The mass-accreting pulsating components of Algols (oEA stars)

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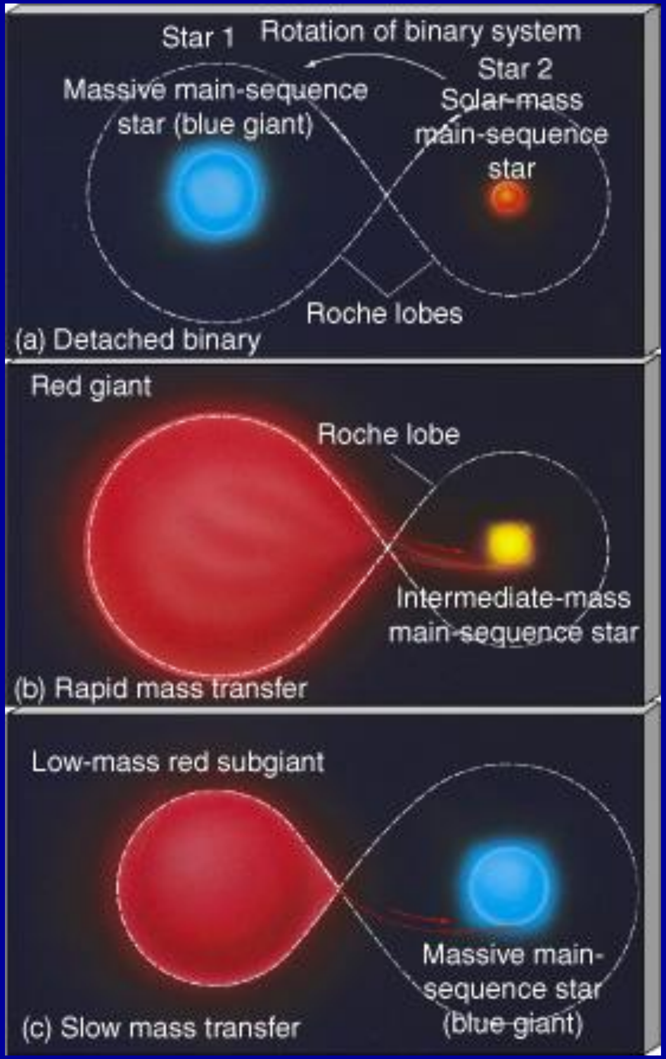
Evolution of (Algol–type) binary system

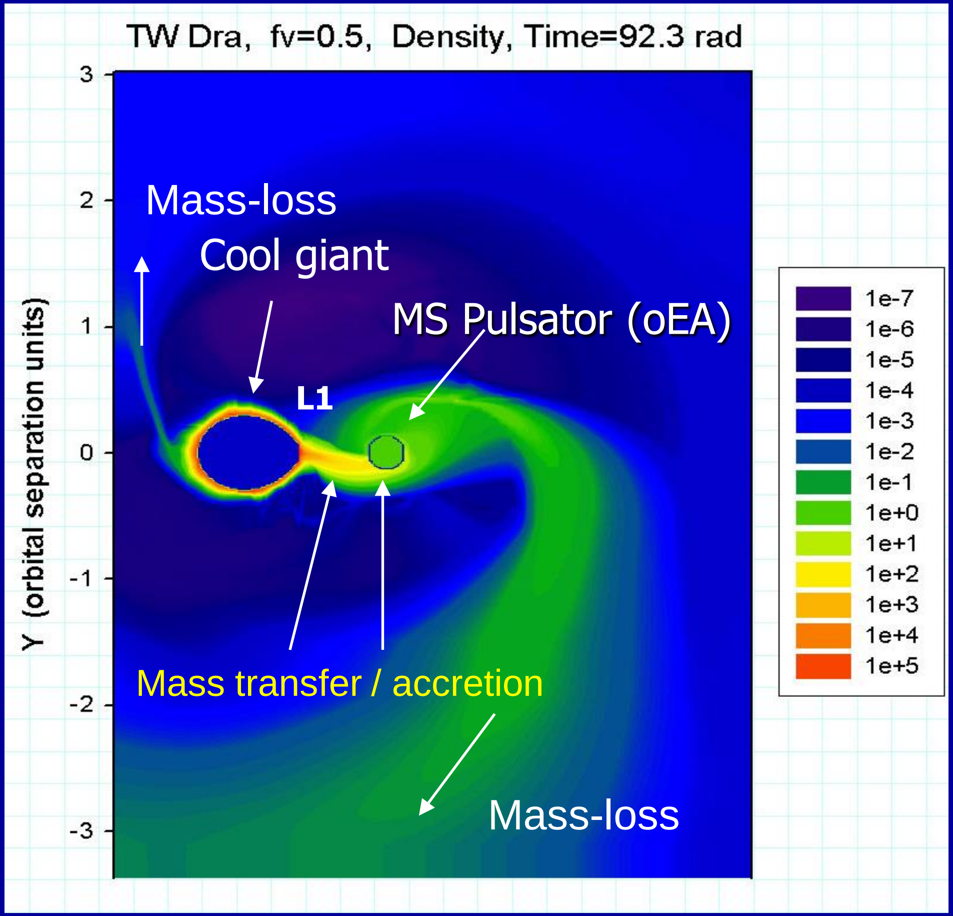
Main sequence evolution:
classical δ Scuti-type
component

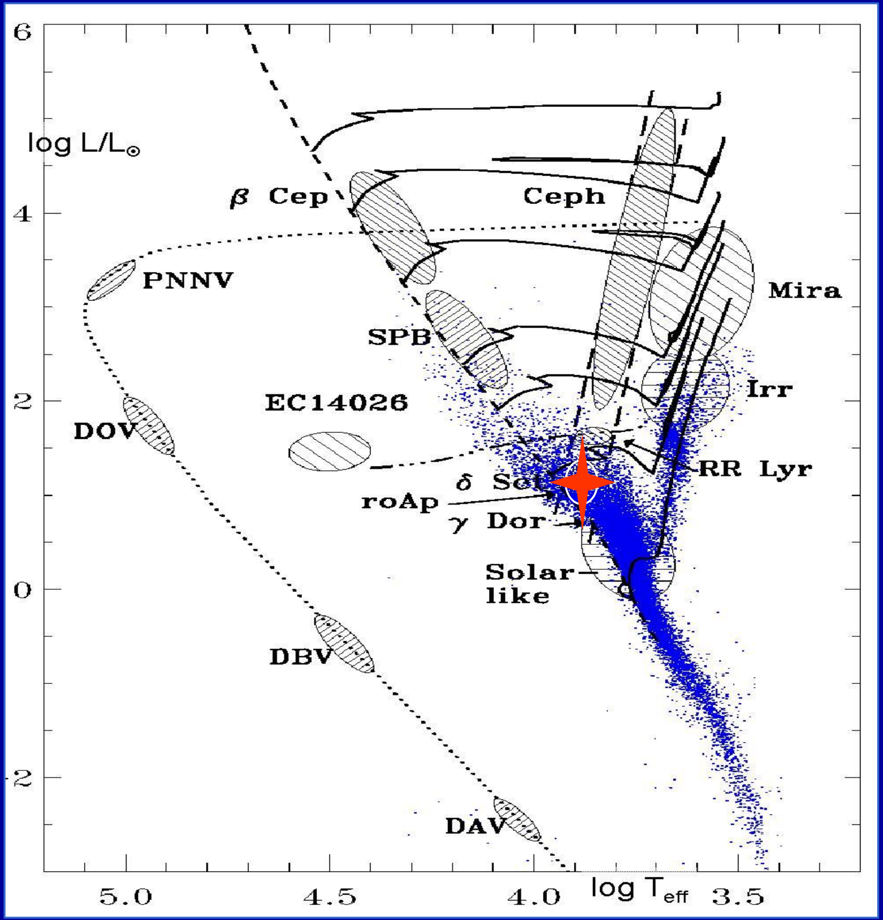
Rapid mass transfer stage, inversion of mass

Slow mass-transfer stage:
Mass-accreting MS pulsator = oEA star



A2 V - F2 V components of Algols





2-D simulations

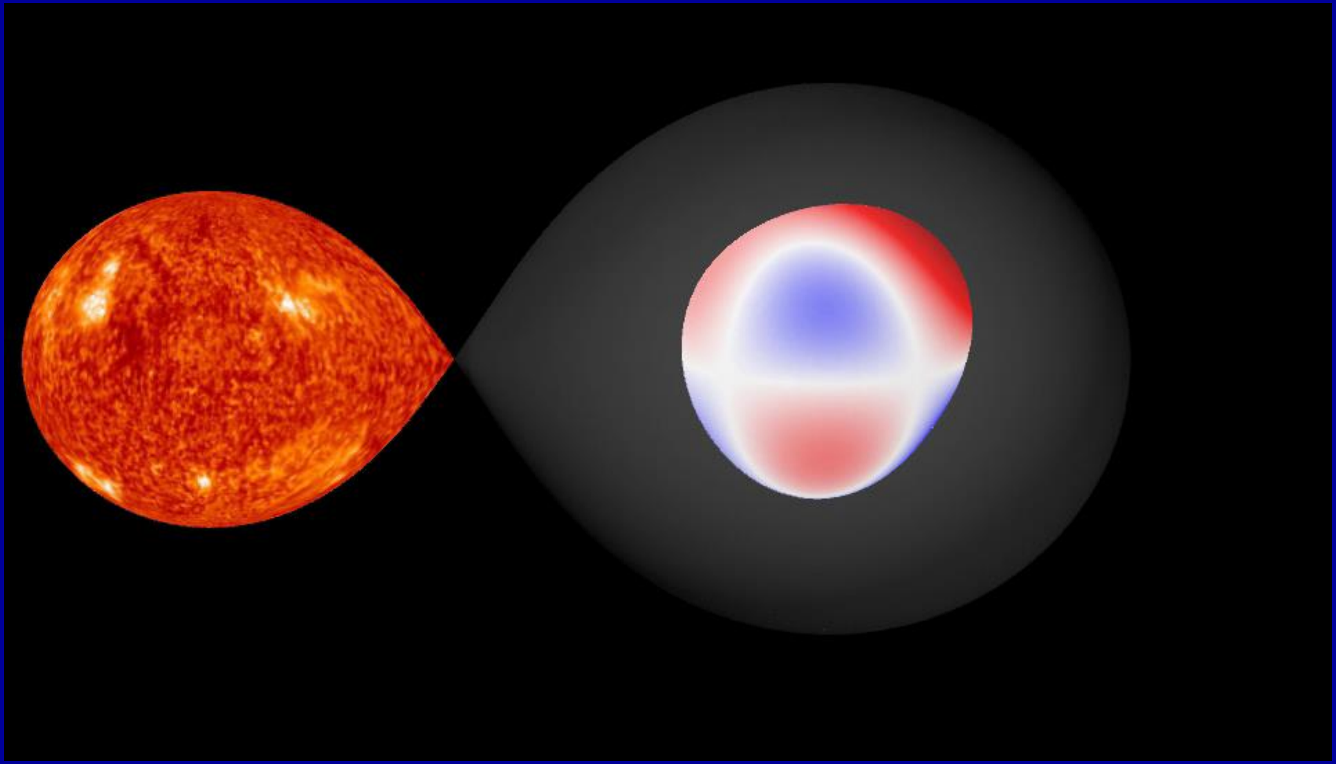
(Nazarenko & Mkrtichian, unpubl)

2002 - up to now

~ 76 oEA stars

The definition of the class of oEA (oscillating EA) stars:

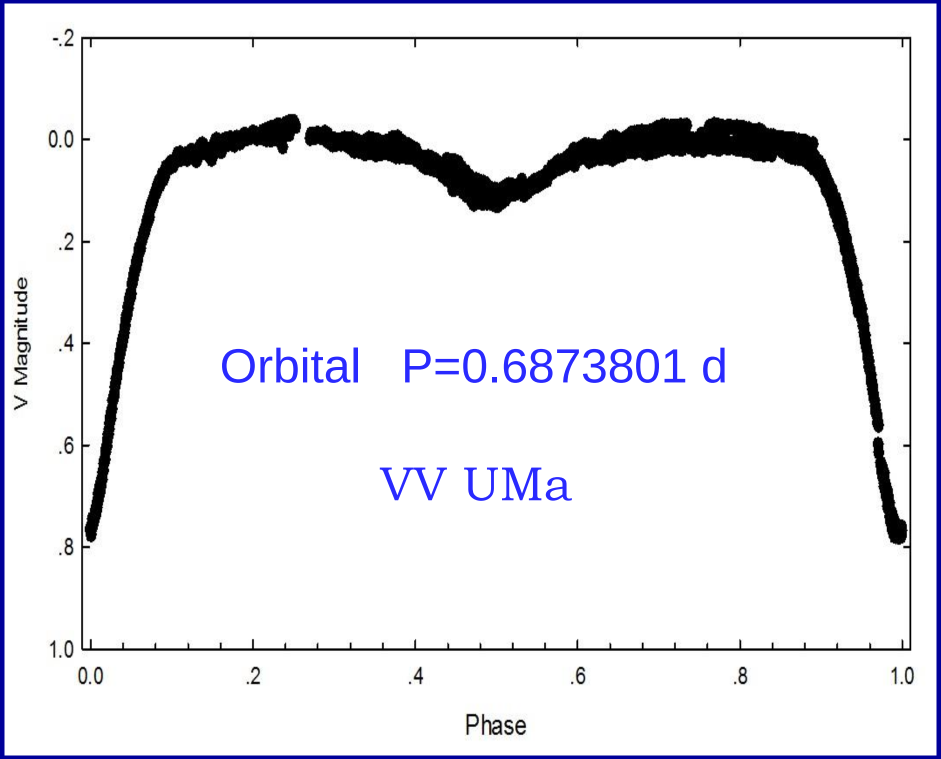
The A-F spectral type mass-accreting Main Seguence pulsating stars in a semi-detached, Algol-type systems (Mkrtichian et al., 2002)

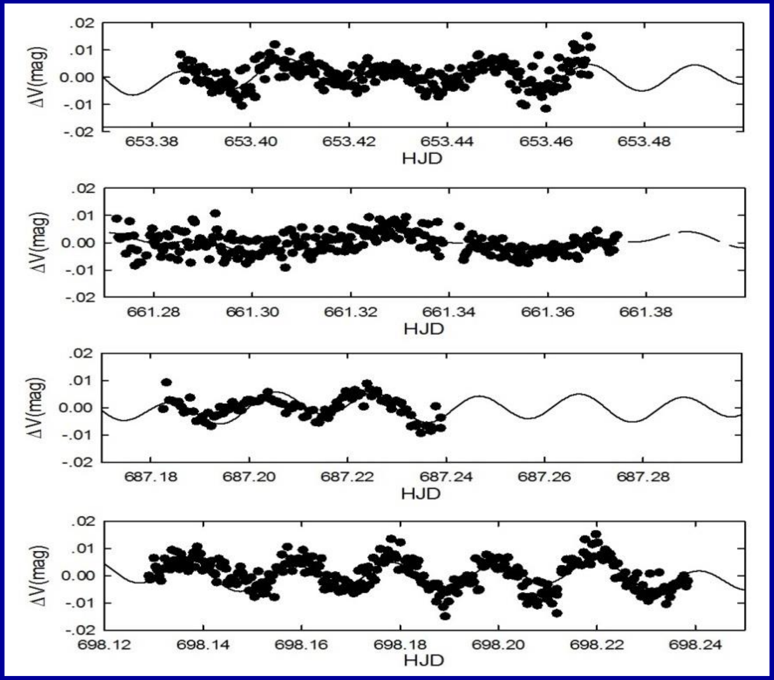


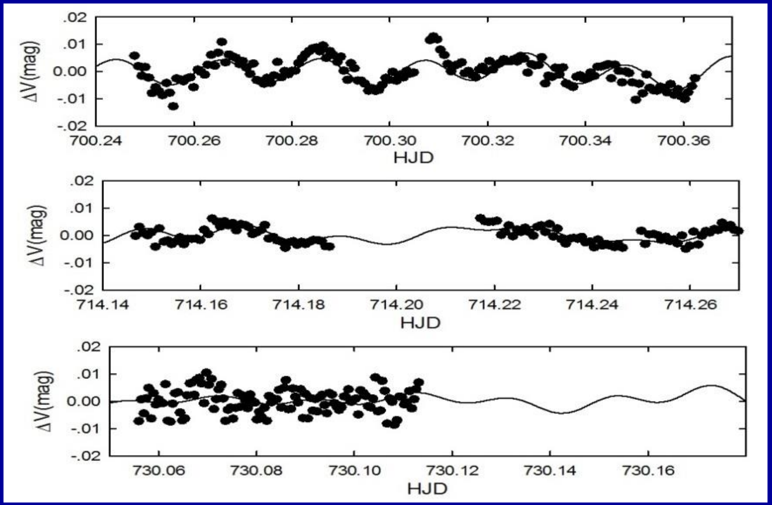
P_{puls}> 21min

The most remarkable peculiarity of oEA stars is co-existence of mass-accretion and pulsations, evolationary track along the MS

Typical light curves of oEA stars

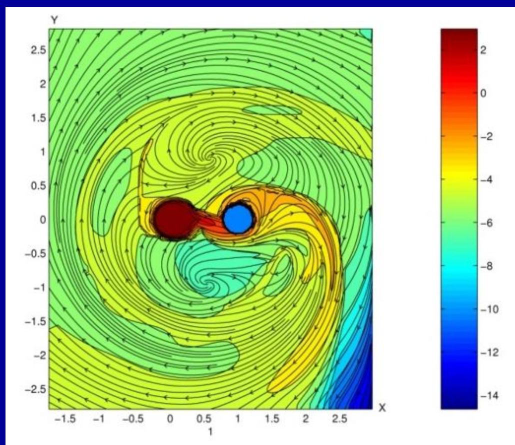


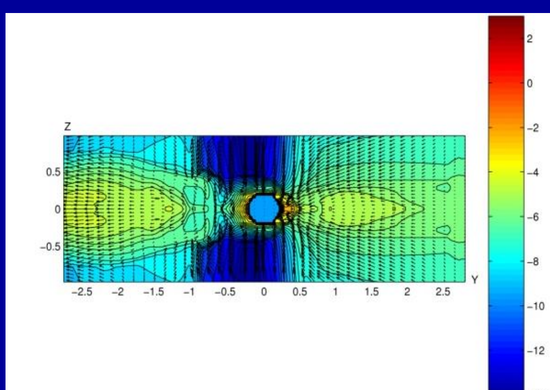


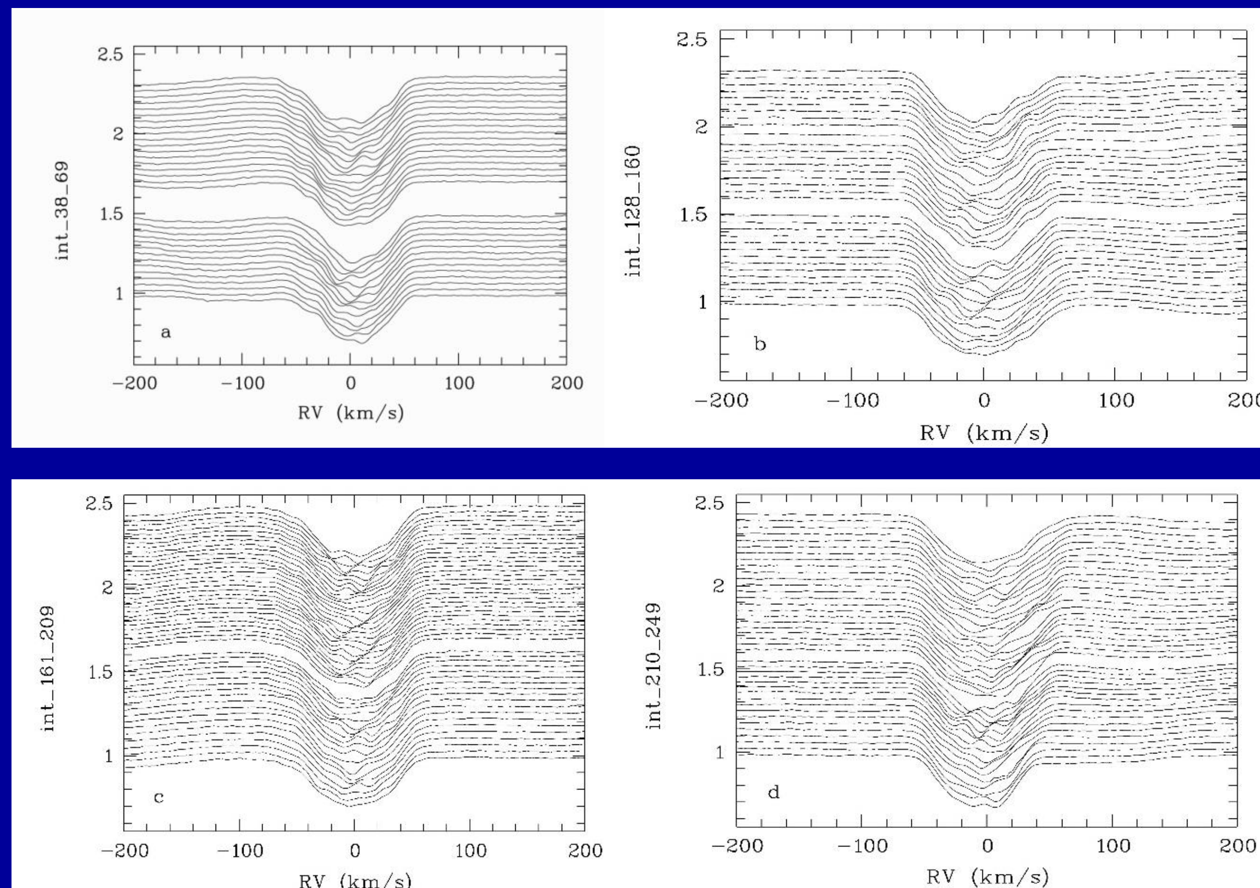


Light variations of the residuals after subtracting the binary curve from the data for each night.

High *l*-degree non-radial pulsations in TW Dra







3-D simulations of TW Dra
(Mkrtichian & Nazarenko, in prep.)

Observed NRP line-profile variations
Lehmann & Mkrtichian (in prep)

What is principally new with the oEA stars?

- Roche-lobe filling late type components could be magnetically active (radio and optical flares have been already registered)
- Magnetic activity of Roche-lobe filling star can trigger significant Roche-lobe overflow and force the high mass transfer/accretion events on the surface of pulsating star.
-

Hypothesis (Mkrtichian et al., 2002):

- Mass transfer/accretion bursts should force changes in the mean density of star and conditions in the outer envelope of oEA gainers and hence should influence on pulsations (amplitudes and periods)

- Thus, the oEA stars are unique stars that can abruptly changes their pulsation properties over the short time-scales

Reasons to study pulsations in oEA stars :

- **Eclipses can help to identify non-radial pulsations (NRPs)**
- **Mass transfer/accretion can influence on pulsation properties of gainers in Algols and hence can be quantitatively measured.**
- **Accretion driven differential rotation and its variation can be quantitatively measured**

New direction of studies

Dynamical asteroseismology

I. We can gain new knowledge <u>about pulsations</u> from studies of binaries with pulsators.

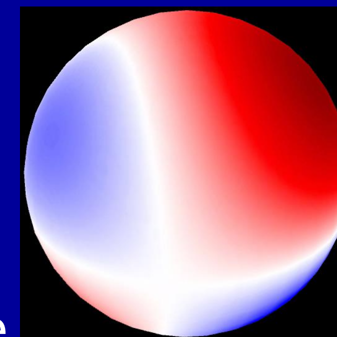
II. We can gain new knowledge <u>about binaries</u> from studies pulsators in binaries.

Part I. What new tools delivers eclipses for asteroseismic studies?

- Asteroseismology uses the information about oscillation spectrum for probing the internal structure of stars.
- Modern space telescopes data (KEPLER) led to revolution in our knowledge about oscillation spectrum (hundreds of detected modes per star)
- Very important, yet unsolved well problem in practical asteroseismology is an identification of Non-Radial Pulsation (NRP) modes
- **Why this problem is so serious?**

Non-radial pulsations

The amplitude of displacement or brightness variation in a pulsating star is described by spherical harmonics:

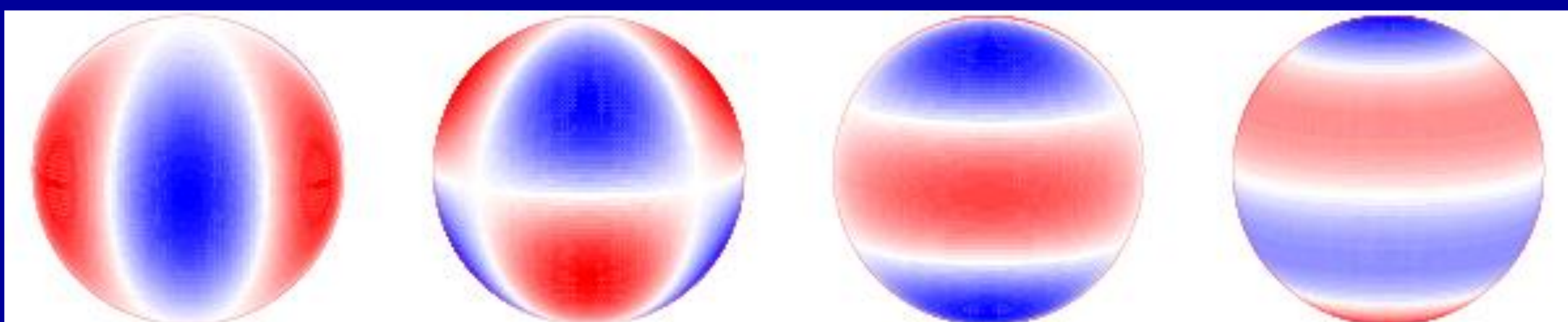


$$Y_l^{m}(\theta,\varphi)$$

degree l ⟶ total number of surface nodes

azimuthal order m ⟶ number of surface nodes in longitude

radial order n ⟶ number of nodes along the radius



l= 3; m = 3 | l = 3; m = 1 | l = 3; m = 2 | l = 3; m = 0

sectoral l=m modes

tesseral modes m<l

zonal modes m=0

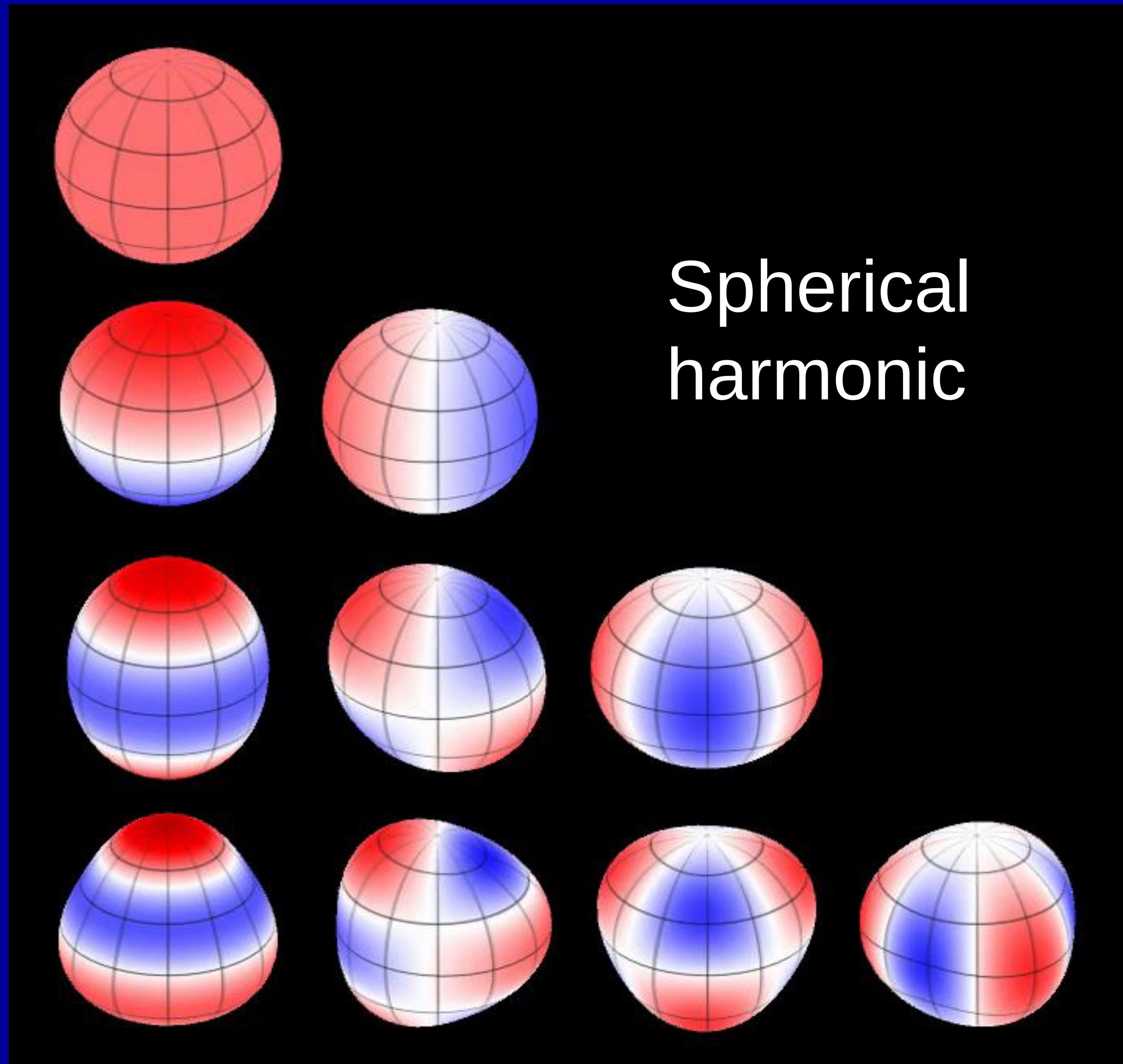
m= 0 ±1 ± 2 ± 3

l = 0

l = 1

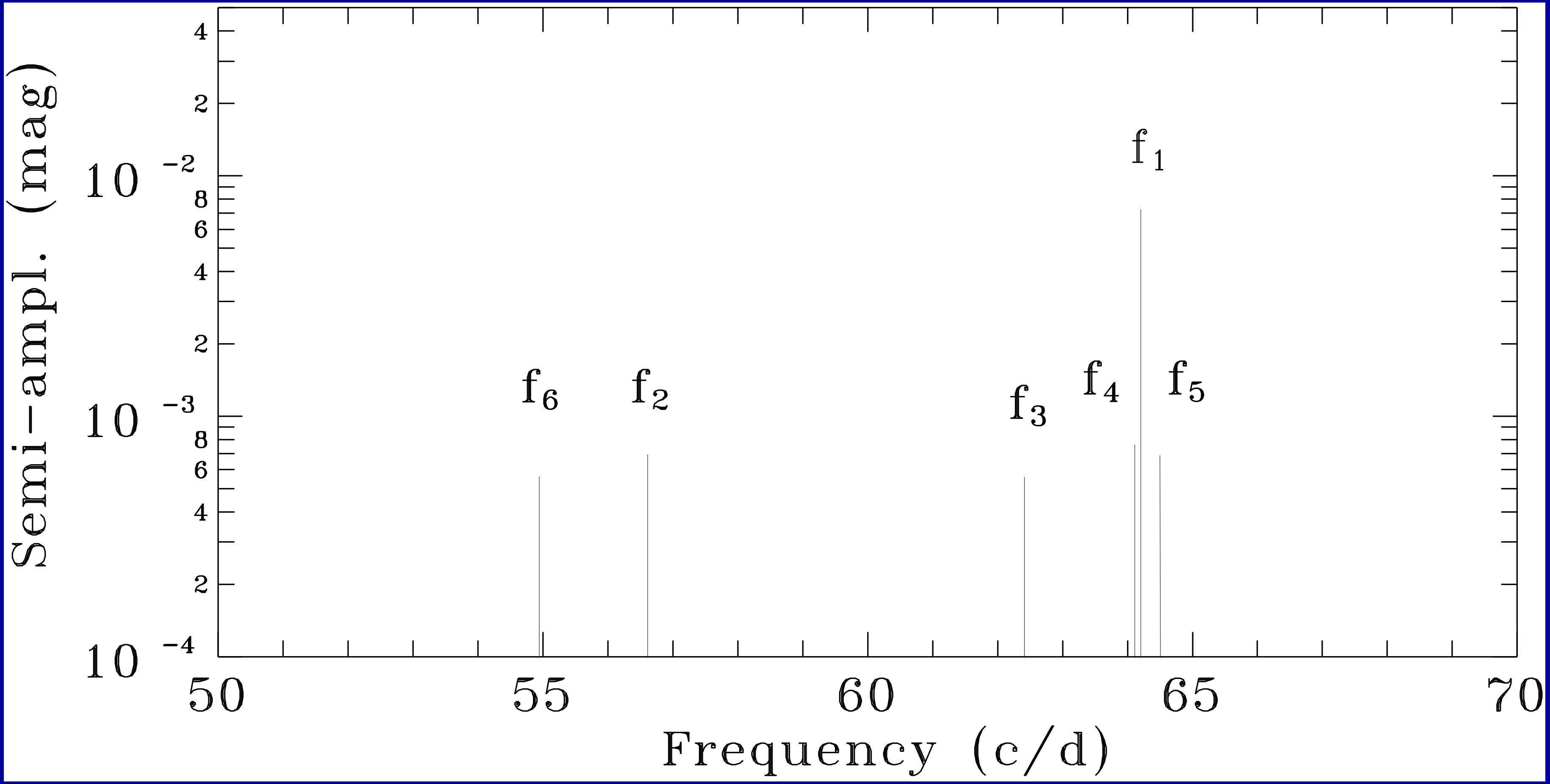
l = 2

l = 3



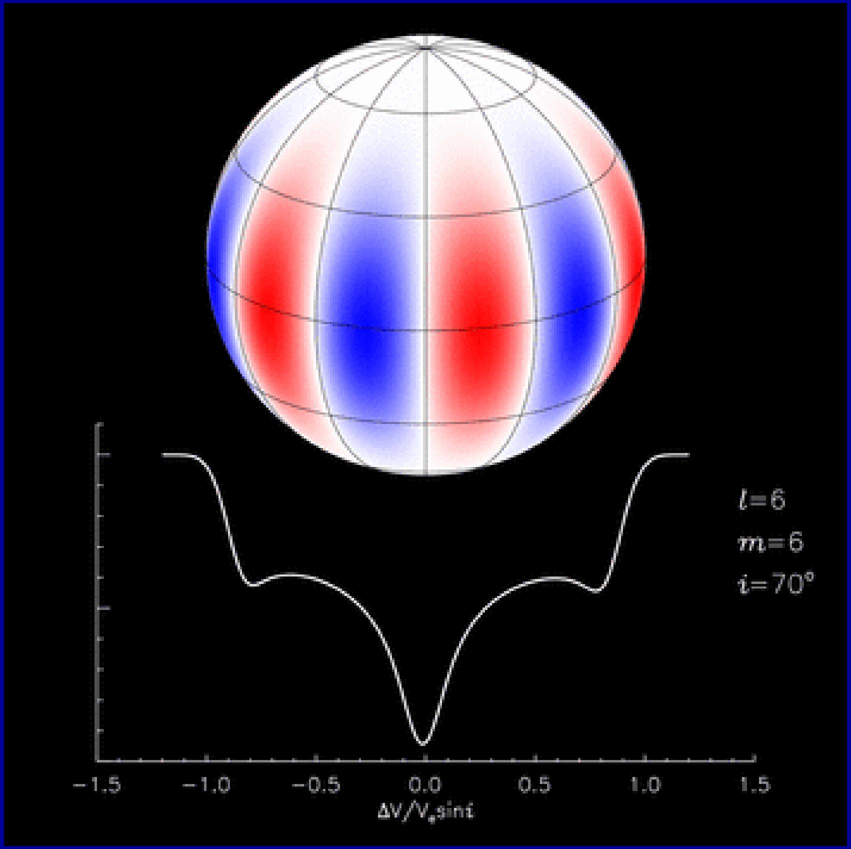
Observables (case of RZ Cas):

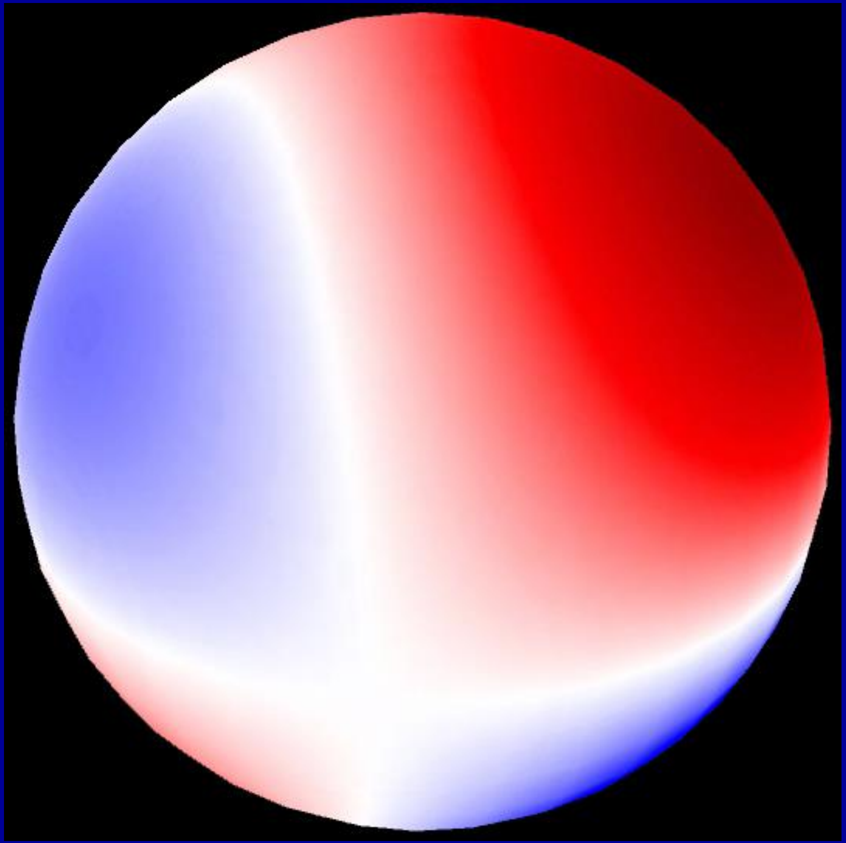
- Frequencies of modes, f_i
- Amplitudes of modes, A_i



Single mode l=6, m=6 pulsation

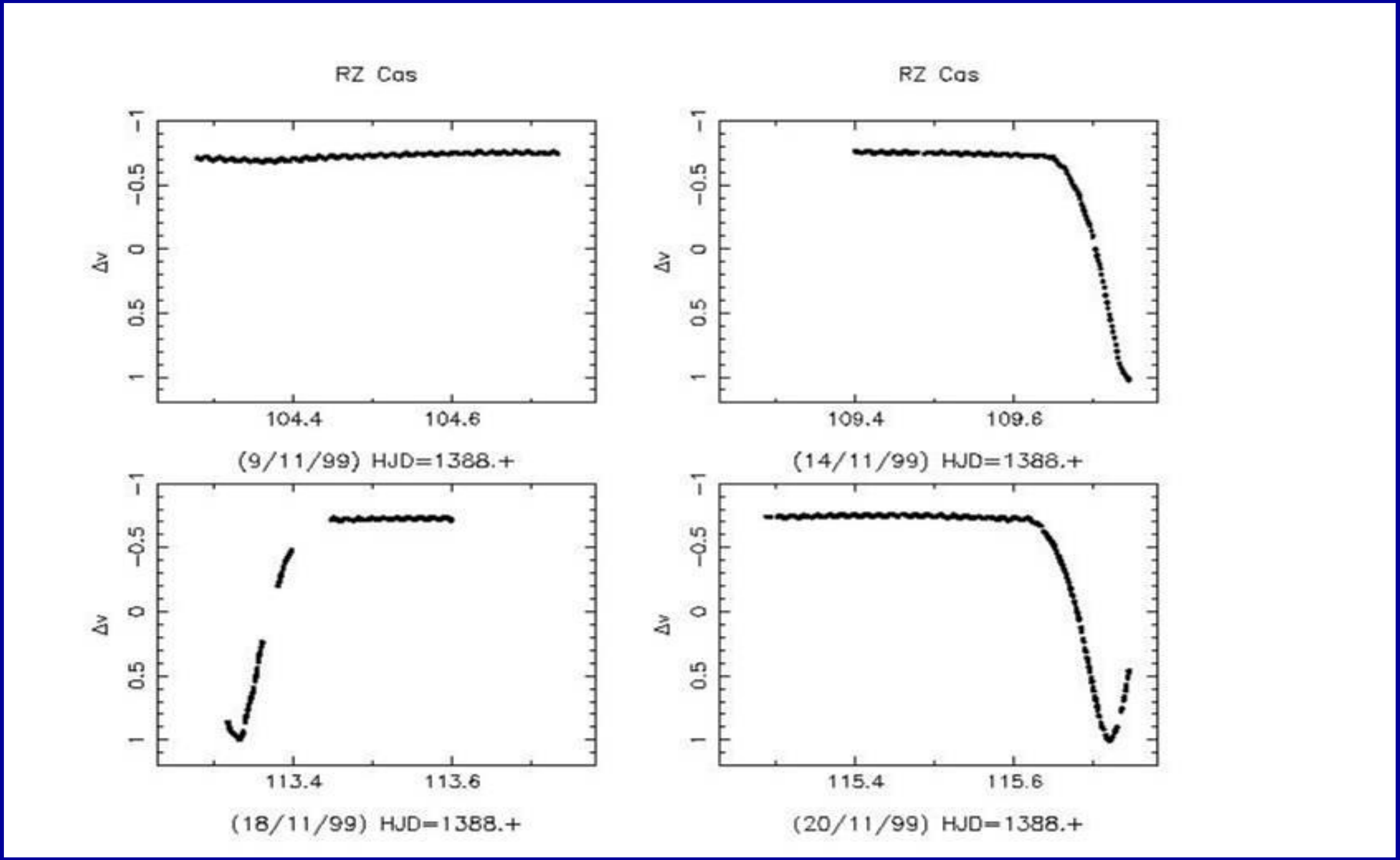
Multimode pulsations: scombination of many l,m integer values





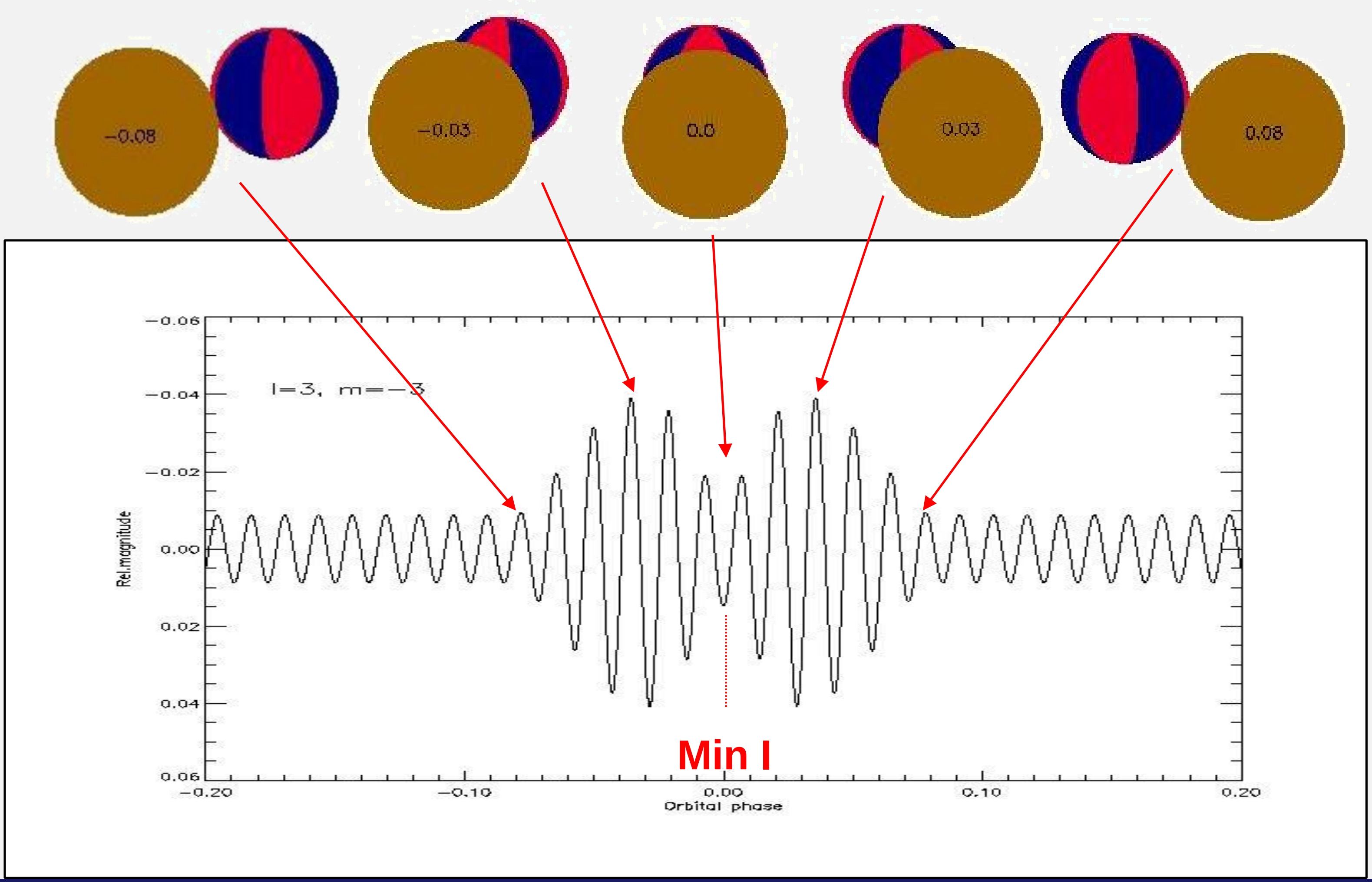
RZ Cas: Superposition of 3 modes:
l=2,m=-1, f1=62.2 c/d (22.4 min)
l=3,m=-2, f2=56.7 c/d (25.4 min)
l=1,m=0, f3=62.3 c/d (23.1 min)

Pulsation (22.4 min) + orbital (1.195d) light curves of RZ Cas



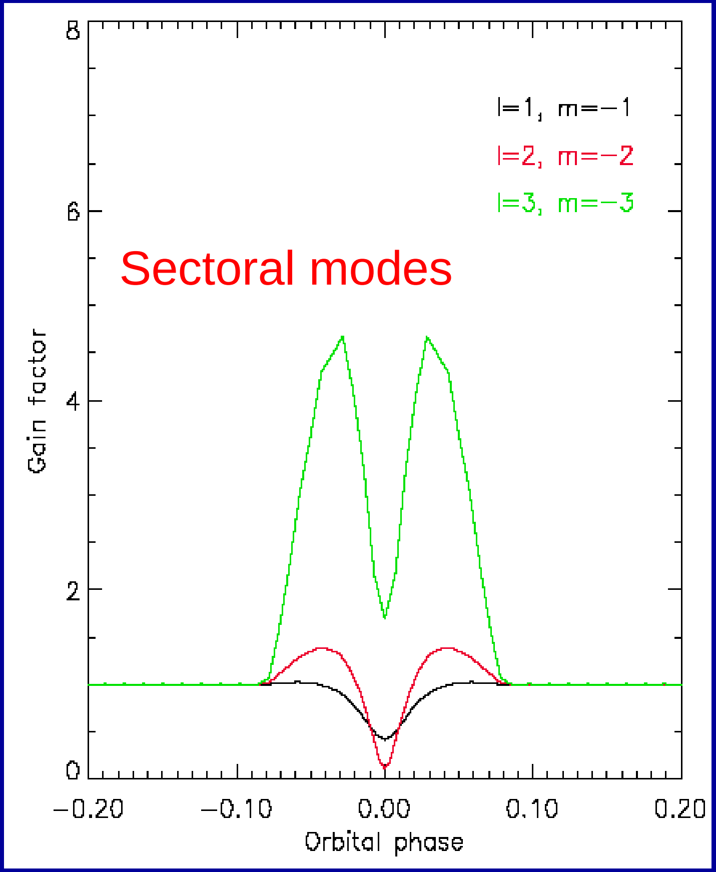
To study pulsations we need to extract the pulsation curve from orbital one

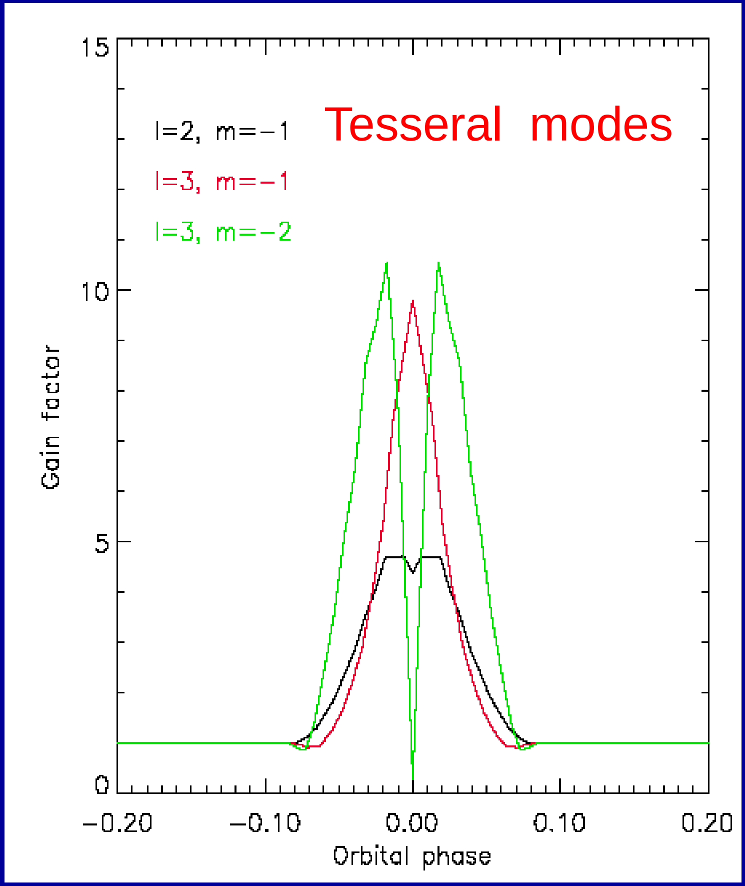
Modeling of Periodic Spatial Filters (PSF) (Gamarova & Mkrtichian, 2003):

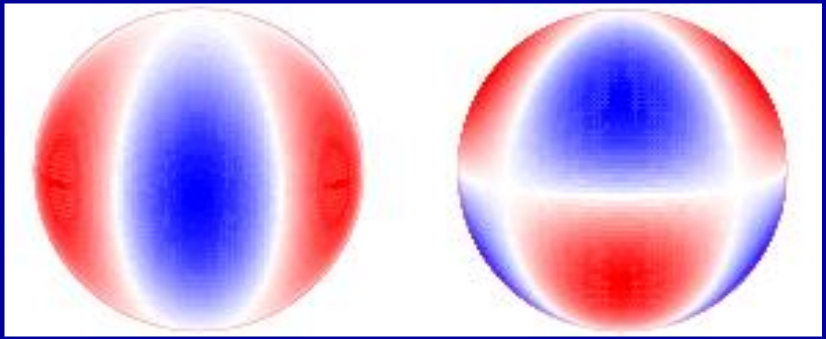


The eclipse effect on pure pulsational light curve for prograde NRP mode l=3, m=-3. Above the graph the different phases of eclipse are shown.

Gain (ϕ)= A(ϕ)/A(outside)

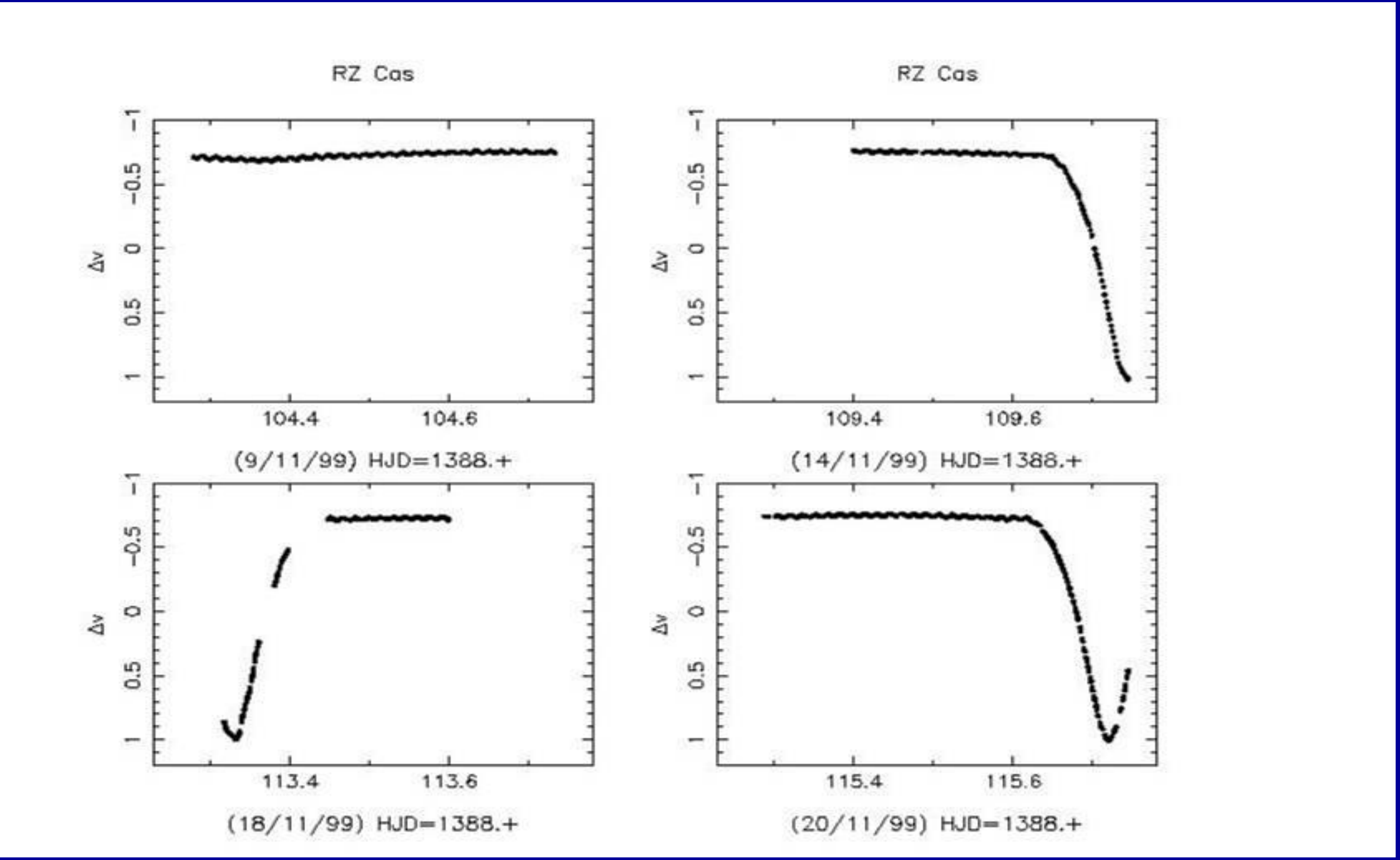






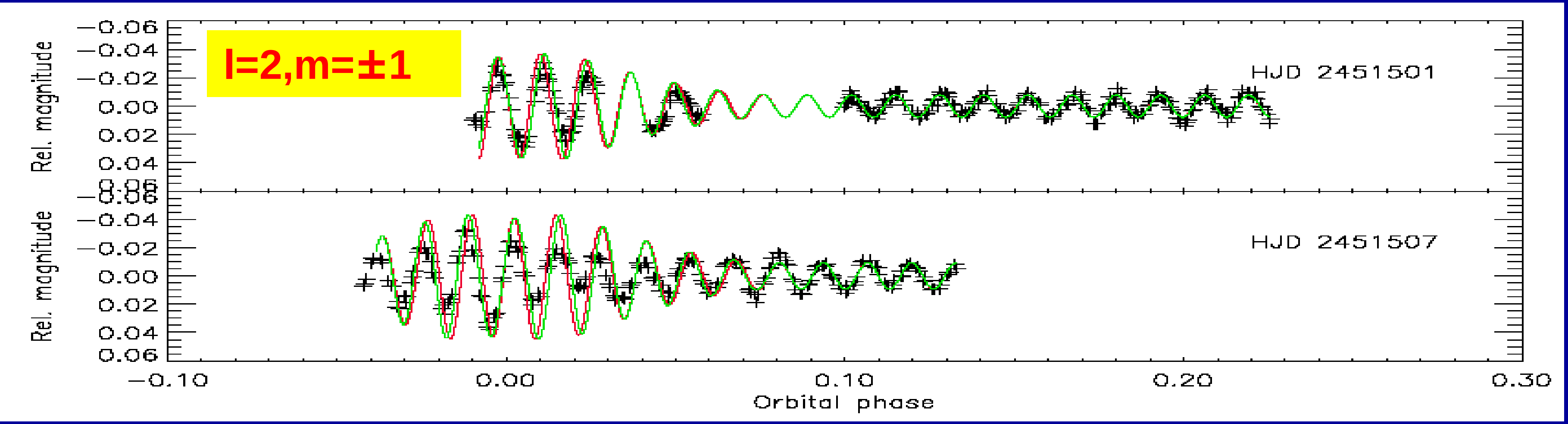
Tracking of pulsation amplitude changes during an eclipse help to identify mode

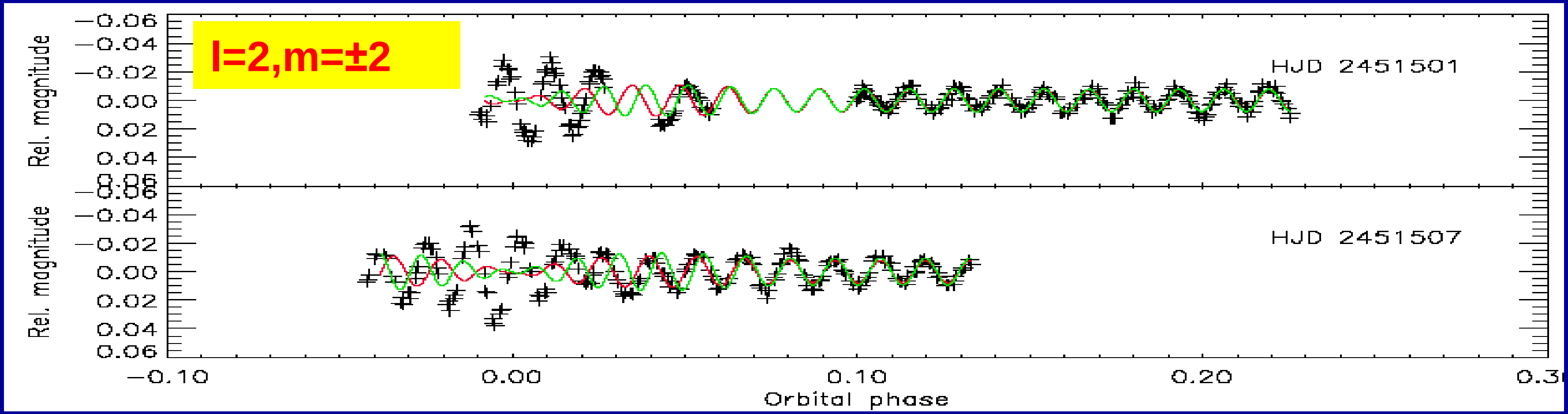
Pulsation (22.4 min) + orbital (1.195d) light curves of RZ Cas



To study pulsations we need to extract the pulsation curve from orbital one

Modeling of NRP PSF effects for RZ Cas system

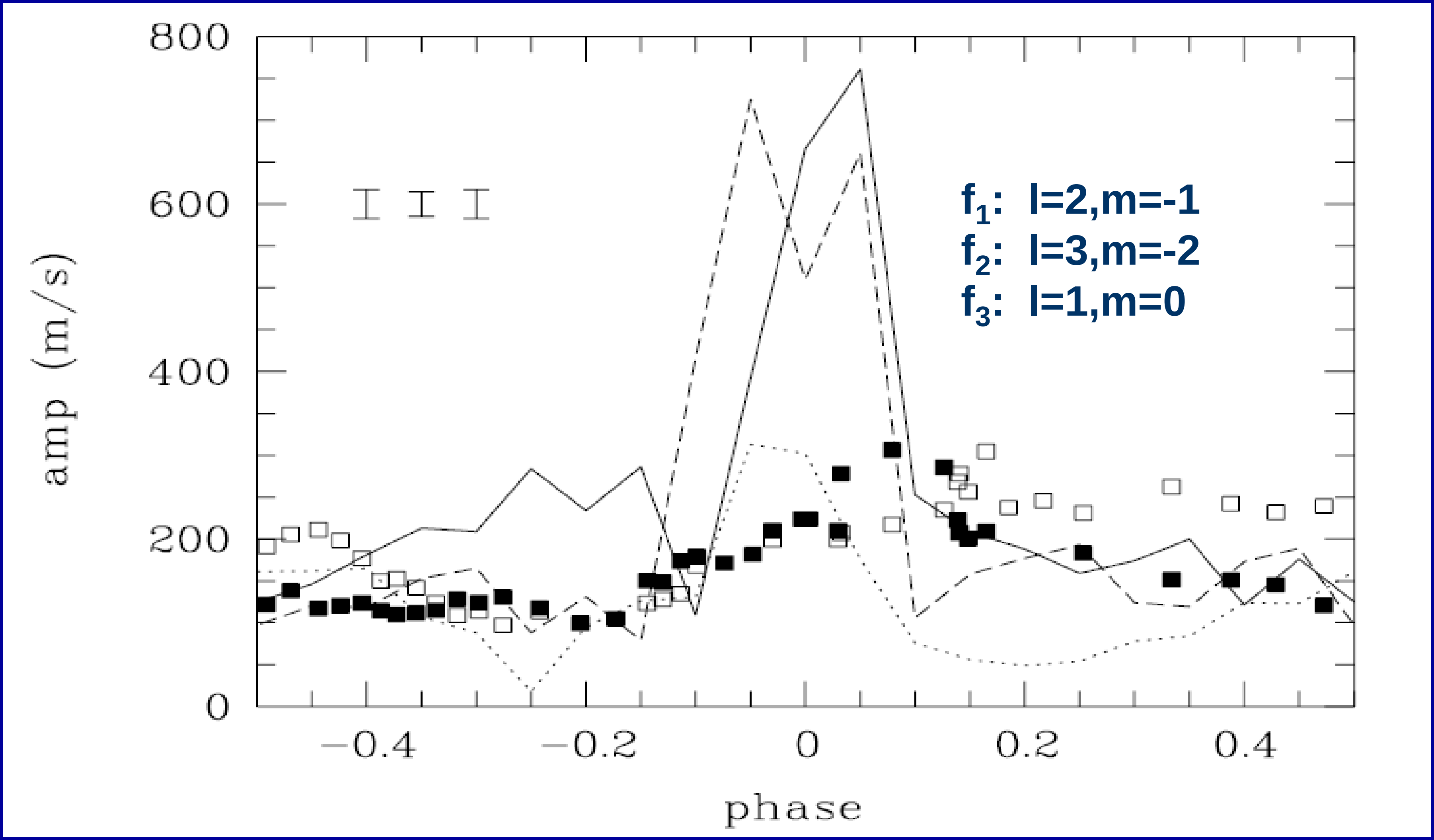




PSF-technique is promising to apply to KEPLER oEA stars

Spectroscopic PSF effect for amplitudes of non-radial modes in RZ Cas system (2001 & 2006)

(Lehmann& Mkrtichian, 2008)



Part II. What new tools asteroseismology provides for studies of binaries?

Problems to solve

•Rotation of components and asynchronicity problem.

•Origin of orbital period changes (likely caused by magnetic activity)

•Methods of detection of magnetic activity cycles and mass-transfer bursts (MTB)

•Accurate measurement of MTB-induced differential rotation

Reasons to use asteroseismology:

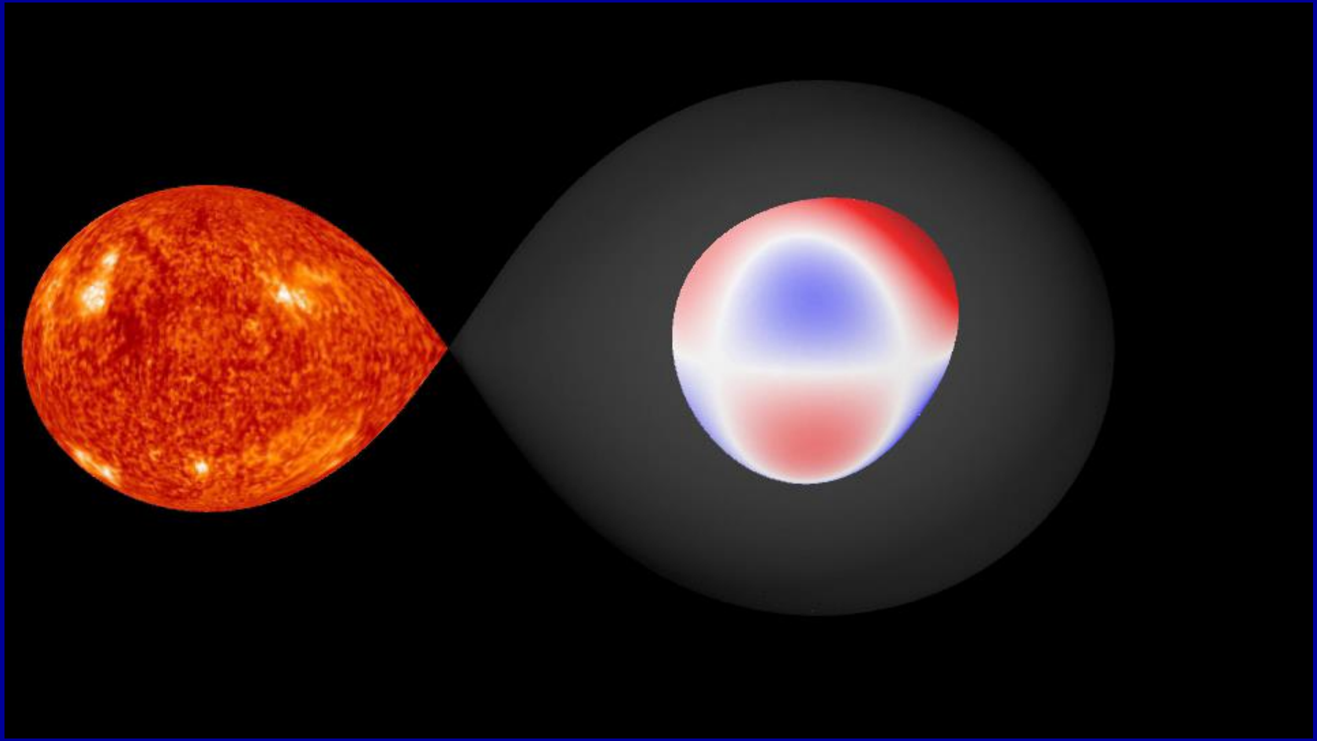
- Mass transfer/accretion can influence on pulsation properties of gainers in Algols and hence cold be quantitatively measured (via amplitude and spectrum changes)

- Accretion driven differential rotation and its variation in post-burst times can be quantitatively measured (via the frequency variations)

How to prove the effect of the mass-transfer on pulsations?

I. It is necessary to detect evidences of magnetic activity (direct effect or via orbital period variations)
II. To detect (spe.&phot.) facts of the mass transfer burst(s) forced by magnetic activity
III. To detect changes in pulsations
IV. To prove that magnetic activity and mass-transfer cause pulsation spectrum changes via the mass-accretion

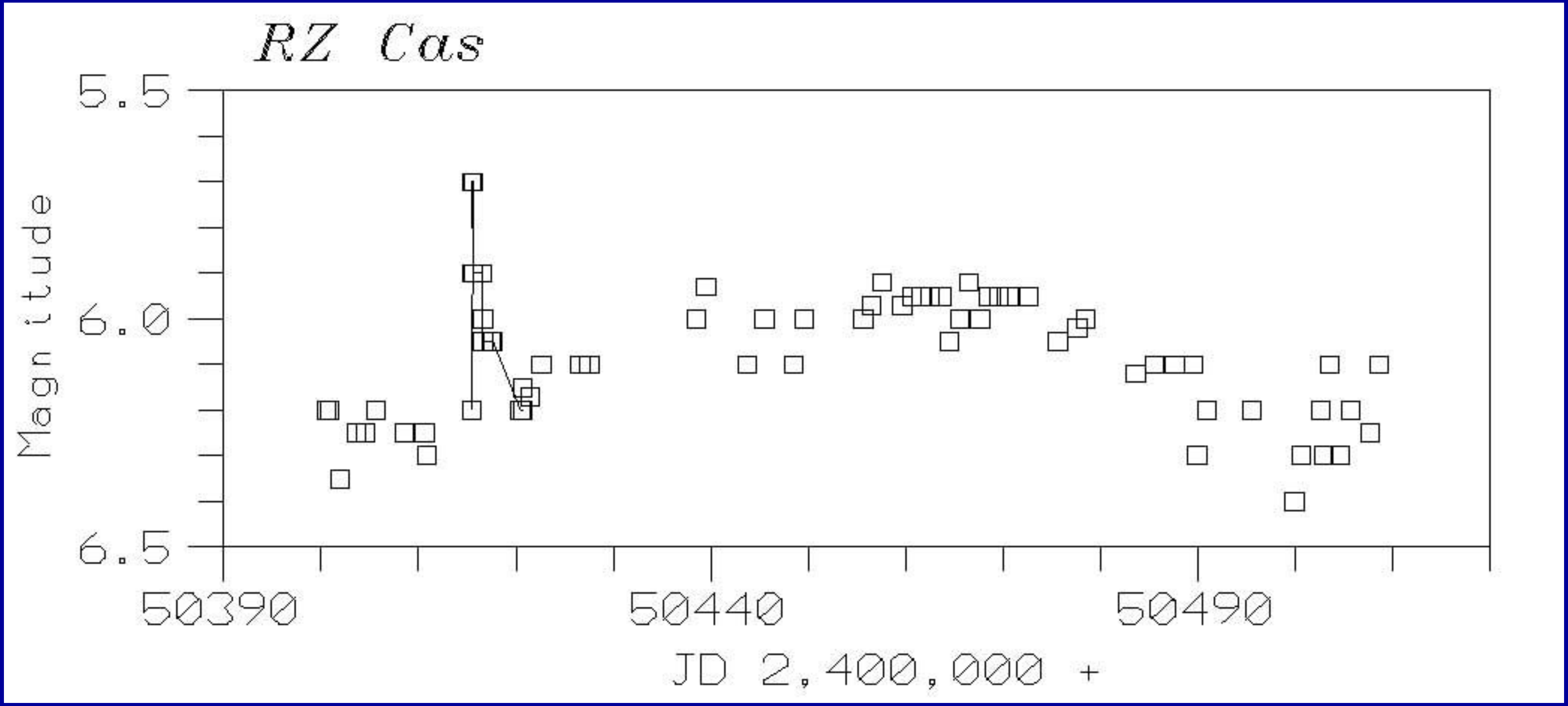
RZ Cas – the key oEA star for testing hypothesis of accretion-pulsation interaction



- Bright system: V~6.1
- Donor :   K0 III
- Gainer):   A3 V, rapidly oscillating & multi-periodic (22-26 min)

Active Algol system:

First detection of optical flare in RZ Cas system in 1997 (Lowder, 2006)



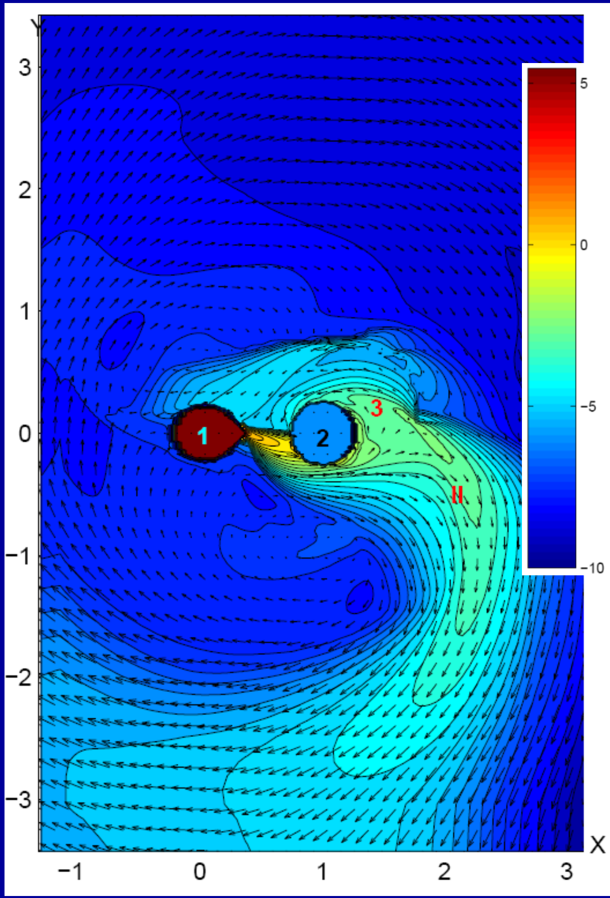
- Radio flares are common in Algols (Richards et al., 2003)
- RZ Cas is X-ray and radio flux variable

Search for evidences of the mass-transfer bursts

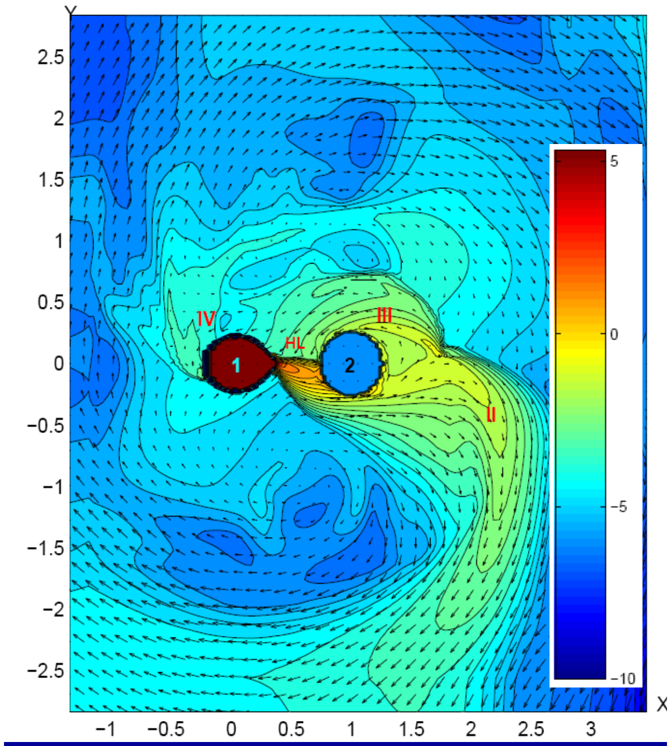
- Mass-transfer 3-D modeling (expectations)
- Photometric search
- Spectroscopic search

Grid of 3-D hydrodynamic simulations of mass transfer in RZ Cas (X-Y cross-section)

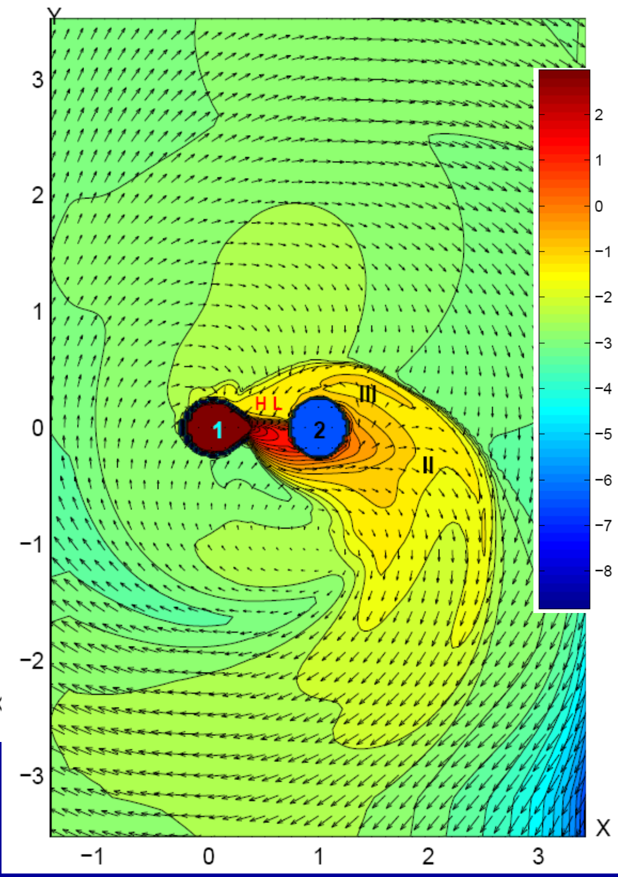
$dM/dt=10^{-10}\ M_{\odot}\,yr^{-1}$



$dM/dt=10^{-9}\ M_{\odot}\,yr^{-1}$

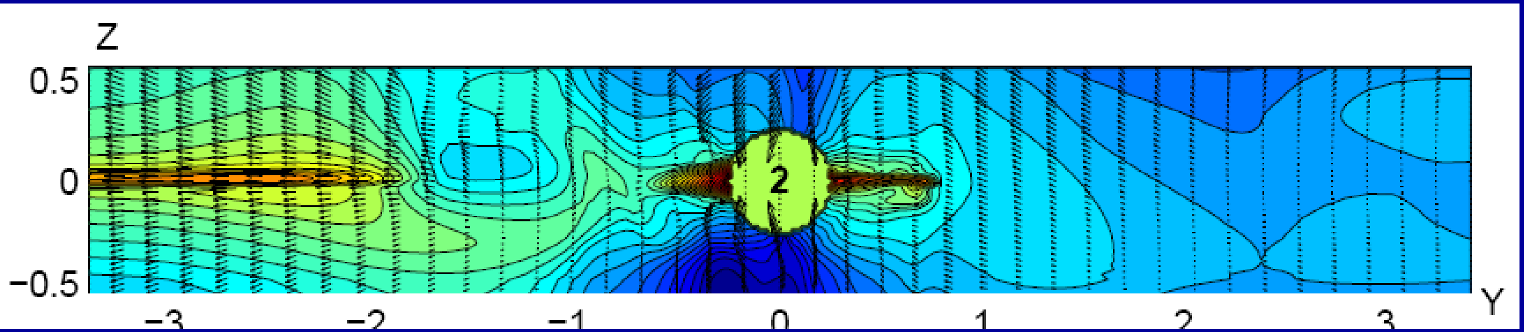


$dM/dt=10^{-6}\ M_{\odot}\,yr^{-1}$

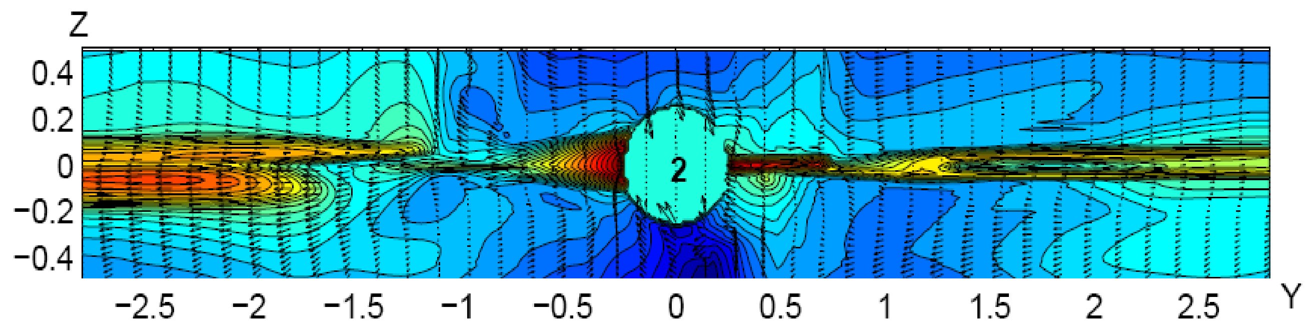


Mkrtichian & Nazarenko in prep.

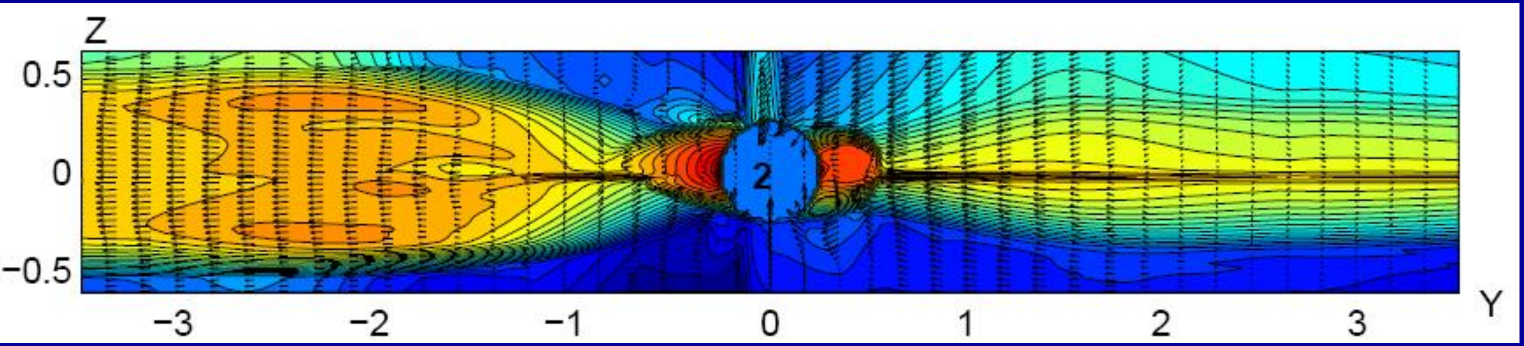
Equatorial gas “disks” Y-Z cross-section



dM/dt=10^{-10}

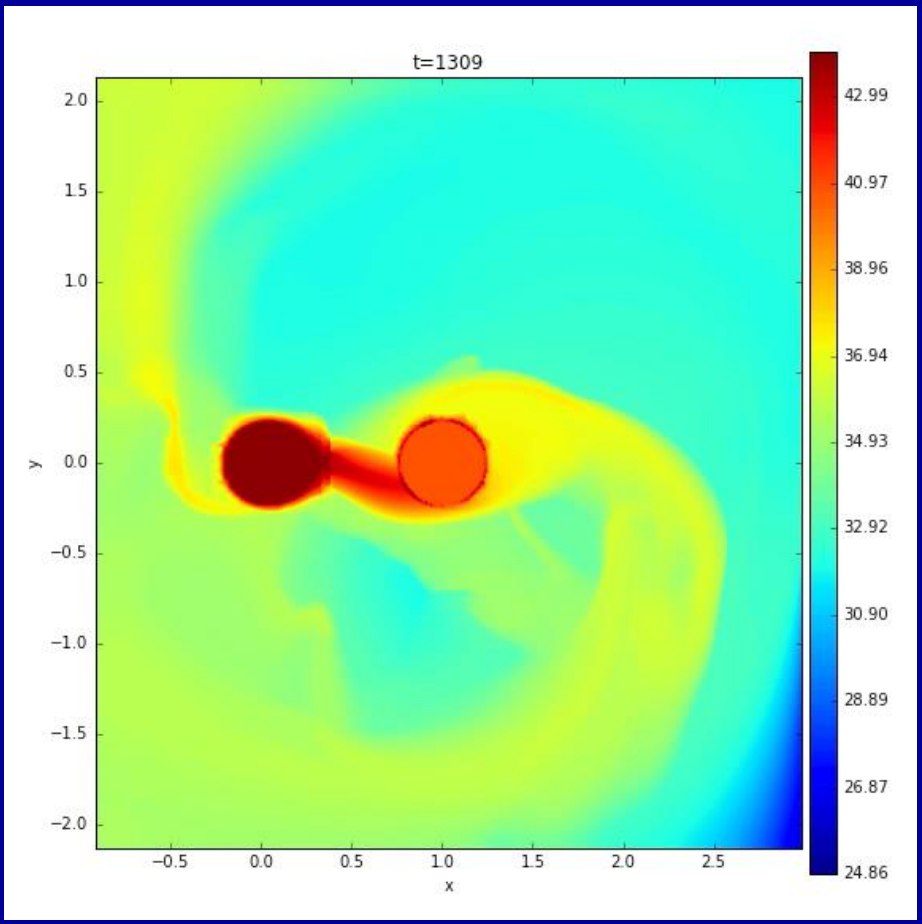


dM/dt=10^{-9}

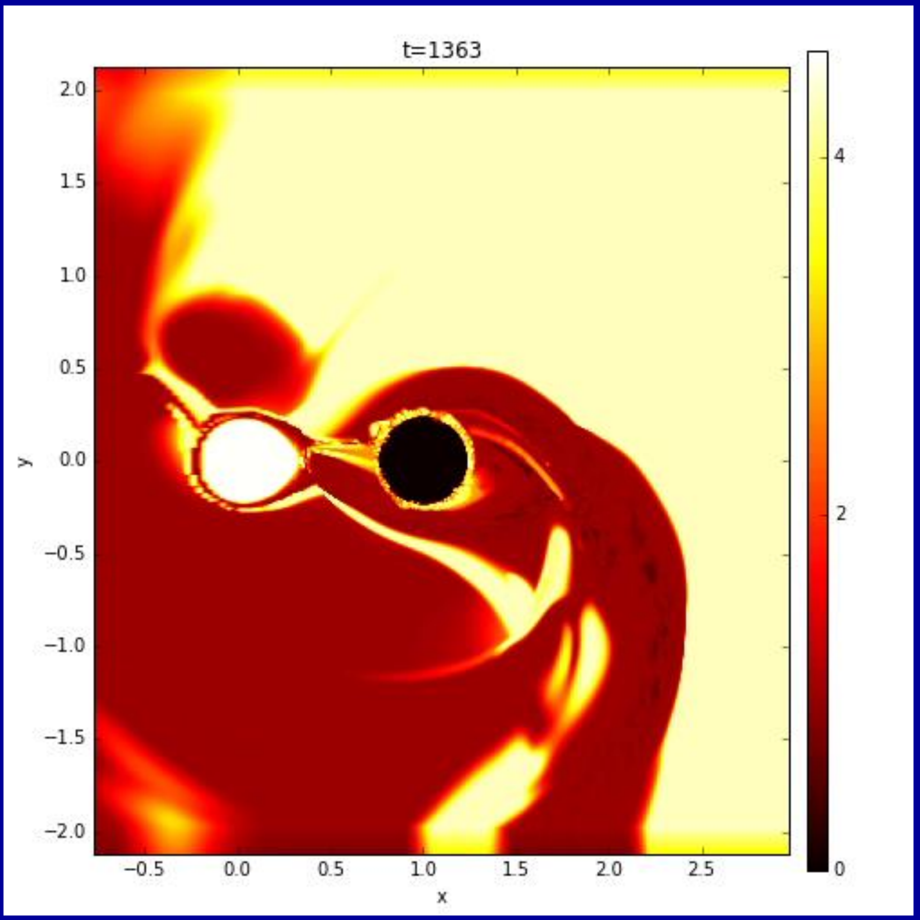


dM/dt=10^{-6}

3-D simulations (V. Nazarenko code)



Density



Temperature

Results from 3-D hydrodynamic simulations

- The RZ Cas system is direct gas-stream-star impact system - the surface of gainer should accelerate during high mass transfer episodes

- The mass transfer at slow-mass transfer stage is conservative ($M_{loss}/M_{tr}<10^{-3}$)
- Changes in mass-transfer rate leads to changes in a structure and a density of circum-binary gas environment, and hence, should have variable influence on observables(screening etc.)

Ondjeov Obs.

14 years of oEA and RZ Cas observations:

TLS

Spectroscopy

2001, N= 962 spectra,

2006 , N= 498 spectra

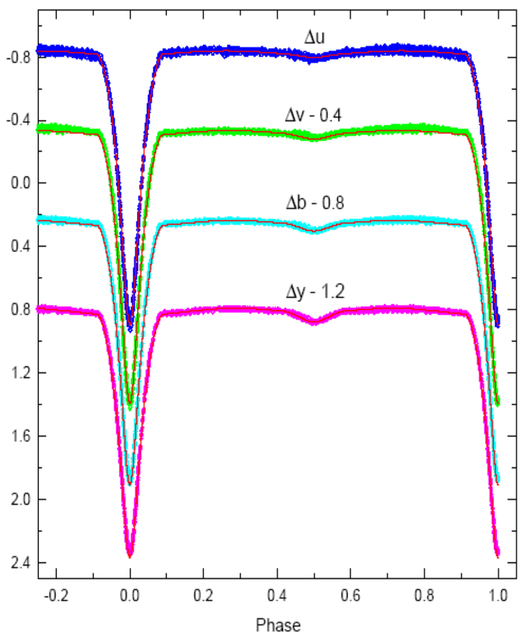
2007 – 2014 , N~ 1000

Peak Terskol Obs.

NARIT

- 2.0m tel., TLS, Germany
- 2.0m PTO, Ukr./Russia
- 2.0m OO, Czech Rep.
- 2.6m CrAO , Ukraine
- 2.4m NARIT, Thailand
- 1.5m, Spain

Simultaneous photometric and spectroscopic orbital solution with using WD code



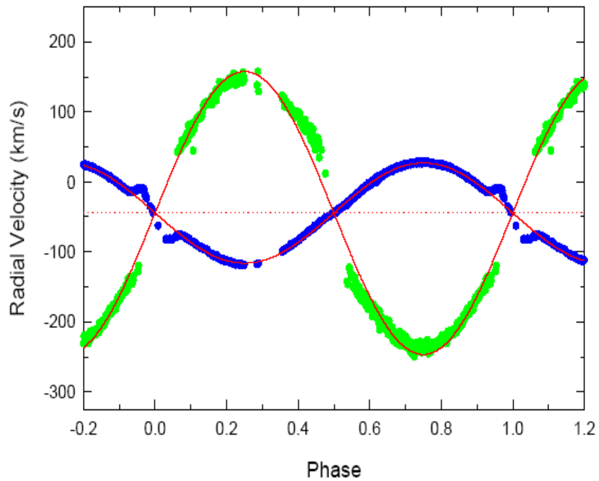
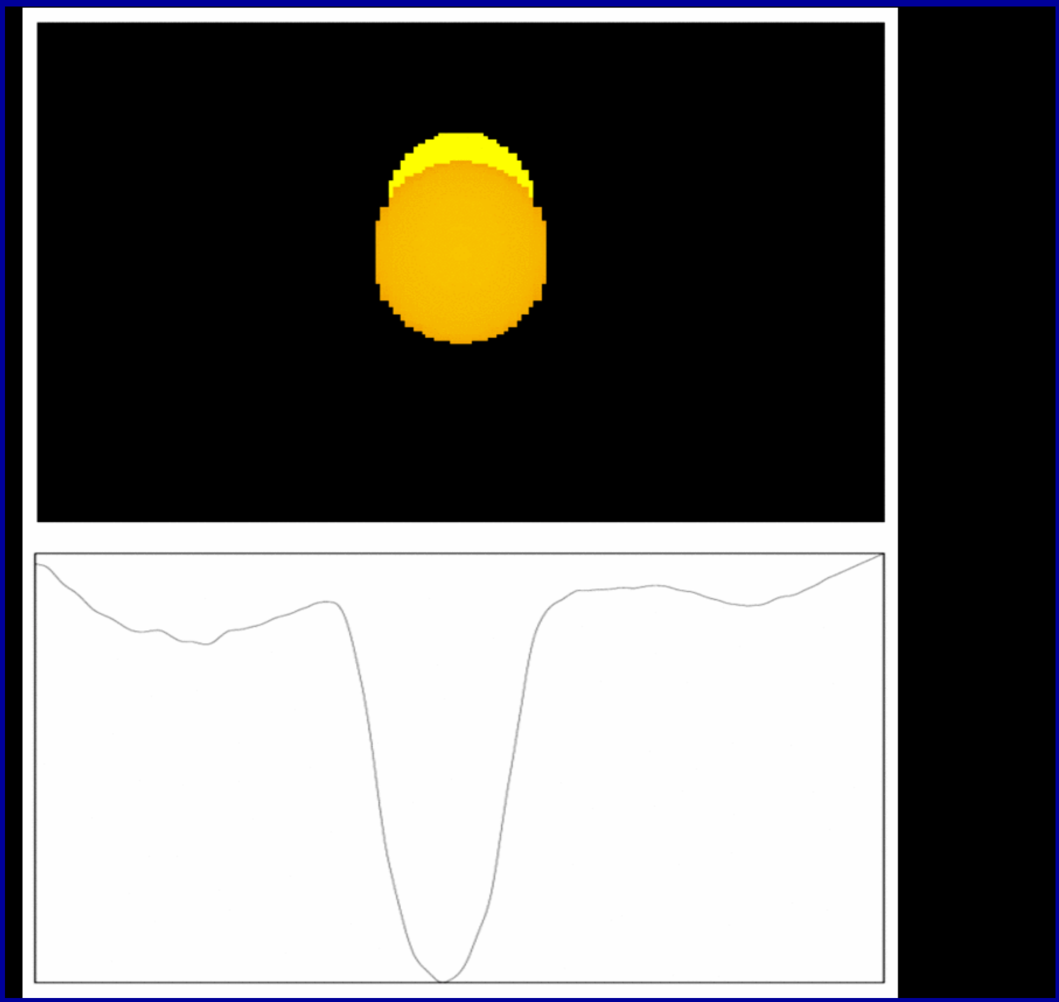


Table 2: Absolute parameters of RZ Cas.

Parameter	Primary	Secondary
$M/M_{\odot}$	1.924(23)	0.682(8)
$R/R_{\odot}$	1.647(6)	1.909(5)
$logg$ (cgs)	4.288(7)	3.710(8)
$T(K)^{a}$	8600(100)	4442(200)
$L/L_{\odot}$	13.3(1.7)	1.27(23)
$M_{\rm bol}$ (mag)	1.88(5)	4.43(20)
B.C. (mag)	-0.02	-0.64
MV (mag)	1.90(5)	5.09(20)
Distance (pc)	73.4(2.2)	

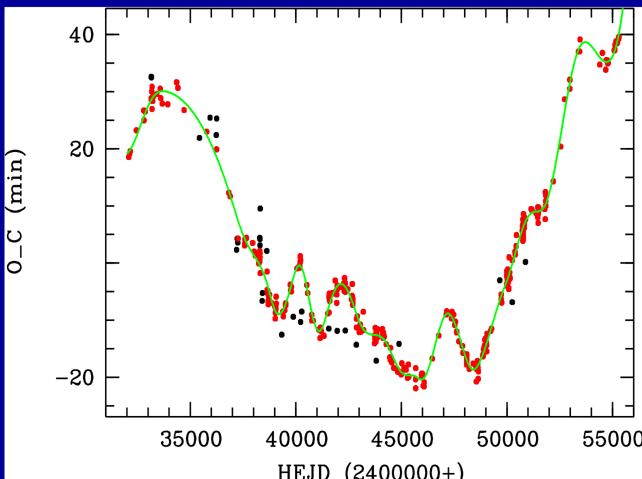
Updated spectroscopic solution for RZ Cas system with SHELLSPEC-INVERSE (Tkachenko, Lehmann & Mkrtichian, 2009)

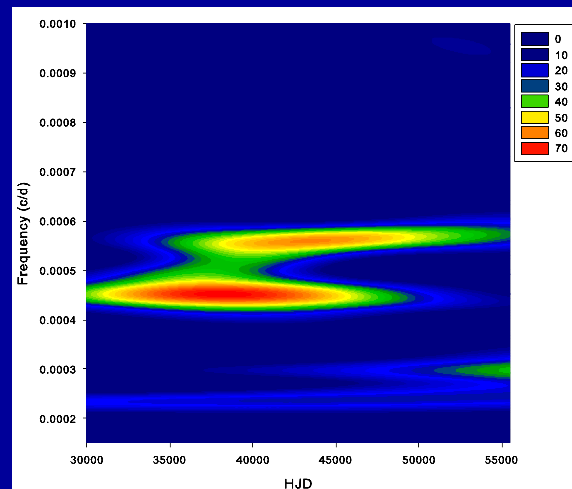


Potentially, we want to d include 3-D simulations to a SHELLSPEC code by

(Budaj & Richards)

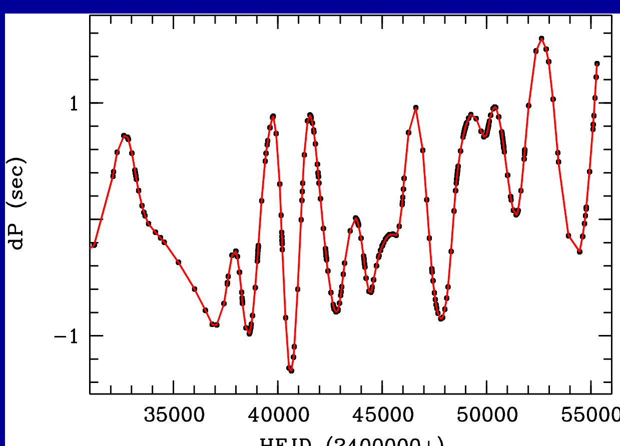
Detection of ~6-9 year cyclic variations of P(orb) most likely caused by magnetic activity cycle of a donor star

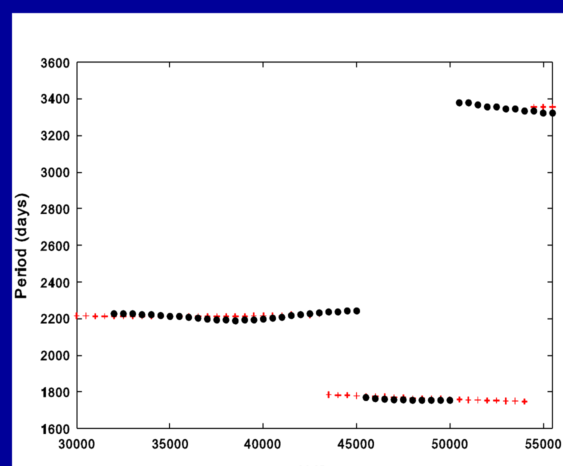




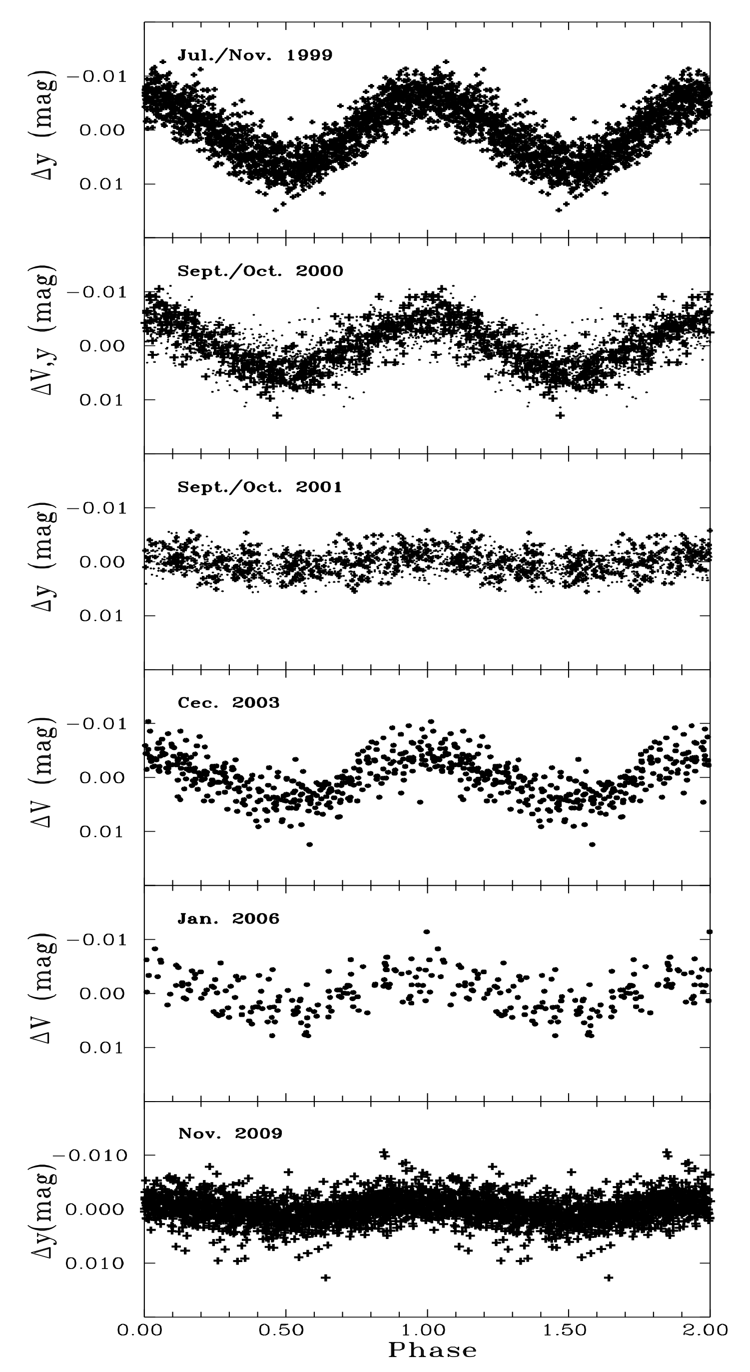
Wavelet analysis

	f ($c\,d^{-1}$)	Period (d)	Period (yr)	Amplitude (sec)	Interval JD
			DFT		
f1	0.000561(1)	1782(3)	4.85(4)	0.42(2)	30000-55500
f2	0.000442(1)	2262(5)	6.15(6)	0.34(2)	-
f3	0.000298(2)	3356(22)	9.22(3)	0.31(2)	-
f4	0.000374(2)	2674(14)	7.32(3)	0.24(2)	-
			WWA		
f1	0.000568(1)	1758(5)	4.81(1)	0.39(1)	43500-54000
f2	0.000451(3)	2215(16)	6.06(5)	0.49(5)	30000-42500
f3	0.000298(1)	3348(20)	9.16(6)	0.41(4)	54500-55500





Skeleton of Wavelet periods



1999

2000

2001

2003

2006

2009

Detection of 8-9 year seasonal variation of amplitude of the the dominant

f=64.14 c/d (P=22.4 min) mode

This is exactly the duration of the last magnetic cycle.

The modal pulsation amplitude reduction could be caused by a mass transfer bursts in 2000/2001 and in 2009

RZ Cas: Excitation of high-degree NRP modes

Lehmann & Mkrtichian, in prep.

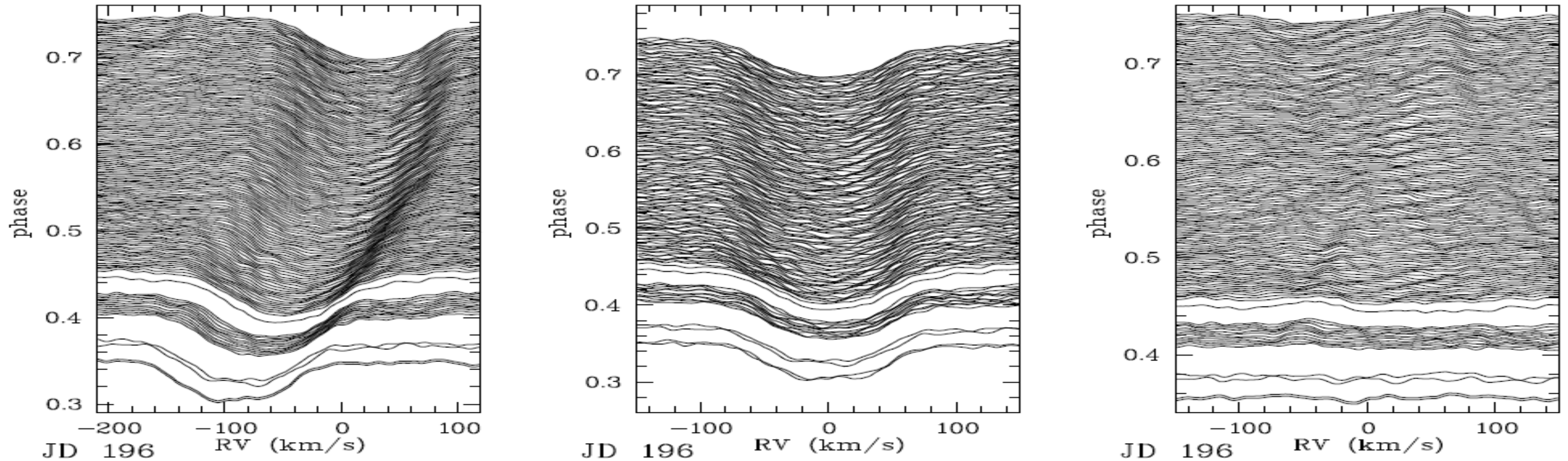


Fig. 1. LSD profiles of RZ Cas from one run (JD 2 452 196) in 2001. Mean exposure time of 150 sec. Profiles are vertically sl
according to the position in orbital phase. From left to right: Original profiles, corrected for orbital motion, and differential profil

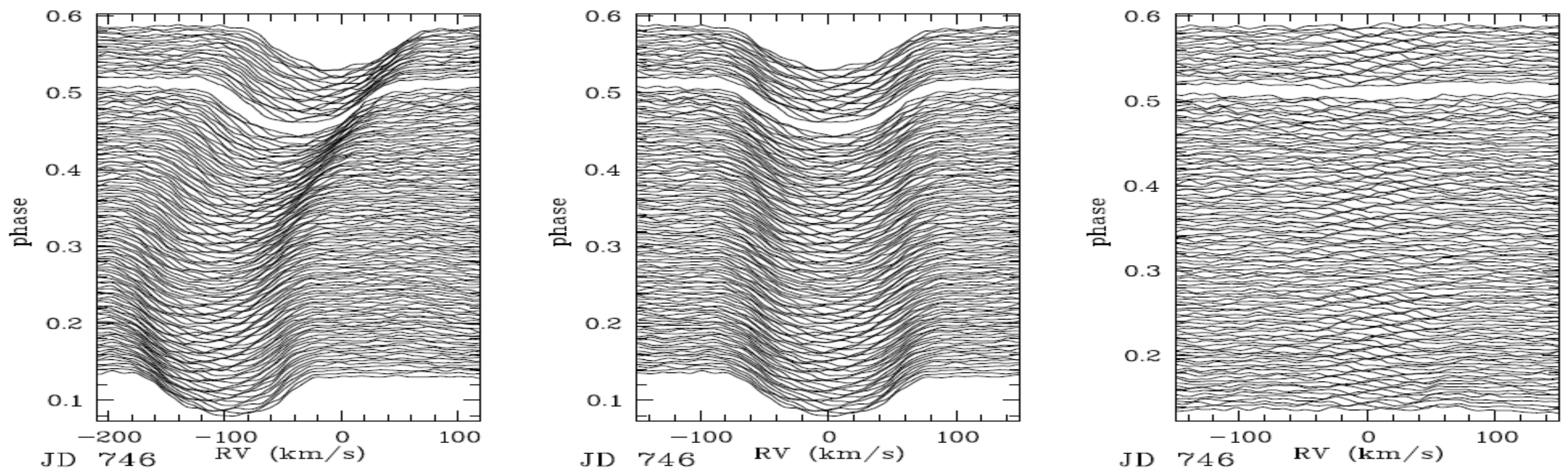


Fig. 2. As Fig. 1 but for one run (JD 2 453 746) in 2006. Mean exposure time of 300 sec.

2-D and 1-D DFT analyses

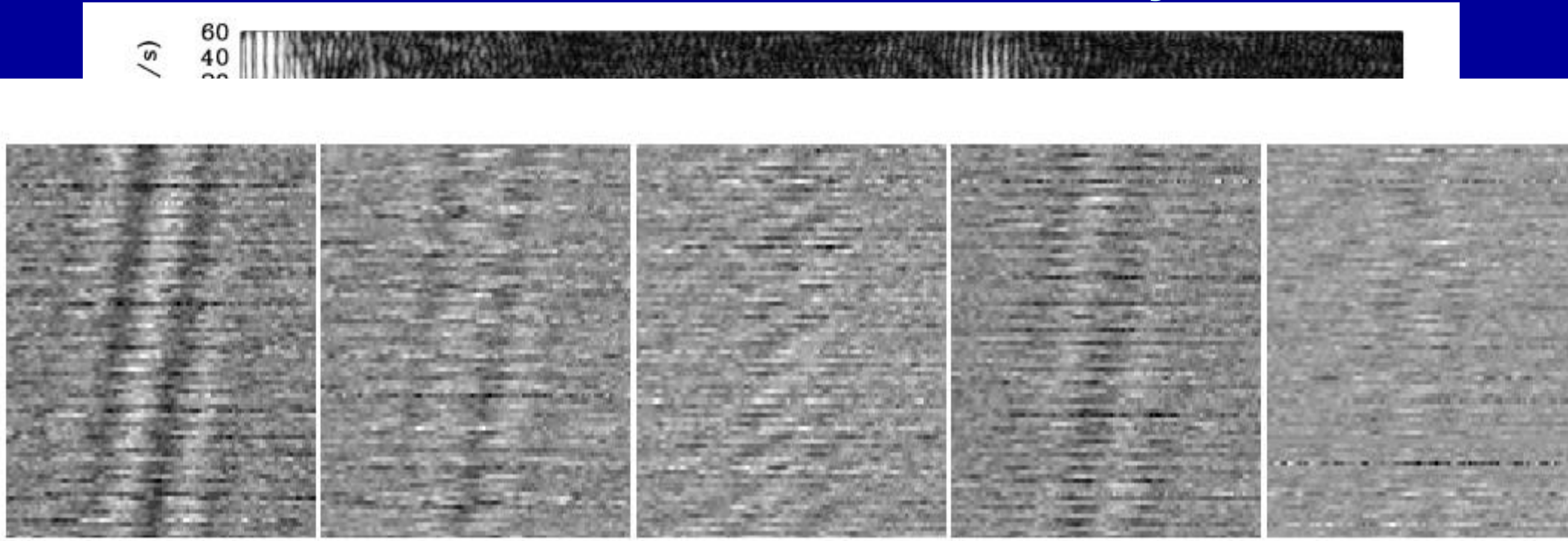
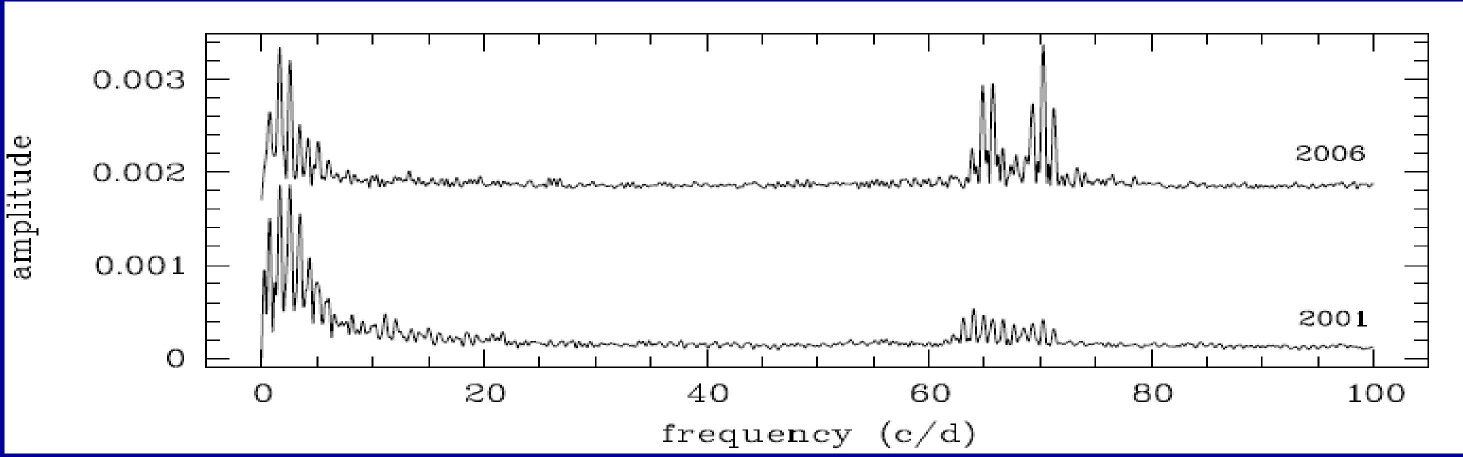
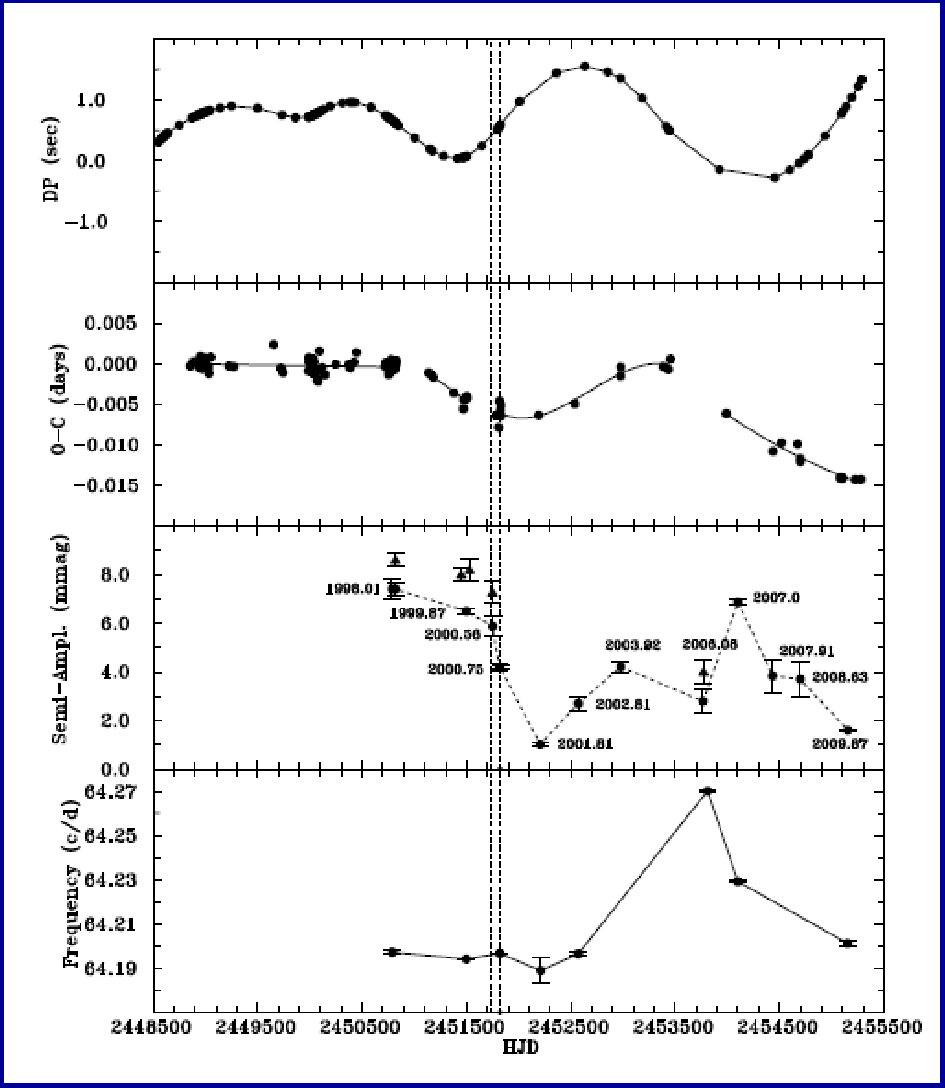


Fig. 7. Differential LSD profiles folded with f_1 to f_5 (from left to right, respectively). The vertical axis gives the corresponding oscillation phase from 0 (bottom) to 1 (top). In each panel, the horizontal axis spans $-100\ \mathrm{km\,s^{-1}}$ (left) to $+100\ \mathrm{km\,s^{-1}}$ (right).



The first detection of simultaneous (accretion driven) abrupt changes in the orbital period and pulsation spectrum of RZ Cas



Detection of orbital period jump

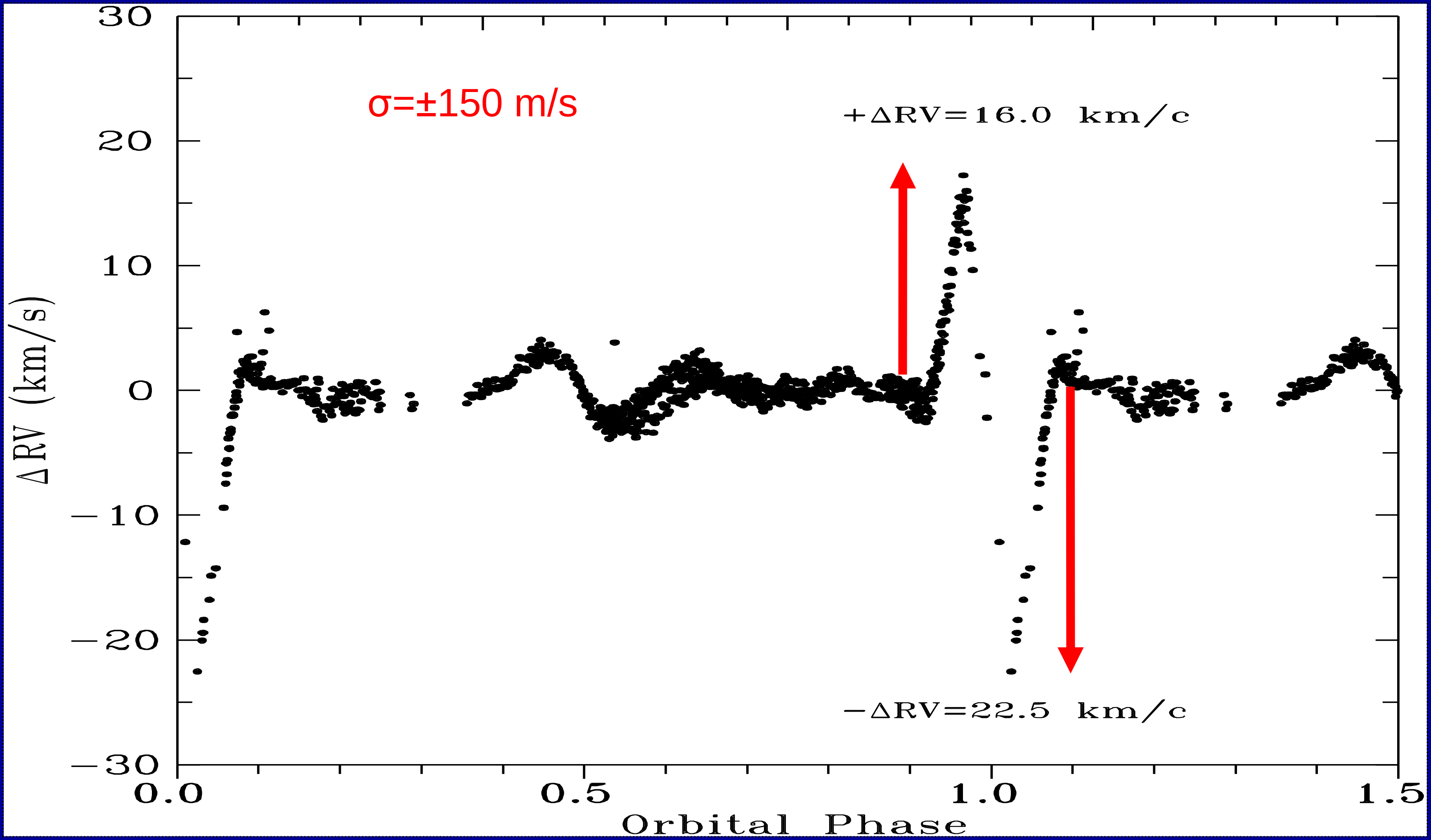
Detection of O-C jump

1.6 10^{-6} Mo / yr

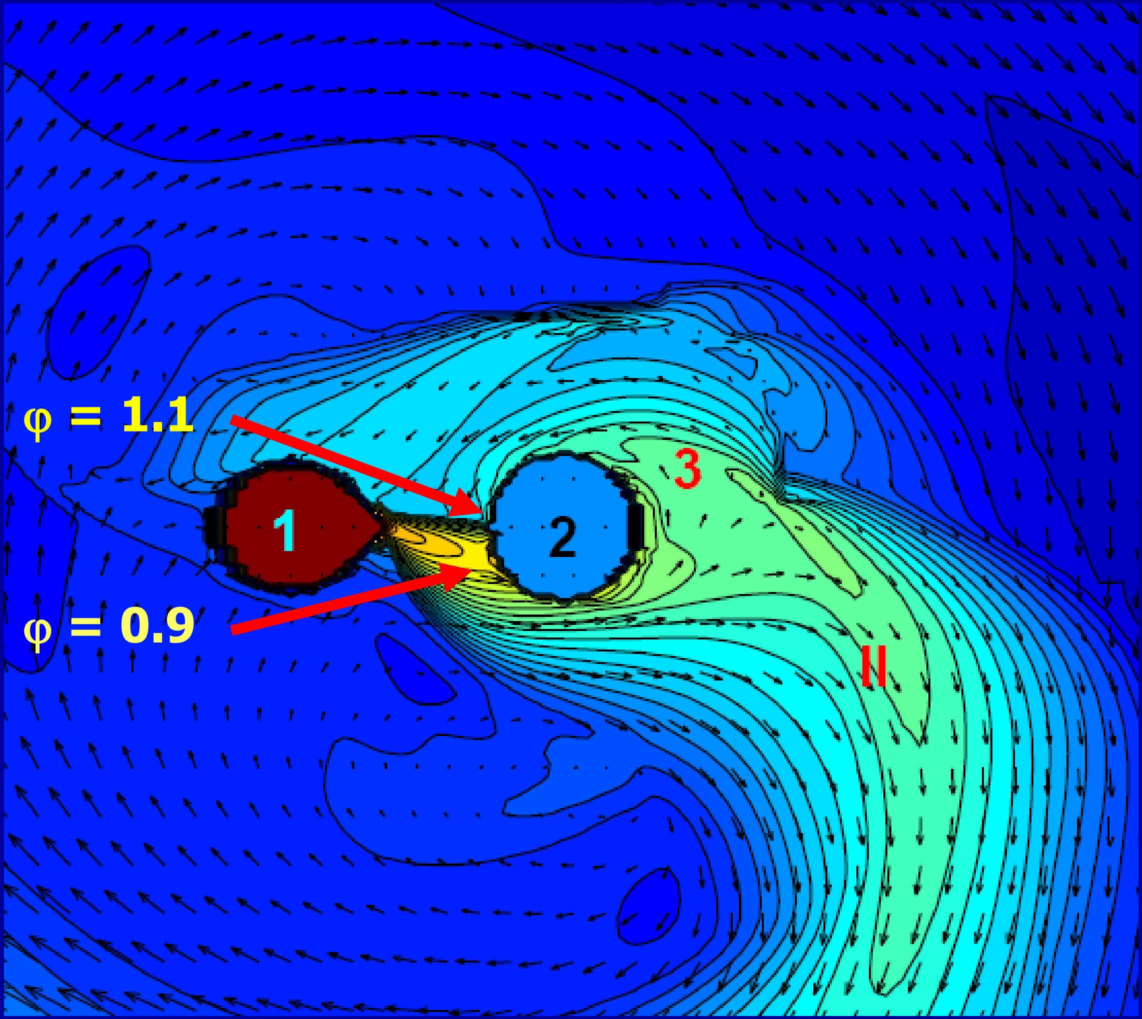
Detection of amplitude variations

Detection of frequency variations

Optical effect of HMTB and detection of asymmetric Rossiter effect in 2001:

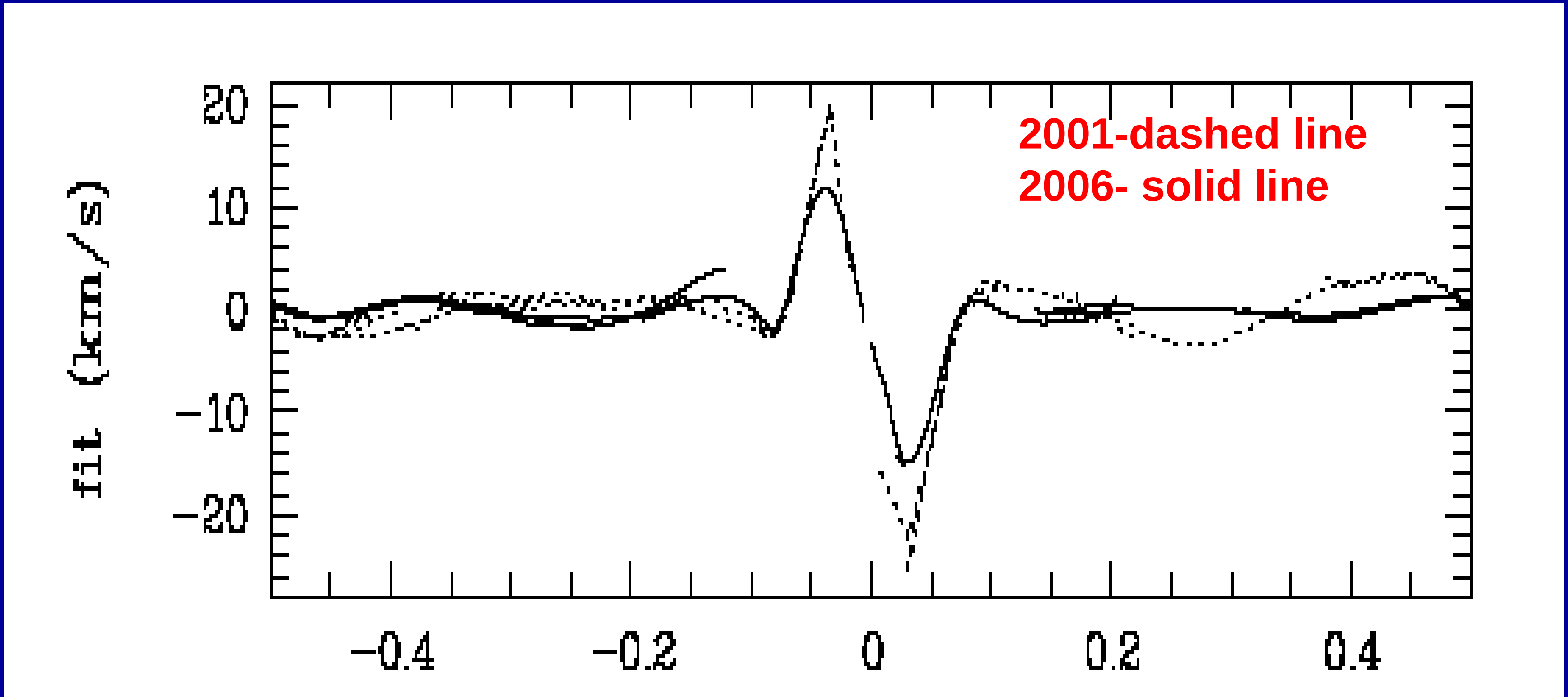


Variable projection of gas stream on the surface of gainer



Variations in the amplitude and the asymmetry of Rossiter effect in 2001 and 2006

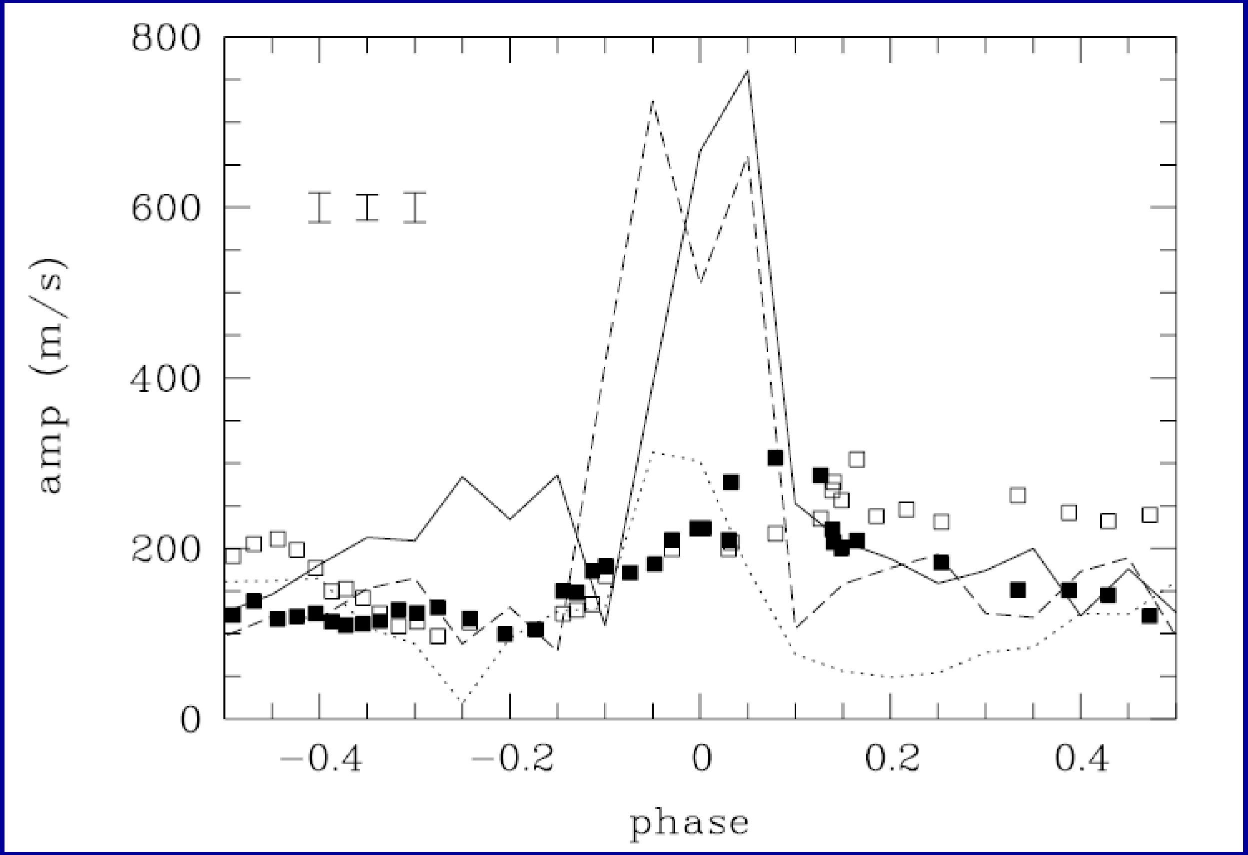
(Lehmann & Mkrtichian, 2008)



Variable Rossiter-McLaughlin effect can be explained only by variable screening effect by circumbinary gas envelope.

Spectroscopic PSF effect:
2001 vs 2006 show variable screening effect

(Lehmann& Mkrtichian, 2008)



f_1: l=2,m=-1
f_2: l=3,m=-2
f_3: l=1,m=0

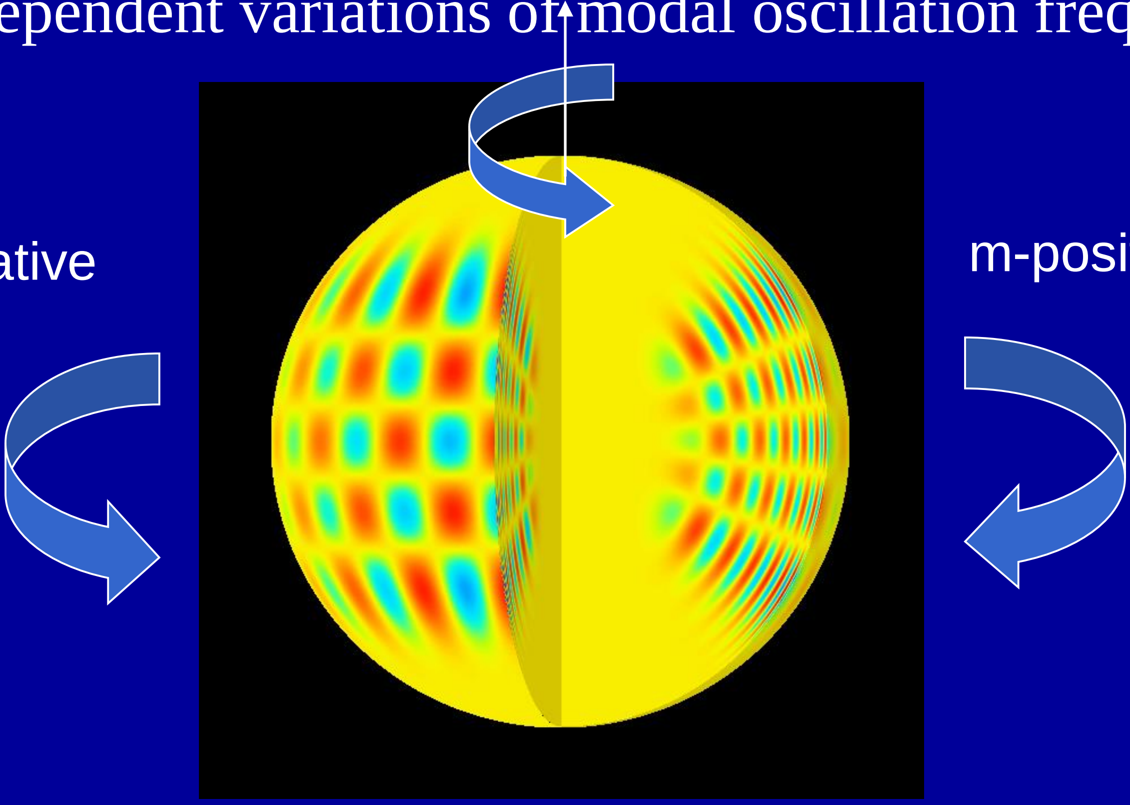
How to measure precisely the rotation of star?

Doppler effect caused the rotational splitting of modes

$\nu_m = \nu_0 - m(1+C_{nl})$ $\nu_m = \nu_{cor} - m\nu_{rot}$ $\Delta\nu_m = - m\Delta\nu_{rot}$

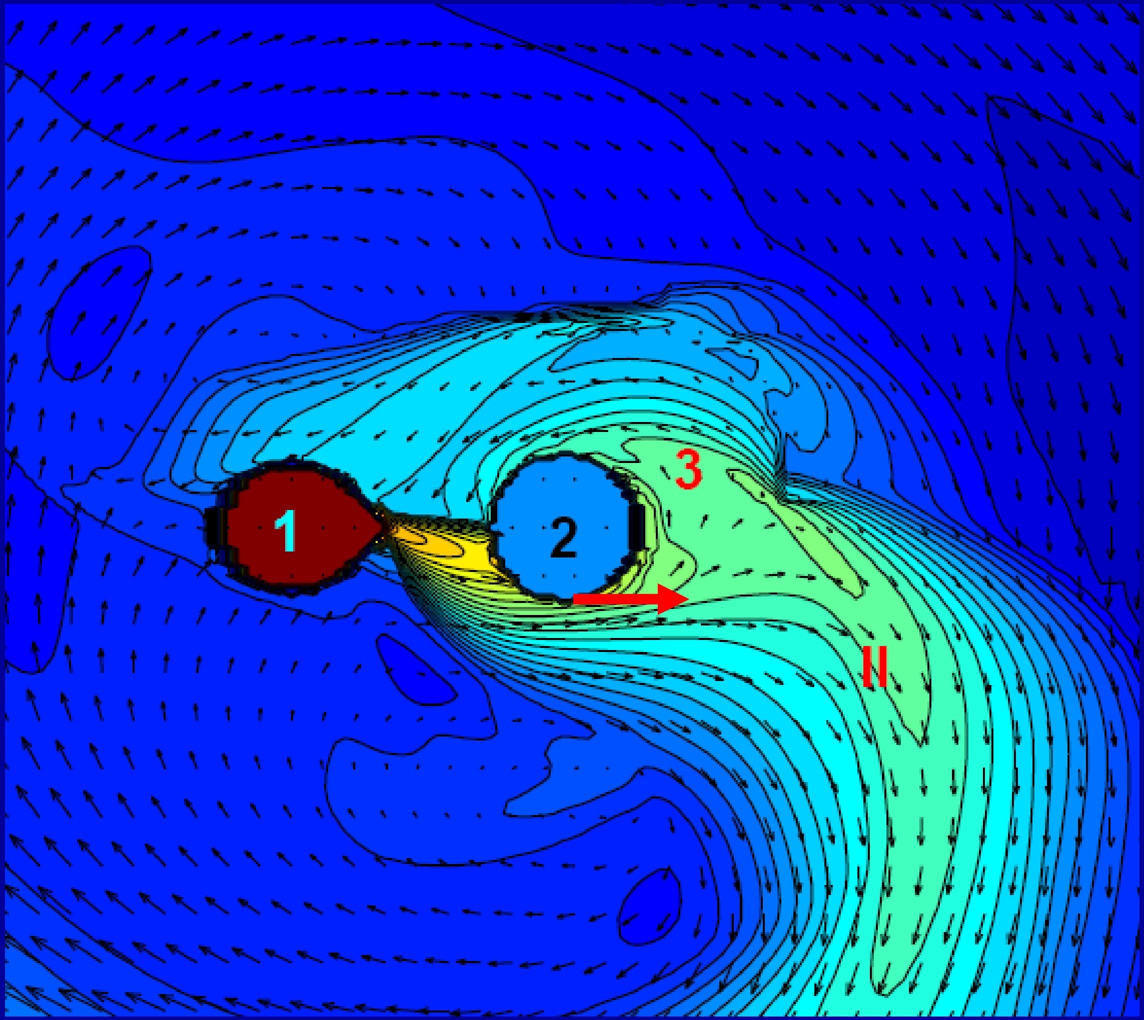
The variation in the rotation rate generates apparent m-dependent variations of modal oscillation frequencies

m-negative



m-positive

Effect of accretion induced acceleration of RZ Cas mass-accreting component



Detection of pulsation frequency variations

(Effect of the acceleration of star envelope by the mass and the angular momentum transfer on oscillation frequencies)

- 1999 f_1= 64.1941 ± 0.00006 c/d
- 2001 64.189 ± 0.006
- 2006 64.2702 ± 0.00025

- 1999 f_2= 56.59553 ± 0.00046 c/d
- 2001 56.600 ± 0.004
- 2006 56.76104± 0.00055

Frequency variations

Δf_1 (2006-1999) = 0.0761 c/d,

Δf_2 (2006-1999) = 0.16551 c/d

$\Delta f_1/\sigma(f_1)=304$ and $\Delta f_2/\sigma(f_2)=301$

Very safe discovery of frequency changes after the mass-transfer burst

What is a reason?

The acceleration: $\Delta\nu_m = -\, m\Delta\nu_{rot}$

m-dependent modal frequency variation

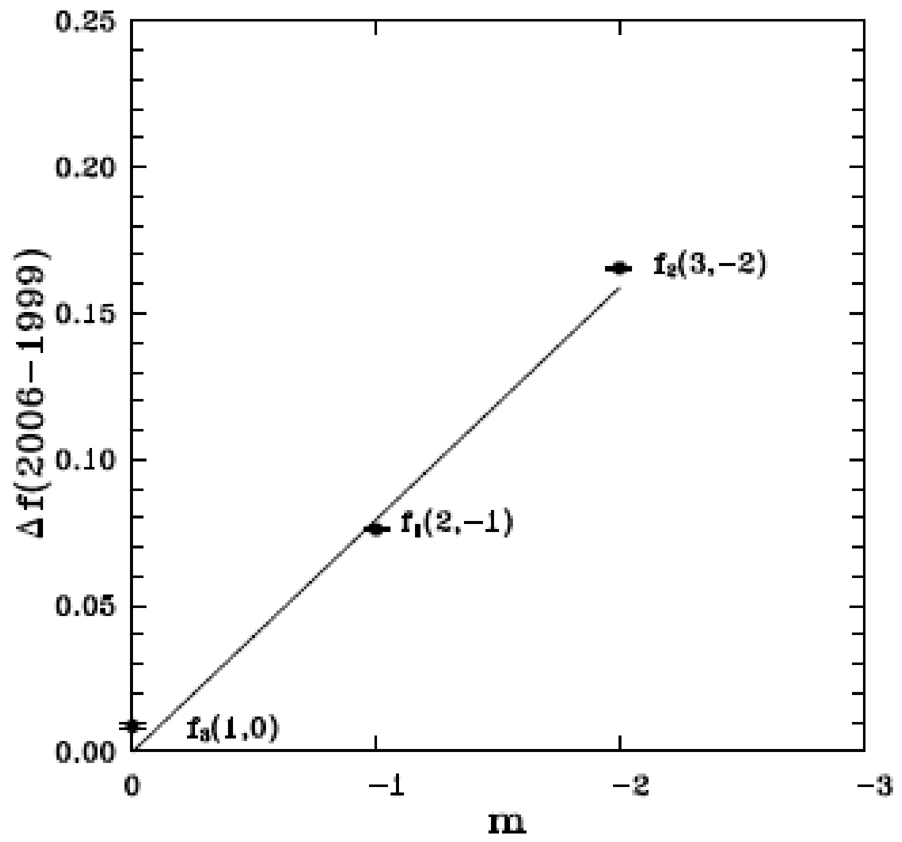


Figure 18. The modal frequency variations in 1999-2006 vs modal m-orders. The solid line is linking the Doppler effect m-dependent modal frequency variation for RZ Cas gainer, caused by rotational acceleration on 0.0794 c d^{-1}.

Detection of acceleration of rotation after mass-transfer burst in 2001

- Remarkably, we detected m-dependent frequency variation and got m=-2 identification for f2 and m=-1 identification for f1.
- m=-1 identification for f1 is in excellent agreement with PSF identifications from photometry!!!!!
- Thus, the frequency changes might be causes by acceleration of rotation of outer layers of

RZ Cas gainer on the value ~0.0761 c/d = 9%

This value looks in agreement with vsini variations ~ ± 6 %

New tools:

- Magnetic cycles (Roche lobe overlows) force:
- Mass-transfer/accretion events which force changes in:
- pulsation amplitude (variable mode excitation effect)
- pulsation frequencies (acceleration of envelope)
- envelope optical screening effect: asymmetric Rossiter
- asymmetric PSF effect

Mode identification:

- The acceleration of envelope and frequency changes precisely measured gives unique chance to do mode identification
- Eclipses gives another (PSF) method for mode identification

- Mass accretion produced hot gas stream impact zone (variable He I line)

Summary

- The oEA stars is an exotic class of interacting pulsating binary stars
- About 14 years ago, when we discovered this class, we did several predictions about expected properties oEA stars and suggested new astrophysical tools for their studies
- We used the key oEA system RZ Cas to prove these ideas about influence of the magnetic activity cycles of Roche lobe filling star on pulsation properties of the primary pulsating component via the mass transfer bursts .
- We confirmed that the pulsation ampiltude rapid changes (drops) were triggered by mass-transfer bursts and magnetic activity of donor star. These MTB changed the amplitudes of oscillation spectrum of gainer and accelerated the surface layers.
- We found also a m-dependent   frequency changes
- We measured the amount of acceleration of very surface layers after the mass transfer burst in 2001
- This methods could be used for all class of oEA stars

THE END