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Recent developments in the theory of RR Lyrae stars

Zoltán Kolláth

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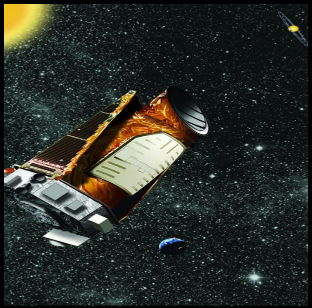
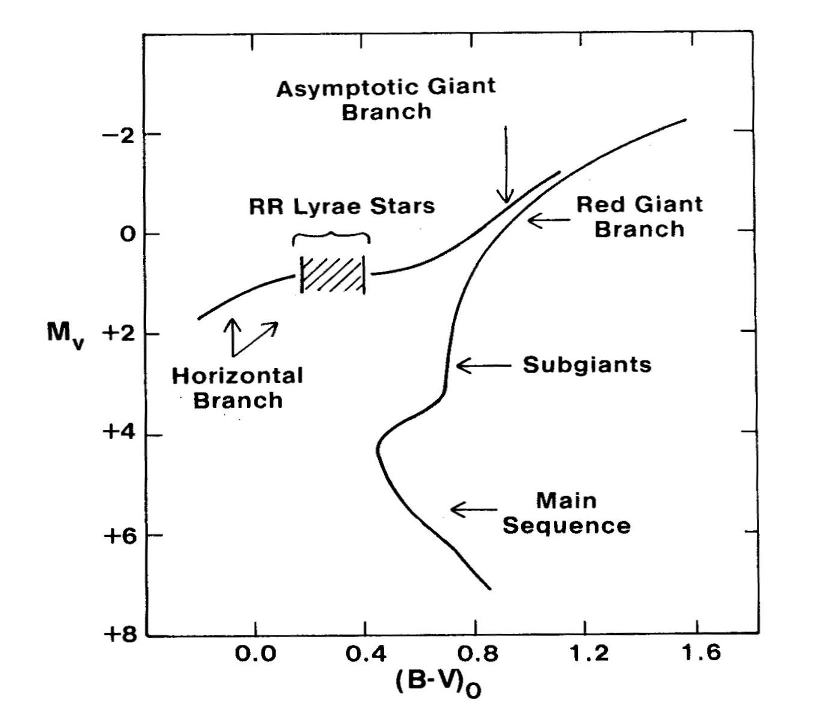
+ KASC WG#13 members

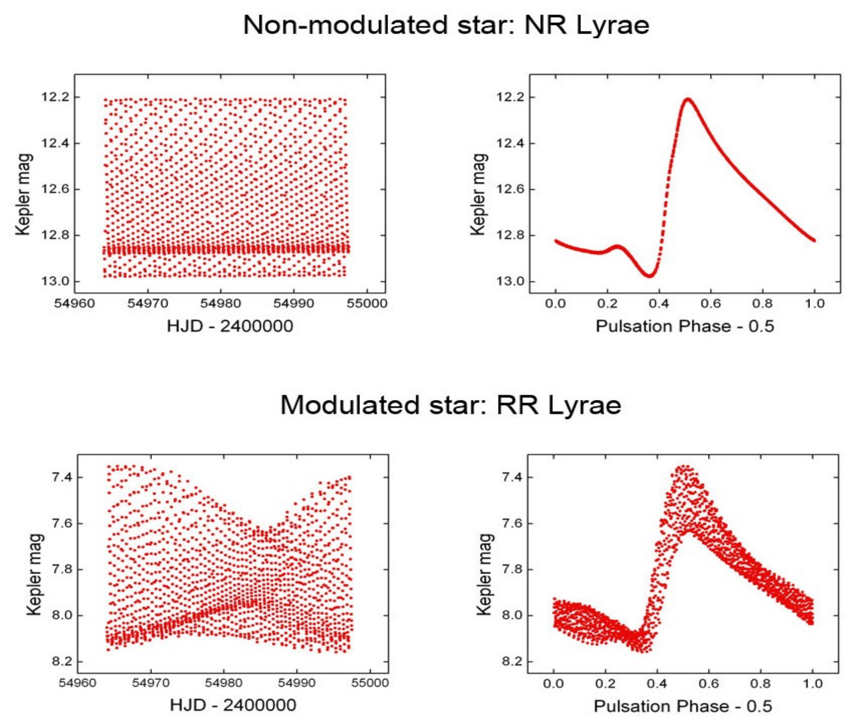


27 October 2011
The Impact of Asteroseismology across Stellar Astrophysics
Santa Barbara

RR Lyrae stars and the Blazhko effect



H.A. Smith: RR Lyrae stars, 1995



Gilliland et al. PASP, 122, 131, 2010

- RRab (F), RRc (O1), RRd (F+O1)
- per: 0.2 – 1.0^d ampl: $0.5\text{-}1.5^m$
- Pop II. horizontal branch
- core He, shell H-burning
- standard candles

- amplitude & phase modulation
- light curve shape deformation
- ampl. mod.: $A_{max}-A_{min} / A_{max} \sim 0.03\text{-}0.87$
- period var: 1-4 % dP/P
- Blazhko period: 5^d - $\sim 1000^d$

Blazhko effect – recent progress

Konkoly Blazhko Survey (ground-based GB)

- Occurrence rate 50% for RRab stars (GB, SB) *Jurcsik et al. MNRAS 400, 1006, 2009*
- Multiple modulation periods (GB, SB) *Sódor et al. MNRAS, 411, 1585, 2011*
- Long-term modulations (GB) *Detre & Szeidl 1973, IAU Coll. 21, 31*
- Modulation can stop and restart (GB) *Sódor et al. A&A 469, 1033, 2007*
- Cycle-to-cyle variations (SB) *Guggenberger et al. MNRAS, 415, 1577, 2011*
- Blazhko-period changes (SB) *Kolenberg et al. MNRAS 411, 878, 2011*
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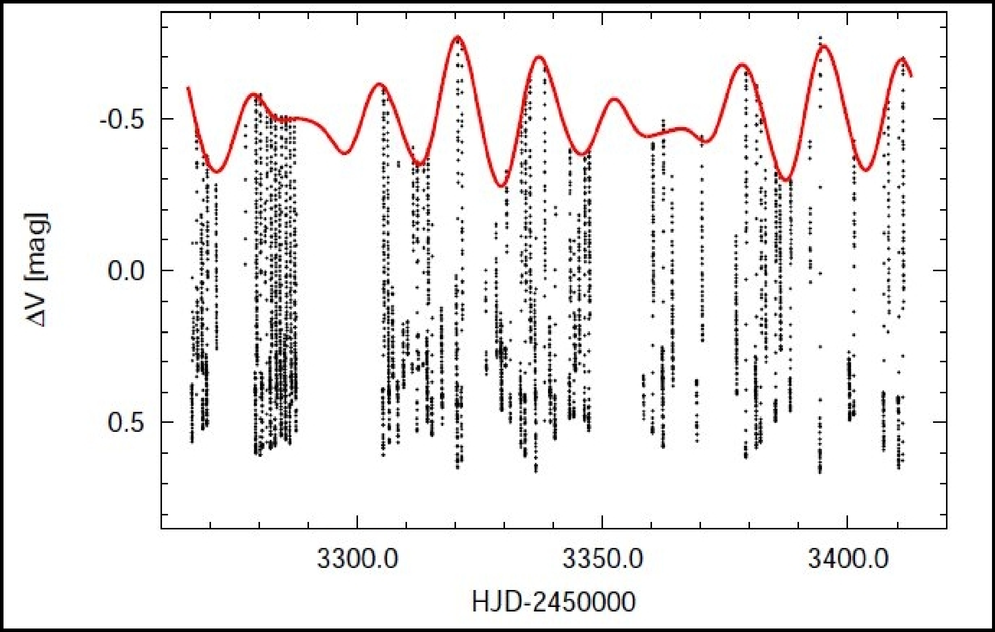
CoRoT, Kepler (space-based, SB)



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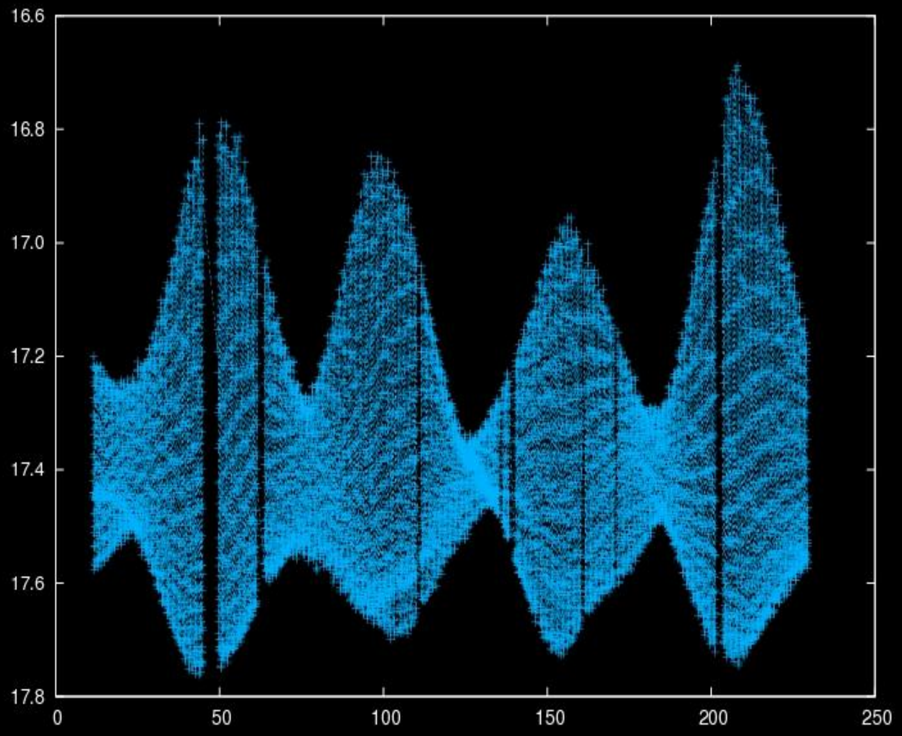

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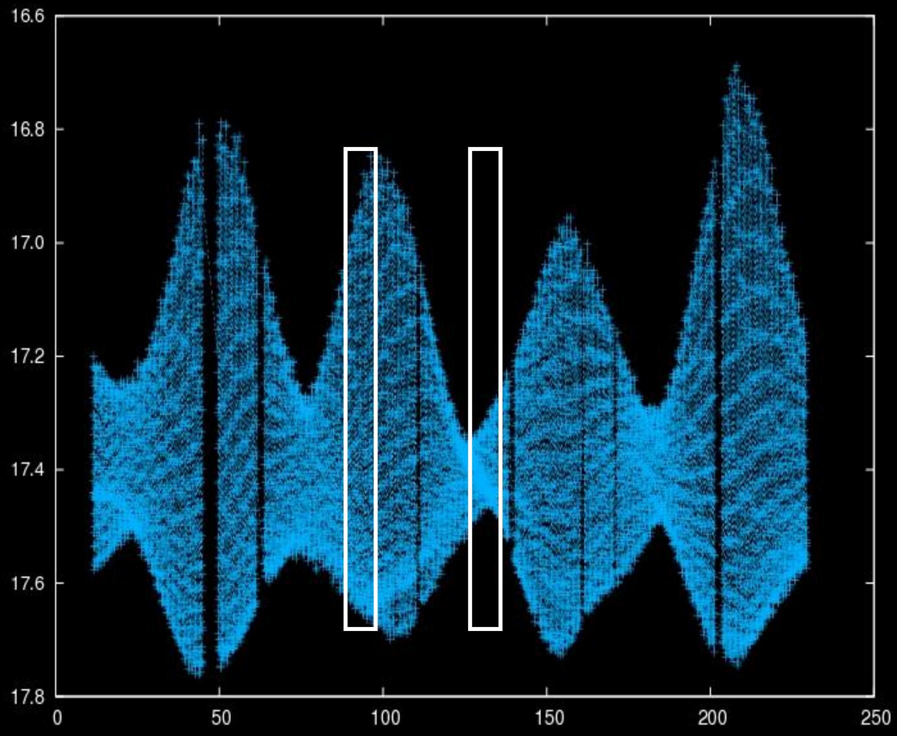

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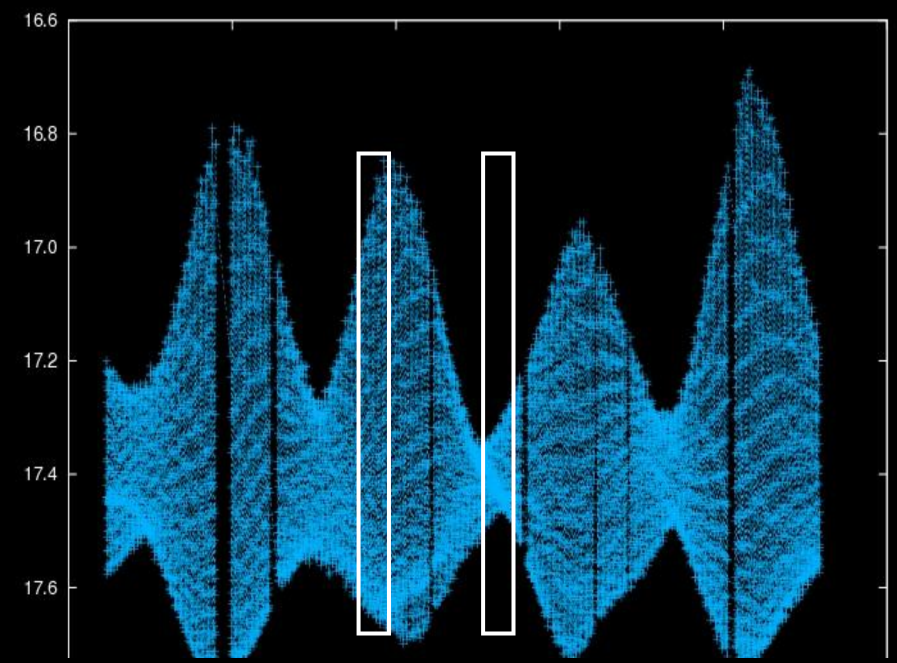
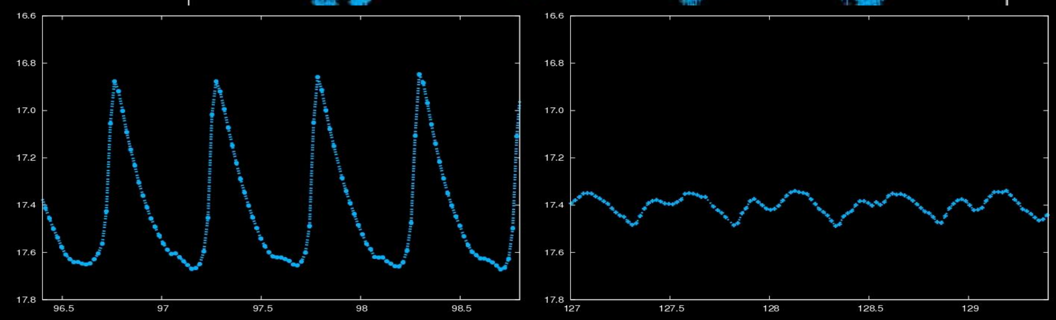
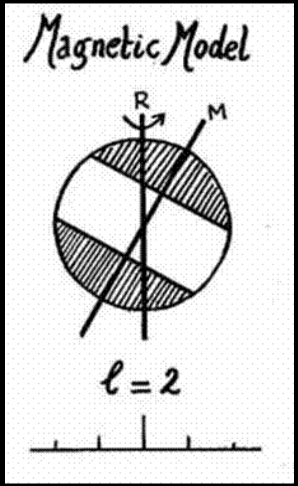
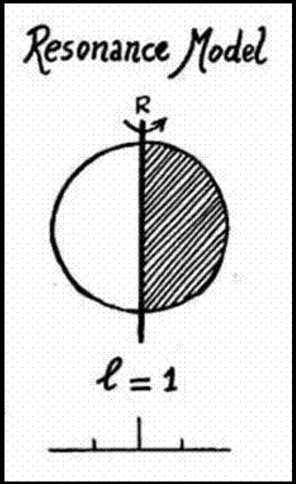
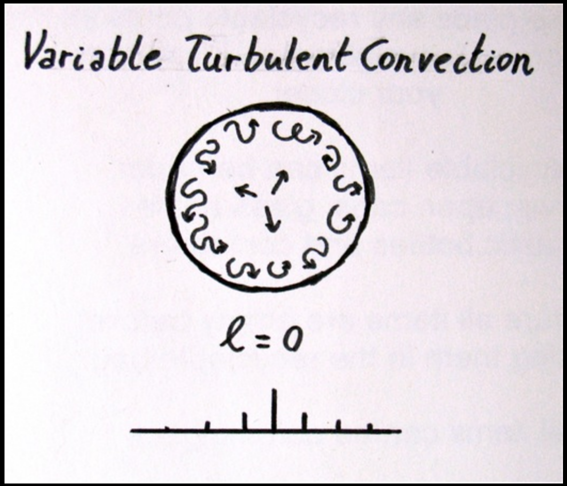




Blazhko effect – proposed mechanisms







1. Magnetic oblique rotator /pulsator model
Shibahashi 2000

Strong magnetic field deforms the purely radial pulsation

Strong magnetic field was ruled out *Chadid et al. 2004, Kolenberg & Bagnulo 2009*
Blazkho period is the rot. period

2. Resonance model
Van Hoolst et al. 1998
Dziembowski & Mizerski 2004

1:1 nonlinear resonance between the radial fundamental mode and a nonradial mode

Too high amplitude required for the nonradial mode in some cases

3. Stothers' idea
Stothers 2006
Stothers 2010

Magnetic dynamo effect altering the stellar structure by causing variable turbulent convection

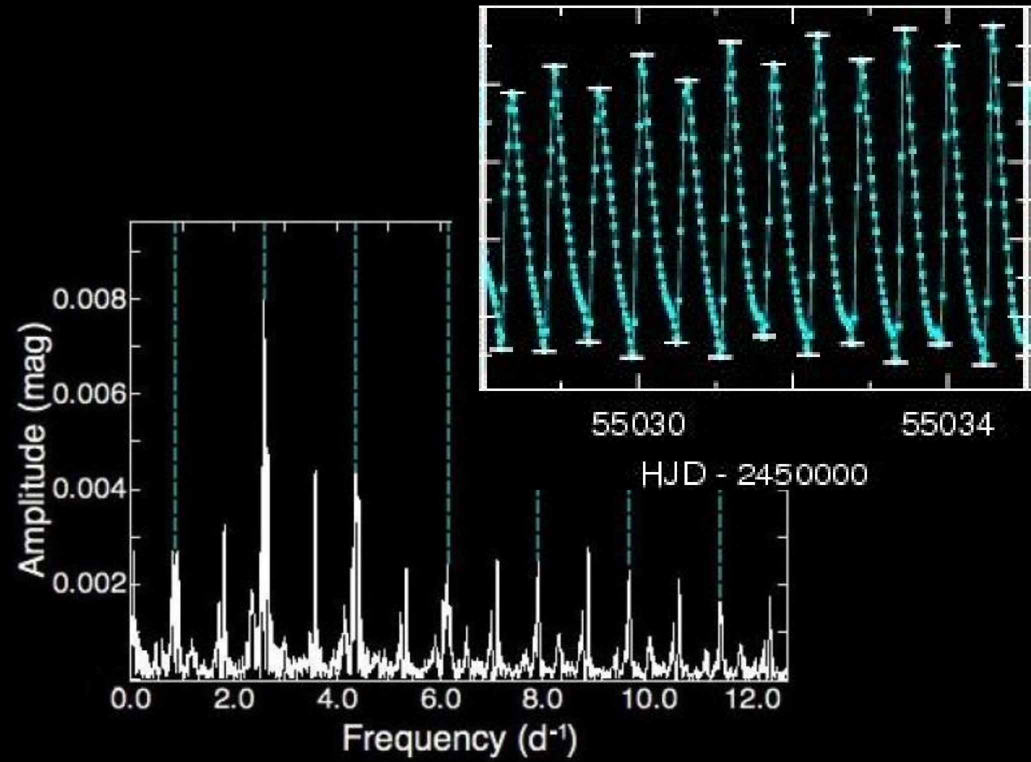
Complex interaction of the turbulence and the magnetic dynamo. It is hard to model.
Smolec et al. 2011

Period doubling (PD) – a surprise

<u>Manifestation:</u>
- alternating cycles
- half-integer frequencies
  ($1/2\ f_o$, $3/2\ f_o$, $5/2\ f_o$…)

<u>3 Kepler PD RRab Blazkho stars</u>
RR Lyr KIC 7198959
V808 Cyg KIC 4484128
V355 Cyg KIC 7505345

<u>4 other RRab stars show signs of the PD effect</u>
V2178 Cyg KIC 3864443
V354 Lyr KIC 6183128
V445 Lyr KIC 6186029
V360 Lyr KIC 9697825



RR Lyr Q1 Kolenberg et al. 2010

Other Kepler stars do not show the signs of the PD effect
Limit: Blazkho: 0.2-2.0 mmag non-Blazkho: 0.1-1.0 mmag

Period doubling in pulsating stars history

RV Tauri stars:
Definition: alternating deep and shallow minima

Period doubling in Cepheid, W Vir, RV Tauri models
Buchler & Kovács (1987, 1988)
Moskalik & Buchler (1991, 1992)

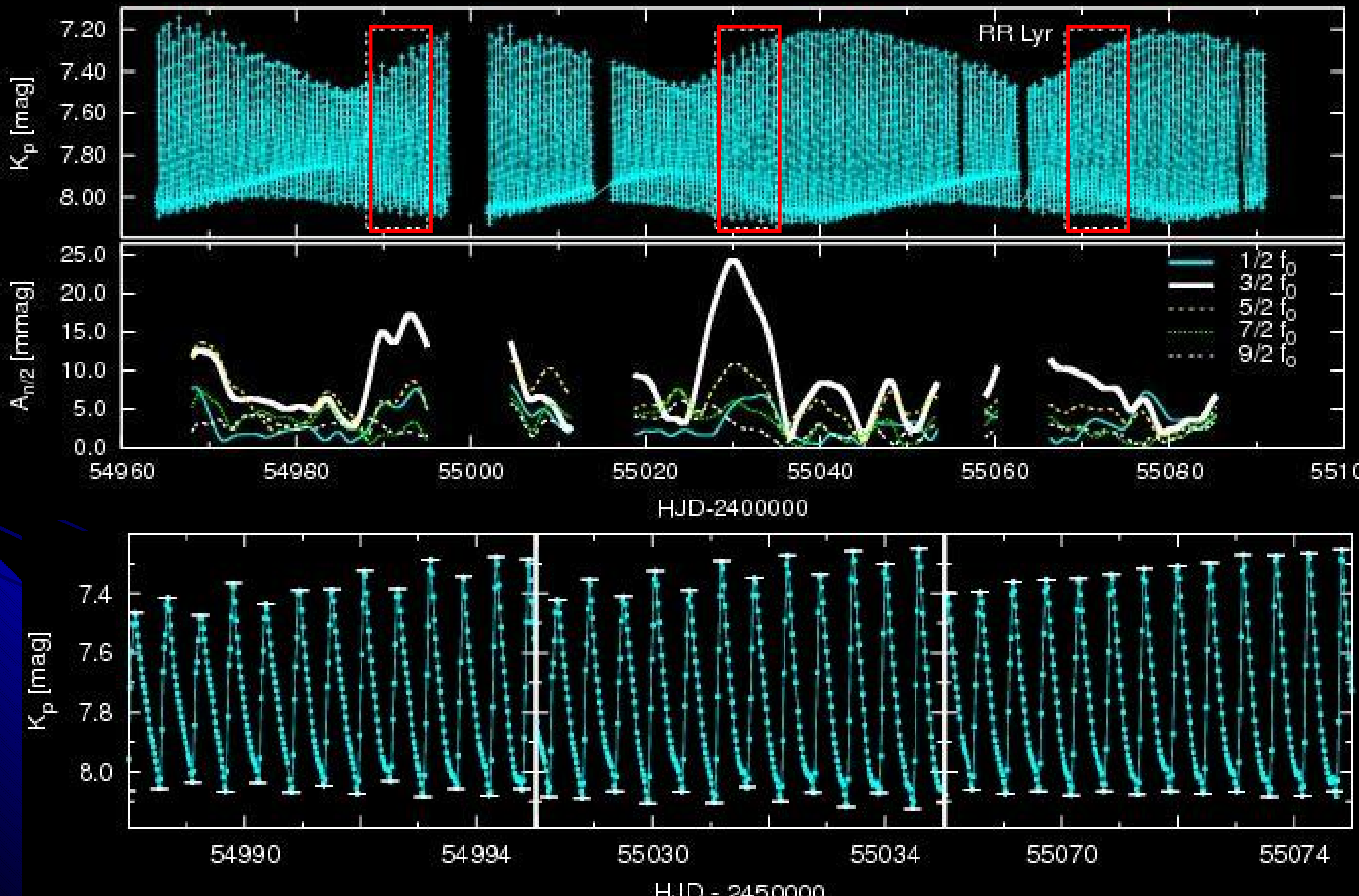
Period doubling in a Mira star (R Cyg)
Kiss & Szathmáry 2002

Period doubling in BL Her stars in OGLE-III
Smolec et al. (2011)

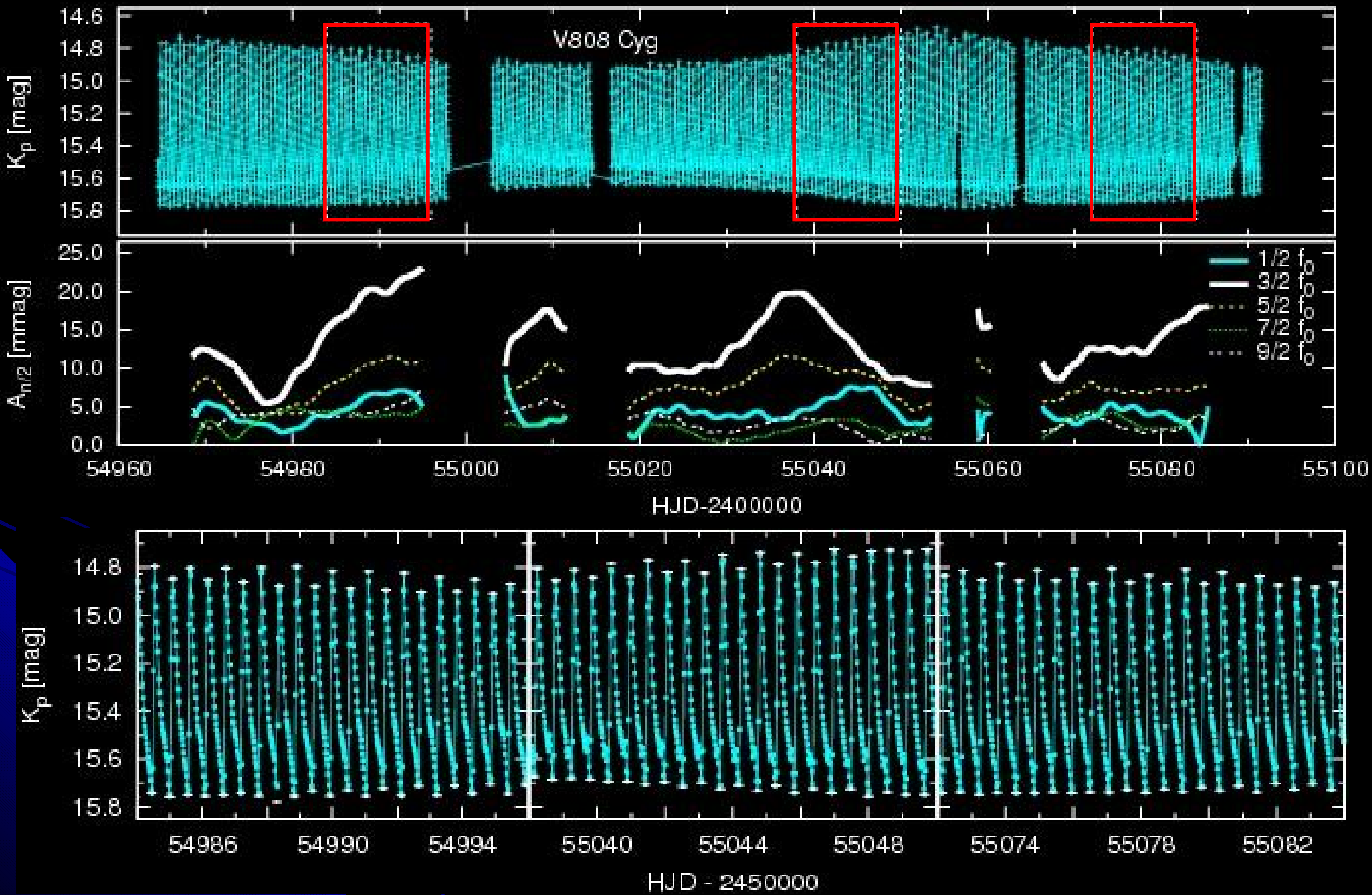
Cause of PD in the hydro models:
low order resonance between the *fundamental mode* and a *low-order radial overtone*
$(2n+1)\ \omega_0 \approx 2\omega_k$ n=1,2 0: fundamental mode k: k^{th} overtone

PD has never been observed in RR Lyr stars nor in RR Lyr models.

Period doubling in RR Lyr (Q1+Q2)



Period doubling in V808 Cyg (Q1+Q2)



Significance of period doubling

- PD and the Blazhko effect are strongly related
- PD is seen only in Blazhko stars
- strong PD is present only in certain Blazkho phases

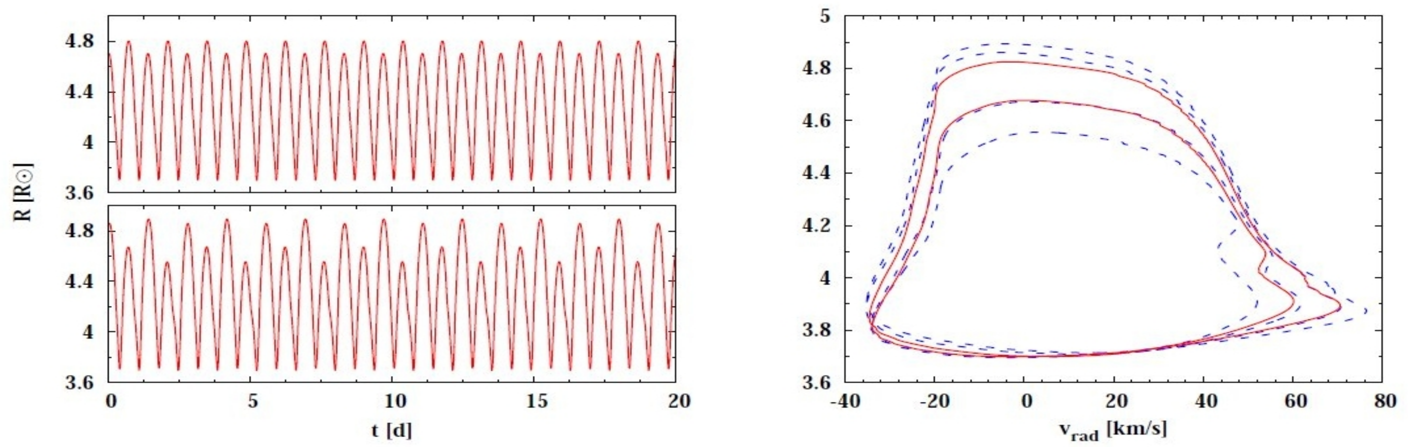


Figure 2. Bifurcated solutions of a radiative model (6500 K, 0.57 $M_{\odot}$, 40 $L_{\odot}$). The blue dashed line is a double-period, the red solid line is a four-period solution. Both models were calculated with 100 mass shells and identical parameters except the value of the artificial viscosity.

<u>Models and explanation</u>

Hydrodynamical calculations proved that the cause of the period doubling effect is a **high order resonance** (9:2) between the fundamental mode and the 9th radial overtone (strange mode).

Szabó, Kolláth, Molnár et al. MNRAS, 409, 1244, 2010

Kolláth, Molnár, Szabó MNRAS, 414, 1111, 2011

Strange modes

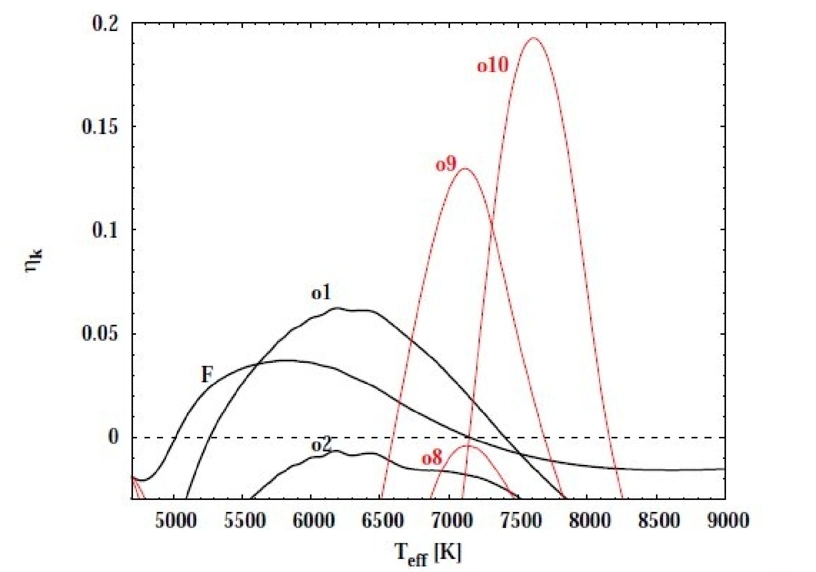


Figure 4. Linear growth rates of radial modes. Starting with the second overtone, modes become more and more damped, but then overtone eight gets close to the unstable regime, indicating its strangeness. Overtone nine and then could become excited on their own.

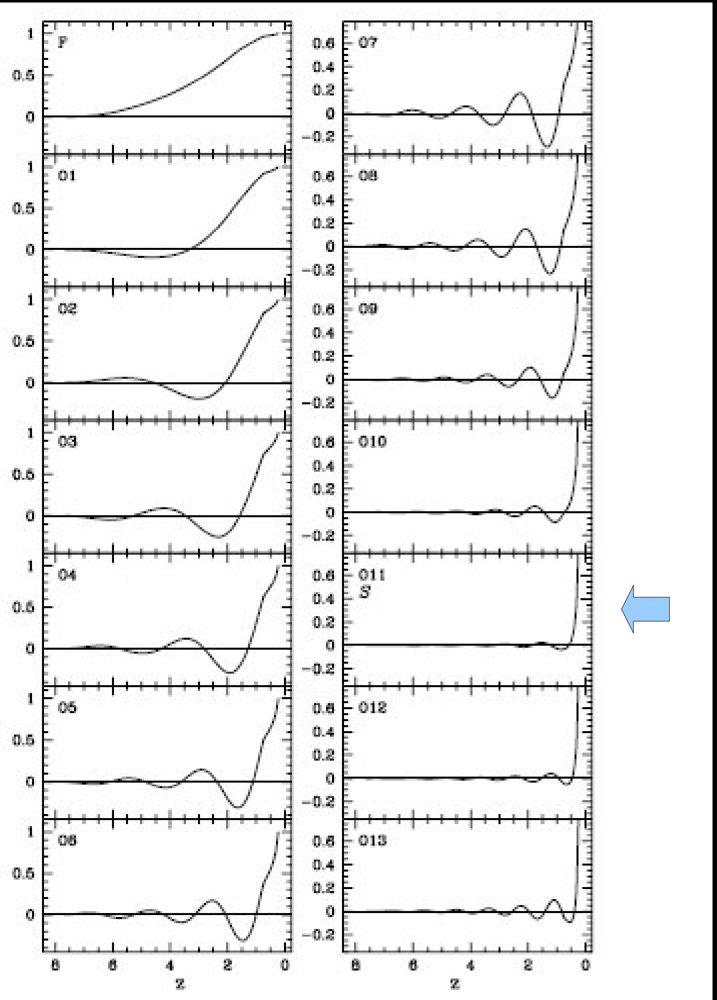
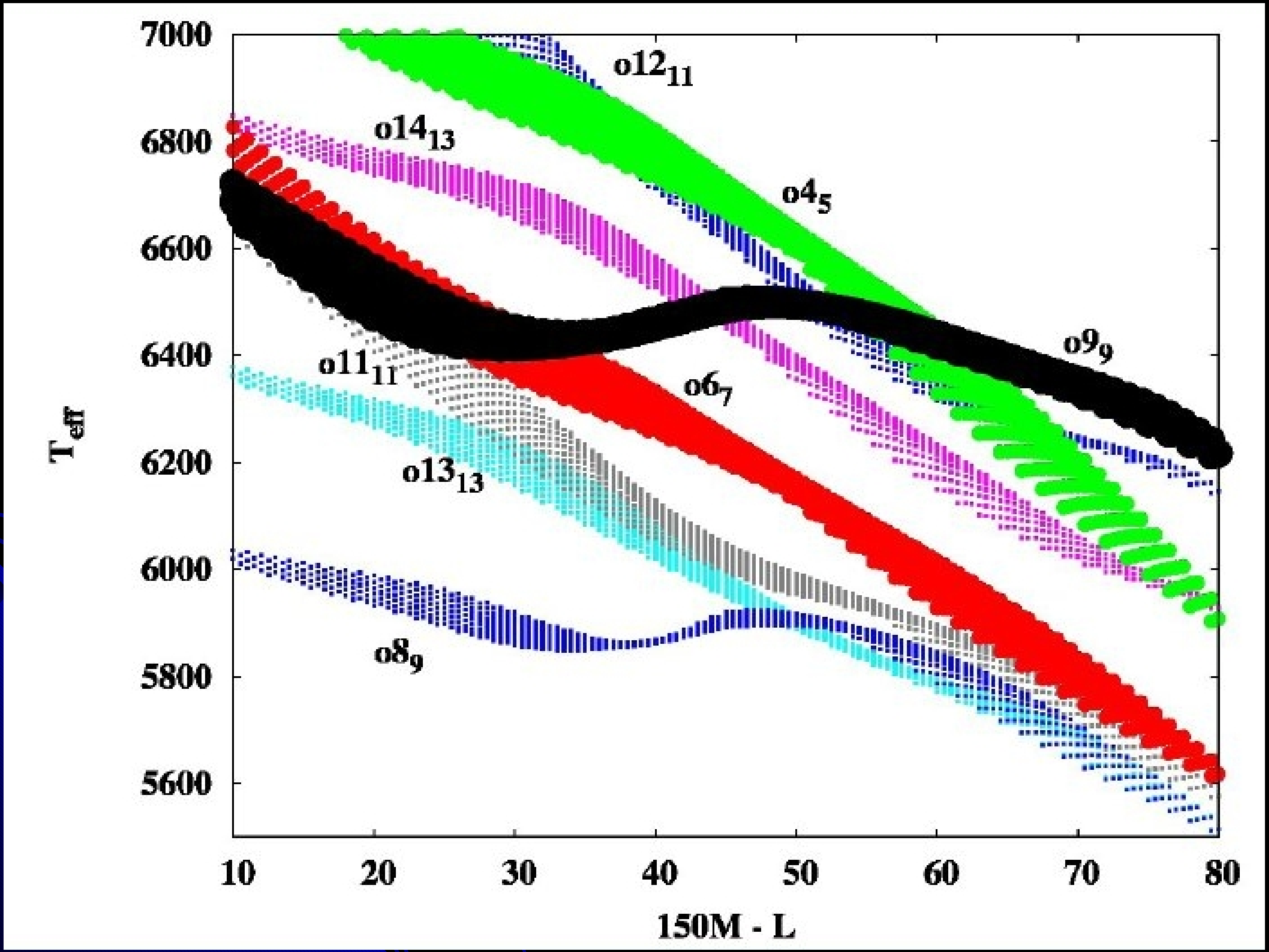


Fig. 6. Adiabatic eigenvectors $\delta r_n / r$ vs. acoustic depth for the Cepheid Model; note the different scales on the left and on the right column. The strange mode is labelled by $\mathcal{S}$.

Kolláth, Molnár, Szabó MNRAS, 414, 1111, 2011

Strange modes:
- trapped surface modes
- can be excited, despite being high order overtones.

Linear 'diagnostic' diagram of half-integer resonances



Notation: $o6_7$: 6^{th} overtone with a 7:2 resonance with the fundamental mode

Candidates: $o9_9$ $o6_7$ $o4_5$

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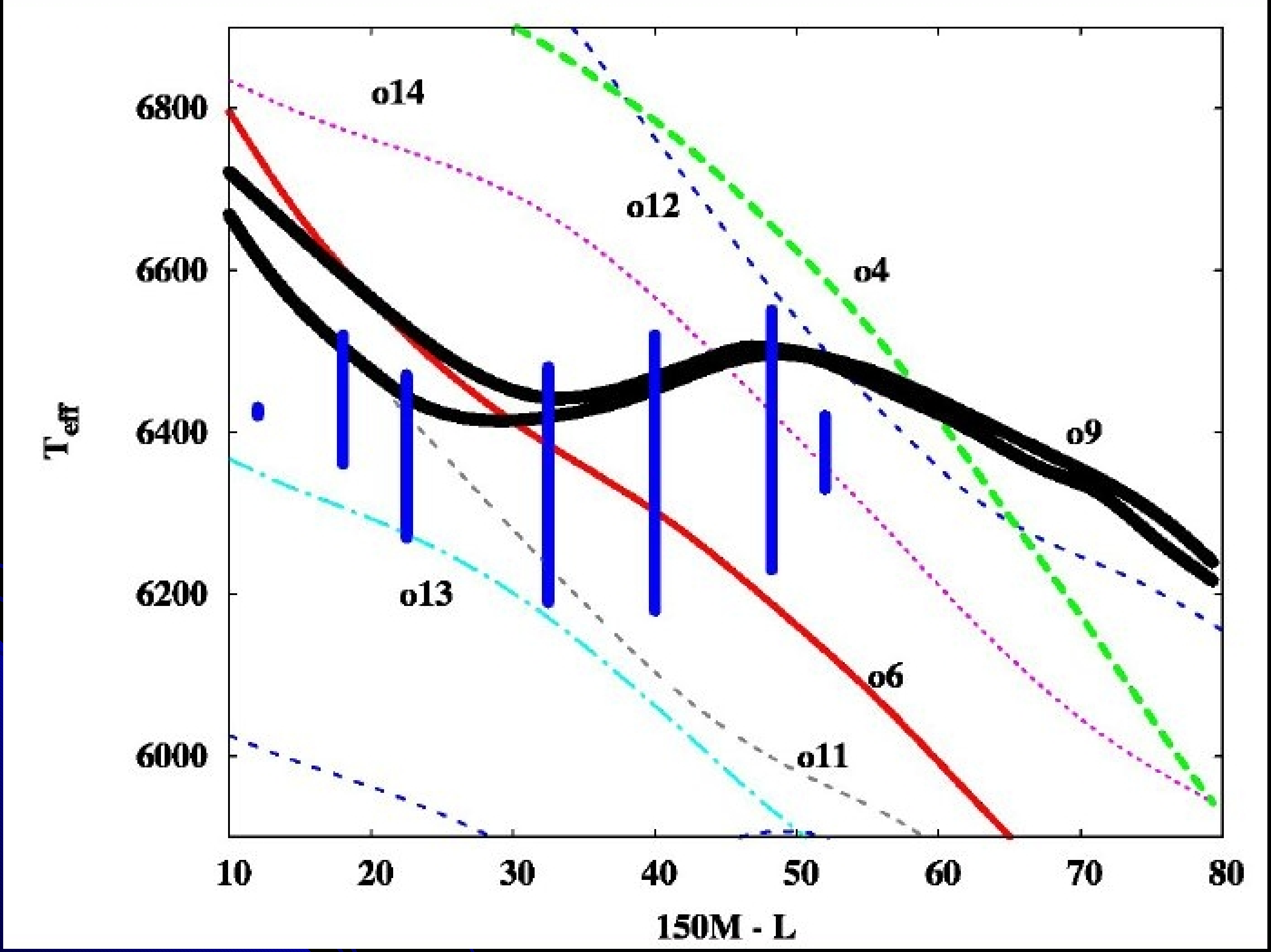
Nonlinear 'diagnostic' diagram



Blue region: resonant positive Floquet exponent (PD)

It follows the 9:2 resonance with the 9th strange overtone.

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Bifurcation cascade

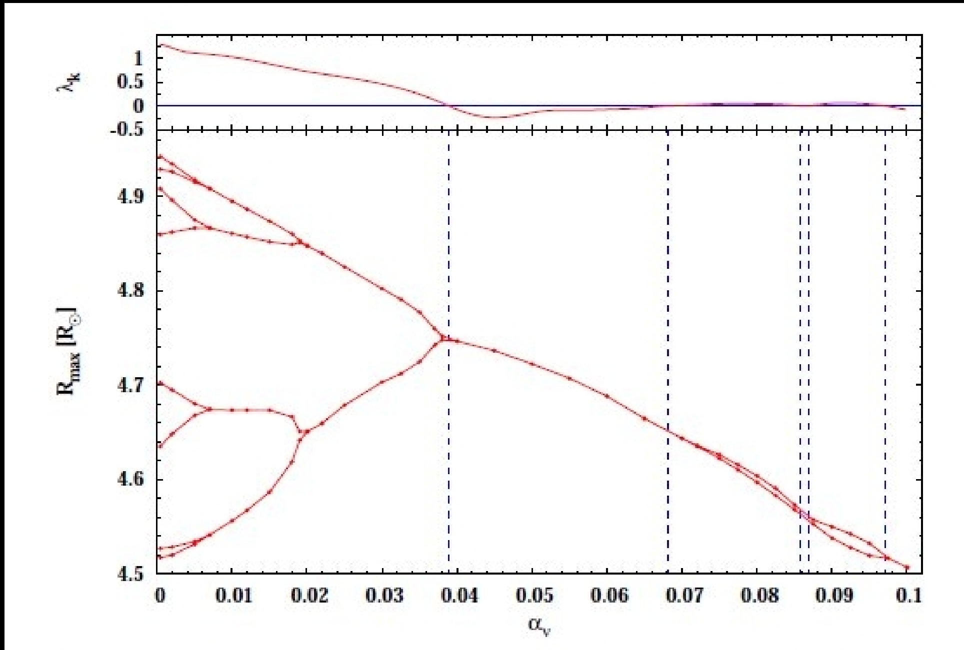


Figure 7. Bifurcation cascade of an RR Lyrae model ($T_{eff} = 6500K, M = 0.59M_\odot, L = 56L_\odot$). Each model correspond to a limit cycle solution with different α_ν eddy viscosity parameters. The plotted values are the maximum stellar radii of all different cycles. The upper panel shows the corresponding Floquet-exponent. When the exponent is positive, the limit cycle is bifurcated. The vertical lines indicate the successive zero-crossings of

Kolláth, Molnár, Szabó
MNRAS, 414, 1111, 2011

Bifurcation-cascade (Feigenbaum)

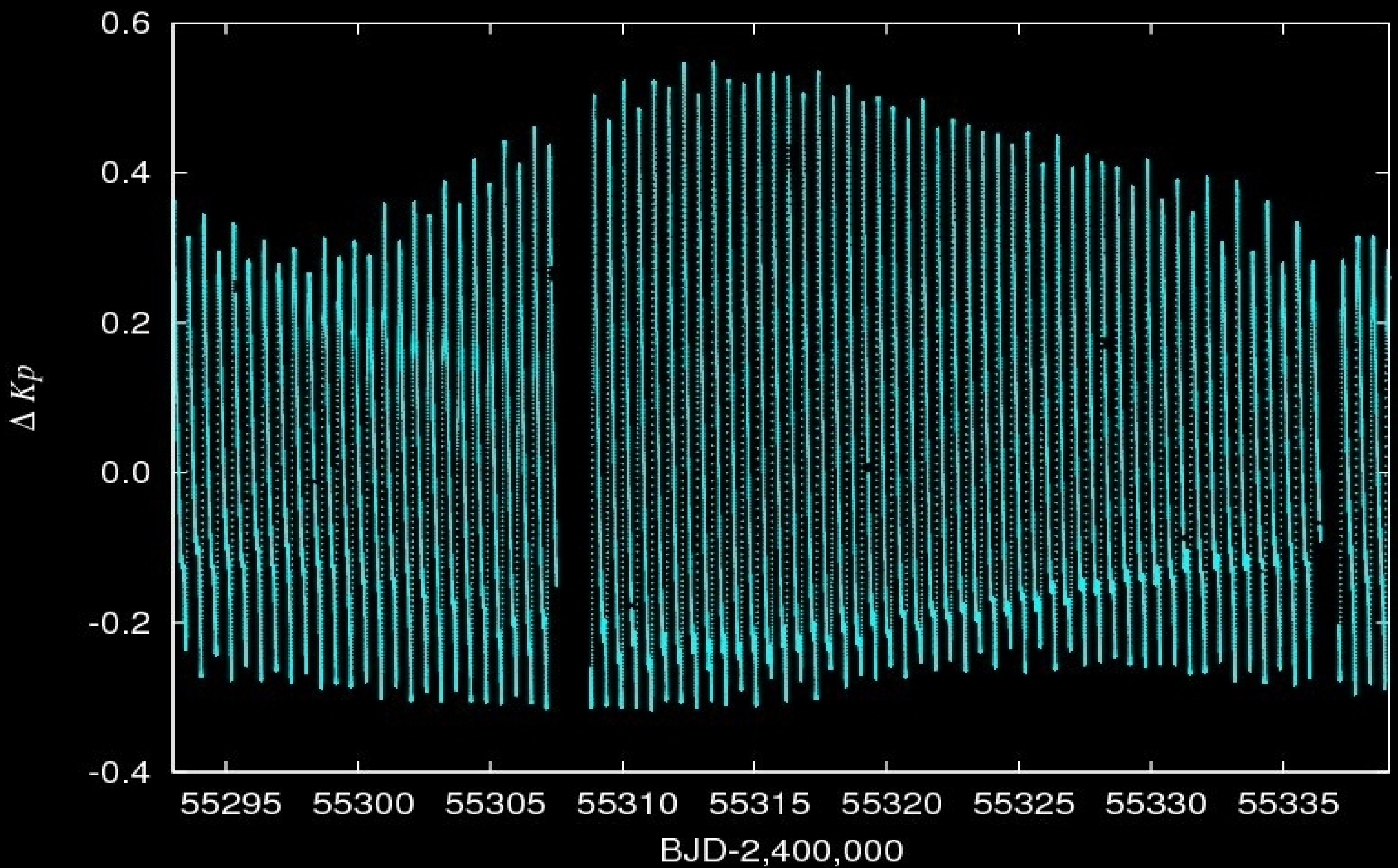
This phenomenon is a true bifurcation in a dynamical sense confirmed by the cascade.

The cascade can lead to chaos.

Chaos in RV Tau and semiregular stars
Buchler et al. 1996, 2004, Kolláth et al. 1998

<u>Chaos in RR Lyrae models?</u>

A *Kepler* RR Lyr short-cadence data set



Period doubling throughout the Blazhko cycle.

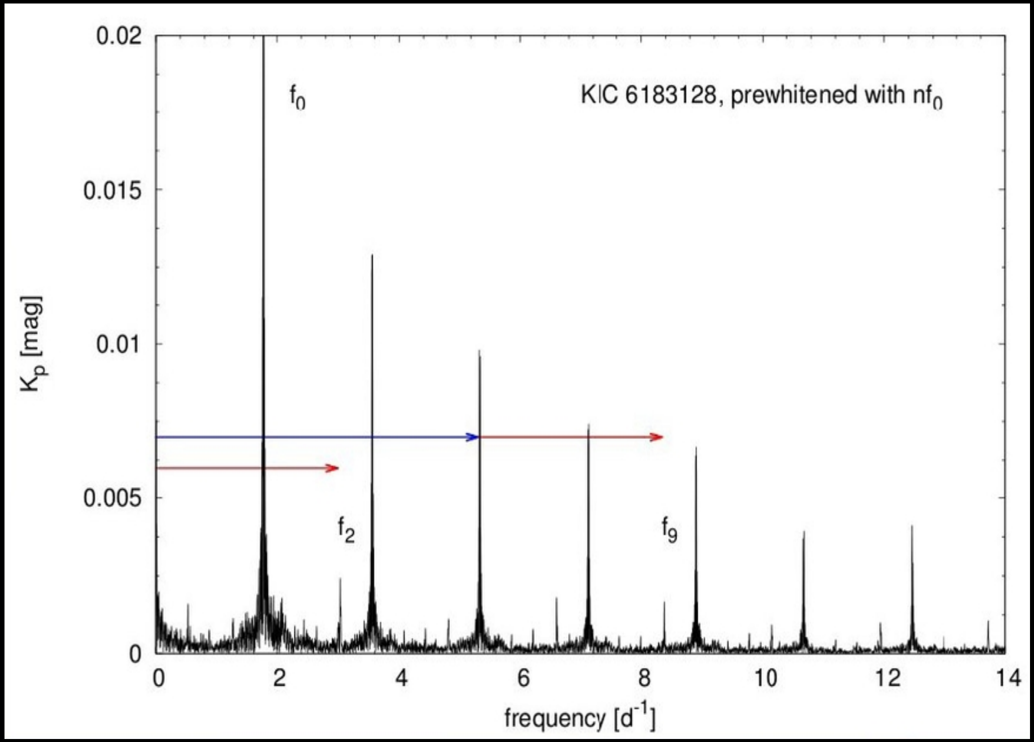
Possible three-mode resonances

Additional frequencies, close to the 1st and 2nd overtones.

Most stars are modulated and show period doubling as well.

V354 Lyr (KIC 6173128)

$3f_0 + f_2 = f_9$



Resonances involving nonradial modes are also possible.

A new explanation for the Blazhko effect

9:2 resonance: cause or effect?

Buchler & Kolláth ApJL, 731, 24, 2011

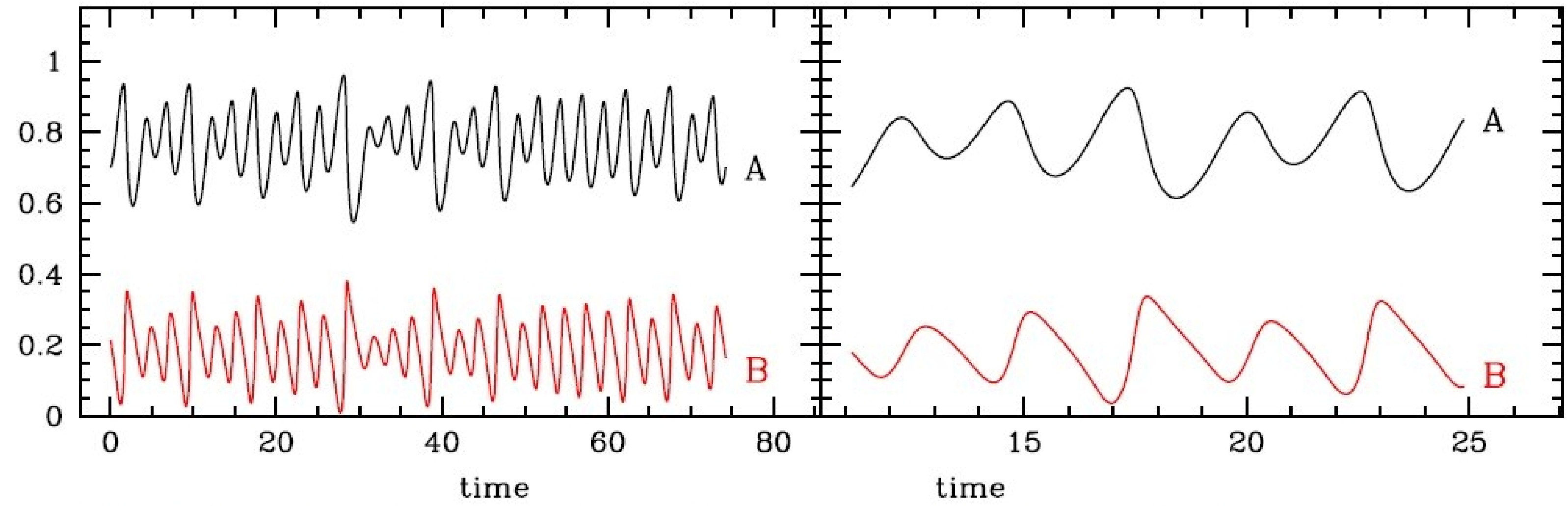


FIG. 1.— Temporal modulation of the two amplitudes of the irregularly modulated period two pulsation.

Irregular (chaotic) amplitude modulations naturally result from the **nonlinear resonant mode coupling** between the fundamental mode and the 9th overtone using amplitude equations.

Blazhko effect is much more complicated than previously thought.

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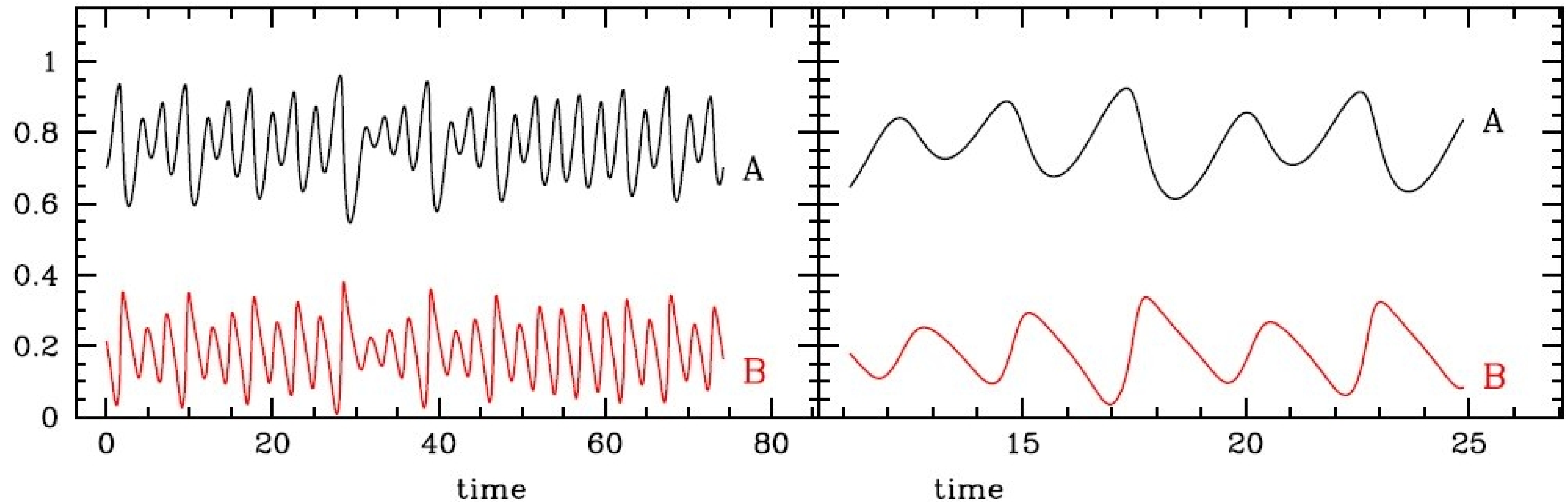

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Blazhko effect is much more complicated than previously thought, but thanks to Kepler we may have found the solution.