ELTE “Az atomoktól a csillagokig” előadássorozat
2016. február 18.

Csillagrengések kutatása: hogyan tekinthetünk be a csillagok belsejébe?

Kiss L. László

MTA Csillagászati és Földtudományi Kutatóközpont

Csillagászati Intézet

Vörös óriásoktól...

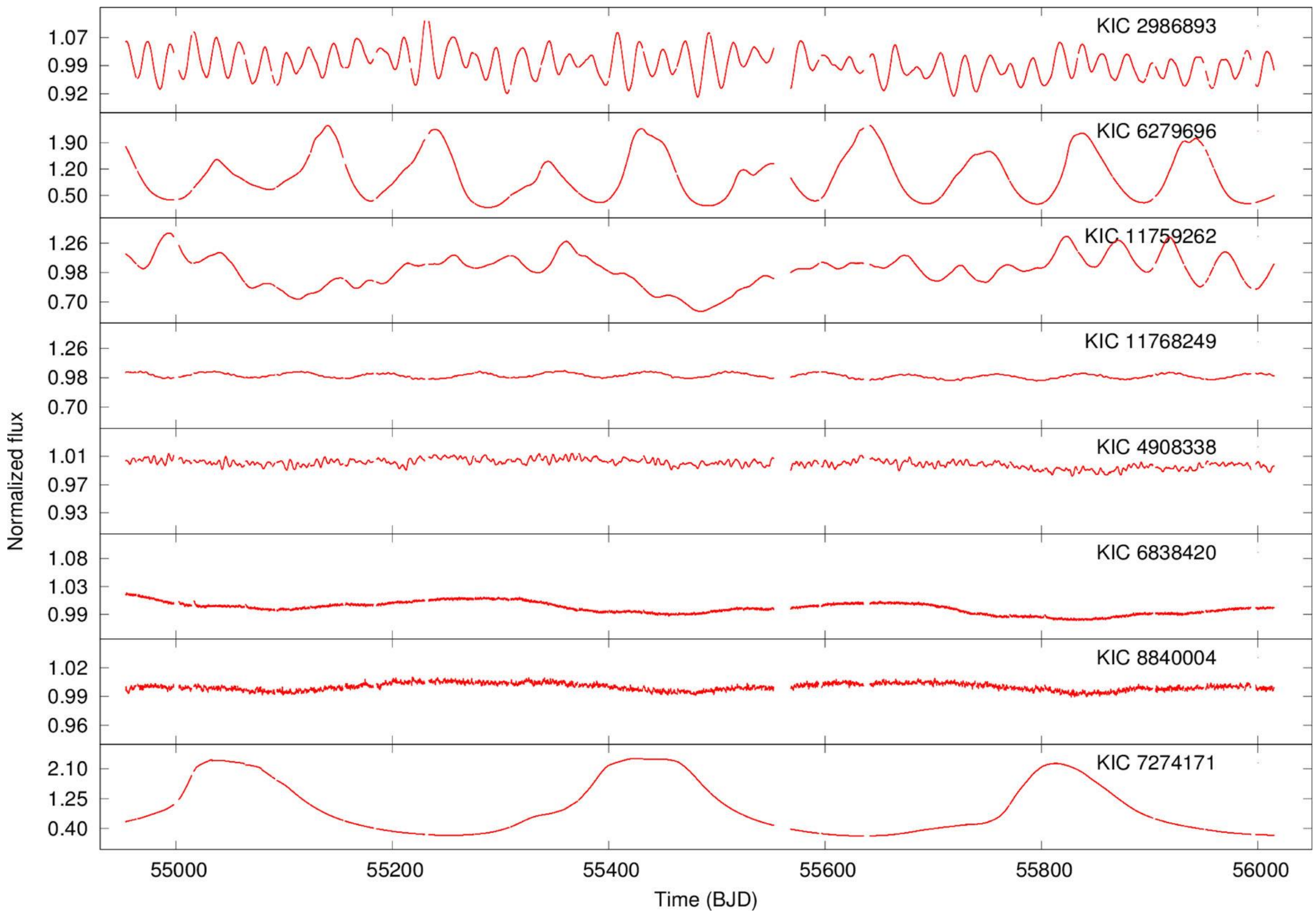


Figure 4. Data for the same stars as in Fig. 2 after the correcting procedure.

...a fehér törpékig

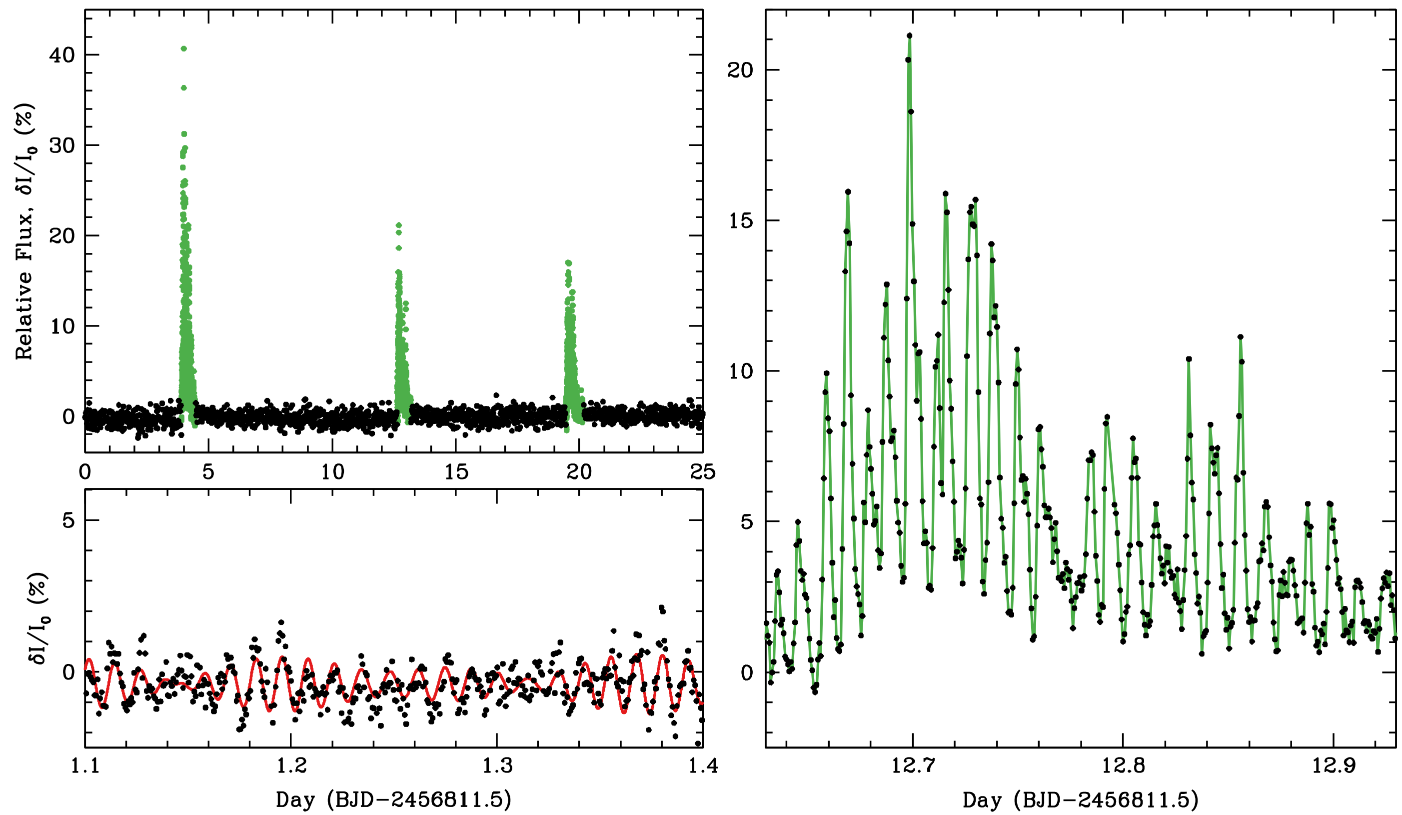
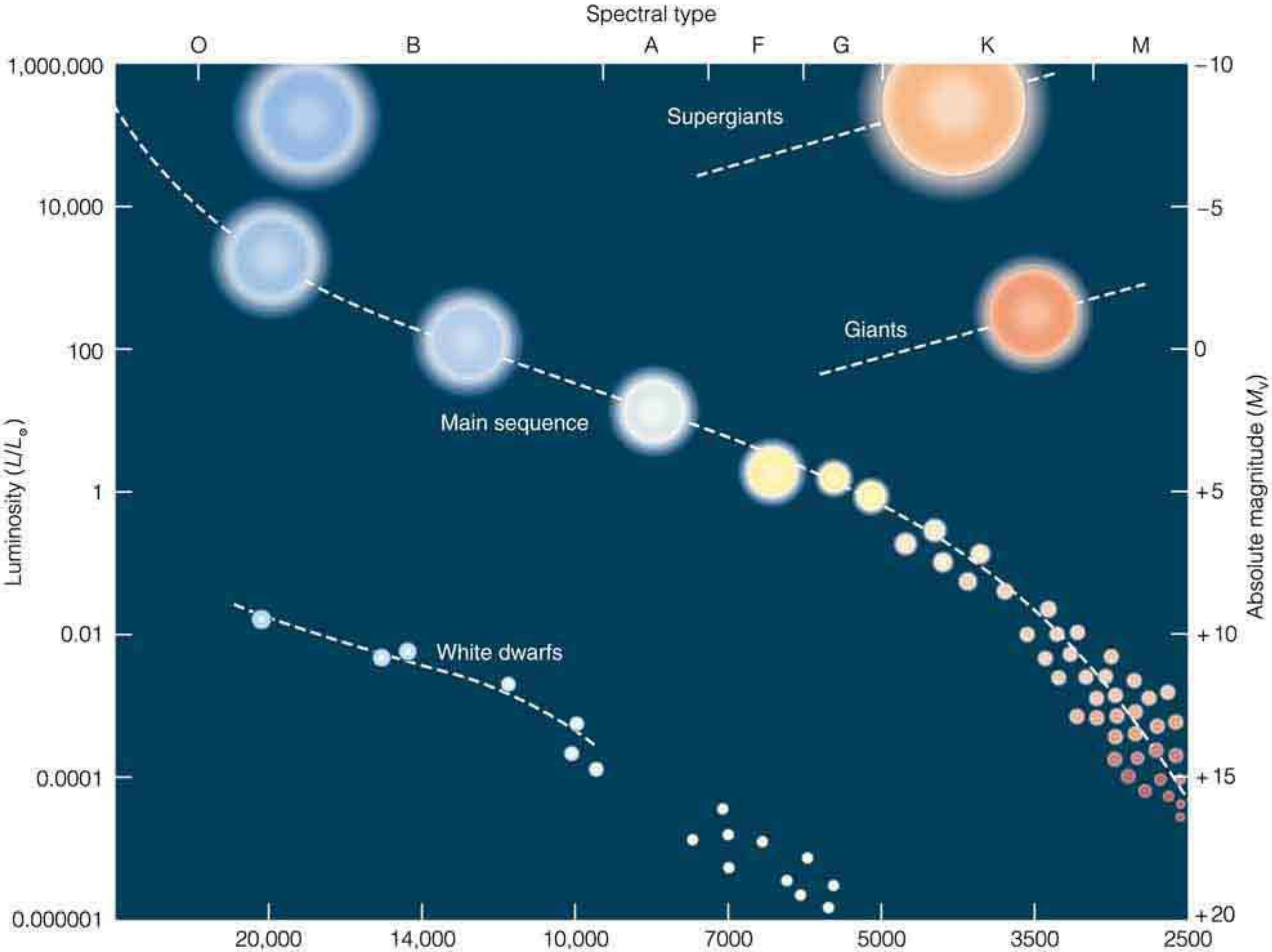
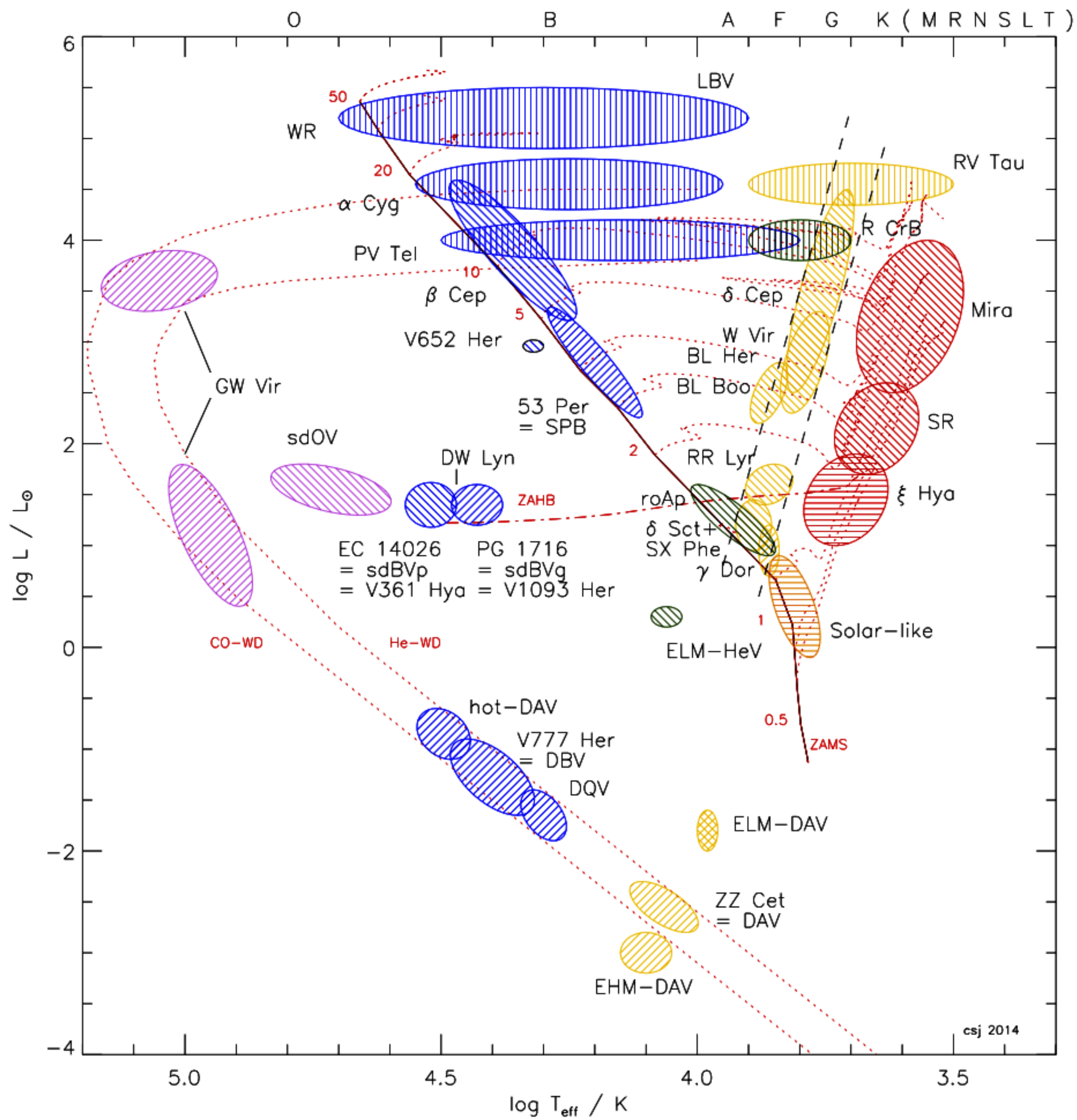


Figure 1. Representative portions of the *K2* Campaign 1 light curve of the pulsating white dwarf PG 1149+057. The top left panel shows the first 25 days of observations; three outburst events are denoted in green. The bottom left panel shows 7.2 hr of data on the second day of *K2* observations; the white dwarf pulsations are clearly visible, and underplotted is a best-fit to the three highest-amplitude signals (with periods of 1145.7, 998.1, and 1052.8 s). The right panel shows 7.2 hr during the second outburst, with points connected in green.

Hertzsprung–Russell-diagram




O B A F G K (M R N S L T)
LBV
WR
RV Tau
α Cyg
R CrB
PV Tel
β Cep
δ Cep
Mira
V652 Her
W Vir
BL Her
GW Vir
BL Boo
53 Per
= SPB
SR
sdOV
DW Lyn
RR Lyr
ZAHB
roAp
ξ Hya
δ Sct+
SX Phe
γ Dor
EC 14026
= sdBVp
= V361 Hya
PG 1716
= sdBVg
= V1093 Her
ELM−HeV
Solar−like
CO−WD
He−WD
ZAMS
hot−DAV
V777 Her
= DBV
DQV
ELM−DAV
ZZ Cet
= DAV
EHM−DAV
csj 2014
log L / L⊙
log Teff / K

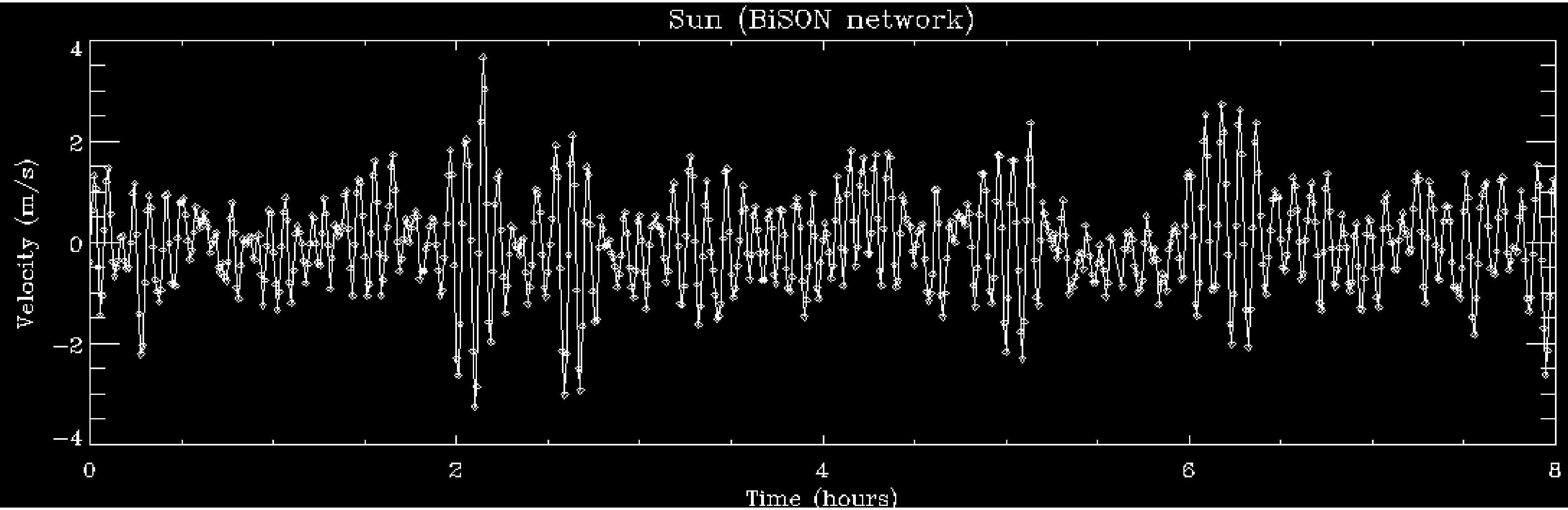
Mire jók a csillagok rezgései?

- a pulzáció fizikájának megértése (pl. gerjesztési és csillapítási mechanizmusok)
- meghatározhatók a csillagok tulajdonságai (sűrűség, kor, belső forgás, távolság, stb.)
- tesztelik az anyag fizikáját szélsőséges körülmények között (pl. opacitások, napneutrínó-probléma)

Hogyan mérhetjük meg egy csillag rezgéseit?

- fényességváltozás
- sebességváltozás

A Nap sebességgörbéje



BiSON (Birmingham Solar Oscillations Network)

Hogyan észlelhetjük más csillagok parányi rezgéseit?

Exobolygók: 51 Pegasi (1995)

ARTICLES

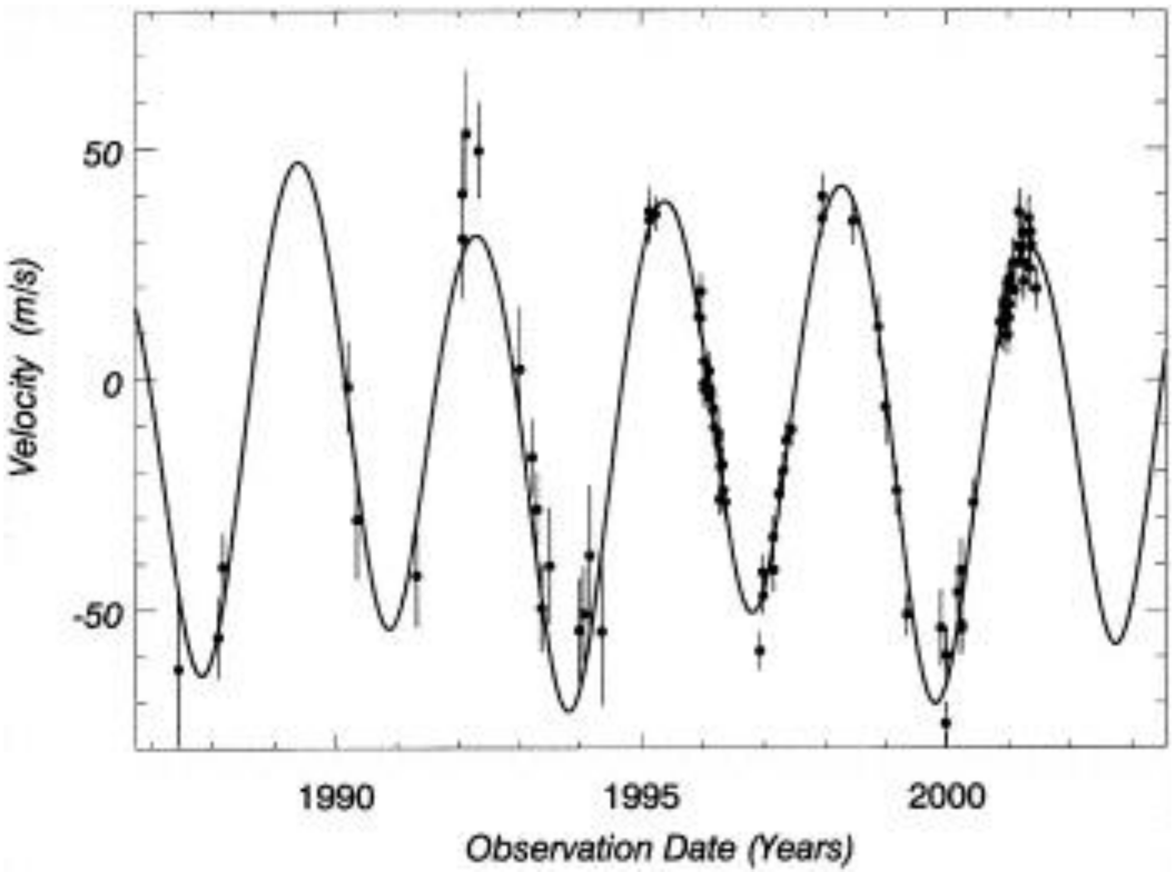
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

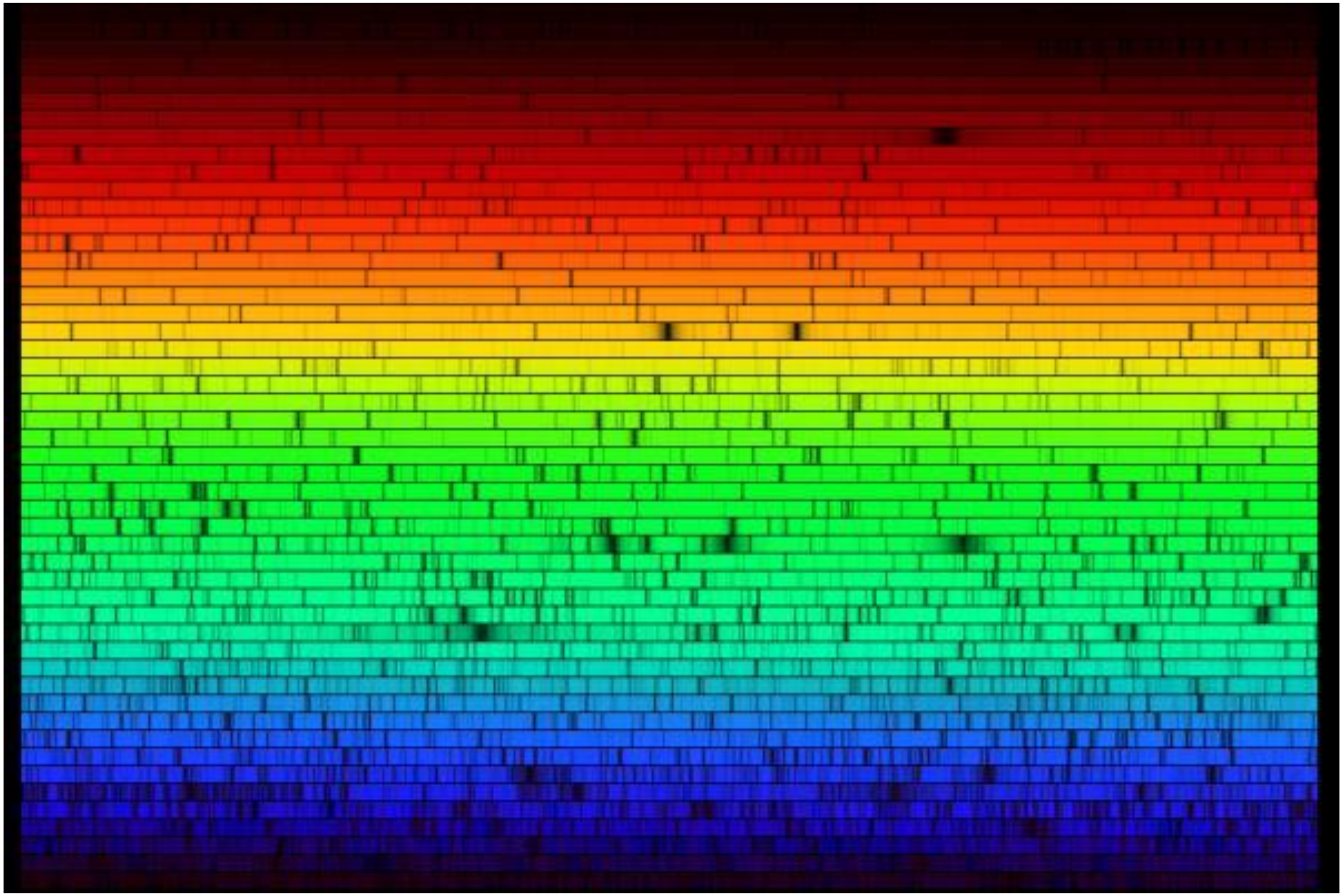
The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

15 éve az exobolygászokkal!



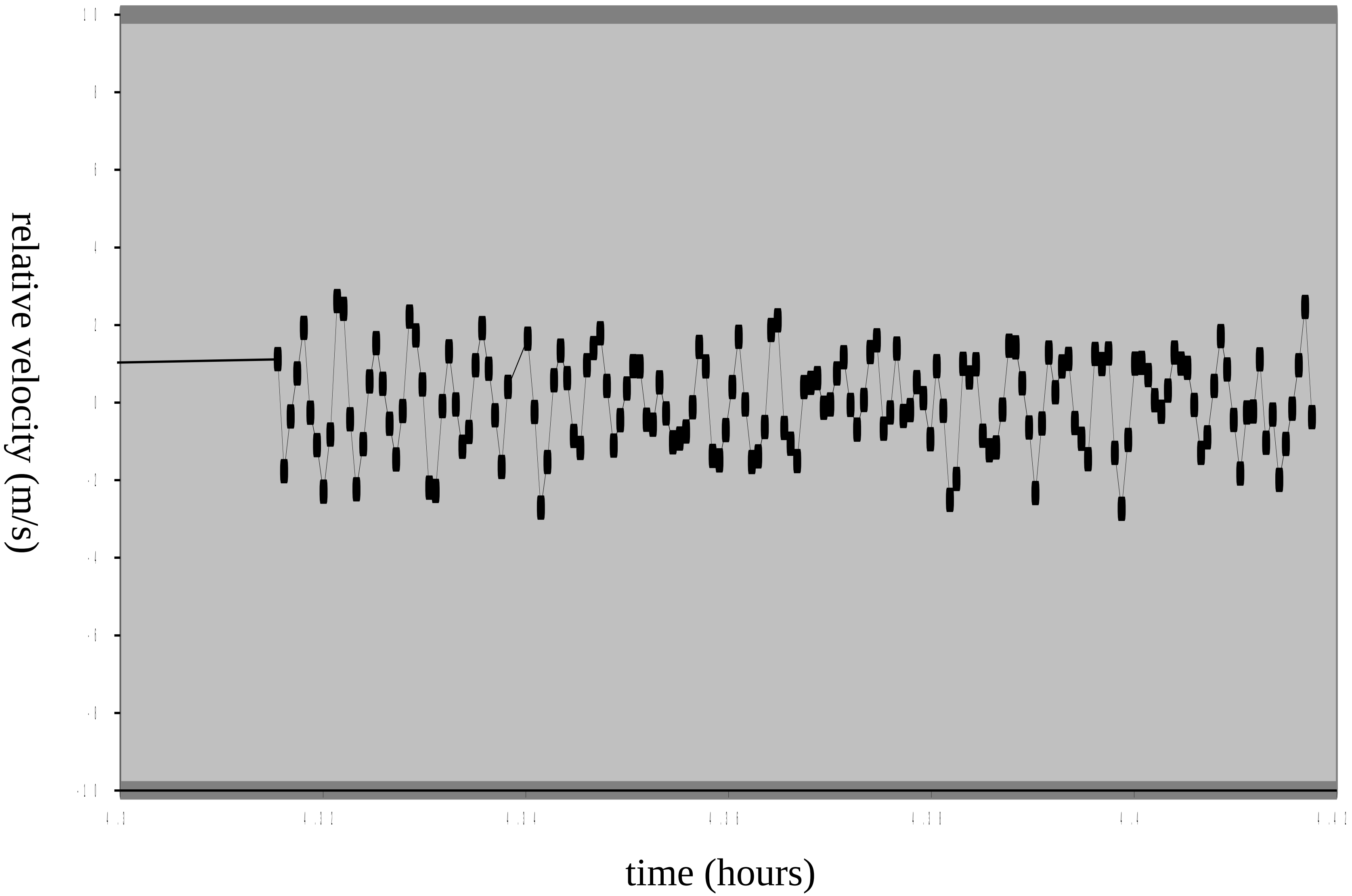
47 UMa (Fischer et al. 2002)

A Nap spektruma

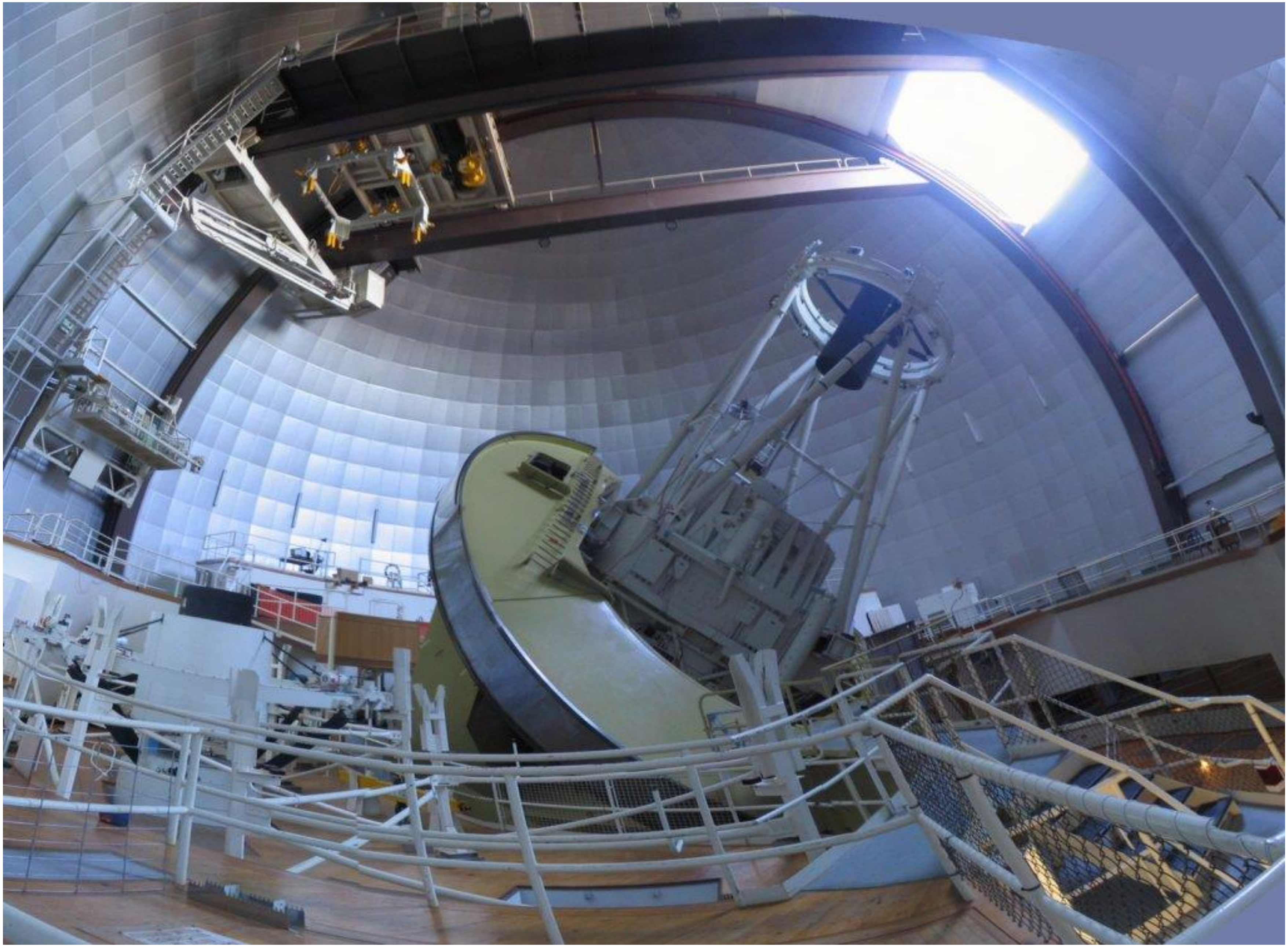


Egy jódcella és más semmi...

A Nap rezgései a nappali ég spektrumából (HARPS)

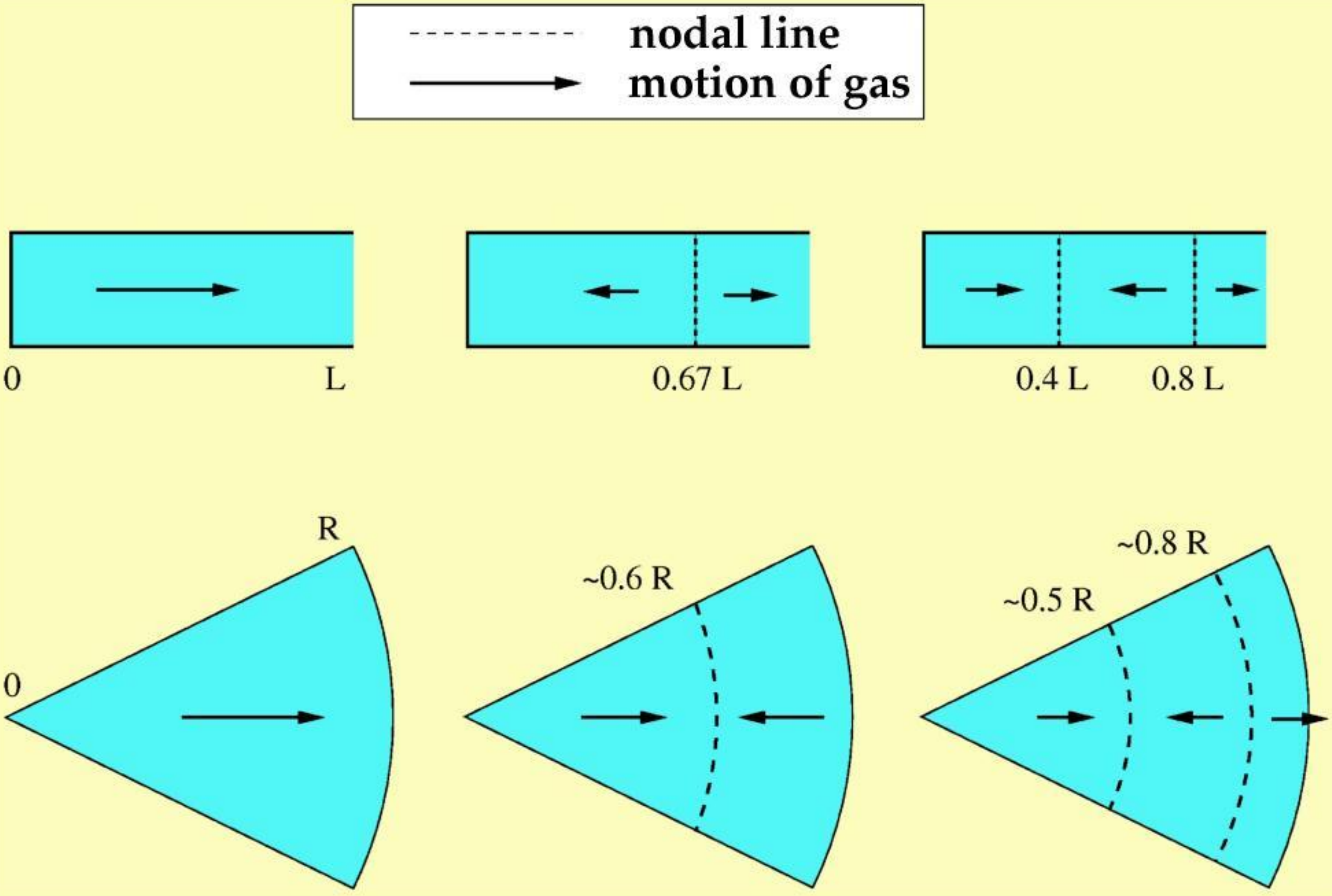


A világ legnagyobb naptávcsöve



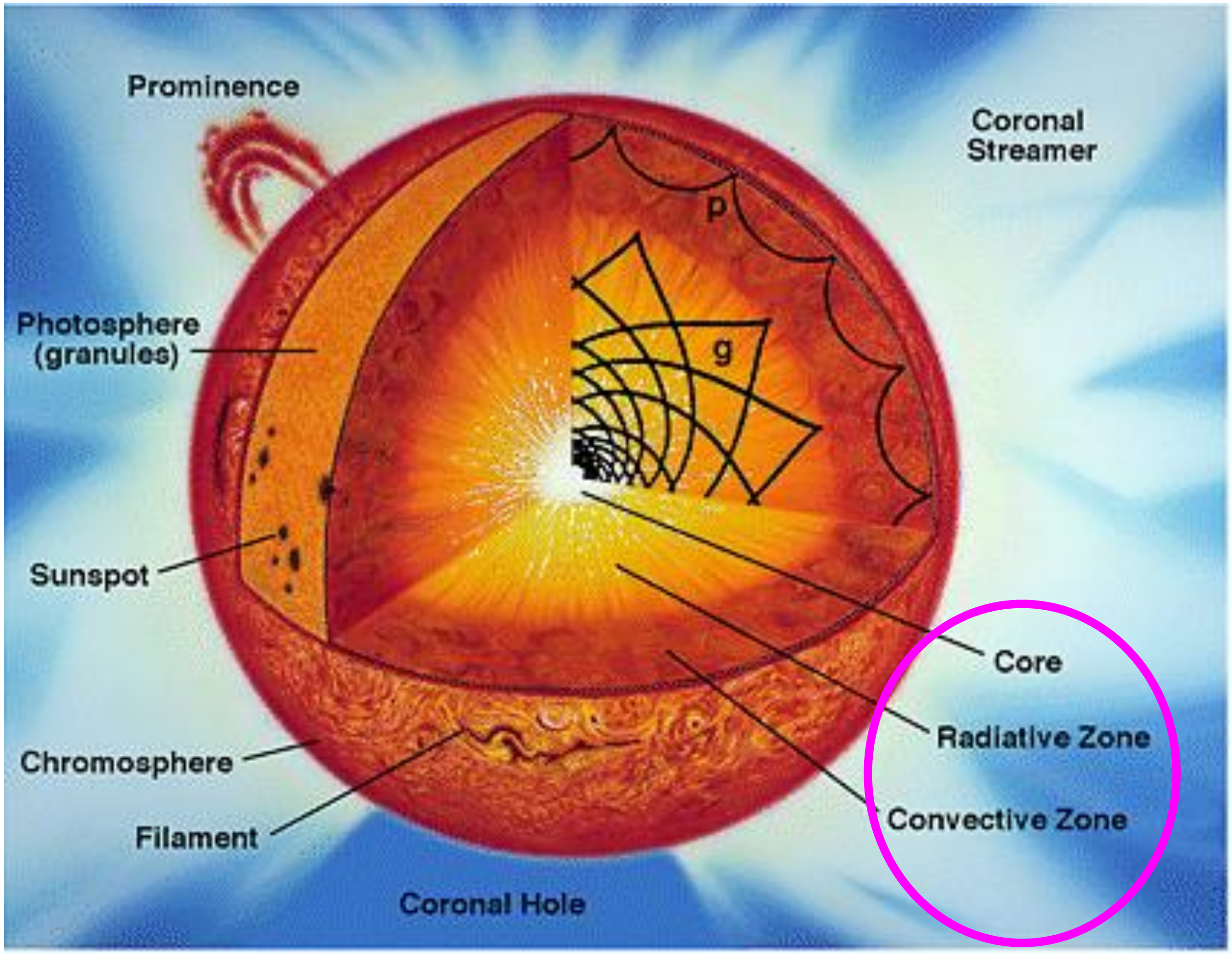
Milyen rezgések ezek?

- hanghullámok (p-módusok)
- gravitációs hullámok (g-módusok) (NEM a tér gravitációs hullámai)

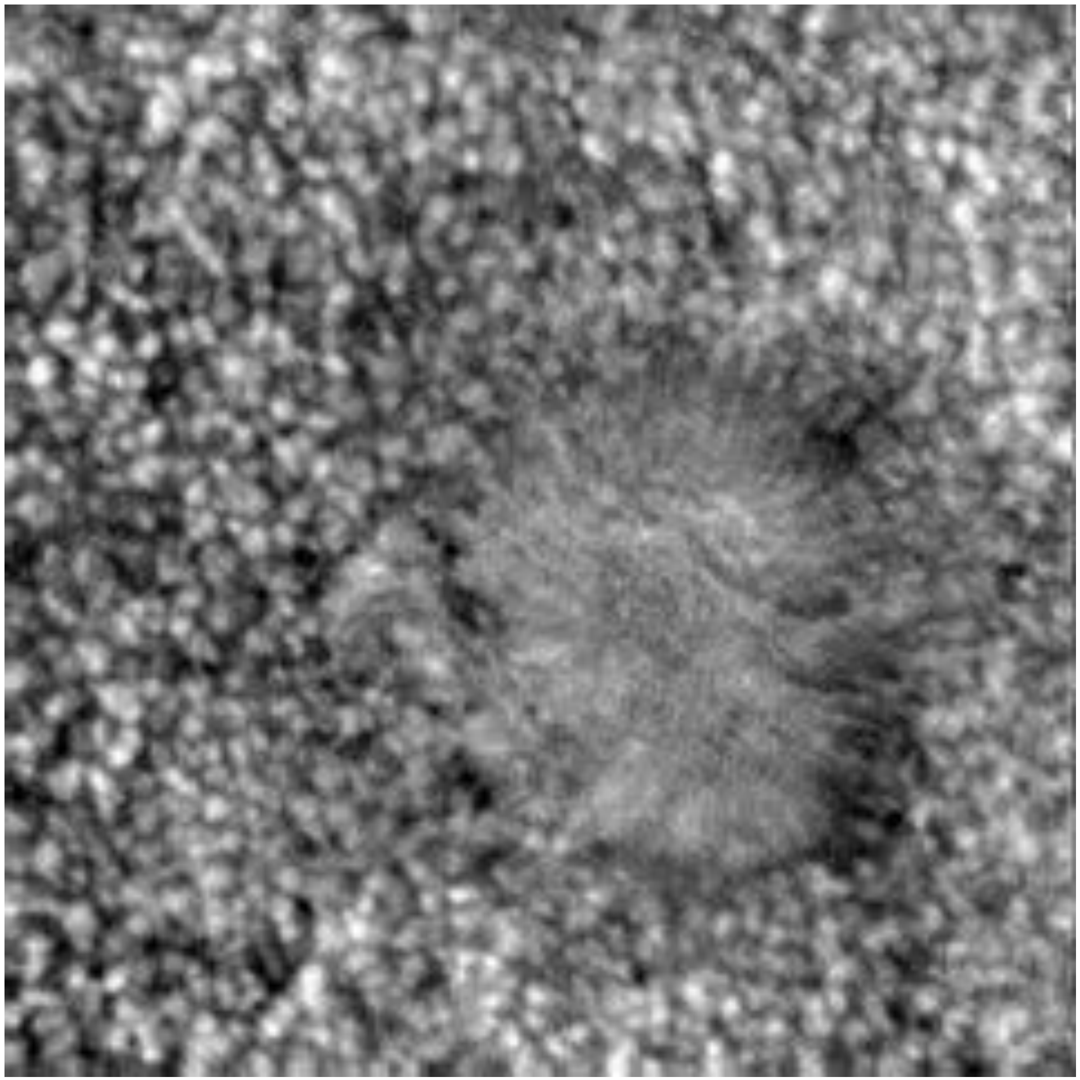


nodal line
motion of gas
0
L
0.67 L
0.4 L
0.8 L
R
0
~0.6 R
~0.5 R
~0.8 R

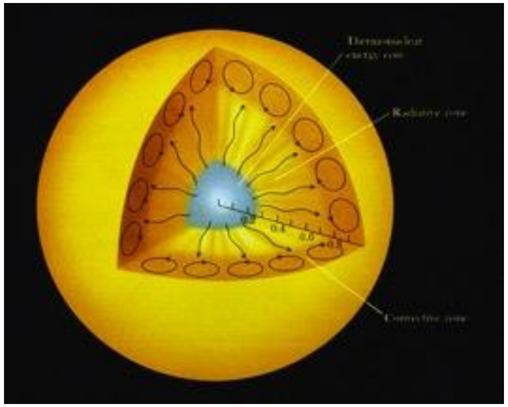
A Nap belsejében



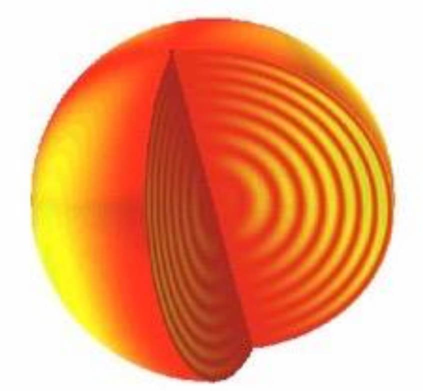
A konvekció gerjeszti a rezgéseket



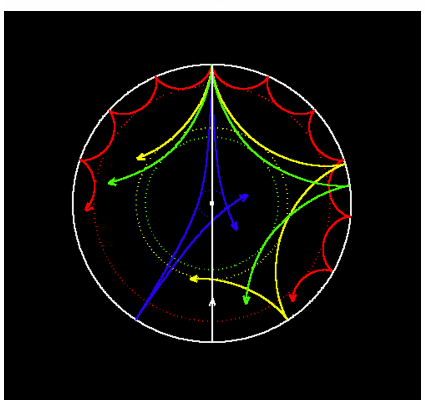
Nap típusú csillagrezgések



A konvektív zóna rezgéseket gerjeszt a felszín közelében.



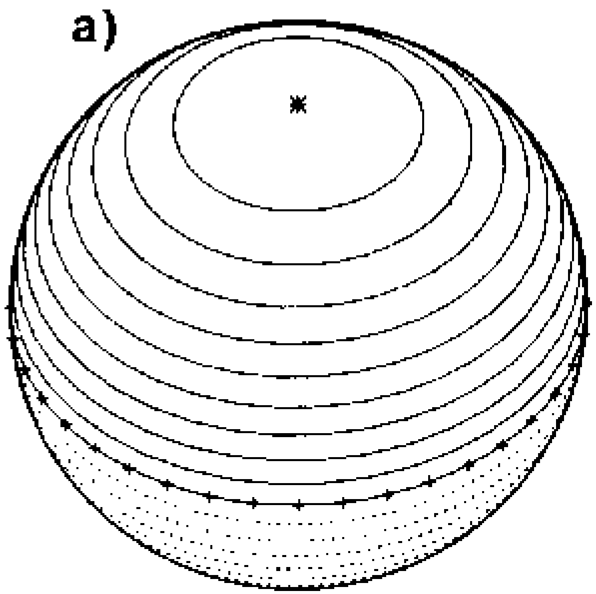
A módusok egy szférikus orgonasíp sajátrezgéseivel ekvivalensek. Radiális és nemradiális rezgések.

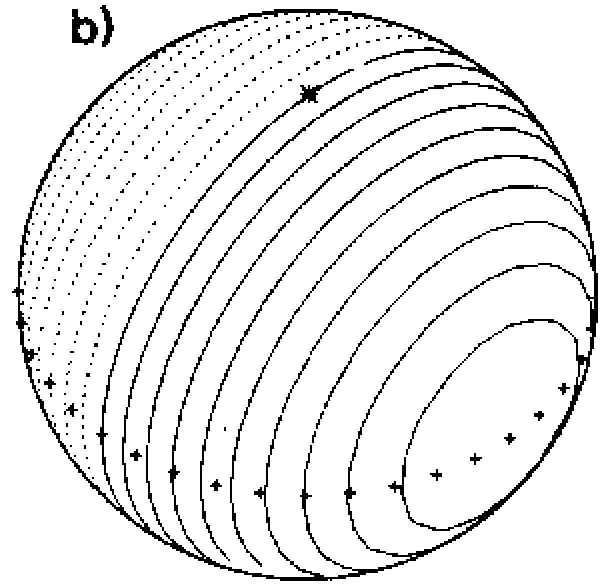


A frekvenciák mérésével a csillag belsejéről szerzünk információkat, mivel a hullámok áthaladnak a belső tartományokon.

$$c^2 \simeq \frac{\gamma \cdot k_B \cdot T}{\mu \cdot m_u}$$

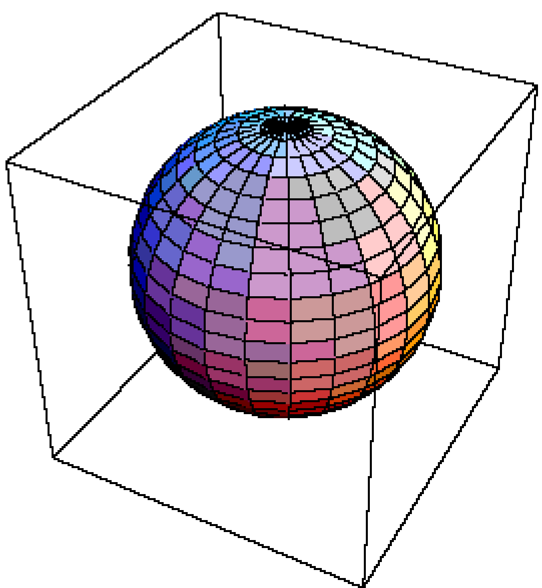
Gömbi harmonikusok

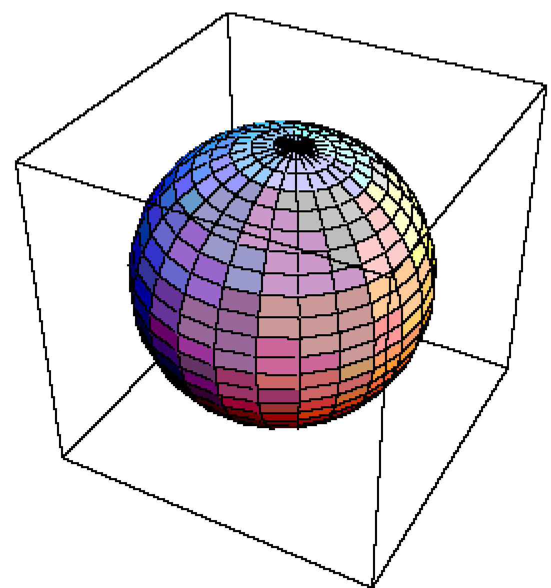


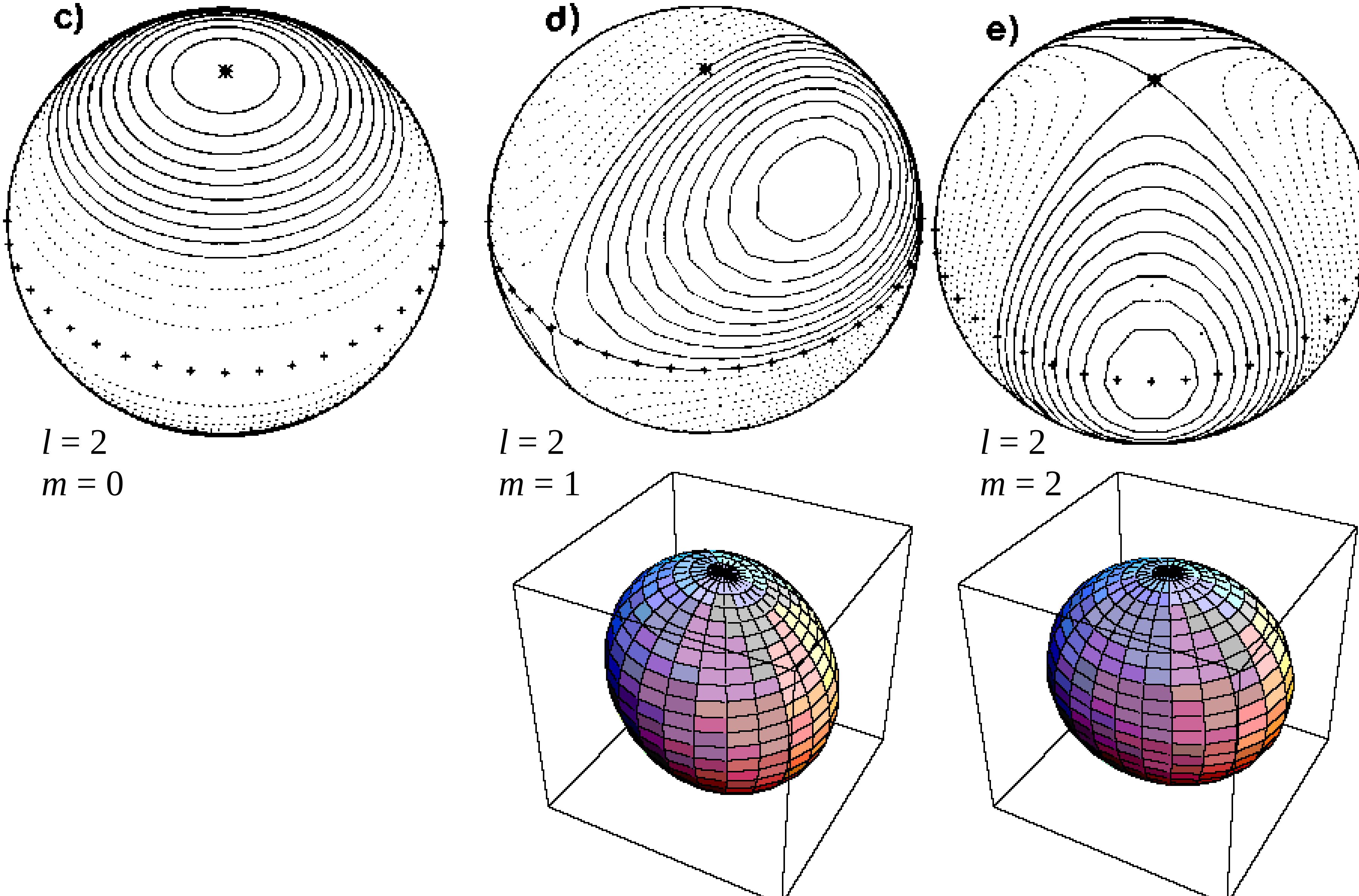


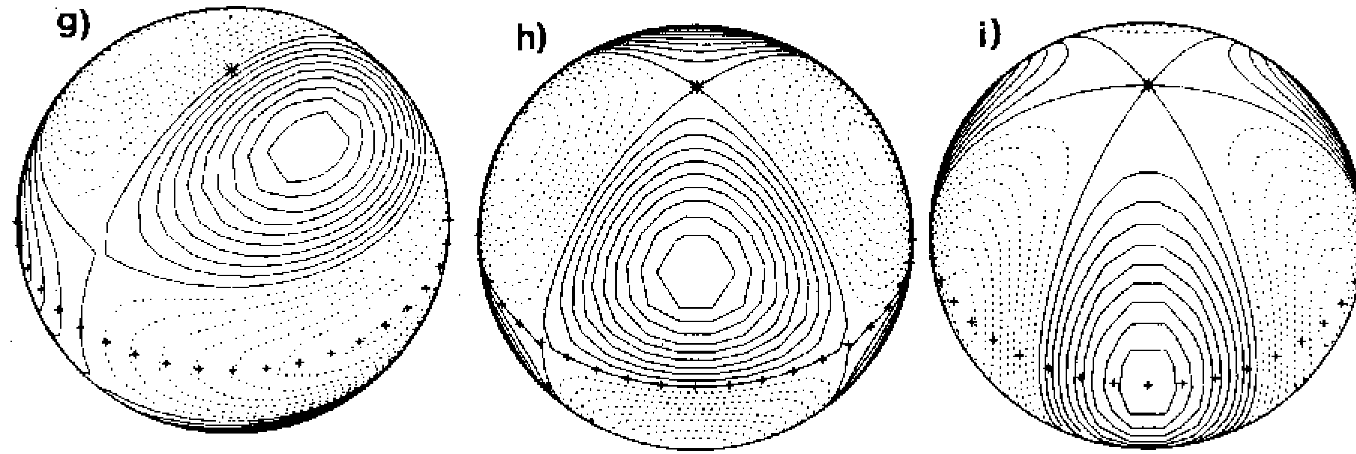
$l = 1$
$m = 0$

$l = 1$
$m = 1$






c)
d)
e)
$l = 2$
$m = 0$
$l = 2$
$m = 1$
$l = 2$
$m = 2$

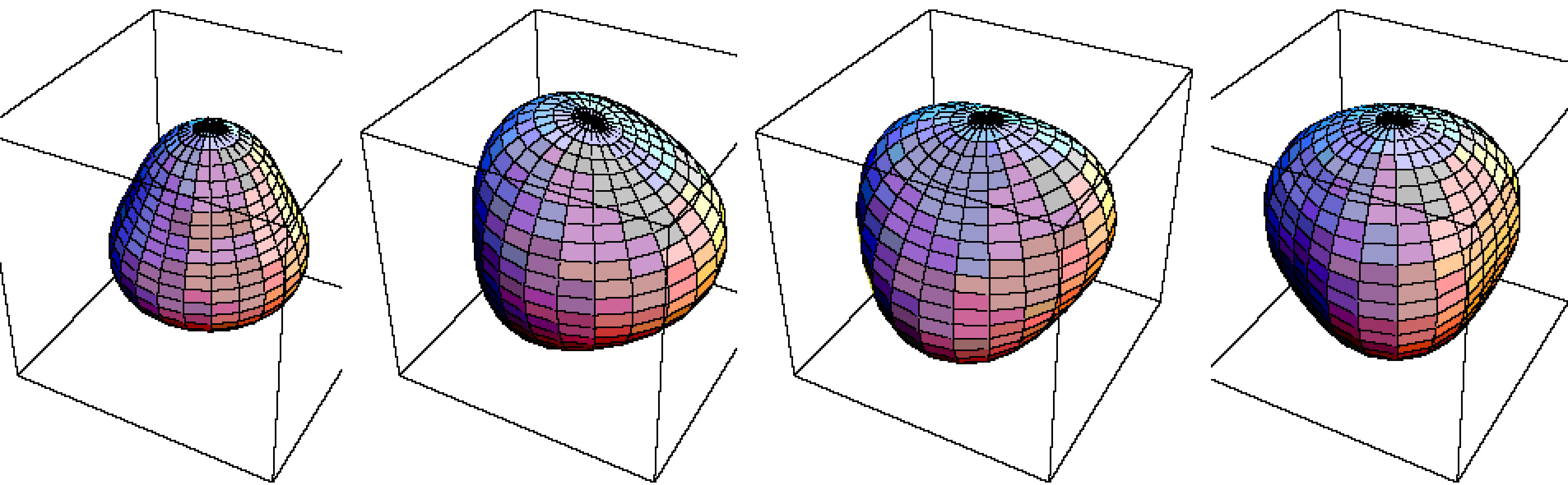


$l = 3$ $m = 0$

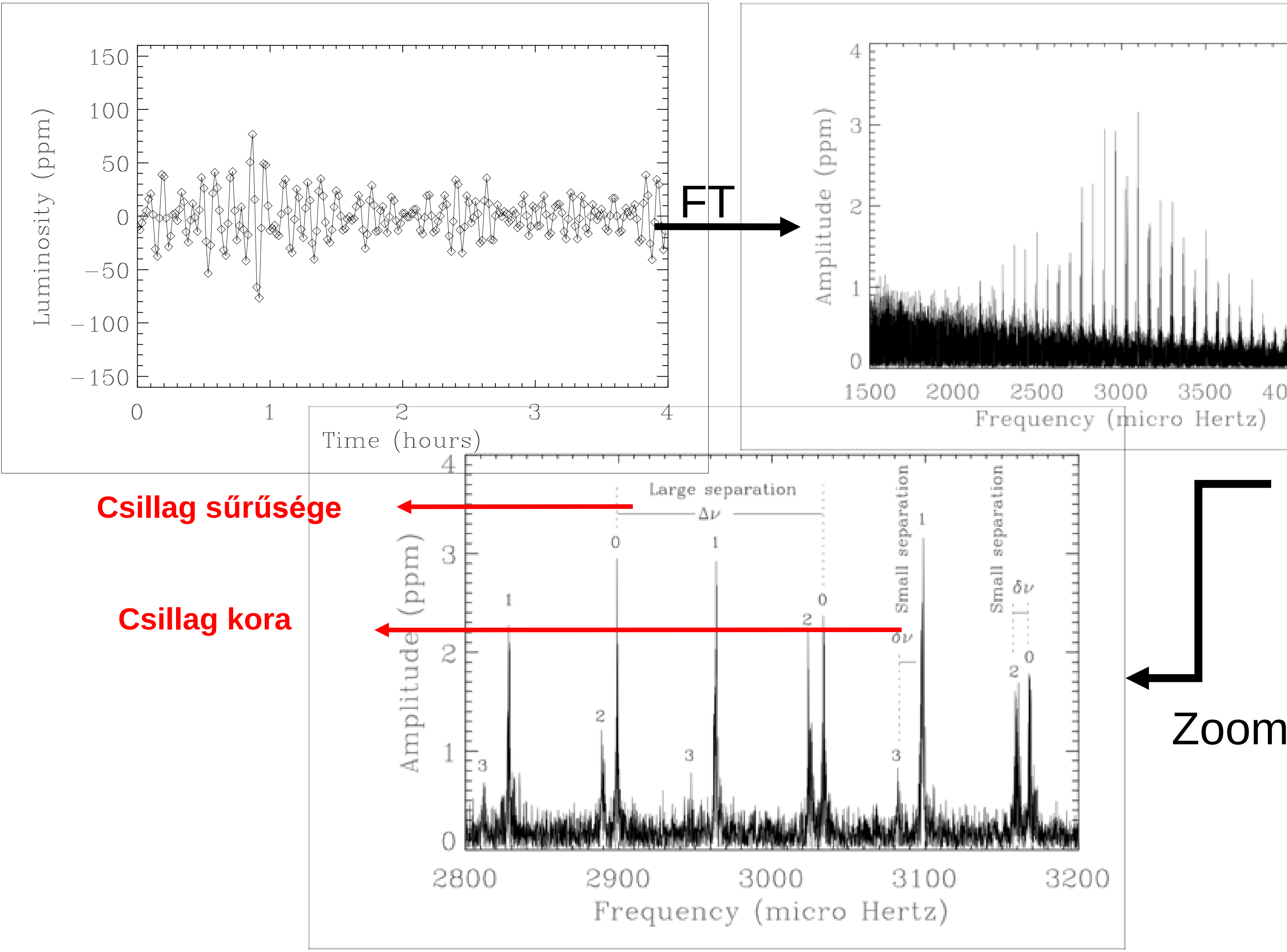
$l = 3$ $m = 1$

$l = 3$ $m = 2$

$l = 3$ $m = 3$

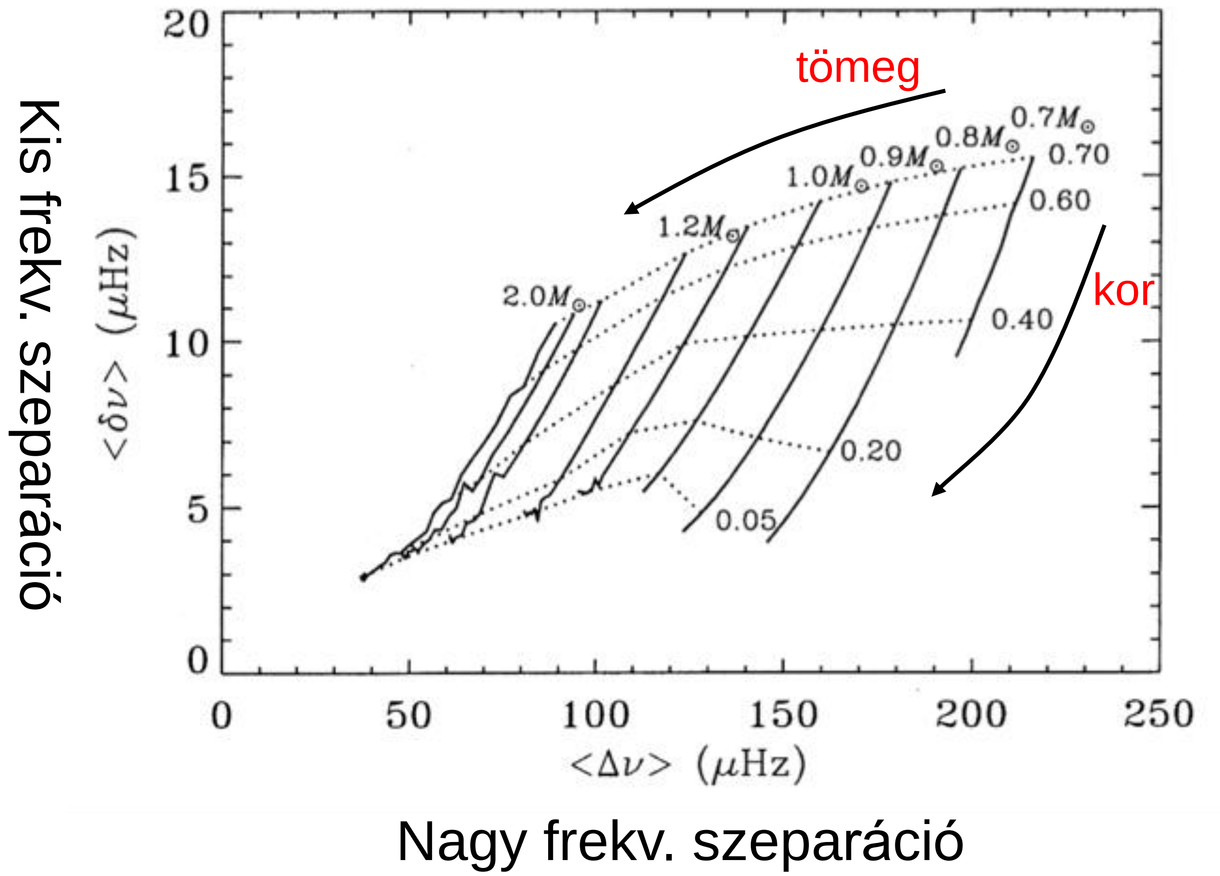


Nap típusú csillagrezgések

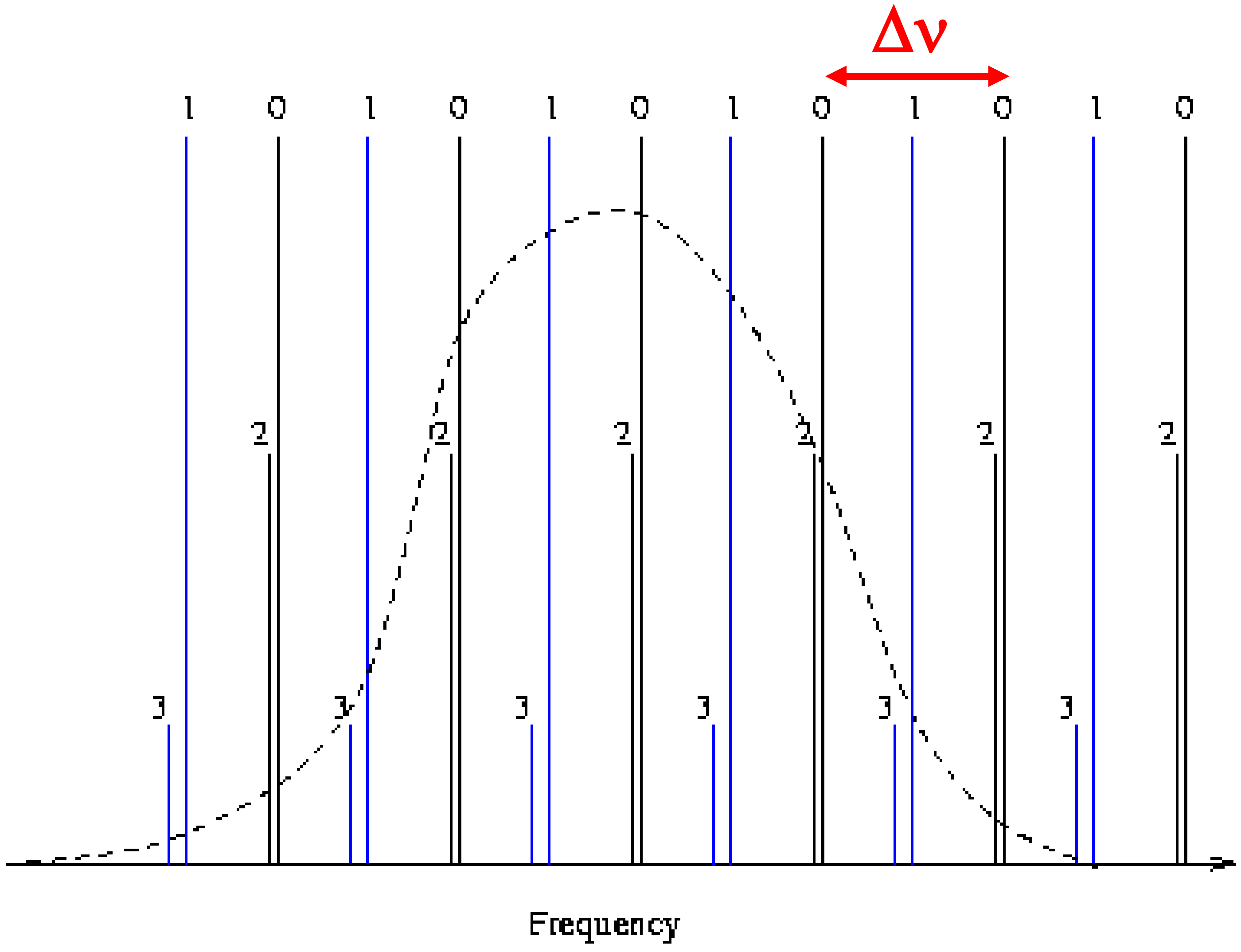


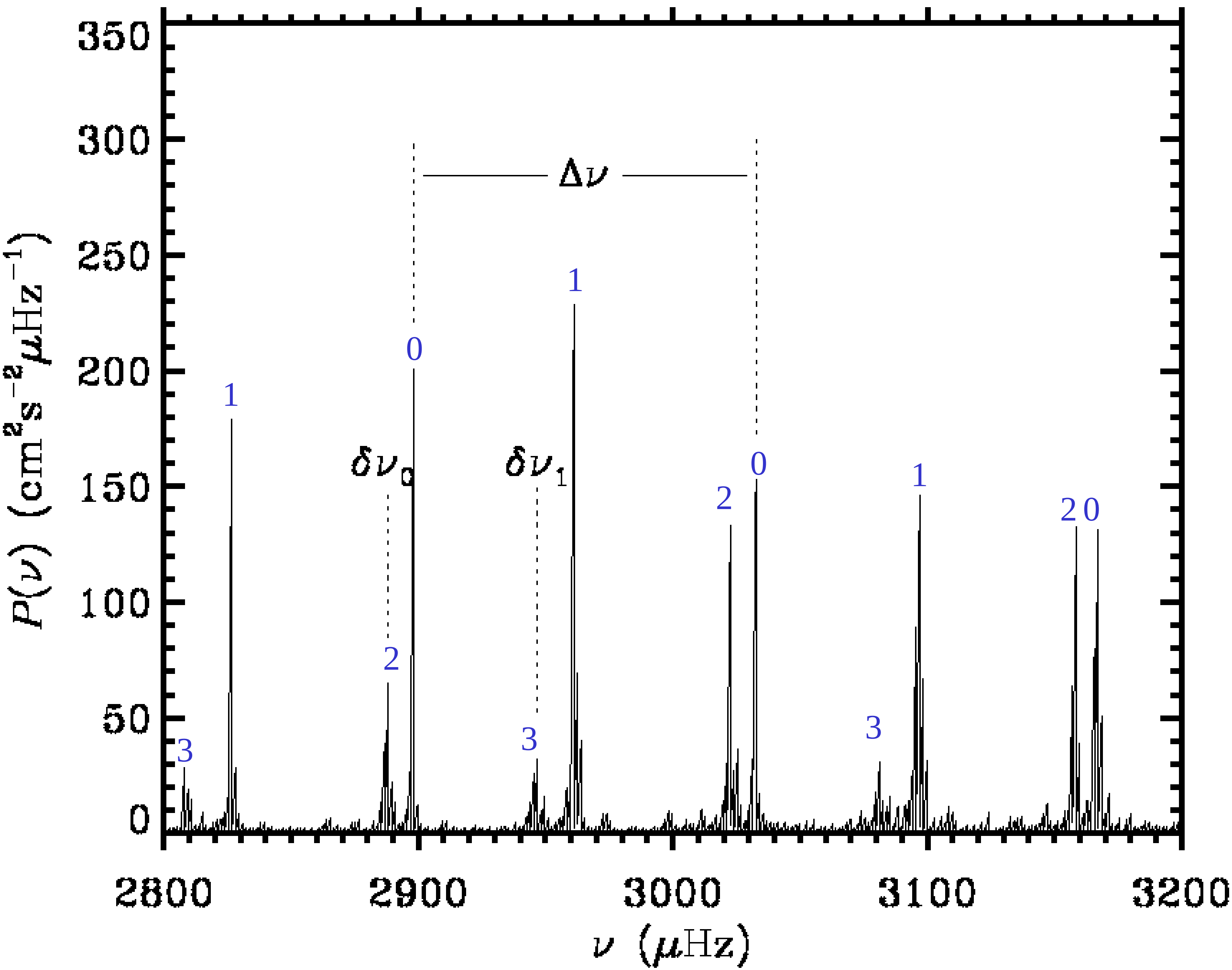
x

CD-diagram (szeizmikus HRD)



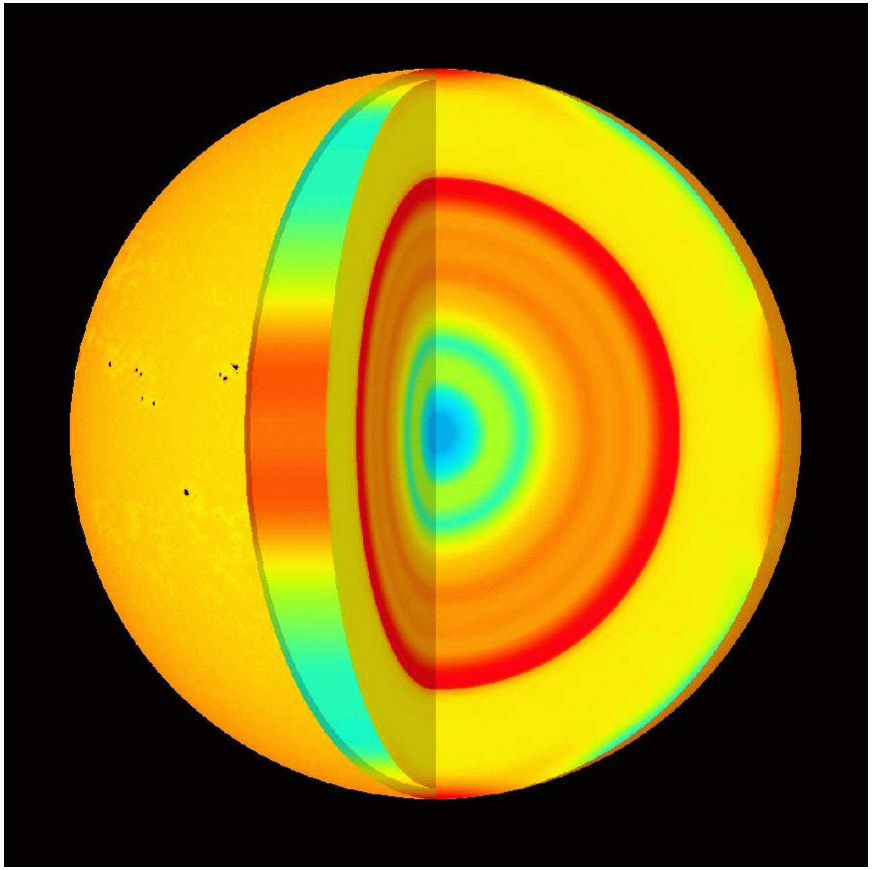
Szoláris oszcillációk teljesítményspektruma





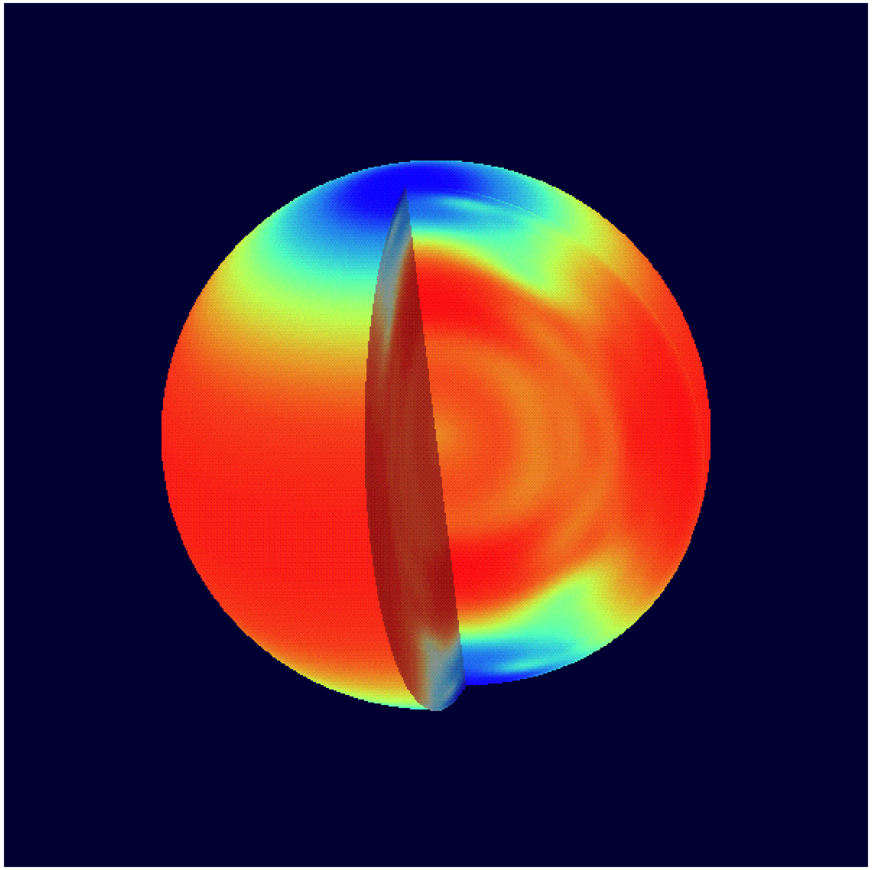
350
300
250
200
150
100
50
0
2800
2900
3000
3100
3200
$P(\nu)$ $(\mathrm{cm^2 s^{-2} \mu Hz^{-1}})$
ν $(\mu\mathrm{Hz})$
$\Delta\nu$
$\delta\nu_0$
$\delta\nu_1$
3
1
2
0
3
1
2
0
3
1
2
0

Szeizmikus inverzió



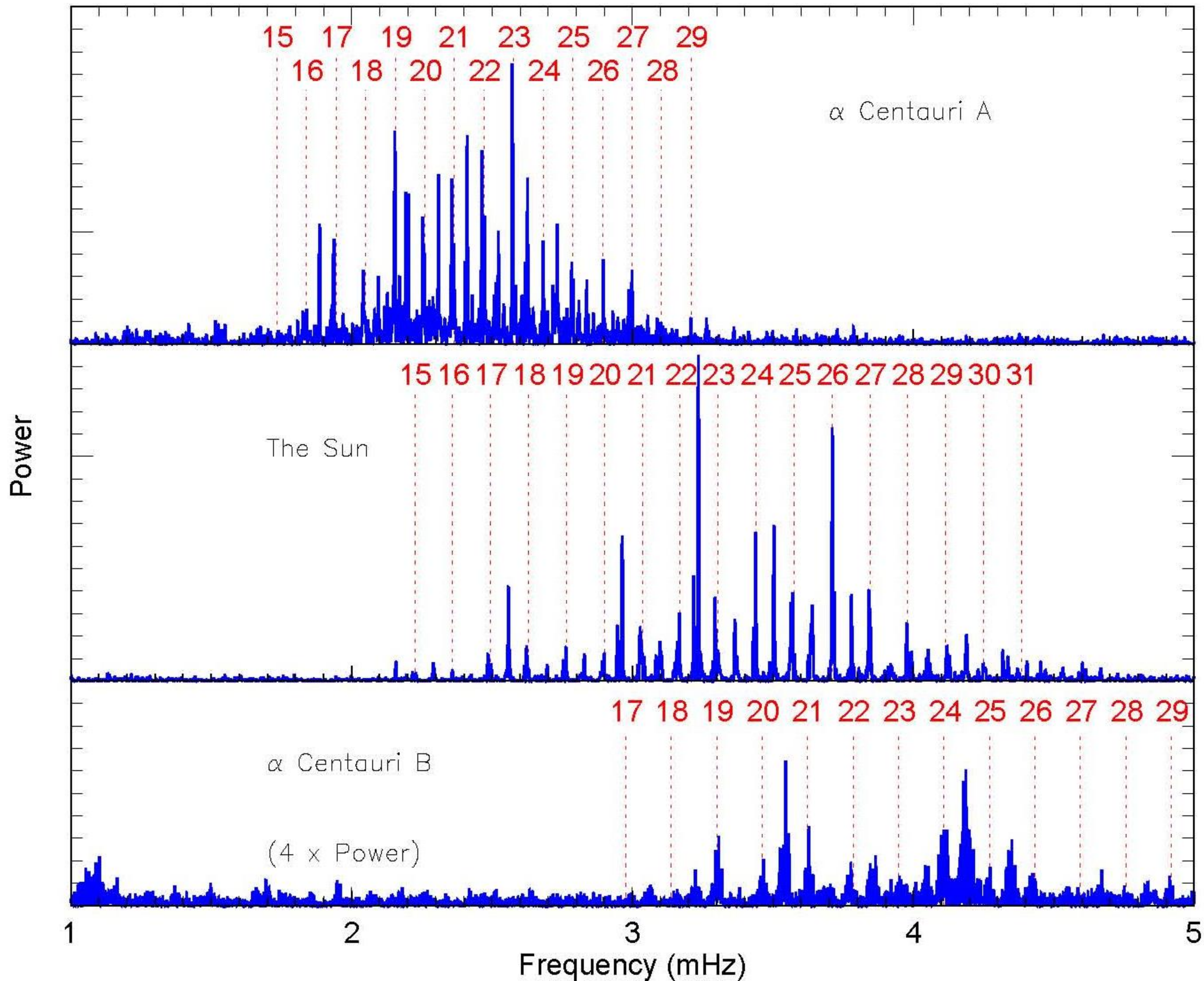
A belső hangsebesség (SOHO/MDI)

Belső rotáció



(SOHO/MDI)

Mi a helyzet más Nap típusú csillagokkal?



15 17 19 21 23 25 27 29
16 18 20 22 24 26 28
α Centauri A
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
The Sun
17 18 19 20 21 22 23 24 25 26 27 28 29
α Centauri B
(4 x Power)
Power
1 2 3 4 5
Frequency (mHz)

Űrfotometria: mire jó az?

Nagyságrendi ugrások a fényességmérés *relatív pontosságában*

- Új fizika!
- 100%: Mirák, (szuper)nóvák
- 1–10%: Geometriai és fizikai (pulzáló, eruptív és kataklizmikus) változócsillagok
- 0,1%: Fedési exobolygók – forró jupiterek
- 0,0001–0,01%: Nap típusú csillagrezgések, exoholdak, exoföldek, ???

Űrfotometria: mire jó az?

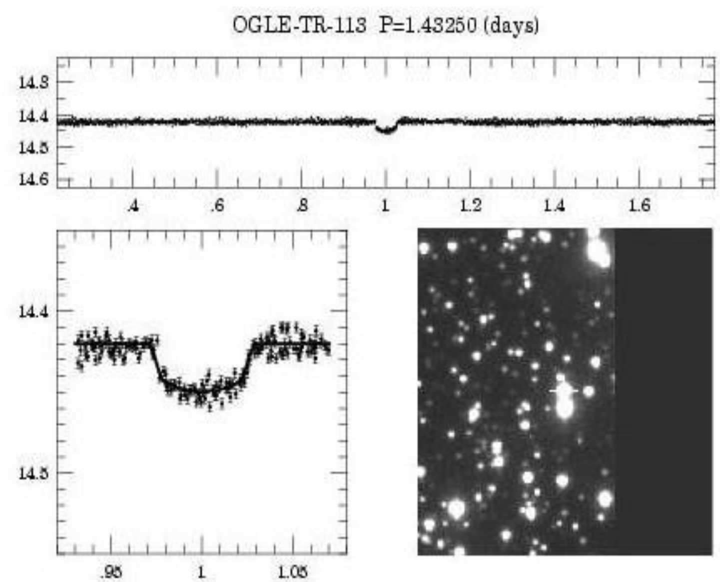
Az űrbéli mérések célja

- A földi légkör zavaró hatásaitól mentes adatgyűjtés
- A nappalok és éjszakák váltakozásaitól mentes mérések
- Fotonzaj-limitált adatok (0,1% – 1 millió foton)
- Kis távcső – fényes csillag!

Más csillagok napfogyatkozásai

Fedési exobolygók: a bolygó elhalad a csillag előtt, és kitakarja. Ebből megállapítható, kiszámítható, detektálható:

- a valós méret (a csillagsugár arányában)
- a sűrűség
- a bolygó szerkezete!
- a bolygólégkör színképe
- a visszavert fény
- a bolygólégkör szerkezete
- a csillag légkörének szerkezete



Kepler-űrtávcső

A Kepler célja Föld típusú, lakható bolygók felfedezése a fedési módszerrel

Szimultán észlelt több mint 150 ezer csillagot

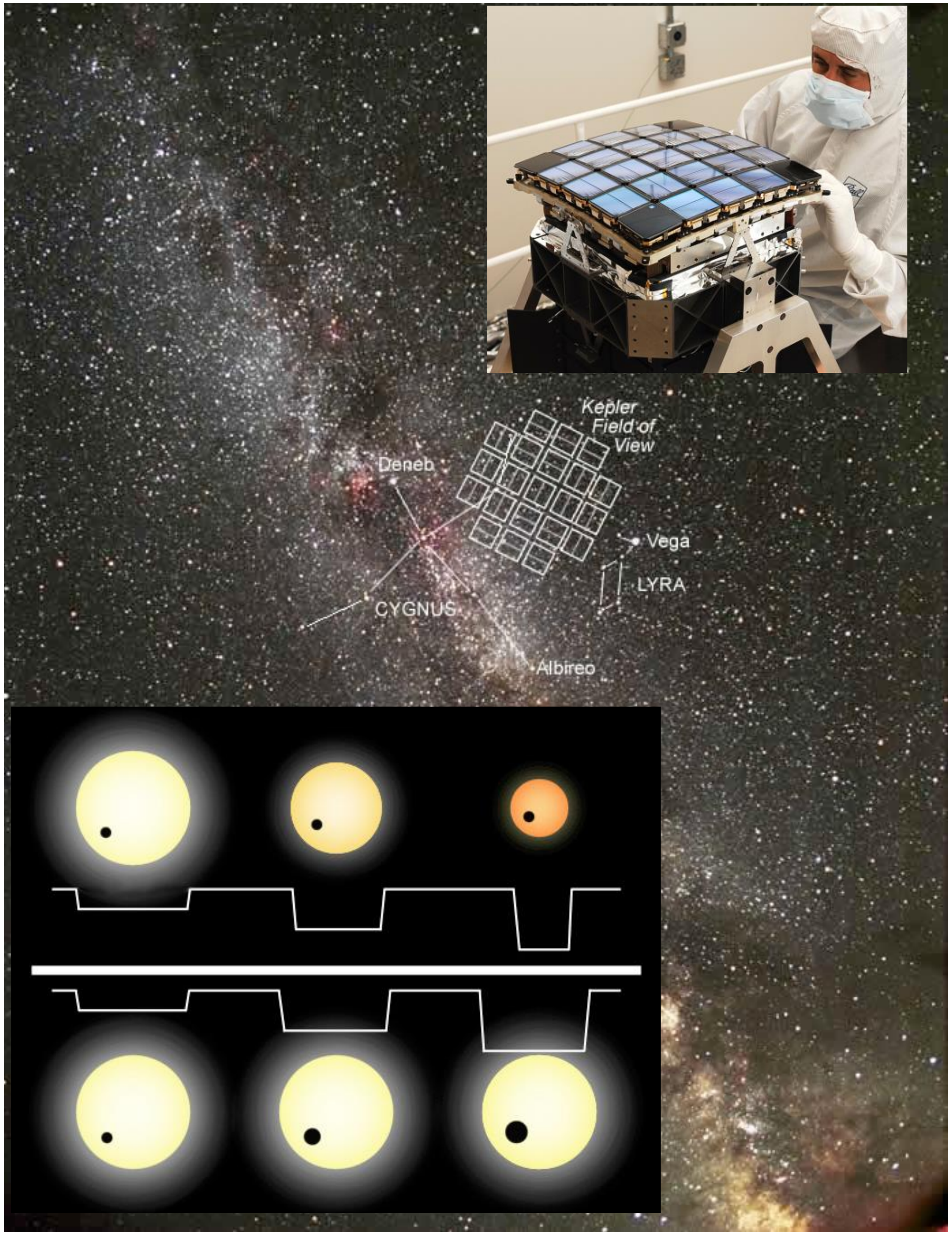
95 cm-es belépő nyílású Schmidt-távcső, látómezeje mintegy 100 négyzetfok, 42 CCD-ből álló mozaikkal

Fotometriai pontosság:

A zaj < 20 ppm 6,5 órányi mérés után egy 12 magn. Nap típusú csillagra

=> 4-szigma detektálás egy exoföld tranzitja esetén.

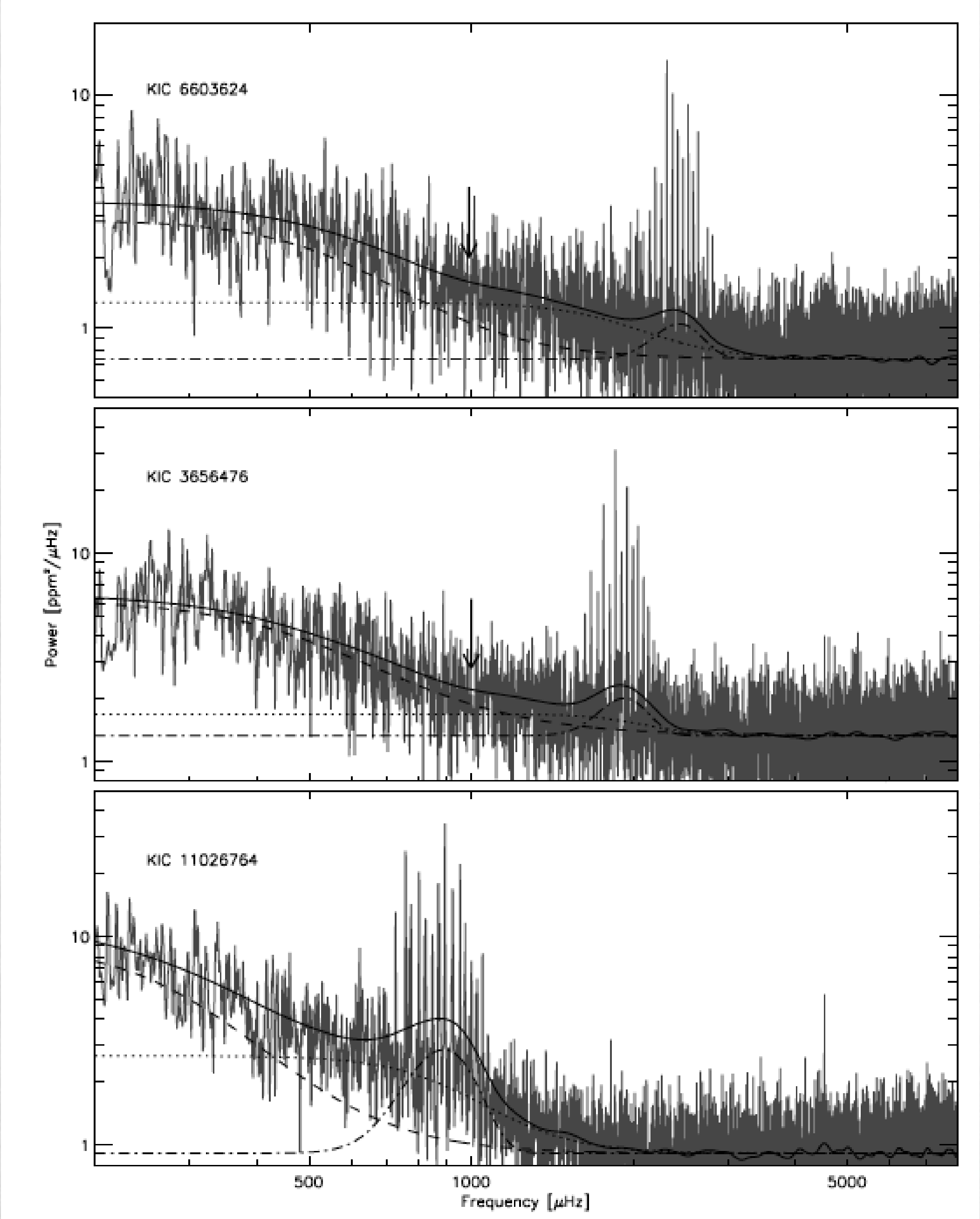
Heliocentrikus pálya, 2009-2013



KEPLER ASZTROSZEIZMOLÓGIA

- Kb. 4000 csillag
- LC és SC adatok (30 percenként, 1 percenként egy pont)
- A teljes HRD-t lefedik a csillagtípusok: szoláris csillagok, fehér törpék, vörös óriások, klasszikus pulzáló változók
- KASC: >400 tudós együttműködése
- 14 munkacsoport, ebből kettőnek magyar vezetője (Szabó Róbert, Kiss László)

Nap típusú csillagok



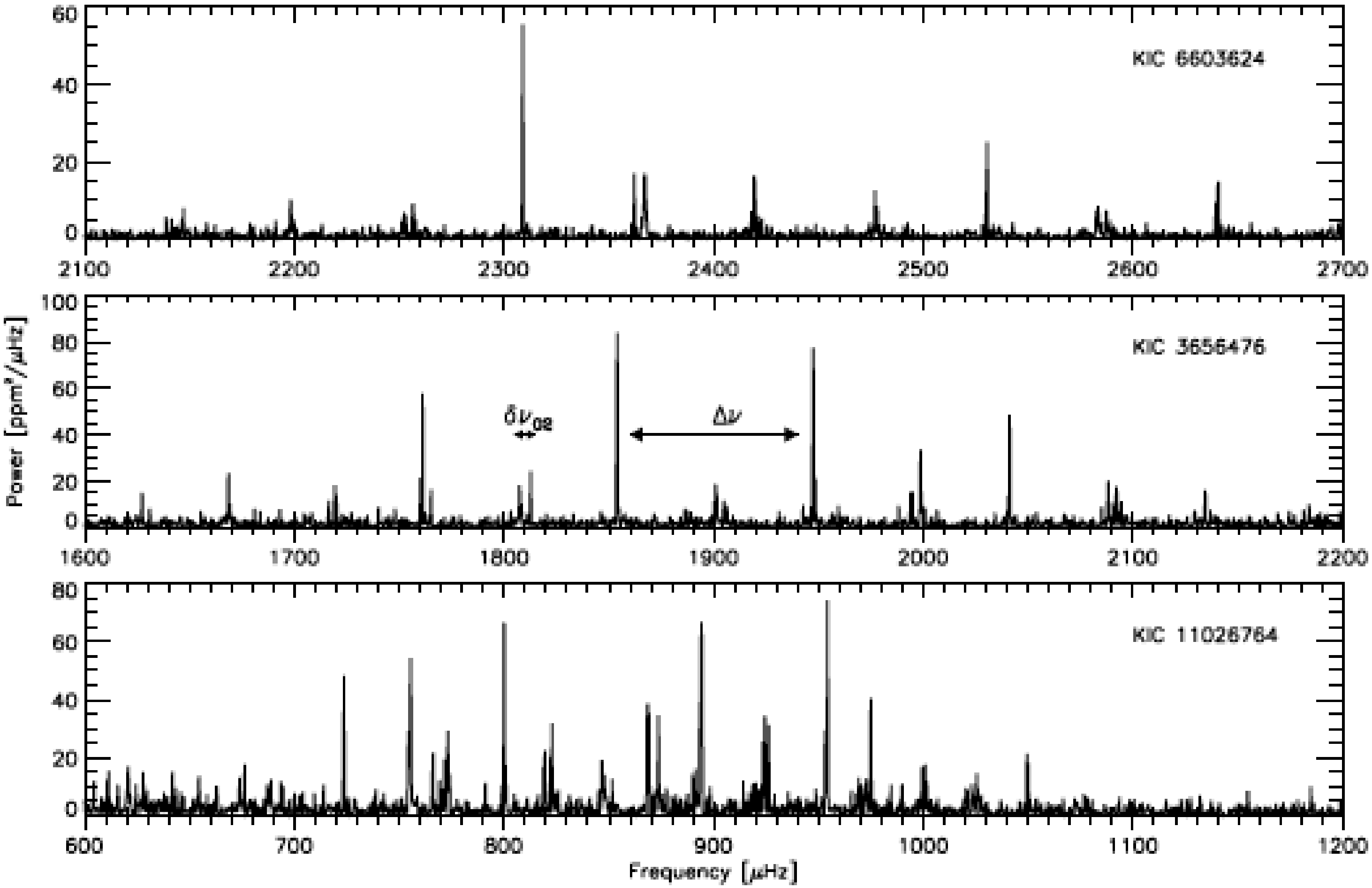


Figure 2. Frequency–power spectra of the three stars, plotted on a linear scale over the frequency ranges where the mode amplitudes are most prominent. Examples of the characteristic large ($\Delta\nu$) and small ($\delta\nu_{02}$) frequency separations are also marked on the spectrum of KIC 3656476.

Table 1
Non-seismic and Seismic Parameters, and Preliminary Stellar Properties[a]

Star	2MASS ID	T_{eff} (K)	log g (dex)	[Fe/H] (dex)	$\Delta\nu$ (μHz)	$\delta\nu_{02}$ (μHz)	R ($R_\odot$)	M ($M_\odot$)
KIC 6603624[b]	19241119+4203097	5790 ± 100	4.56 ± 0.10	0.38 ± 0.09	110.2 ± 0.6	4.7 ± 0.2	1.18 ± 0.02	1.05 ± 0.06
KIC 3656476[c]	19364879+3842568	5666 ± 100	4.32 ± 0.06	0.22 ± 0.04	94.1 ± 0.6	4.4 ± 0.2	1.31 ± 0.02	1.04 ± 0.06
KIC 11026764[b]	19212465+4830532	5640 ± 80	3.84 ± 0.10	0.02 ± 0.06	50.8 ± 0.3	4.3 ± 0.5	2.10 ± 0.10	1.10 ± 0.12

Kis luminozitású vörös óriások: szoláris oszcillációk mindenütt

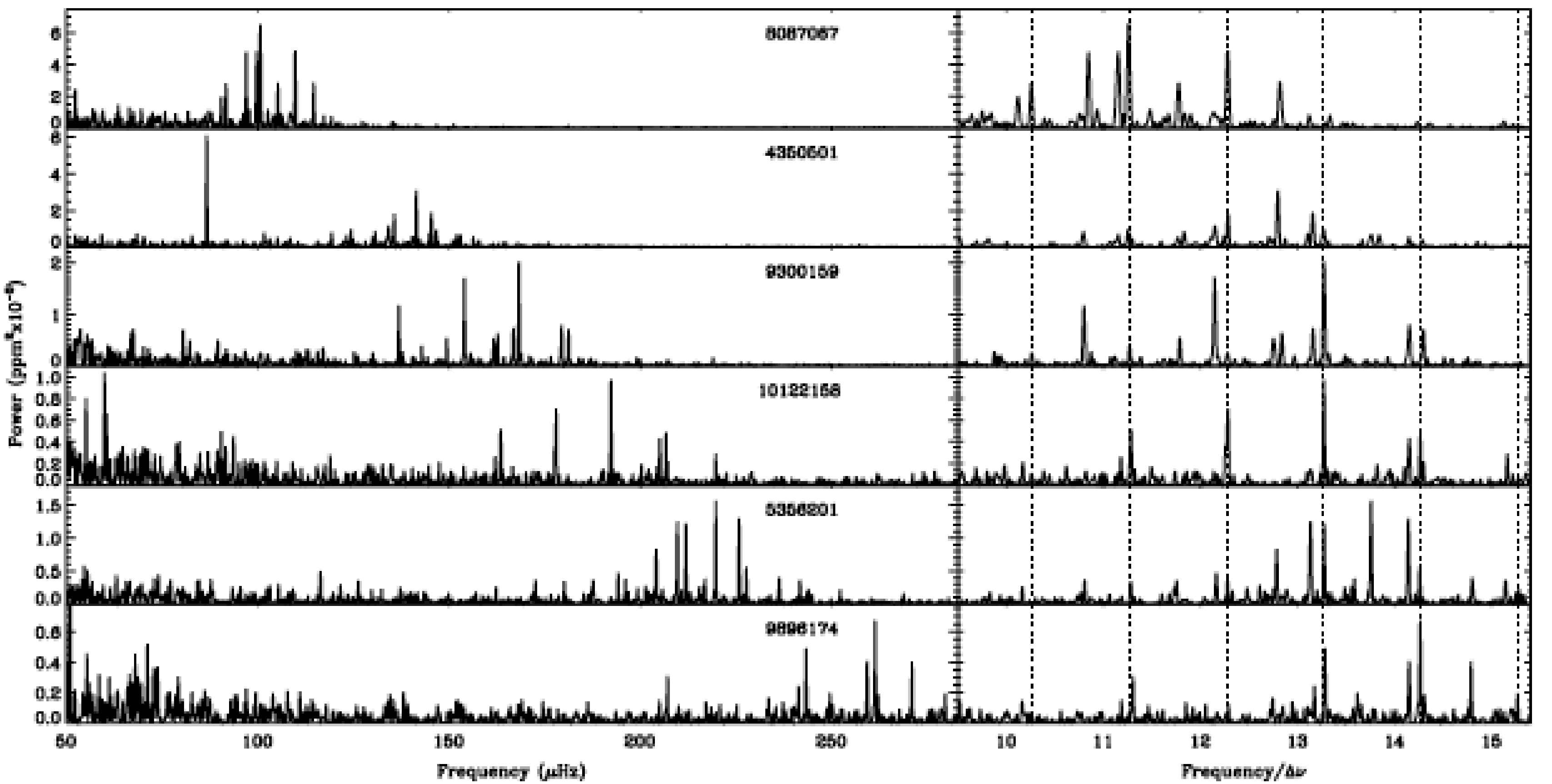


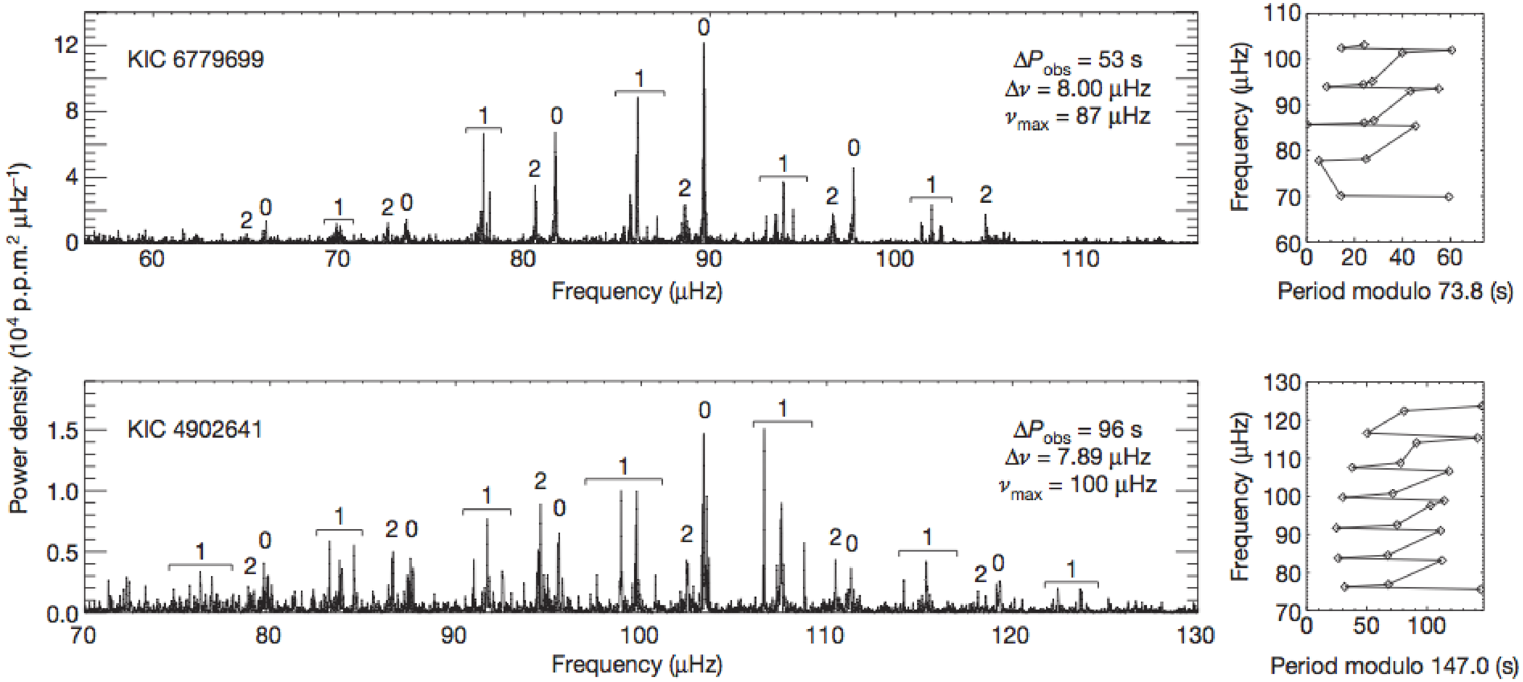
Figure 2. Left: power spectra of six representative low-luminosity red giants. Right: the same power spectra plotted against scaled frequency (see Section 3.2). The dotted lines are equally spaced, having unit separation and being aligned with the $l = 0$ modes. Stars are labeled with identification numbers from the KIC (Latham et al. 2005).

LETTER

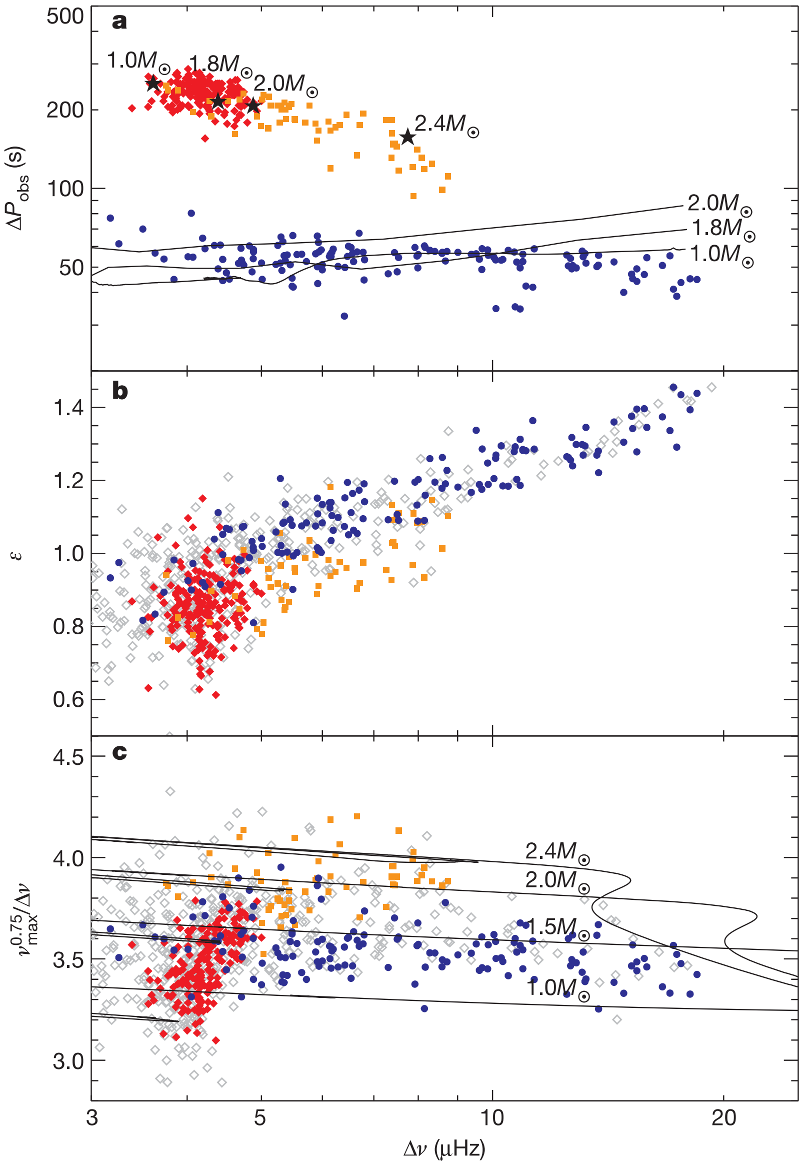
doi:10.1038/nature09935

Gravity modes as a way to distinguish between hydrogen- and helium-burning red giant stars

Timothy R. Bedding[1], Benoit Mosser[2], Daniel Huber[1], Josefina Montalbán[3], Paul Beck[4], Jørgen Christensen-Dalsgaard[5], Yvonne P. Elsworth[6], Rafael A. García[7], Andrea Miglio[3,6], Dennis Stello[1], Timothy R. White[1], Joris De Ridder[4], Saskia Hekker[6,8], Conny Aerts[4,9], Caroline Barban[2], Kevin Belkacem[10], Anne-Marie Broomhall[6], Timothy M. Brown[11], Derek L. Buzasi[12], Fabien Carrier[4], William J. Chaplin[6], Maria Pia Di Mauro[13], Marc-Antoine Dupret[3], Søren Frandsen[5], Ronald L. Gilliland[14], Marie-Jo Goupil[2], Jon M. Jenkins[15], Thomas Kallinger[16], Steven Kawaler[17], Hans Kjeldsen[5], Savita Mathur[18], Arlette Noels[3], Victor Silva Aguirre[19] & Paolo Ventura[20]



Bedding et al., Nature, 2011.03.11.



Bedding et al., Nature, 2011.03.11.

LETTER

doi:10.1038/nature16171

A prevalence of dynamo-generated magnetic fields in the cores of intermediate-mass stars

Dennis Stello[1,2], Matteo Cantiello[3], Jim Fuller[3,4], Daniel Huber[1,2,5], Rafael A. García[6], Timothy R. Bedding[1,2],
Lars Bildsten[3,7] & Victor Silva Aguirre[2]

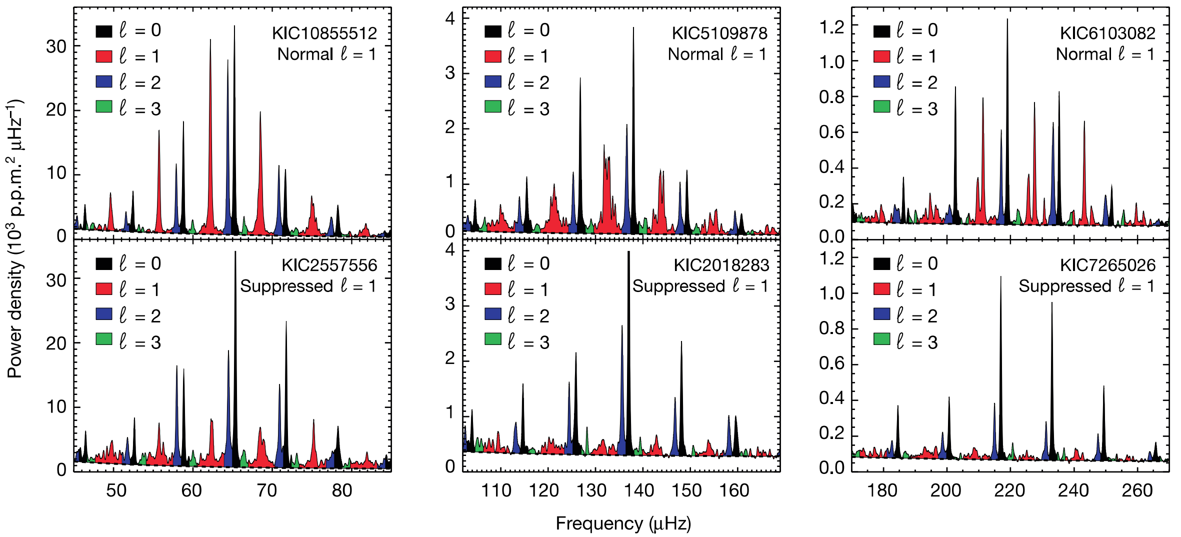
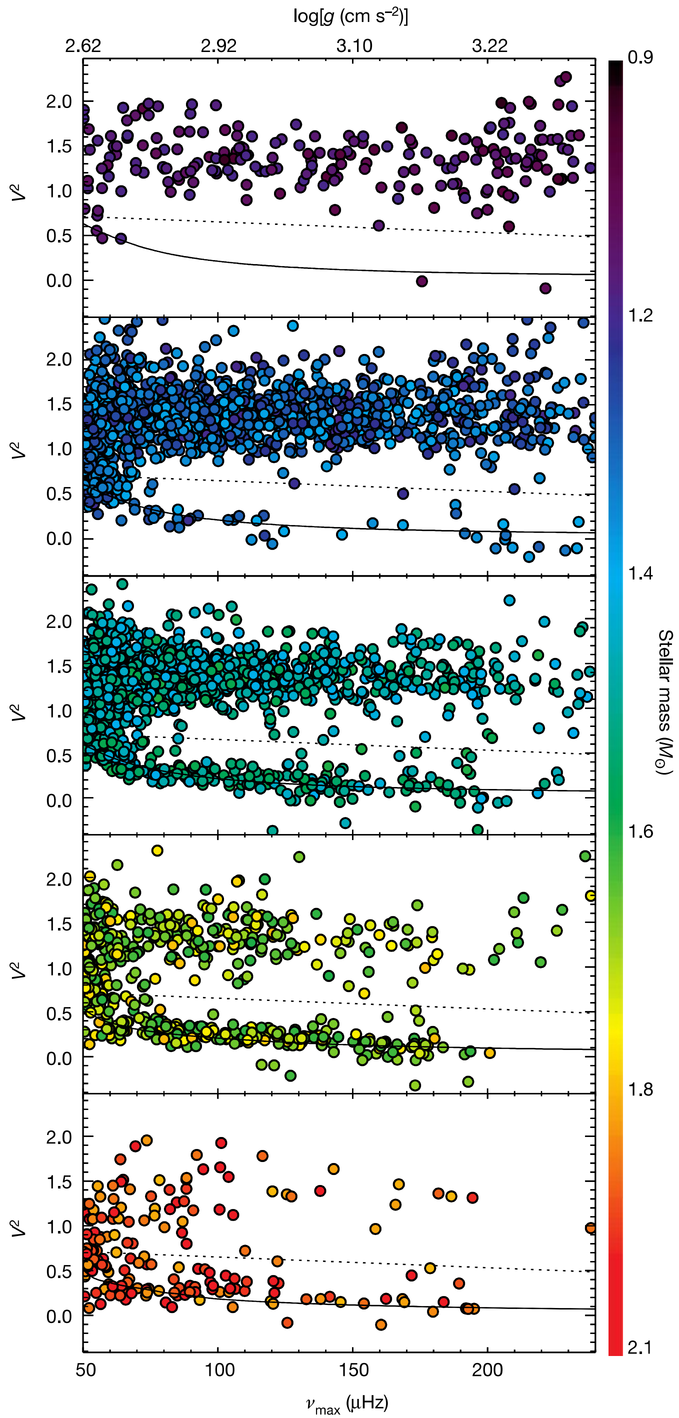


Figure 1 | Oscillation spectra of six red giants observed with Kepler. The stars are grouped into three pairs, each representing a different evolution stage ranging from the most evolved (lowest ν_{max}) on the left to the least evolved (highest ν_{max}) to the right. The coloured regions mark the power density dominated by modes of different degree $\ell = 0$–3. For clarity the spectra are smoothed by $0.03\Delta\nu$, which for the most evolved stars tends to create a single peak at each acoustic resonance, although each peak comprises multiple closely spaced mixed modes (red peaks in the left and centre panels). The slightly downward-sloping horizontal dashed line indicates the noise level.

Stello et al., Nature, 2016.01.21.



Stello et al., Nature, 2016.01.21.

Asteroseismology can reveal strong internal magnetic fields in red giant stars

Jim Fuller,[1,2]*† Matteo Cantiello,[2]*† Dennis Stello,[3,4] Rafael A. Garcia,[5] Lars Bildsten[2,6]

Internal stellar magnetic fields are inaccessible to direct observations, and little is known about their amplitude, geometry, and evolution. We demonstrate that strong magnetic fields in the cores of red giant stars can be identified with asteroseismology. The fields can manifest themselves via depressed dipole stellar oscillation modes, arising from a magnetic greenhouse effect that scatters and traps oscillation-mode energy within the core of the star. The Kepler satellite has observed a few dozen red giants with depressed dipole modes, which we interpret as stars with strongly magnetized cores. We find that field strengths larger than ~10^5 gauss may produce the observed depression, and in one case we infer a minimum core field strength of ≈10^7 gauss.

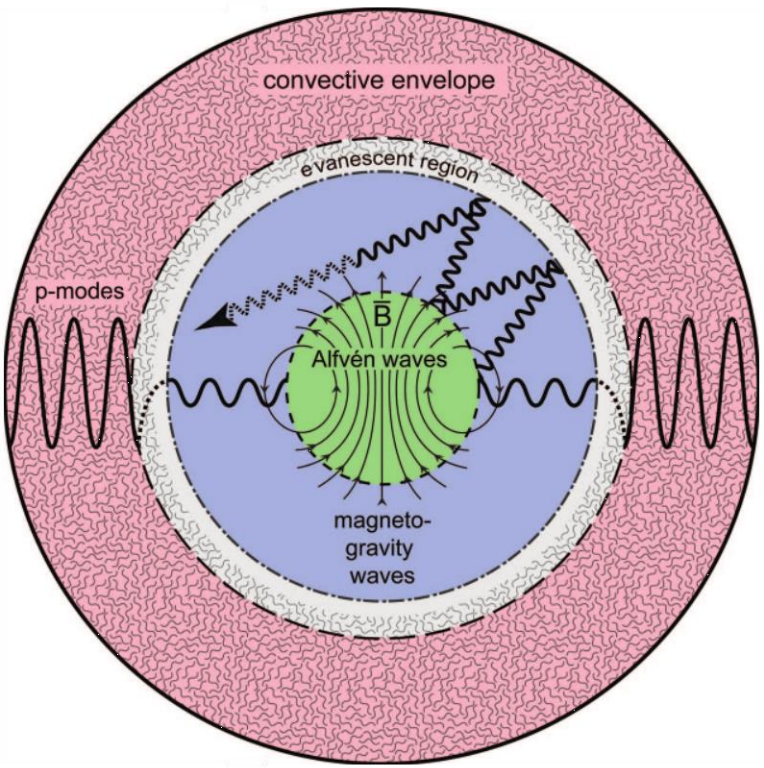


Fig. 1. Wave propagation in red giants with magnetized cores. Acoustic waves excited in the envelope couple to gravity waves in the radiative core. In the presence of a magnetic field in the core, the gravity waves are scattered at regions of high field strength. Because the field cannot be spherically symmetric, the waves are scattered to high angular degree ℓ and become trapped within the core, where they eventually dissipate (dashed wave with arrow). We refer to this as the magnetic greenhouse effect.

Fuller et al., Science, 2015.10.23.

The Astrophysical Journal, 790:12 (16pp), 2014 July 20 doi:10.1088/0004-637X/790/1/12

KEPLER-93b: A TERRESTRIAL WORLD MEASURED TO WITHIN 120 km, AND A TEST CASE FOR A NEW *SPITZER* OBSERVING MODE

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ABSTRACT

We present the characterization of the Kepler-93 exoplanetary system, based on three years of photometry gathered by the *Kepler* spacecraft. The duration and cadence of the *Kepler* observations, in tandem with the brightness of the star, enable unusually precise constraints on both the planet and its host. We conduct an asteroseismic analysis of the *Kepler* photometry and conclude that the star has an average density of 1.652 ± 0.006 g cm^{-3}. Its mass of $0.911 \pm 0.033\ M_\odot$ renders it one of the lowest-mass subjects of asteroseismic study. An analysis of the transit signature produced by the planet Kepler-93b, which appears with a period of $4.72673978 \pm 9.7 \times 10^{-7}$ days, returns a consistent but less precise measurement of the stellar density, $1.72^{+0.02}_{-0.28}$ g cm^{-3}. The agreement of these two values lends credence to the planetary interpretation of the transit signal. The achromatic transit depth, as compared between *Kepler* and the *Spitzer Space Telescope*, supports the same conclusion. We observed seven transits of Kepler-93b with *Spitzer*, three of which we conducted in a new observing mode. The pointing strategy we employed to gather this subset of observations halved our uncertainty on the transit radius ratio $R_P/R_\star$. We find, after folding together the stellar radius measurement of $0.919 \pm 0.011\ R_\odot$ with the transit depth, a best-fit value for the planetary radius of $1.481 \pm 0.019\ R_\oplus$. The uncertainty of 120 km on our measurement of the planet's size currently renders it one of the most precisely measured planetary radii outside of the solar system. Together with the radius, the planetary mass of $3.8 \pm 1.5\ M_\oplus$ corresponds to a rocky density of 6.3 ± 2.6 g cm^{-3}. After applying a prior on the plausible maximum densities of similarly sized worlds between 1 and 1.5 $R_\oplus$, we find that Kepler-93b possesses an average density within this group.

Key words: eclipses – methods: observational – planetary systems – stars: individual (KOI 69, KIC 3544595)

Online-only material: color figures

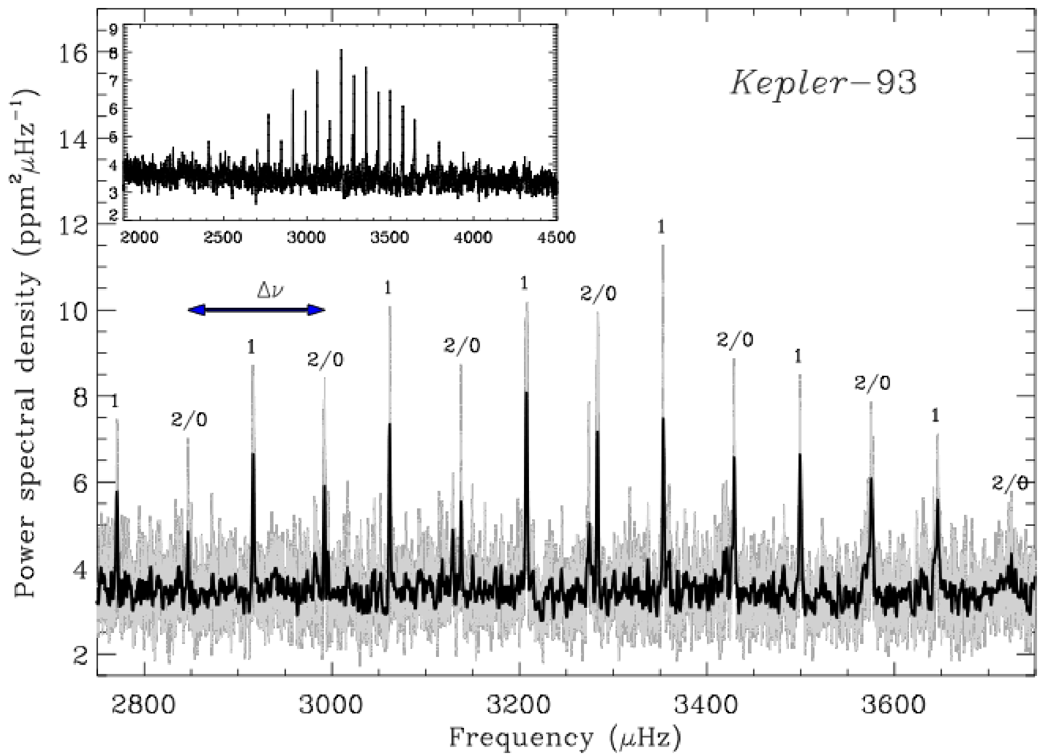

Figure 1. Power spectrum of Kepler-93. The main plot shows a close-up of the strongest oscillation modes, tagged according to their angular degree, l. The large frequency separation, here between a pair of adjacent $l = 0$ modes, is also marked. The black and gray curves show the power spectrum after smoothing with boxcars of widths 1.5 and 0.4 μHz, respectively. The inset shows the full extent of the observable oscillations.

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AN ANCIENT EXTRASOLAR SYSTEM WITH FIVE SUB-EARTH-SIZE PLANETS

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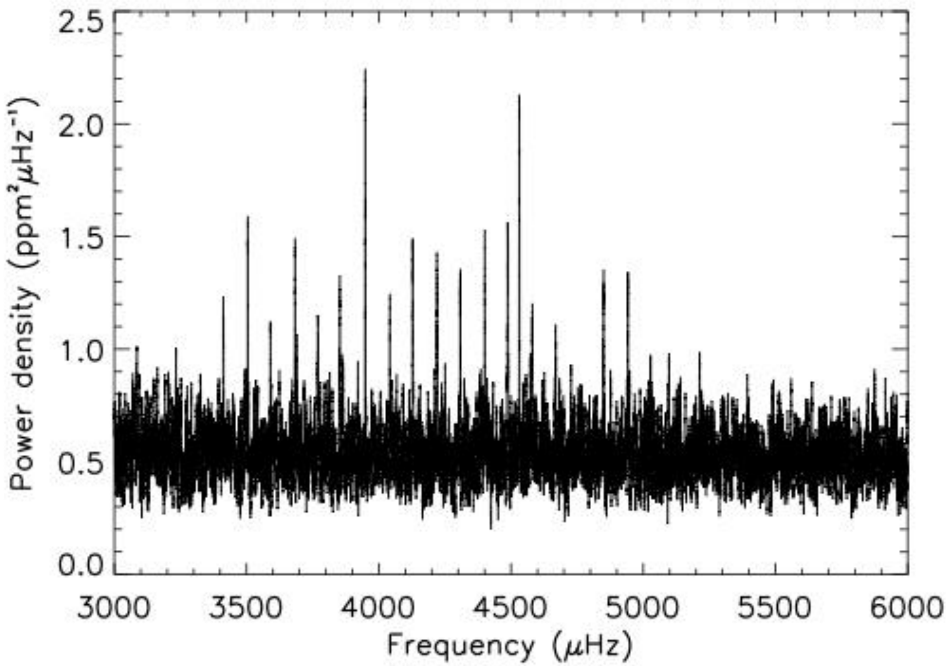
ABSTRACT

The chemical composition of stars hosting small exoplanets (with radii less than four Earth radii) appears to be more diverse than that of gas-giant hosts, which tend to be metal-rich. This implies that small, including Earth-size, planets may have readily formed at earlier epochs in the universe's history when metals were more scarce. We report *Kepler* spacecraft observations of Kepler-444, a metal-poor Sun-like star from the old population of the Galactic thick disk and the host to a compact system of five transiting planets with sizes between those of Mercury and Venus. We validate this system as a true five-planet system orbiting the target star and provide a detailed characterization of its planetary and orbital parameters based on an analysis of the transit photometry. Kepler-444 is the densest star with detected solar-like oscillations. We use asteroseismology to directly measure a precise age of 11.2 ± 1.0 Gyr for the host star, indicating that Kepler-444 formed when the universe was less than 20% of its current age and making it the oldest known system of terrestrial-size planets. We thus show that Earth-size planets have formed throughout most of the universe's 13.8 billion year history, leaving open the possibility for the existence of ancient life in the Galaxy. The age of Kepler-444 not only suggests that thick-disk stars were among the hosts to the first Galactic planets, but may also help to pinpoint the beginning of the era of planet formation.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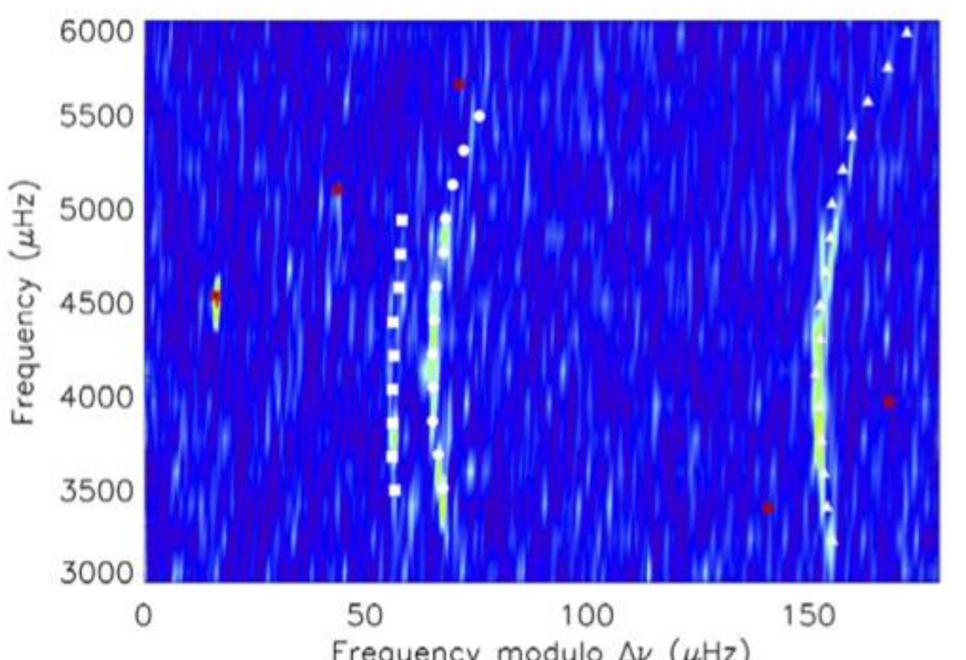
Frequency (μHz)
Frequency modulo Δν (μHz)
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5500
5000
4500
4000
3500
3000
0
50
100
150

1. At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?

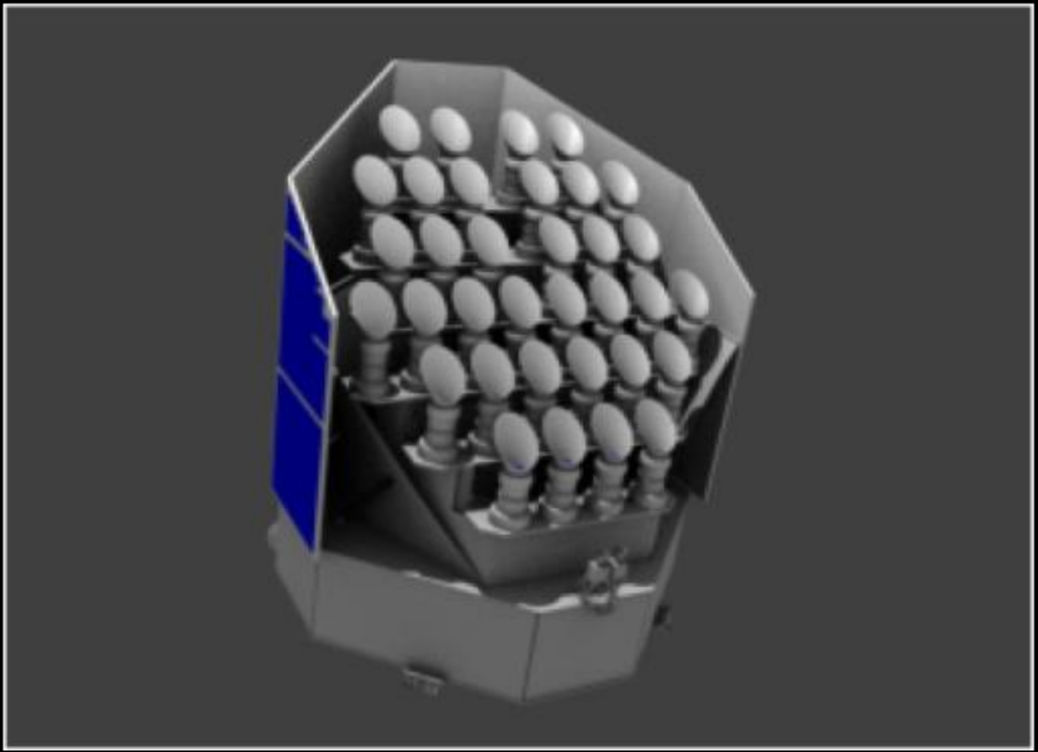
Eddington (1926): "The Internal Constitution of the Stars"

A jövő űrfotometriai missziói

TESS 2017-
NASA

CHEOPS 2017-
ESA S-misszió

PLATO 2024-
ESA M-misszió

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PLATO 2.0
Planetary Transits and Oscillation of Stars