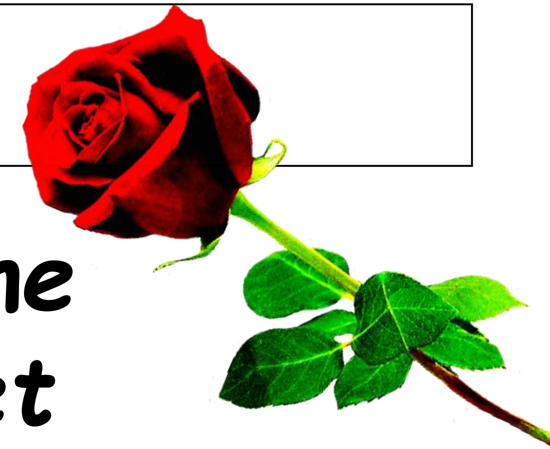
What's in a name?



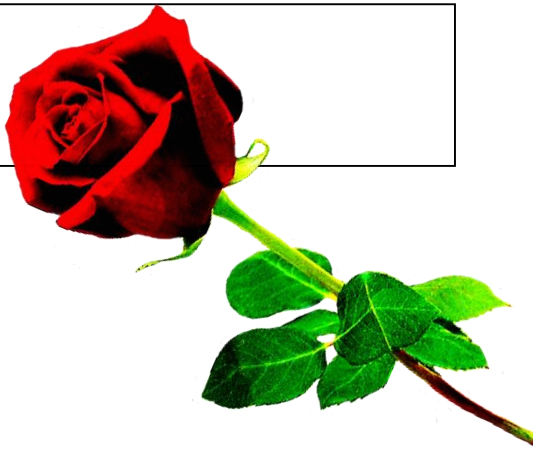
An roAp by any other name would cast a spell as sweet

Observations of roAp stars

Jaymie Matthews
University of British Columbia
Vancouver, Canada

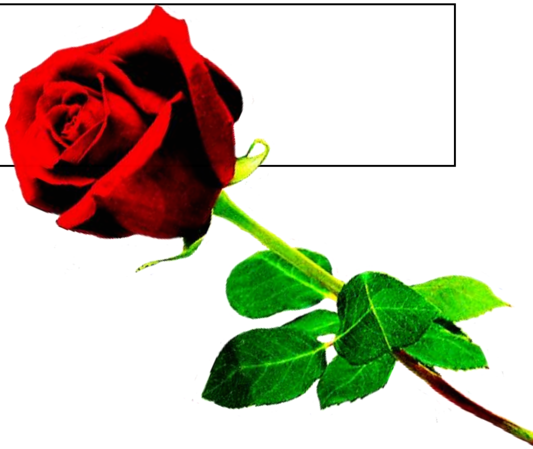
W. Shakespeare
The Globe Theatre
Stratford-on-Avon, UK

What's in a name?



rapidly oscillating Ap star

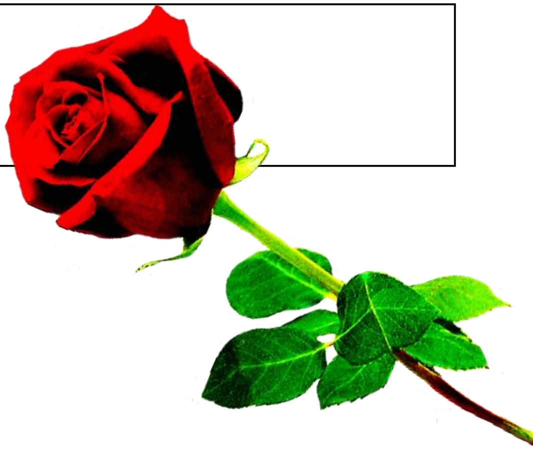
What's in a name?



rapidly oscillating Ap star

"r-o-A-p" abbreviation

What’s in a name?



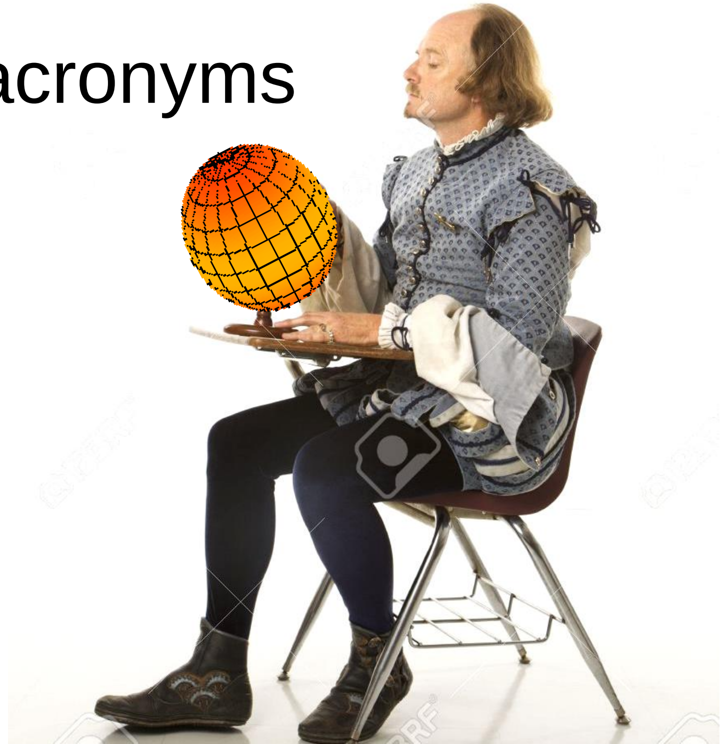
rapidly oscillating Ap star

“r-o-A-p“ abbreviation

“rope“

“rho-App“

acronyms



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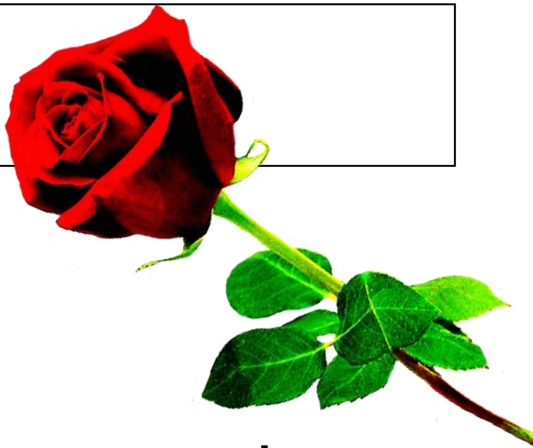
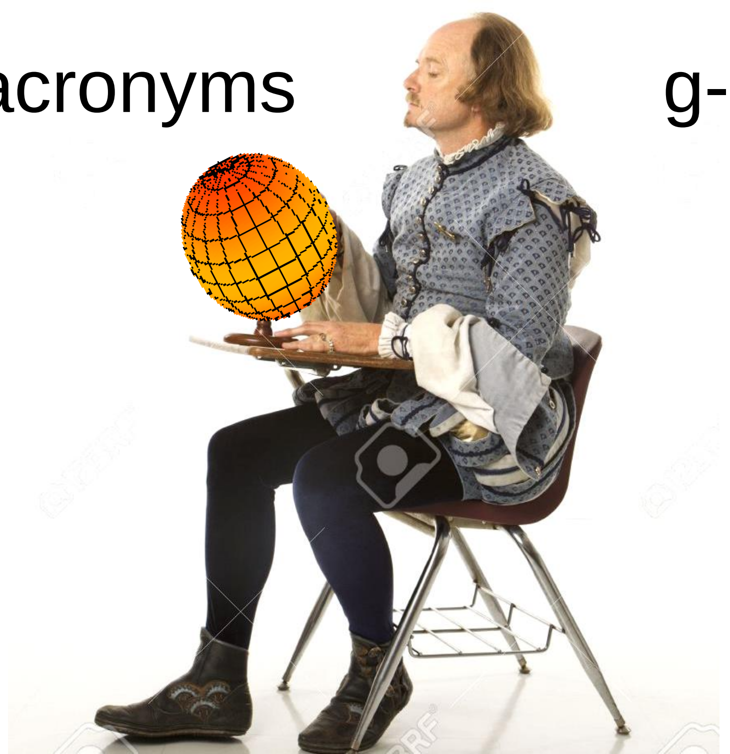


rapidly oscillating Ap star

"r-o-A-p" abbreviation p-mode

"rope"

"rho-App" acronyms g-modes



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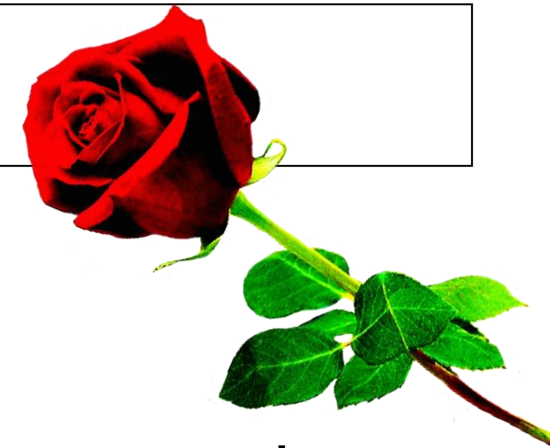
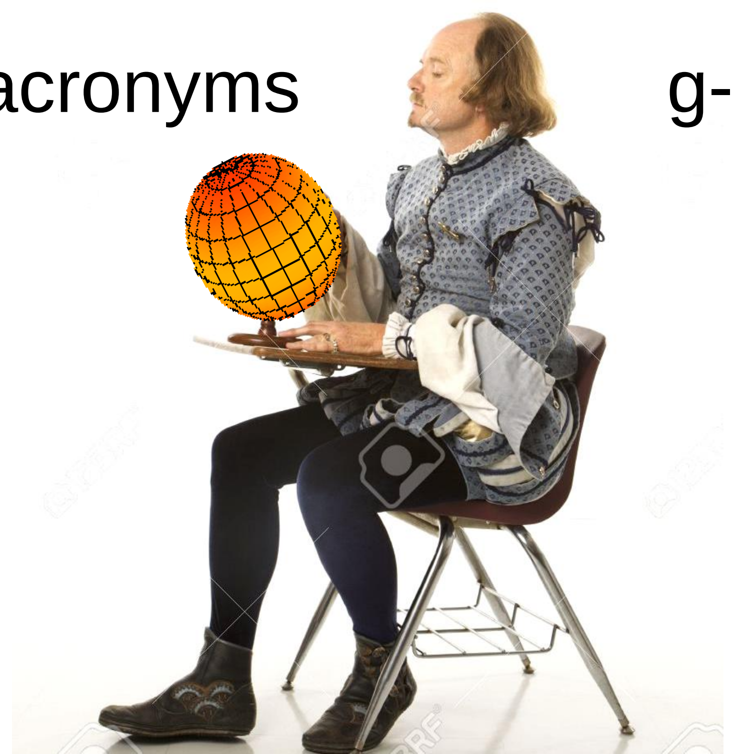


rapidly oscillating Ap star

_"r-o-A-p"_ abbreviation p-mode

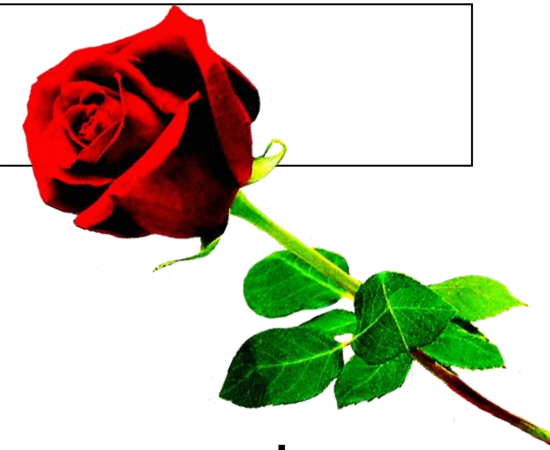
"rope"

"rho-App" acronyms g-modes



"rho-A-p"

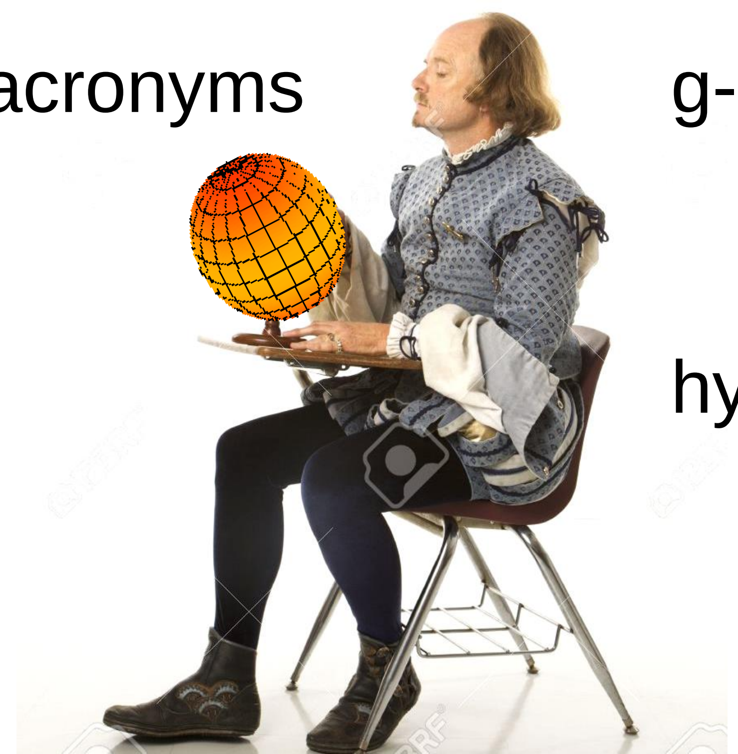
What's in a name?



rapidly oscillating Ap star

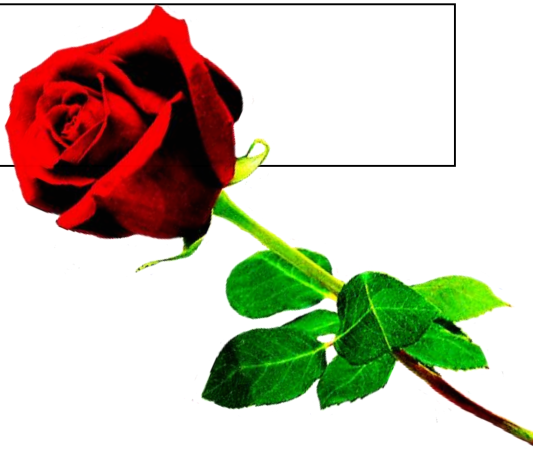
"r-o-A-p" abbreviation p-mode

"rope"
"rho-App" acronyms g-modes



"rho-A-p" hybrid

What's in a name?

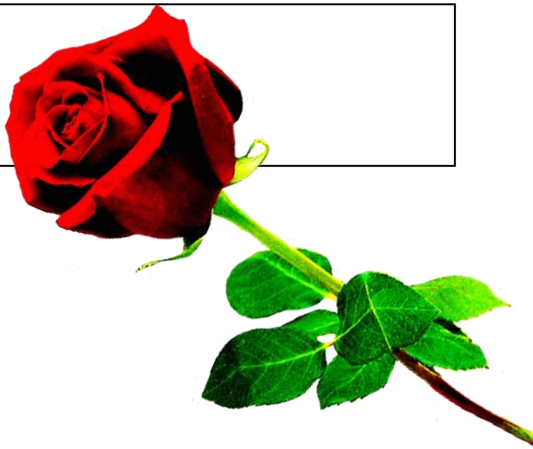


slowly pulsating B star

The new class was announced at the 1986 pulsation conference in Los Alamos

Christoffel Waelkens

What's in a name?

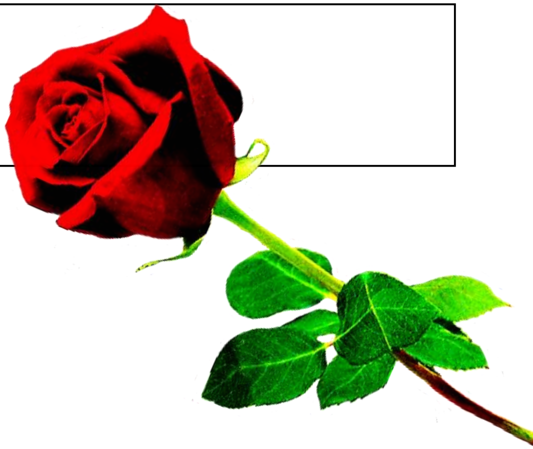


slowly oscillating B star

The new class was announced at the 1986 pulsation conference in Los Alamos but with a different name

Christoffel Waelkens

What's in a name?



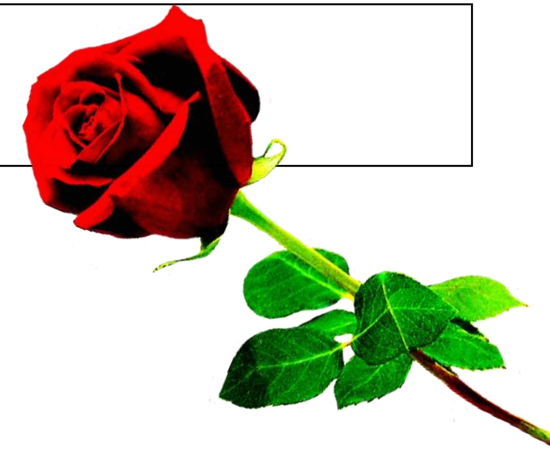
slowly oscillating B star

The new class was announced at the 1986 pulsation conference in Los Alamos but with a different name and this abbreviation

Christoffel Waelkens

S.O.B.

What's in a name?



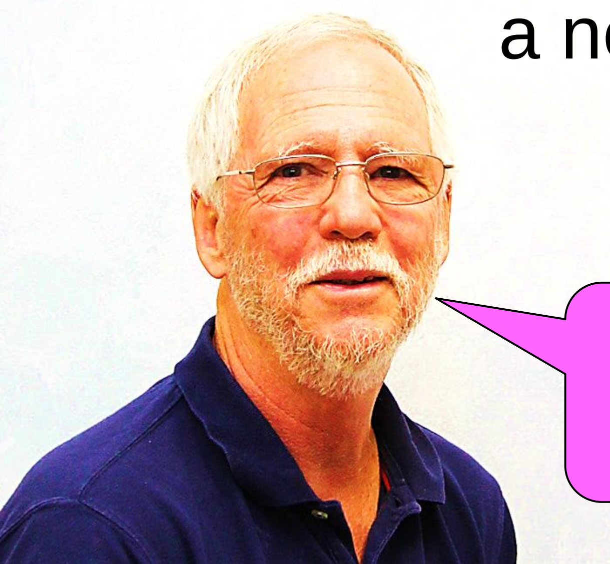
<u>s</u>lowly <u>o</u>scillating <u>B</u> star

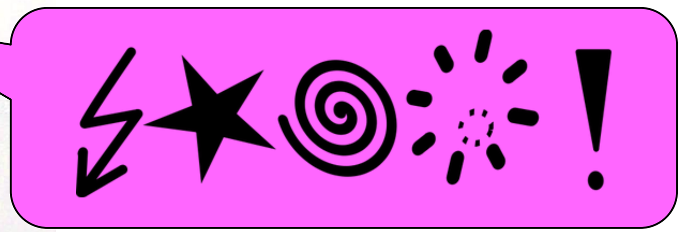
The new class was announced at the 1986 pulsation conference in Los Alamos but with a different name and this abbreviation

Christoffel Waelkens

Don and I suggested a new name

S.O.B.





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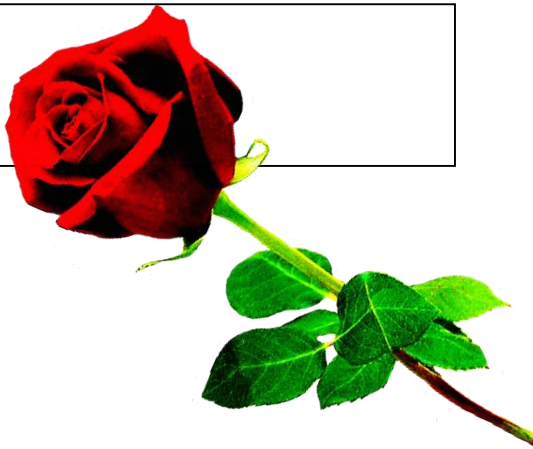
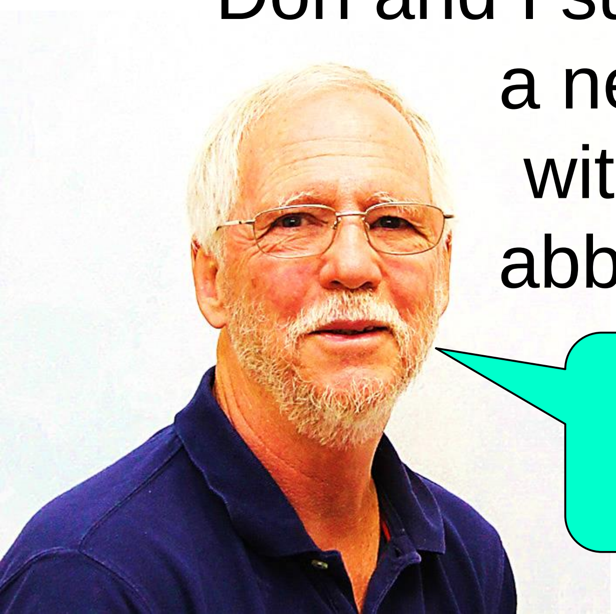


***s**lowly **p**ulsating **B** star*

The new class was announced at the 1986 pulsation conference in Los Alamos but with a different name and this abbreviation

Christoffel Waelkens

Don and I suggested a new name with a safer abbreviation



Much better.

S.P.B.

A tough name to say

Przybylski

A tough name to say

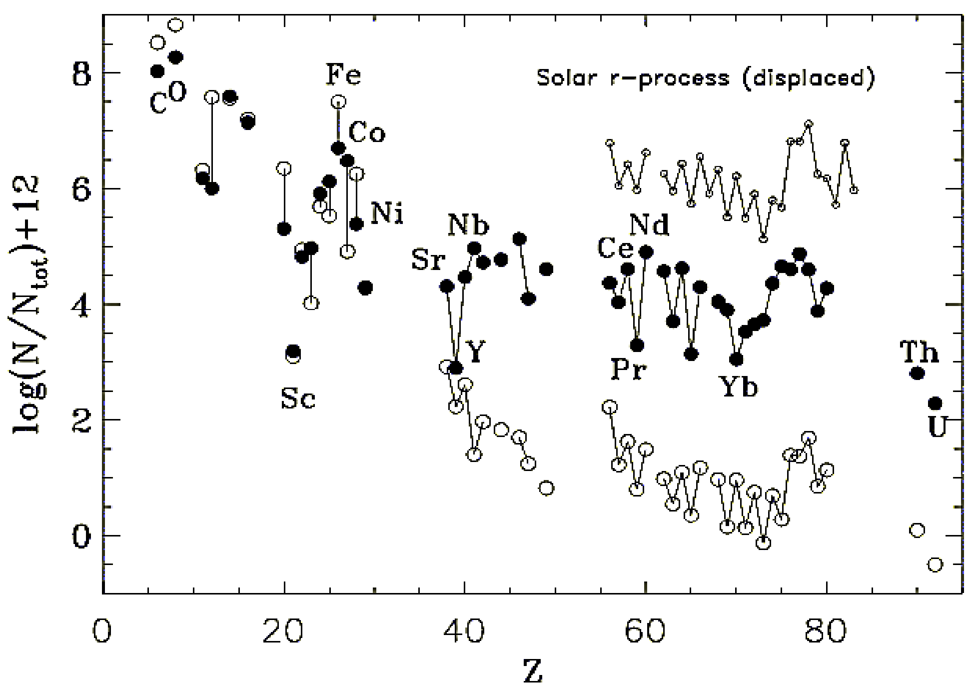
Przybylski, Antoni (Bill)

A Polish émigré to Australia in 1950 who in 1954 obtained his PhD in astronomy – the first PhD from ANU

A tough star to understand

Przybylski's star = HD 101065

In 1961, Przybylski found the star HD 101065 has an extremely peculiar spectrum, dominated by lines of lanthanides 1000 – 10,000 times stronger than solar



A stable star for photometry

Przybylski's star = HD 101065

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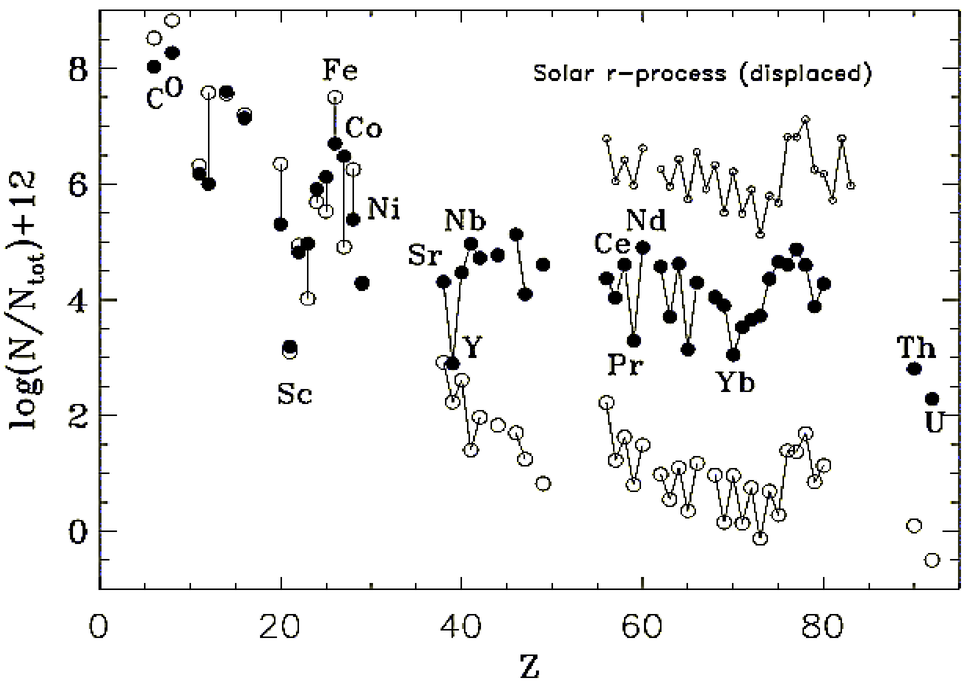


Like other members of the Ap (CP2) class this star was believed stable to pulsation

→ good comparison for differential photometry of δ Scuti variables

A δ Sct star ?

Przybylski's star = HD 101065

In 1978, Don decided to check whether HD 101065 was a δ Scuti pulsator with SAAO 0.5-m telescope at Sutherland, using a comparison and a check star.

A check star mystery

Przybylski's star = HD 101065

In 1978, Don decided to check whether HD 101065 was a δ Scuti pulsator with SAAO 0.5-m telescope at Sutherland, using a comparison and a check star.

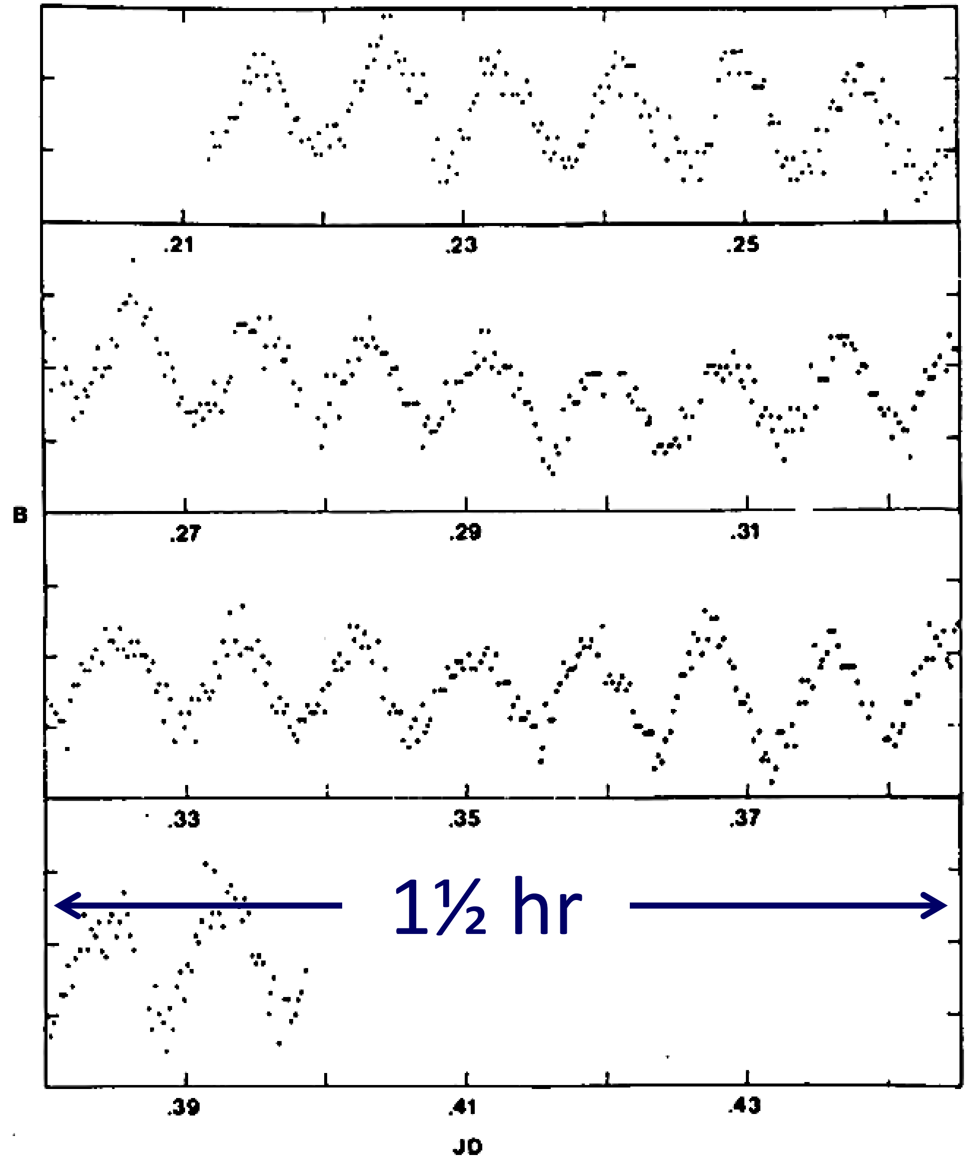
The scatter in the light curve was only 0.003 mag, but it was a night of such quality that it should have been smaller. The data suggested a pattern of alternating high and low values in the ~8-minute cadence.

The next night, Don observed HD 101065 non-differentially, with 20-sec integrations …

An roAp star discovered !

Przybylski's star

… and discovered unexpected 12-minute oscillations in an Ap star



An roAp star discovered !

Przybylski's star: the 1st roAp star

1978

HD 101065

COMMISSION 27 OF THE I. A. U.

INFORMATION BULLETIN ON VARIABLE STARS

Number 1436

Konkoly Observatory
Budapest
1978 June 12

12.15 MINUTE LIGHT VARIATIONS IN PRZYBYLSKI'S STAR, HD101065

Light variations of amplitude 0.01 to 0.02 mag and period 12.15 minutes have been discovered in the magnetic Holmium star, HD101065.

Observations have been made on 23/24 Apr, 09/10, 13/14, 14/15, and 15/16 May 1978 using the People's Photometer attached to the 0.5 m telescope of the South African Astronomical Observatory (SAAO). Figure 1 shows the observations made on 15/16 May 1978 through a Johnson B filter. Each point represents the extinction corrected magnitude of HD101065 computed from the sum of two 10 second integrations. The slow drift in mean light level is due to change in sky transparency during the observing run.

HD101066 was monitored as a comparison star for 15 minute periods at the beginning and end of each observing run and

A new class of pulsators

5 rapidly oscillating Ap (roAp) stars

1982

HR 1217
HR 3831
33 Lib
HD 101065
α Cir

Mon. Not. R. astr. Soc. (1982) **200**, 807–859

Rapidly oscillating Ap stars

D. W. Kurtz* *Department of Astronomy, University of Cape Town, Rondebosch, South Africa*

Received 1981 December 9; in original form 1981 September 9

Summary. Rapid light variations with periods in the range of 6 to 12 min have been discovered in five cool magnetic Ap stars. All of the data for these stars are consistent with the hypothesis that they are pulsating in $l = 1$ or $l = 2$ non-radial p-modes of very high overtone, k, with their pulsation axes and magnetic axes aligned. By extension of the oblique rotator model we

A new class of pulsators ?

5 rapidly oscillating Ap (roAp) stars

There was skepticism about Don's early detections because of the (necessary) non-differential nature of the rapid photometry. Many attributed the oscillations, not to the stars, but instead to atmospheric extinction

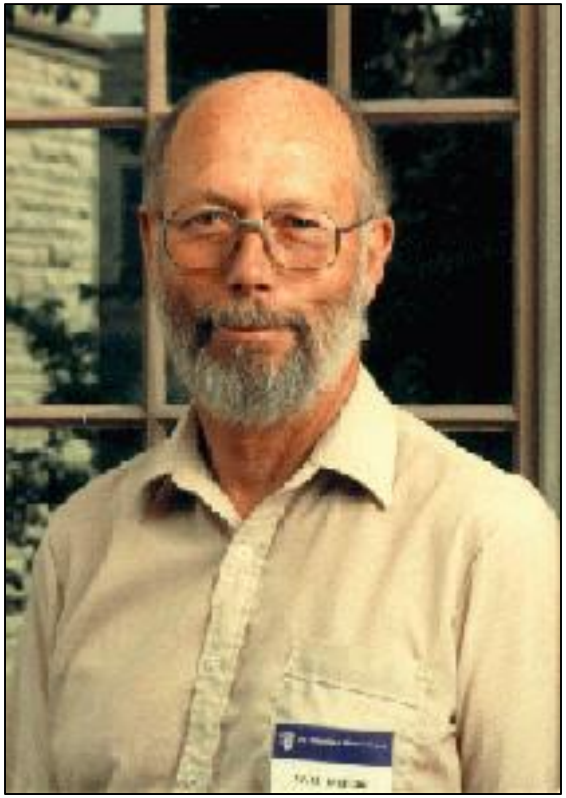
An exciting opportunity

5 rapidly oscillating Ap (roAp) stars

I was starting my PhD thesis research in 1982 and I was intrigued by this new strange class of variables

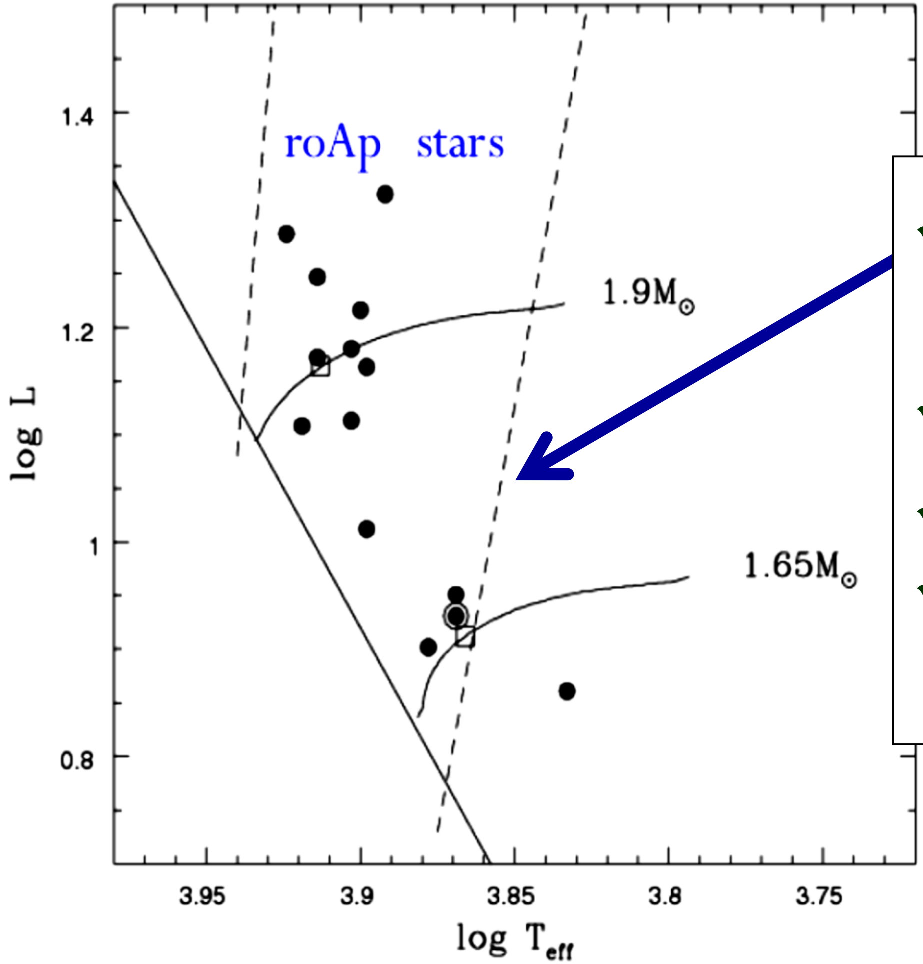
My supervisor Bill Wehlau told me:

"I know SAAO; the site is superb. Kurtz seems reliable, and his PhD supervisor was Michel Breger. I'm sure these signals are stellar. If I'm right, this may be a chance for you to be on the ground floor of a new frontier in astrophysics."



Rapidly oscillating Ap stars

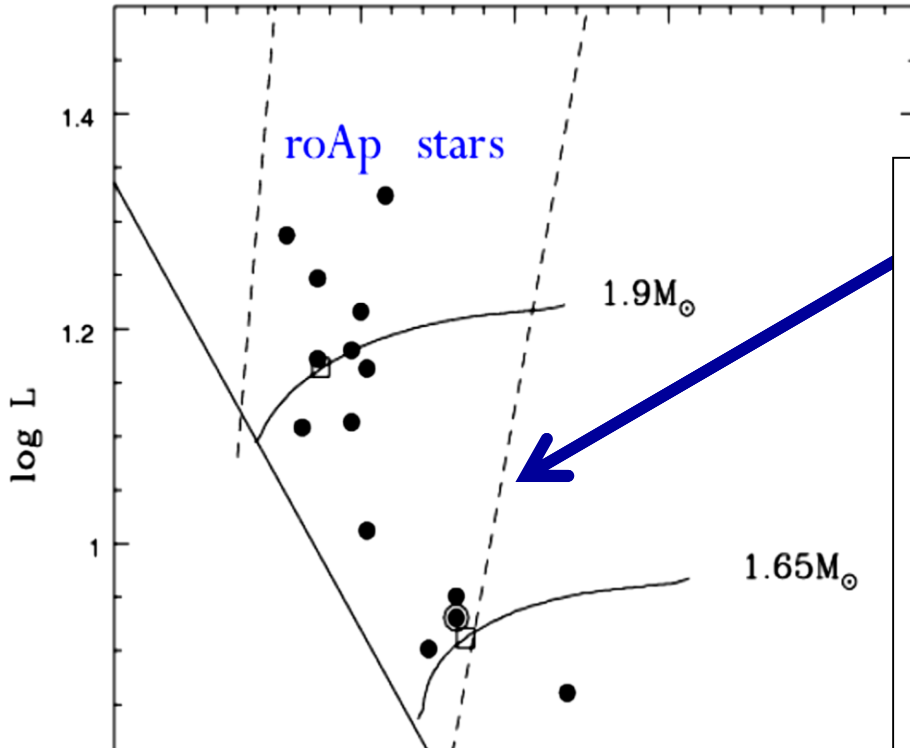
roAps



- ✓ discovered by *Don Kurtz* during 1978 – 1982
- ✓ ~*60 members* of the class
- ✓ periods: *6 ~ 21 minutes*
- ✓ amplitudes: *few mmag* and less

***review* Kurtz & Martinez 2000**

Rapidly oscillating Ap stars



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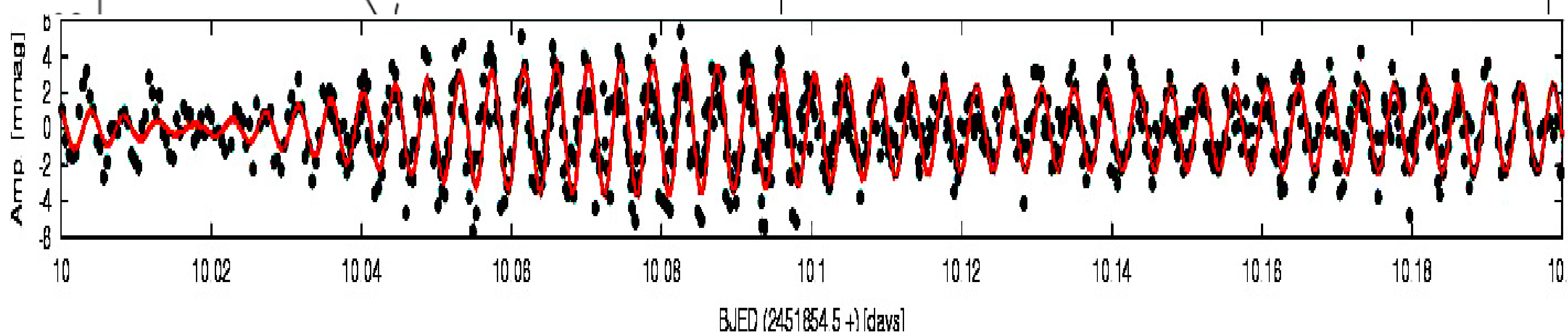
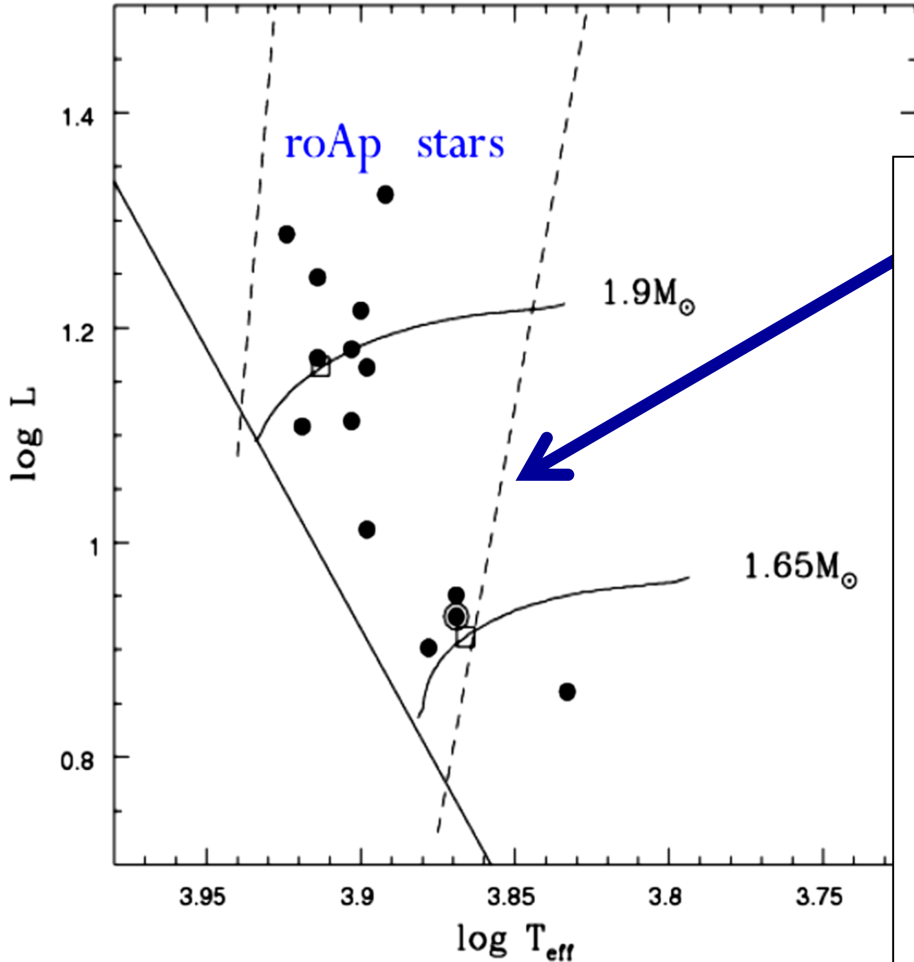


Rapidly oscillating Ap stars



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- ✓ global magnetic fields: *<u>B ~ 1 - 35 kG</u>*

<u>review</u>
Kurtz & Martinez 2000

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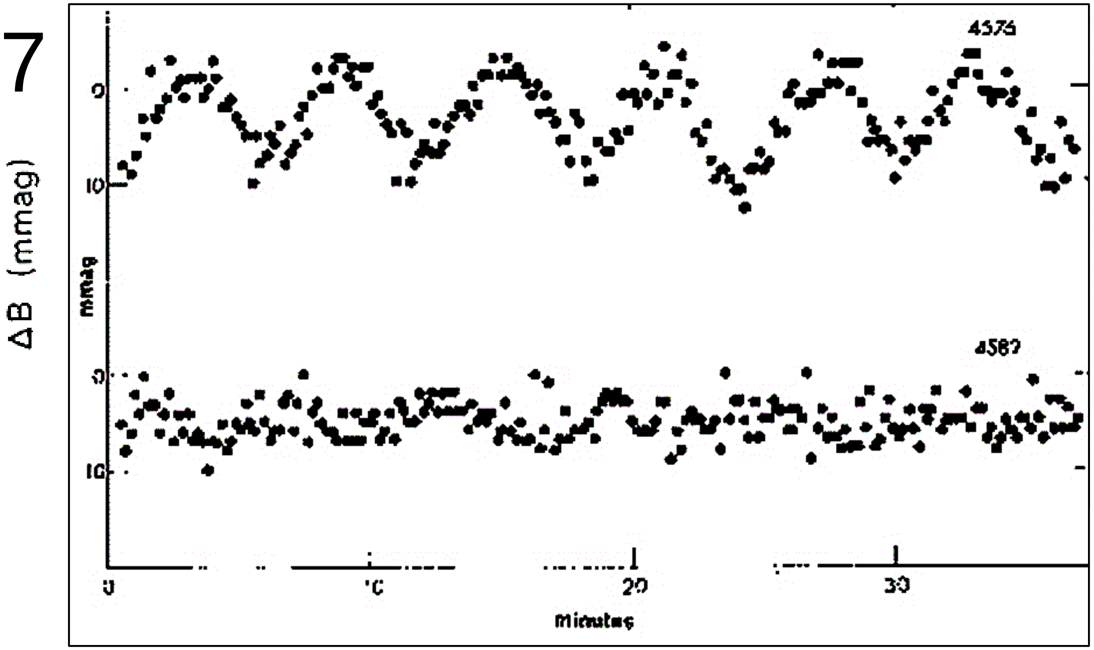
Amplitude modulation

HR 1217

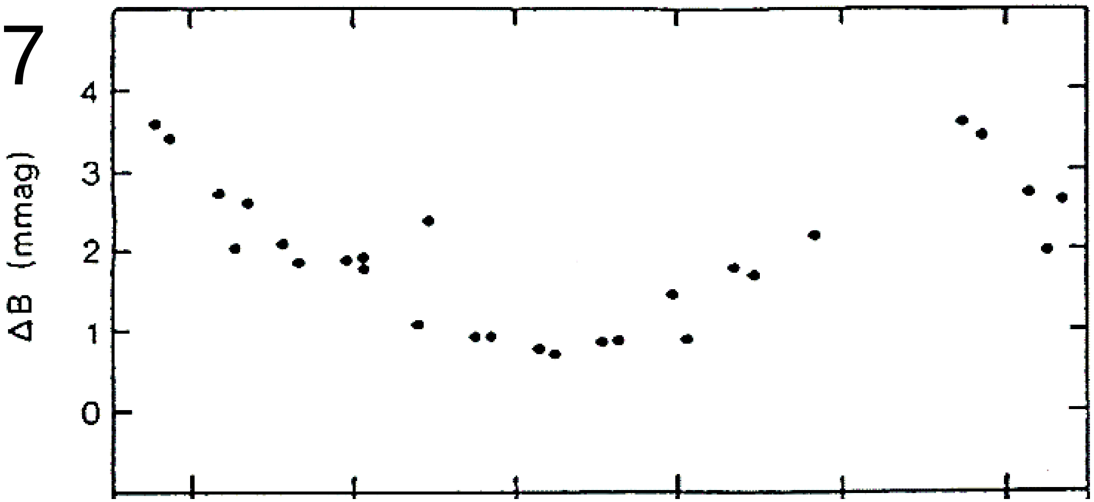


B light curves
Kurtz 1981

two segments of the HR 1217
light curve obtained 6 days apart

Amplitude modulation

HR 1217

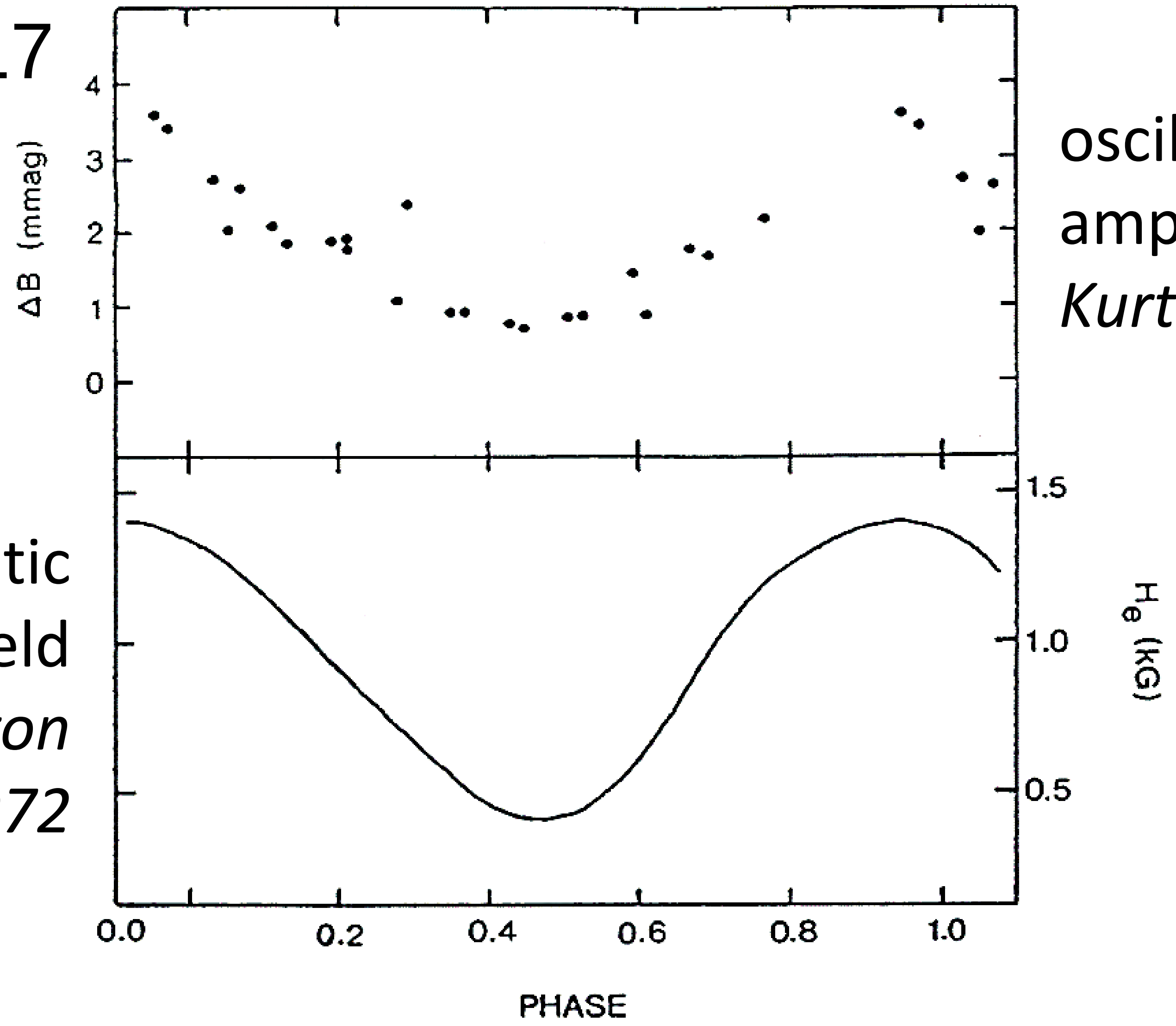


oscillation amplitude *Kurtz 1982*

Magnetic modulation

HR 1217

oscillation amplitude *Kurtz 1982*

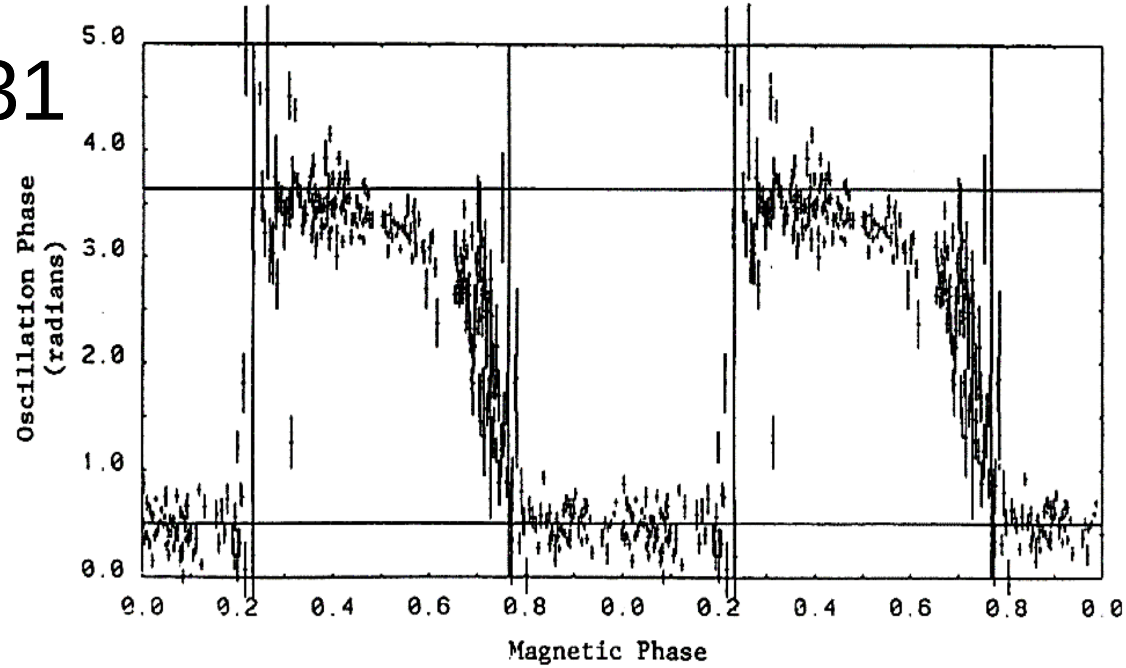


magnetic field *Preston 1972*

Phase modulation

HR 3831

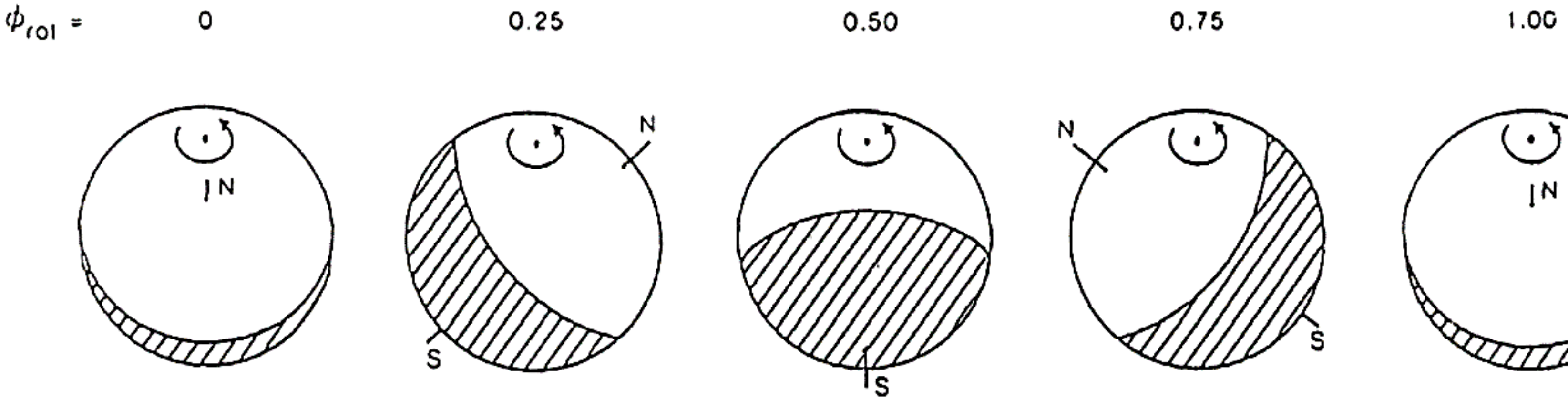
π radians



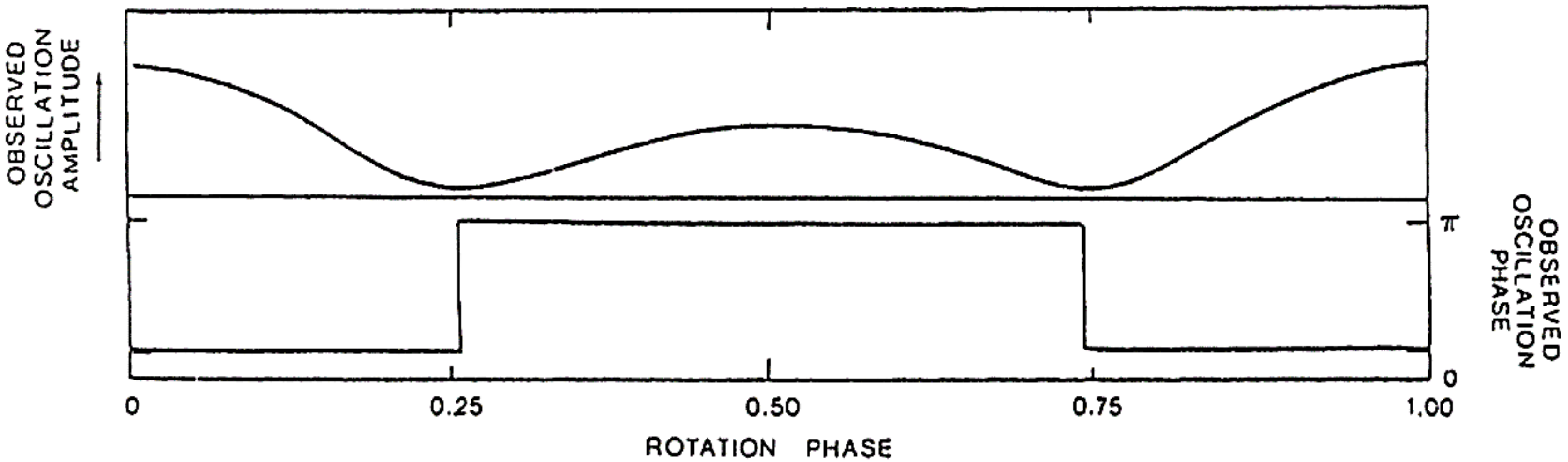
oscillation phase *Kurtz 1982*

The oscillation amplitude and phase are modulated with the magnetic field strength, which varies the oblique dipole field is seen at different projections as the star rotates → ***oblique rotator model***

Oblique Pulsator Model



i = 75°   β = 45°   ℓ = 1   m = 0



Kurtz 1982

Matthews 1991

Magnetoacoustics

pulsation amplitudes & phases modulated with magnetic (= rotation) period

Oblique Pulsator Model

Kurtz 1982 MNRAS 200, 807

Magnetoacoustics

pulsation amplitudes & phases modulated with magnetic (= rotation) period

Oblique Pulsator Model

Kurtz 1982 MNRAS 200, 807

magneto-acoustic coupling

eigenfunction expanded with $Y_\ell^m(\theta,\varphi)$

Dziembowski & Goode 1996

variational principle and WKB approximation

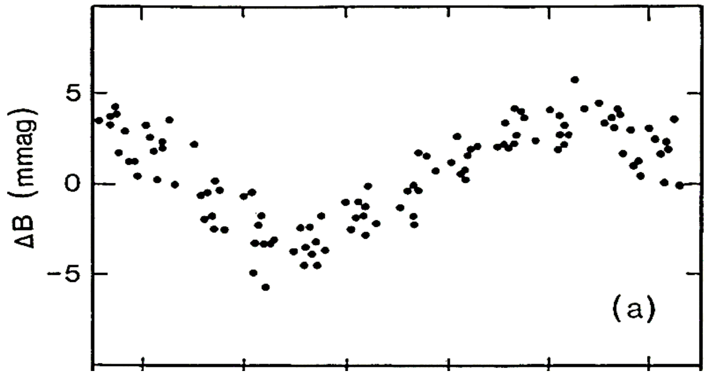
Cunha & Gough 2002, Cunha 2006

including <u>rotation</u>

Bigot & Dziembowski 2002, A&A 391, 235

Saio & Gautschy 2004, Saio 2005

Luminosity variations



modulation of
B amplitude

Radial velocity variations

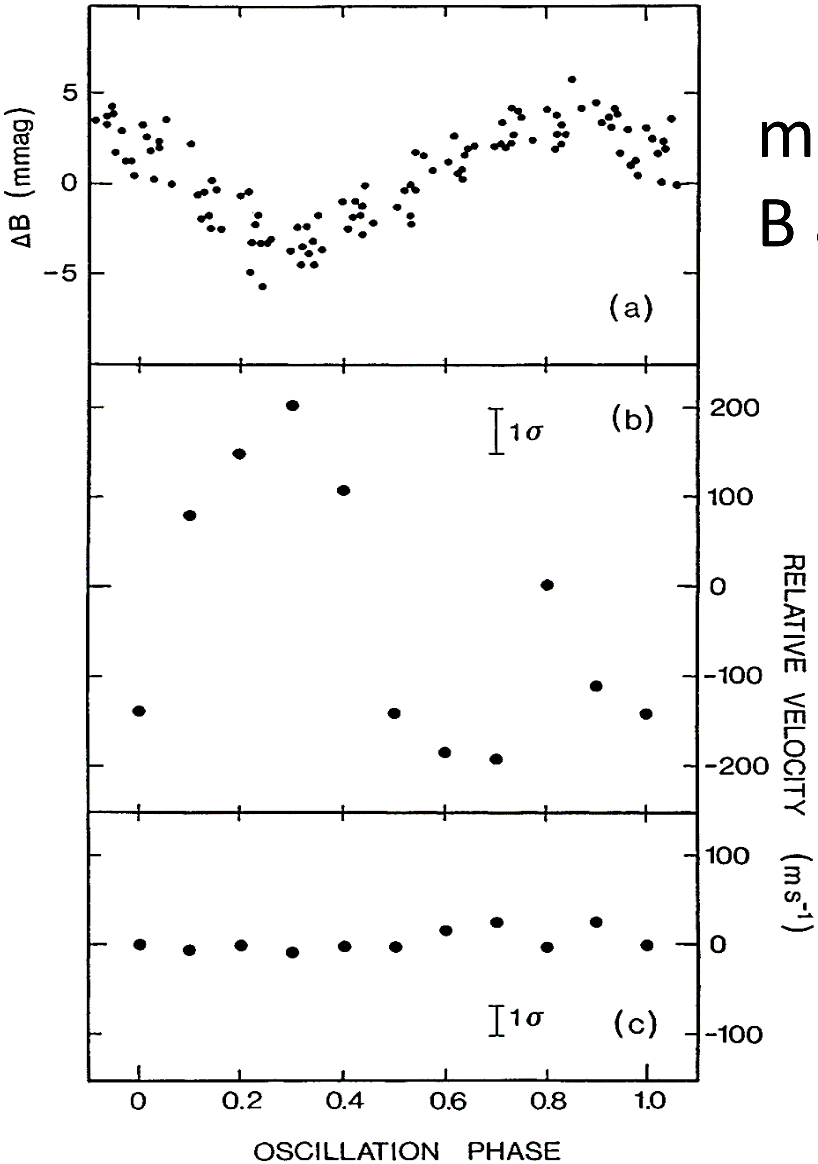
Matthews et al. 1988

modulation of B amplitude

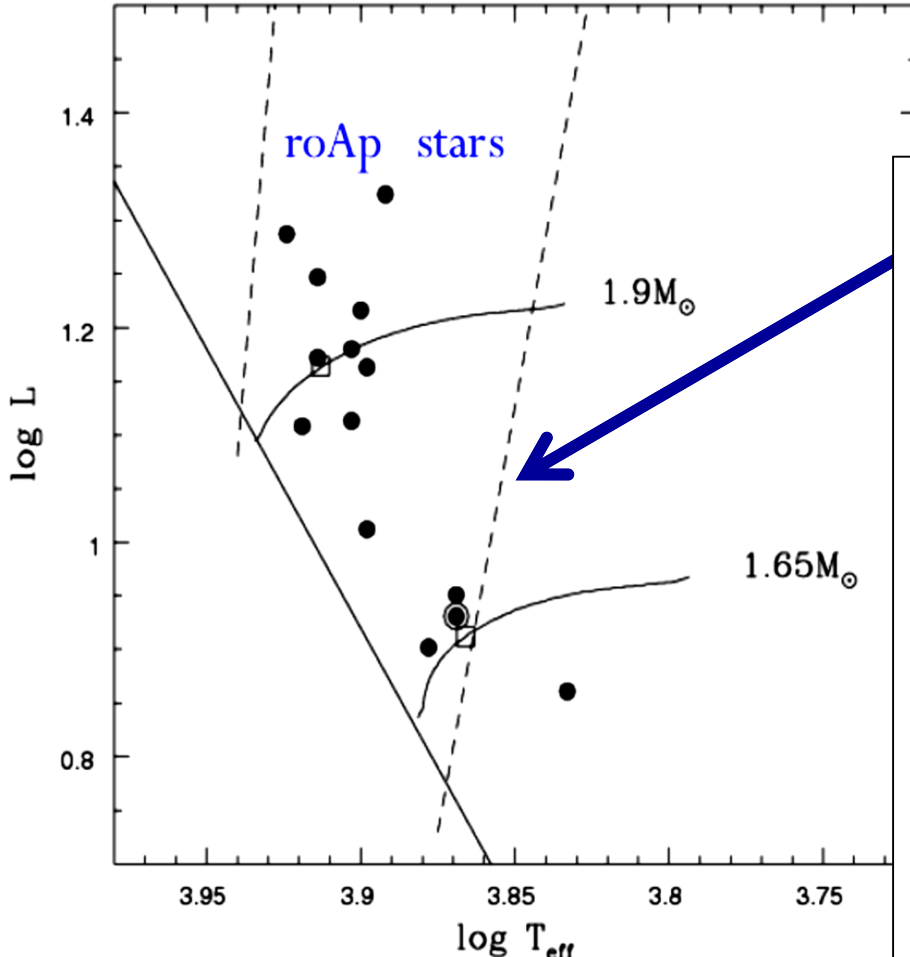
modulation of radial velocity

Hg arc lamp fiducial

CFHT coudé spectra



roAp Instability Strip?



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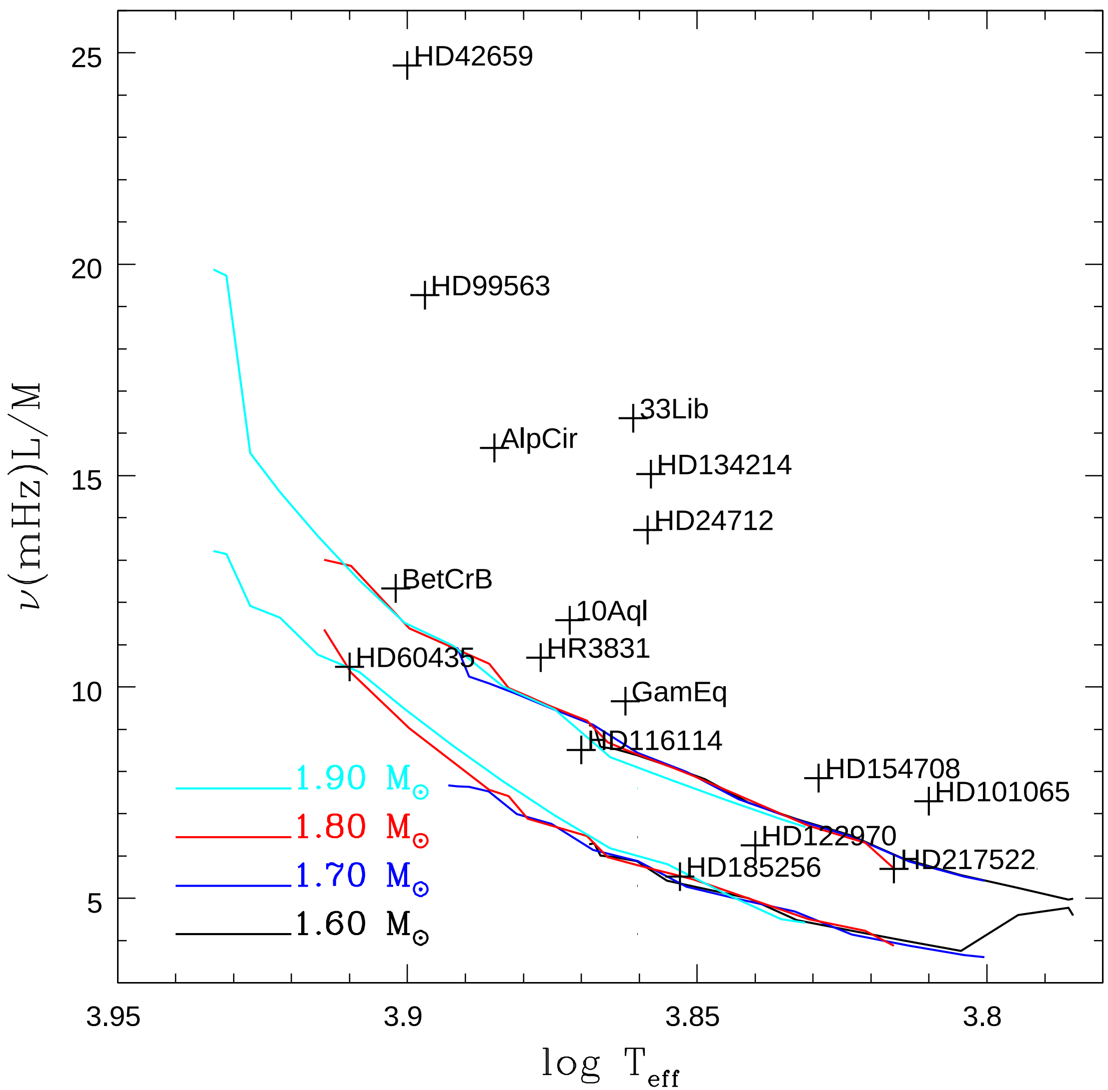
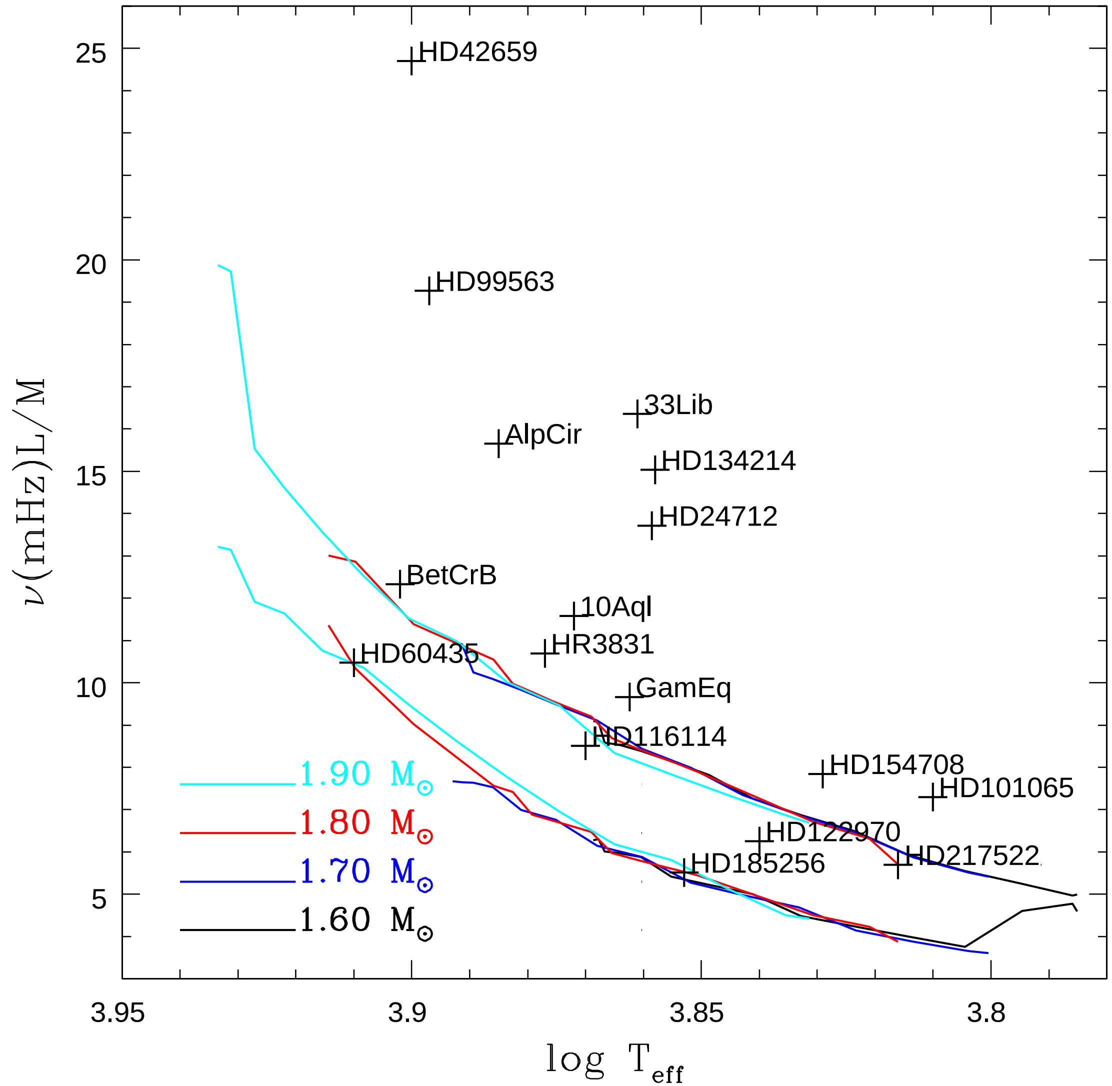
Hideyuki Saio

roAp stars freq. vs. T



models by Hideyuki Saio

roAp stars excitation



$Z = 0.02$ $B_{polar} = 0$

He-depleted

He I ionisation zone

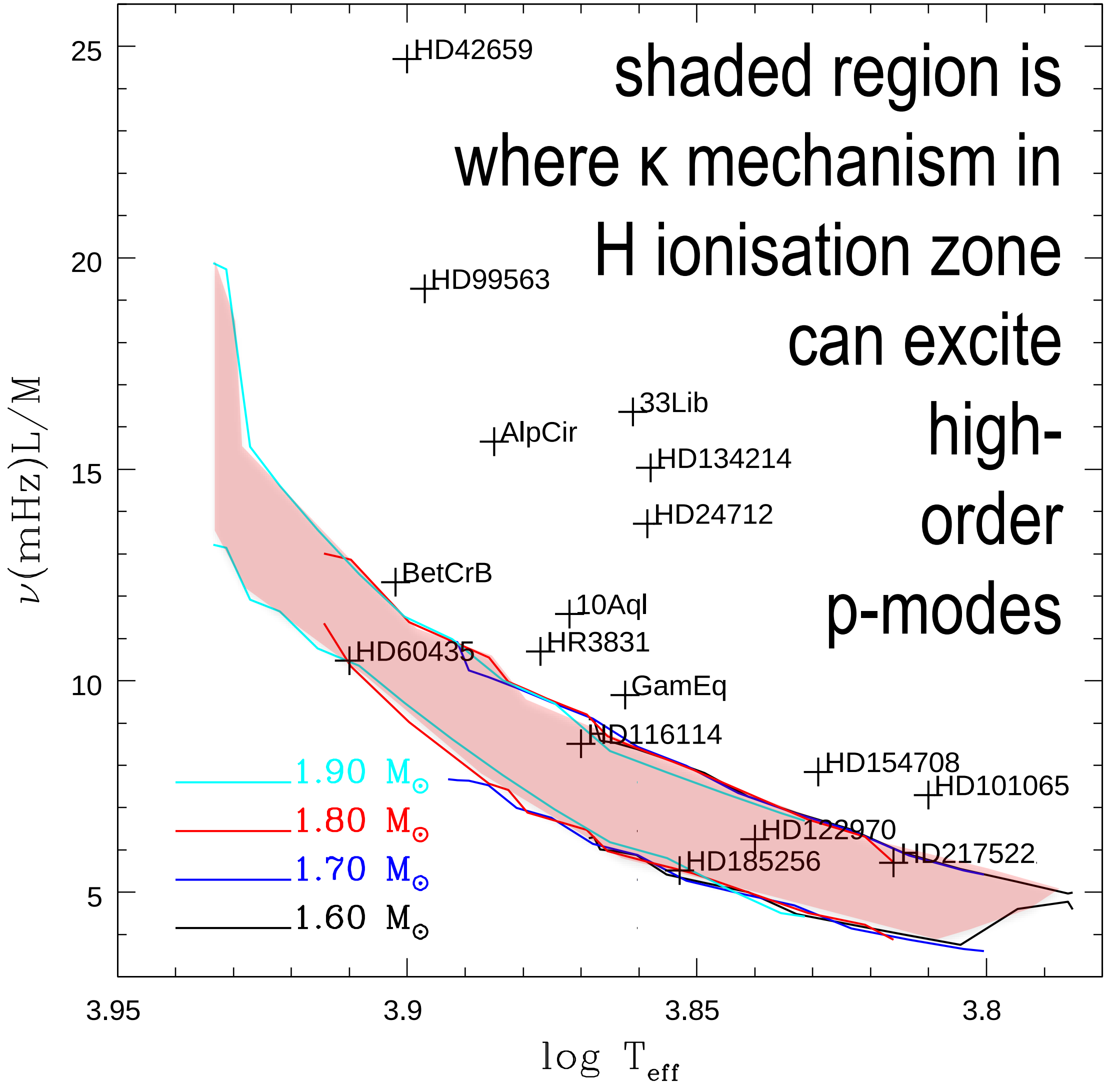
$\ell = 1$ modes

boundary condition at $\log \tau = -6$

running wave for $\omega > \omega_c$

roAp stars excitation

models by Hideyuki Saio



$Z = 0.02 \quad B_{polar} = 0$

He-depleted

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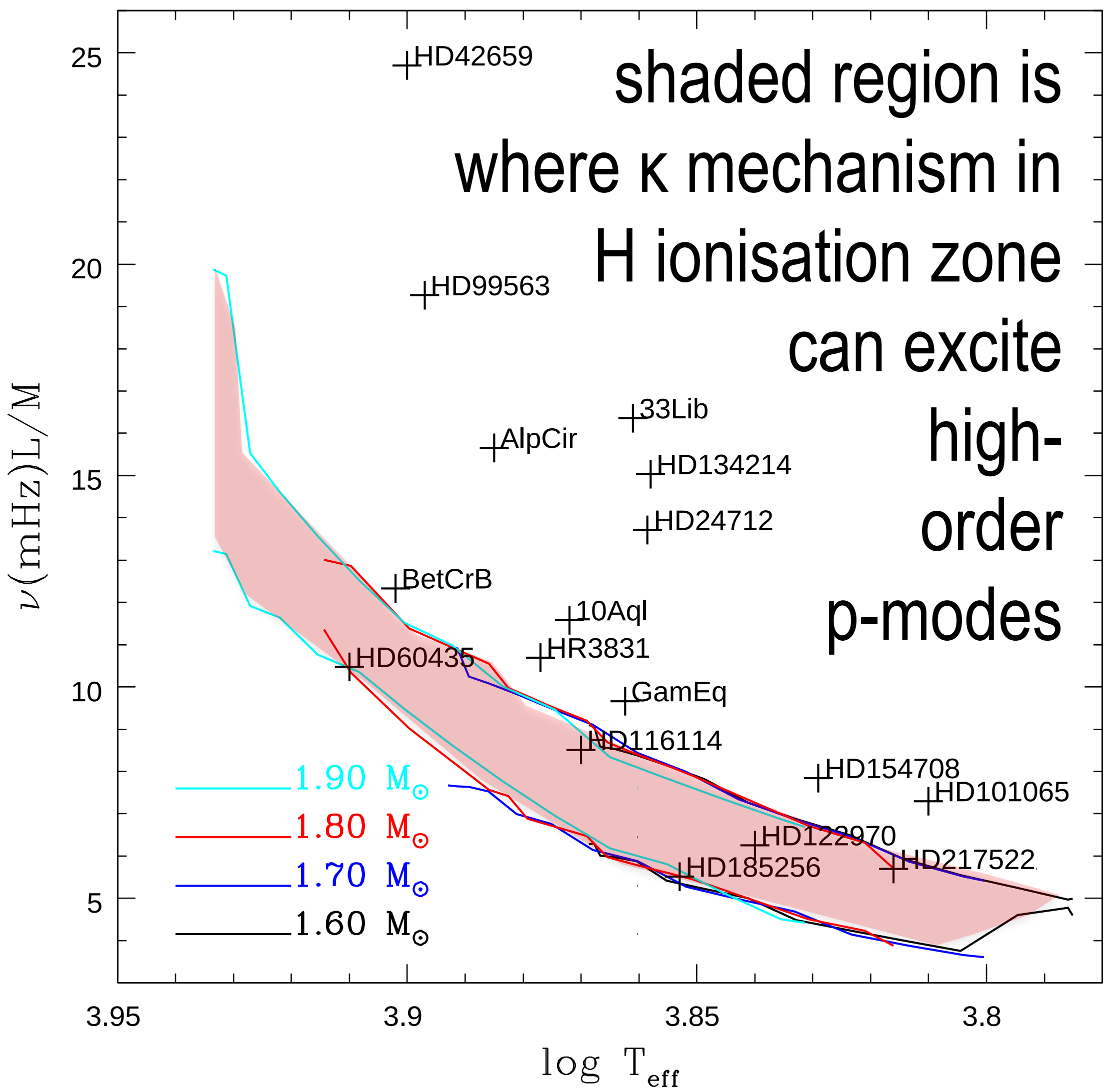
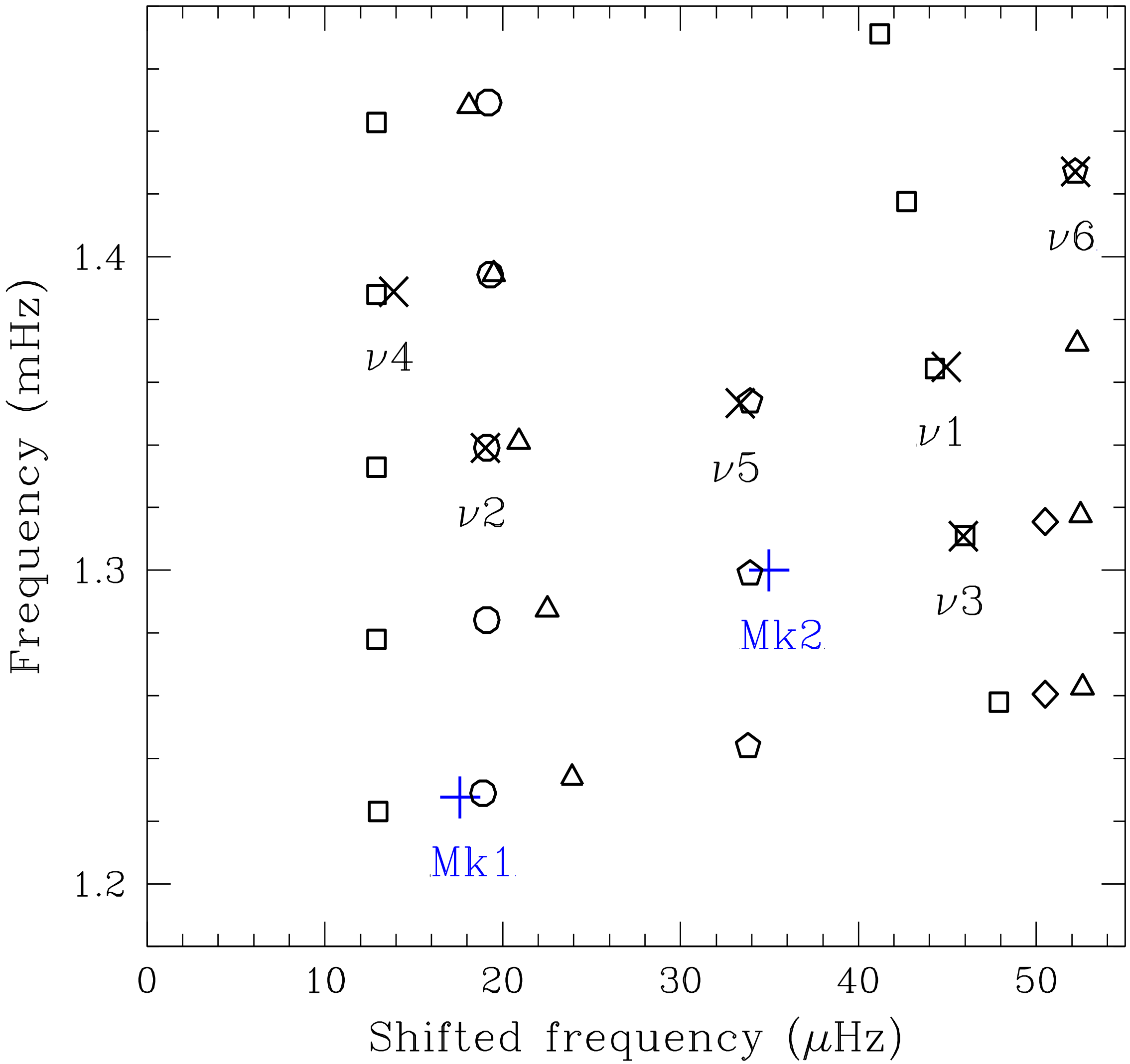
roAp stars excitation



Those preliminary models suggested that a mechanism **other than H ionisation** is needed to excite most roAp pulsations

echelle diagram of modes



roAp stars excitation

gamma Equulei

*v*1 – *v*6

MOST photometry

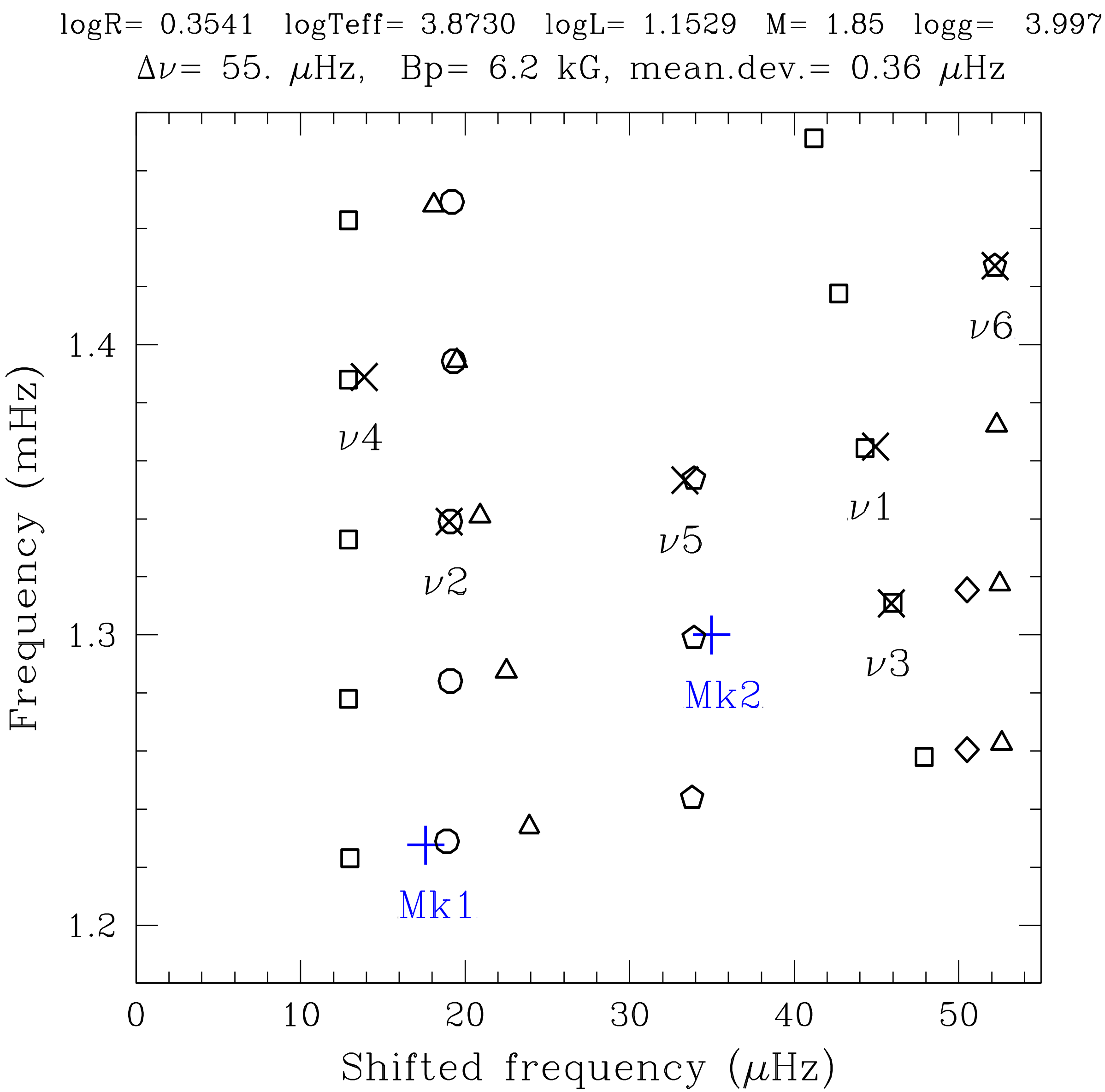
Michael Gruberbauer

(Mk1 – 1 c/d); Mk2

radial velocity data

David Mkrtichian

roAp stars excitation

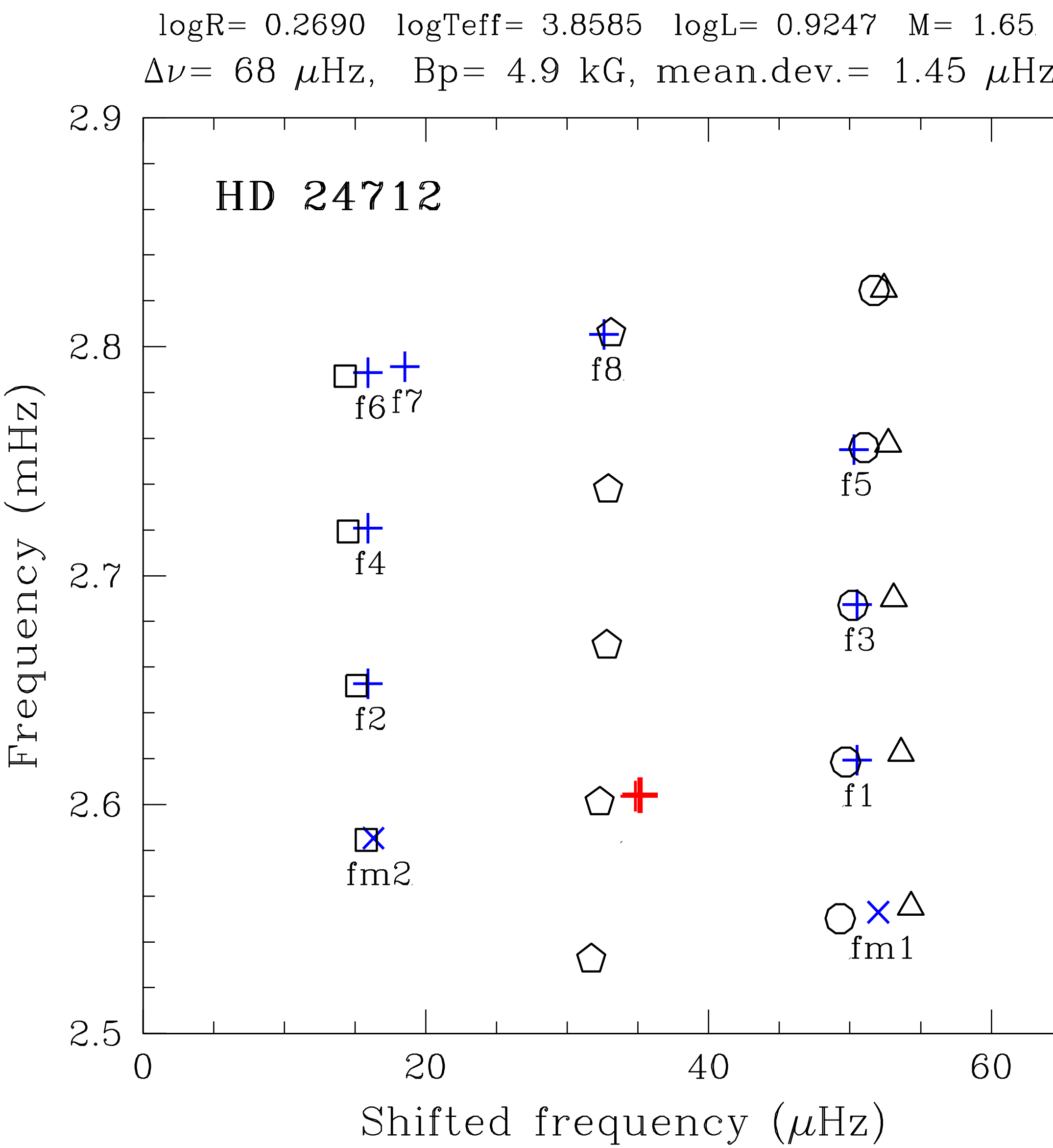


gamma Equulei

ν1 – ν6
MOST photometry
Michael Gruberbauer

(Mk1 – 1 c/d); Mk2
radial velocity data
David Mkrtichian

Model frequencies agree with observation but **none are excited**



roAp stars excitation

HR 1217

f1 – f8

WET photometry

Kurtz, Cameron et al.

fm1 and fm2

radial velocity data

David Mkrtichian

+

MOST photometry

Chris Cameron

HR 1217 = HD 24712

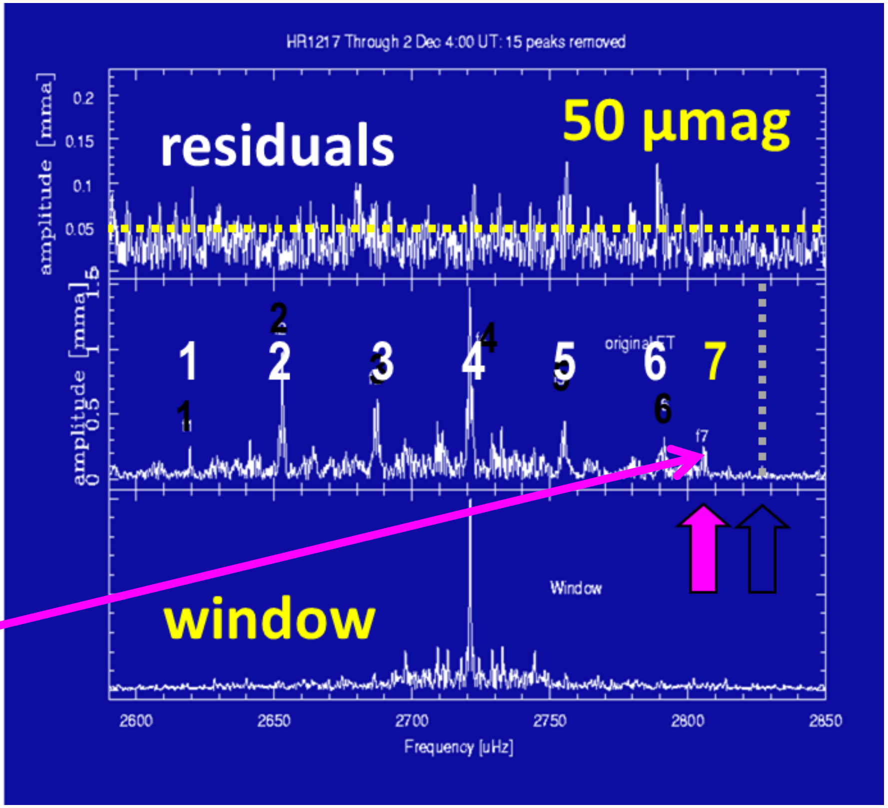
- ✓ *periods near 6 min*
- ✓ *0 < B field < 1.2 kG*

P_{rot} = 12.45877(16) days

Ryabchikova et al. (2005)

rich p-mode spectrum

6 dominant modes
+ 1 anomalous one



2000 WET campaign

Kurtz et al. 2002, MNRAS 330, L57
Kurtz, Cameron et al. 2005, MNRAS

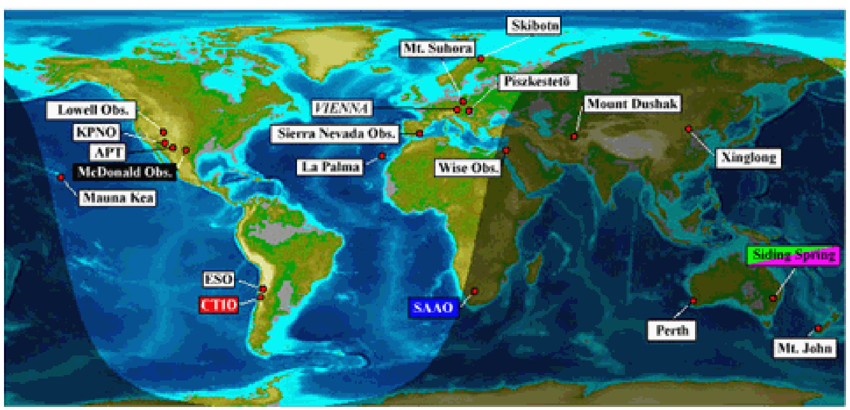
HR 1217 = HD 24712

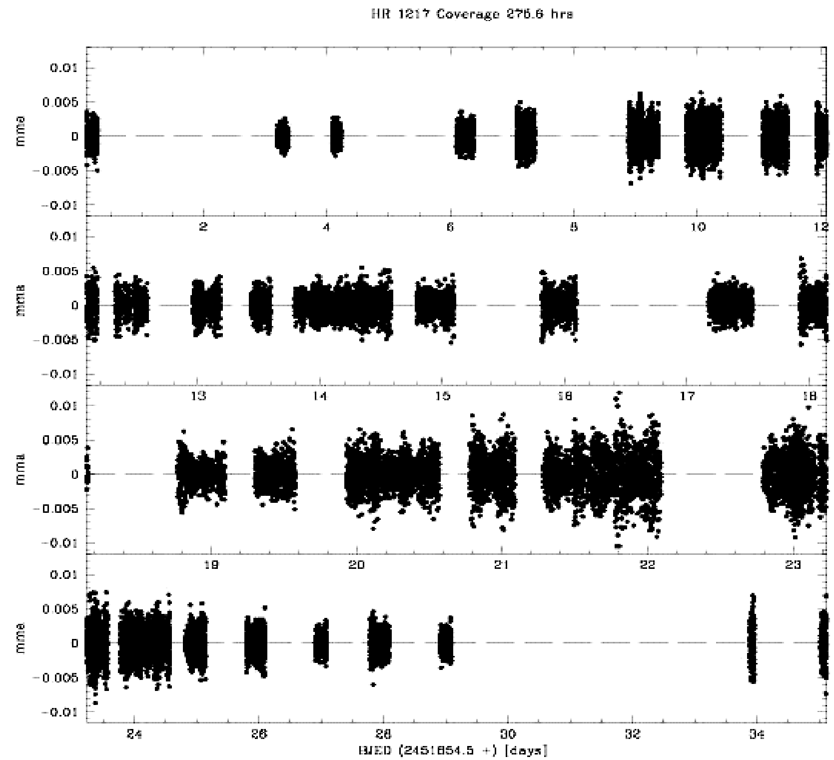
Whole Earth Telescope

Nov – Dec 2000

342 hr over 35 days

duty cycle = 34%





2000 WET campaign

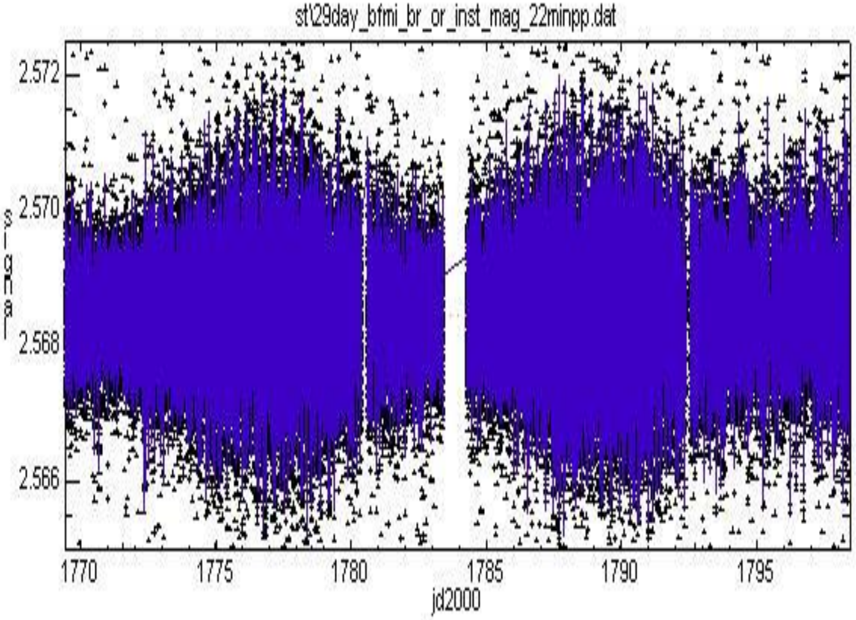
Kurtz et al. 2002, MNRAS 330, L57

Kurtz, Cameron et al. 2005, MNRAS

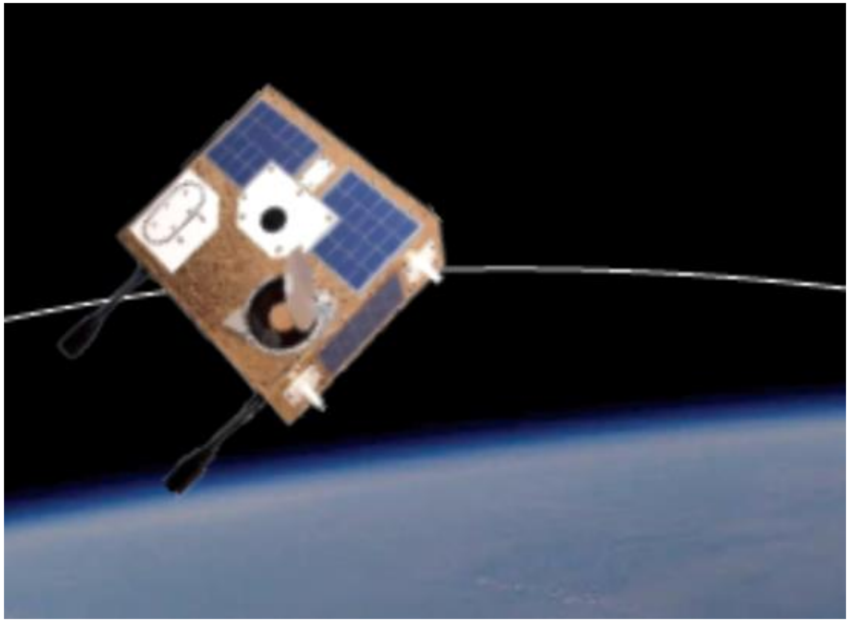
HR 1217 = HD 24712

MOST space telescope

Nov – Dec 2004
666 hr over 29 days
duty cycle = 96%



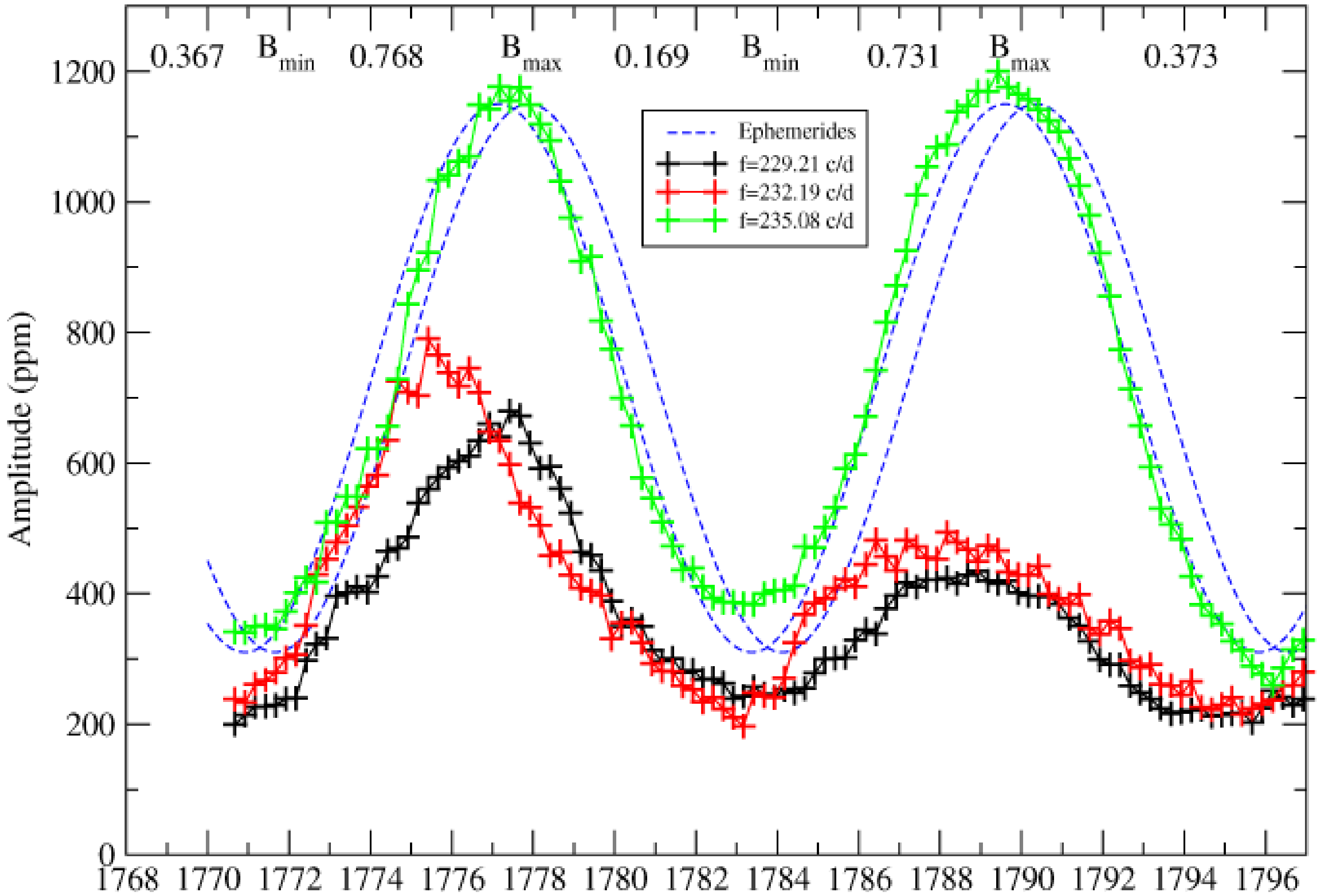
12.5 d = P_{rot}



2004 MOST campaign

Cameron PhD thesis 2010

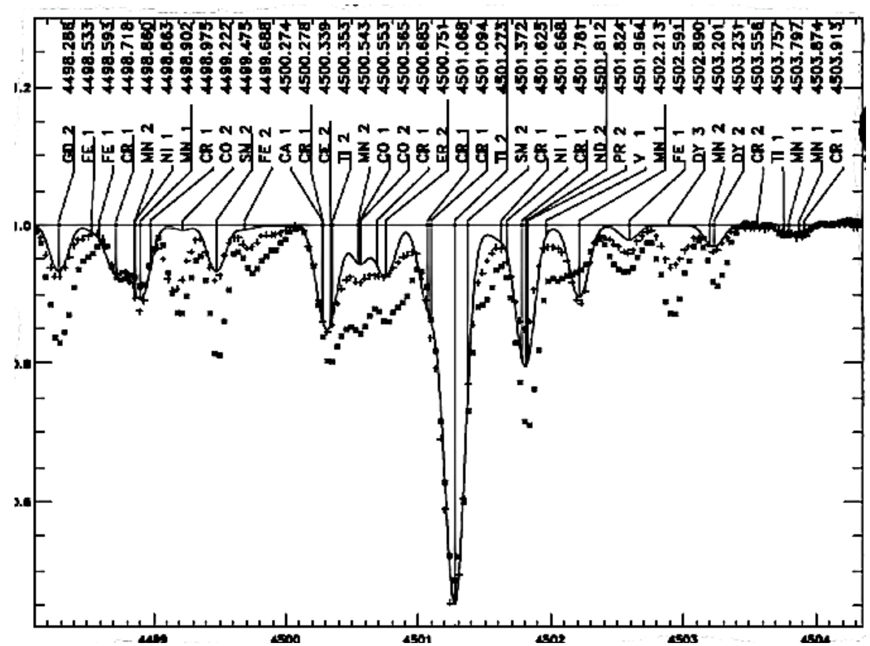
HR 1217 = HD 24712



HJD – HJD 2552000.0

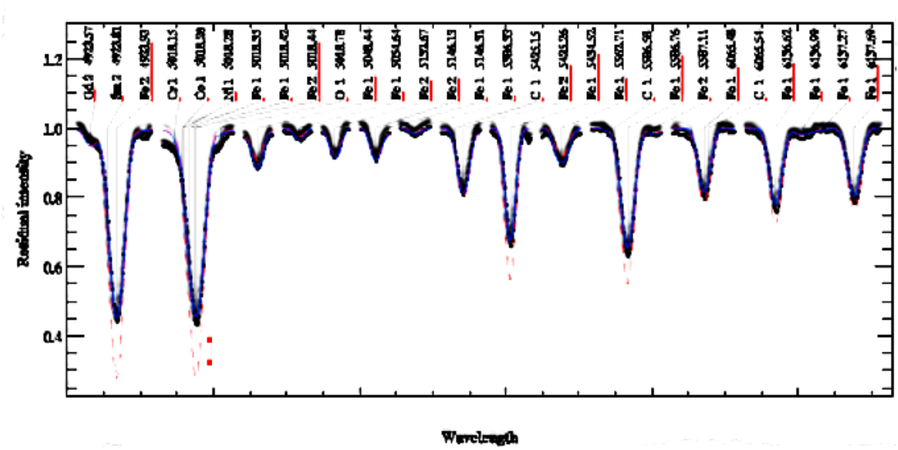
HR 1217 = HD 24712

Ryabchikova et al.
1997

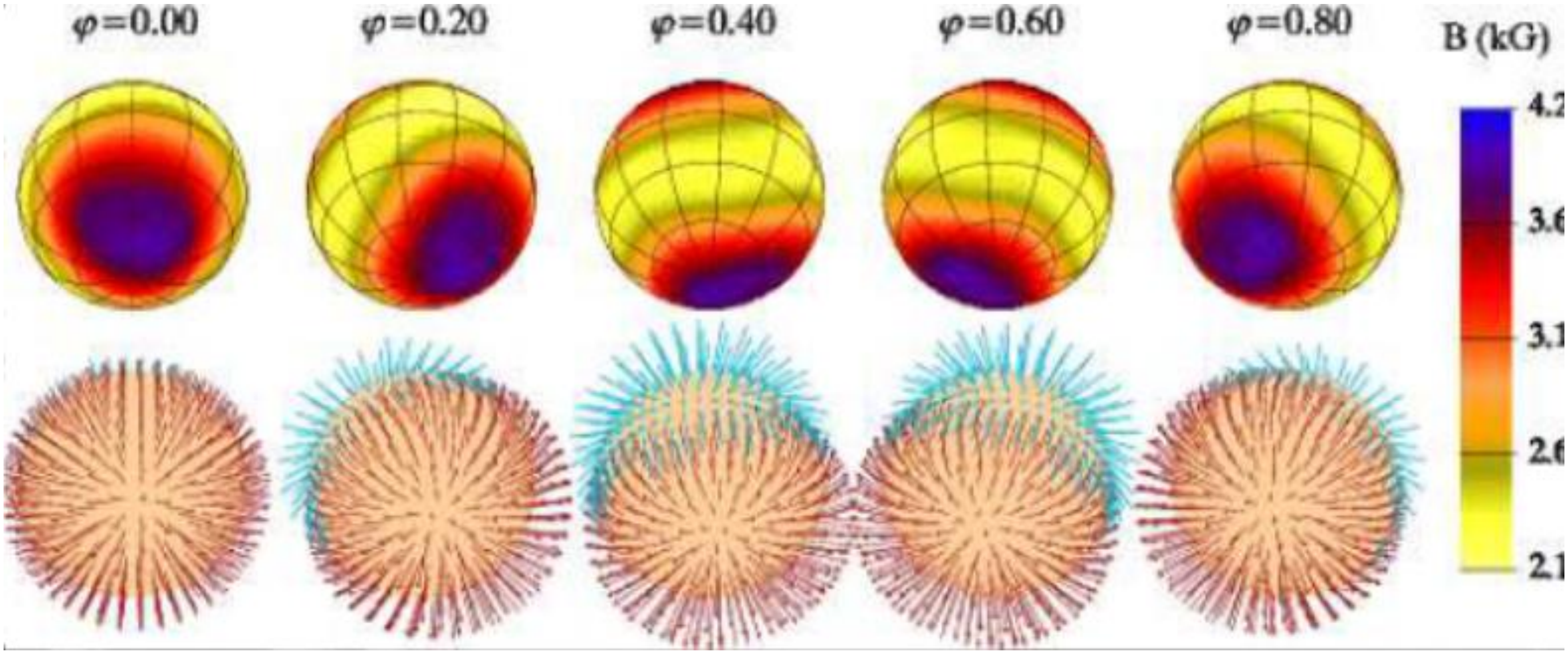


spectral modelling
of atmospheric
abundances

Lüftinger et al.
2010



HR 1217 = HD 24712

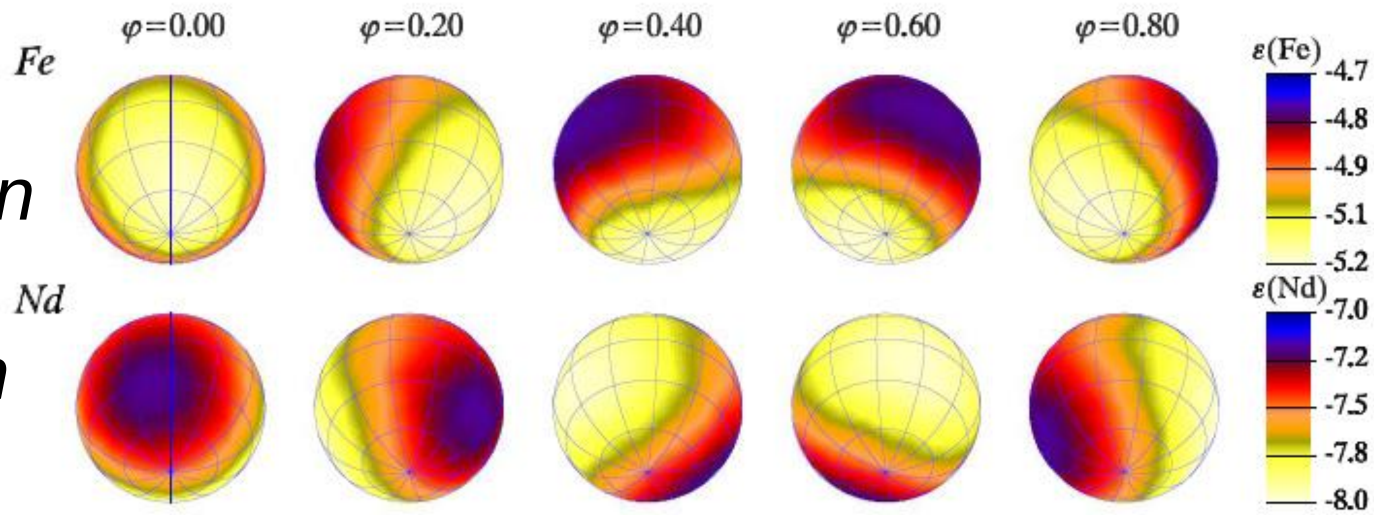


Lüftinger et al. 2010

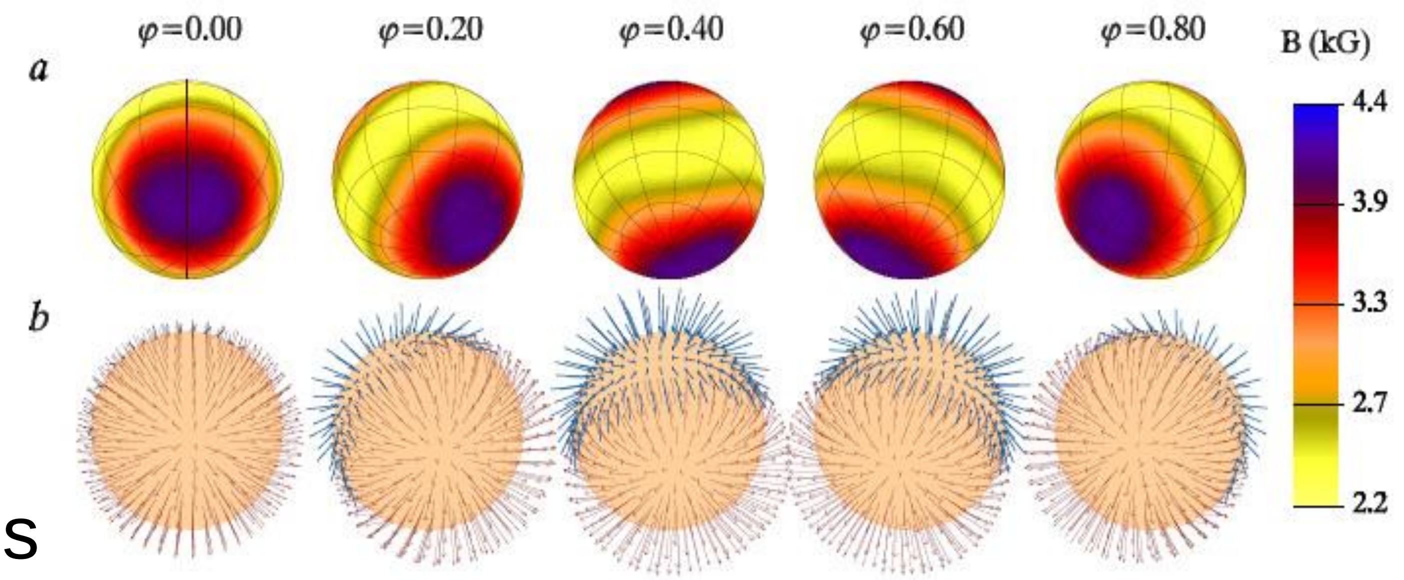
spectropolarimetry → Zeeman Doppler Imaging of magnetic field

HR 1217 = HD 24712

Abundance maps of *iron* (*Fe I*) and *neodymium* (*Nd III*)



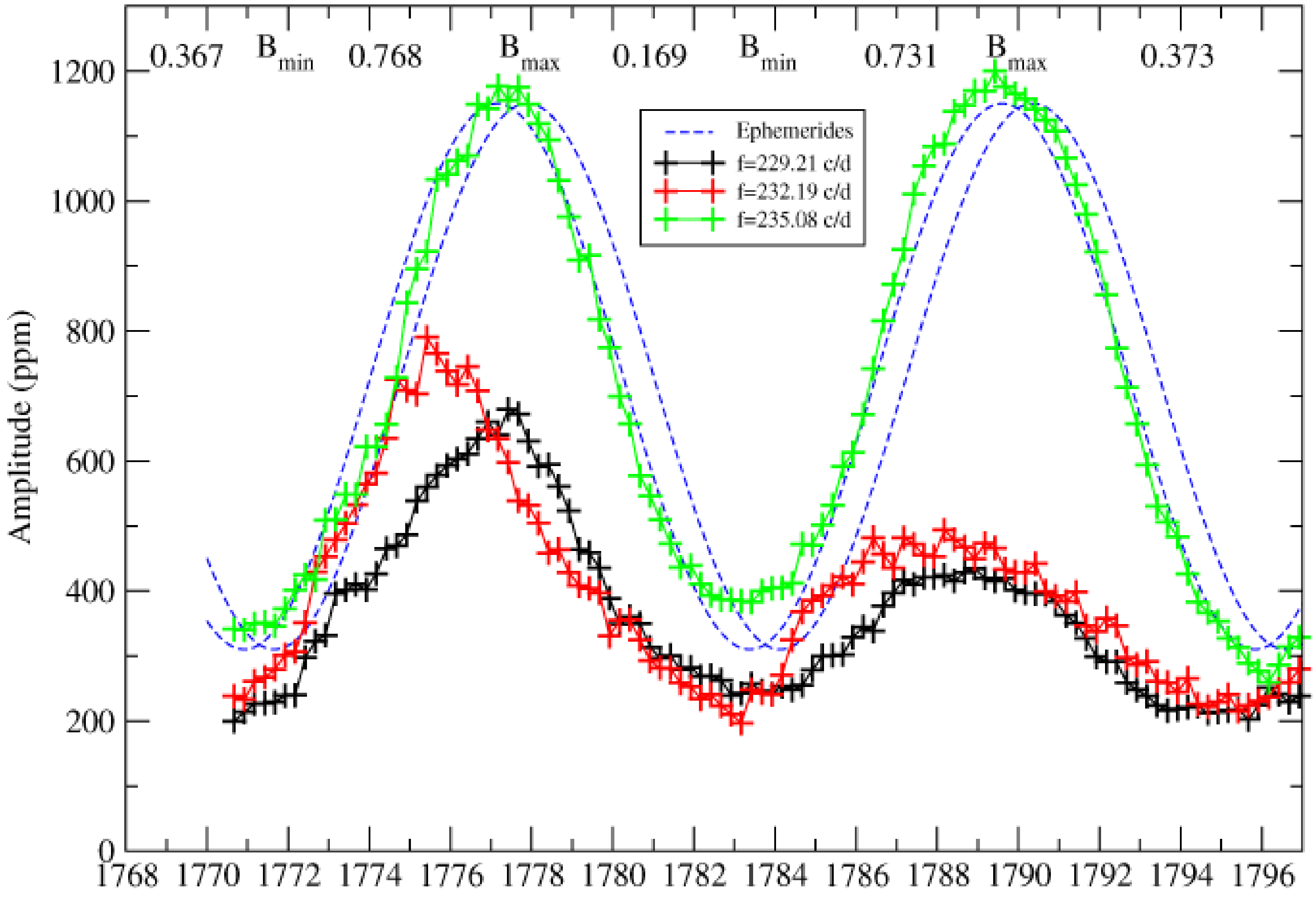
Magnetic field strengths and field orientations



HR 1217 = magnetic lab

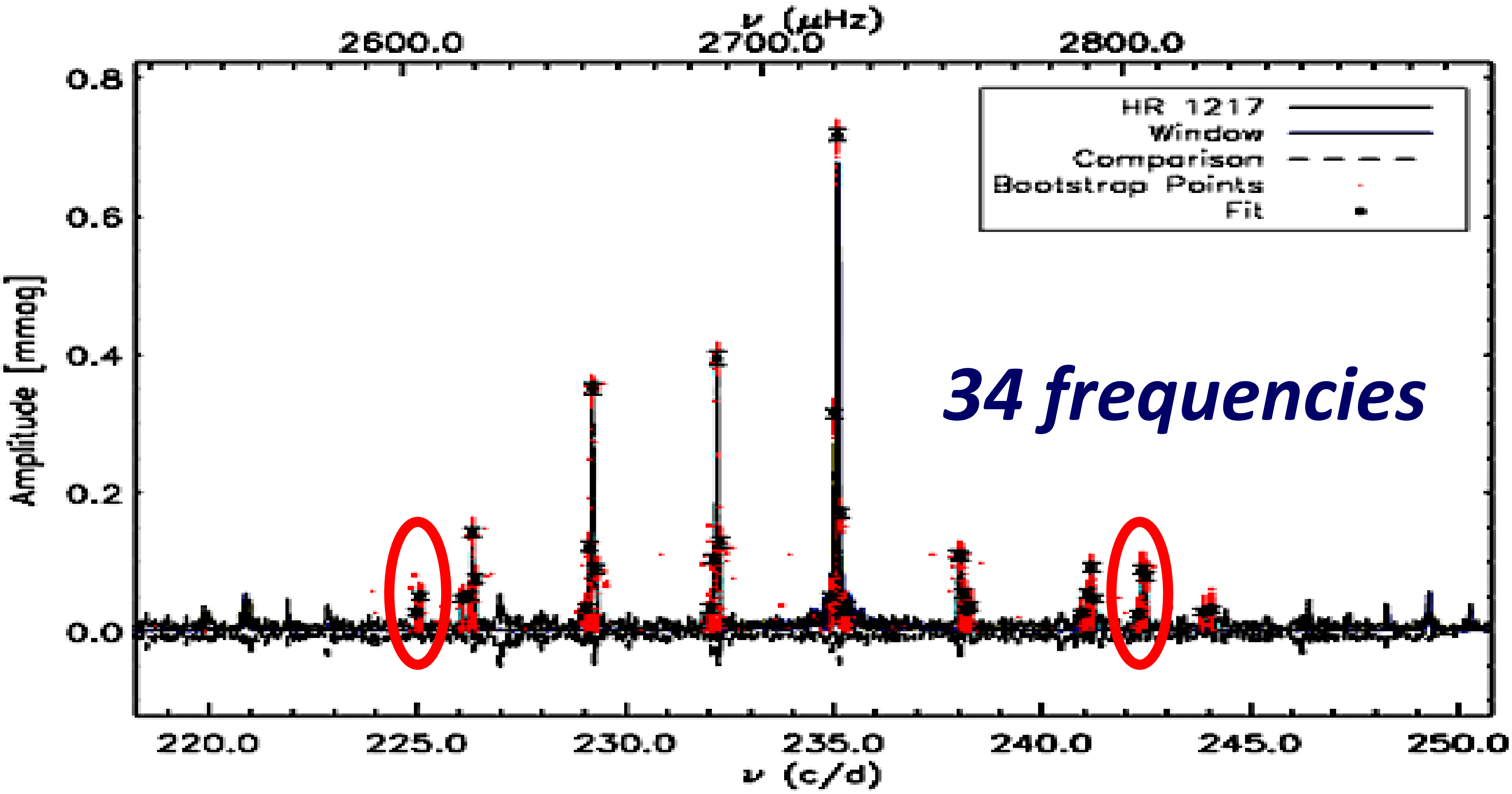
- ✓ This star may well be the best studied magnetically of any star other than the Sun
- ✓ Certain elements show enhanced abundances around phase of magnetic minimum
  - ✓ e.g., *Cr, Ti, Mg, Sc, Fe, Ni*
- ✓ Another group exhibits maximum abundance around one magnetic field maximum (all *rare earth elements*, plus *Ca*, *Co* and *Y*) – which is surprising, because the ‘classical model’ would predict abundance spots on both poles

HR 1217 = HD 24712



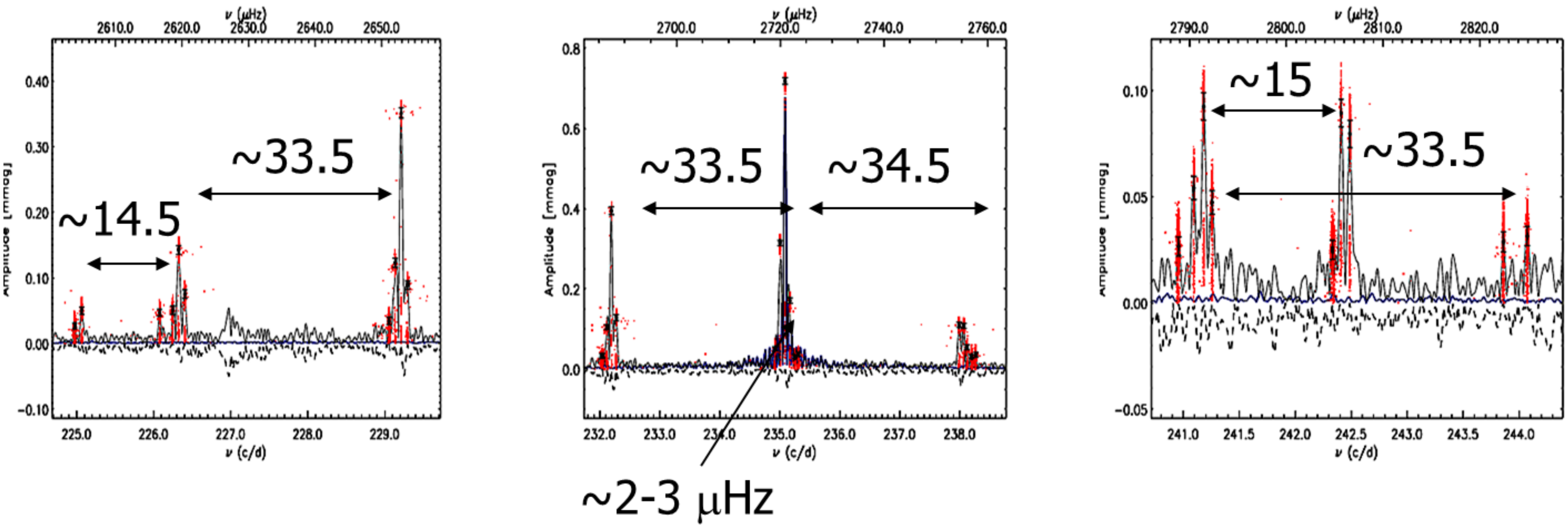
HJD – HJD 2552000.0

HR 1217 = HD 24712



34 frequencies

HR 1217 = HD 24712



large spacing

small spacing?

HR 1217 = HD 24712

10^5 *YREC* models

Yale Rotating Evolution Code

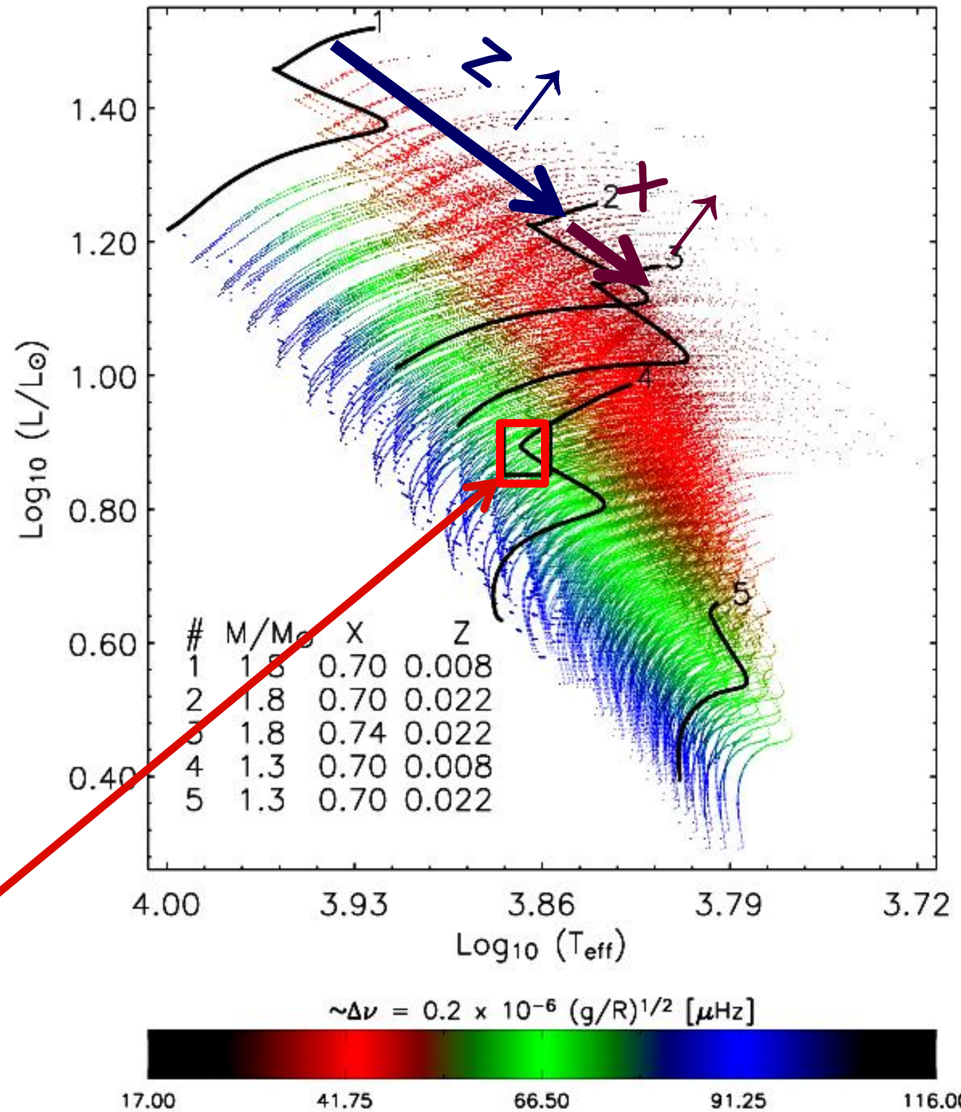
M = 1.3 → 1.8 $M_\odot$
in steps of 0.05 $M_\odot$

Z = 0.008 → 0.022
in steps of 0.002

X = 0.70, 0,72, 0.74

α = 1.4, 1.6, 1.8

569 models in error box
used for frequency fitting

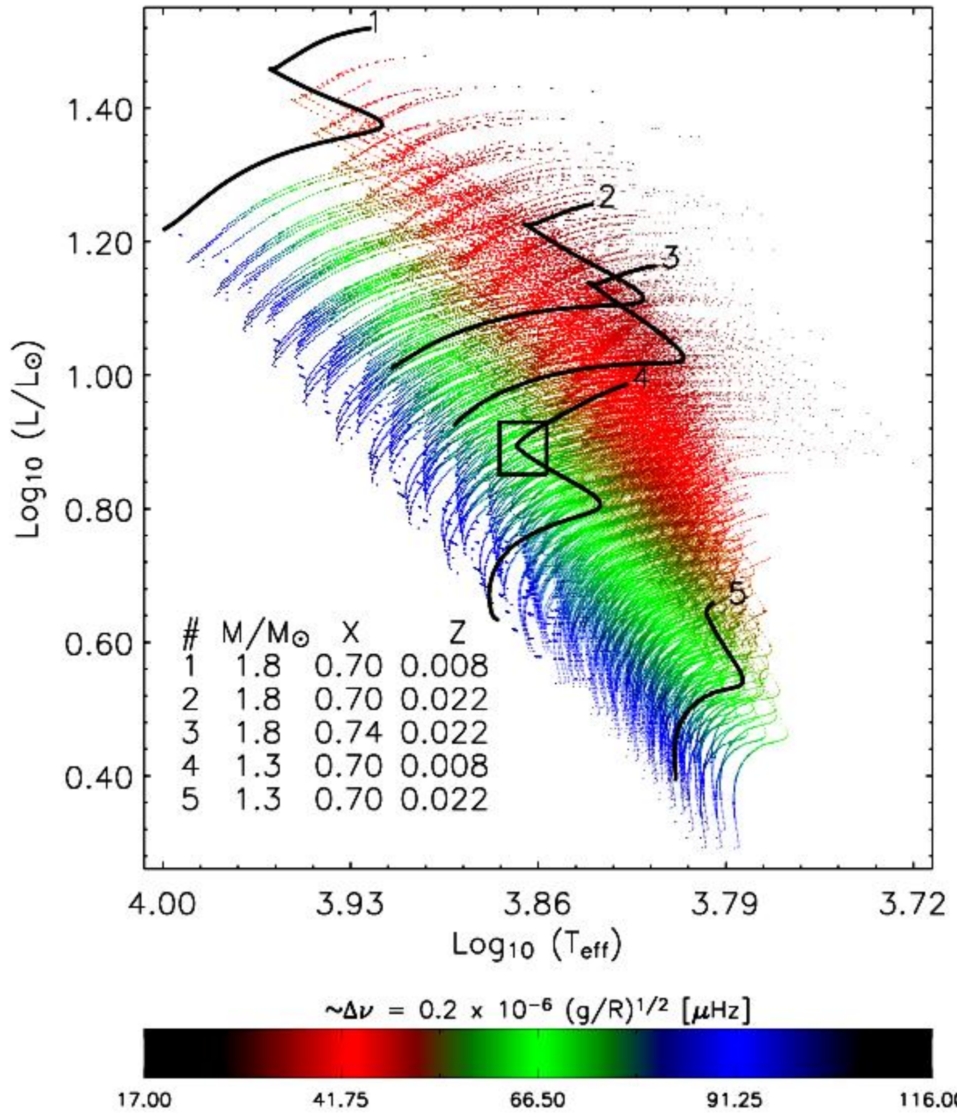


values of large frequency spacing Δν

HR 1217 = HD 24712

- ✓ Only half of 52,000 models match even only <u>one</u> frequency

- ✓ Only 0.5% of models have a fit probability within a factor of 100 of the model with the highest probability
  → *only a few × 100 models give a "good" match*

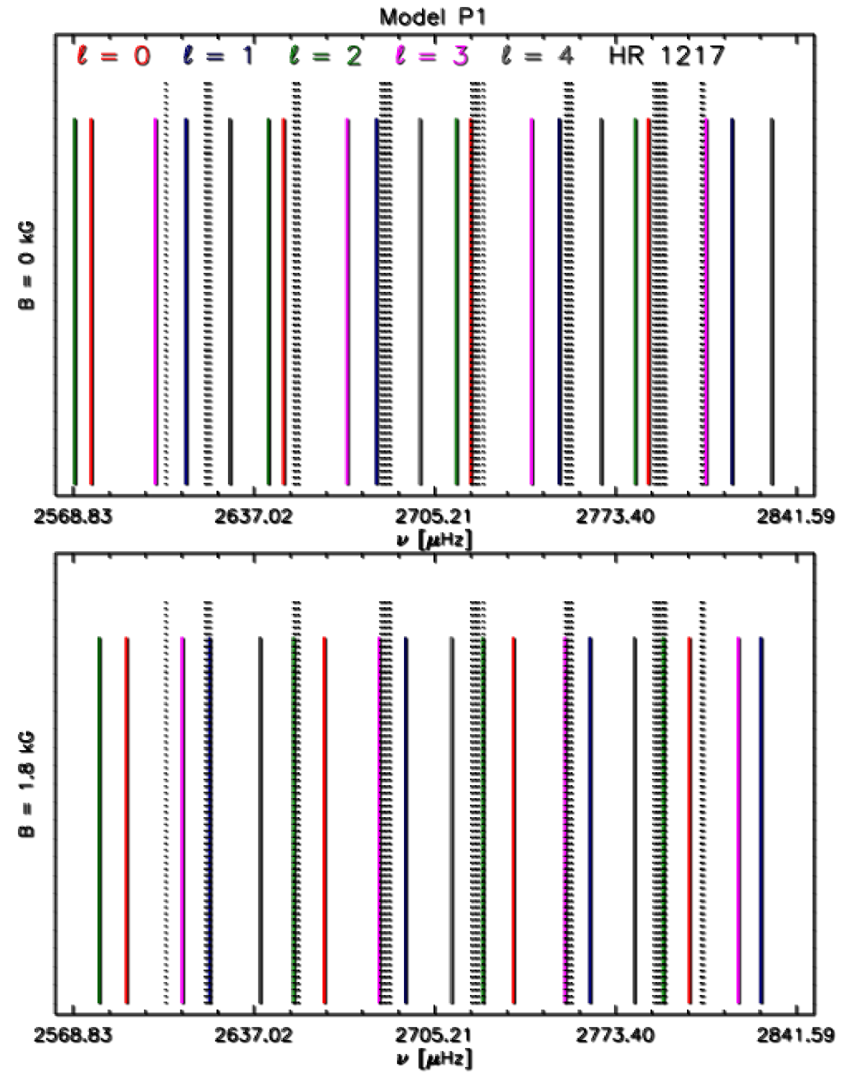


HR 1217 = HD 24712

Magnetic fields **essential** to model observed very rich roAp eigenspectra

… but parameter space is **very complex** with many local false minima

Interpolations of limited model grids are dangerous



HR 1217 = HD 24712

observed
small spacing
~ 2.5 μHz

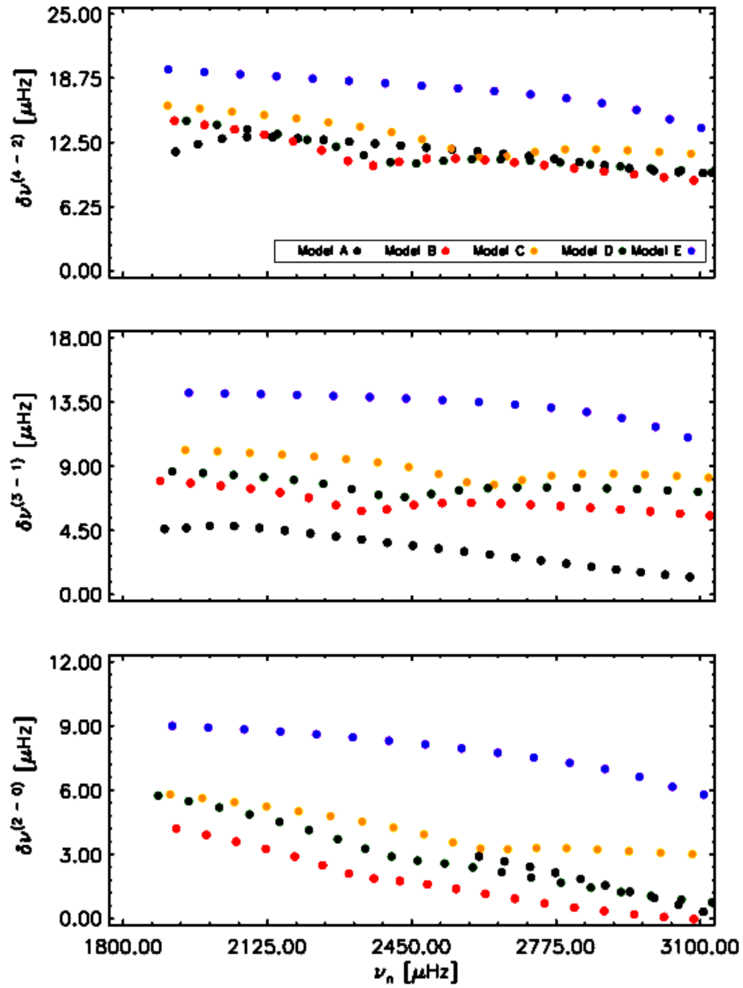
This value consistent with models of

✓ **low metallicity** *$Z < 0.01$*

✓ mass $M \sim 1.5\, M_\odot$

✓ age $t > 1$ Gyr

small spacings of models



Magnetoacoustics

- Magnetic fields shift pulsation frequencies
  - The frequency shift changes depending on the structure of the stellar envelope
- Magnetic fields tend to damp pulsations
  - This effect seems strong enough to damp low-overtone p-modes in roAp stars
- Magnetic fields modify the latitudinal distribution of pulsation amplitude
  - Amplitude confined to polar regions, as in HR 3831
- Theoretical models for Przybylski's Star, γ Equ, and 10 Aql agree with observed frequencies

but required B_p might be too big

Thanks for everything, Don!

I can no other answer make

but thanks, and thanks,

and ever thanks.

Twelfth Night

Act 3, Scene 3