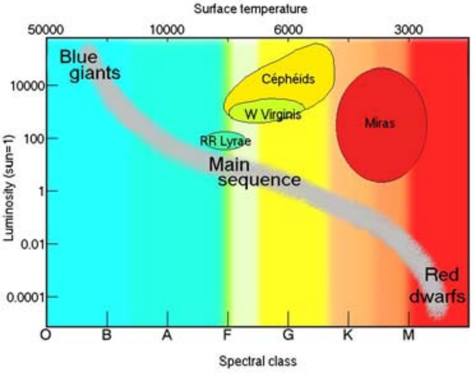

Pulsating Stars

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Observatoire de Haute Provence
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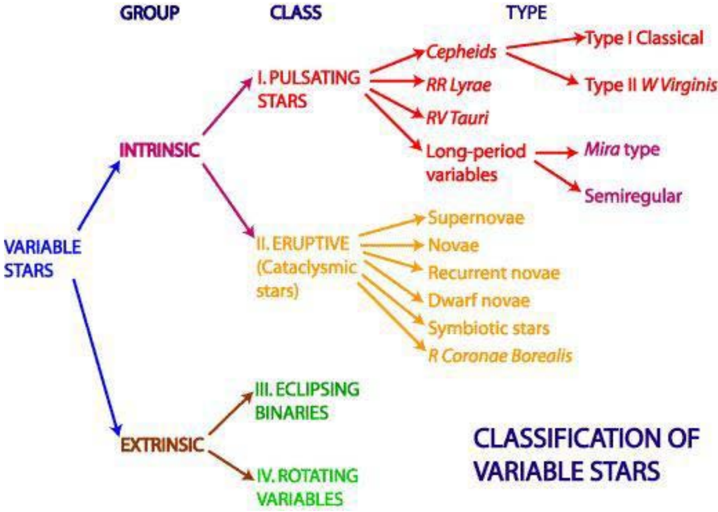
Star Party dedicated to Spectroscopy
12th to 17th August 2012 at OHP


GROUP
CLASS
TYPE
VARIABLE STARS
INTRINSIC
EXTRINSIC
I. PULSATING STARS
Cepheids
Type I Classical
Type II W Virginis
RR Lyrae
RV Tauri
Long-period variables
Mira type
Semiregular
II. ERUPTIVE (Cataclysmic stars)
Supernovae
Novae
Recurrent novae
Dwarf novae
Symbiotic stars
R Coronae Borealis
III. ECLIPSING BINARIES
IV. ROTATING VARIABLES

CLASSIFICATION OF VARIABLE STARS

three - body recombination :

$\mathrm{H}^+ + e + e \rightarrow \mathrm{H}^* + e$ with kinetic energy

$$\boxed{H \leftrightarrow H^+ + e^-}$$

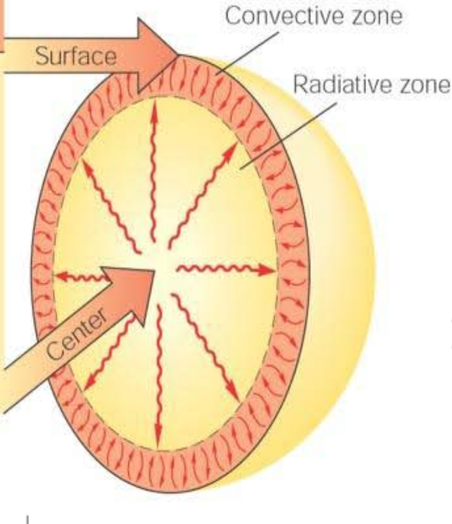
$$\boxed{He \leftrightarrow He^+ + e^-}$$

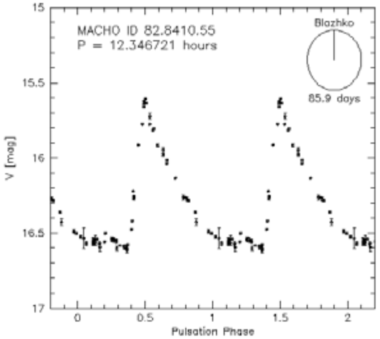
$$\boxed{He^+ \leftrightarrow He^{++} + e^-}$$

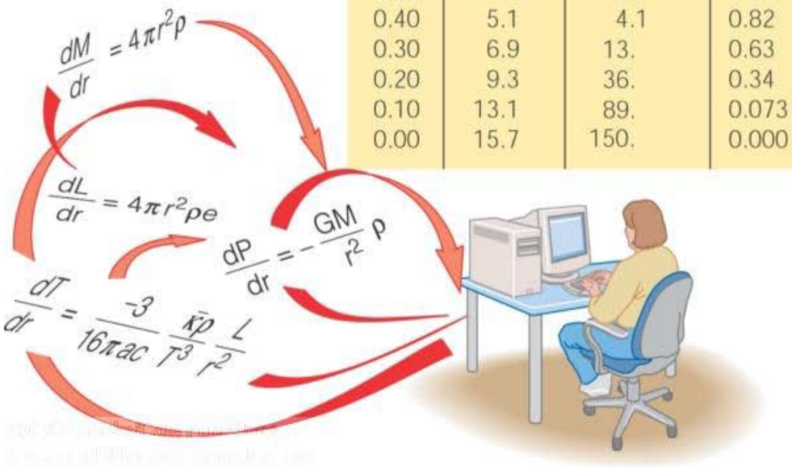
$$\eta_\rho \equiv \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{2+(\gamma-1)M_1^2}$$

$$\eta_\rho \rightarrow \frac{\gamma+1}{\gamma-1} \quad \text{if } M_1 \rightarrow \infty$$

$R/R_\odot$	T (10^6 K)	Density (g/cm^3)	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.2	0.035	0.996	1.00
0.70	2.3	0.12	0.990	1.00
0.60	3.1	0.40	0.97	1.00
0.50	4.9	1.3	0.92	1.00
0.40	5.1	4.1	0.82	1.00
0.30	6.9	13.	0.63	0.99
0.20	9.3	36.	0.34	0.91
0.10	13.1	89.	0.073	0.40
0.00	15.7	150.	0.000	0.00





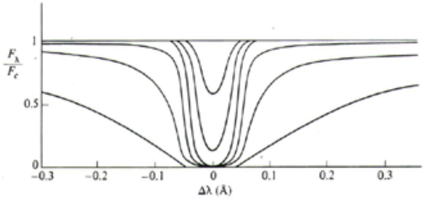


$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon$$

$$\frac{dP}{dr} = -\frac{GM}{r^2}\rho$$

$$\frac{dT}{dr} = \frac{-3}{16\pi ac}\frac{\kappa\rho}{T^3}\frac{L}{r^2}$$

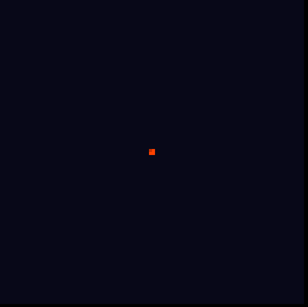


$$\boxed{\kappa \propto \frac{\rho}{T^{3.5}}}$$

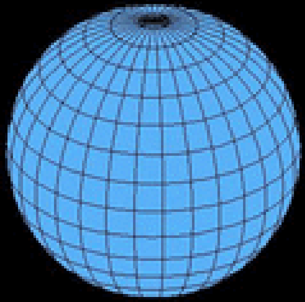
An outstanding laboratory

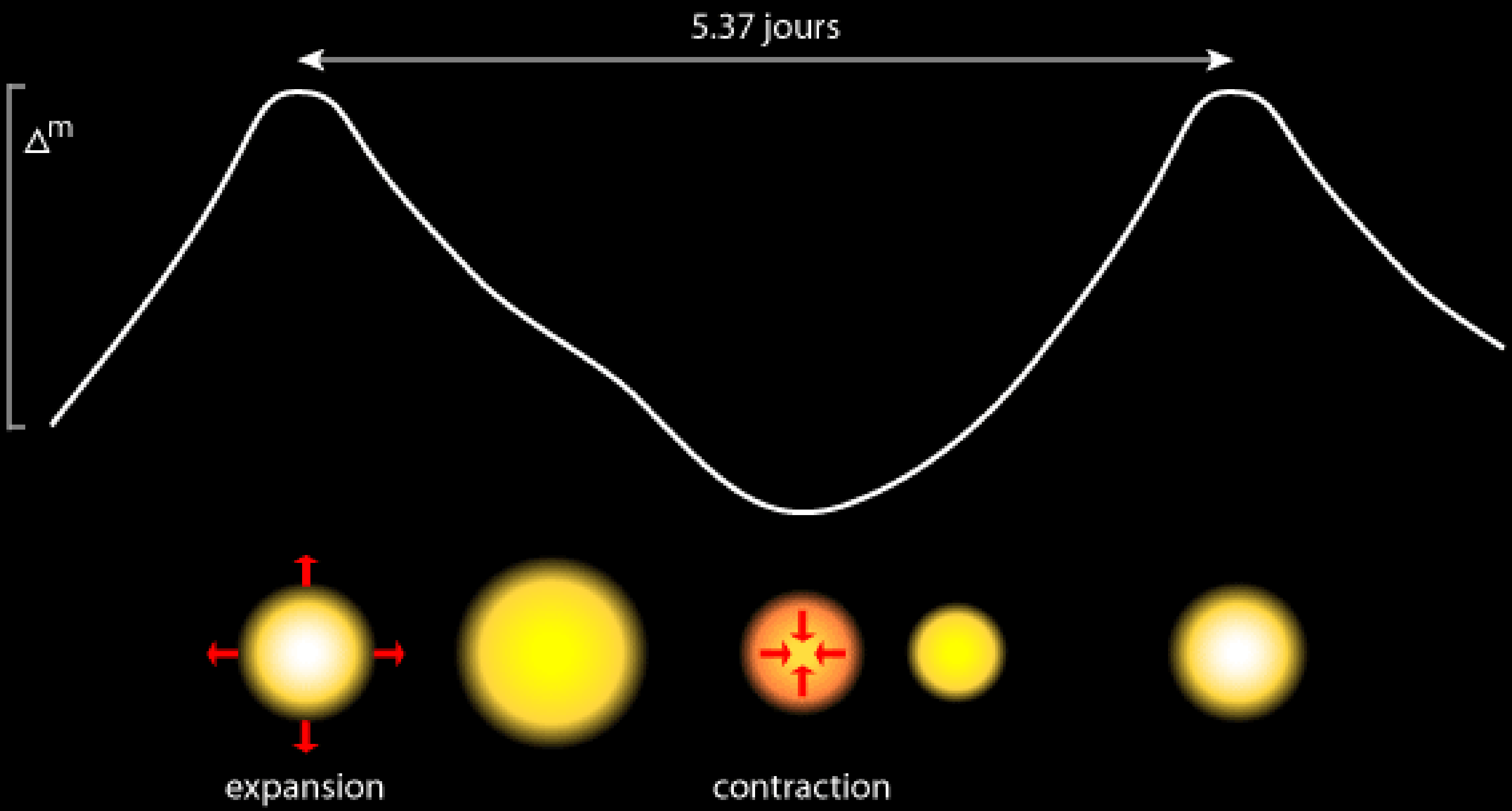
Our Galaxy:
100 billion stars

about
a star
on 100,000
is pulsating

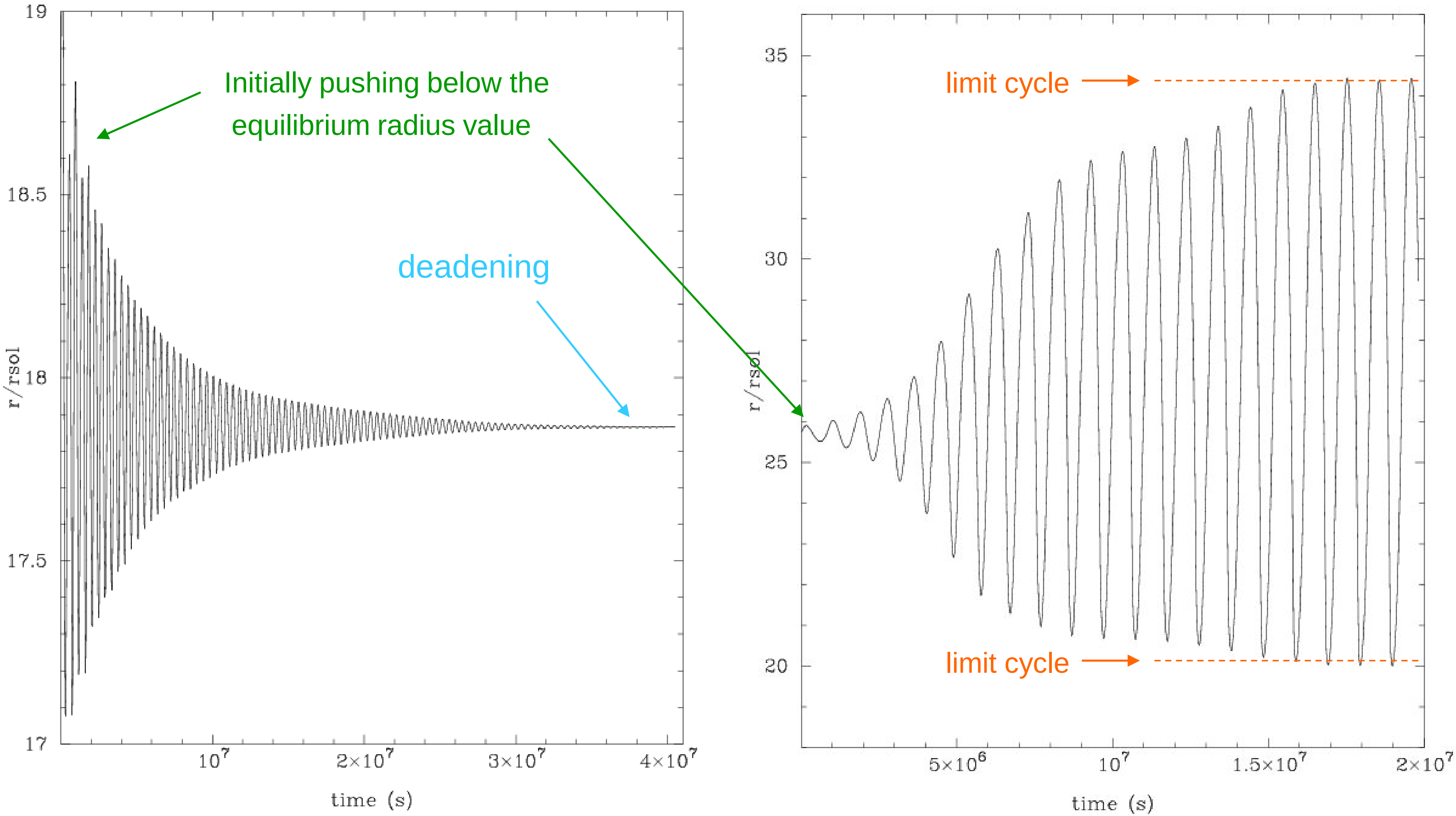


Stellar pulsation





Stable (ordinary star) & Unstable (pulsating star)



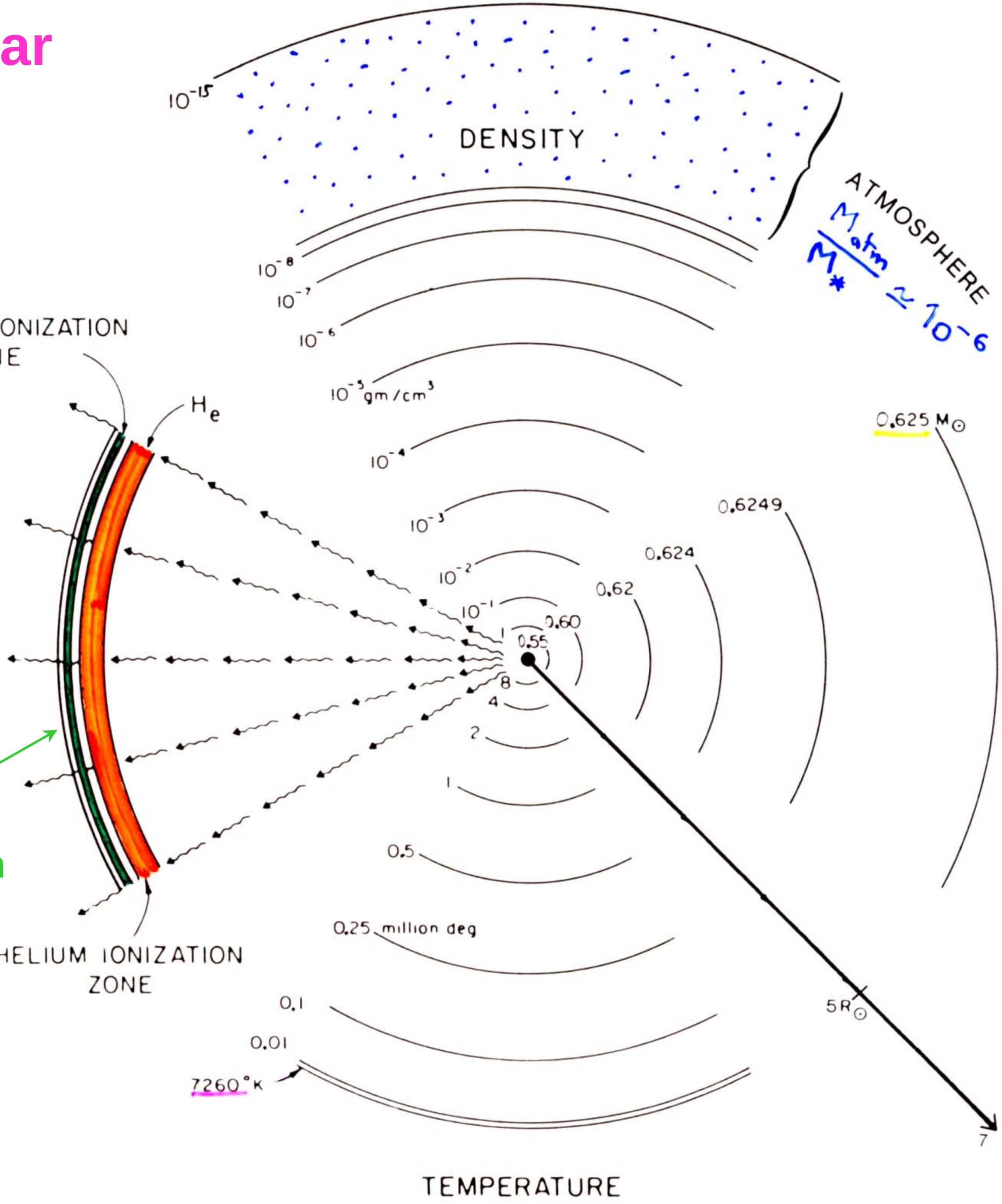
Initially pushing below the equilibrium radius value

deadening

limit cycle

limit cycle

RR Lyrae star

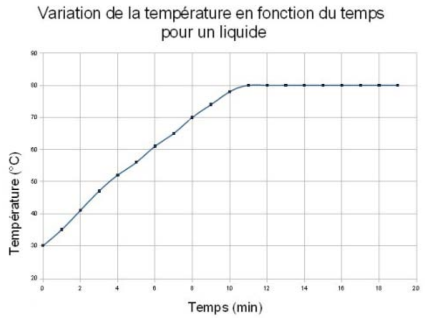


$\frac{M_{atm}}{M_*} \simeq 10^{-6}$

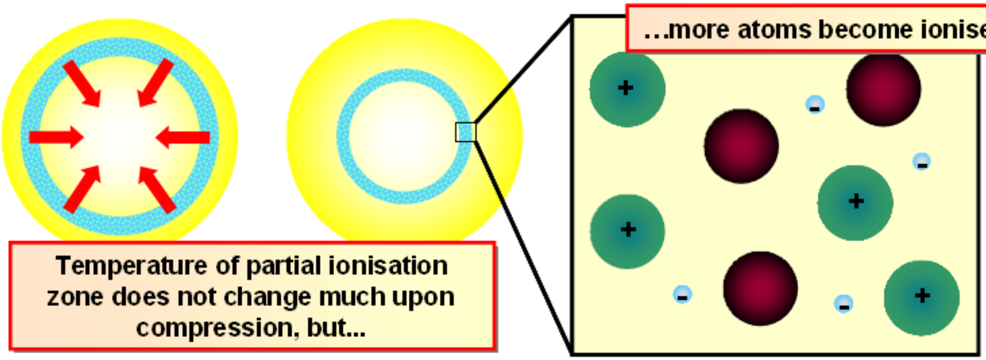
$R_* = 40\ 000\ 000$ km

70% H
29.9% He
0.1% other

Iben 1971 PASP 83, 697



The κ-mechanism



...more atoms become ionised.

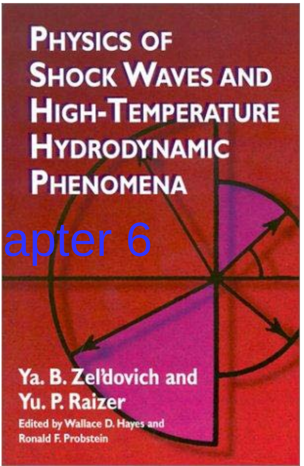
Temperature of partial ionisation zone does not change much upon compression, but...

three - body recombination :

$$H^+ + e + e \rightarrow H^* + e \text{ with kinetic energy}$$

~~Radiative recombination~~

$$\cancel{H^+ + e \longrightarrow H + h\nu}$$



Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena

Ya. B. Zel'dovich and Yu. P. Raizer

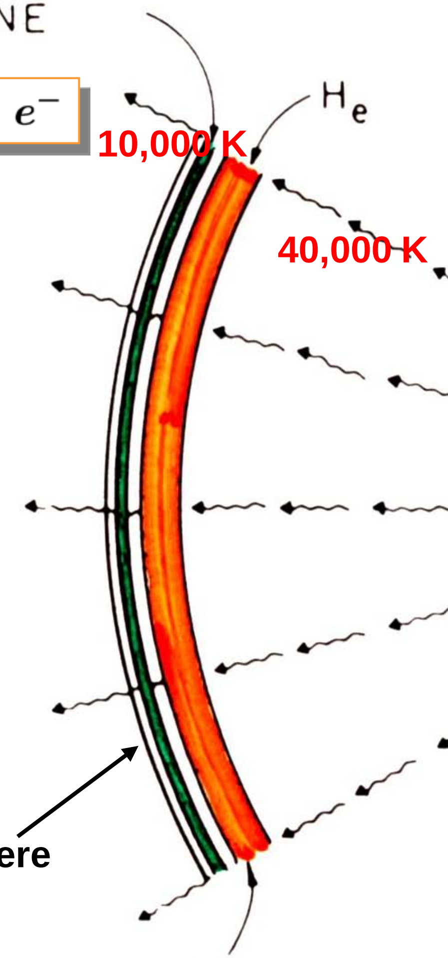
Edited by Wallace D. Hayes and Ronald F. Probstein

Chapter 6

$$\kappa \propto \frac{\rho}{T^{3.5}}$$

HYDROGEN IONIZATION ZONE

$$H \leftrightarrow H^+ + e^-$$



HELIUM IONIZATION ZONE

$$He \leftrightarrow He^+ + e^-$$

$$He^+ \leftrightarrow He^{++} + e^-$$

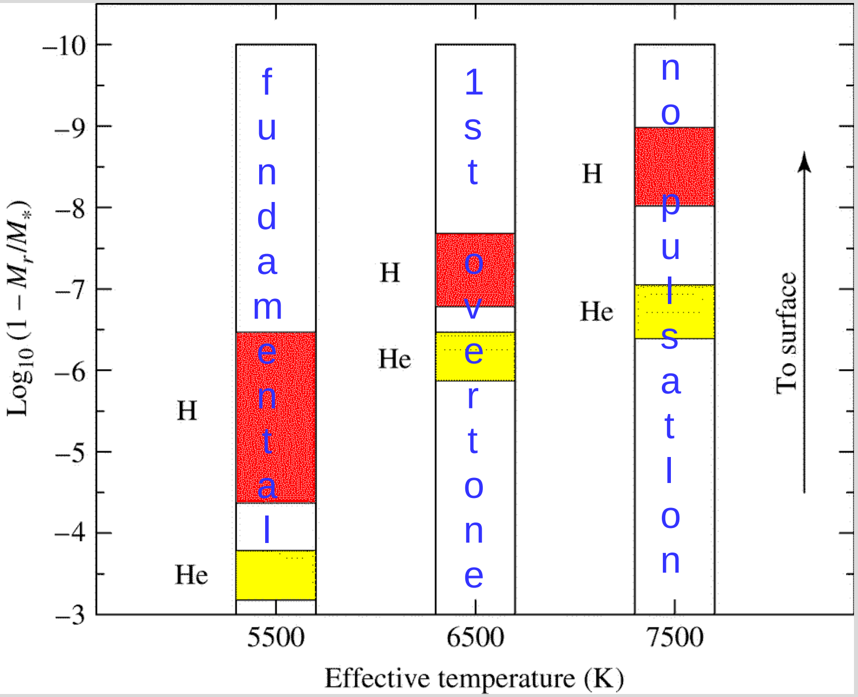
- **hydrogen ionization zone** (H ⟺ H^+ and He ⟺ He^+)

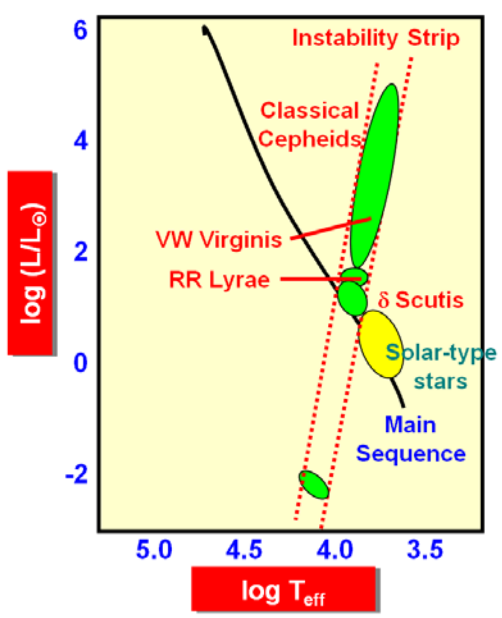
T = 10,000 – 15,000 K

- **helium II ionization zone** (He^+ ⟺ He^{++})

T = 40,000 K

The instability strip





- If the star is too hot, the ionization zones will be too near the surface to drive the oscillations.
- This accounts for the "**blue edge**" of the instability strip.
- The "**red edge**" is probably due to the onset of convection.

RR Lyr

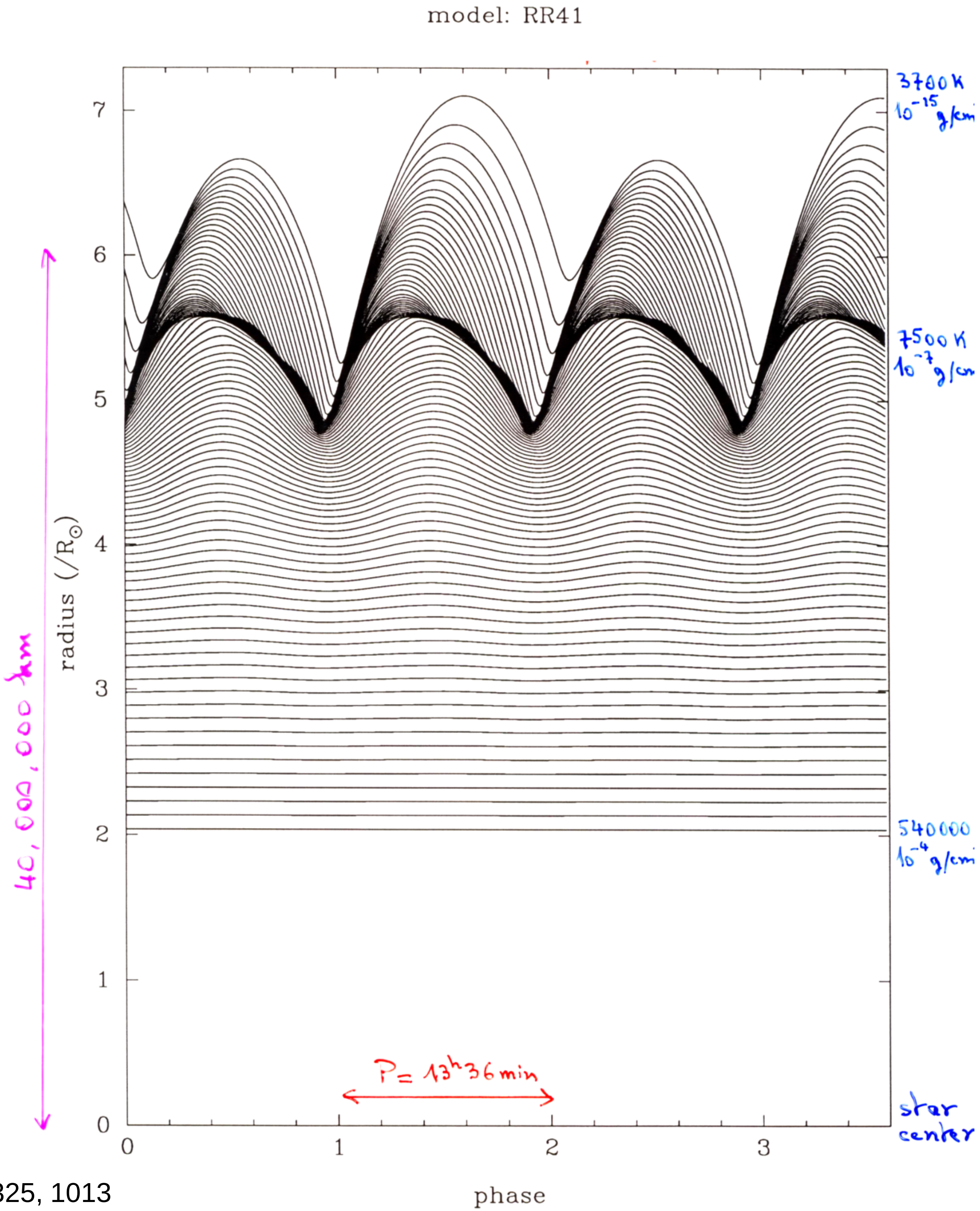
$T_{eff} = 7175$ K

$M = 0.6\ M_{sun}$

$L = 62\ L_{sun}$

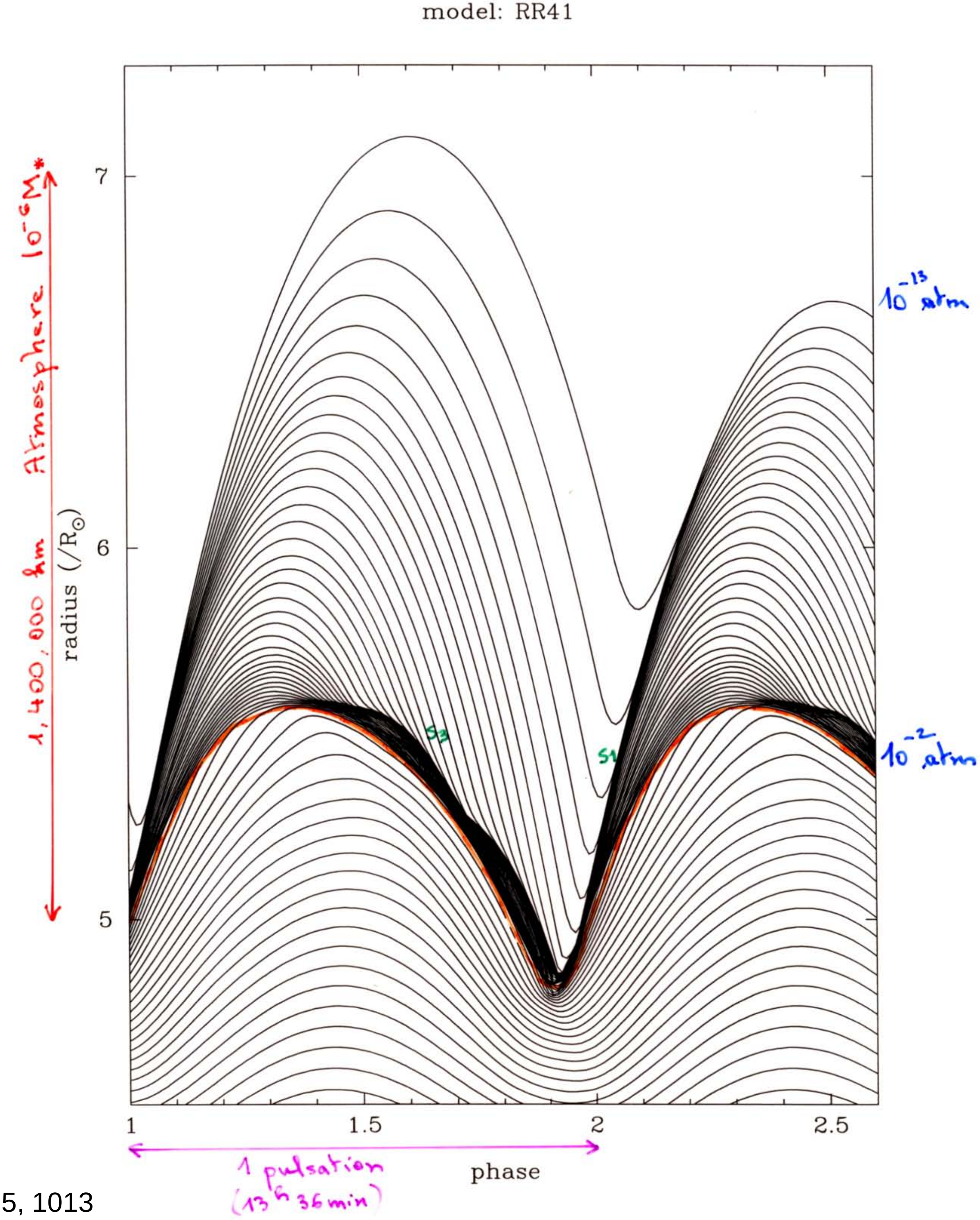
90 layers

opacity with Fe



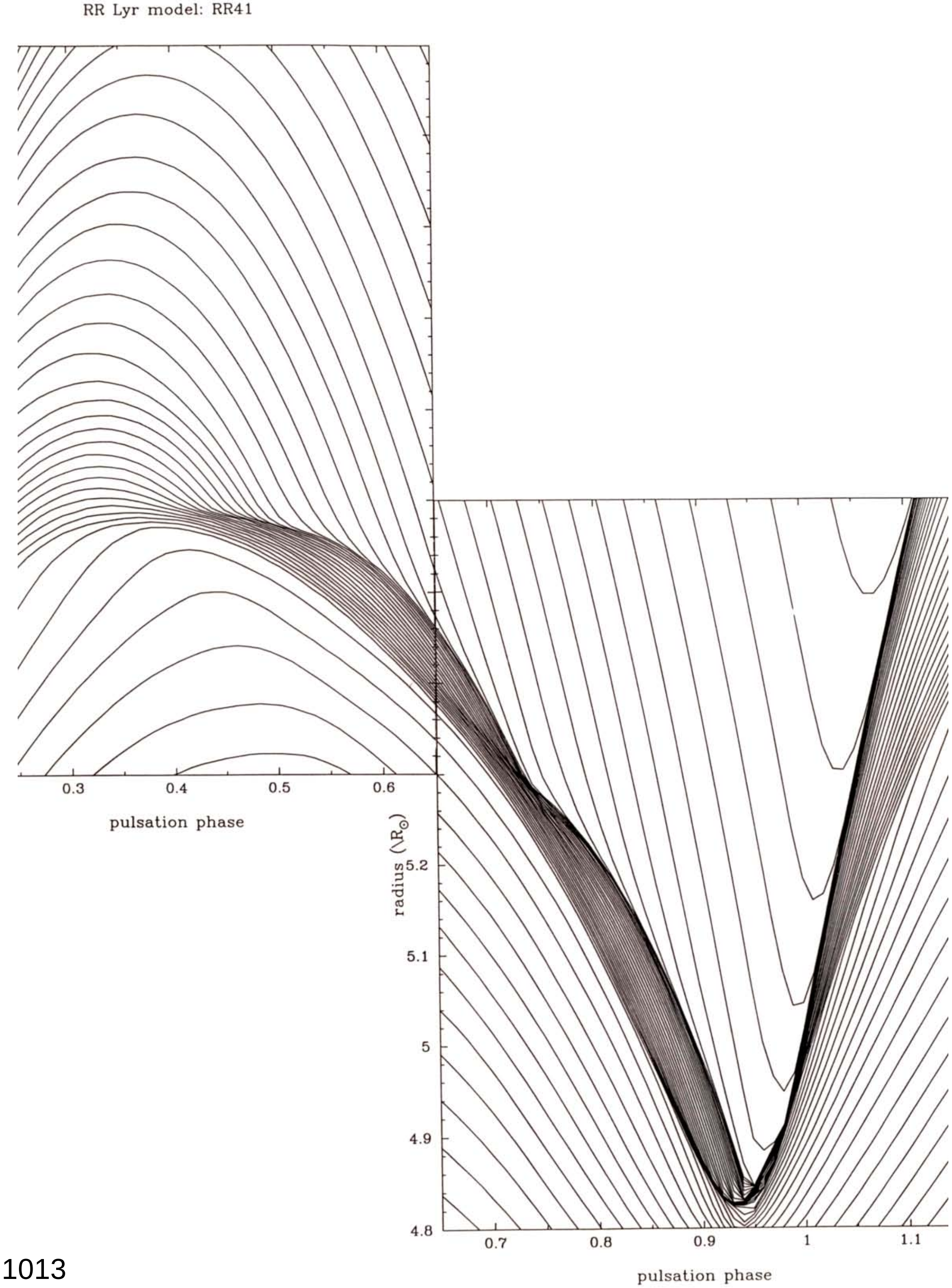
Fokin & Gillet 1997 A&A 325, 1013

RR Lyr



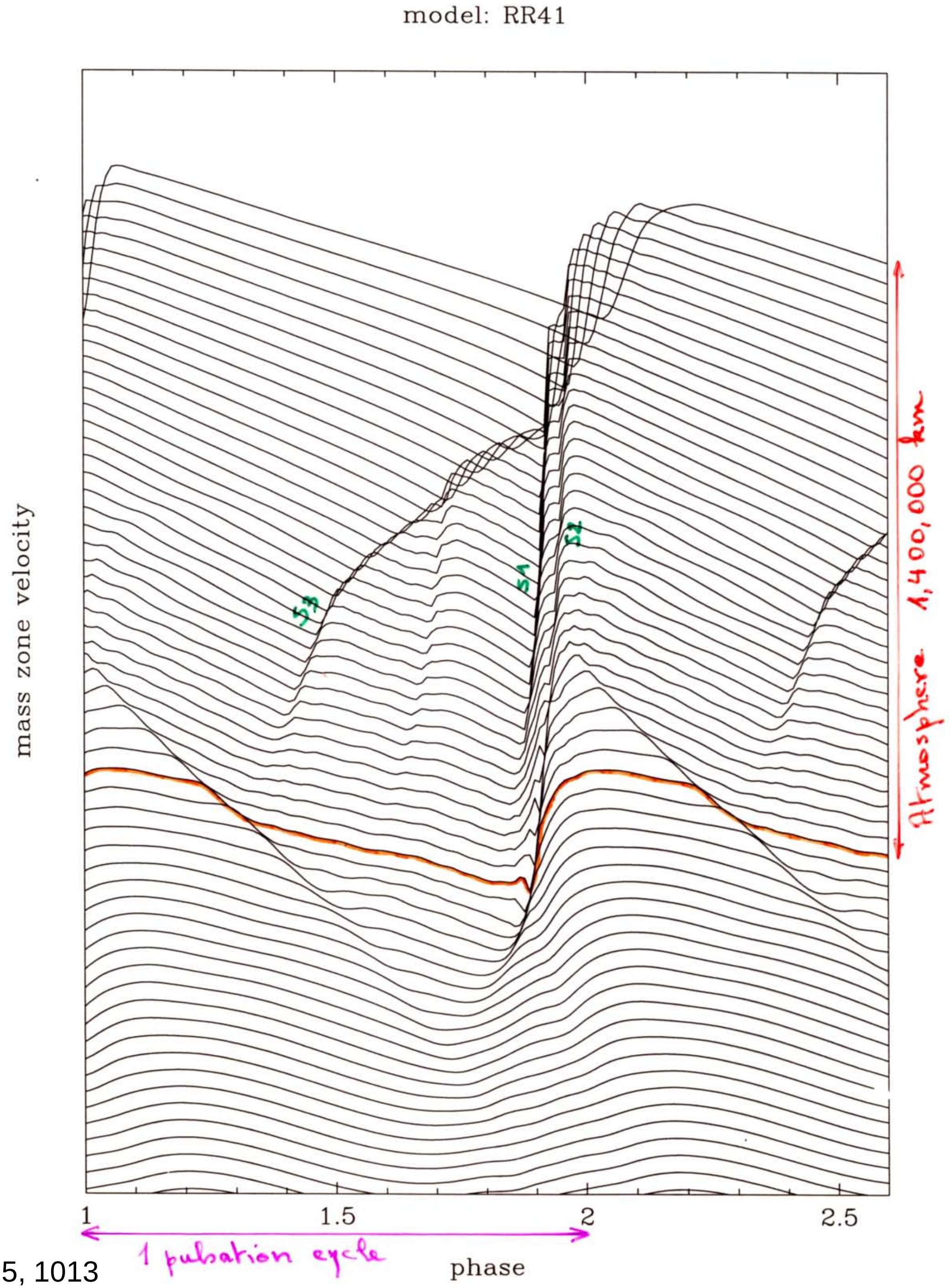
Fokin & Gillet 1997 A&A 325, 1013

RR Lyr



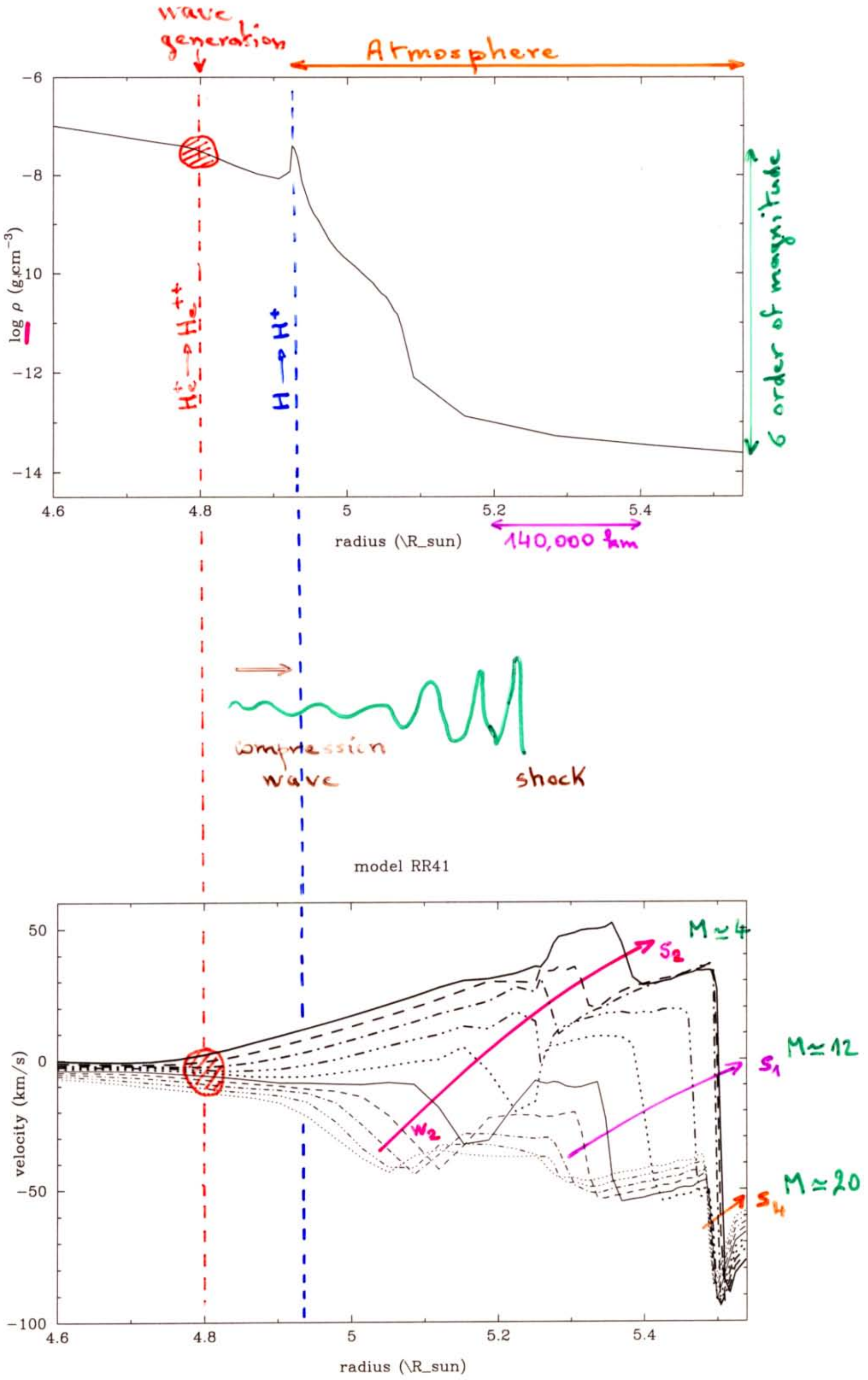
Fokin & Gillet 1997 A&A 325, 1013

RR Lyr



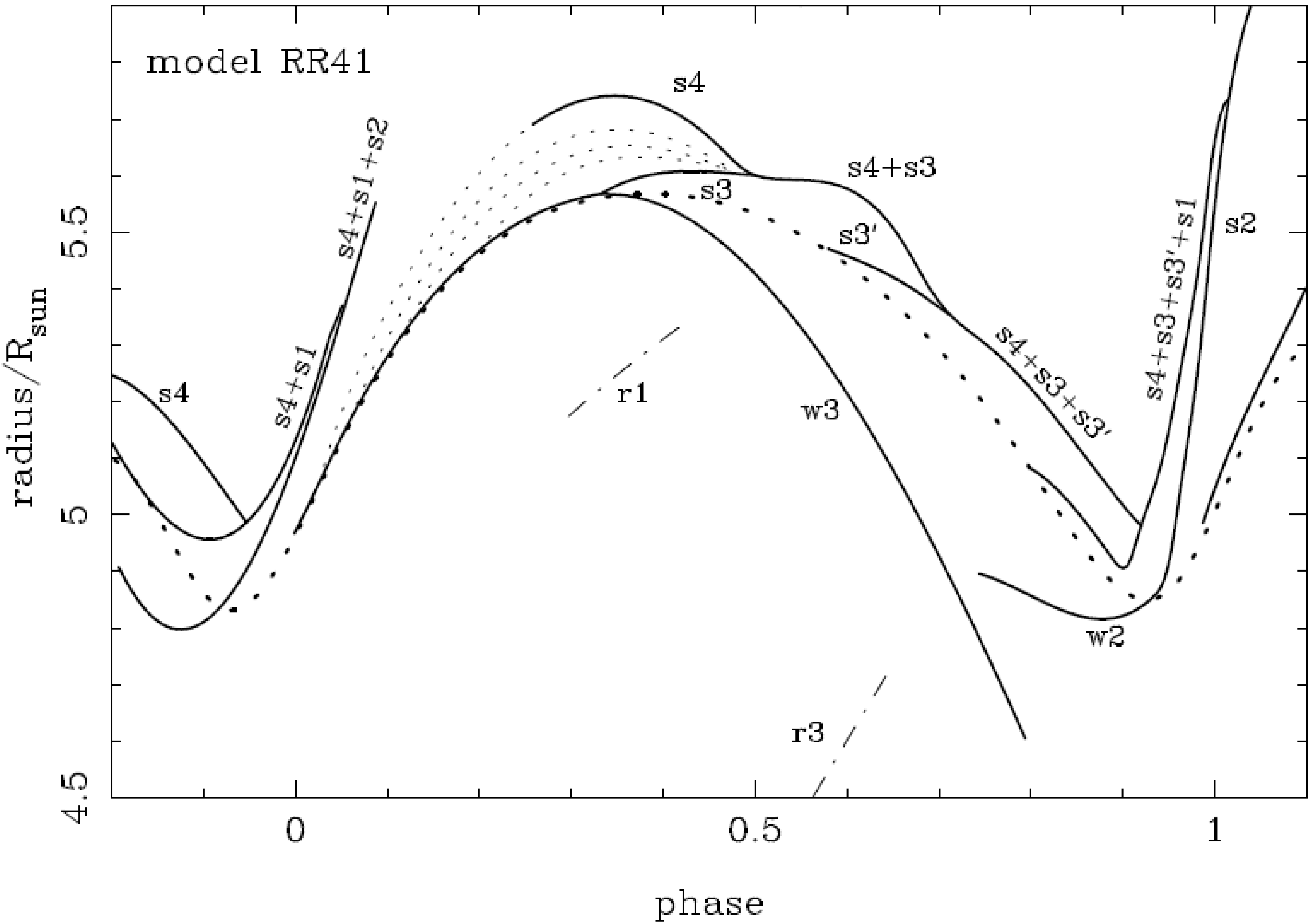
Fokin & Gillet 1997 A&A 325, 1013

RR Lyr



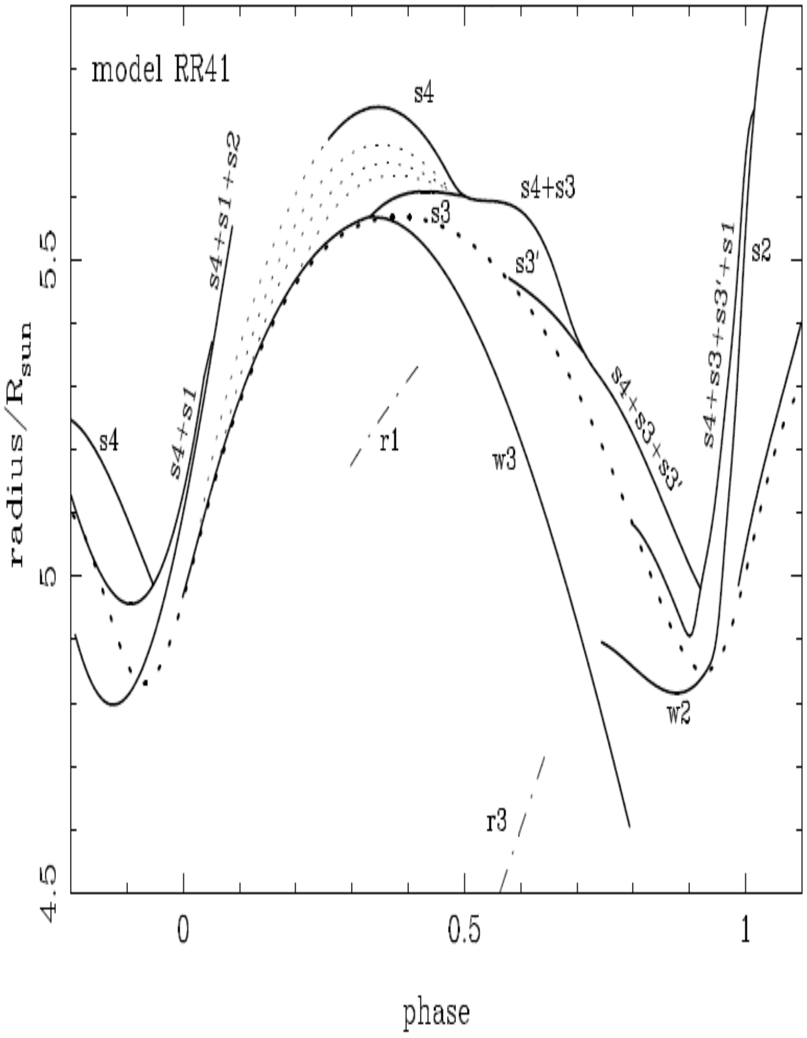
Fokin & Gillet 1997 A&A 325, 1013

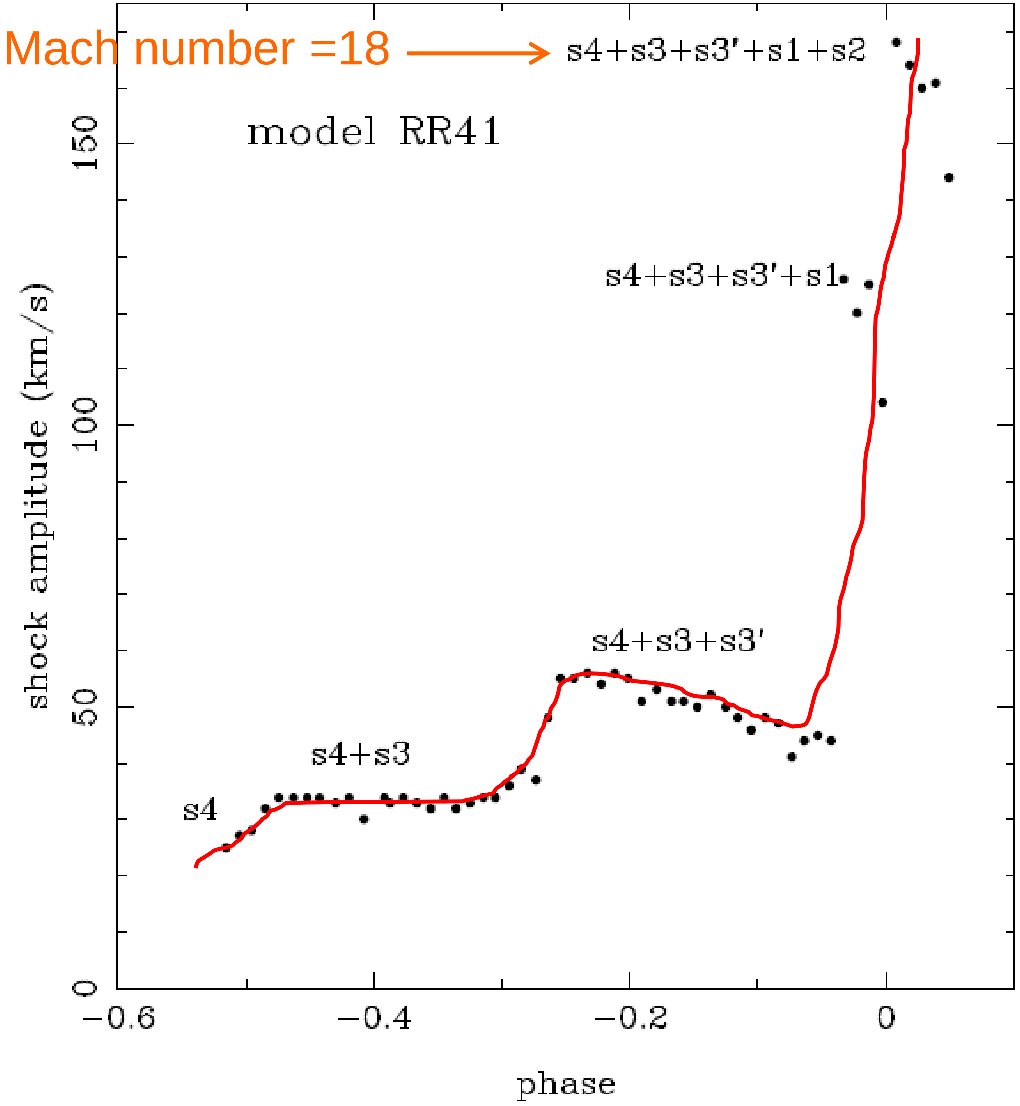
The 5 shock waves in **RR Lyr**



Fokin & Gillet 1997 A&A 325, 1013

The velocity of the 5 shock waves in **RR Lyr**

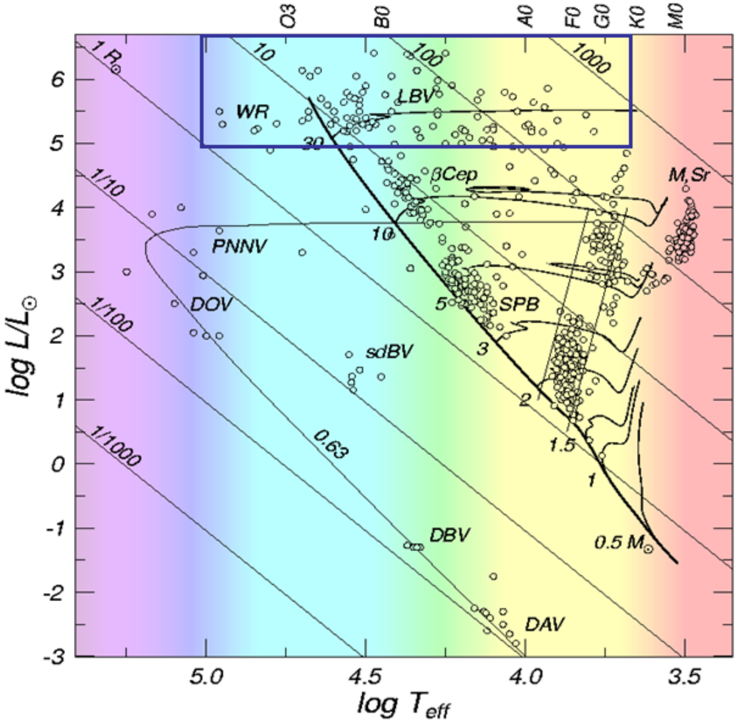




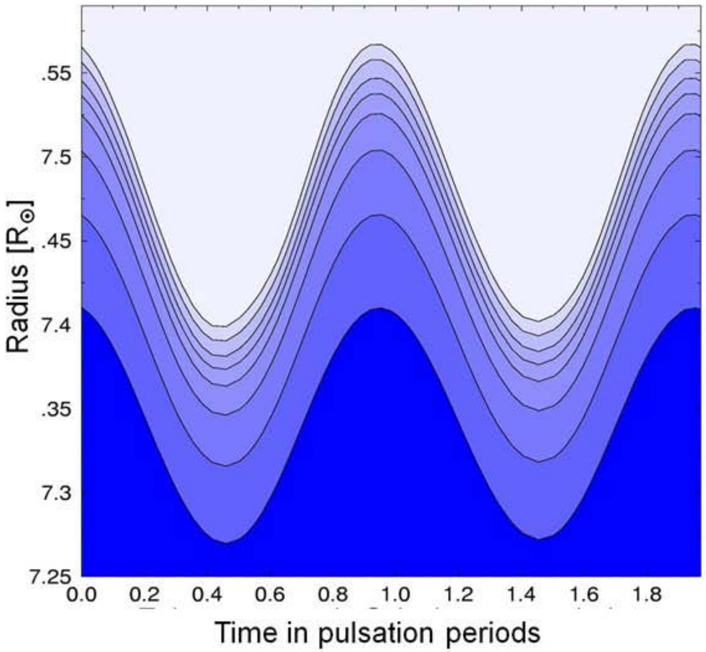
Fokin & Gillet 1997 A&A 325, 1013

Comparaison de la dynamique atmosphérique dans le cas d'une pulsation classique (small amplitudes) et dans le cas d'une pulsation de fortes amplitudes (atmosphere with shock waves).

From Ernst A. Dorfi
Universität Wien.



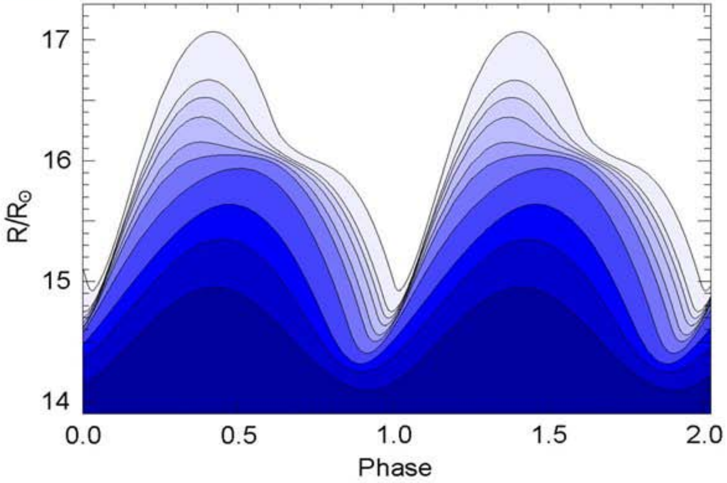
Pulsations with small amplitudes



$M = 20\,M_\odot$
$L = 66\,000\,L_\odot$
$T_{eff} = 27\,100$ K
$P = 0.29$ days

Synchronous motion of mass shells

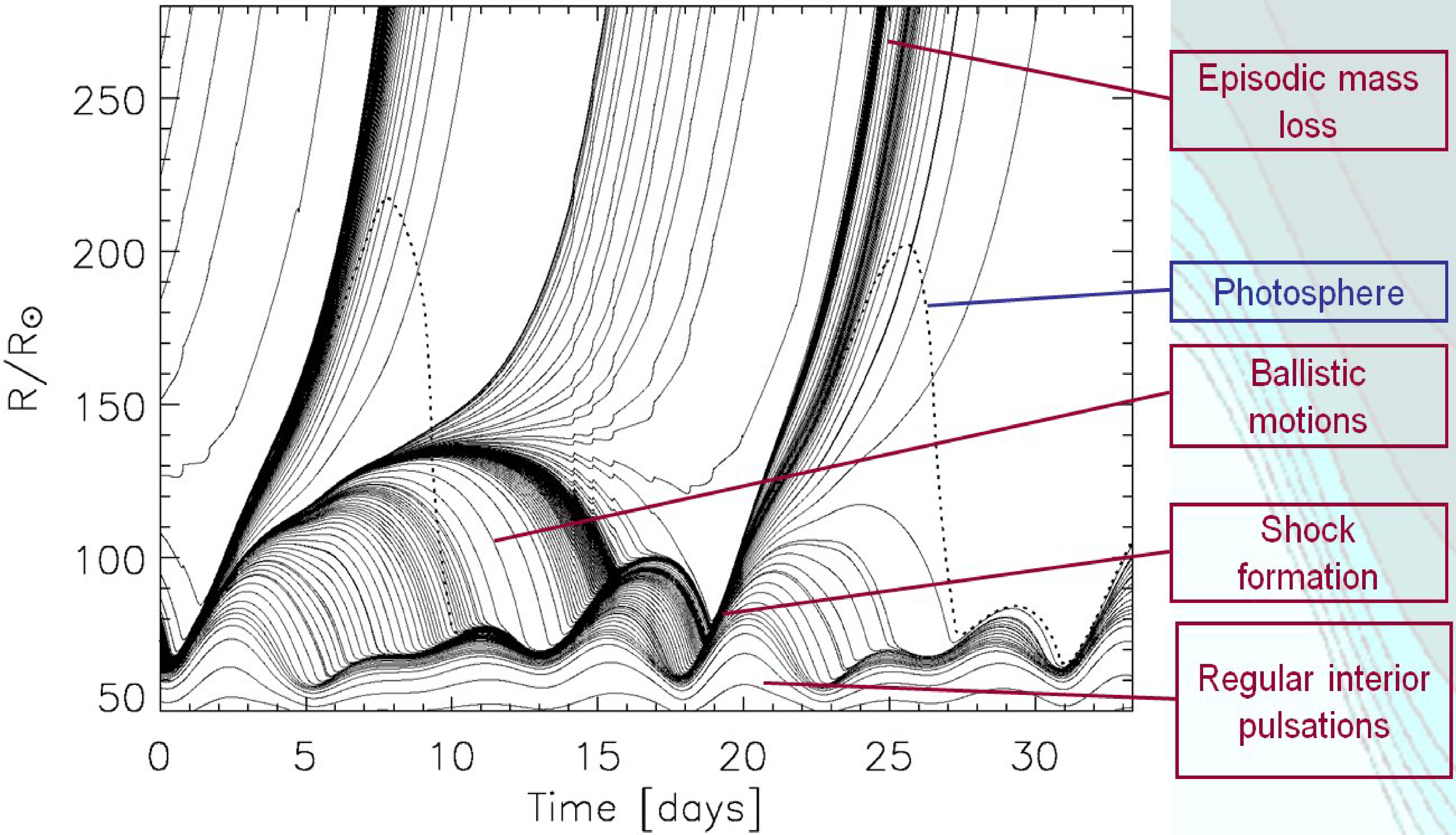
Atmosphere with shock waves



$M = 25\,M_\odot$
$L = 282\,000\,L_\odot$
$T_{eff} = 33\,900$ K
$P = 0.49$ days

Ballistic motions on the scale of t_{ff}

Motion of mass shells



Episodic mass loss

Photosphere

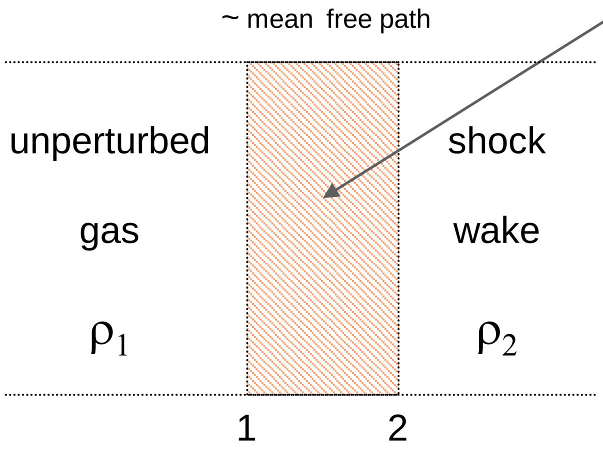
Ballistic motions

Shock formation

Regular interior pulsations

Dynamique extrême de l'atmosphère d'une supergéante pulsante subissant des chocs de très forte intensité conduisant à des phénomènes de perte de masse sporadiques. From Ernst A. Dorfi Universität Wien.

The weak shock: viscous shock front



~ mean free path

unperturbed

gas

ρ_1

shock

wake

ρ_2

1

2

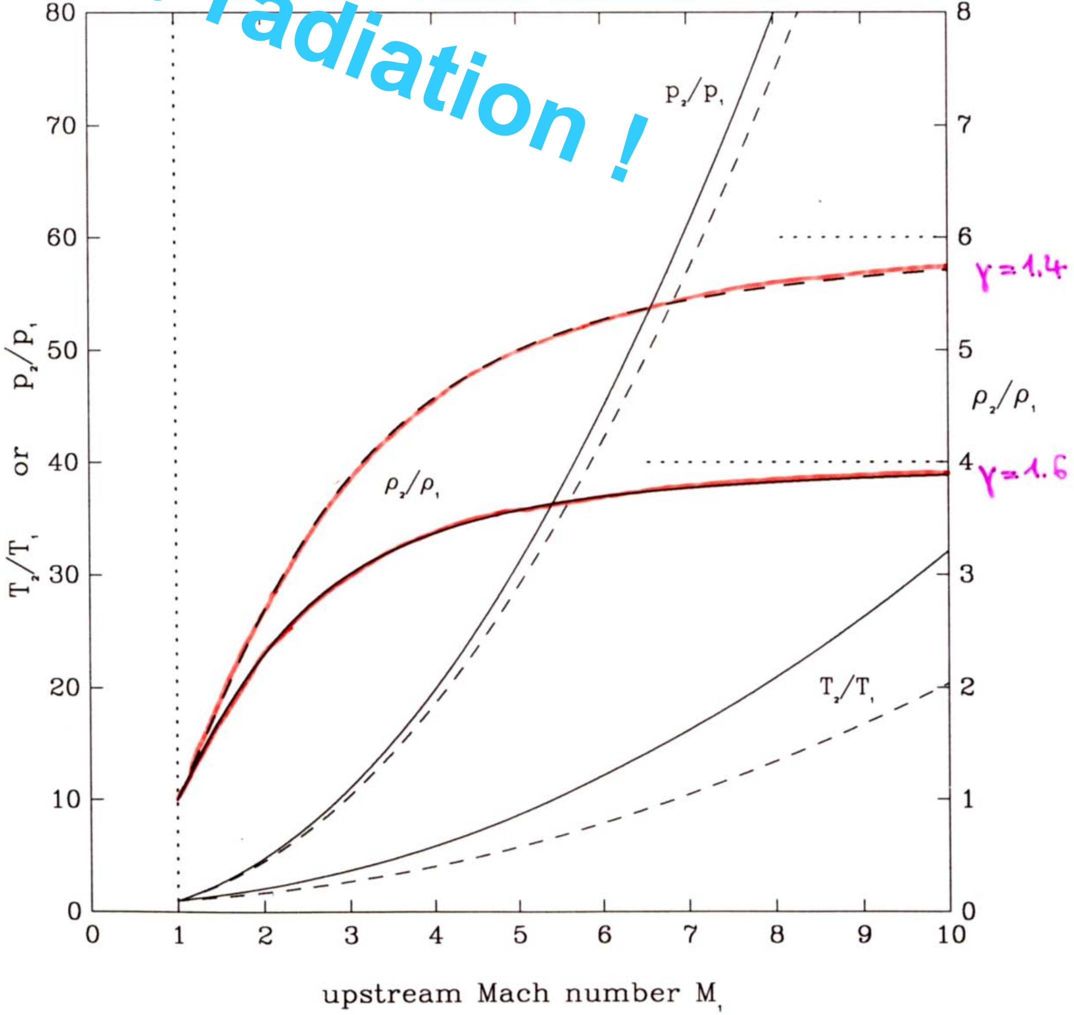
$$\frac{u_1^2}{2}+h_1=\frac{u_2^2}{2}+h_2$$

$$h \equiv \frac{1}{\gamma-1}\frac{p}{\rho}+\frac{p}{\rho}$$

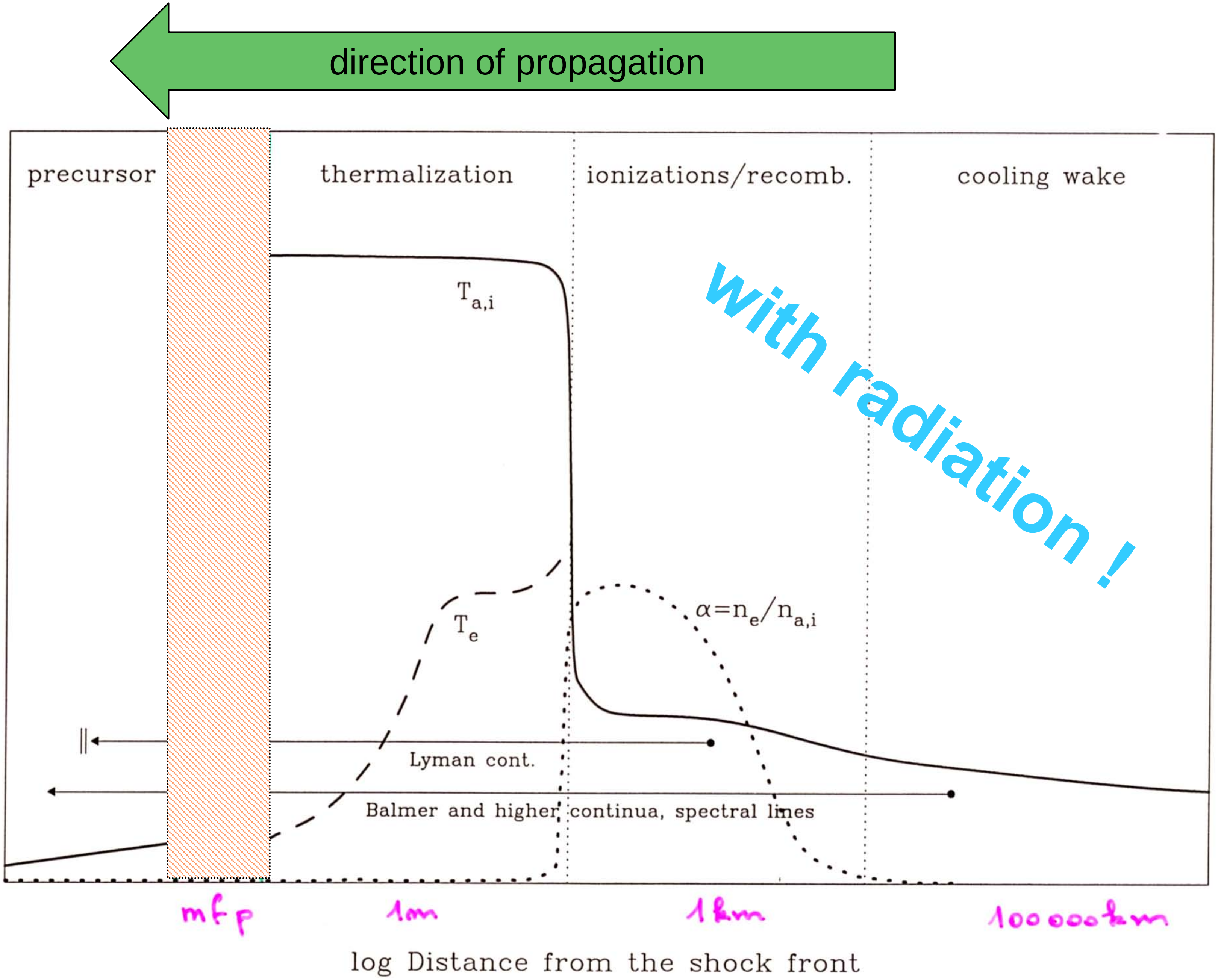
$$\eta_\rho \equiv \frac{\rho_2}{\rho_1}=\frac{(\gamma+1)M_1^2}{2+(\gamma-1)M_1^2}$$

$$\eta_\rho \to \frac{\gamma+1}{\gamma-1} \quad \text{if } M_1 \to \infty$$

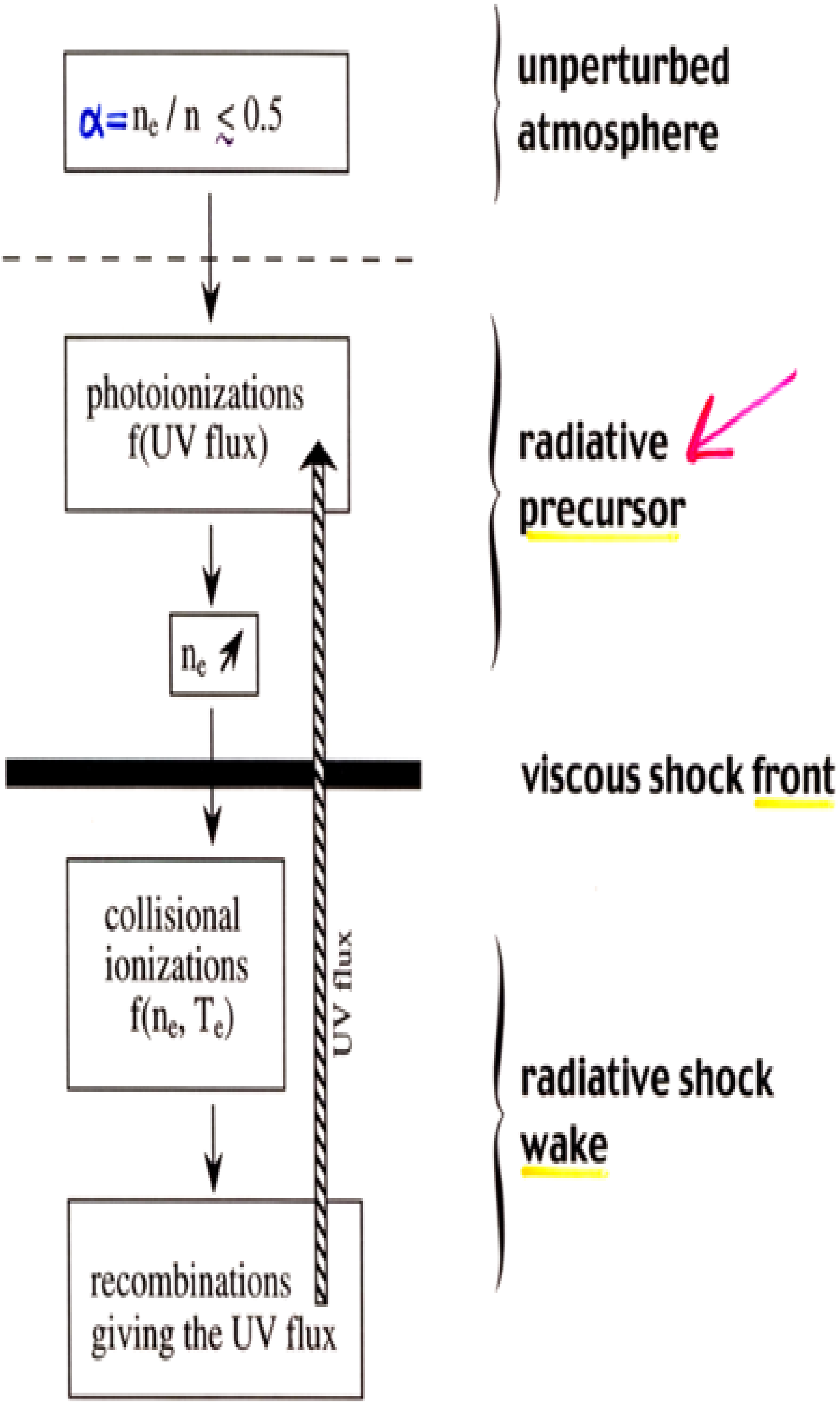
No radiation !



The strong shock: Hypersonic/Radiative shock wave



with radiation !



$\alpha = n_e / n \lesssim 0.5$

unperturbed
atmosphere

photoionizations
f(UV flux)

radiative
precursor

$n_e \nearrow$

viscous shock front

collisional
ionizations
$f(n_e, T_e)$

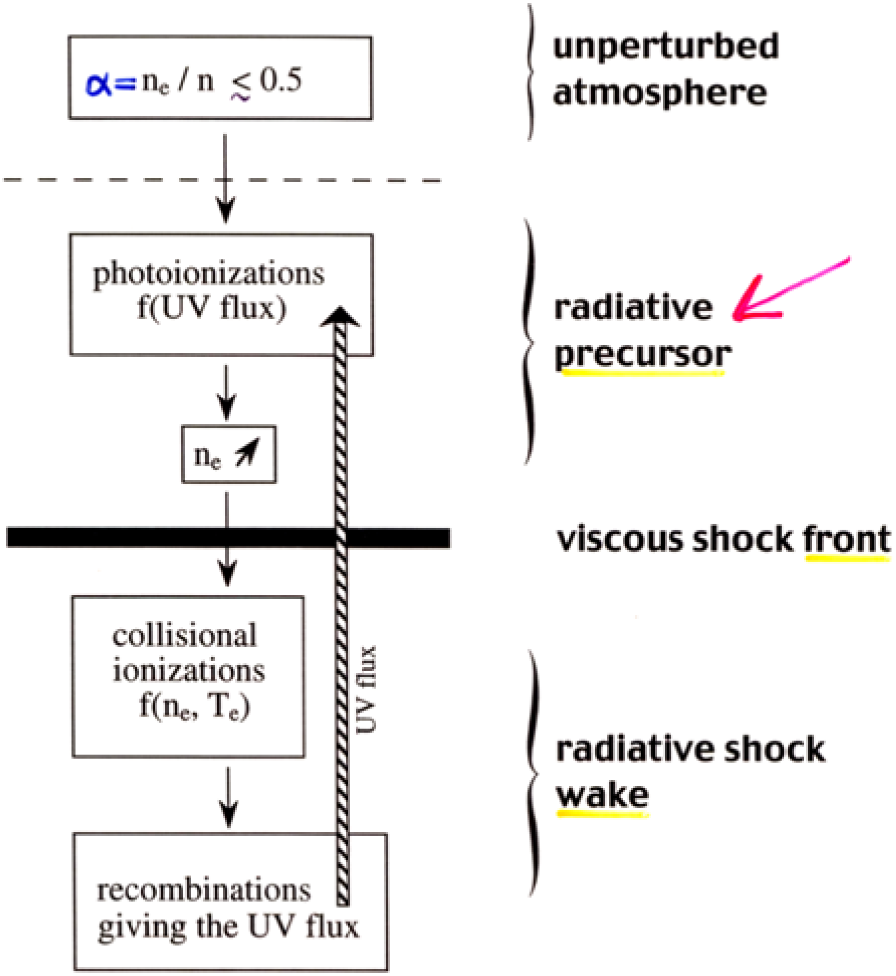
UV flux

radiative shock
wake

recombinations
giving the UV flux

A Strong Coupling

origin:
- partially ionized medium
- $v_s = 50$ km/s << $c = 300{,}000$ km/s



$\alpha = n_e / n \lesssim 0.5$

unperturbed atmosphere

photoionizations f(UV flux)

$n_e \nearrow$

radiative precursor

viscous shock front

collisional ionizations $f(n_e, T_e)$

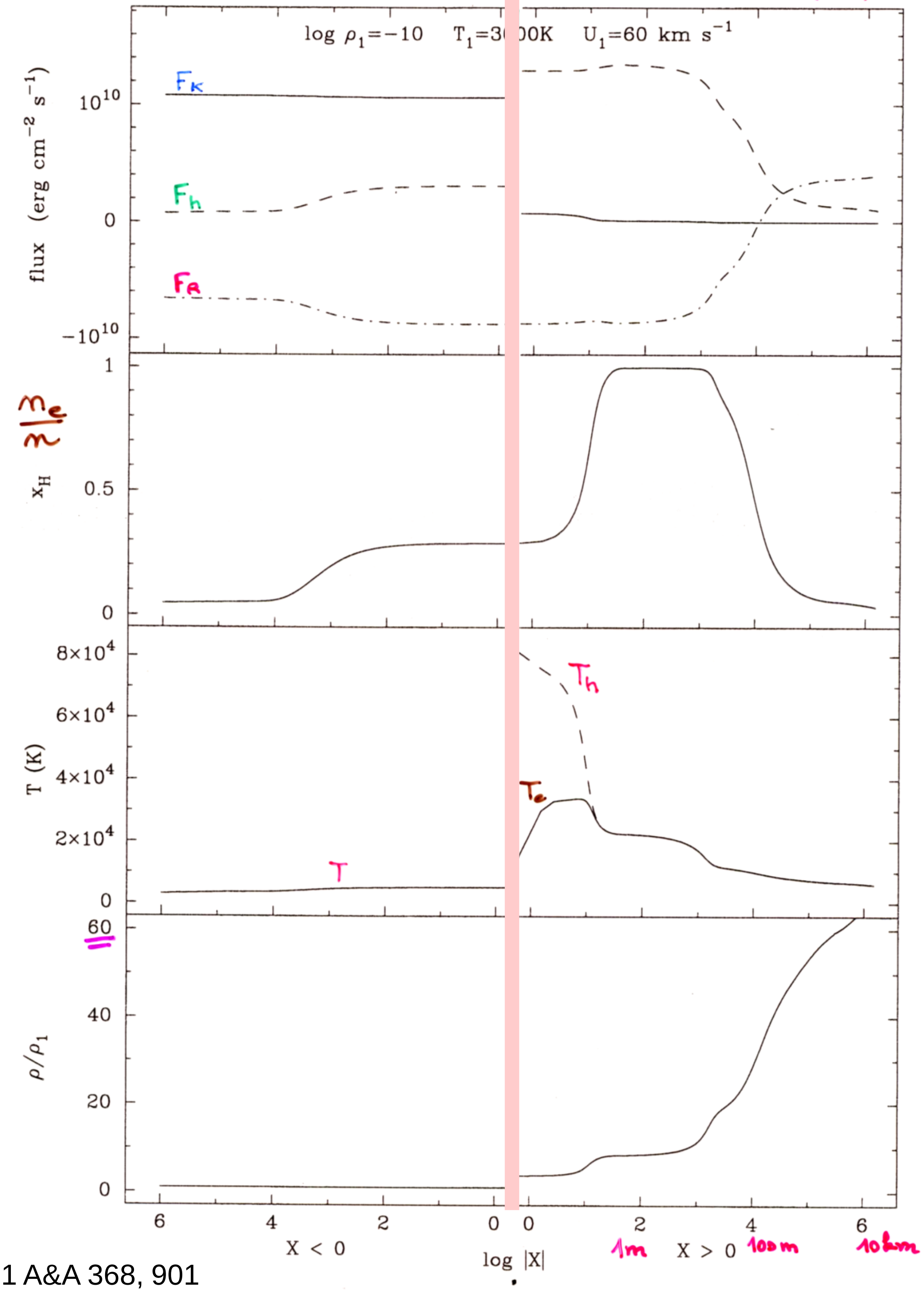
UV flux

radiative shock wake

recombinations giving the UV flux

→ *self consistent solution*

$M_1 = 6.5$



$$\eta_\rho = \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{2+(\gamma-1)M_1^2}$$

$$\eta_\rho \to \frac{\gamma+1}{\gamma-1} \text{ if } M_1 \to \infty$$

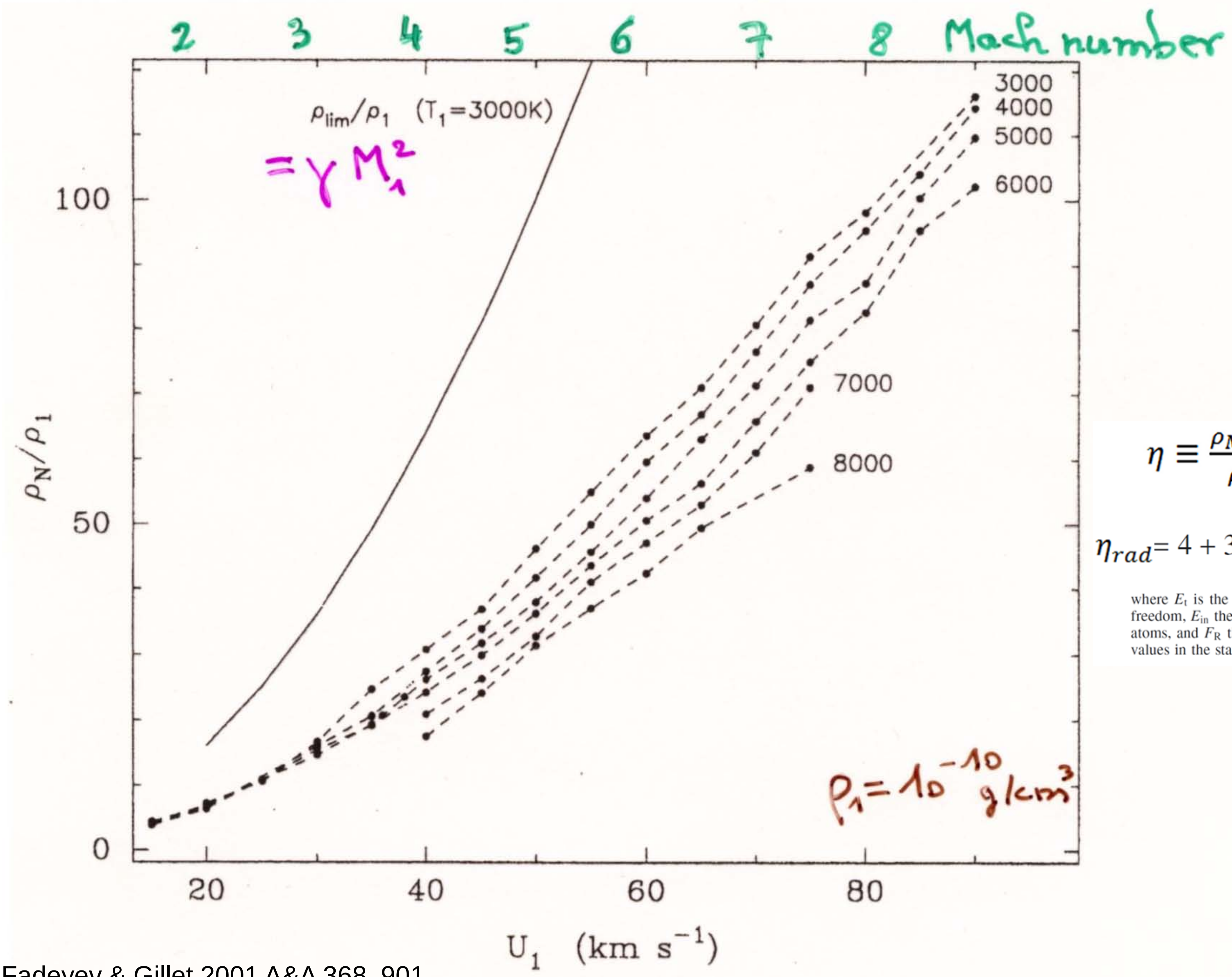
$$\eta \equiv \frac{\rho_{Max}}{\rho_1} = \eta_{rad} \to \gamma M^2$$

$$\eta_{rad} = 4 + 3\frac{E_{\rm in} - E_{\rm in1}}{E_{\rm t}} + 3\frac{F_{\rm R} - F_{\rm R1}}{\rho U E_{\rm t}}$$

where $E_{\rm t}$ is the specific energy in the translational degrees of freedom, $E_{\rm in}$ the specific energy of excitation and ionization of atoms, and $F_{\rm R}$ the radiation flux. The subscript 1 refers to the values in the state ahead of the shock.

Fadeyev & Gillet 2001 A&A 368, 901

Final compression ratio ρ_N/ρ_1 at the postshock outer boundary X_N of shock

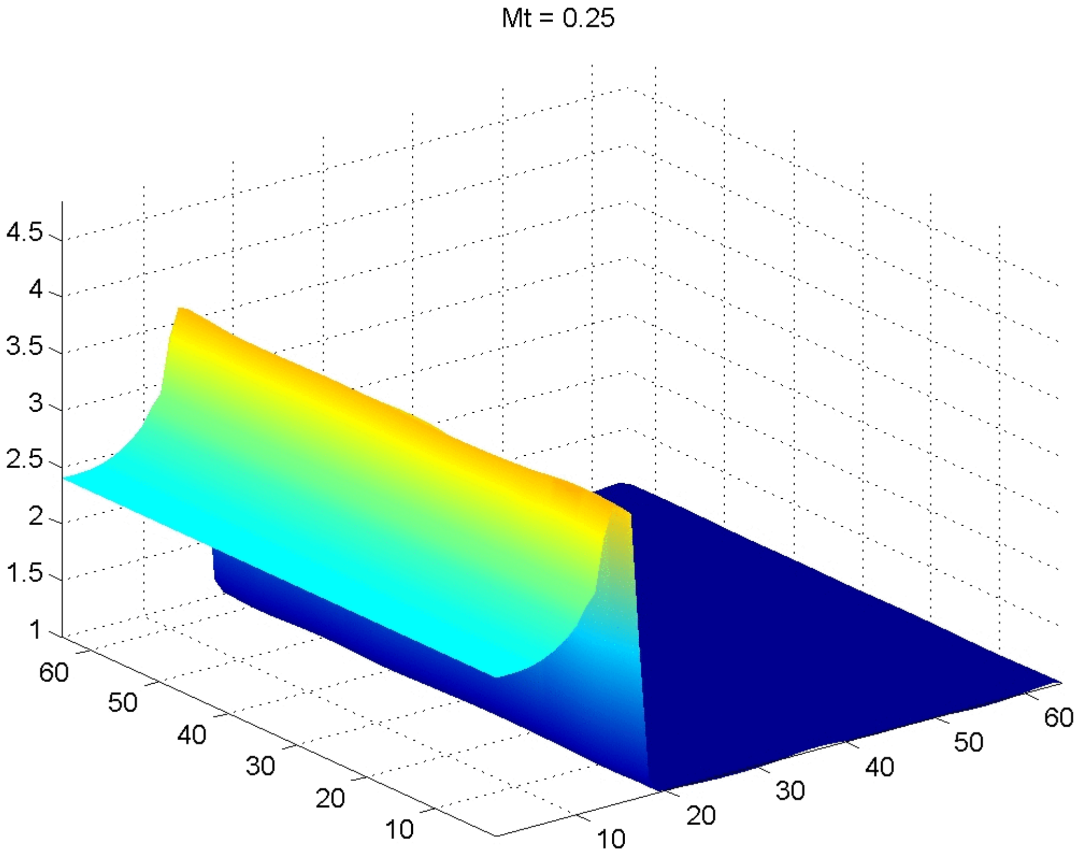


$$\eta \equiv \frac{\rho_{Max}}{\rho_1} = \eta_{rad} \to \gamma M^2$$

$$\eta_{rad} = 4 + 3\frac{E_{\rm in} - E_{\rm in1}}{E_{\rm t}} + 3\frac{F_{\rm R} - F_{\rm R1}}{\rho U E_{\rm t}}$$

where E_t is the specific energy in the translational degrees of freedom, E_{in} the specific energy of excitation and ionization of atoms, and F_R the radiation flux. The subscript 1 refers to the values in the state ahead of the shock.

Fadeyev & Gillet 2001 A&A 368, 901



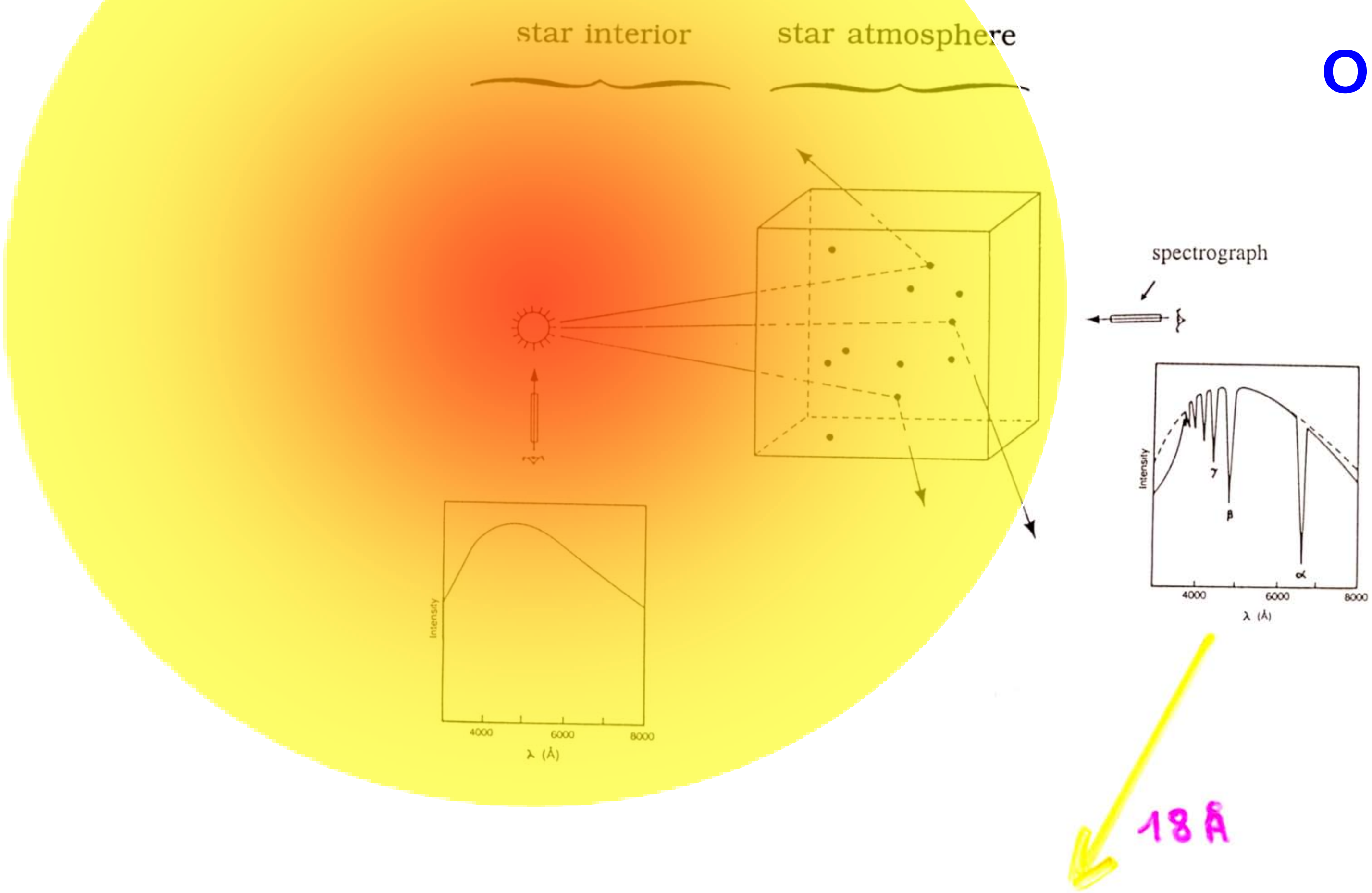
3D simulation of shock wave with turbulence

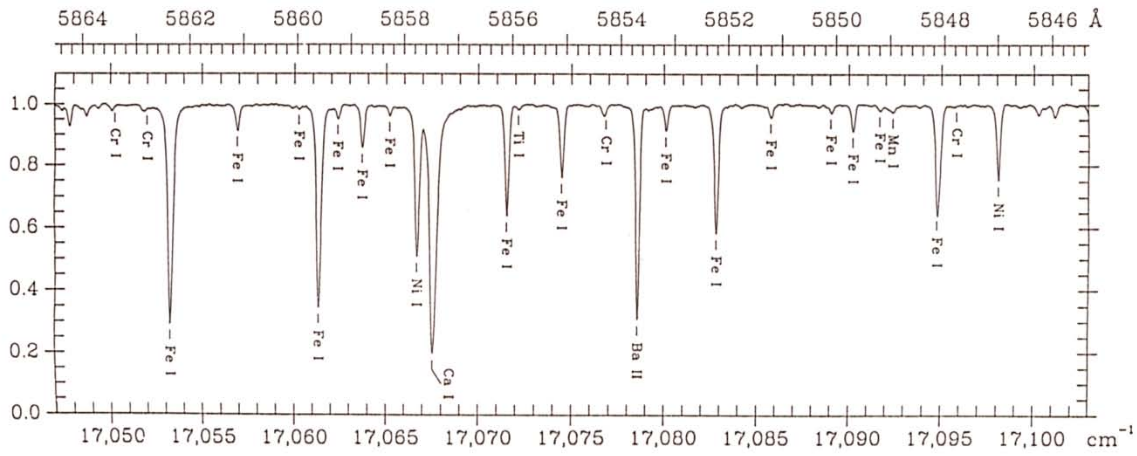
using detailed chemistry. M = 4.156 Mt = 0.25.

Master of science in aerospace engineering by H.Narayanan Nagarajan 2009 University of Texas at Arlington.

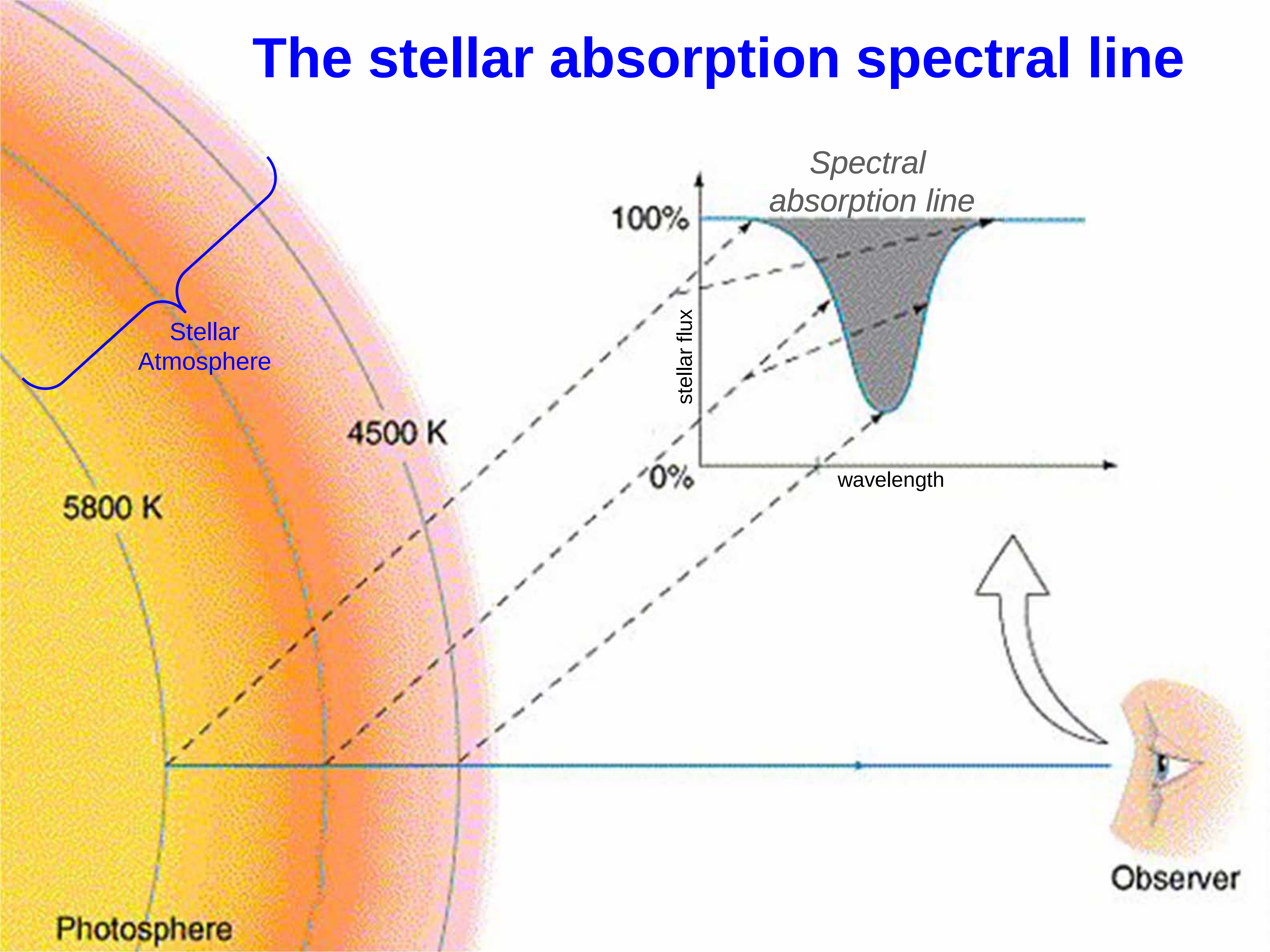
Spectroscopy
Of
Pulsating Stars

Origin of stellar photons ?

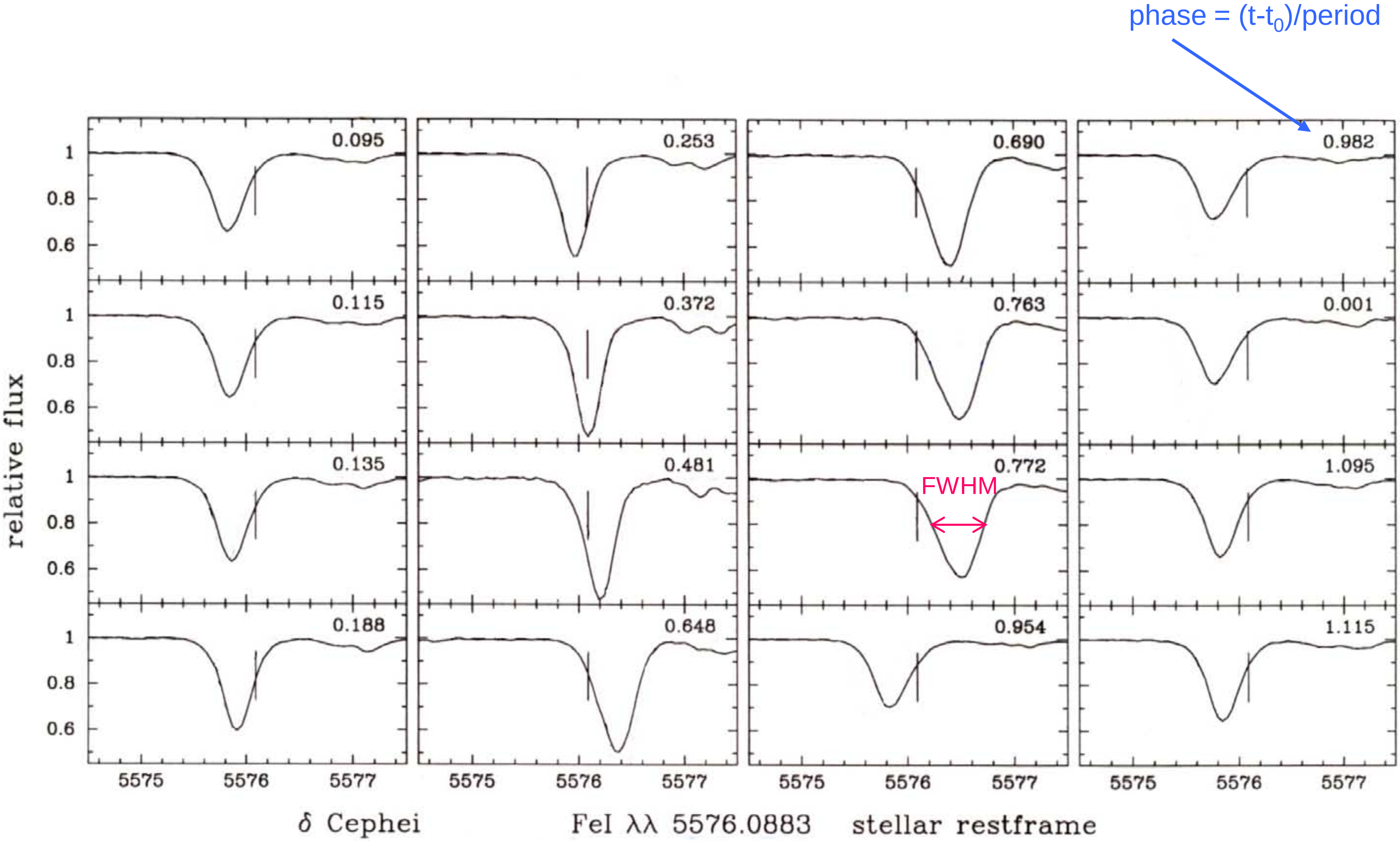




The stellar absorption spectral line




SOPHIE
SOPHIE
SOPHIE

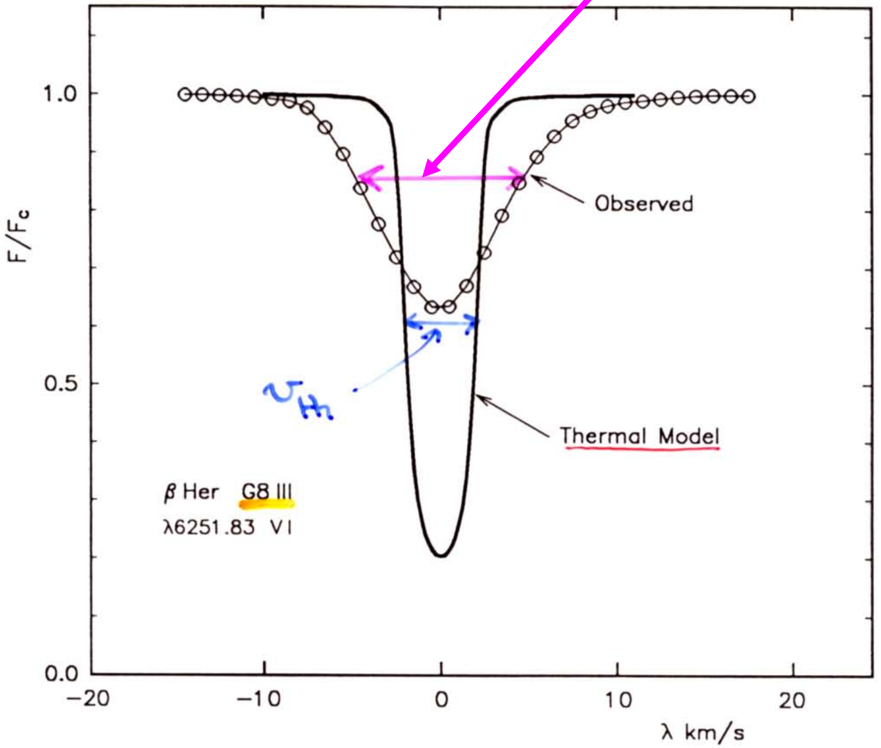


phase = $(t-t_0)$/period

FWHM

turbulence

$$\text{line width} = \sqrt{V_{\text{th}}^2 + \xi^2}$$



The thermal profile computed from a model photosphere does not look much like the observed one.

$$\text{line width} = \sqrt{V_{\text{th}}^2 + \xi^2} = \Delta\lambda \times \frac{c}{\lambda}$$

$$\frac{E_{turb}}{E_{th}} \approx \frac{\xi^2}{V_{th}^2} = \frac{1}{5}$$

Profil des raies spectrales

Effets intrinsèques

- **Largeur naturelle**

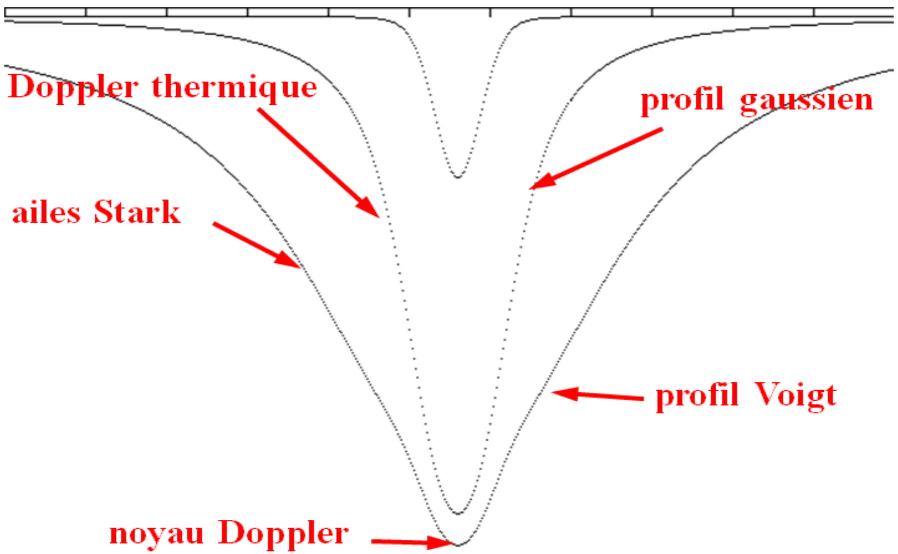
  $\Delta\lambda \sim 0.0001$ A $\propto 1/ t_{vie}$ avec $t_{vie} \sim 10^{-8}$ s
  Profil lorentzien

- **Élargissement Doppler thermique**

  $\Delta\lambda \sim 0.5$ A $\propto \sqrt{}$ (T/m)
  Profil gaussien

- **Élargissement "Stark" par collision**

  $\Delta\lambda > 10$ A $\propto$ densité . section de collision
  Profil "plutôt" lorentzien (Holtsmark)



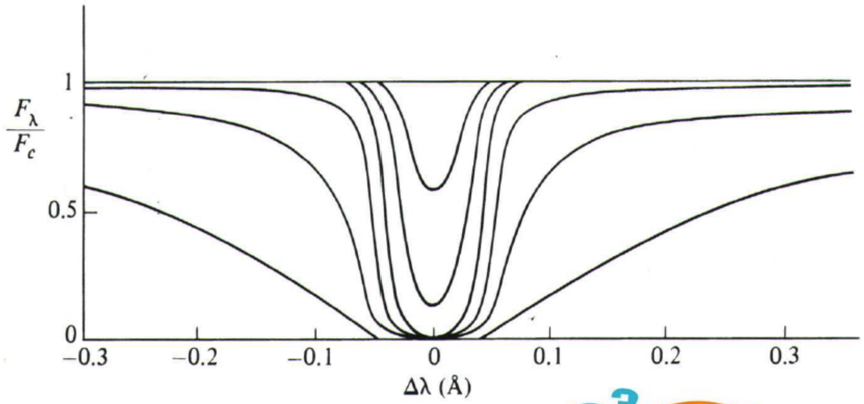
Causes extérieures

- **Élargissement Doppler dynamique**

  rotations, expansions, etc.
  $\Delta\lambda$ de 0 à >1000Å $\propto$ v/c où z

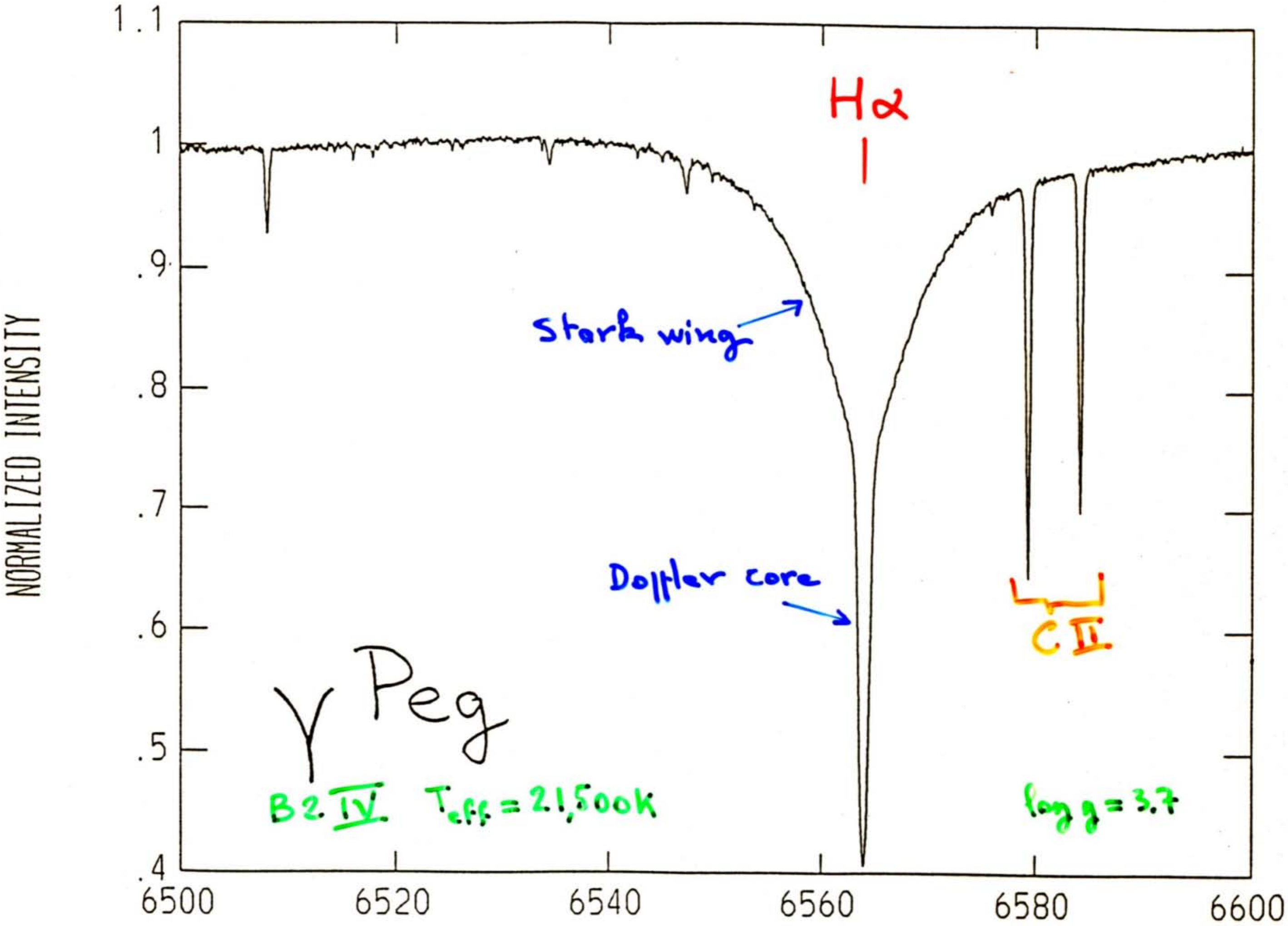
- **Élargissement par levée de dégénérescence**

  champ magnétique (effet Zeeman), etc.
  $\Delta\lambda \sim 1$Å $\propto$ champ magnétique



- **Élargissement instrumental**

  $\Delta\lambda$ = résolution $\propto$ min (1/dimension du réseau-échantillonnage)

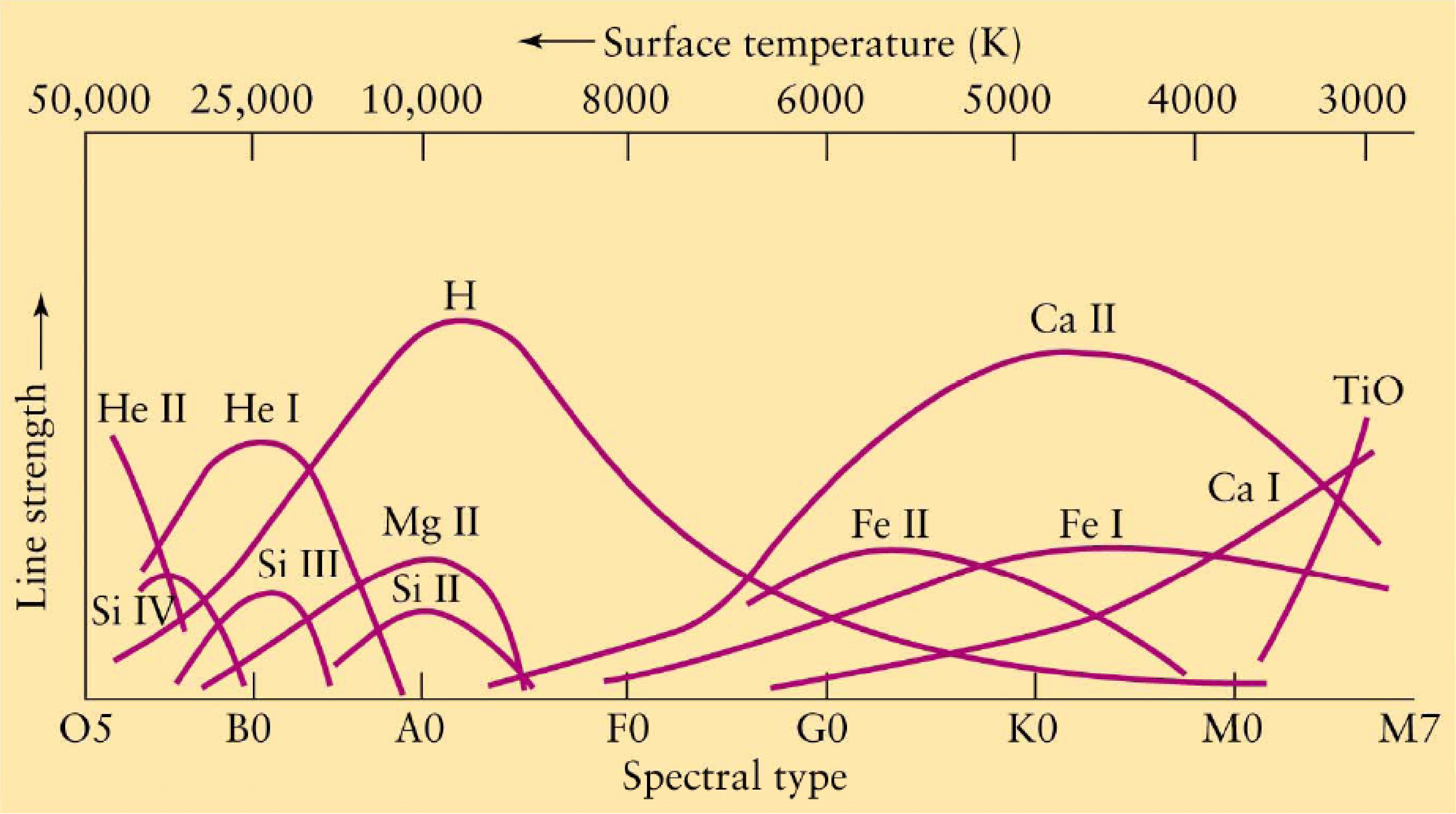


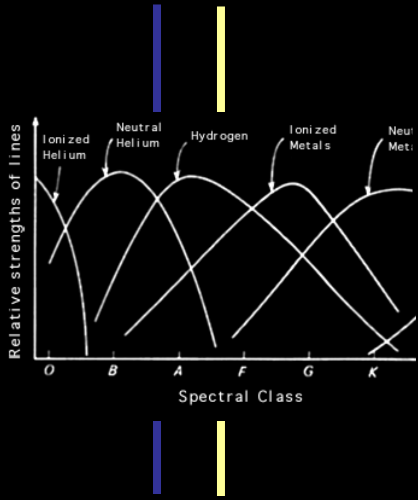
CFH

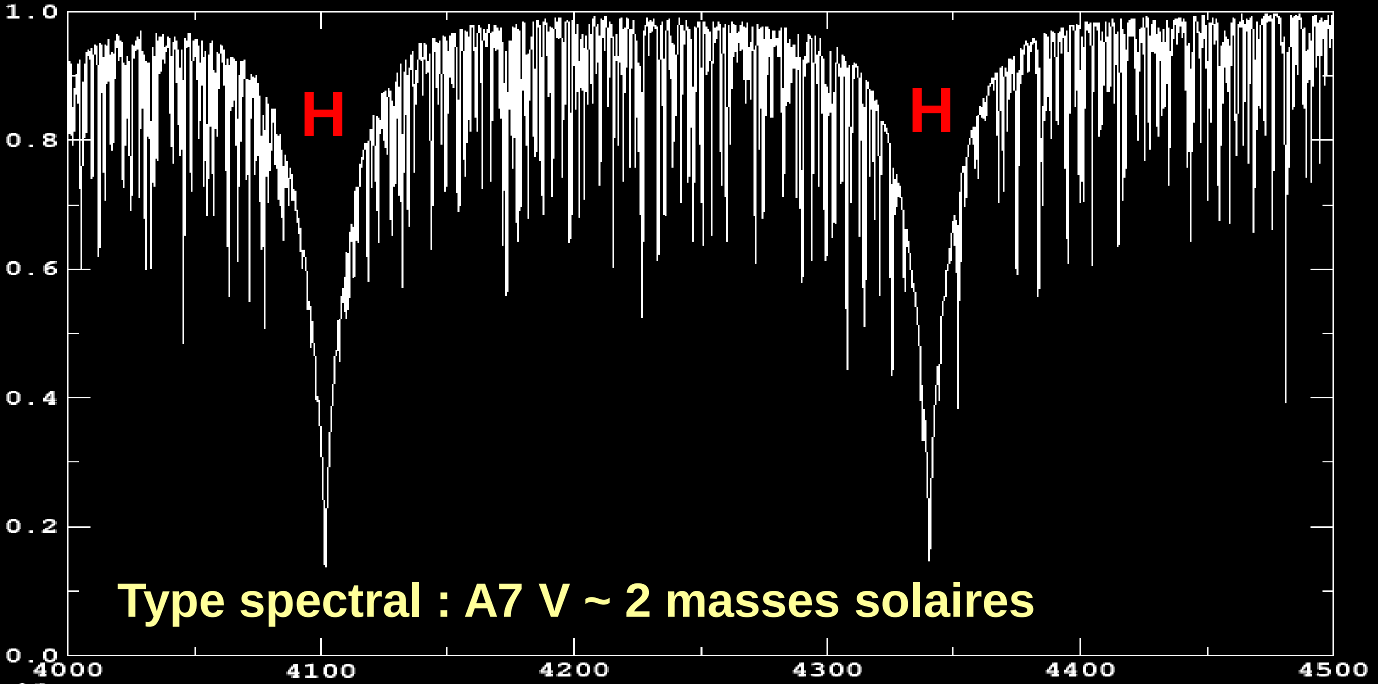
R=33,000

$\Delta\lambda = 0.2$ Å

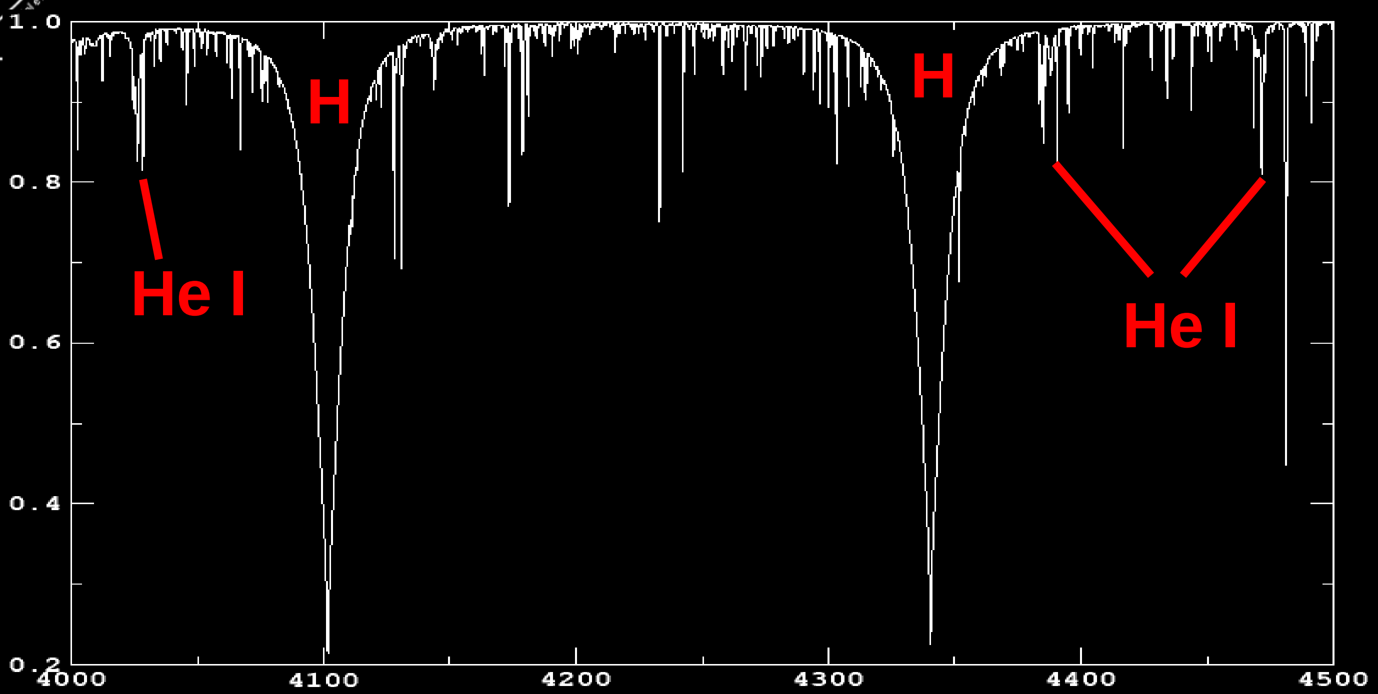
Ionization via Temperature





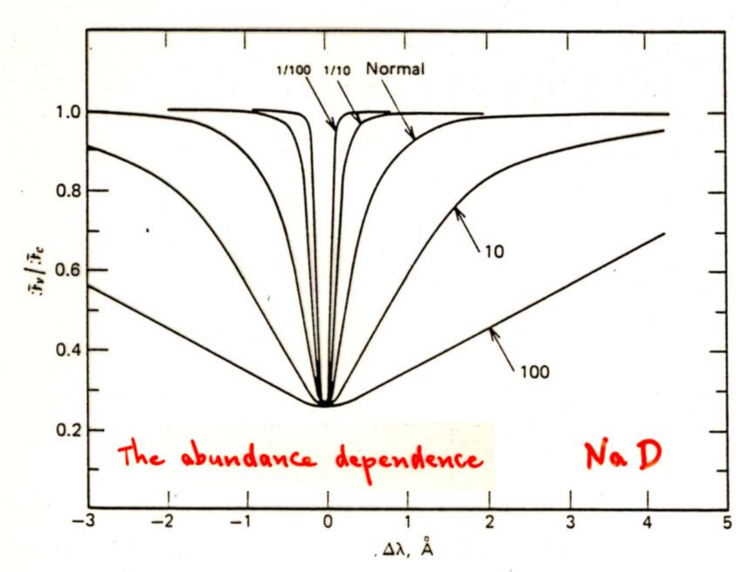


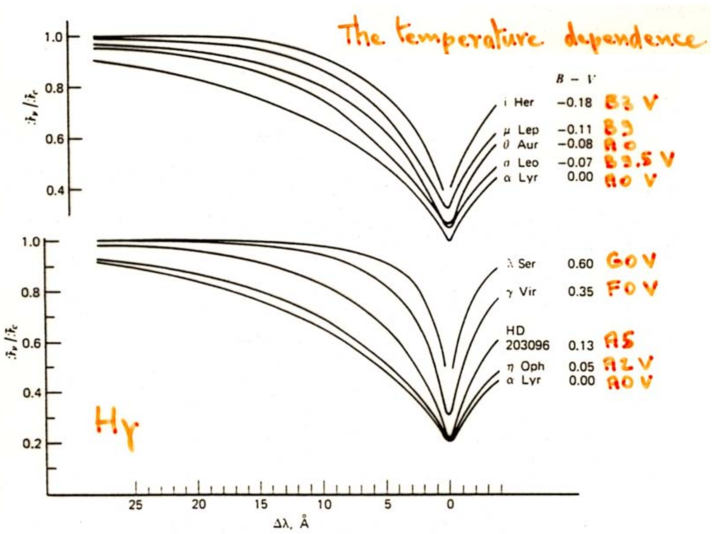
Type spectral : A7 V ~ 2 masses solaires

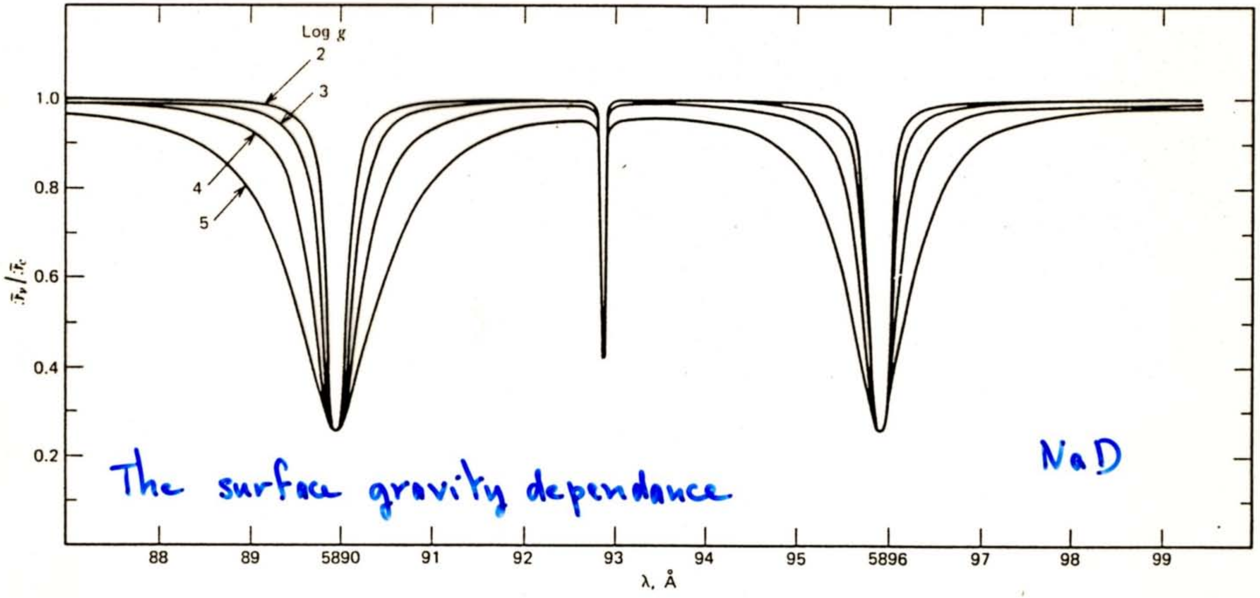


Type spectral : B8 V ~ 3 masses solaires

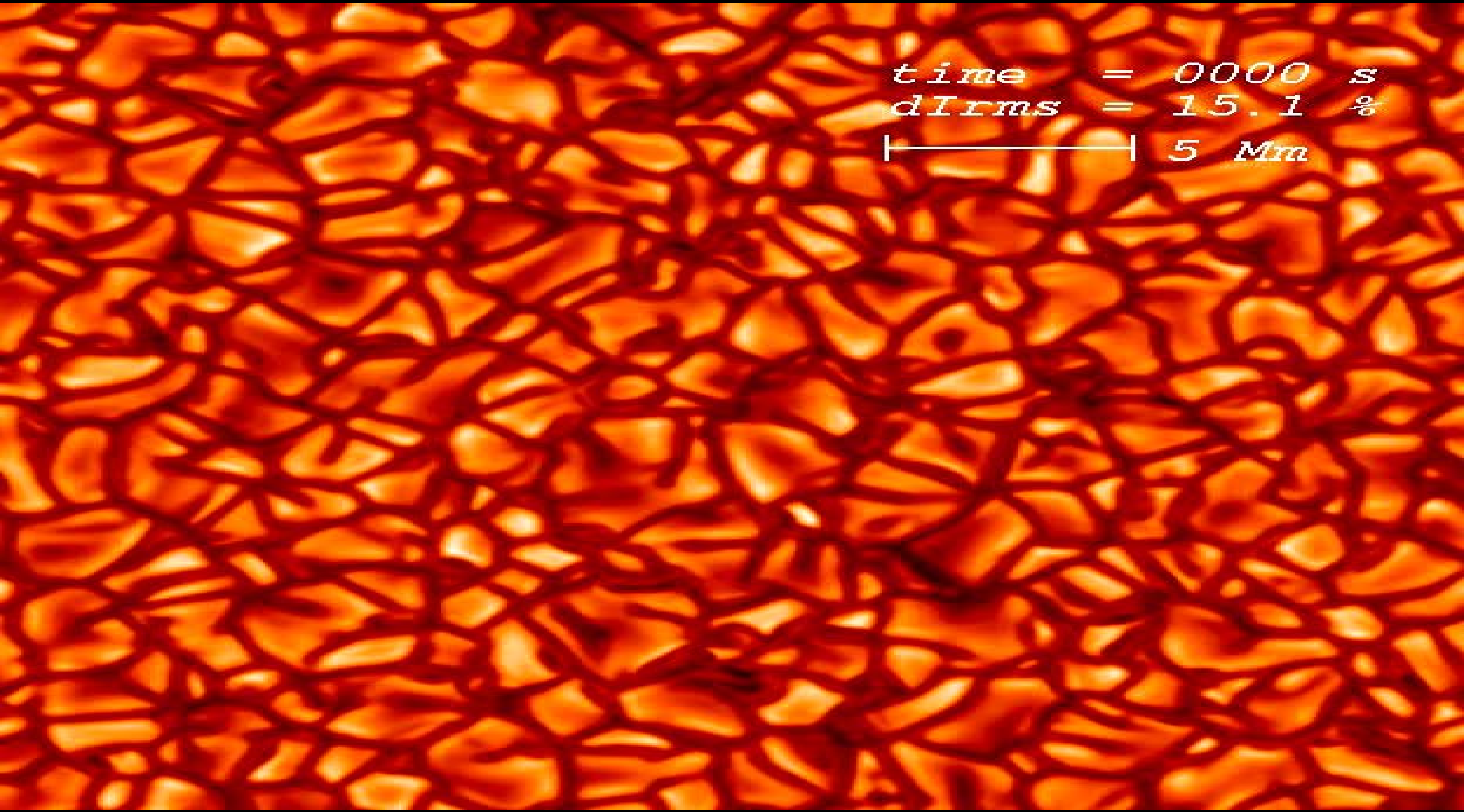
The behaviour of the line strength







STELLAR GRANULATION



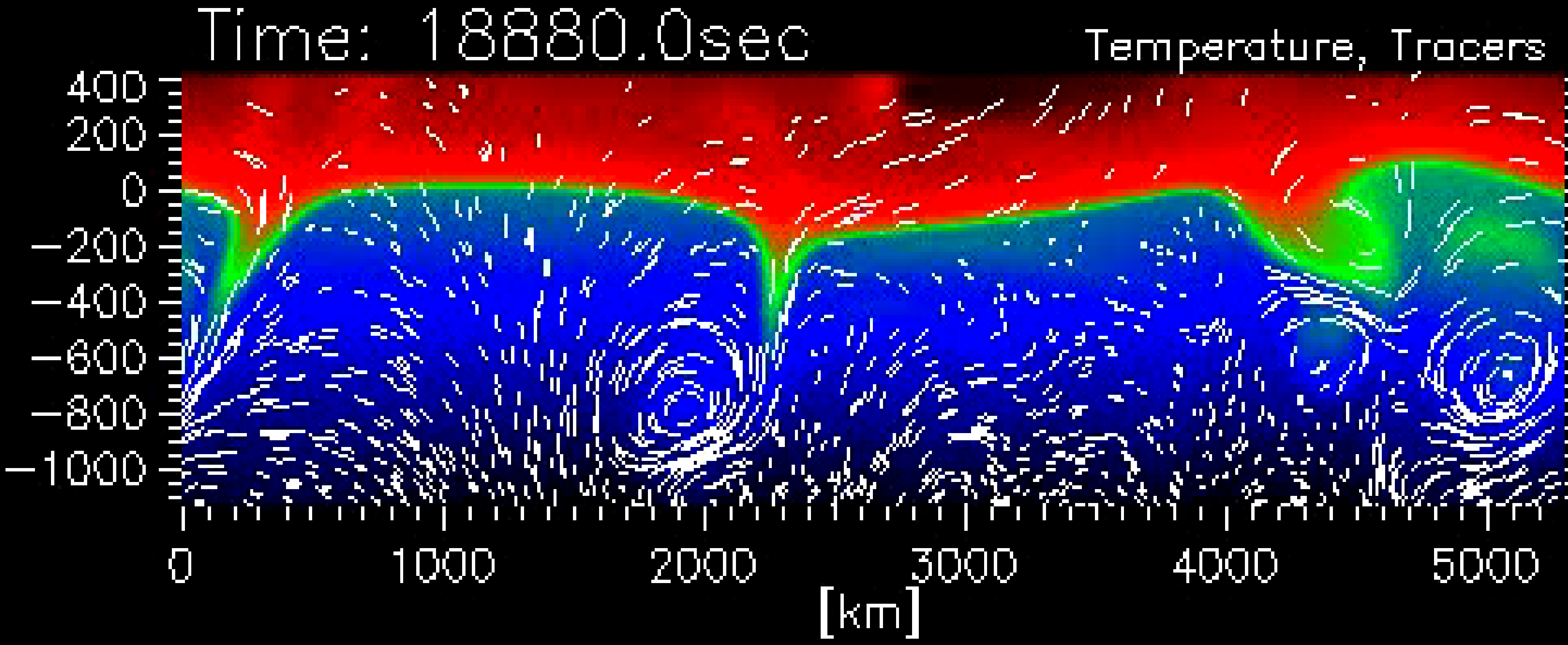
Hans-Günter Ludwig (Lund)

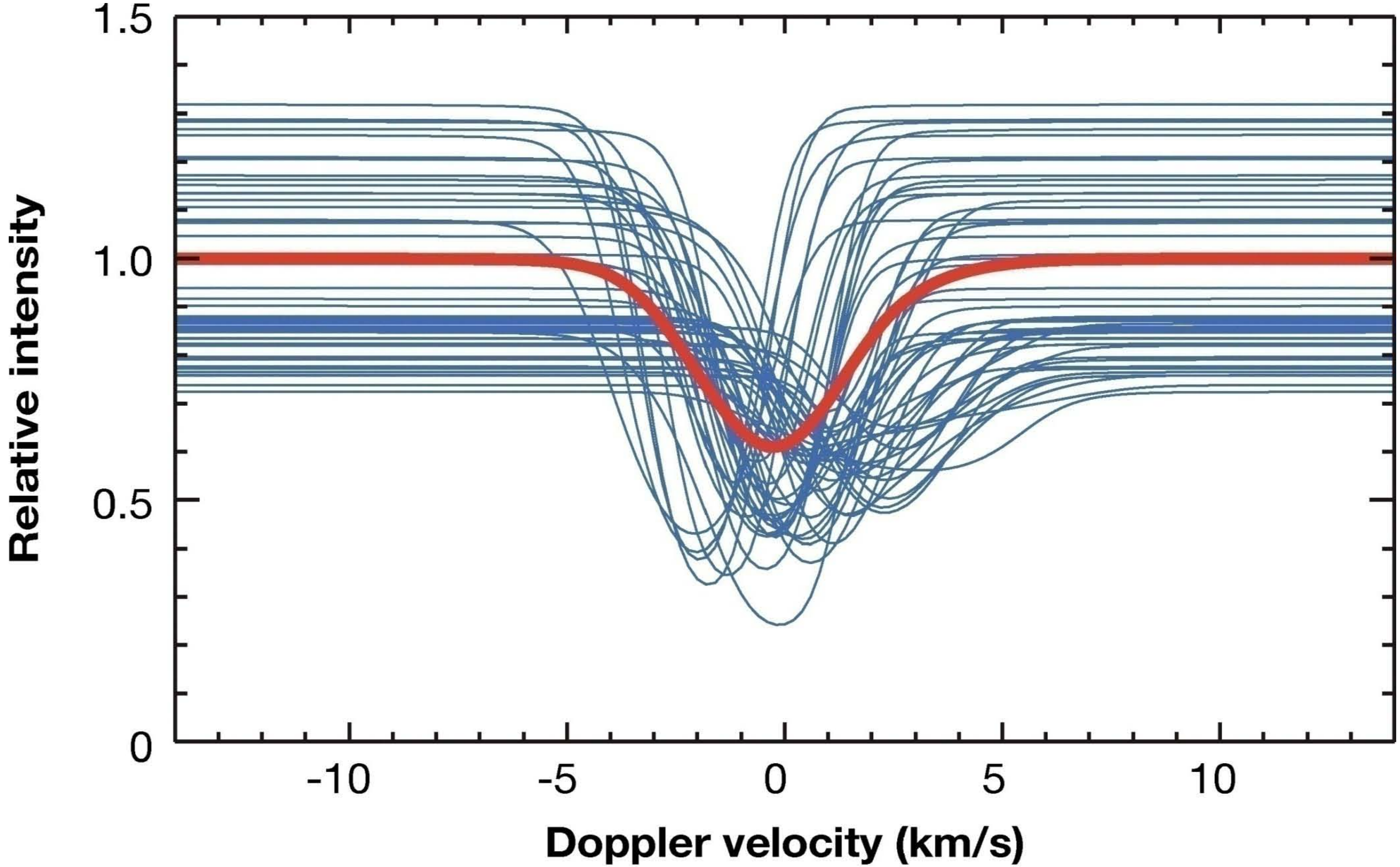
STELLAR CONVECTION

Sun (L71D09), T_{eff}=5770 K, logg=4.44

212 x 106 grid points, 11540 s (Δt=20 s)

Matthias Steffen, Bernd Freytag



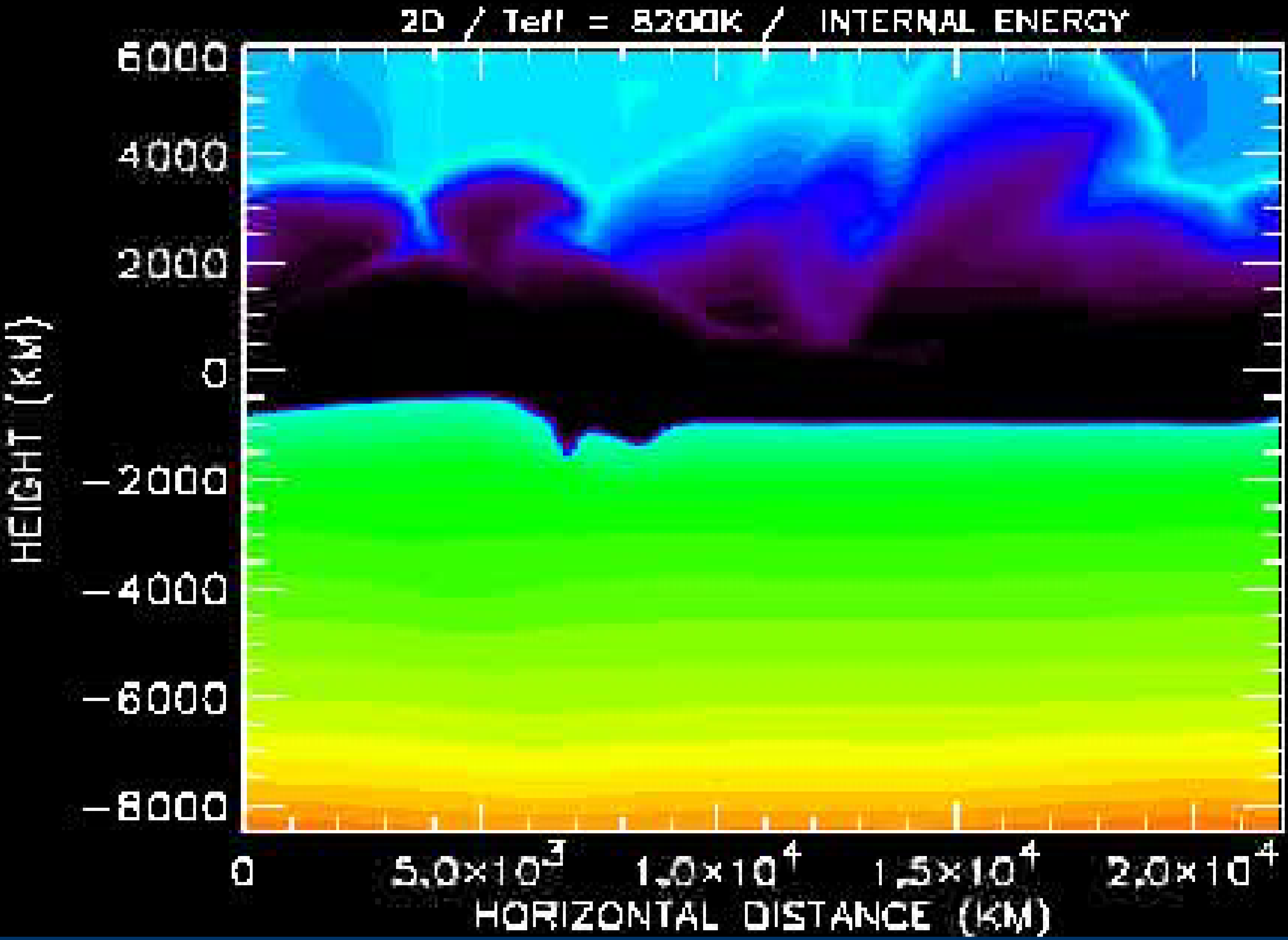


Spatially resolved line profiles of the Fe I 608.27 nm line in a 3-D solar simulation.
Thick red line is the spatially averaged profile.
Steeper temperature gradients in upflows tend to make their blue-shifted lines stronger

M.Asplund: *New Light on Stellar Abundance Analyses: Departures from LTE and Homogeneity*, Ann.Rev.Astron.Astrophys. **43**, 481

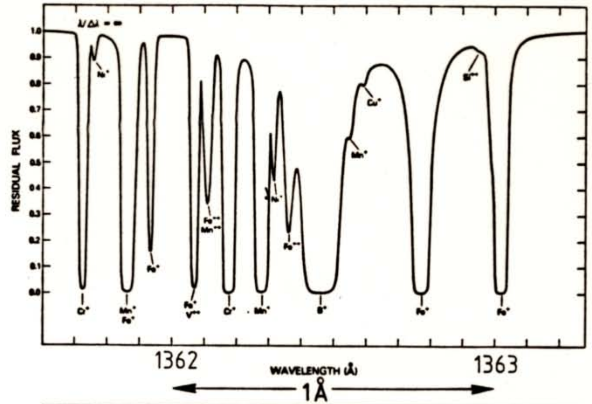
Betelgeuse M2 Iab T_{eff}=3300K

Freytag et al Astron. Nachr. 323, 213, 2002



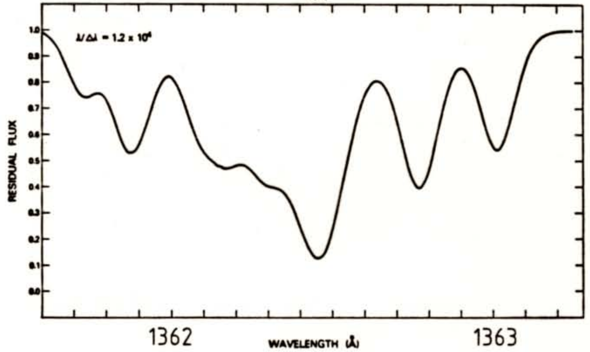
Atmospheric shockwaves *(Hartmut Holweger, Kiel)*

Spectral Resolution



Theoretical Spectrum

$R \equiv \frac{\lambda}{\Delta\lambda} = \infty$

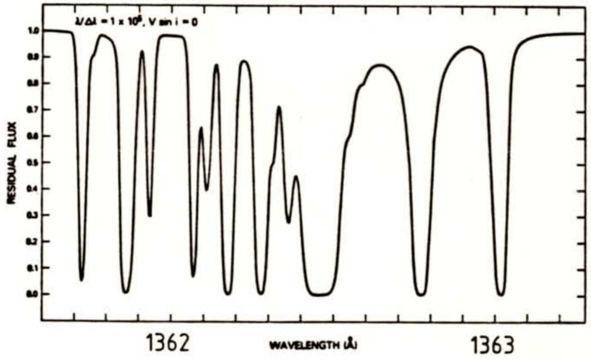


IUE

High Resolution Mode

R=12,000

$\Delta\lambda$=114mÅ=25km/s



Space Telescope

High Resolution Spectrograph

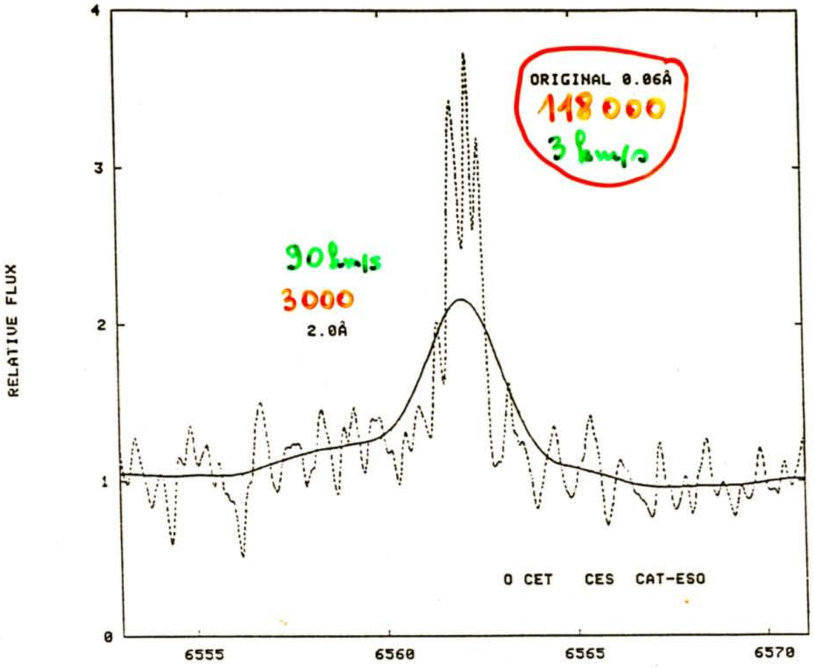
R=100,000

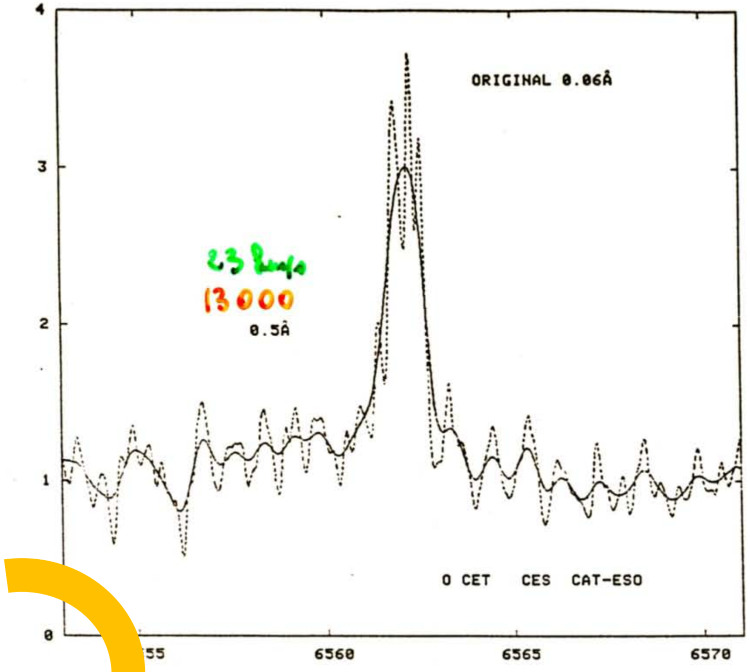
$\Delta\lambda$= 14mÅ=3km/s

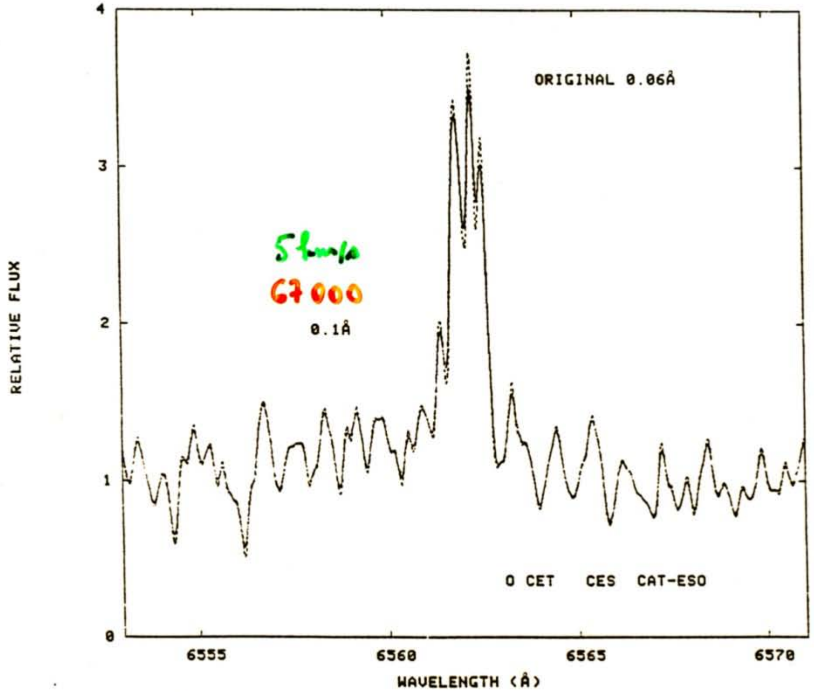
In each case S/N = ∞ and no Rotation.

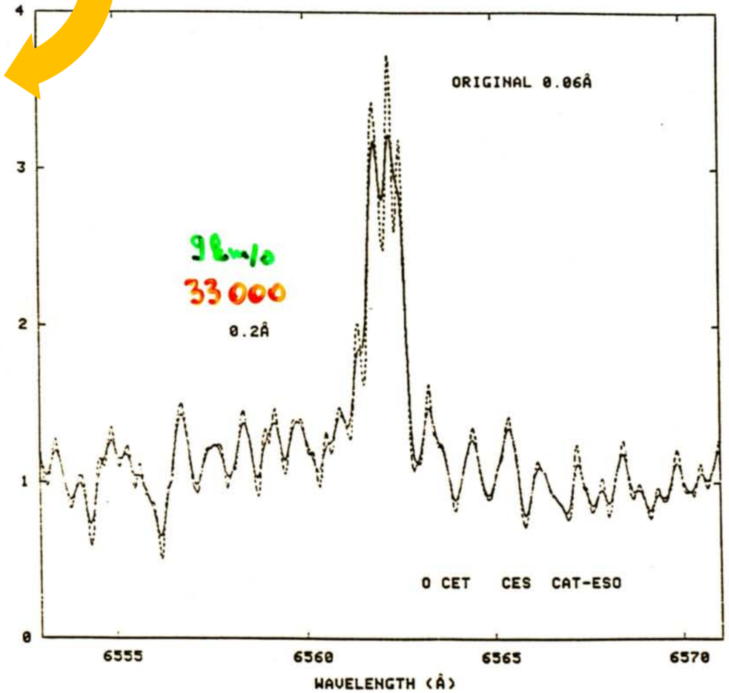
From J.C. Brandt in "The Space Telescope Observatory"

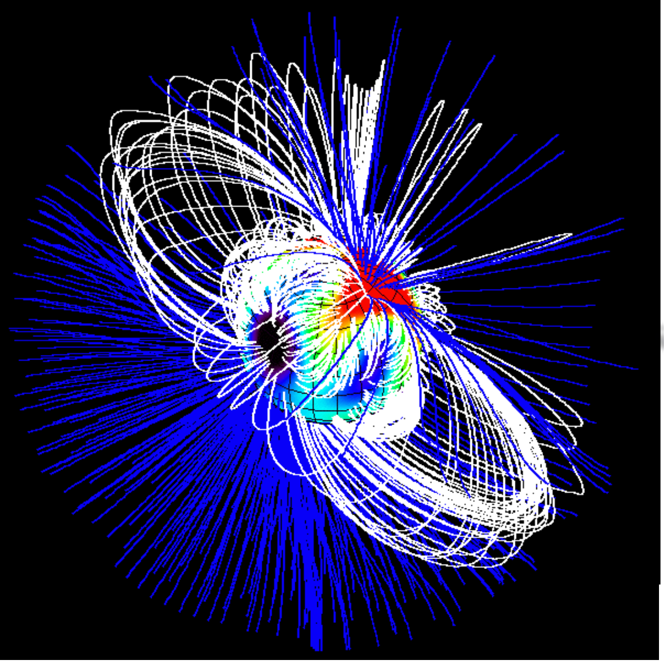
Ed. D.N.B. Hall, 1982, NASA-CP-2244 p.76


ORIGINAL 0.06Å
118 000
3 km/s
90 km/s
3000
2.0Å
O CET CES CAT-ESO
RELATIVE FLUX
0
1
2
3
4
6555
6560
6565
6570

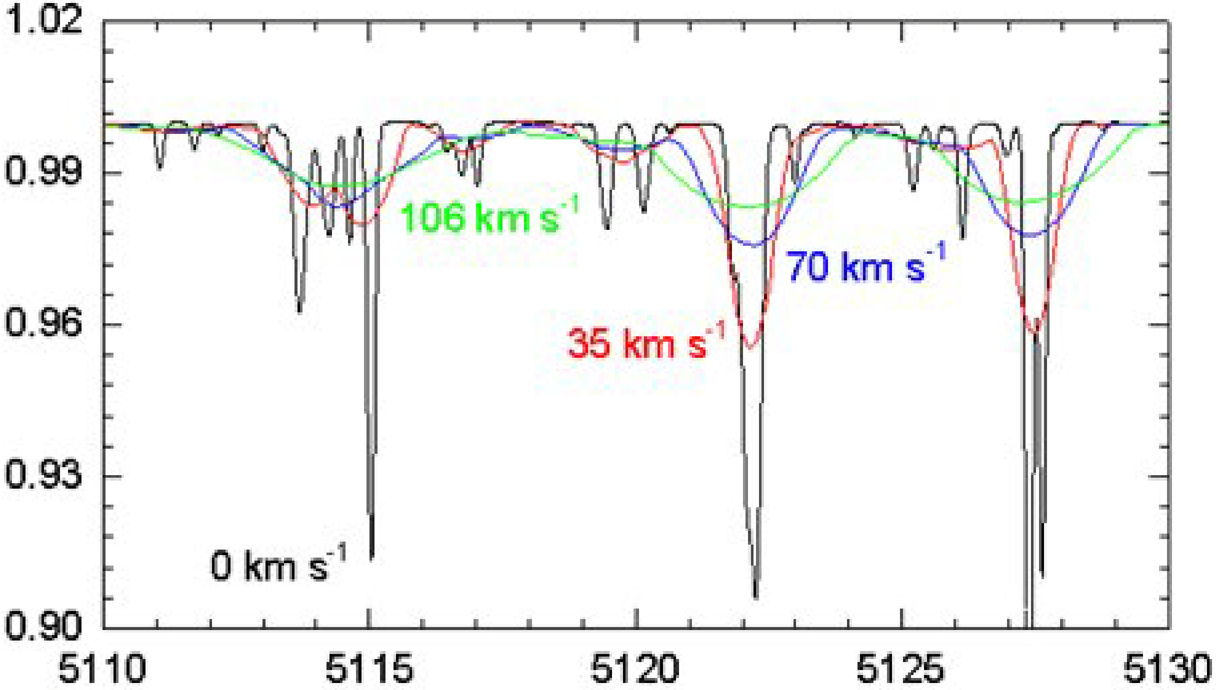

ORIGINAL 0.06Å
23 km/s
13 000
0.5Å
O CET CES CAT-ESO
0
1
2
3
4
6555
6560
6565
6570

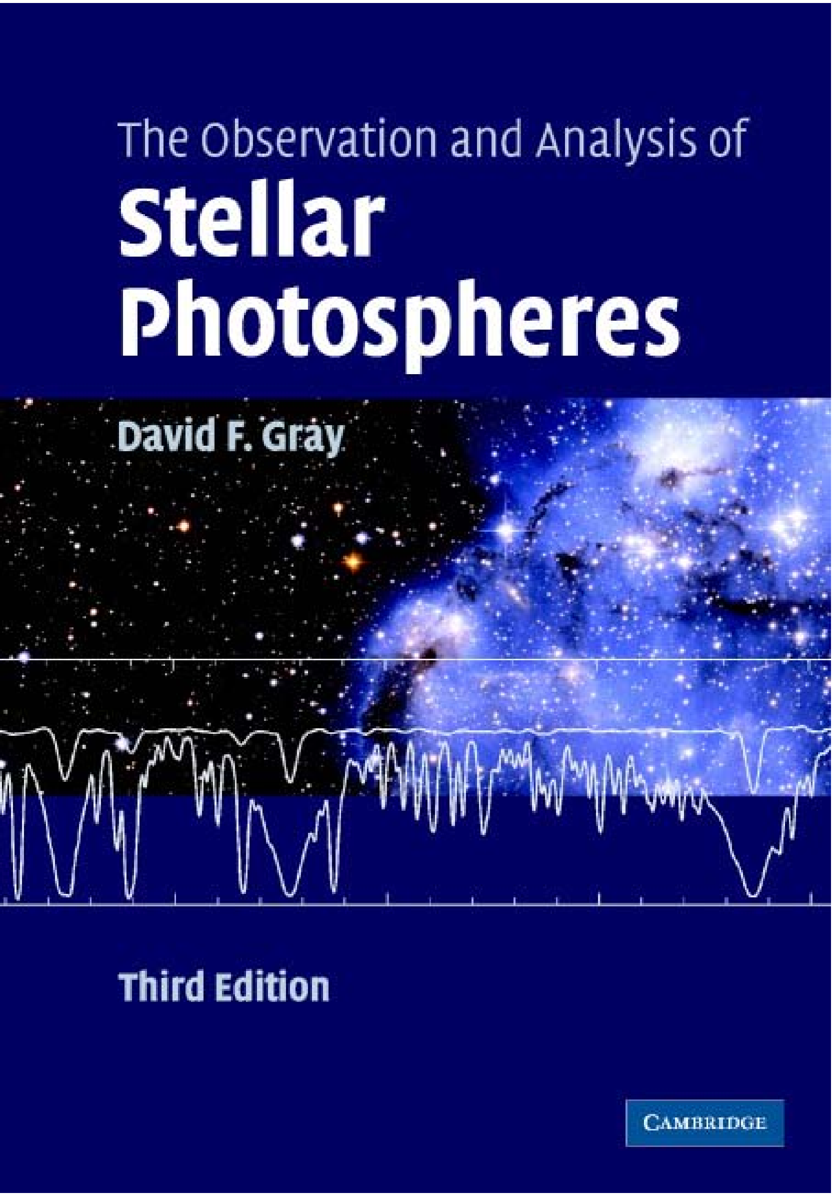

ORIGINAL 0.06Å
5 km/s
67 000
0.1Å
O CET CES CAT-ESO
RELATIVE FLUX
0
1
2
3
4
6555
6560
6565
6570
WAVELENGTH (Å)


ORIGINAL 0.06Å
9 km/s
33 000
0.2Å
O CET CES CAT-ESO
0
1
2
3
4
6555
6560
6565
6570
WAVELENGTH (Å)



Et la rotation de l'étoile…





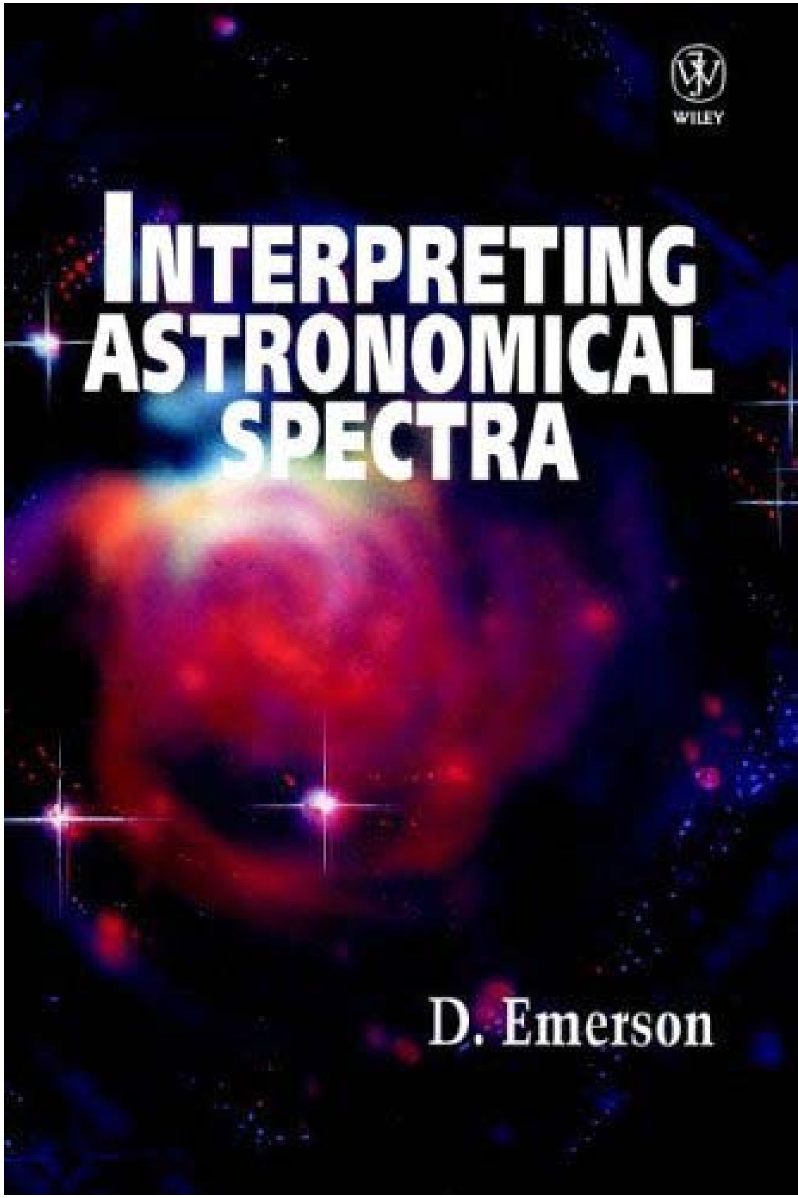
The Observation and Analysis of

Stellar Photospheres

David F. Gray

Third Edition

CAMBRIDGE

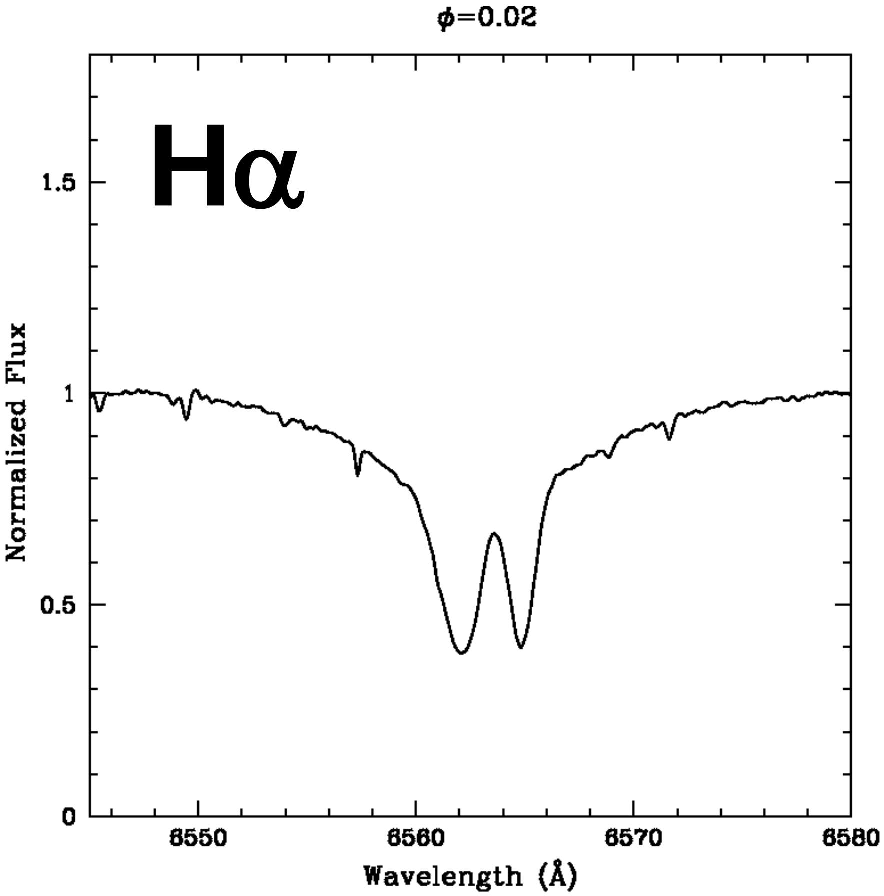


WILEY

INTERPRETING ASTRONOMICAL SPECTRA

D. Emerson

RR Lyrae @ R = 27,000 and 2.5 m



- 2.5 m telescope
Las Campanas Observatory

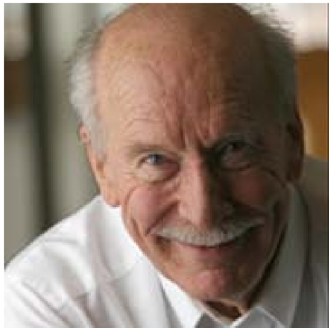
- R = 27,000

-Time resolution: 3-10 min

- S/N = 20

- 3500-9000 A

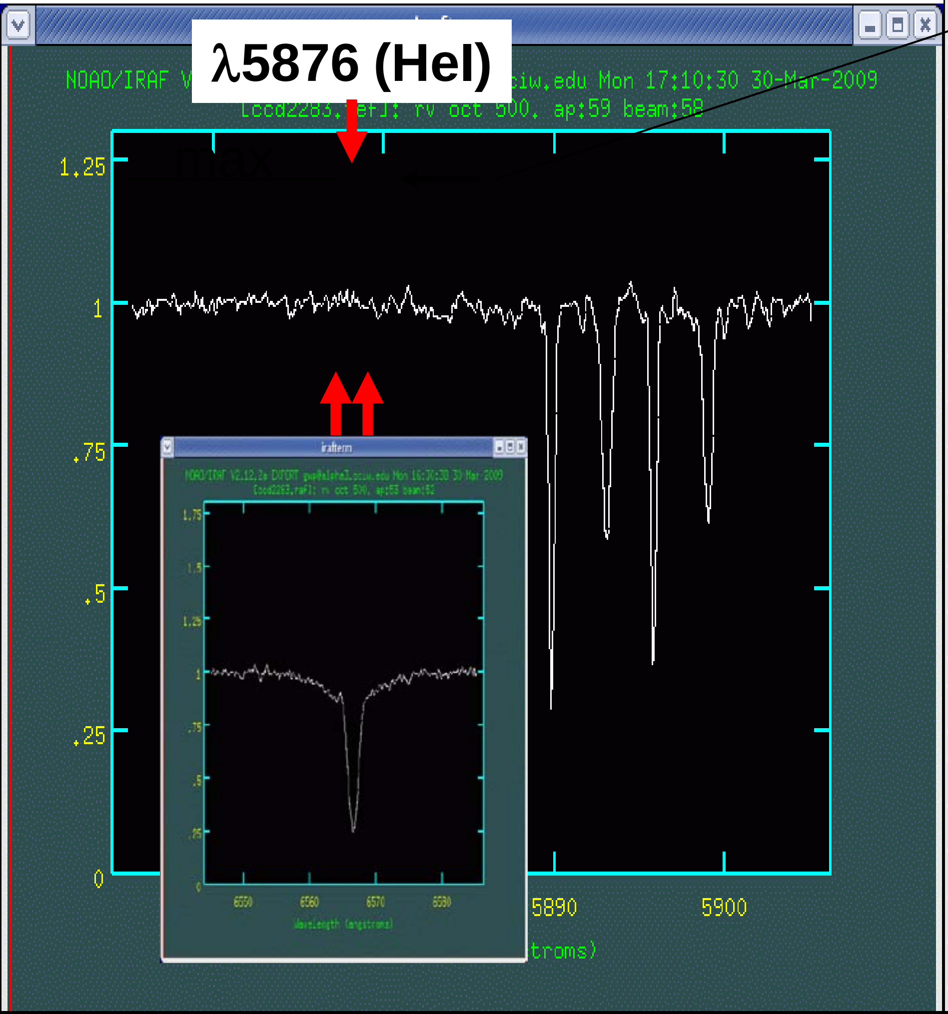
The evolution of Hα *profiles during* pulsation cycles for WY Ant and XZ Aps, as well as for RV Oct based on many more observations, can be viewed as GIF animations in slides 83–86 of the PowerPoint file HNRLecture2009 at ftp: //ftp.obs.carnegiescience.edu/pub/gwp/HNRLecture.



George W. Preston

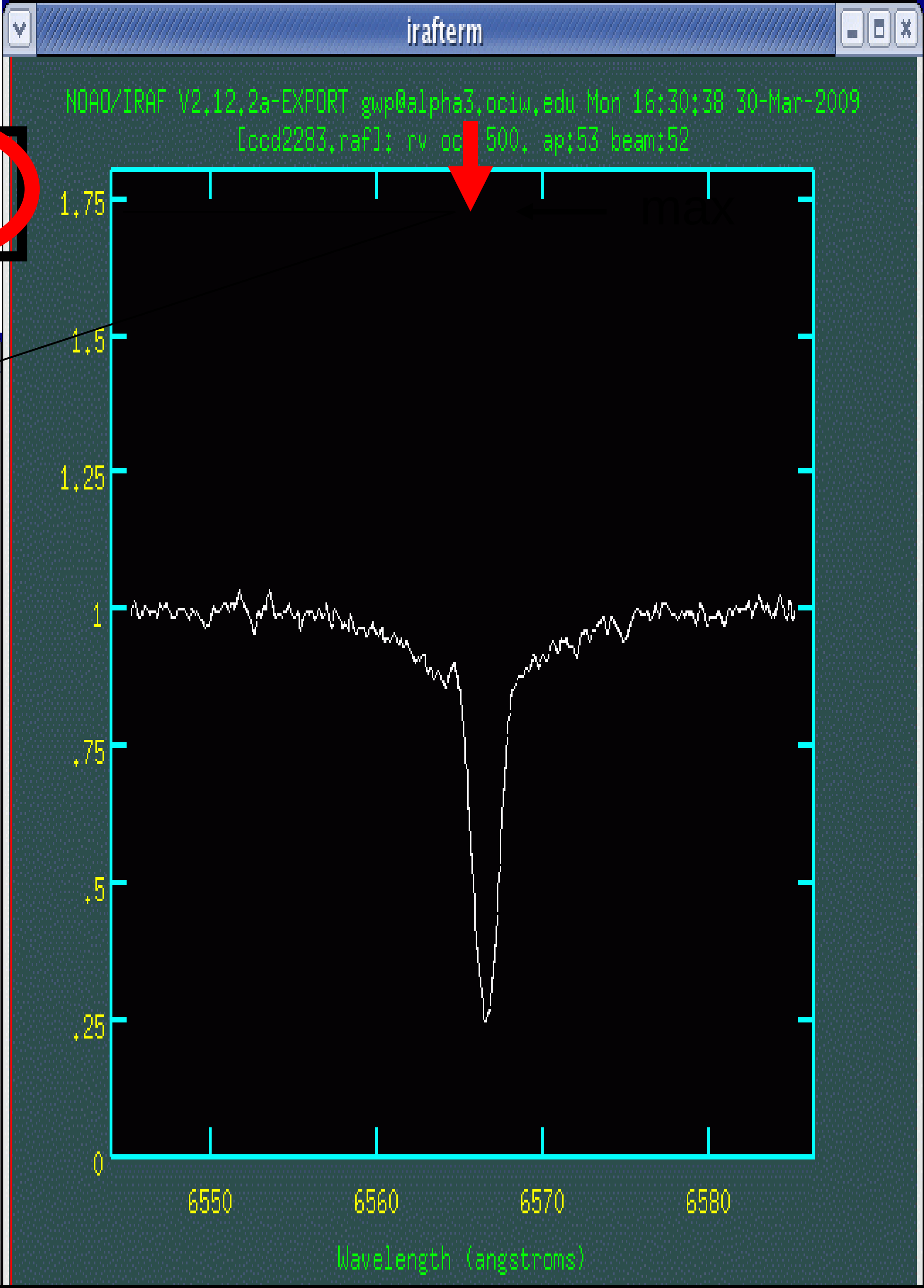
RV Oct in April 2007

I(Hα)/I(He) = 1.75/1.20 = 1.46



λ5876 (HeI)

NOAO/IRAF V ciw.edu Mon 17:10:30 30-Mar-2009
[ccd2283. ef]: rv oct 500. ap:59 beam:58

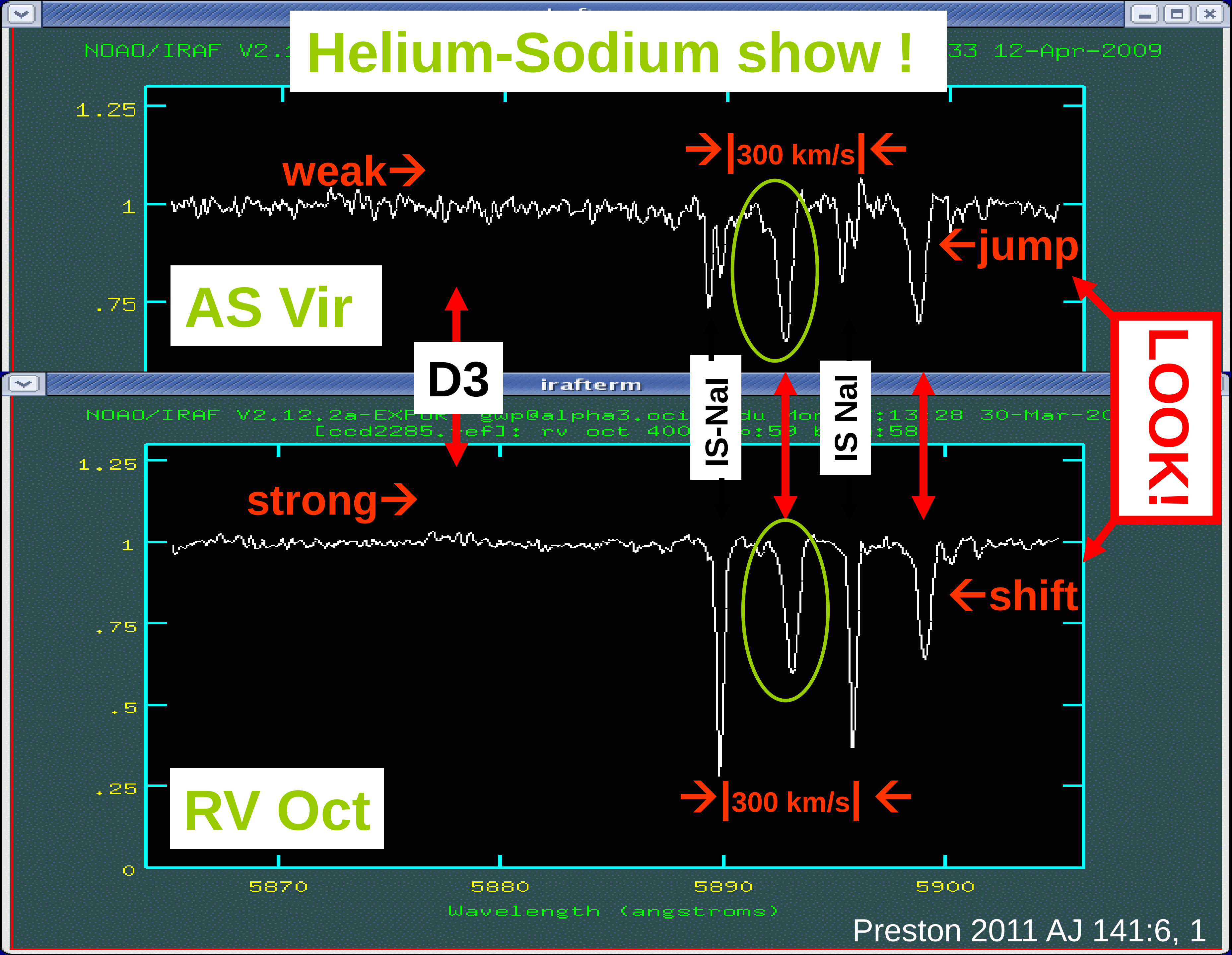


irafterm

NOAO/IRAF V2.12.2a-EXPORT gwp@alpha3.ociw.edu Mon 16:30:38 30-Mar-2009
[ccd2283.raf]: rv oct 500. ap:53 beam:52

Preston 2011 AJ 141:6, 1

Helium-Sodium show !



AS Vir

weak→

→|300 km/s|←

←jump

D3

IS-NaI

IS NaI

LOOK!

RV Oct

strong→

←shift

→|300 km/s|←

Preston 2011 AJ 141:6, 1

RR Lyr @ R = 65,000 and 3.6 m

- 3.6 m telescope
CFHT Observatory

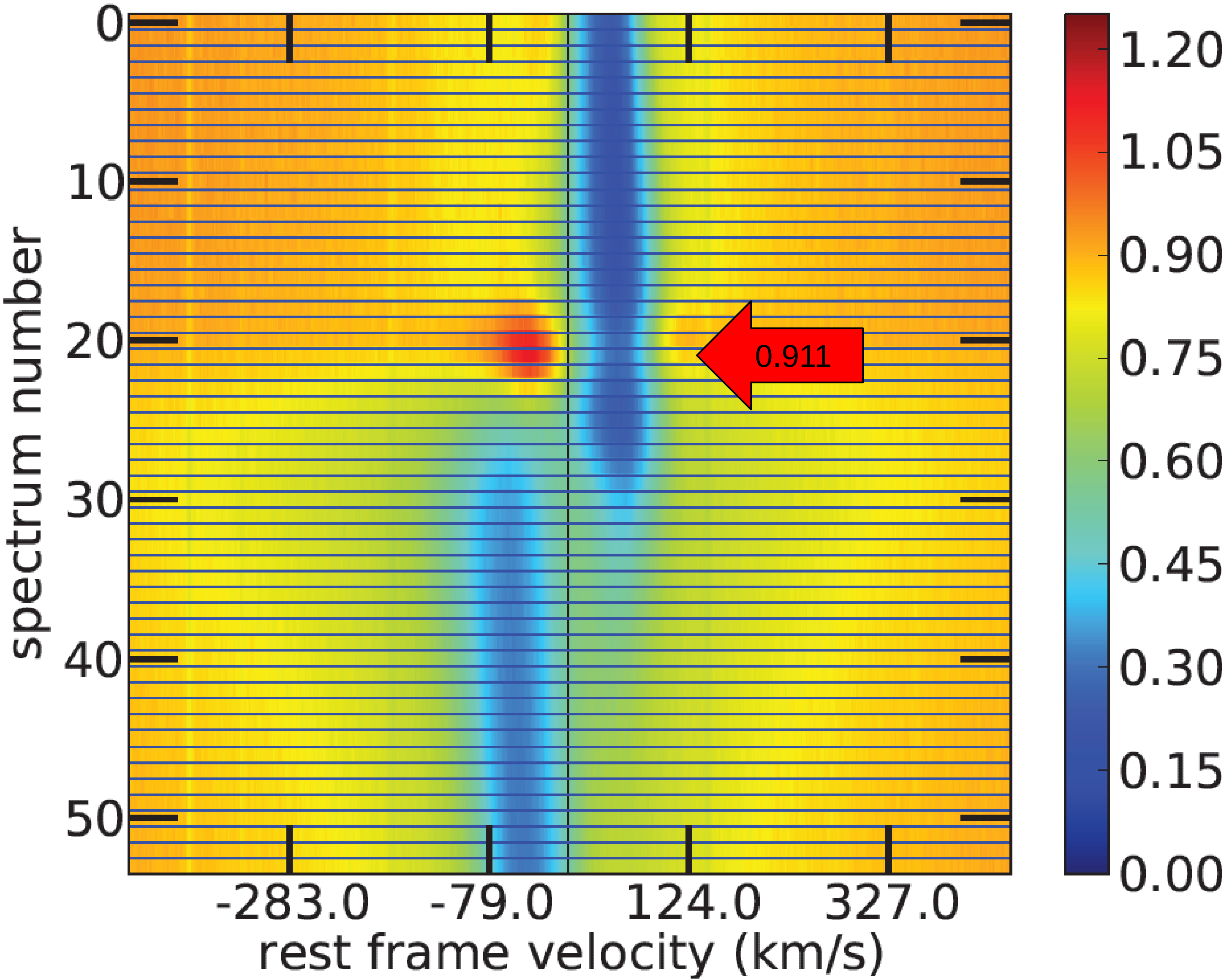
-R = 65,000

-Time resolution: 7 min

-S/N = 180 - 210

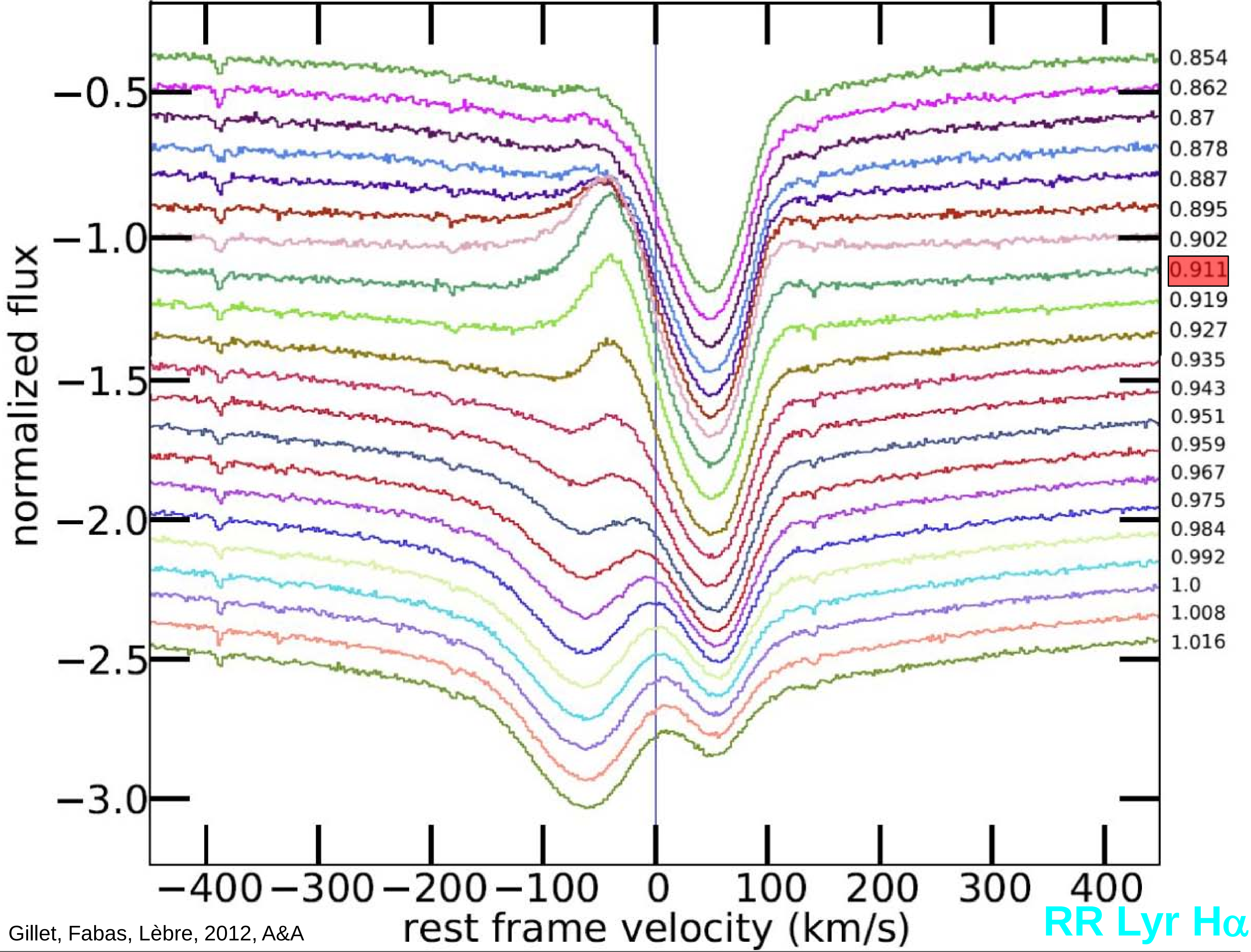
- 3000-10100 A

Observations by Gillet, Fabas, Lèbre, 2012, A&A



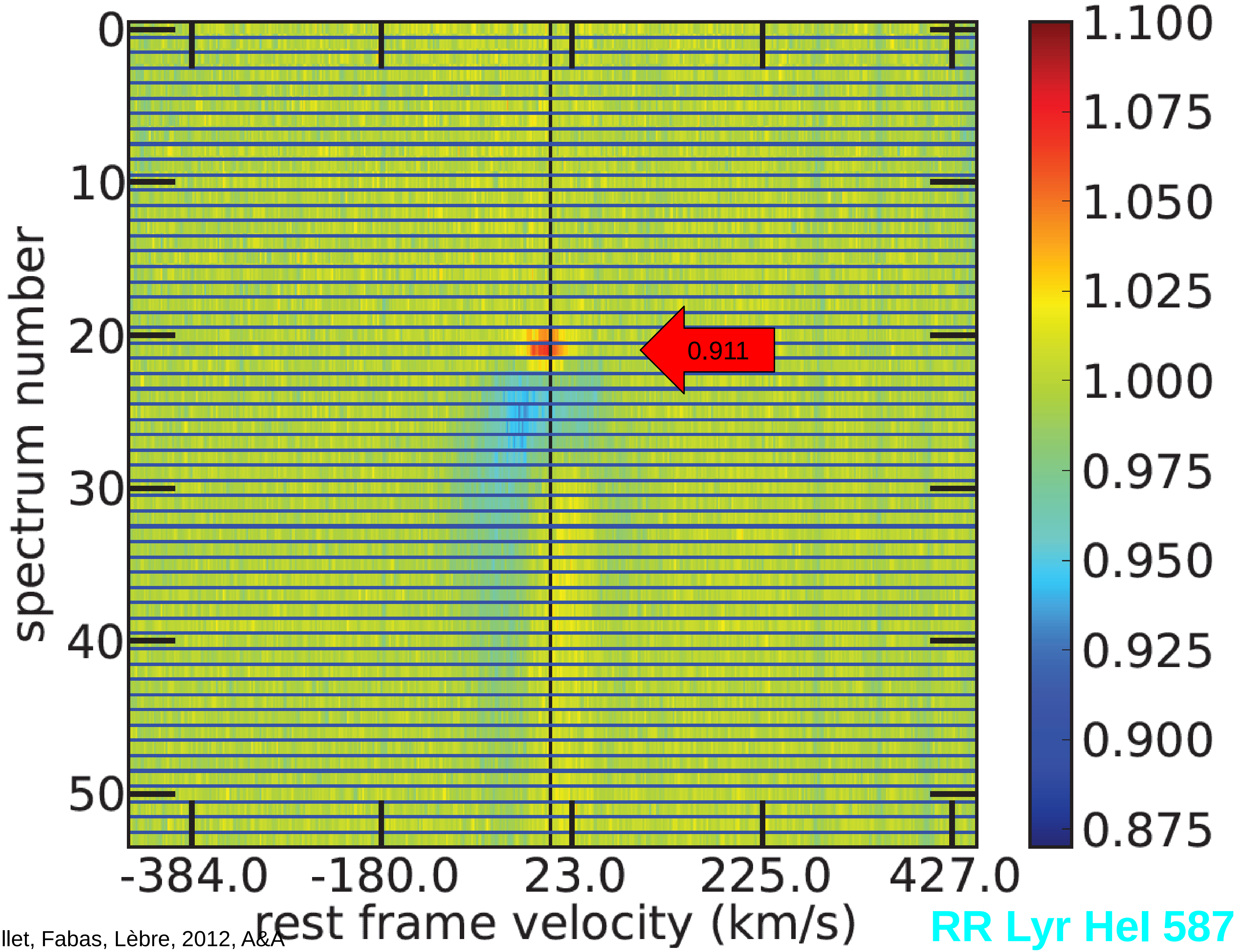
RR Lyr Hα

Gillet, Fabas, Lèbre, 2012, A&A



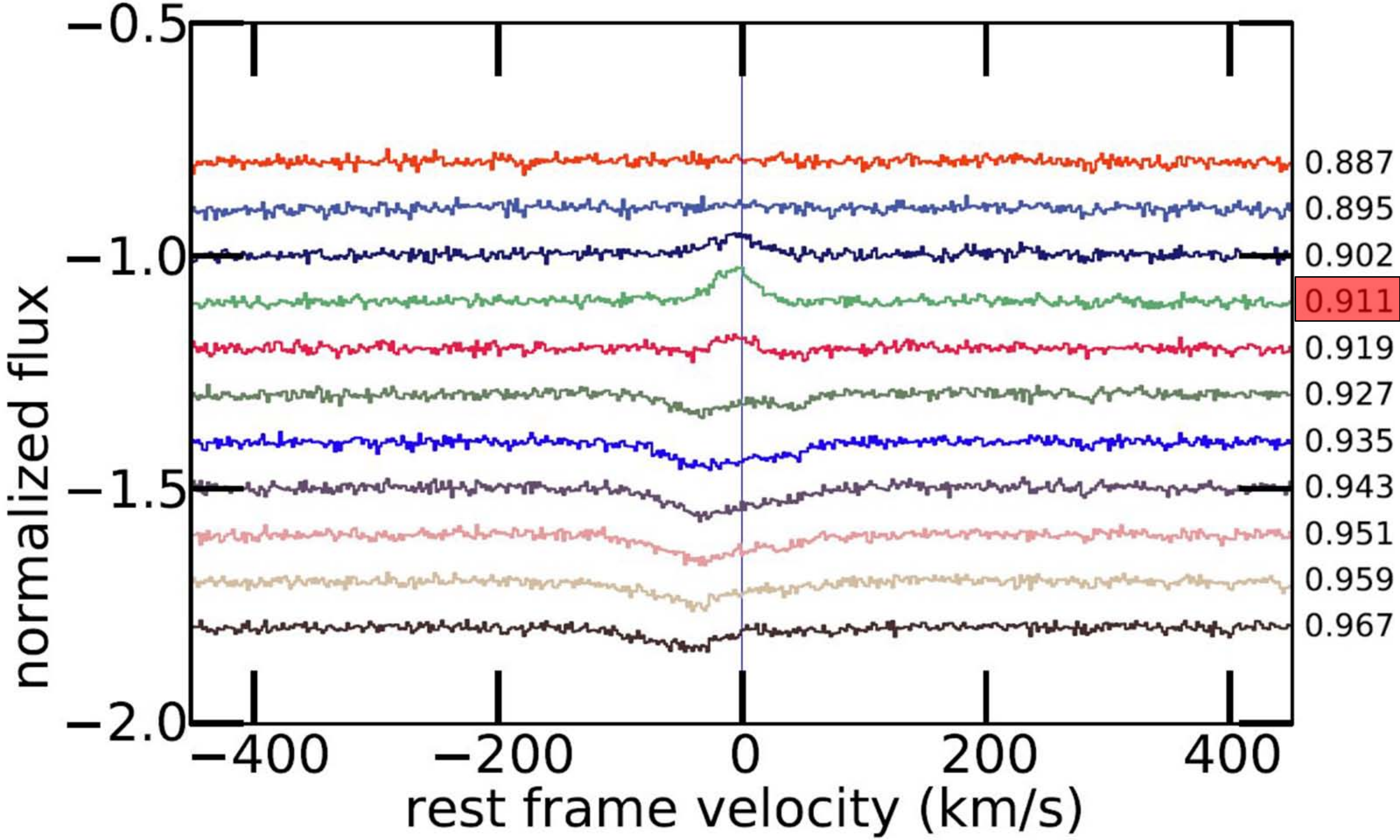
Gillet, Fabas, Lèbre, 2012, A&A

RR Lyr Hα



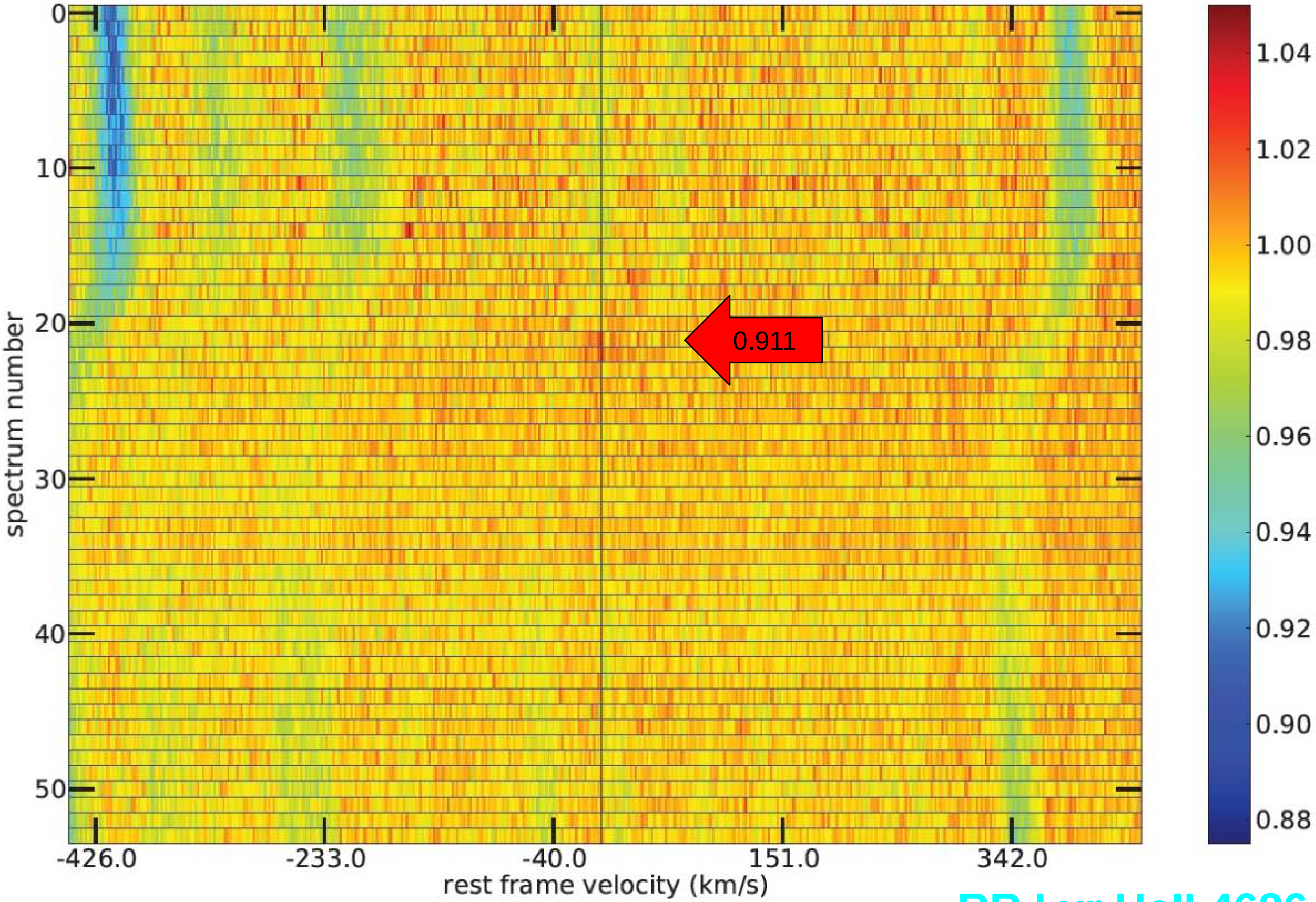
Gillet, Fabas, Lèbre, 2012, A&A

RR Lyr HeI 5875



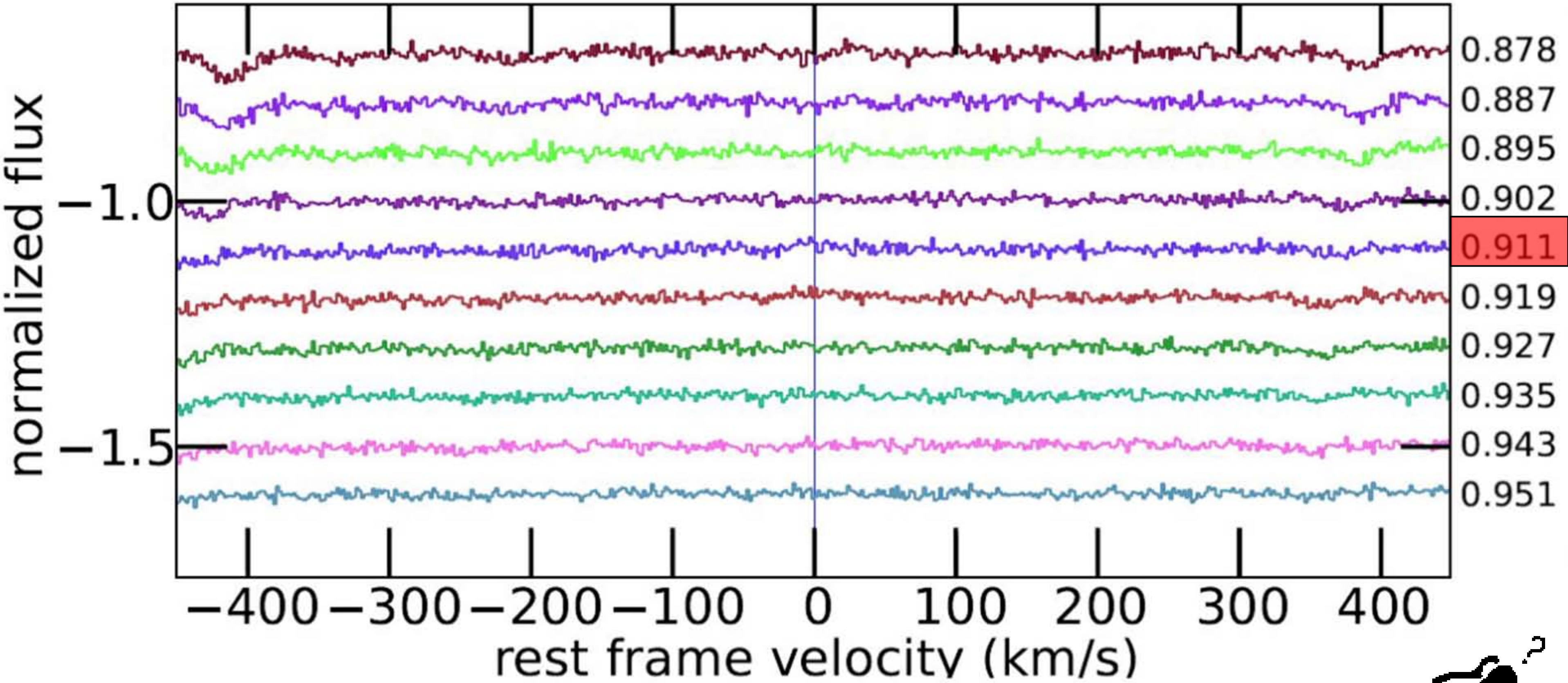
Gillet, Fabas, Lèbre, 2012, A&A

RR Lyr HeI 5875



Gillet, Fabas, Lèbre, 2012, A&A

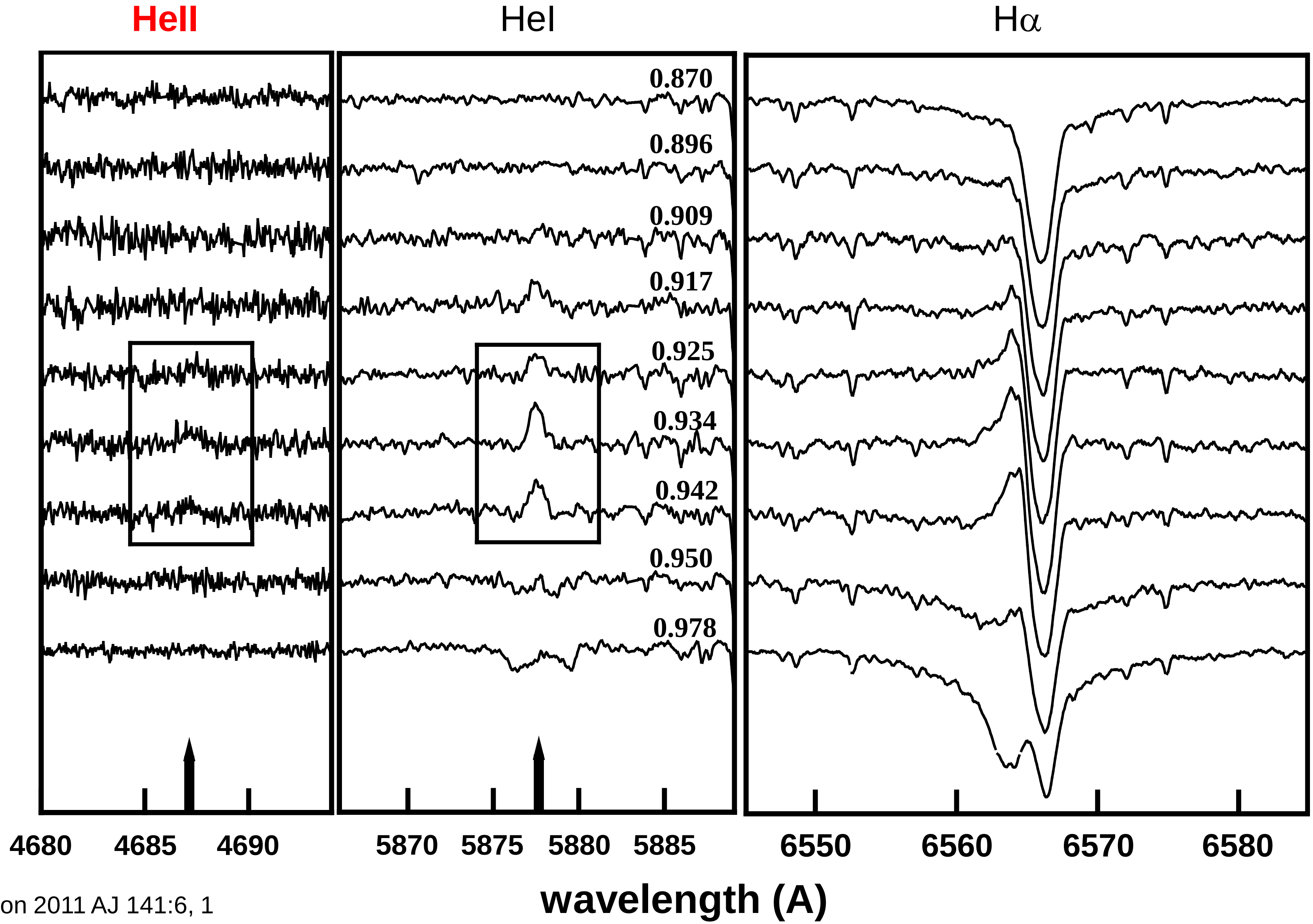
RR Lyr HeII 4686



Gillet, Fabas, Lèbre, 2012, A&A

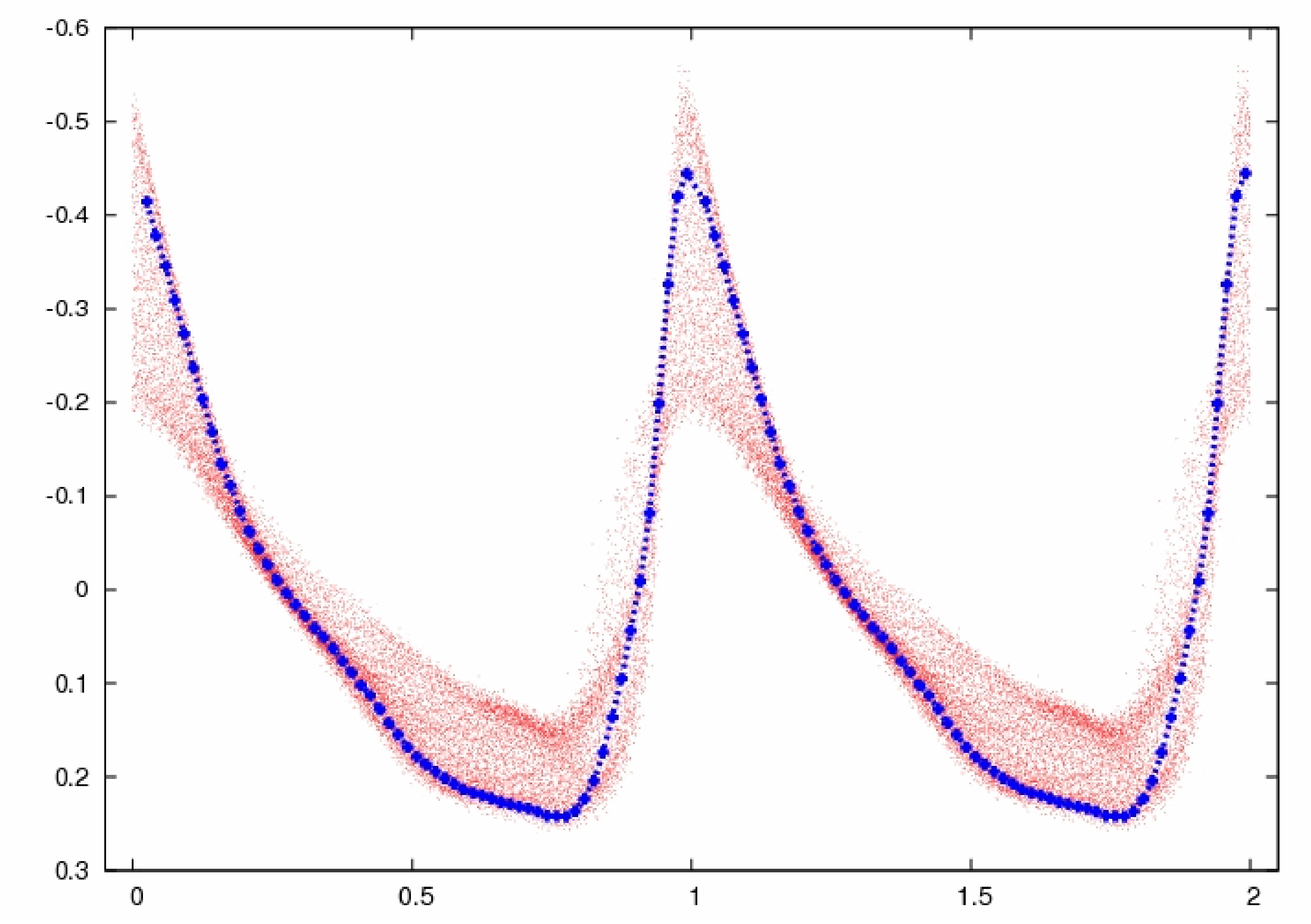
RR Lyr HeII 4686

AS Vir : inset boxes surround HeII and HeI emission lines in 3 successive spectra



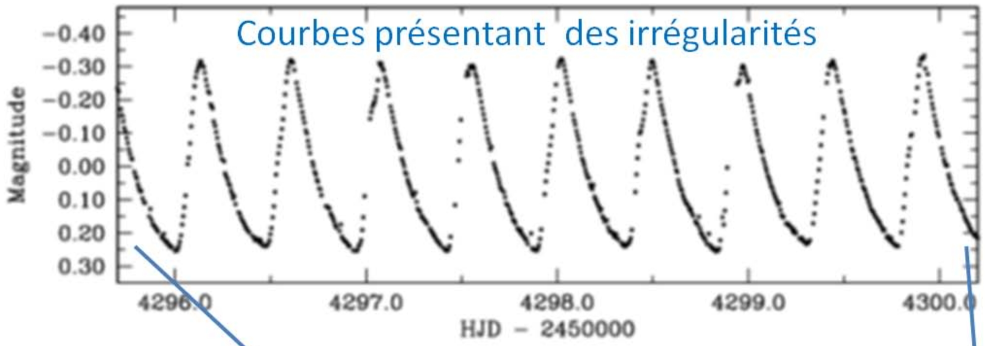
Preston 2011 AJ 141:6, 1

The Blazhko effect

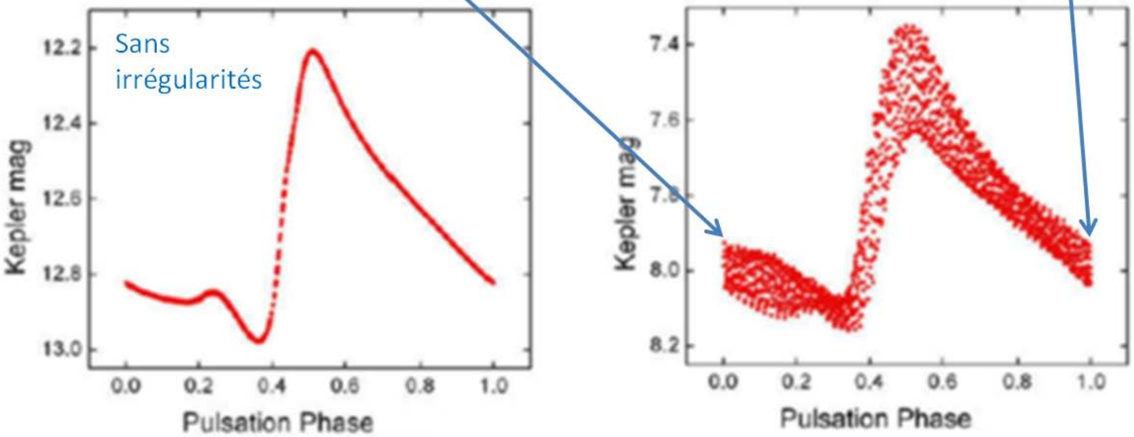


Courbe de lumière montrant 2 cycles de pulsations de l'étoile RR Lyrae V 1127 Aql évoluant au cours du temps (en bleu), on observe parfaitement l'effet Blazhko. Au cours des 400 cycles (en rouge) observés par le satellite CoRoT, on distingue à la fois une modulation de l'amplitude (sur l'axe vertical des ordonnées), et une modulation de la période de pulsation (sur l'axe horizontal des abscisses).

The Blazhko effect



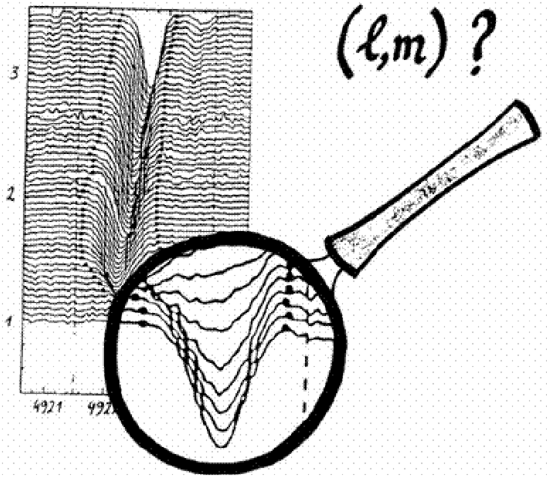
Courbes de lumière de l'étoile Blazhko CoRoT 101128793
d'après Poretti et al 2010



sans effet Blazhko avec effet Blazhko

Figure d'après Stellingwerf 2011

The explanation of the Blazhko effect???



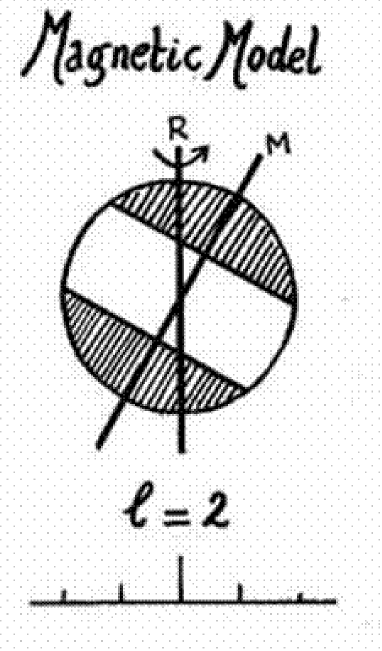
Until today, after over 100 years of research, there were more than 10 explanations proposed but none is satisfactory.

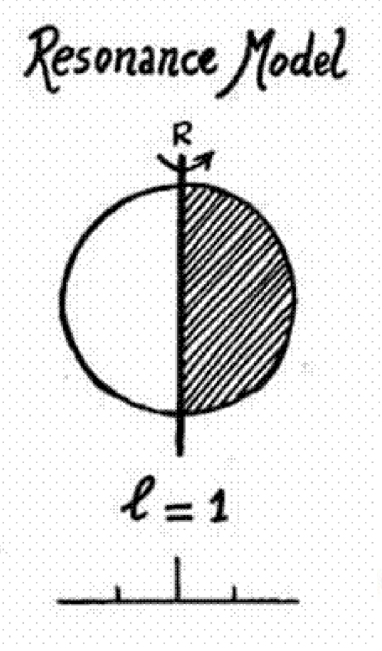
What is the correct explanation?

Blazhko Sergey Nikolaevich

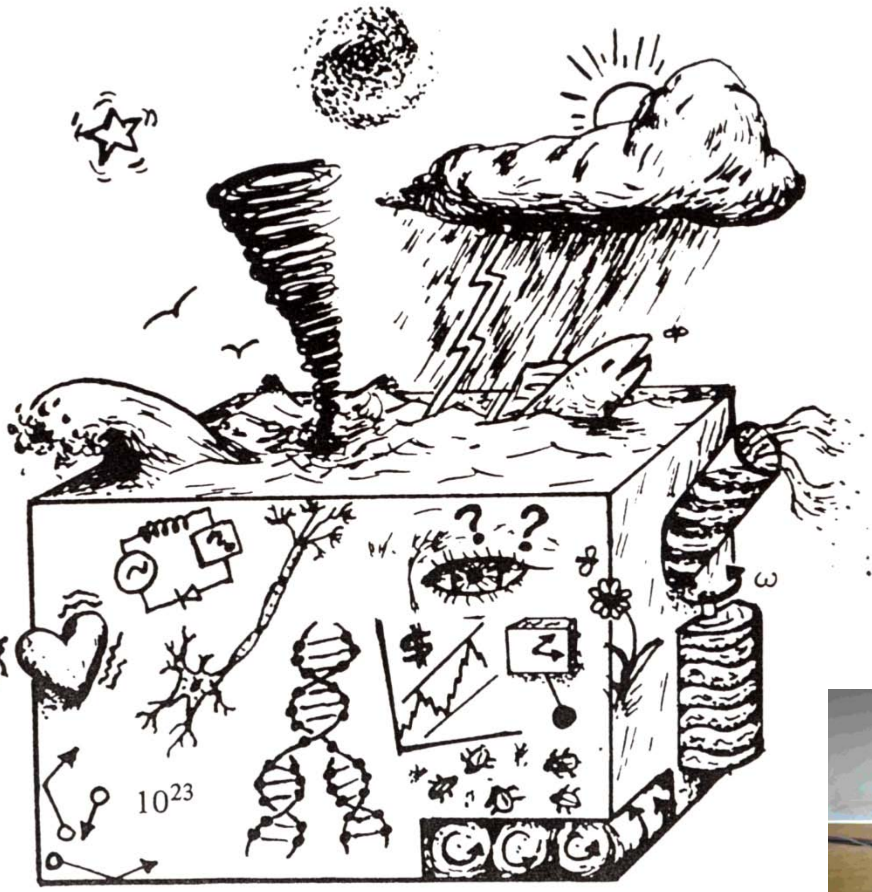
Connection with :

- ➔ shock(s)?
- ➔ helium emission?
- ➔ atmospheric dynamics?

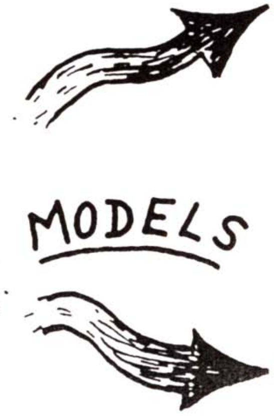




Conclusion



$$\rho u = \rho_0 u_0$$
$$p + \rho u^2 = p_0 + \rho_0 u_0^2$$
$$\frac{p}{\rho} + e + \frac{1}{2}u^2 = \frac{p_0}{\rho_0} + e_0 + \frac{1}{2}u_0^2$$



$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_1^{\ 2} - 1\right)$$
$$\frac{\rho_2}{\rho_1} = \frac{u_2}{u_1} = \frac{(\gamma+1)M_1^{\ 2}}{2+(\gamma-1)M_1^{\ 2}}$$
$$\frac{T_2}{T_1} = \frac{\left[2\gamma M_1^{\ 2} - (\gamma-1)\right]\left[2+(\gamma-1)M_1^{\ 2}\right]}{(\gamma+1)^2 M_1^{\ 2}}$$