Pulsations and planets at late stages of stellar evolution

Sonja Schuh[1,2]

[1]Eberhard-Karls-Universität Tübingen
[2]Georg-August-Universität Göttingen

Kepler Kolloquium, November 6 2009

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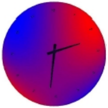
1. Asteroseismology
2. Subdwarf B stars
3. PG 1159 white dwarfs

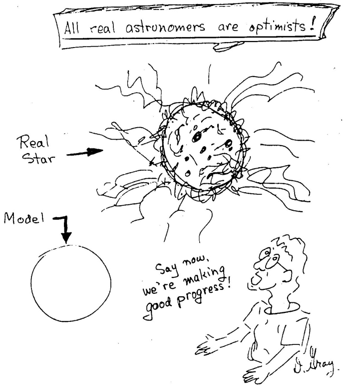


Collaborators

- Georg-August-Universität Göttingen
  - **Dreizler, Lutz, Stahn (now MPS), Kruspe, Beeck (now MPS), Traulsen, Loeptien, Glatzel, Huber**
- Eberhard-Karls-Universität Tübingen
  - **Nagel, Werner** PG 1159 white dwarfs
- Friedrich-Alexander-Universität Erlangen-Nürnberg
  - **Heber, Falter, Tillich** subluminous B stars
- INAF – Istituto Nazionale di AstroFisica, Neapel/Turin
  - **Silvotti** subluminous B stars
- University of Arizona, Tucson – Steward Observatory
  - **Green** observations of sdBs
- Université de Montréal
  - **Fontaine, Charpinet (at Toulouse), Randall (now ESO)** pulsation theory of sdBs

Stellar models

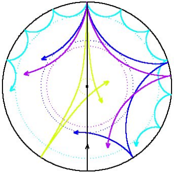
- self-gravitating fluid sphere
  described by stellar structure equations
  - conservation of mass
  - conservation of momentum
  - conservation of energy
  - transport of energy
- as well as properties
  of stellar matter
  - equation of state
  - energy production
  - opacity

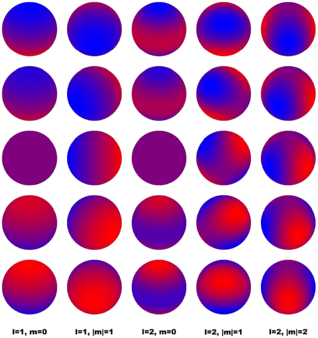


Probing stellar interiors

Asteroseismology:
infer inner structure of stars from oscillatory eigenmodes

non-radial modes particularly useful

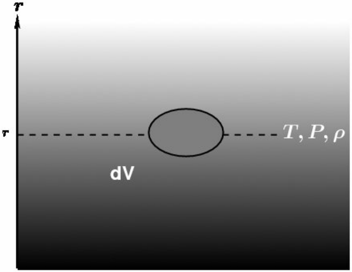


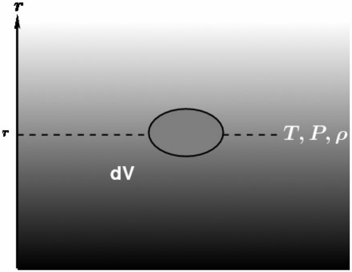


two limiting cases of gravo-acoustic modes:

the equilibrium solution

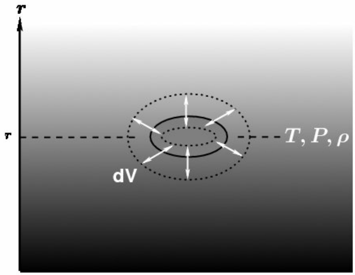
temperature, pressure, density and chemical composition as a function of a spatial radial coordinate



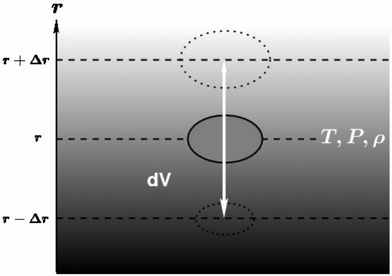


Deviations from the equilibrium solution

temperature, pressure, density and chemical composition as a function of a spatial radial coordinate

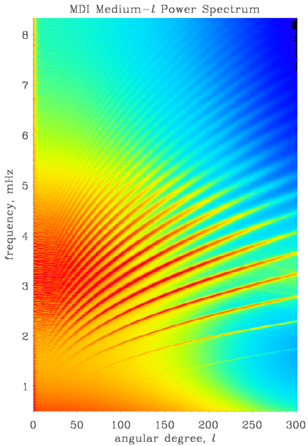


Lamb frequency
p modes



Brunt-Väisälä frequency
g modes

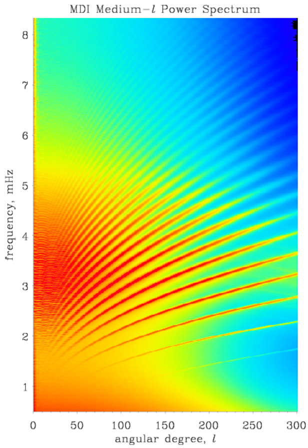
Helio- and asteroseismology

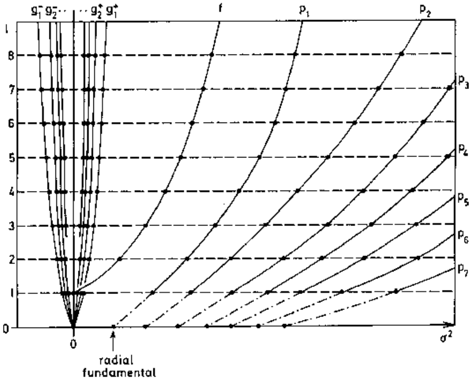


- comparison of full frequency spectrum ν_{nlm} to theoretical predictions **(forward modelling) requires**
  - high frequency resolution, many modes, mode identification
  - parameters for the models: stellar mass, T_{eff} or L, chemical composition and stratification, rotation, magnetic field
  - need appropriate theory for convection, equation of state, opacities

allows to probe interior physics

Helio- and asteroseismology





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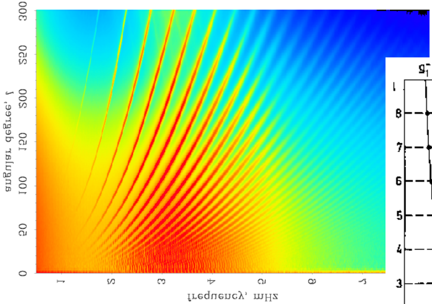
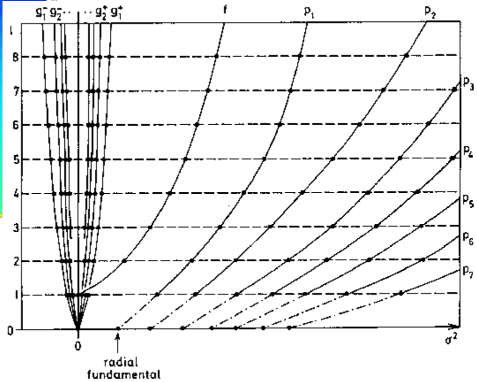
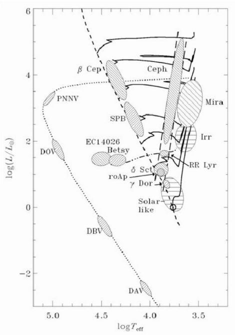




Science with pulsating stars

Asteroseismology useful to study ...

- depth of the convection zone in solar-like stars
- Classical pulsators: driving, opacities, rotation, magnetic fields ...
- non-standard feeder channels for white dwarfs
  - overshoot efficiency parameter in PG 1159 white dwarfs (GW Vir, born-again evolutionary scenario)
  - clues about the evolutionary history of subdwarf B stars (sdB), diffusion
  - secular evolution from $\dot{P}$ measurements



Solar-like pulsators

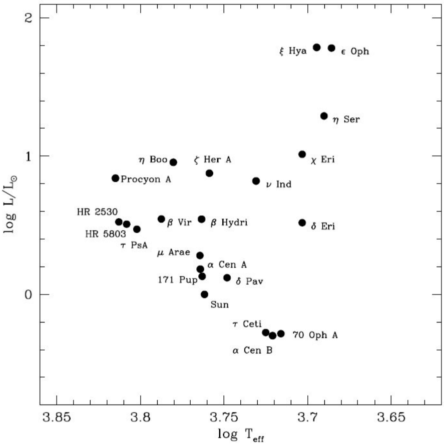
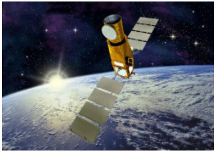


Figure 1. HR diagram showing the stars in which solar-like oscillations have been detected (with HR 2530 = HD 49933). The discoveries for 171 Pup, HR 5803 (HD 139211) and τ PsA are unpublished (Carrier *et al.*, in preparation). Figure courtesy of Fabien Carrier.

← ground-based observations



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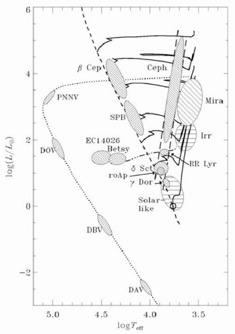

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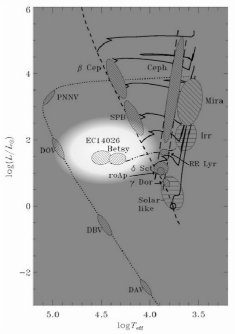
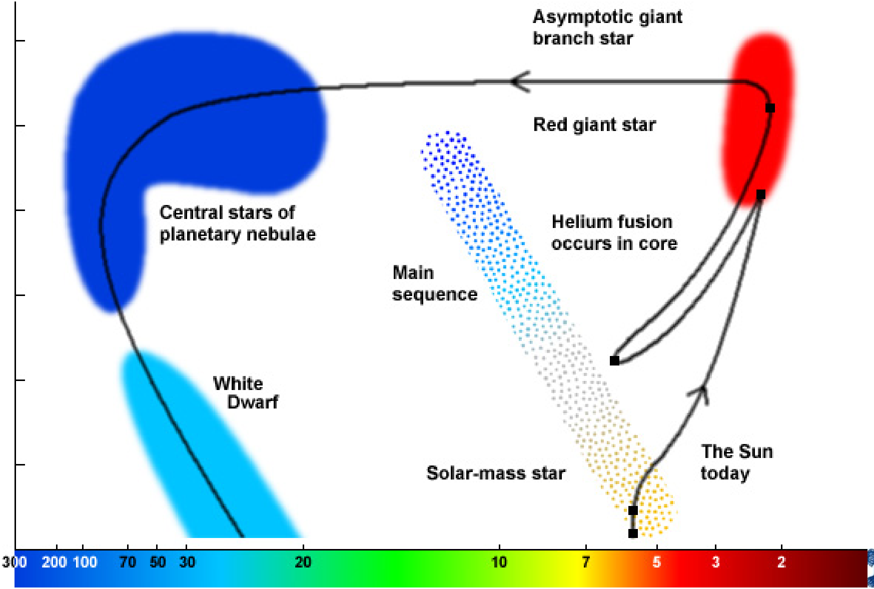
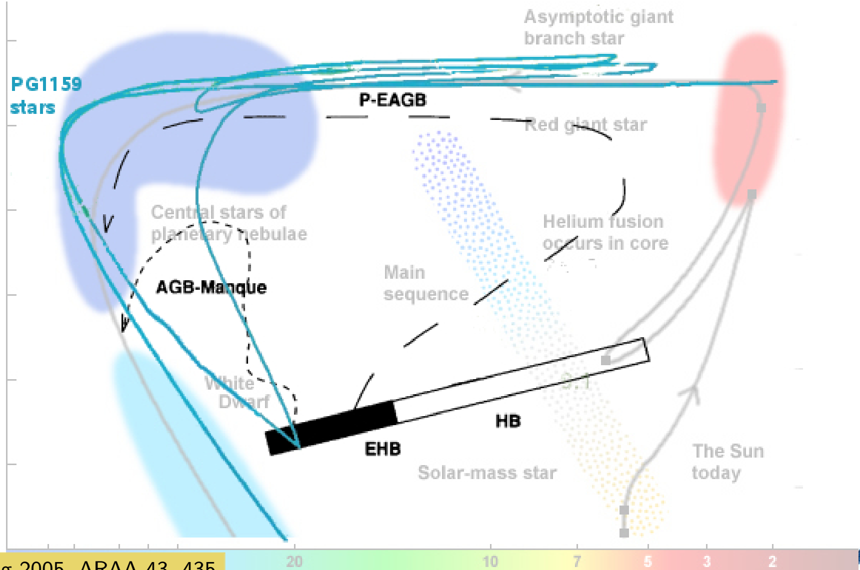
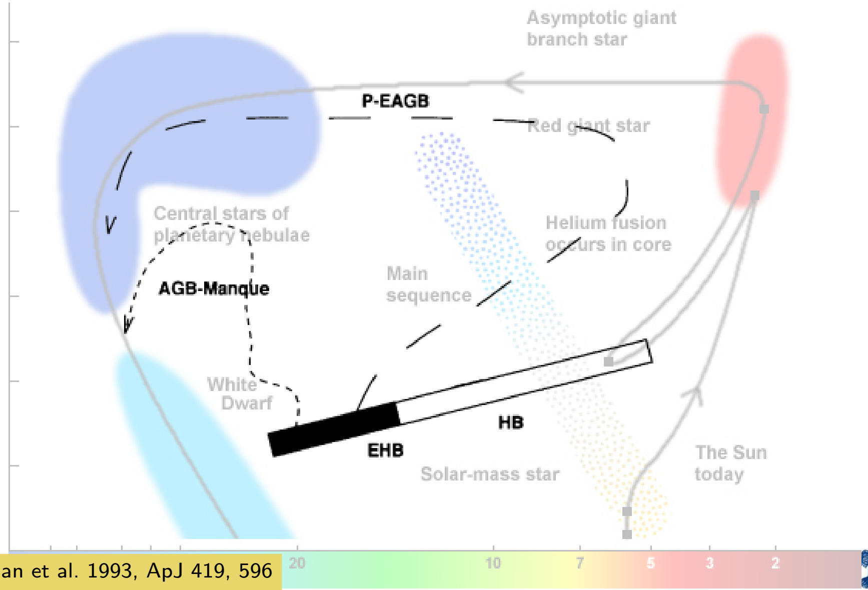


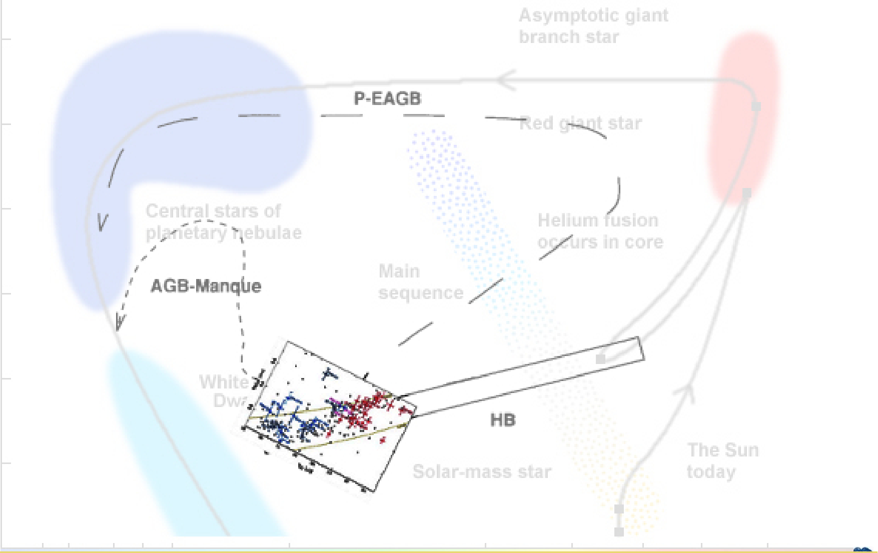

Asymptotic giant branch star
Red giant star
Central stars of planetary nebulae
Helium fusion occurs in core
Main sequence
White Dwarf
The Sun today
Solar-mass star
300 200 100 70 50 30 20 10 7 5 3 2



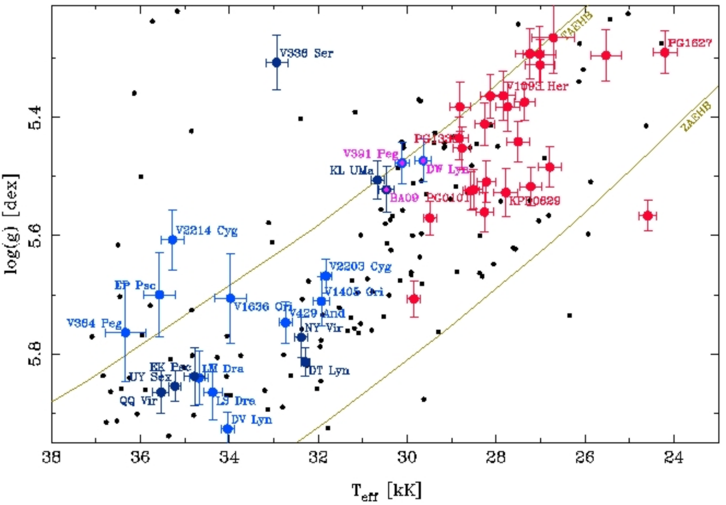
Herwig 2005, ARAA 43, 435

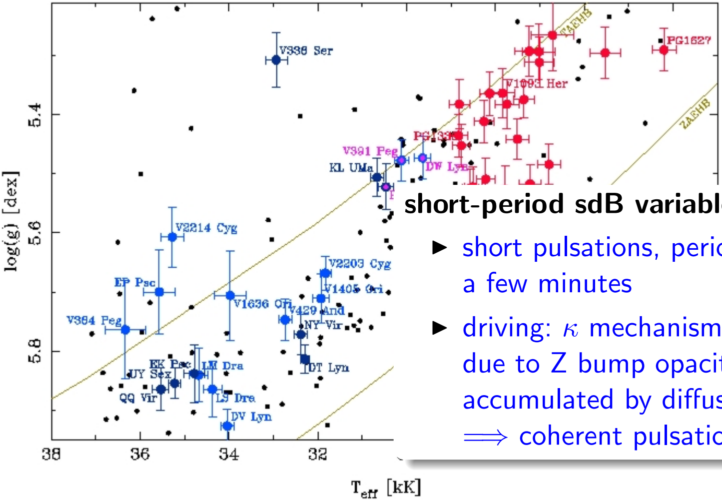


Dorman et al. 1993, ApJ 419, 596



Green, Fontaine, Hyde et al. 2008, ASPC 392, 75 ++++++ Østensen 2009, CoAst 159, 75


V338 Ser
PG1627
V1093 Her
ZAEHB
ZAEHB
V391 Peg
DW Lyn
KL UMa
BA09
KPD0629
V2214 Cyg
V2203 Cyg
V1405 Ori
EP Psc
V1636 Ori
V429 And
NY Vir
DT Lyn
LM Dra
UY Sex
QQ Vir
LS Dra
DV Lyn
log(g) [dex]
5.4
5.6
5.8
38
36
34
32
30
28
26
24
T_eff [kK]



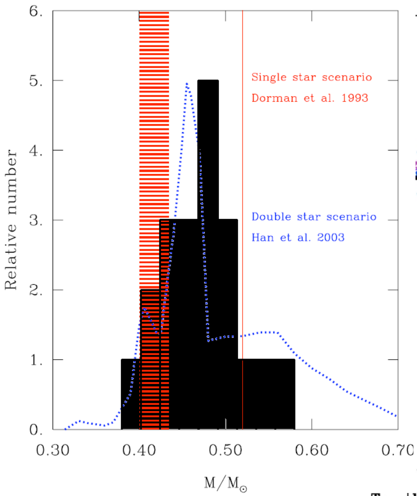
short-period sdB variable stars

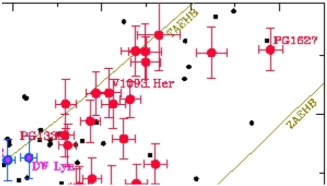
- short pulsations, periods of a few minutes
- driving: κ mechanism due to Z bump opacity accumulated by diffusion $\Longrightarrow$ coherent pulsations

Kilkenny et al. 1997, MNRAS 285, 640

Charpinet et al. 1996, ApJL, 471, 103

Dreizler, Schuh, Deetjen et al. 2002, A&A 386, 24





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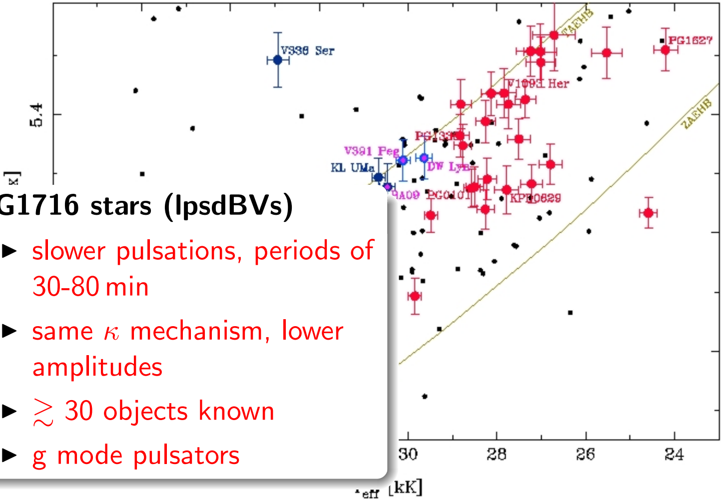
Randall, Fontaine, Brassard & Charpinet 2008, JPhCS 118, 2022

Han et al. 2003, MNRAS 341, 669

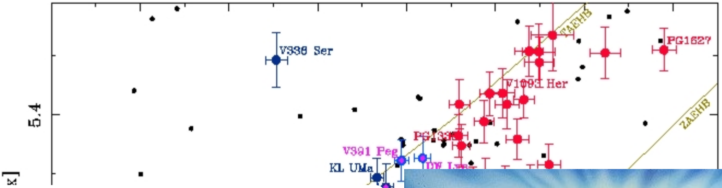


PG1716 stars (lpsdBVs)

- slower pulsations, periods of 30-80 min
- same κ mechanism, lower amplitudes
- $\gtrsim$ 30 objects known
- g mode pulsators

Kilkenny et al. 1997, MNRAS 285, 640

Green, Fontaine, Reed, . . . , Schuh, . . . et al. 2003, ApJ Letters 583, 31



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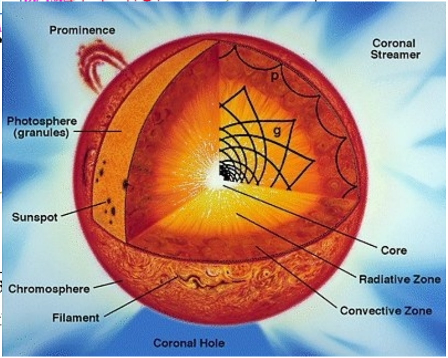

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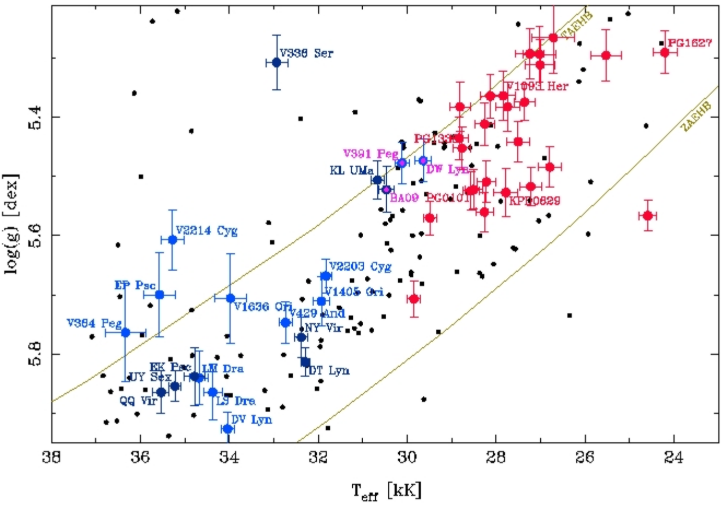

Kilkenny et al. 1997, MNRAS 285, 640

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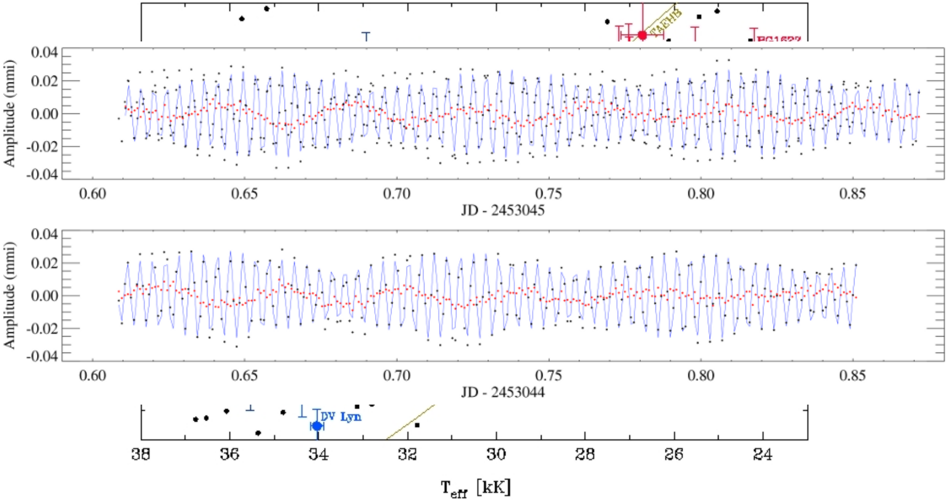
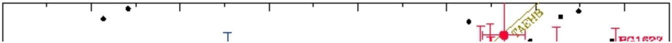
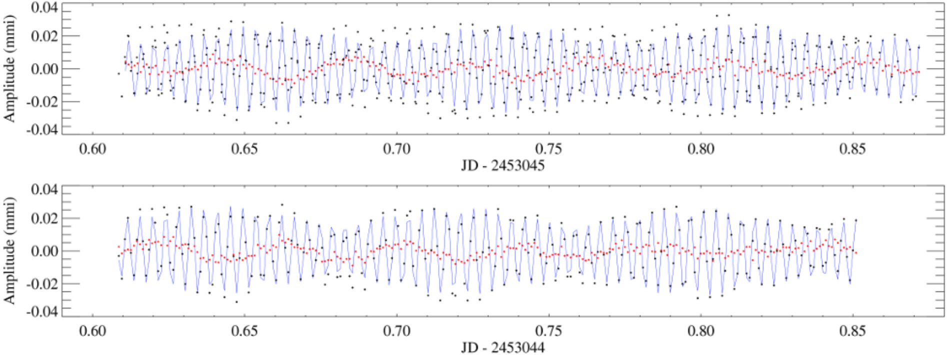


Dreizler, Schuh, Deetjen et al. 2002, A&A 386, 2 49

Schuh, Huber, Dreizler et al. 2006, A&AL 4 45, 31



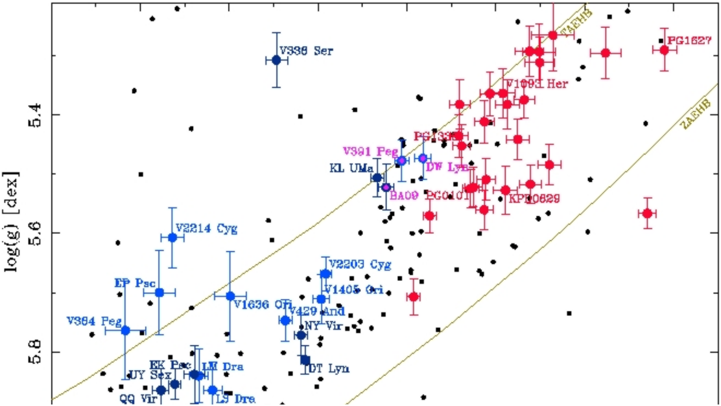


hybrid pulsators with p- and g-modes simultaneously

great potential for asteroseismology

Schuh, Huber, Dreizler et al. 2006, A&AL 4 45, 31

Lutz, Schuh, Silvotti et al. 2009, A&A 496, 469



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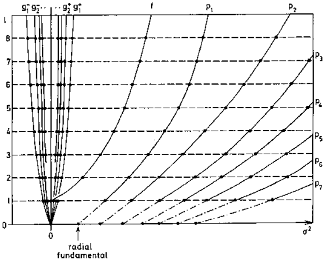
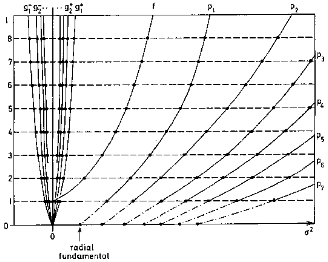
Mode identification – degree l



complex spectrum of frequencies ν
$\longrightarrow$ strong constraint for models
(forward modelling)

Mode identification – degree l

additional constraint from degree l



complex spectrum of frequencies ν
$\longrightarrow$ strong constraint for models
(forward modelling)

l, ν diagram for stars

- pulsation frequency ν
  - photometry
- degree l of pulsation mode
  - geometric consideration for mode identification
  - complementary spectroscopic methods

brightness $\propto cos\theta$

$cos\theta$ area

velocity $\propto cos^2\theta$

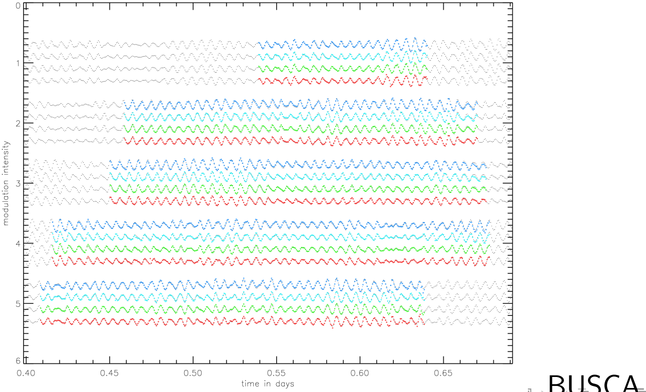
$cos\theta$ area $\times$
$cos\theta$ projected velocity

light-to-velocity ratio differs for different degrees l

l, ν diagram for stars

light-to-velocity ratio differs for different degrees l

wavelength dependency of amplitude differs for different degrees l



l, ν diagram for stars

light-to-velocity ratio differs for different degrees l

l, ν diagram for stars

light-to-velocity ratio differs for different degrees l

$\Longrightarrow$ simultaneous measurement of light (brightness change) and velocity (radial velocity change) for PG 1605+072

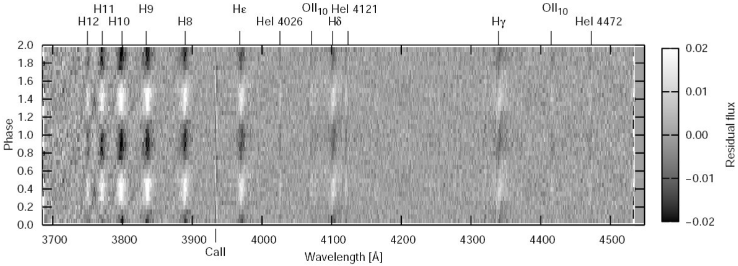
Falter, Heber, Dreizler, Schuh et al. 2003, A&A 401, 289

O'Toole, Heber, Jeffery, . . . , Schuh, . . . et al. 2005, A&A 440,667

Stahn 2005, Diplomarbeit, Georg-August-Universität Göttingen

Tillich, Heber, O'Toole, . . . , Schuh, . . . et al. 2007, A&A 473, 219

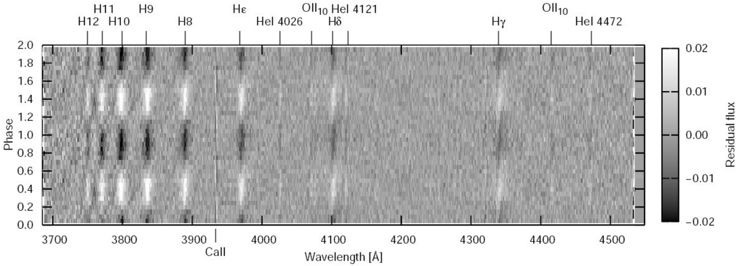
Time series of optical spectra



- deviations from mean spectral line profile

Tillich, Heber, O'Toole, . . . , Schuh, . . . et al. 2007, A&A 473, 219

Time series of optical spectra – phase relations

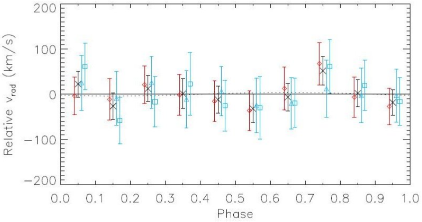


- deviations from mean spectral line profile
- phase relations
  - radial velocity versus temperature variation: $\pi/3$
  - check: radial velocity versus $\log g$ variation: $\pi/2$
- points to non-adiabatic pulsational behaviour
- further result: strongest pulsation corresponds to $l=1$ instead of $l=0$

Tillich, Heber, O'Toole, . . . , Schuh, . . . et al. 2007, A&A 473, 219

Pulsational radial velocity variation

upper limits for line profile variations in V391 Pegasi



Kruspe 2009, Diplomarbeit, Georg-August-Universität Göttingen

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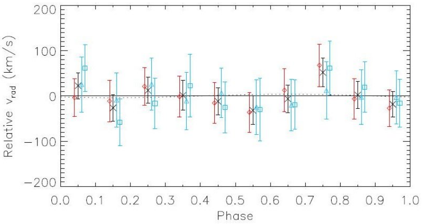
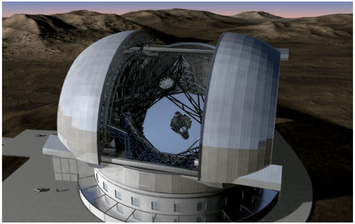


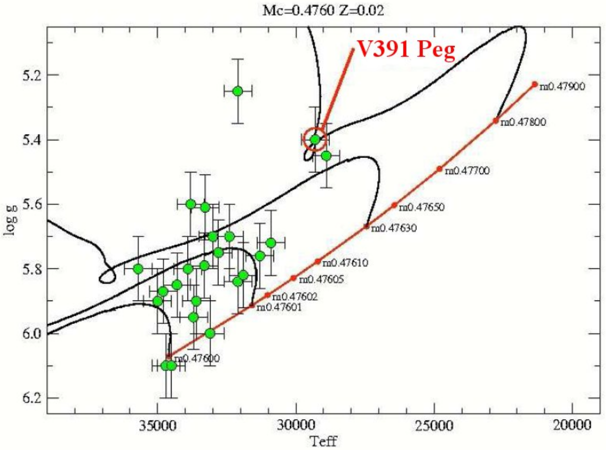


will need E-ELT

Kruspe 2009, Diplomarbeit, Georg-August-Universität Göttingen

subdwarf B stars are hot, but compact and hence faint objects

Timing method - $\dot{P}$ as constraint for models



From Steve Kawaler (2° KASC workshop, Aarhus, June 2008)

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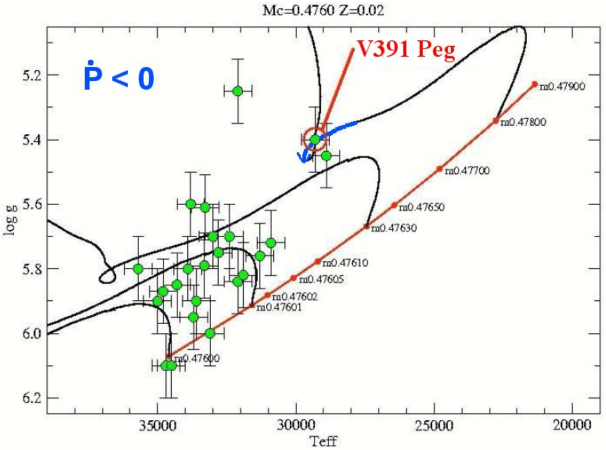

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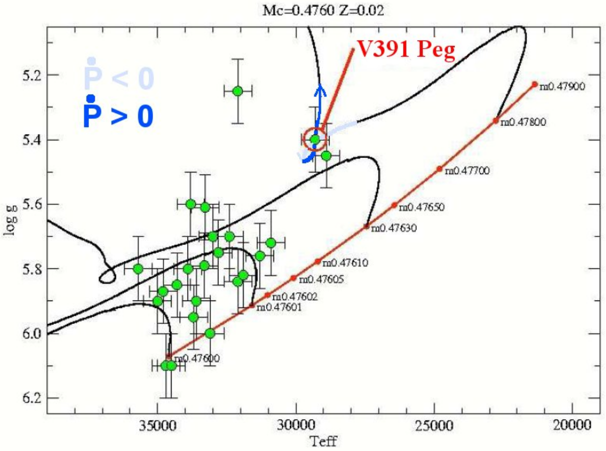
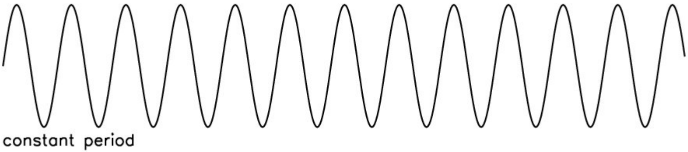


From Steve Kawaler (2° KASC workshop, Aarhus, June 2008)

O−C diagrams

- example: pulsations as regular clock



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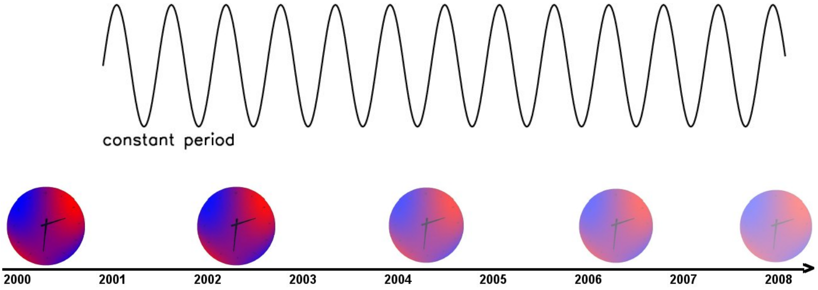
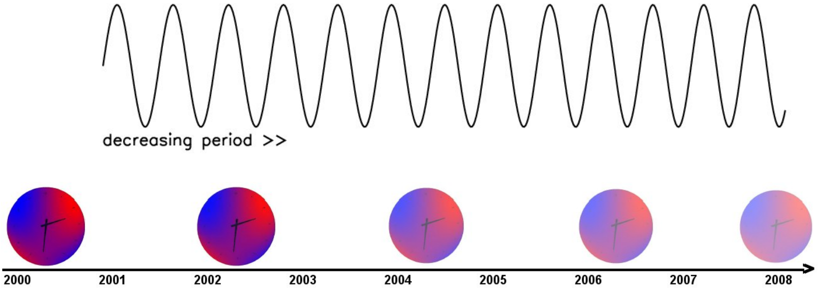


O−C diagrams

- example: pulsations as ~~regular~~ clock
- clock slows down or accelerates due to secular evolution



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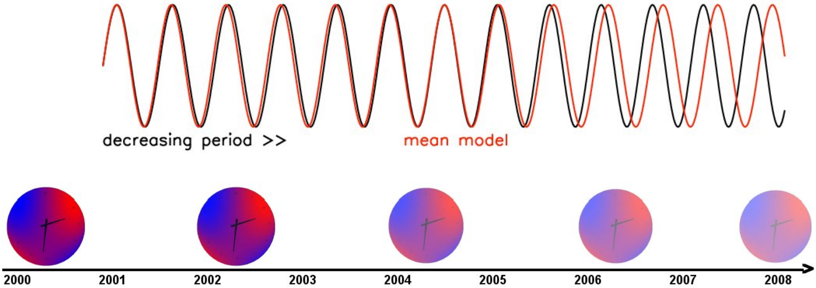

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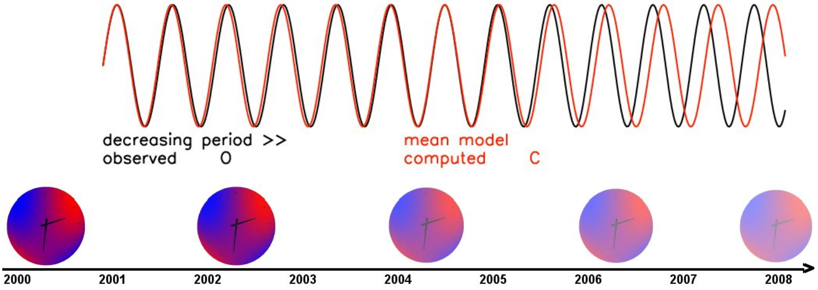
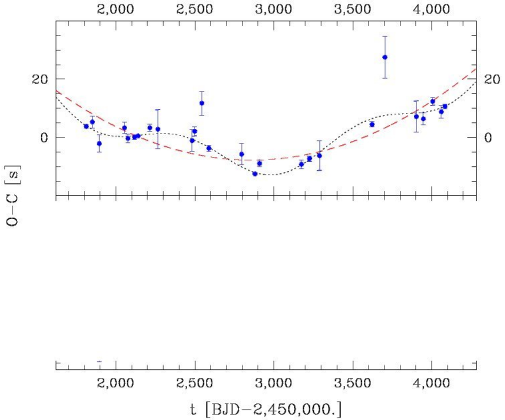


O–C diagrams

- example: pulsations as ~~regular~~ clock
- clock slows down or accelerates due to secular evolution
- previously measured secular $\dot{P}$ for pulsating sdBs:

O−C diagram for V391 Pegasi

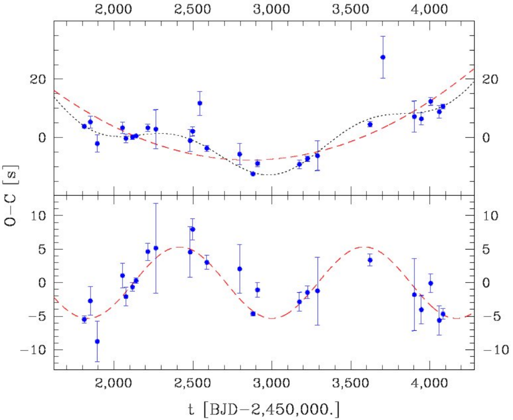


f_1=2860.94μHz

Silvotti, Janulis, Schuh et al. 2002, A&A 389, 180

Silvotti, Schuh, Janulis et al. 2007, Nature 449, 189

O−C diagram for V391 Pegasi



f_1=2860.94μHz

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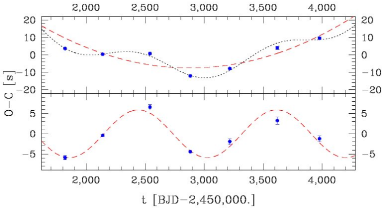
Silvotti, Schuh, Janulis et al. 2007, Nature 449, 189

O−C diagram for V391 Pegasi



$f_1 = 2860.94 \mu\text{Hz}$

Silvotti, Janulis, Schuh et al. 2002, A&A 389, 180

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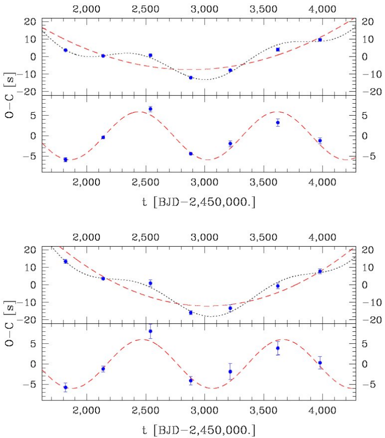


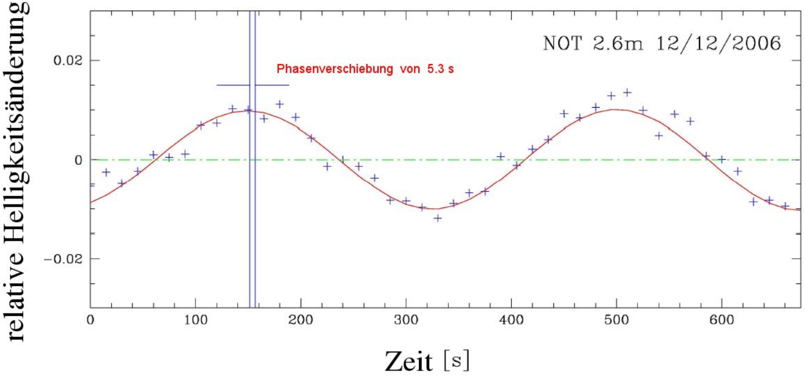
f_1=2860.94μHz
f_2=2824.1 μHz

Silvotti, Janulis, Schuh et al. 2002, A&A 389, 180

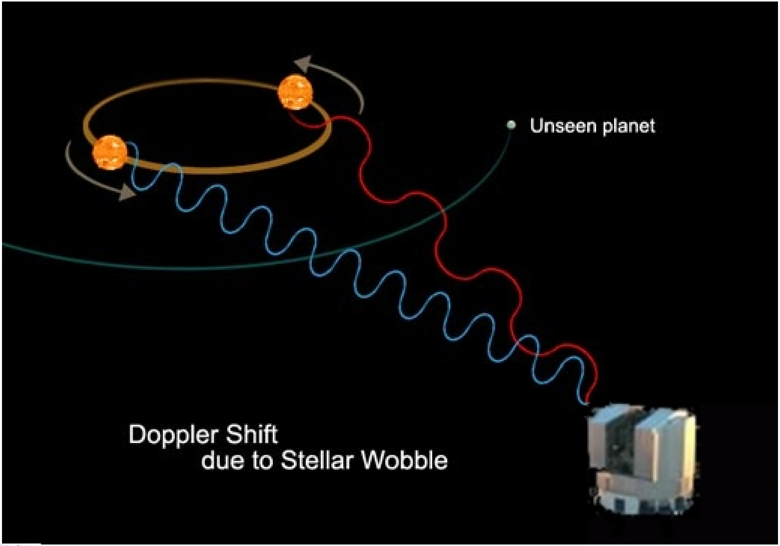
Silvotti, Schuh, Janulis et al. 2007, Nature 449, 189

Coherent pulsations as timing signal

Data points + + + + + compared to mean model



Exoplanets: radial velocity versus timing



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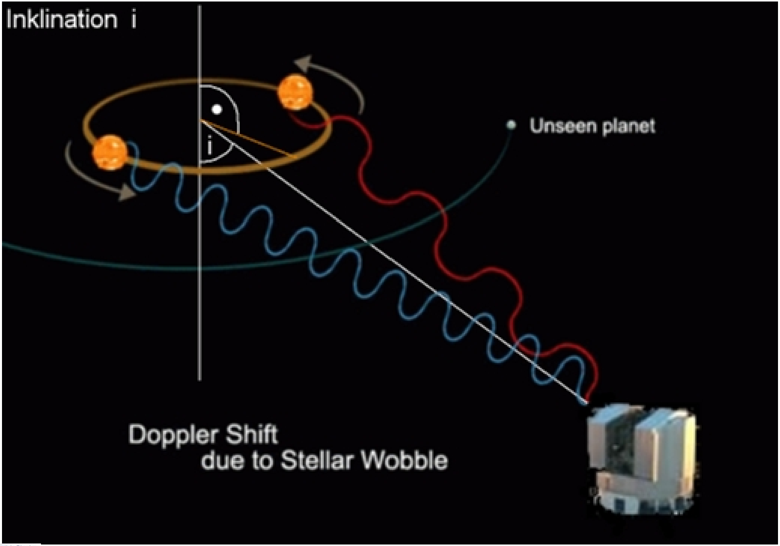
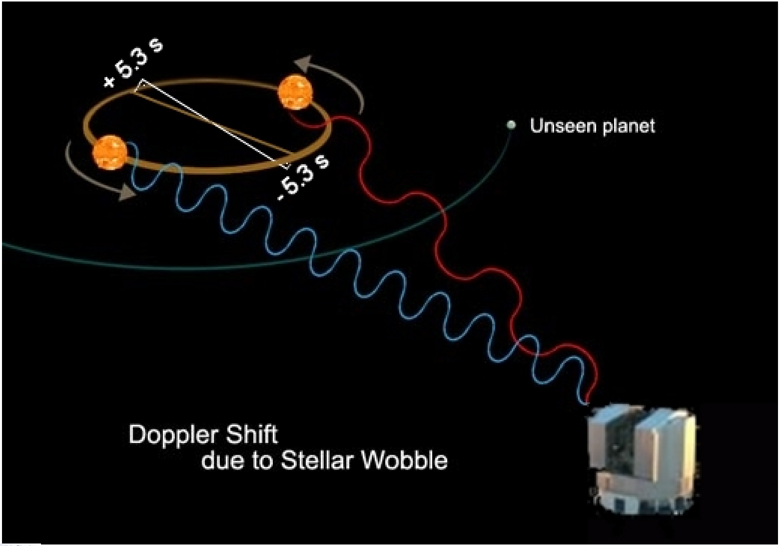


Exoplanets: radial velocity versus timing

time delay of $\pm 5.3\,\mathrm{s} \hat{=}$ projected semi-major axis of 5.3 light seconds



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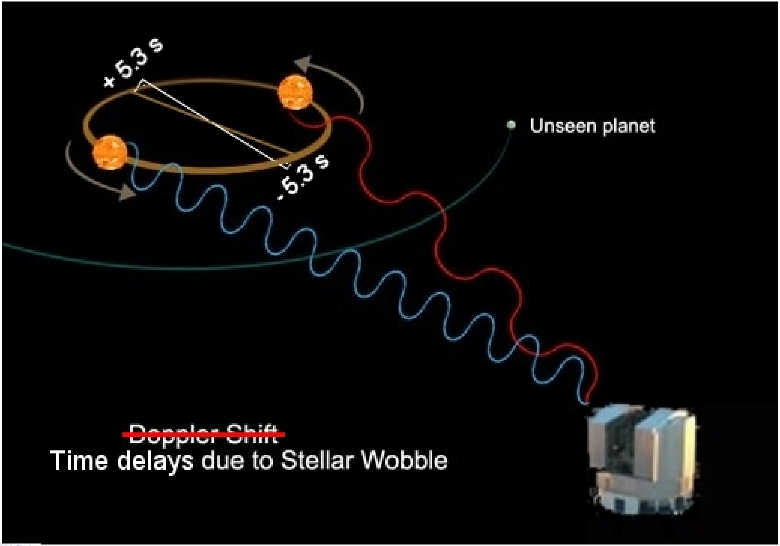
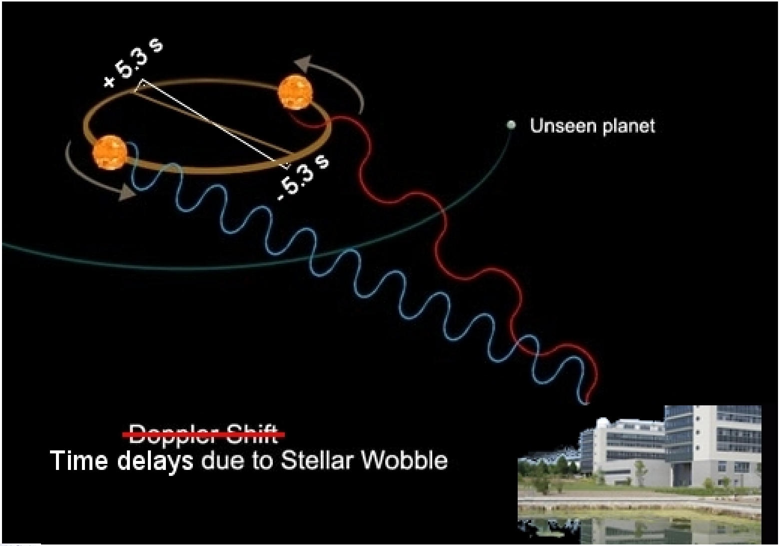
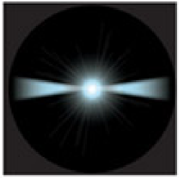


Exoplanets: radial velocity/ pulsation timing

time delay of $\pm 5.3\,\mathrm{s} \hat{=}$ projected semi-major axis of 5.3 light seconds

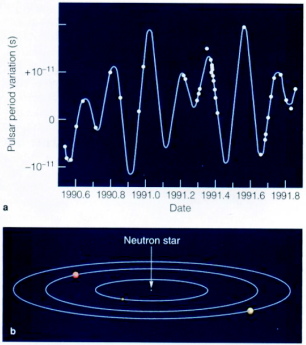


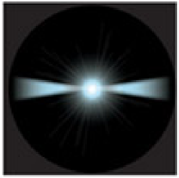
Pulsar planets



Pulsar planets

FIGURE 11-10
(a) The dots in this graph are observations showing that the period of pulsar PSR1257+12 varies from its average value by a fraction of a billionth of a second. The blue line shows the variation that would be produced by planets orbiting the pulsar. (b) As the planets orbit the pulsar, they cause it to wobble by less than 800 km, a distance that is invisibly small in this diagram. *(Adapted from data by Alexander Wolszczan)*





Wolszczan A. & Frail D., 1992, Nature, 355 , 145

Exoplanet search with the timing method

Exoplanet search with the timing method

goal	Find more planets like V 391 Pegasi b
method	Long-term monitoring of pulsations in subdwarf B stars
advantage	Timing method can fill gap: sensitive to planets in wide orbits applicable to evolved stars
follow-up	Characterisation of target stars monitored

- mode splitting
- chromatic amplitudes
- time-dependent spectroscopy

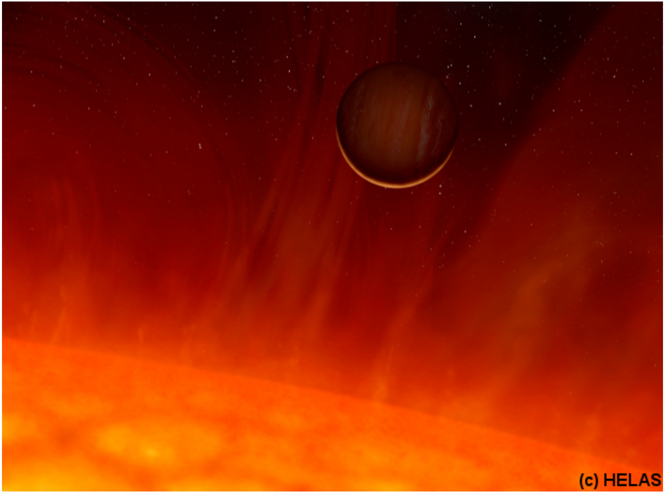
Exoplanet search with the timing method

goal

method

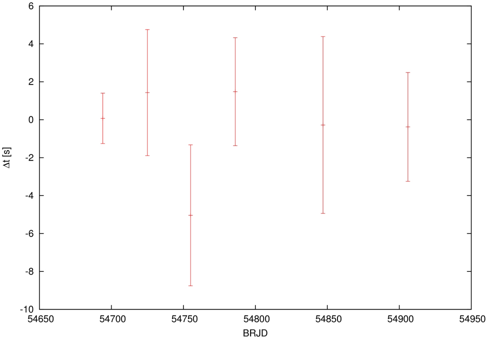
advantage

follow-up



EXOTIME preliminary results

Timing method - long-term stability of the pulsations in HS 0444+0458



Loeptien 2009, Bachelorarbeit, Georg-August-Universität Göttingen

EXOTIME preliminary results

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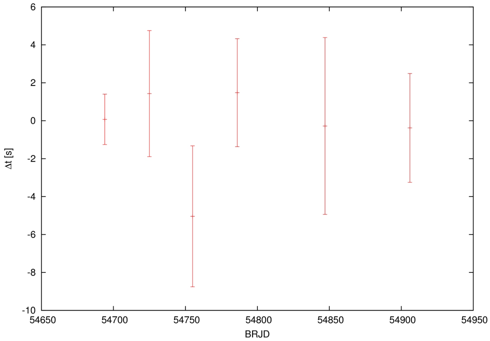
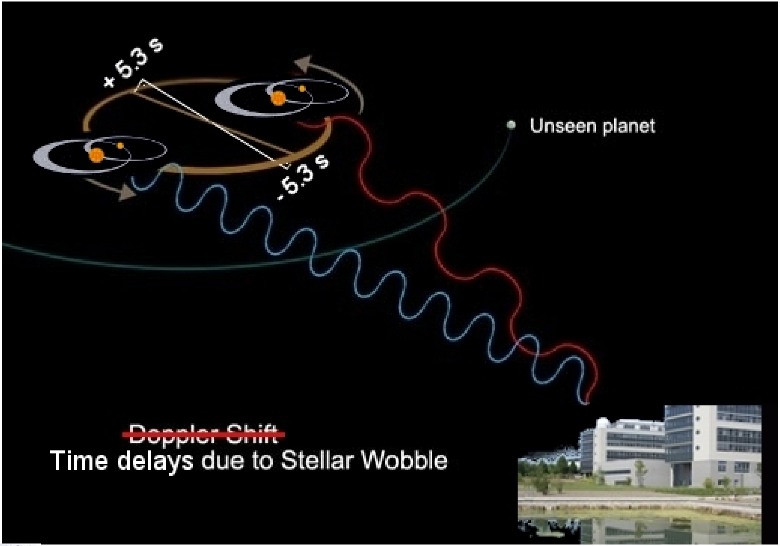


Loeptien 2009, Bachelorarbeit, Georg-August-Universität Göttingen

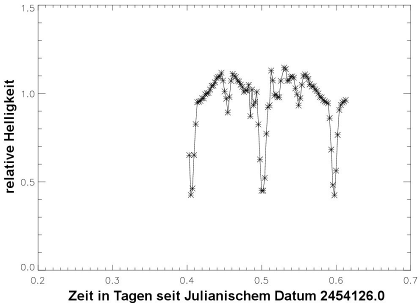
HS0702+6043: Lutz, PhD thesis, on-going

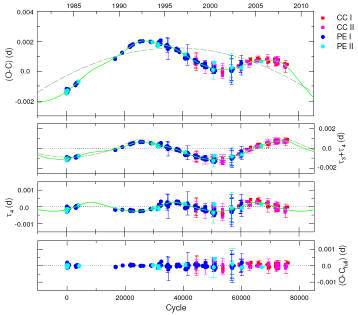
Exoplanets: radial velocity / eclipse timing

time delay of $\pm 5.3\,\mathrm{s} \mathrel{\hat{=}}$ projected semi-major axis of 5.3 light seconds



Timing of binary eclipses

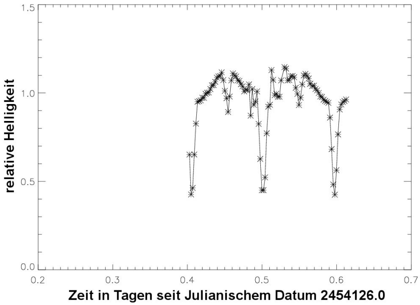


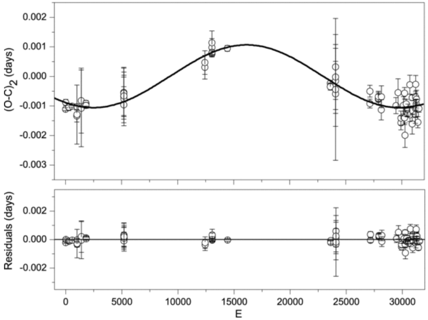


Lee et al. 2009, AJ 137, 3181

discovery of two planetary-mass objects around HW Vir

Timing of binary eclipses



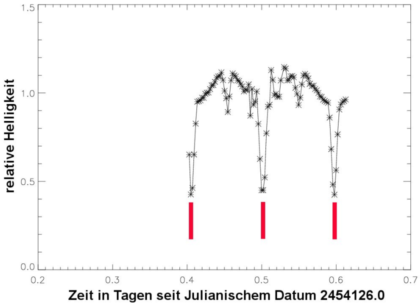


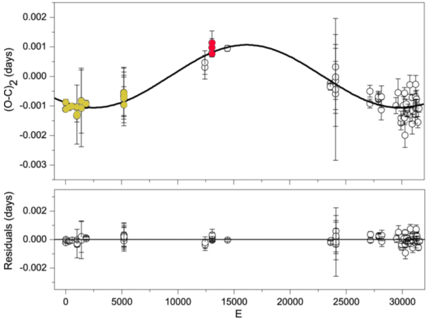
Qian et al. 2009, ApJ Letters 695, 163

discovery of a brown dwarf around HS 0705+6700

Drechsel, Heber, Napiwotzki, . . . , Schuh, . . . et al. 2001, A&A 379, 893

Timing of binary eclipses





Kruspe, Schuh & Traulsen 2007, IBVS 5796, 1

Qian et al. 2009, ApJ Letters 695, 163
discovery of a brown dwarf around HS 0705+6700

Drechsel, Heber, Napiwotzki, . . . , Schuh, . . . et al. 2001, A&A 379, 893

Beyond "extrasolar planet science"

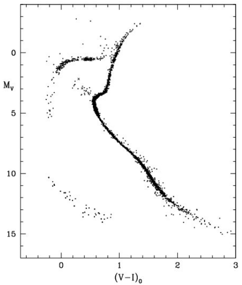
- fate of planetary systems: first or second generation planets?
  - pulsation timing (V 391 Peg)
    eclipse timing (HW Vir, HS 0705+6700)
  - radial velocity planet around the subdwarf B star HD 149382:
    Geier, Edelmann, Heber & Morales-Rueda 2009, ApJL, 702, 96
- origin of subdwarf B stars
  - binarity
  - decisive influence of low-mass companions on RGB evolution
  - complementary to insights from asteroseimology and $\dot{P}$
  - KEPLER/KASC program; target list small due to limited field
    Silvotti, Handler, Schuh et al. 2009, CoAst 159, 97
  - ground-based observations remain important
- morphology of blue horizontal branch

Renaissance of an old idea

suggested **second parameter** influencing the (blue) horizontal branch morphology in globular clusters and elliptical galaxies

- Age of the globular cluster
- Deep helium mixing and radiative levitation
- Large He abundance or fast rotation
- Stellar density in the cluster
- Planets enhancing mass loss on the Red Giant Branch

Soker 1998, AJ 116, 1308



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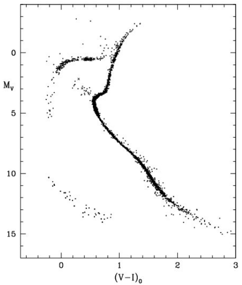
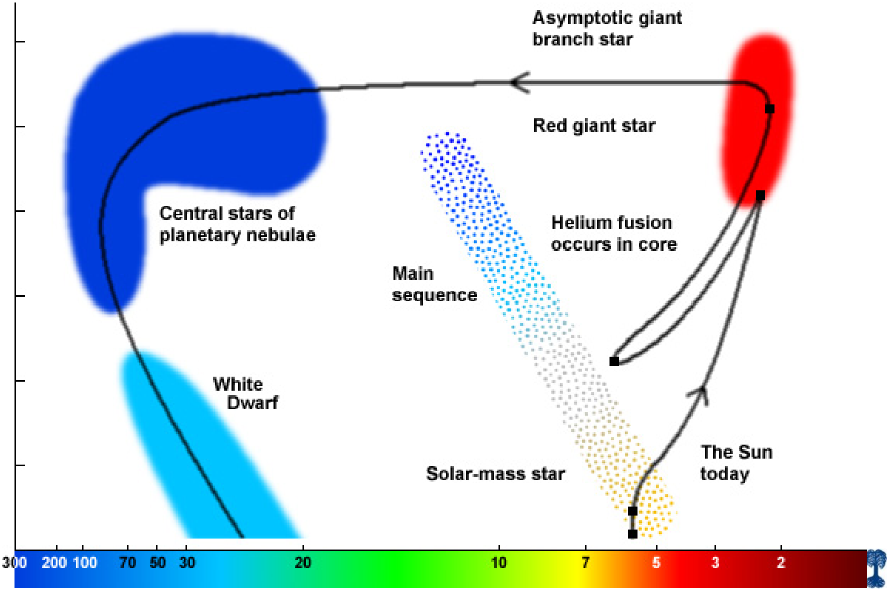
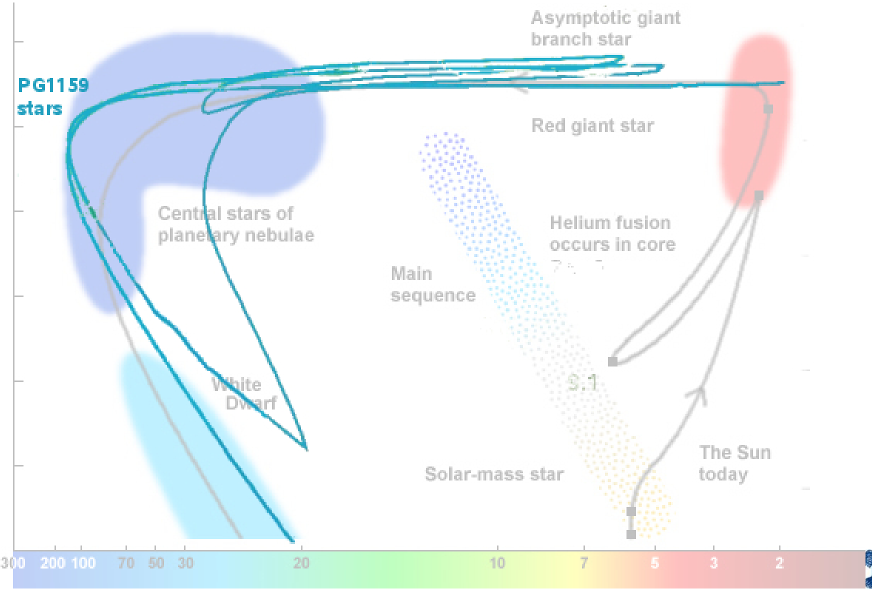


Hot hydrogen-deficient white dwarfs
GW Vir pulsators


Asymptotic giant branch star
Red giant star
Central stars of planetary nebulae
Helium fusion occurs in core
Main sequence
White Dwarf
The Sun today
Solar-mass star
300 200 100 70 50 30 20 10 7 5 3 2


Asymptotic giant branch star
PG1159 stars
Red giant star
Central stars of planetary nebulae
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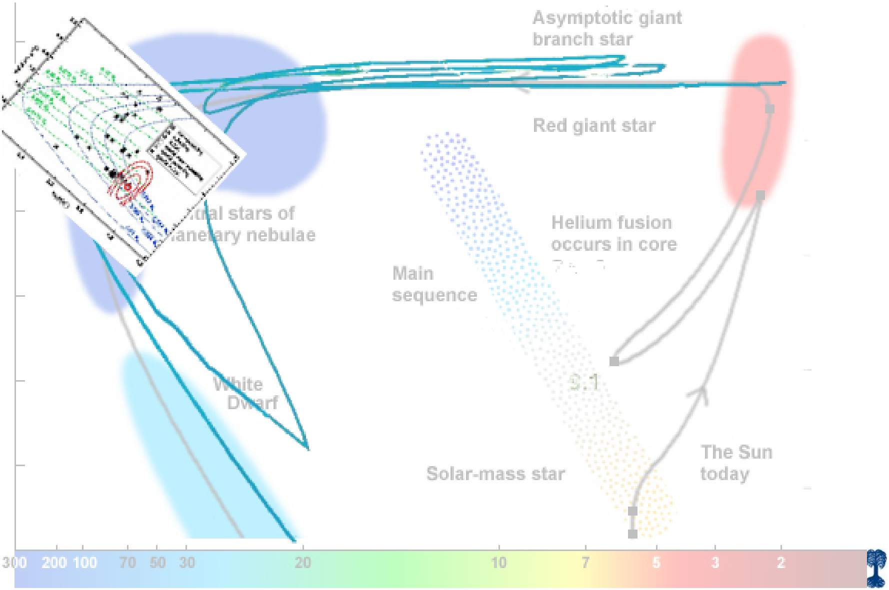
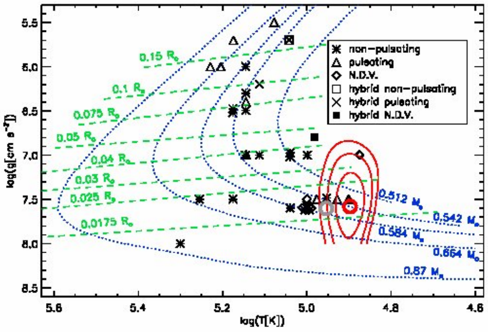
Solar-mass star
The Sun today
300 200 100 70 50 30 20 10 7 5 3 2


Asymptotic giant branch star
Red giant star
Helium fusion occurs in core
Main sequence
White Dwarf
Solar-mass star
The Sun today
300 200 100 70 50 30 20 10 7 5 3 2

Mass determinations with different methods

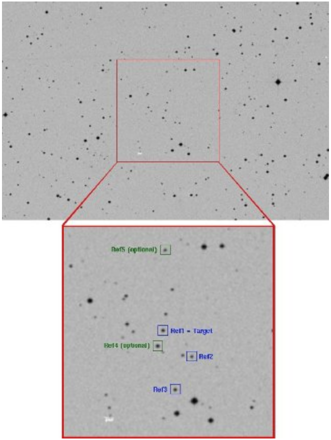
frequencies ν
$\rightarrow$ pulsation models

$T_{\rm eff}$, $\log g$ (stellar atmosphere modelling)
$\rightarrow$ evolutionary models



asteroseismic and spectroscopic masses differ by up to 10%

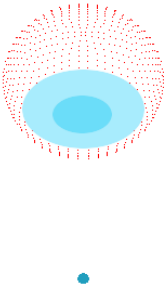
SDSS2125: a PG 1159 close binary system



consistency check with simple physics, no complicated assumptions

SDSS2125: a PG 1159 close binary system

hot white dwarf and late-type main sequence companion



reflection effect ⟶ periodic brightness variation

Nagel, Schuh, Kusterer et al. 2006, A&A Letters 448, 25

Schuh, Traulsen, Nagel et al. 2008, AN 329, 376

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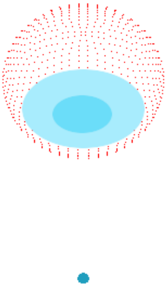

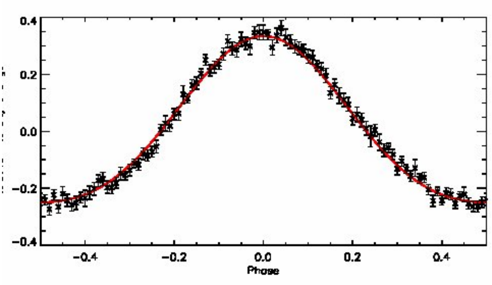

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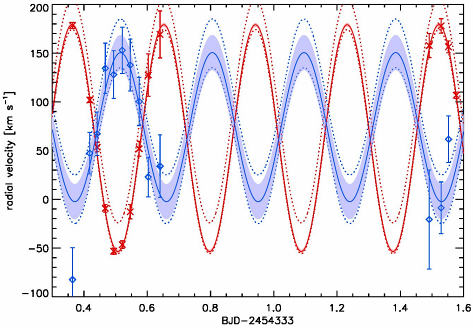

radial velocity curves; inclination a priori unknown

Beeck 2009, Diplomarbeit, Georg-August-Universität Göttingen

⟶ inclination from light curve modelling

Results I: hot hydrogen-deficient white dwarfs (PG 1159)

DONE Frequency spectra of GW Vir pulsators, asteroseismic mass determination

TODO alternative mass determination

ESO: VLT

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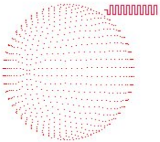
TODO alternative mass determination in the only definite PG 1159 close binary system



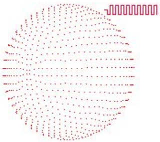
ESO: VLT

Results I: hot hydrogen-deficient white dwarfs (PG 1159)

DONE Frequency spectra of GW Vir pulsators, asteroseismic mass determination

TODO alternative mass determination in the only definite PG 1159 close binary system

independent check of the results through measurement of the predicted gravitational redshift in the white dwarfs' potential well



ESO: VLT

Results II: subdwarf B stars (sdB)

Search for rapidly pulsating subdwarf B stars
discovery of g modes in subdwarf B stars
discovery of hybrid pulsators (p+g modes) in subdwarf B stars

from long-term monitoring of the pulsations in V391 Pegasi:

- slow changes in the two main frequencies due to expansion of the star: $\dot{P}_1$=(1.46±0.07)×10^{-12} $\dot{P}_2$=(2.05±0.26)×10^{-12}
- discovery of a massive gas giant planet ($M \sin i$=3.2$\mathrm{M_{Jupiter}}$) in a 1.7×AU orbit, orbit period 3.2a
- planet survived the red giant phase of its host star

measured frequency spectra, frequency changes, and discovery of stellar, sub-stellar and planetary sdB companions:

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measured frequency spectra, frequency changes, and discovery of stellar, sub-stellar and planetary sdB companions:
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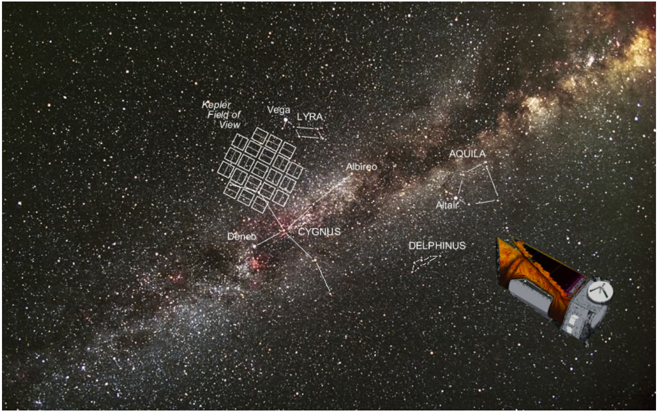
KEPLER mission:

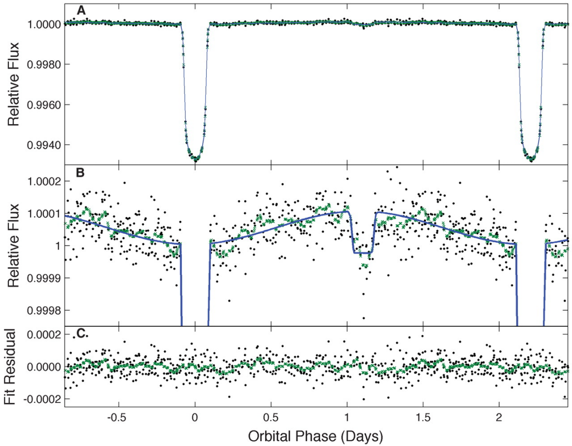
useful tool to do asteroseismology; KEPLER/KASC programs



main objective is exoplanet search with transit method
young stars and main sequence bias

KEPLER mission: transits, transits, transits . . . !

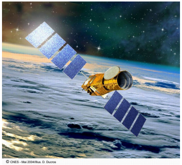
KEPLER mission: transits, transits, transits . . . !

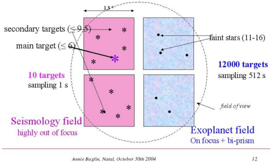


Kepler's Optical Phase Curve of the Exoplanet HAT-P-7b

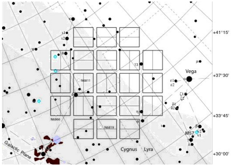
Borucki, Koch, Jenkins et al. 2009, Science 325, 709

Convergence of instrumentation



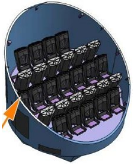


Kepler



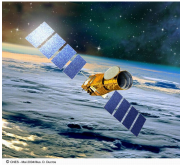
PLATO

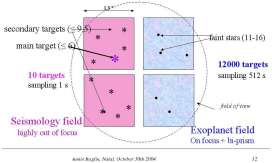
PLAnetary Transits and Oscillations of stars



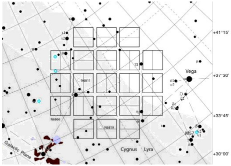
- Detect Earth sized planets around solar type stars
- Detect super-earths around solar type stars
- Measure solar oscillations in the host stars of exoplanets
- Measure oscillations of classical pulsators

Convergence of instrumentation



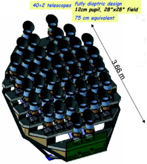


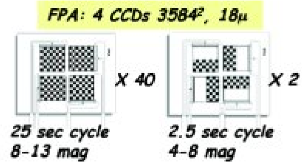
Kepler



PLATO

PLAnetary Transits and Oscillations of stars





Investigation of stellar and planetary systems

Asteroseismology-exoplanet-connection for solar-like pulsators

- accurate radii for (solar-like) host stars of transiting exoplanets

Asteroseismology-exoplanet-connection for post-RGB stars

- fate of planetary systems
  - known planets around extreme horizontal branch stars: first or second generation?
- origin of subdwarf B stars
- second parameter for HB in GC

Characterisation of post-AGB stars