Search for Invisible Companions (Planets, WD, NS, BH) based on Frequency Modulation

Binary

Fundamental source of information of stellar physics

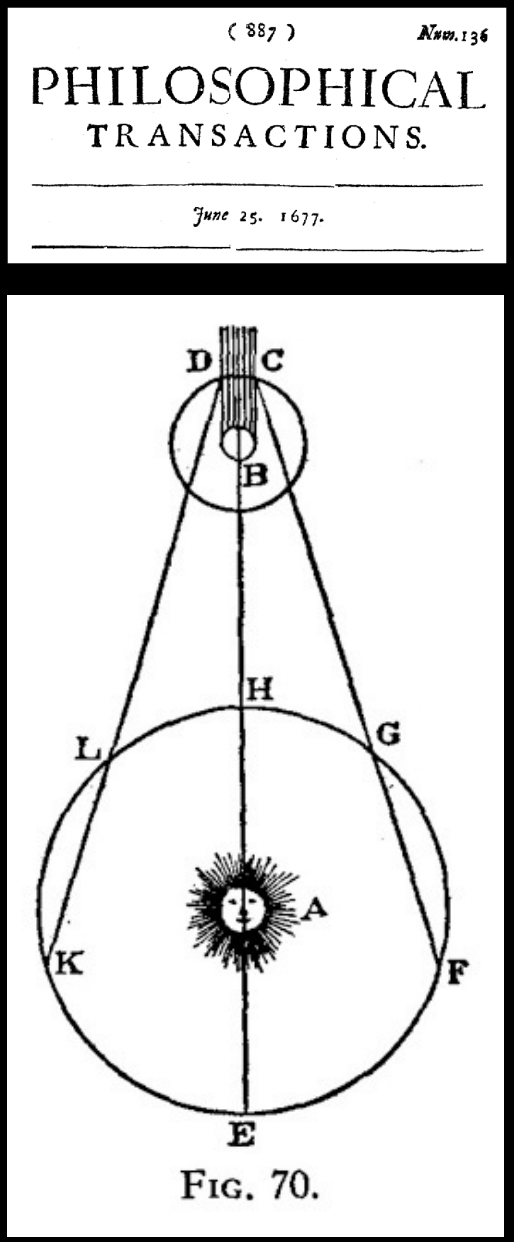
Spectroscopic observations

- telescope time allocation
- long time span to cover the orbital phase

Search for invisible exotic components

- Planets around early-type stars
- Brown dwarfs
- White dwarfs
- Neutron stars
- Stellar origin black holes

Ole Roemer's measurement of the speed of light (1677)

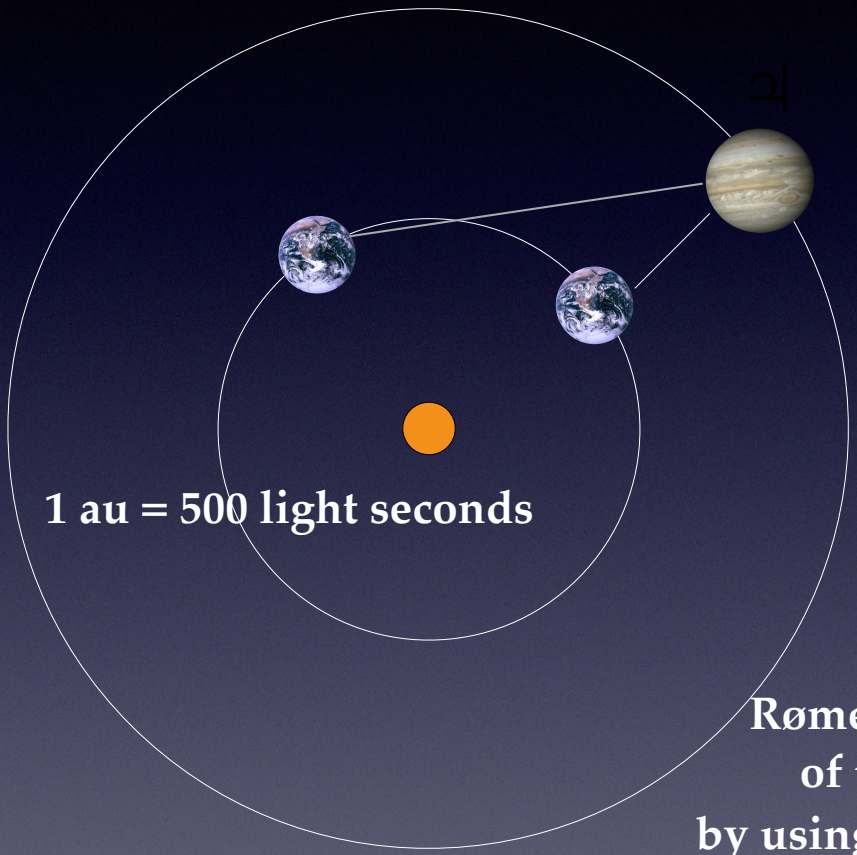

(887) Num. 136

PHILOSOPHICAL
TRANSACTIONS.

June 25. 1677.

FIG. 70.

“light-time effect”



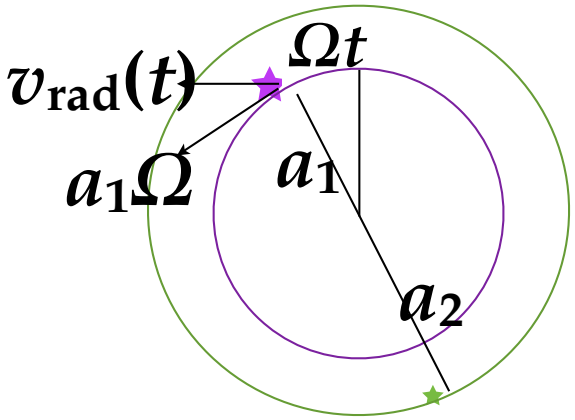
Binary pulsar
(cf. Taylor & Hulse)

Rømer’s measurement
of the light speed
by using Io’s eclipse timing

Clocks in a binary system

The simplest case: circular orbital motion

$$v_{\mathrm{rad}}(t) = a_1 \Omega \sin i \cos \Omega t$$



i : inclination angle

observer

Observed luminosity variation:

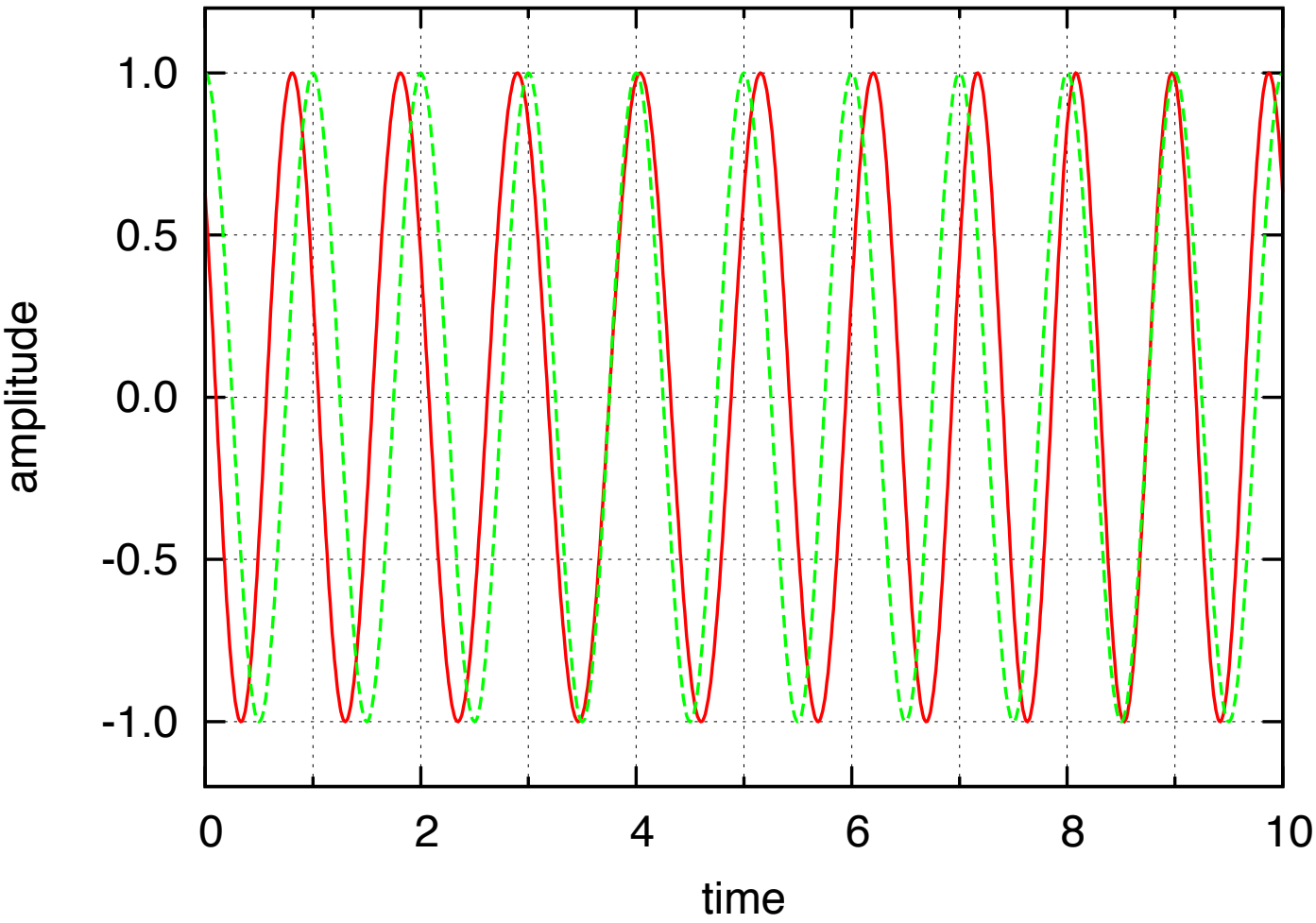
$$\Delta L(t) \propto \cos\left\{\omega_0 \left[t - c^{-1}\int_0^t v_{\mathrm{rad}}(t')\mathrm{d}t'\right] + \phi\right\}$$

arrival time delay

Instantaneously observed frequency:

$$\omega_{\mathrm{obs}}(t) = \omega_0 [1 - v_{\mathrm{rad}}(t)/c]$$

phase modulation



Estimate of the amplitude of phase modulation:

$$(v_{\rm rad}/c)_{\rm max} = a_1 \Omega \sin i / c$$

$$= (2\pi GM)^{1/3} c^{-1} q (1+q)^{-2/3} P_{\rm orb}^{-1/3} \sin i$$

$$\simeq 10^{-3}$$

$$\omega_0 \left(\int v_{\rm rad}/c \, {\rm d}t \right)_{\rm max} = a_1 \omega_0 \sin i / c$$

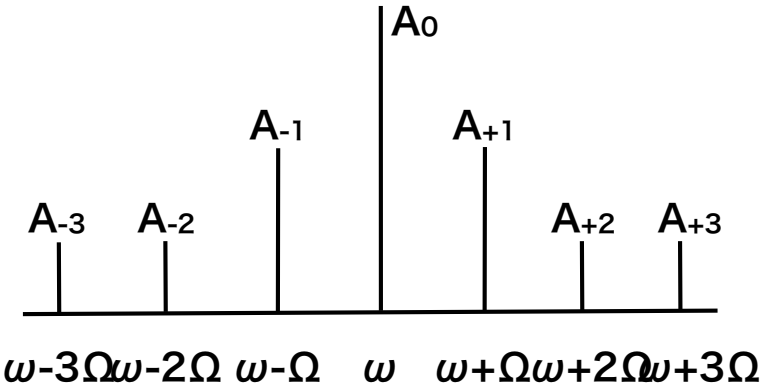
$$= (2\pi GM)^{1/3} c^{-1} q (1+q)^{-2/3} P_{\rm orb}^{2/3} P_{\rm osc}^{-1} \sin i$$

$$\equiv \alpha$$

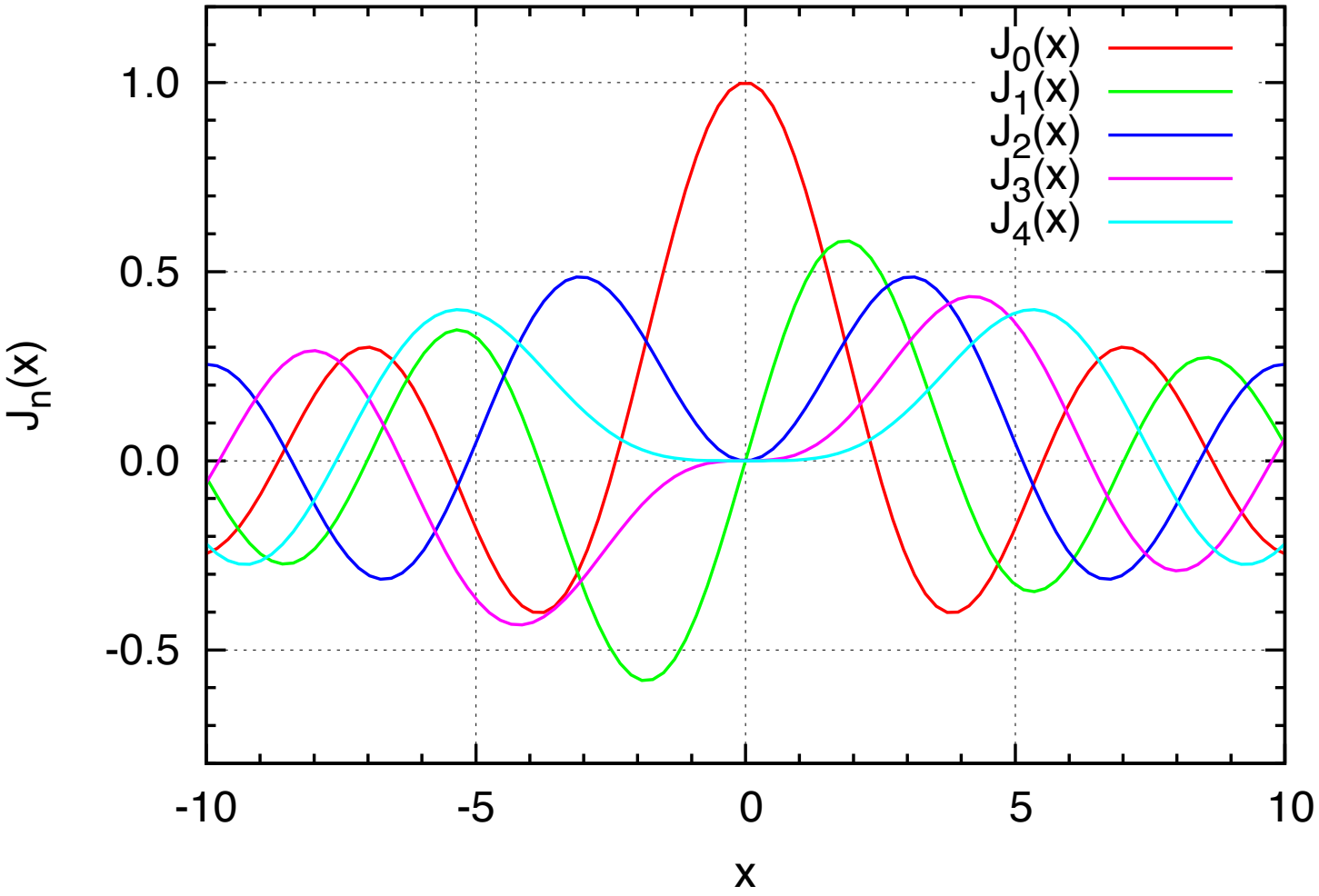
Fourier transform of phase modulation

$$\cos\left(\omega_0 t + \phi - \alpha \sin \Omega t \right)$$

$$= \sum J_n(\alpha) \cos\left[(\omega_0 + n\Omega)t + \phi \right]$$



Bessel functions



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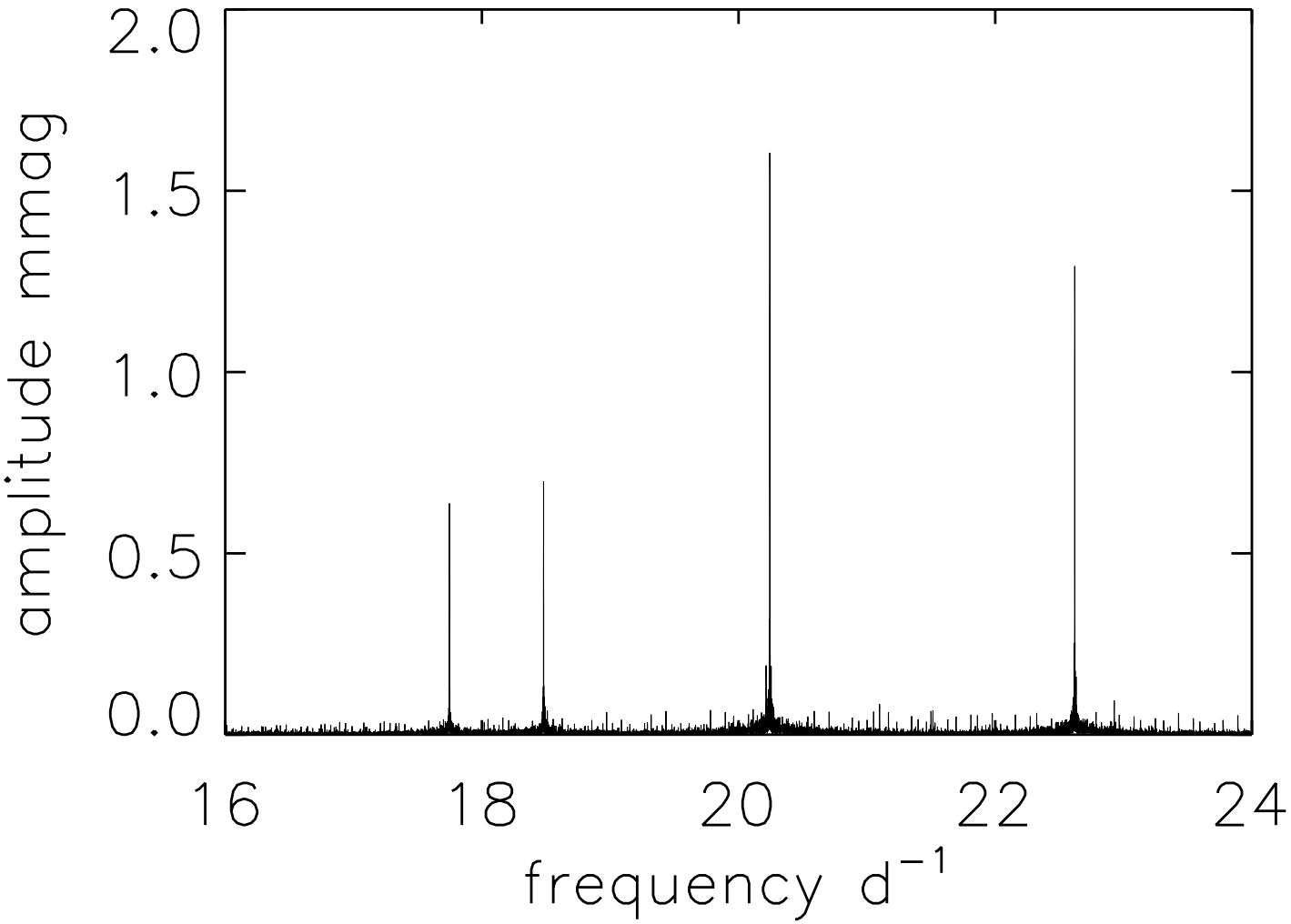

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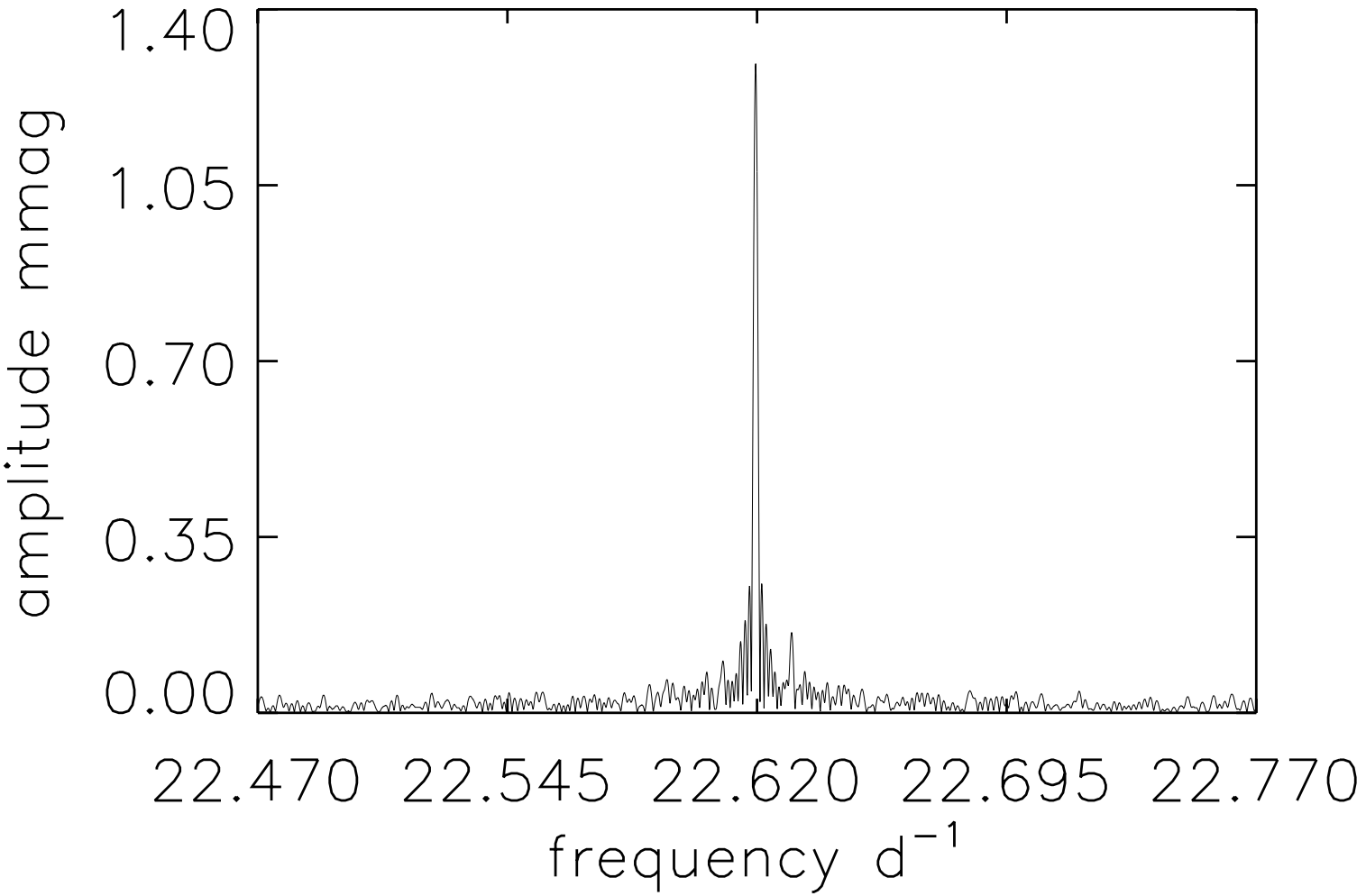
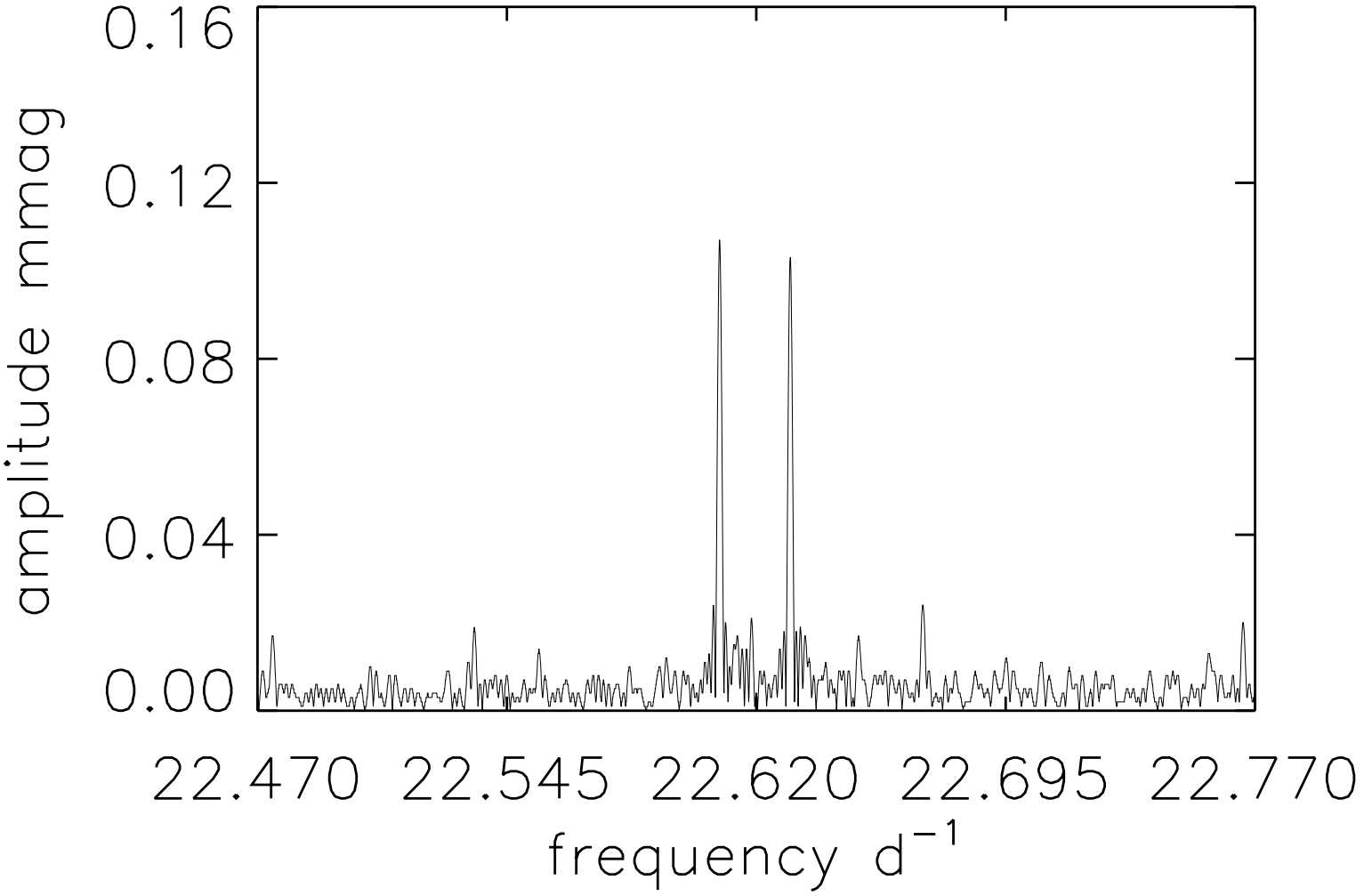

1.40
1.05
0.70
0.35
0.00
amplitude mmag
22.470
22.545
22.620
22.695
22.770
frequency d^{-1}

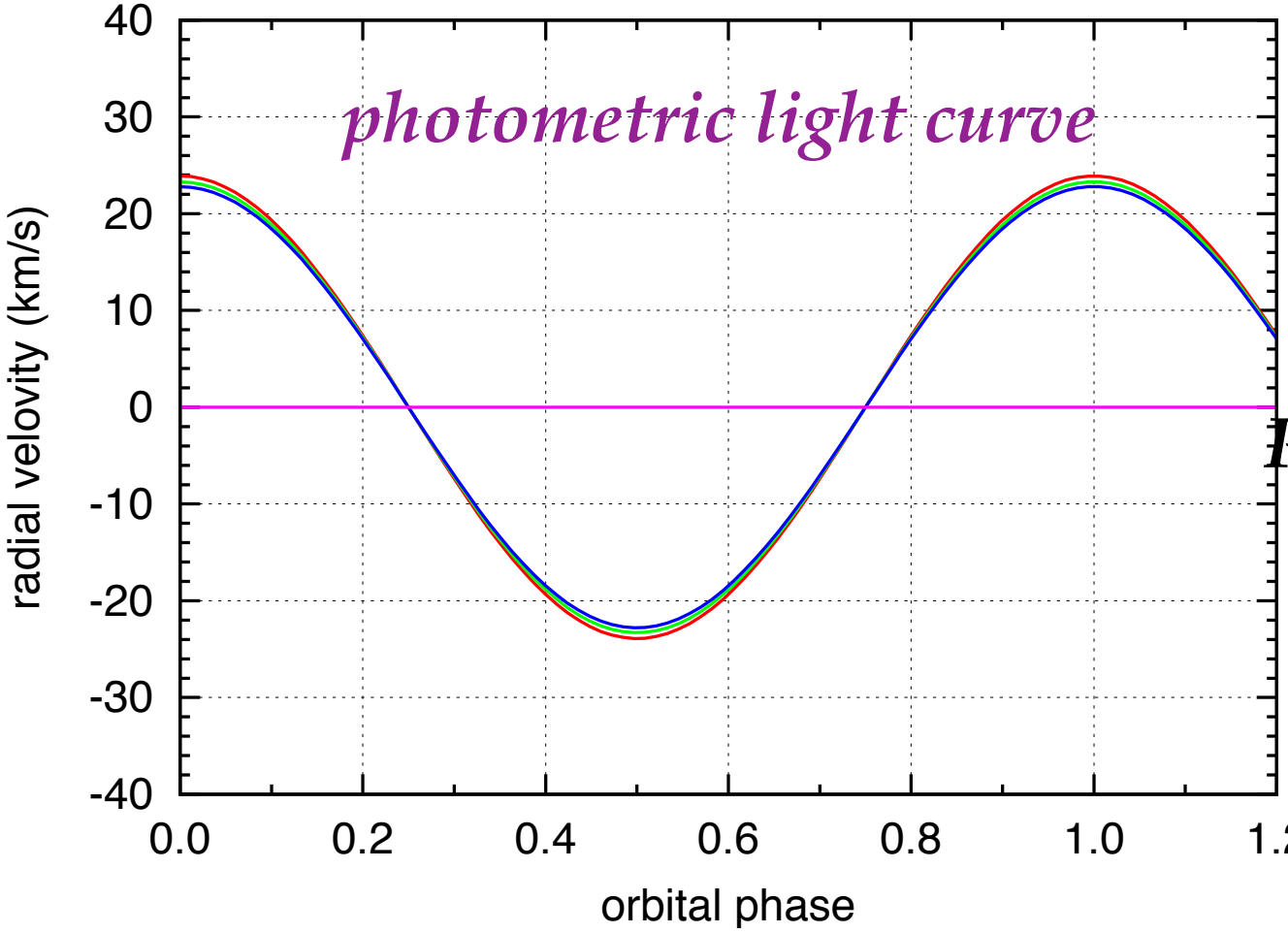
KIC 4150611


0.16
0.12
0.08
0.04
0.00
amplitude mmag
22.470
22.545
22.620
22.695
22.770
frequency d^{-1}

binary parameters determined from FM

frequency d^{-1}	$a_1 \sin i$ au	RV amplitude km s^{-1}	$f(m_1,m_2,\sin i)$ $M_\odot$
17.7466	1.30 ± 0.16	23.9 ± 2.9	0.132 ± 0.116
18.4805	1.30 ± 0.13	23.9 ± 2.4	0.133 ± 0.098
20.2433	1.27 ± 0.05	23.3 ± 1.0	0.124 ± 0.035
22.6196	1.24 ± 0.06	22.8 ± 1.1	0.116 ± 0.034

KIC 4150611



P_{orb}= 94d

$e \lesssim 0.15$

$i \simeq 90°$

Exoplanet hunting

- photometry
  - ★FM of pulsation ⇨ the mass of the planet
  - ★transit ⇨ the size of planet
- The mean density of the planet can be determined from the light curve alone !
- Exoplanet hunting for early type stars

Running Summary

- **Luminosity variations of pulsating stars in binary systems show FM caused by orbital motion.**
- **FT of FM leads to a multiplet separated by the orbital frequency.**
- **The binary parameters can be derived from FT of the light curve alone.**
- **It is possible to detect Jupiter-mass planets orbiting δSct and other pulsating stars with this technique.**

Present work

$$\cos\left[\omega_0\left(t-\frac{1}{c}\int_0^t v_{\mathrm{rad}}(t')\,dt'\right)\right]$$

time delay

$$=\cos\left\{\omega_0 t-\Phi(t)\right\}$$

Phase Modulation **(PM)**

$$\Phi(t):=\frac{\omega_0}{c}\int_0^t v_{\mathrm{rad}}(t')\,dt'$$

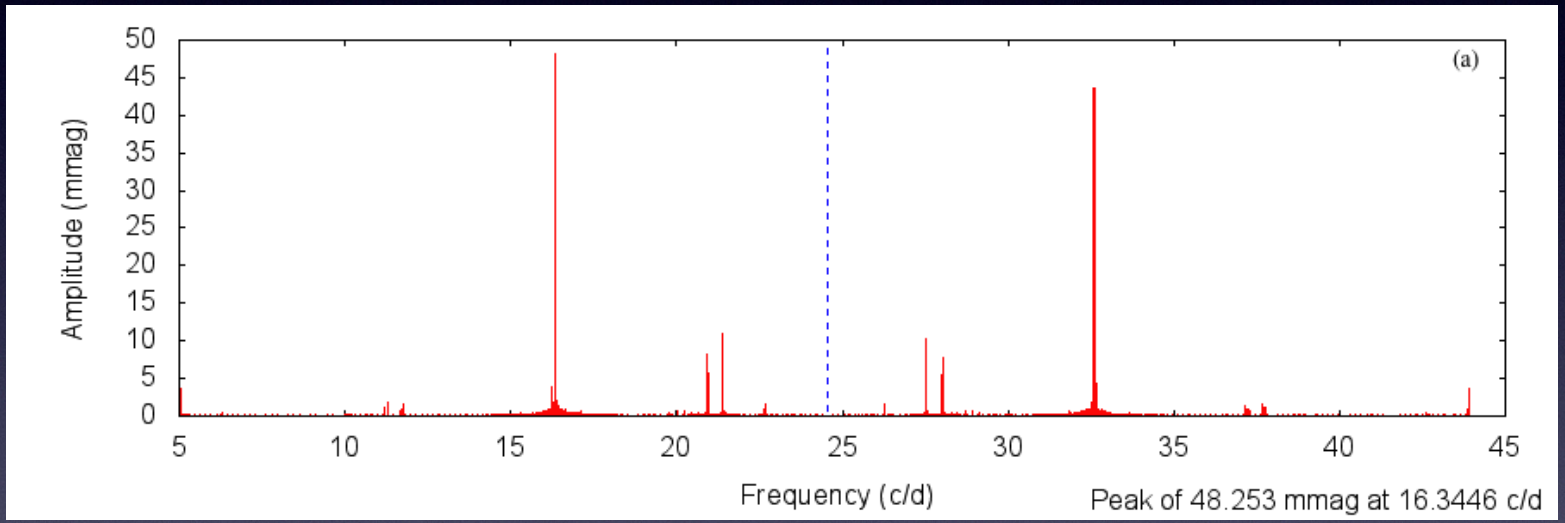
Time delay

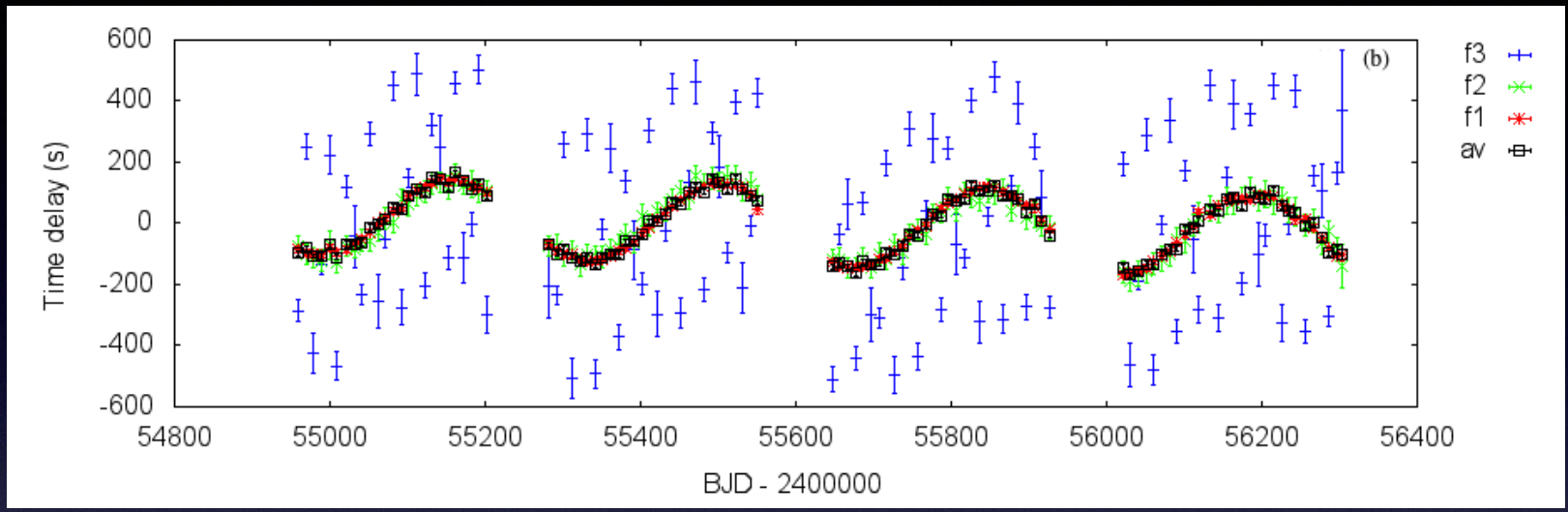
$$\tau(t) = \frac{\Phi(t)}{\omega_0}$$
$$= \sum_{n=1}^{\infty} A_n \sin(n\Omega t + \phi_n)$$

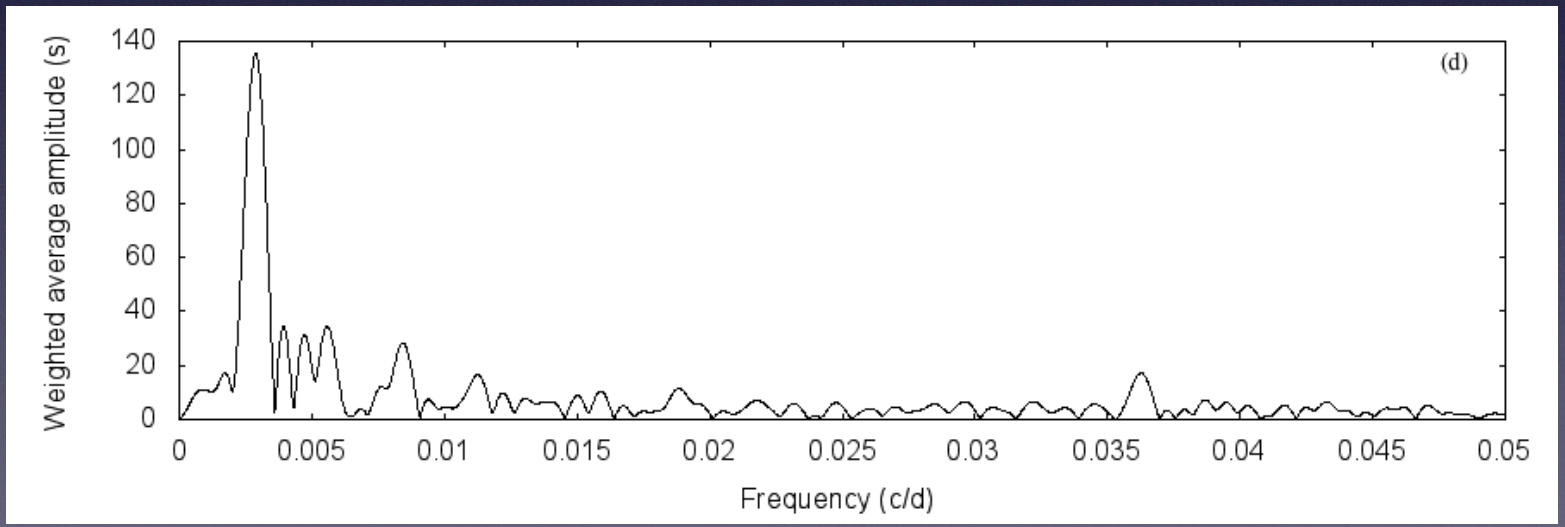
Radial velocity

$$v_{\mathrm{rad}}(t) = c\frac{d\tau(t)}{dt}$$

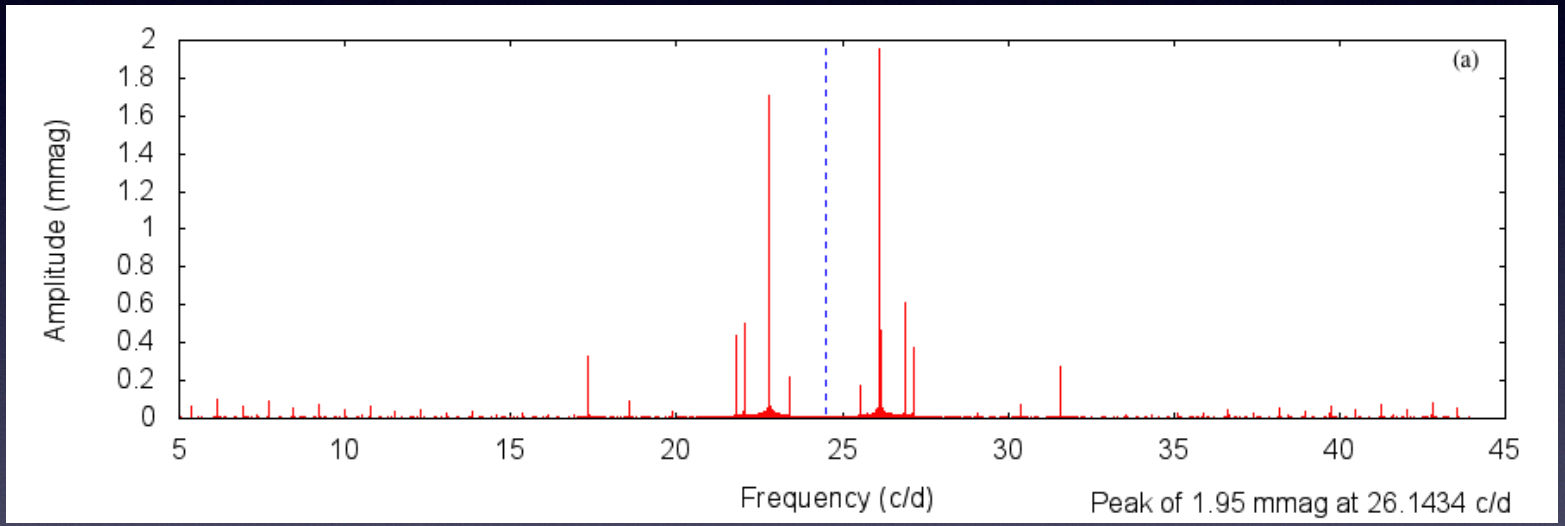
KIC 11754974



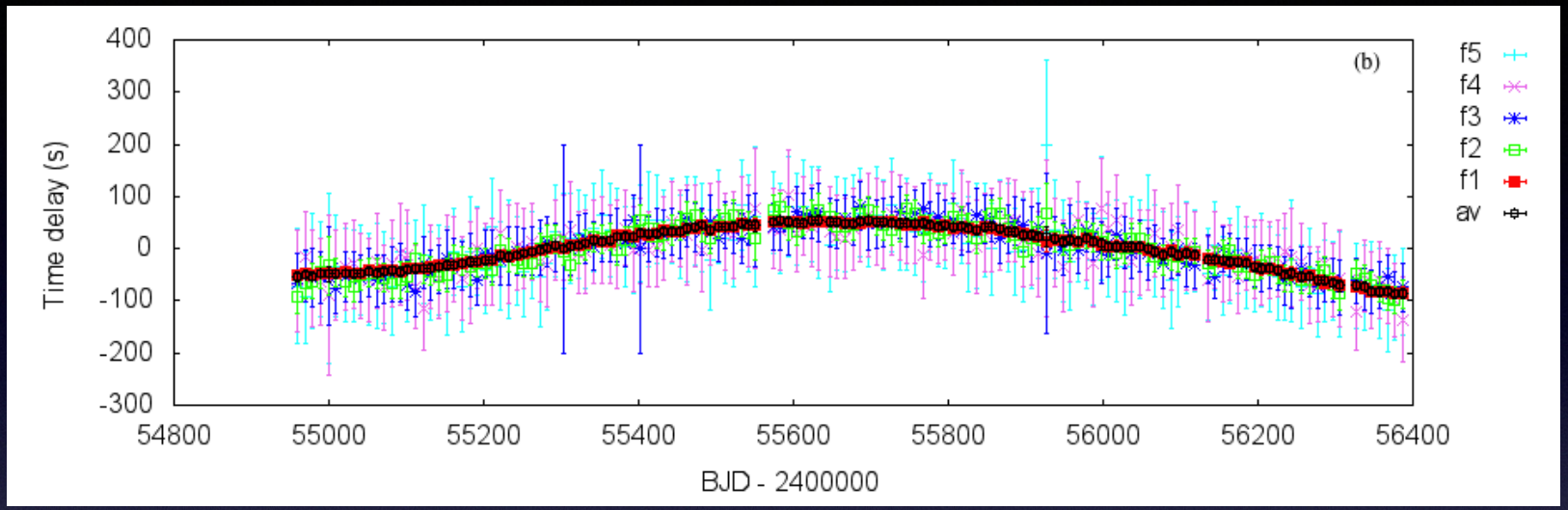

(b)
f3
f2
f1
av
Time delay (s)
600
400
200
0
-200
-400
-600
54800
55000
55200
55400
55600
55800
56000
56200
56400
BJD - 2400000

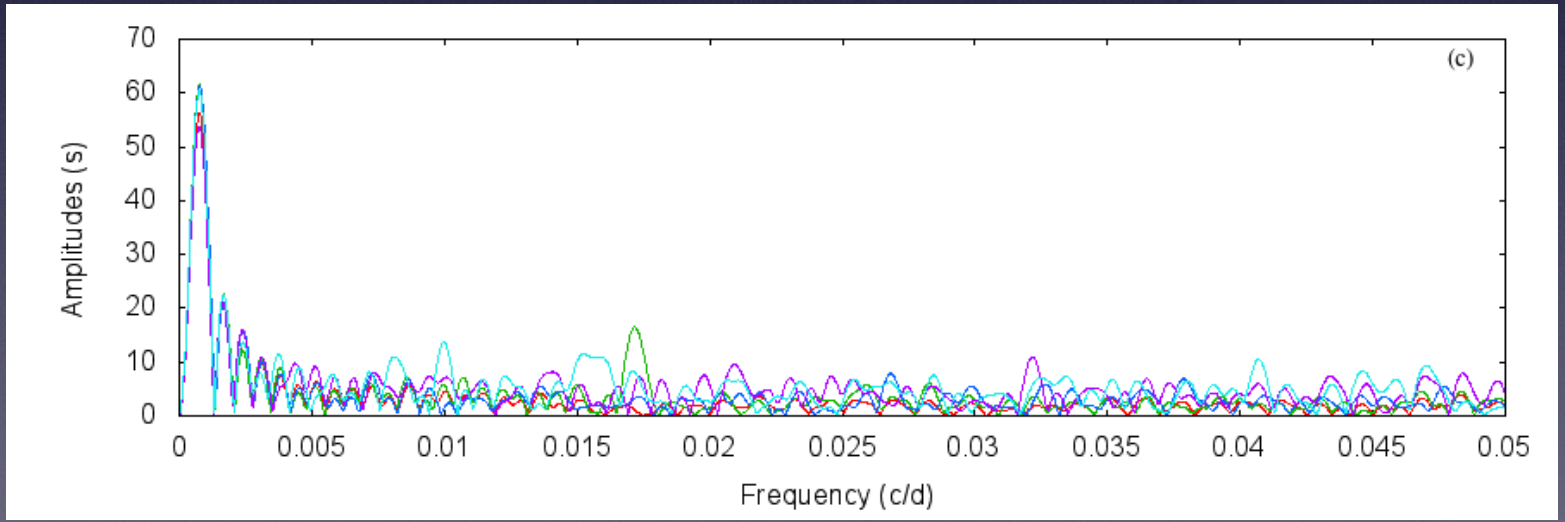

(d)
Weighted average amplitude (s)
140
120
100
80
60
40
20
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Frequency (c/d)

KIC 7618364

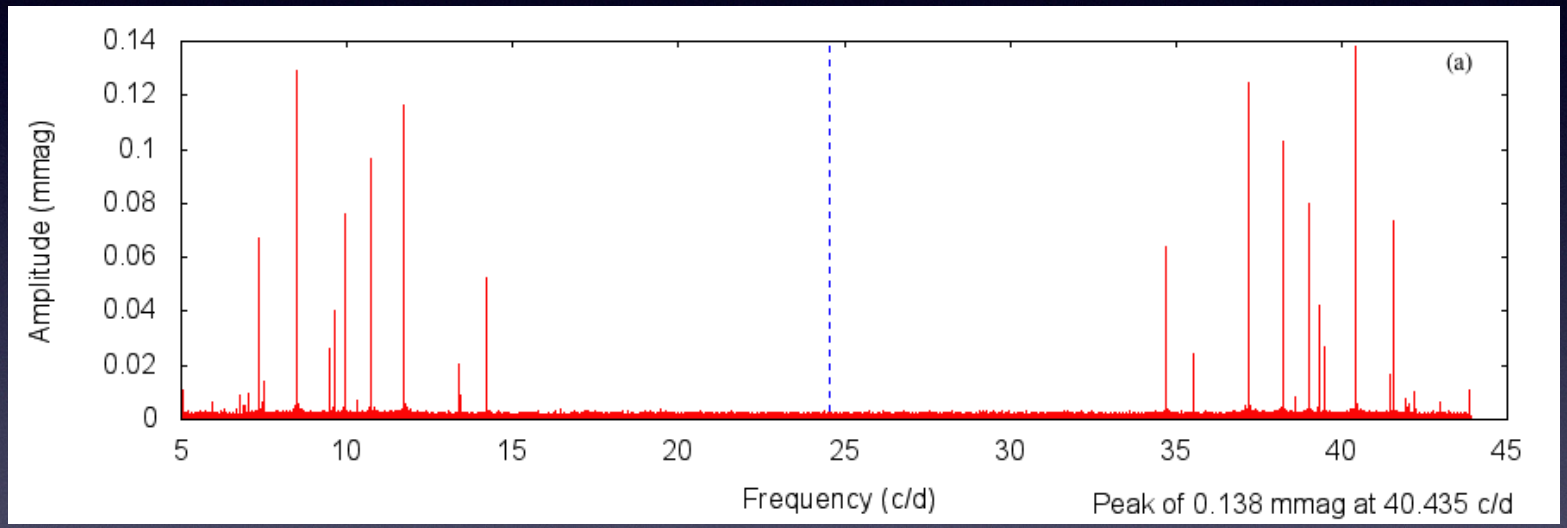


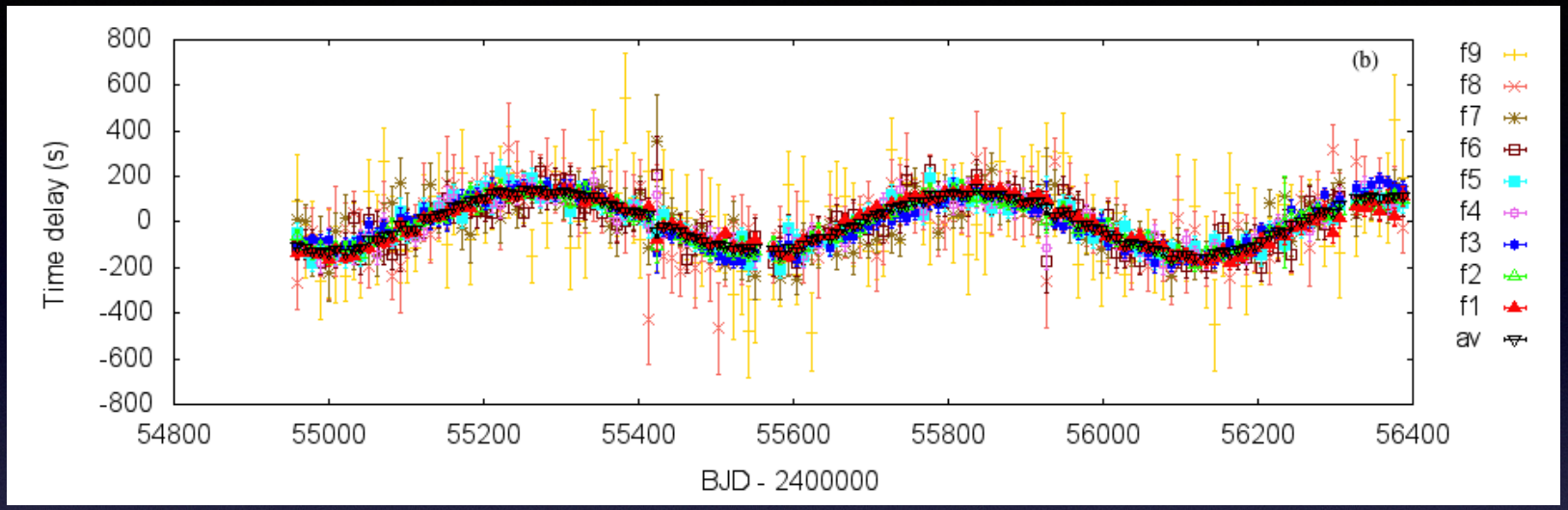
super Nyquist

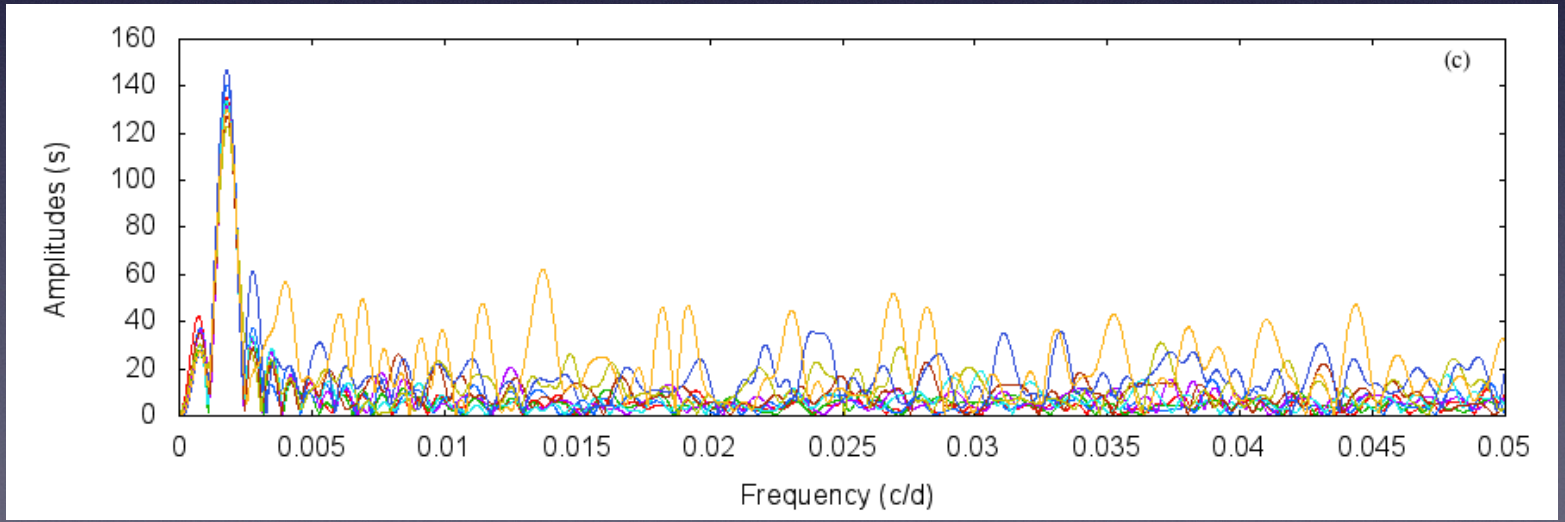

(b)
Time delay (s)
400
300
200
100
0
-100
-200
-300
54800
55000
55200
55400
55600
55800
56000
56200
56400
BJD - 2400000
f5
f4
f3
f2
f1
av


(c)
Amplitudes (s)
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Frequency (c/d)

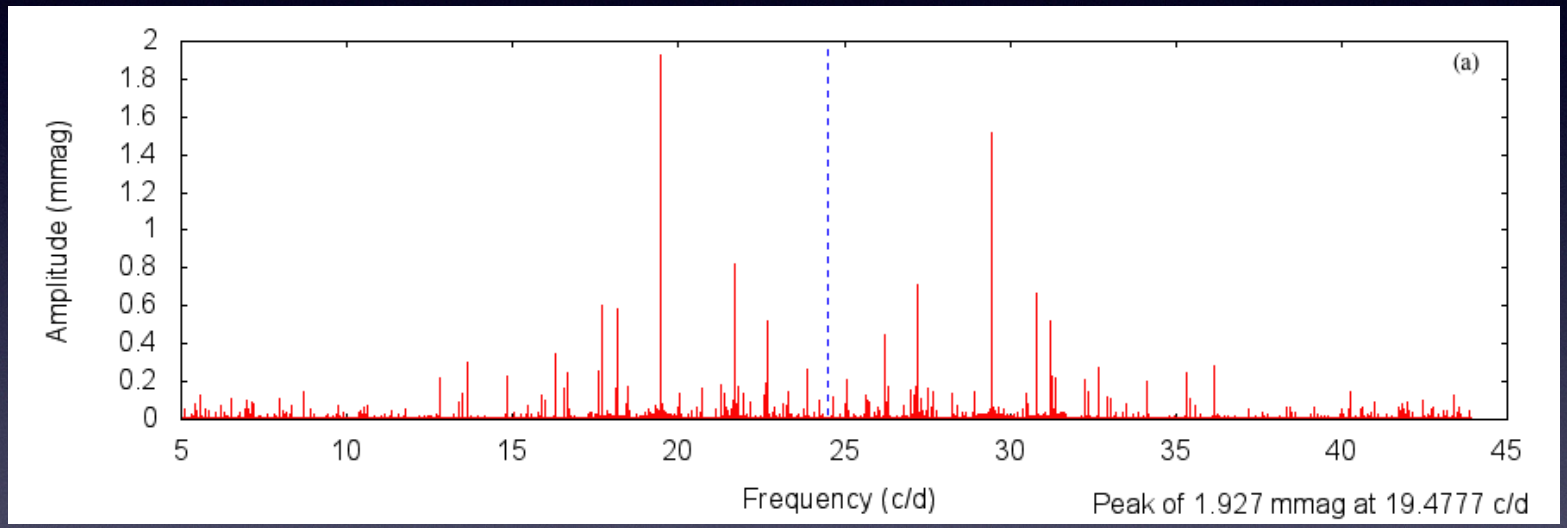
KIC 11771670

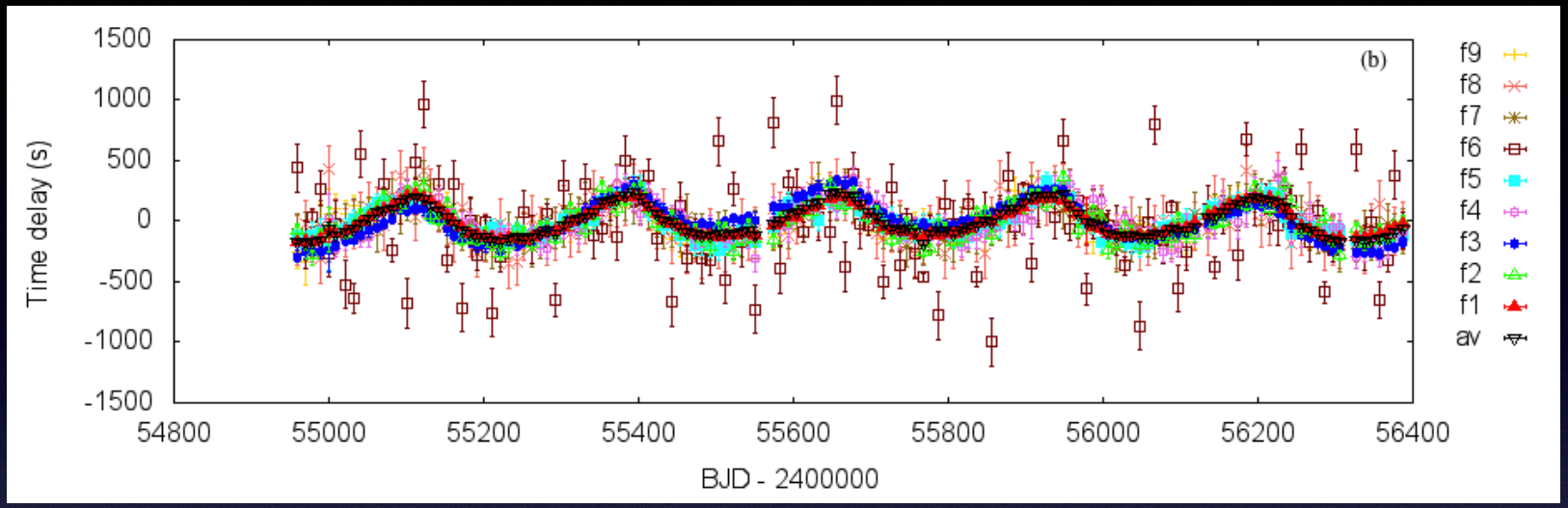



(b)
Time delay (s)
800
600
400
200
0
-200
-400
-600
-800
54800
55000
55200
55400
55600
55800
56000
56200
56400
BJD - 2400000
f9
f8
f7
f6
f5
f4
f3
f2
f1
av

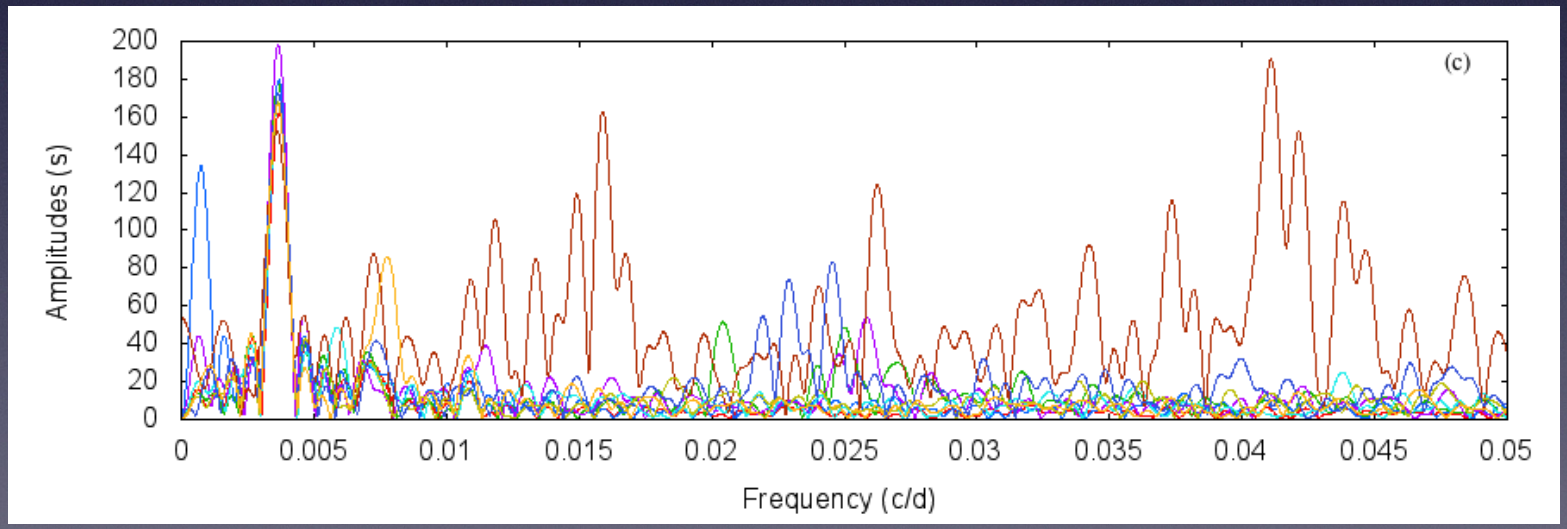

(c)
Amplitudes (s)
160
140
120
100
80
60
40
20
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Frequency (c/d)

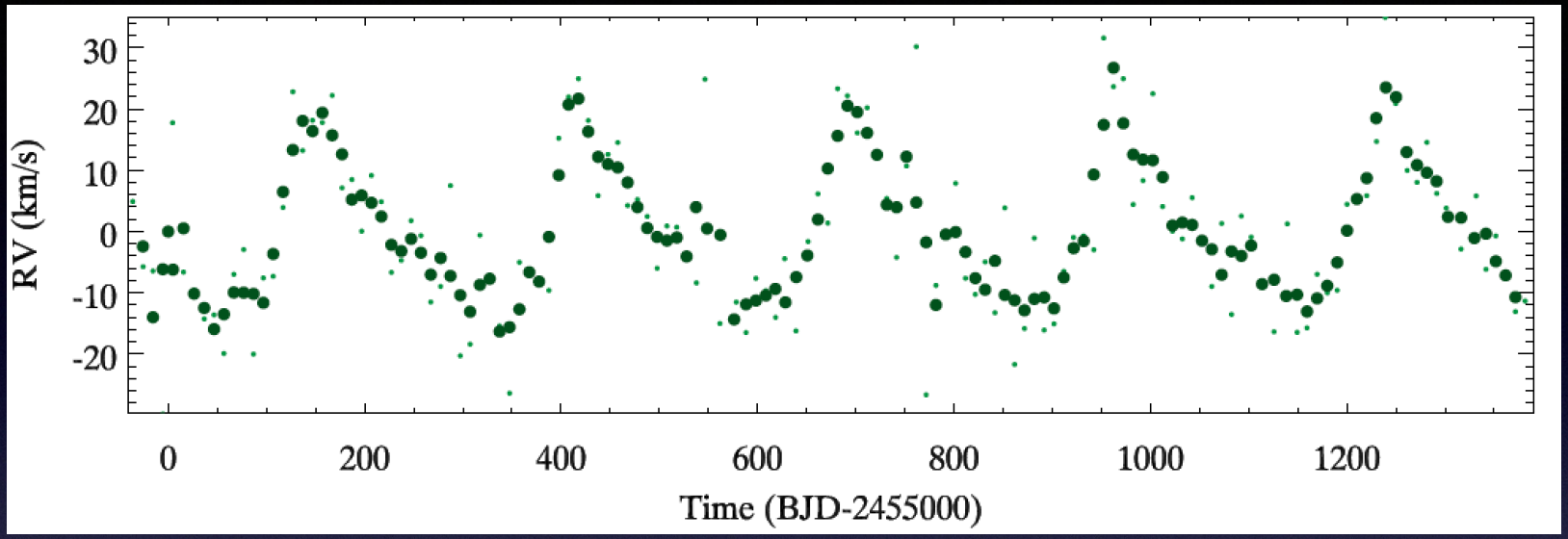
KIC 9651065

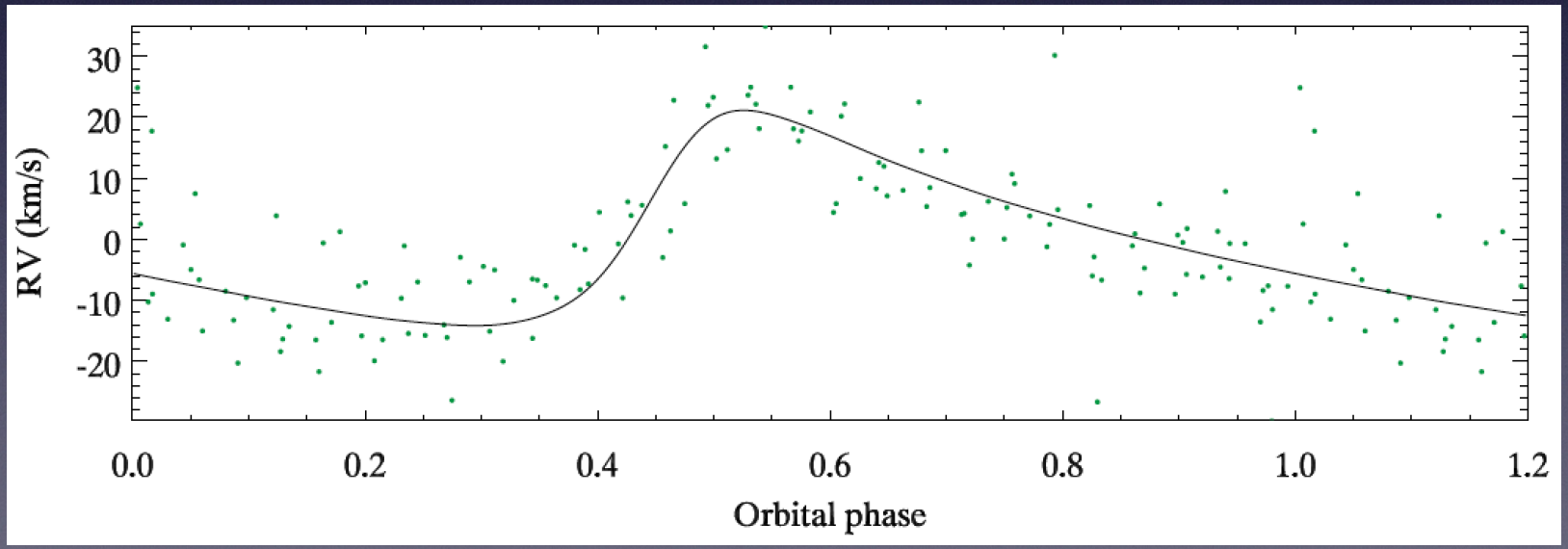

(a)
Amplitude (mmag)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
35
40
45
Frequency (c/d)
Peak of 1.927 mmag at 19.4777 c/d



nonlinear -> highly eccentric orbit

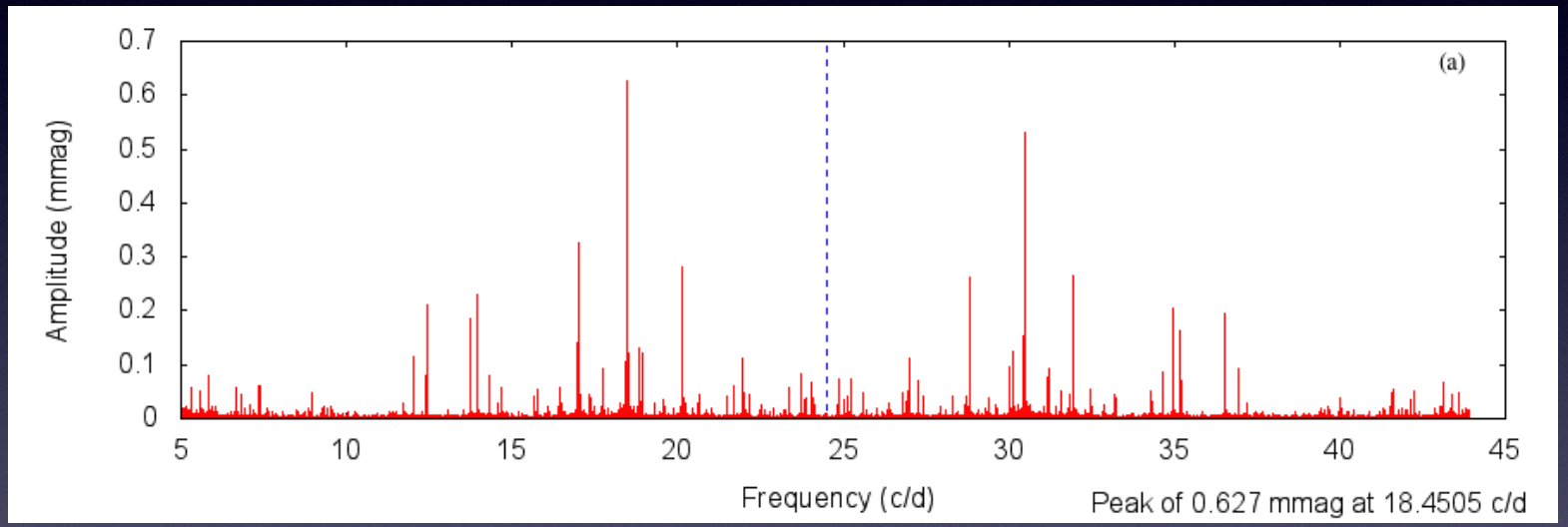


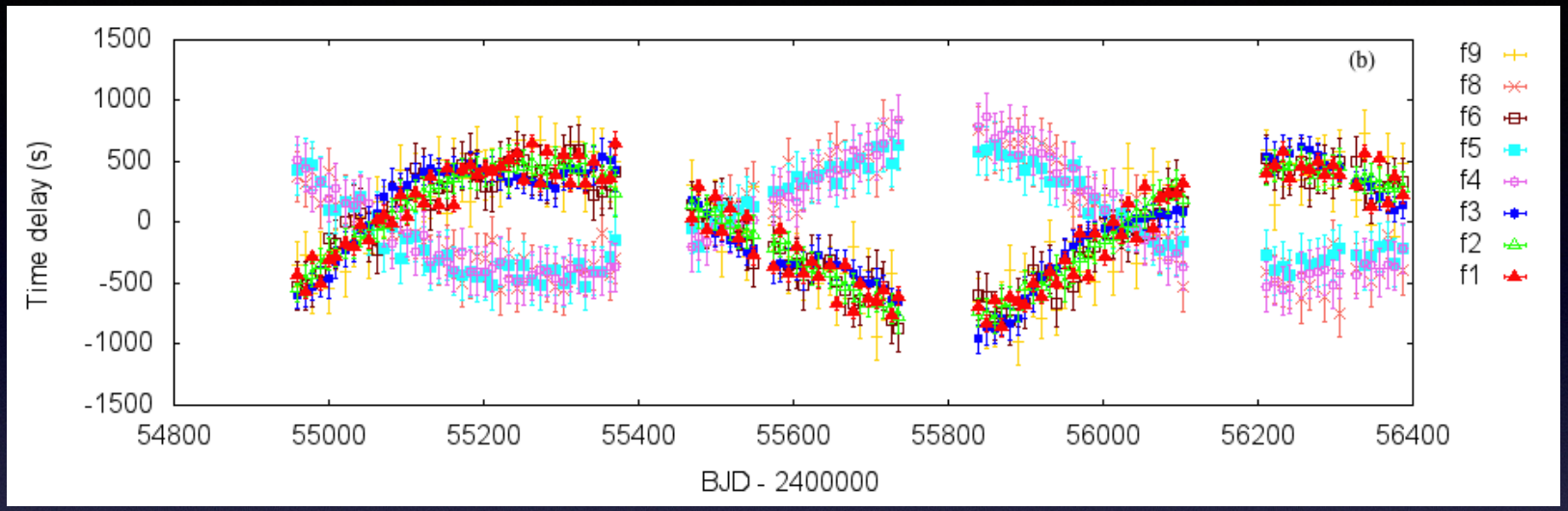

RV (km/s)
30
20
10
0
-10
-20
0
200
400
600
800
1000
1200
Time (BJD-2455000)

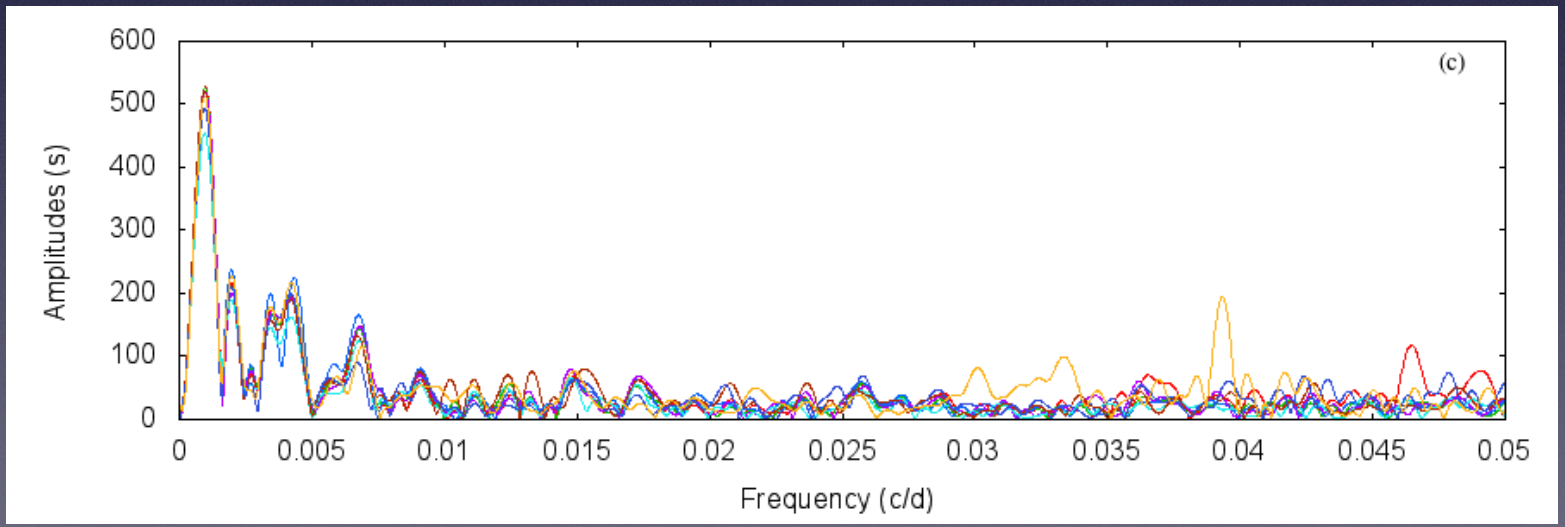

RV (km/s)
30
20
10
0
-10
-20
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Orbital phase

A binary with two pulsating components

KIC 4471379




(b)
Time delay (s)
1500
1000
500
0
-500
-1000
-1500
54800
55000
55200
55400
55600
55800
56000
56200
56400
BJD - 2400000
f9
f8
f6
f5
f4
f3
f2
f1


(c)
Amplitudes (s)
600
500
400
300
200
100
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Frequency (c/d)

Advantages of PM

- Easy for automation
- Visualisation
- Time-domain presentation

Summary

- Preparation: some basics
- Helioseismology: new eyes to see the invisible solar interior
- Sounds of stars: Asteroseismology and Keplerian revolution
- Interesting new techniques inspired by Kepler
    - Super-Nyquist asteroseismology
    - FM stars