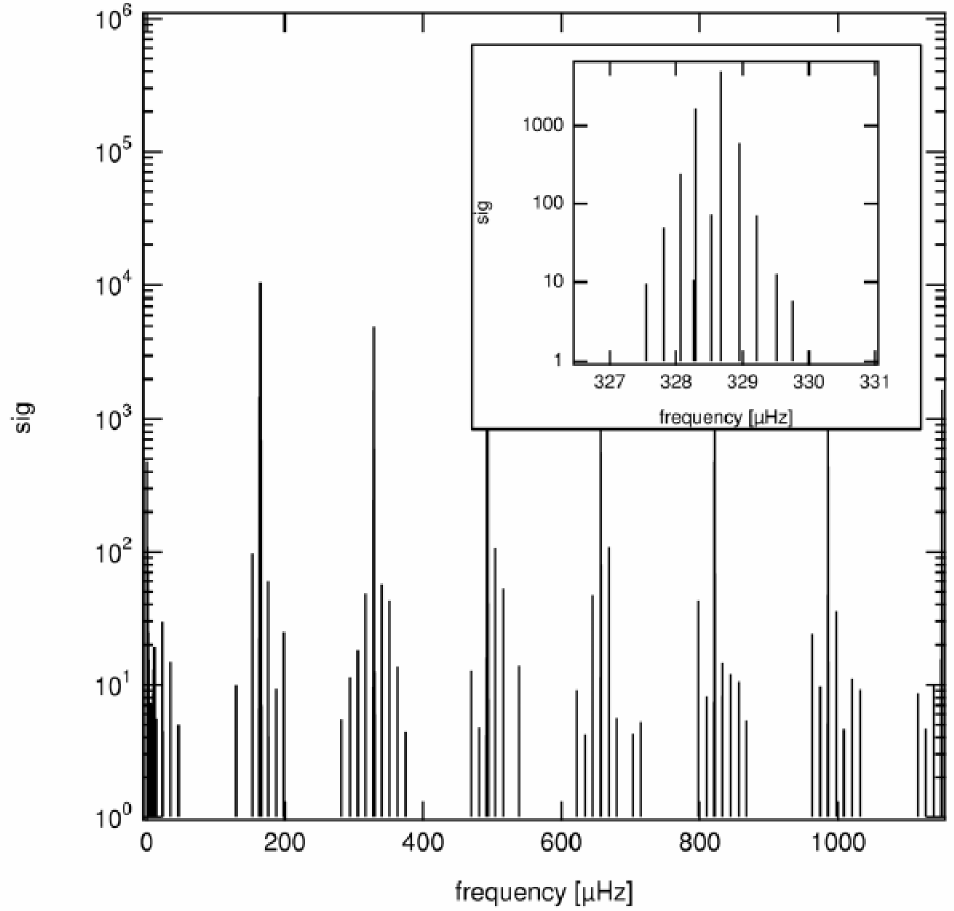
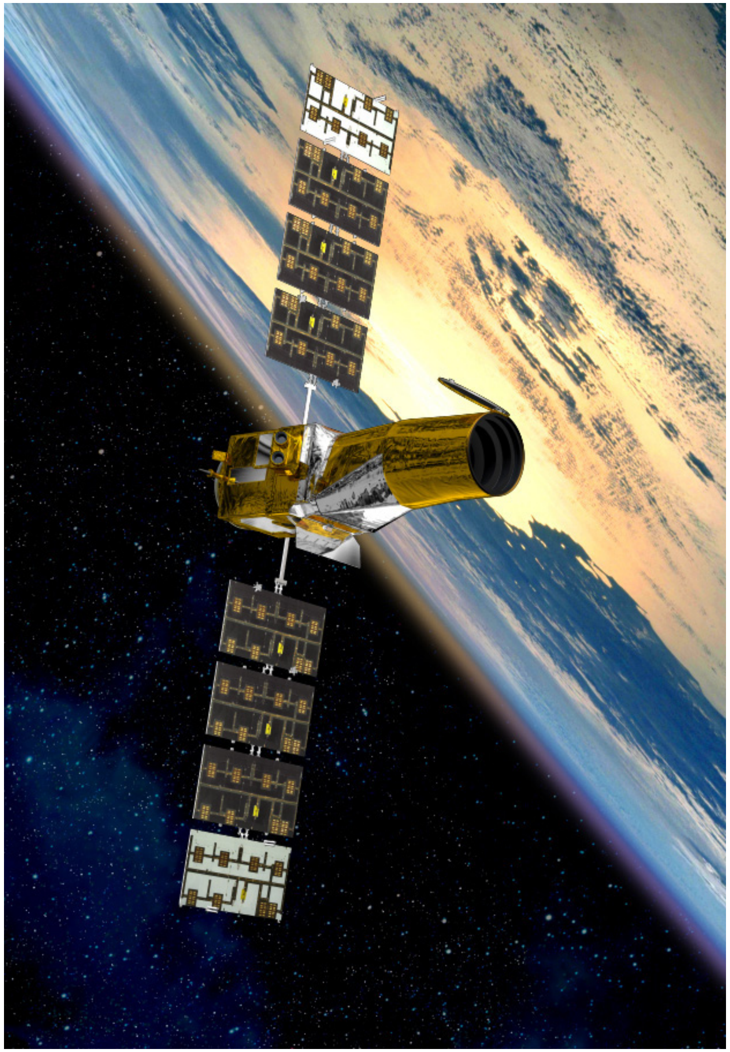


Figure 1: The spectral significance spectrum for the background time series (BTS) of Procyon 2004 data. The highest peaks are due to stray light correlated with orbital harmonics. The secondary peaks in the main figure are 1 cycle day^{-1} aliases due to the changing albedo of the earth reflected sunlight. The insert shows a highly magnified portion of the graph surrounding one of the orbital peaks. The peaks shown in the insert, which lie very close to the orbital harmonic peak, are amplitude modulation peaks due to long period changes in the attitude of the MOST satellite.

27. december 2006

Convection, Rotation & planetary Transits



CoRoT has two scientific objectives:

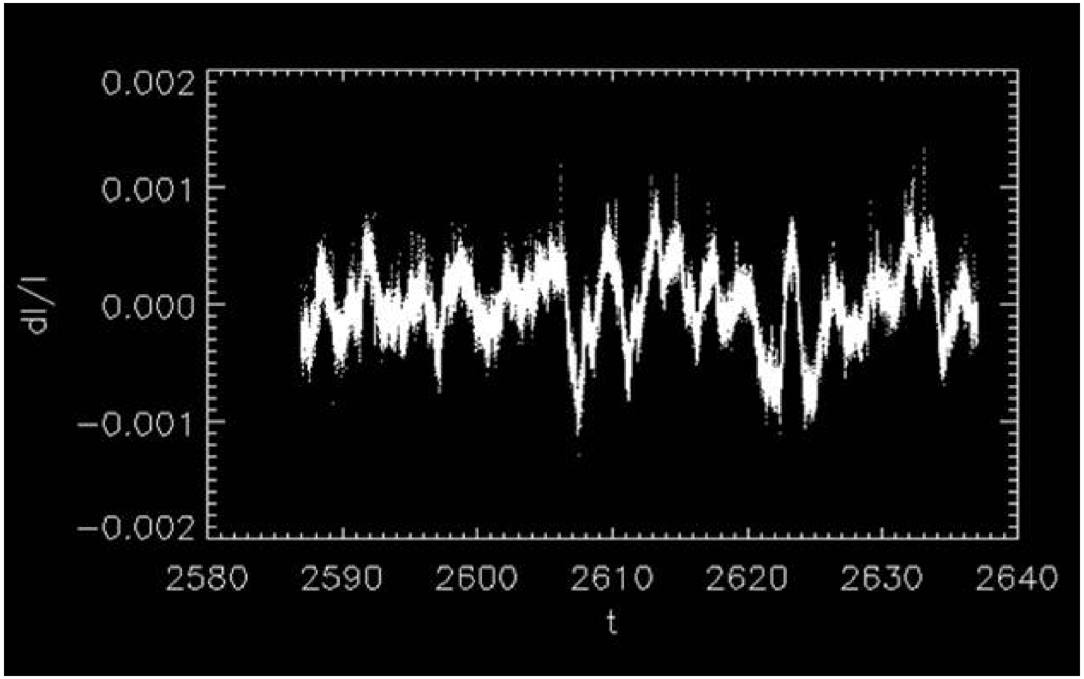
- Stellar Seismology
- Search for Exoplanets.

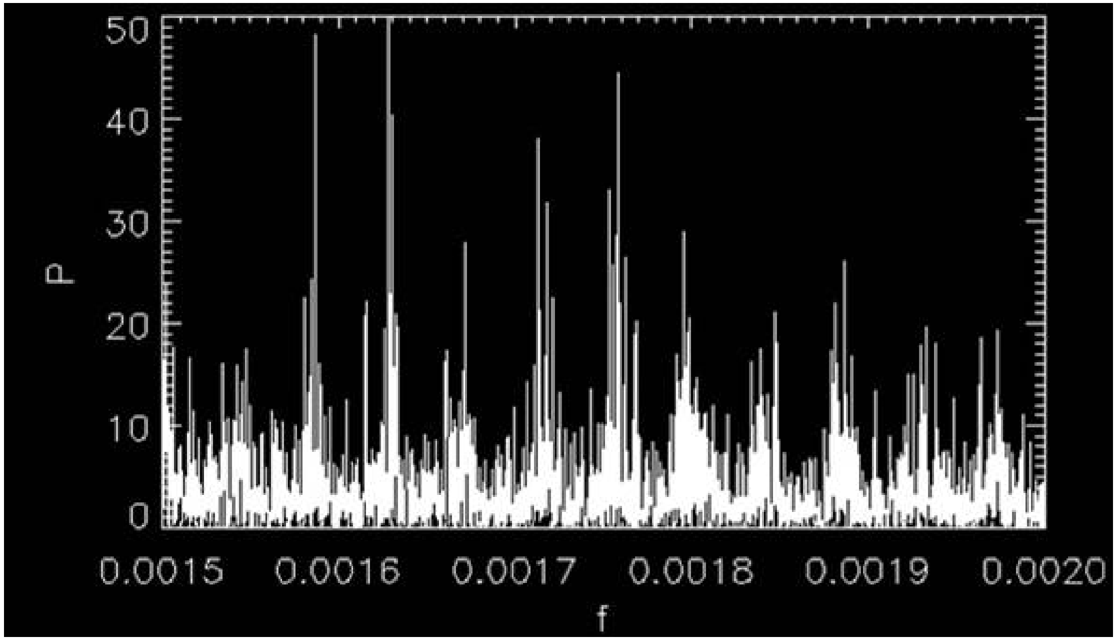
Proteus platform

- 27 cm telescope
- 4 2kx4k frame transfer CCDs
- Colors provided by a prism in front of two of the CCDs

- CoRoT was launched with a Soyuz rocket from Baikonur on the 27th of December 2006.
- Measured precision for Asteroseismology: 0.74 ppm in 5 days.

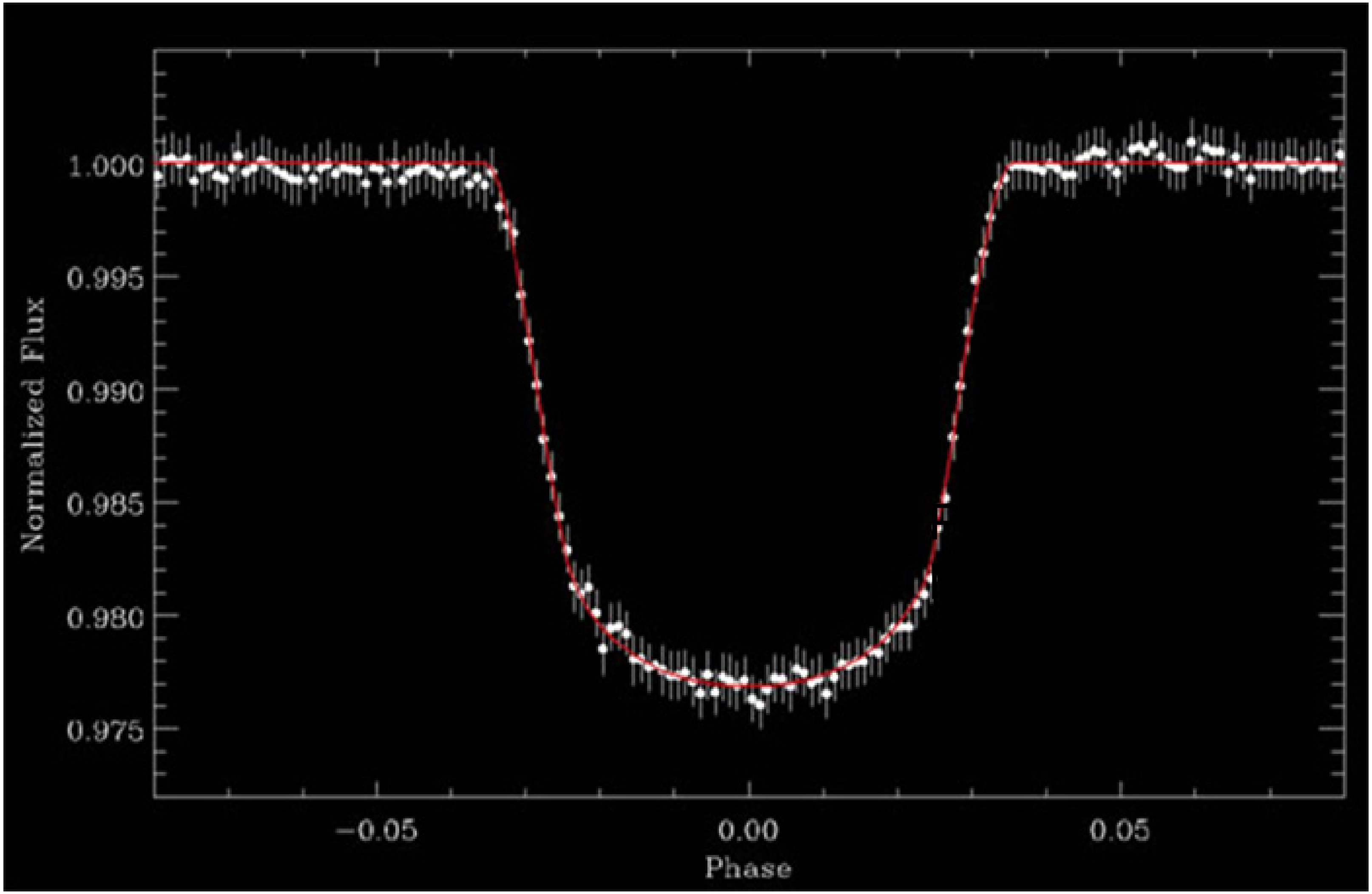
Activity and Oscillations in a Solar-like star



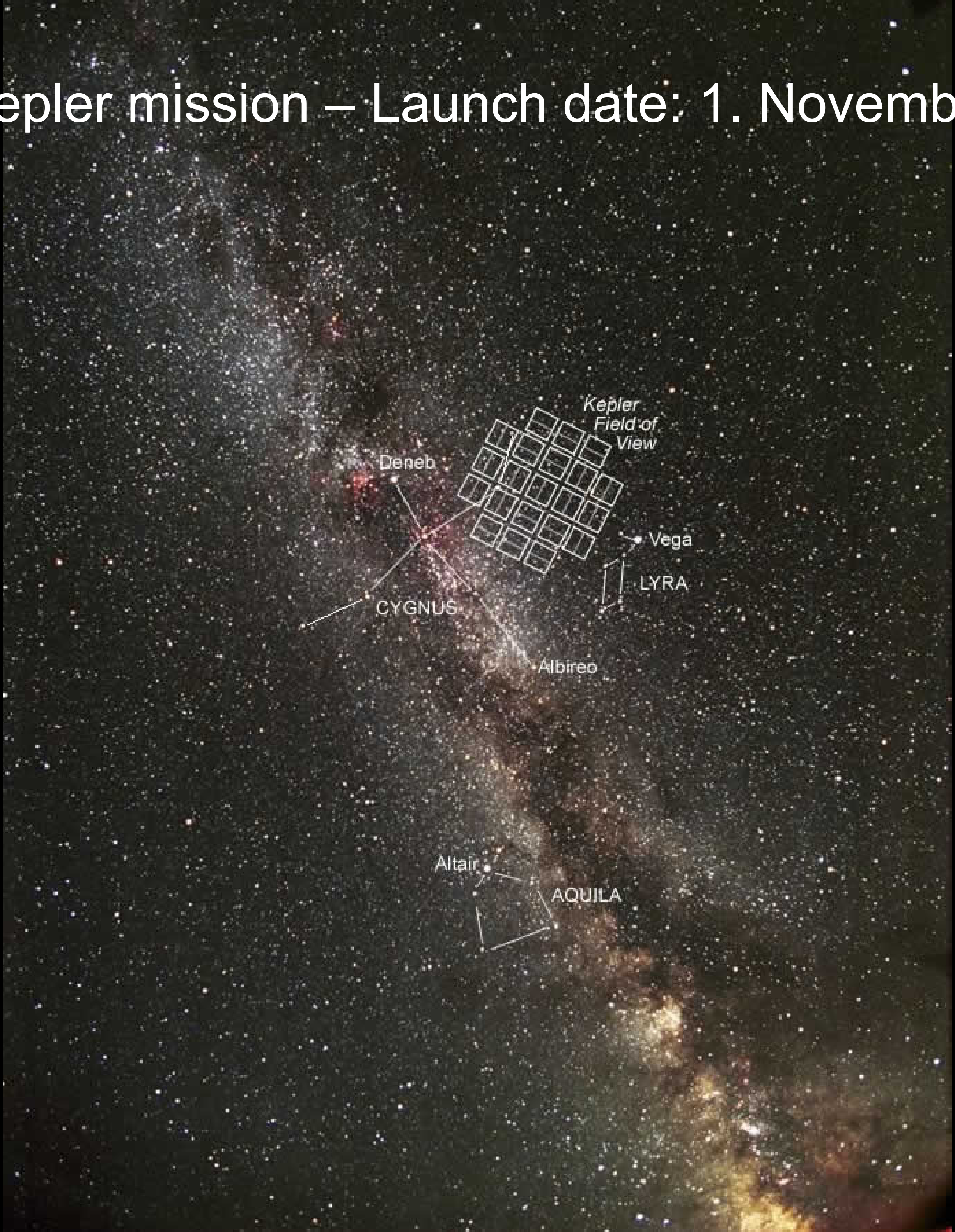


The First Exoplanet detected with CoRoT

Corot-Exo-1b



NASA Kepler mission – Launch date: 1. November 2008



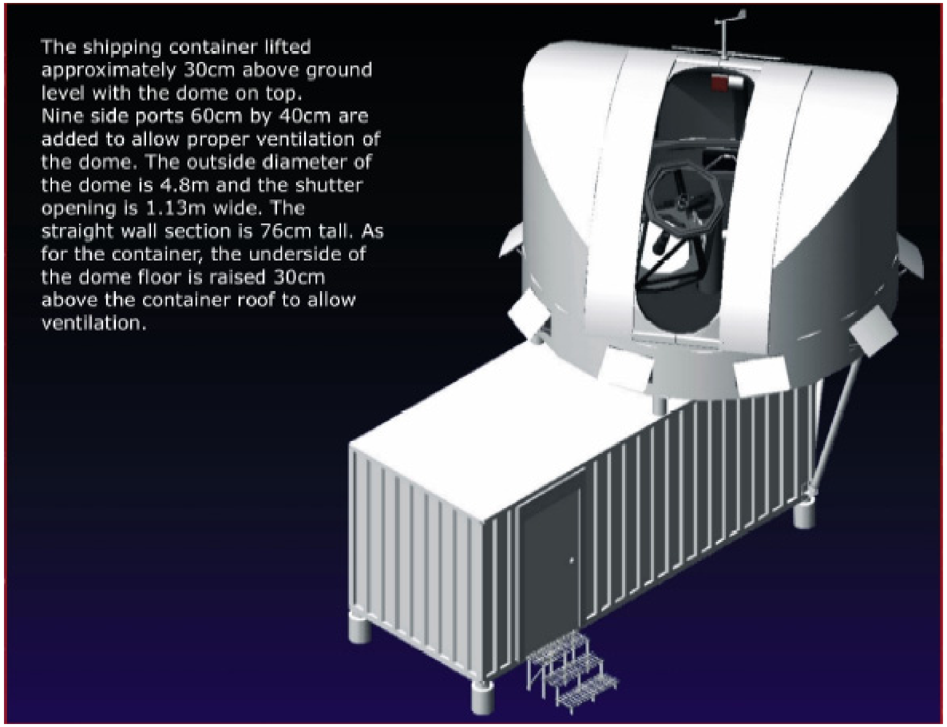
SONG

STELLAR OSCILLATIONS NETWORK GROUP

The scientific goals of **SONG** are:

1. to study the internal structure and evolution of stars at a level of detail similar to that achieved for the Sun, using an advanced technique called asteroseismology, which enables astronomers to "look inside the stars"

2. to search for and characterize planets with masses comparable to the Earth in orbit around other stars.



The shipping container lifted approximately 30cm above ground level with the dome on top.
Nine side ports 60cm by 40cm are added to allow proper ventilation of the dome. The outside diameter of the dome is 4.8m and the shutter opening is 1.13m wide. The straight wall section is 76cm tall. As for the container, the underside of the dome floor is raised 30cm above the container roof to allow ventilation.

- Try it yourself with Period98/Period04:

http://www.univie.ac.at/tops/Period98/current/

http://www.univie.ac.at/tops/Period04

- Data can be found at

http://astro.phys.au.dk/~toar/summer2007