DYNAMICAL MODEL ATMOSPHERES AND EMERGENT SPECTRA FOR PULSATING PROTO-SUBDWARFS

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1) V652 HERCULIS - the rocket star

- History - He+He WD merger? - proto-sdB star

2) NEW OBSERVATIONS

- Atmosphere tomography

3) SOME THEORY

- Hydrodynamical models
- Modelling line profiles (rt, hydro, result)

4) OTHER APPLICATIONS

- BX Cir
- LS IV-14 116
- sdBVp (eg. PG1605, Balloon, CS1246)
- beta Cep, etc.

V652 HERCULIS

1963 B-type Hydrogen-Deficient Star
(Berger & Greenstein)

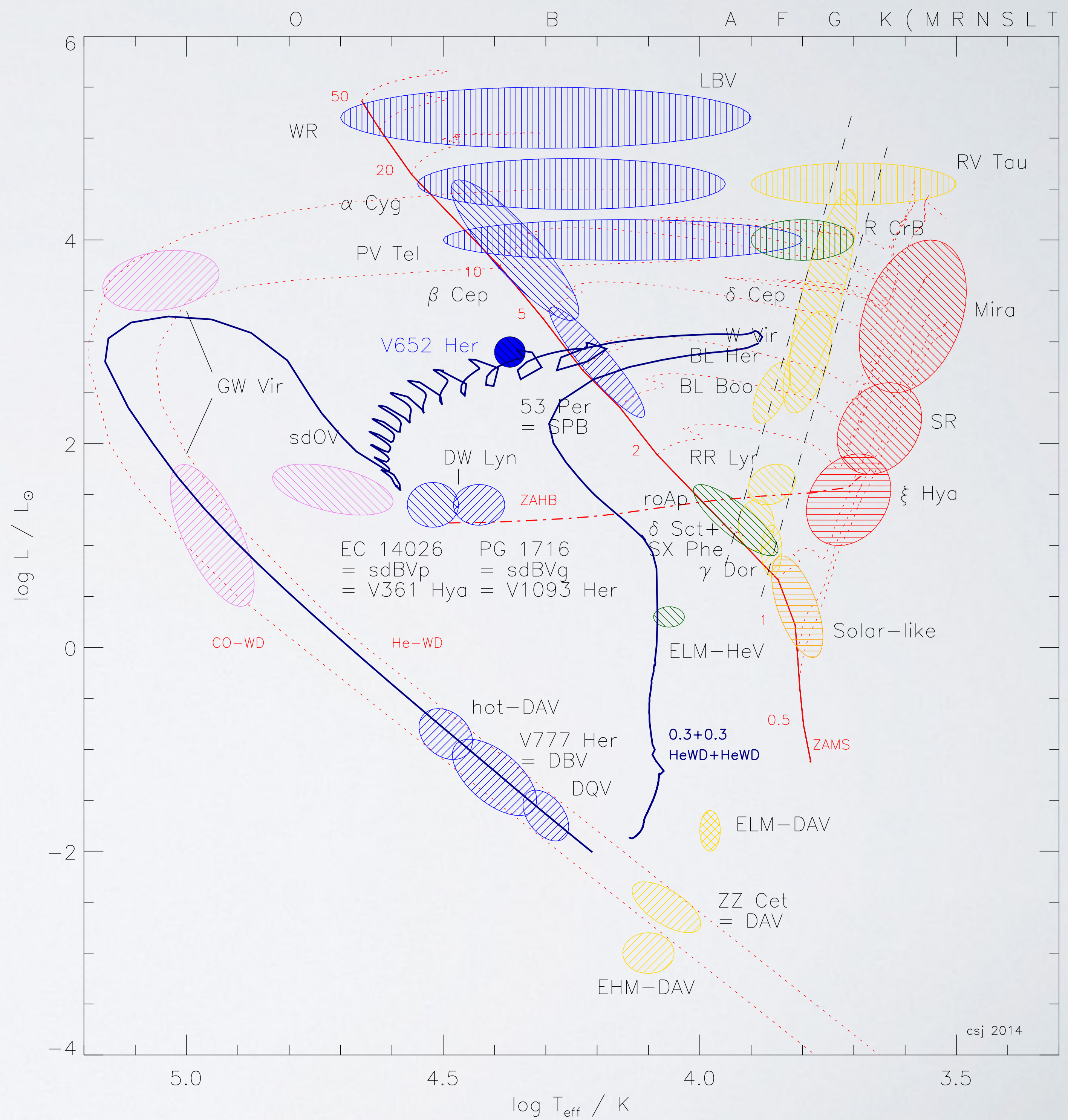
1970 Photometric variable ~ 2.5 hrs
(Landolt)

1982... Velocities ➞ pulsations - the rocket star
(Hill et al, Lynas-Gray et al., Jeffery et al.)
➞ radius, mass ...

1982... $\dot{P}, \ddot{P}$ ➞ contraction (Kilkenny et al.)
➞ evolution ...

1993... Z-bump driving
(Saio, Montanes-Rodriguez, Fadeyev, ...)

2000: Double-helium-white-dwarf merger
- the born-again star (Saio & Jeffery)



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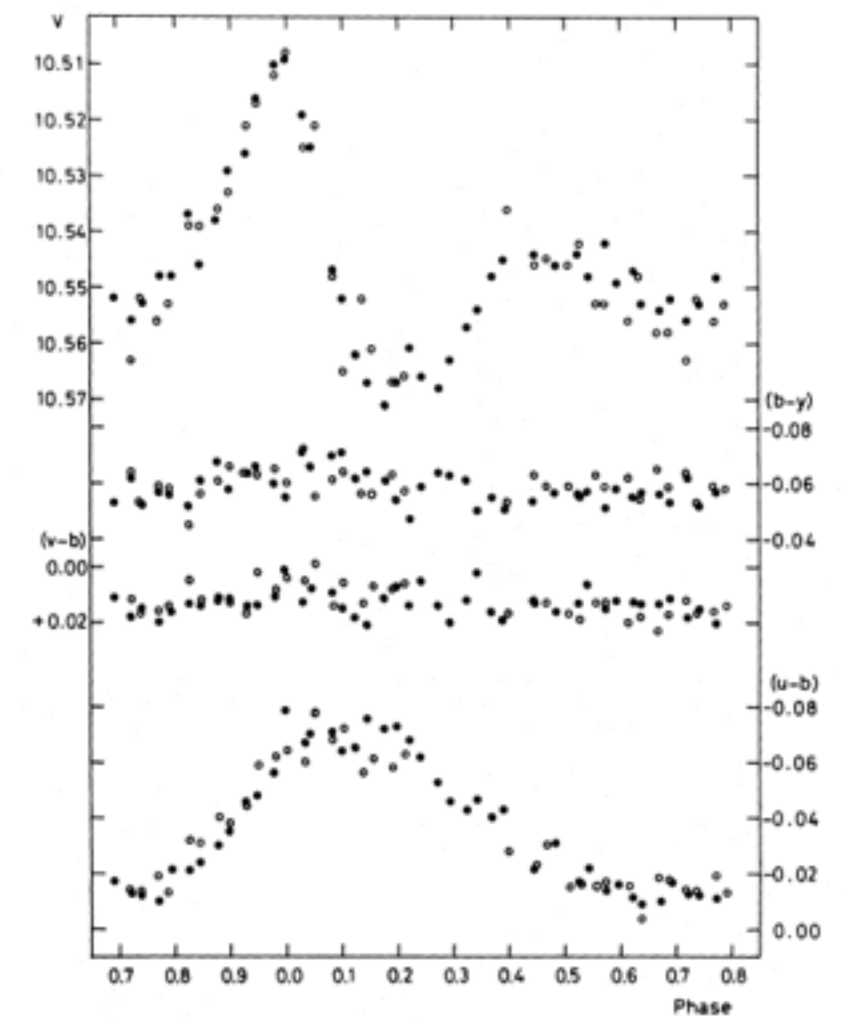

Figure 1. Four colour photometry of BD + 13°3224. Filled and open circles indicate observations on two consecutive nights. Smoothed mean colours from this data are given in Table 2.

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→ $\langle R \rangle = 2.31 \pm 0.02 R_\odot$ $M = 0.59 \pm 0.18 M_\odot$

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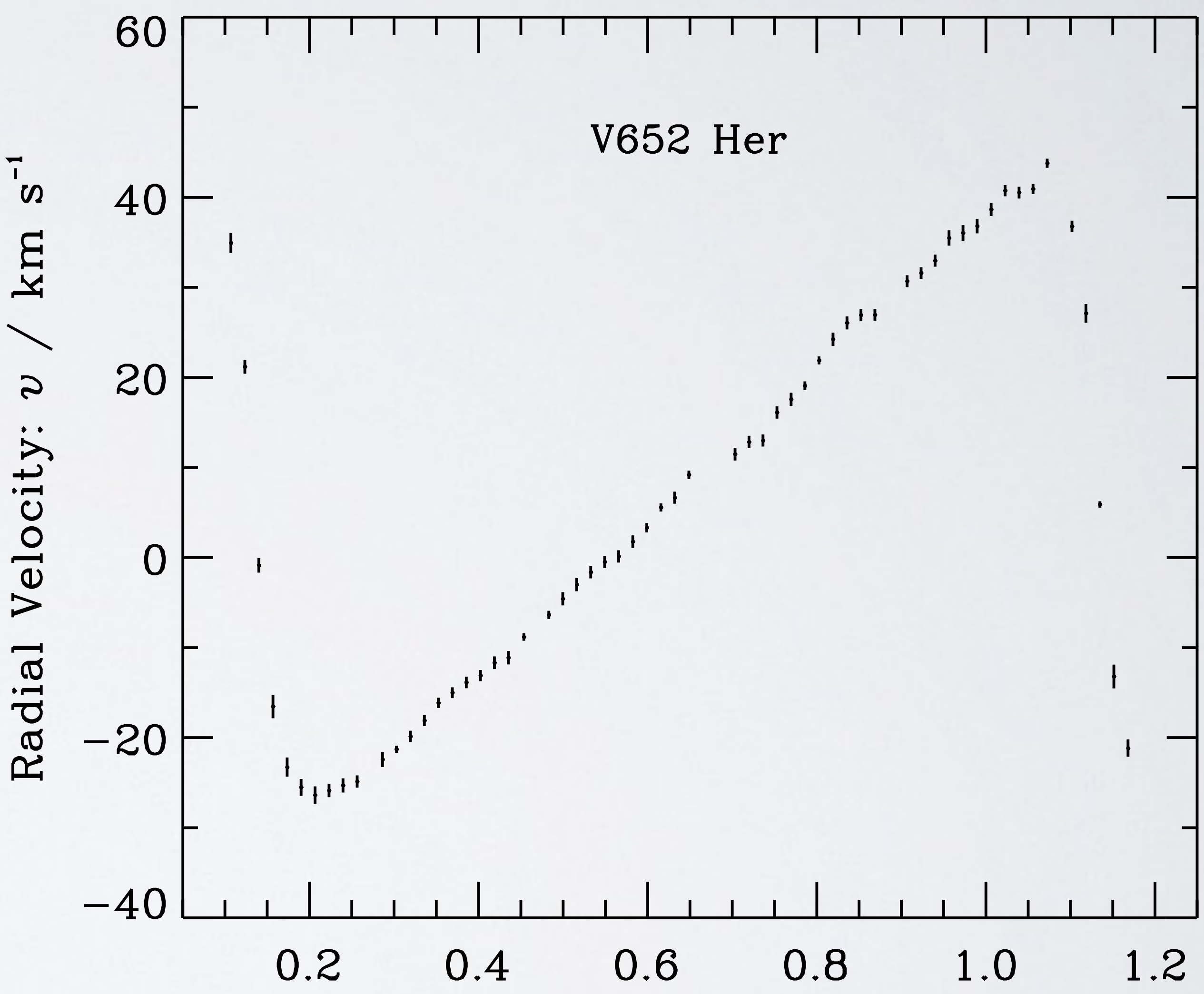


V652 HERCULIS

Is there a hydrodynamic shock ?

Consequences of pulsation for the photosphere ?
both at minimum radius and during the rest of the cycle

=> Radiative transfer in a moving medium …

When can the hydrostatic approximation be justified
when modelling the photospheres of pulsating stars?

V652 HER: SUBARU HDS

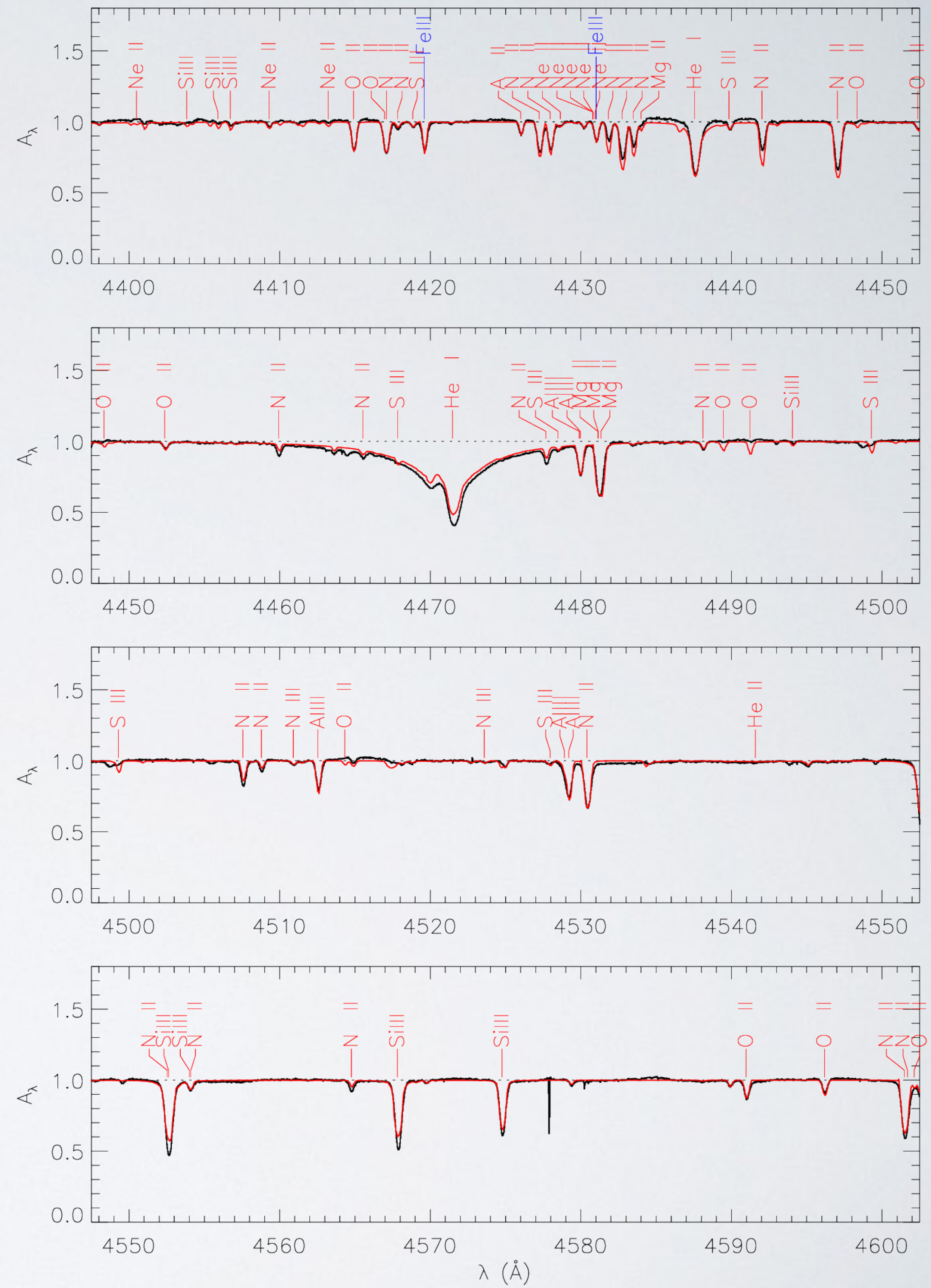
120s exposure, 56s readout
~0.020 cycle sampling

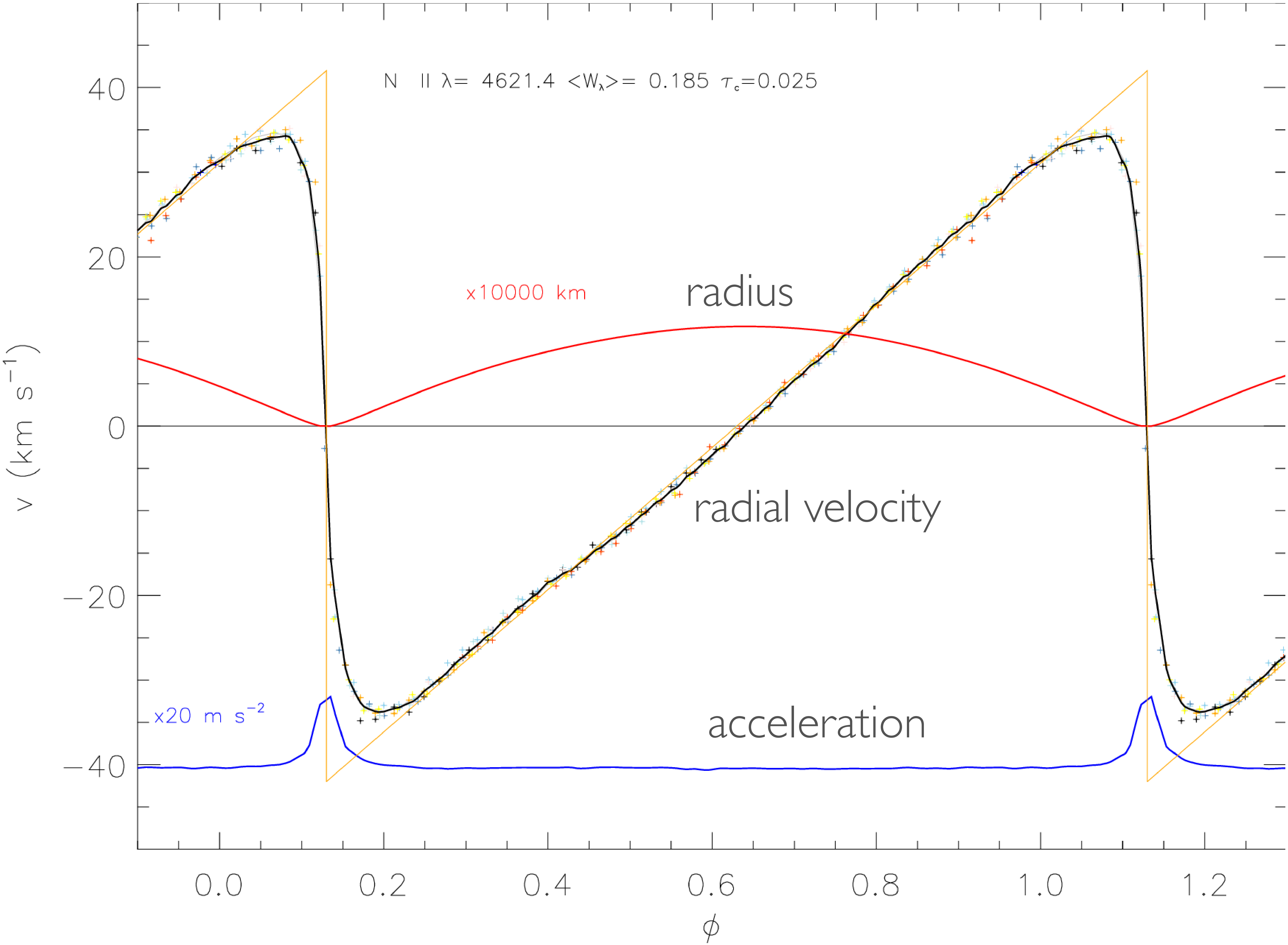
386 observations over 2 nights, 6 cycles, 8 R_{min}

132 lines measured: (CoG) wavelength and equivalent widths

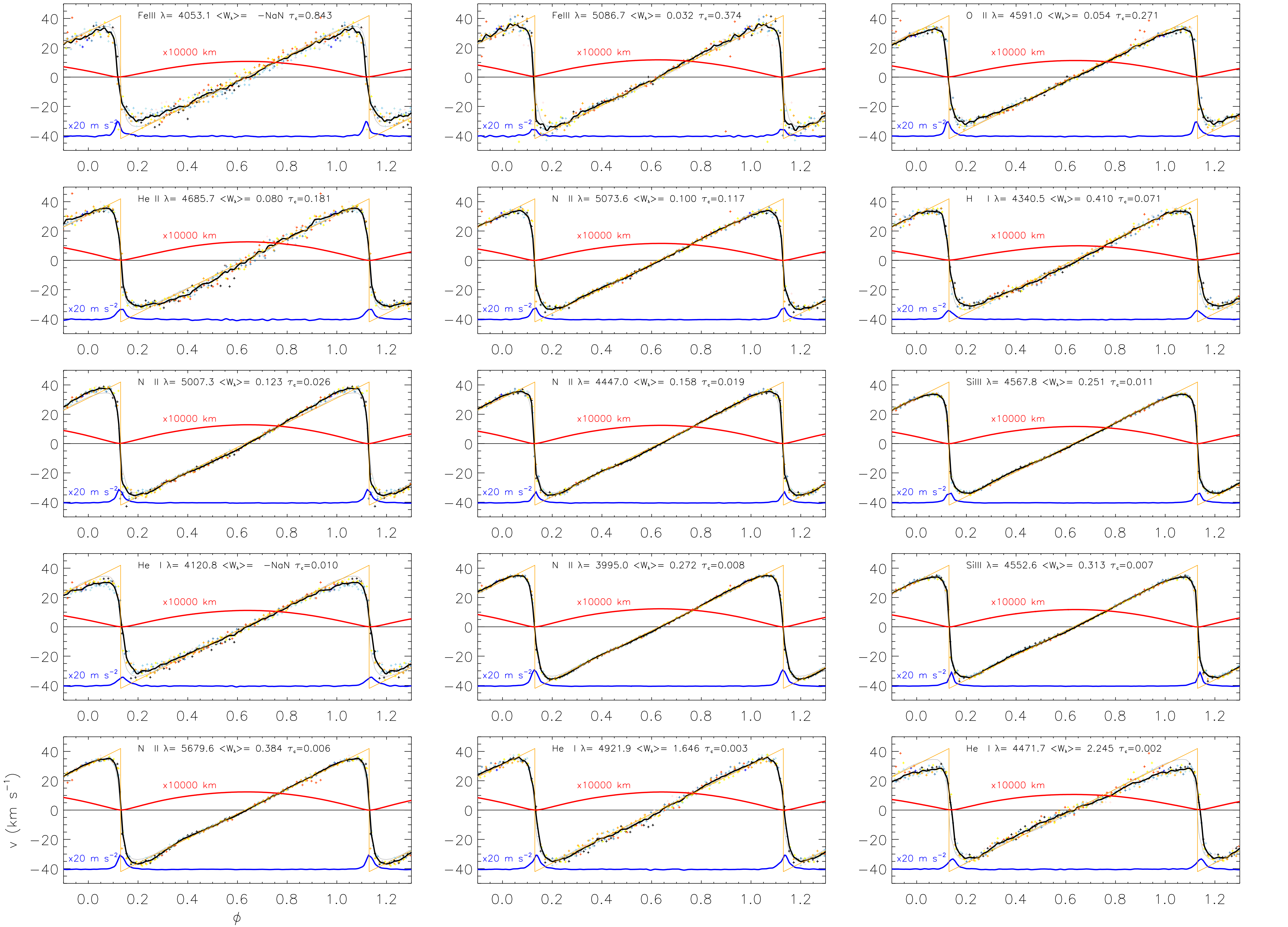
50 952 velocity measurements

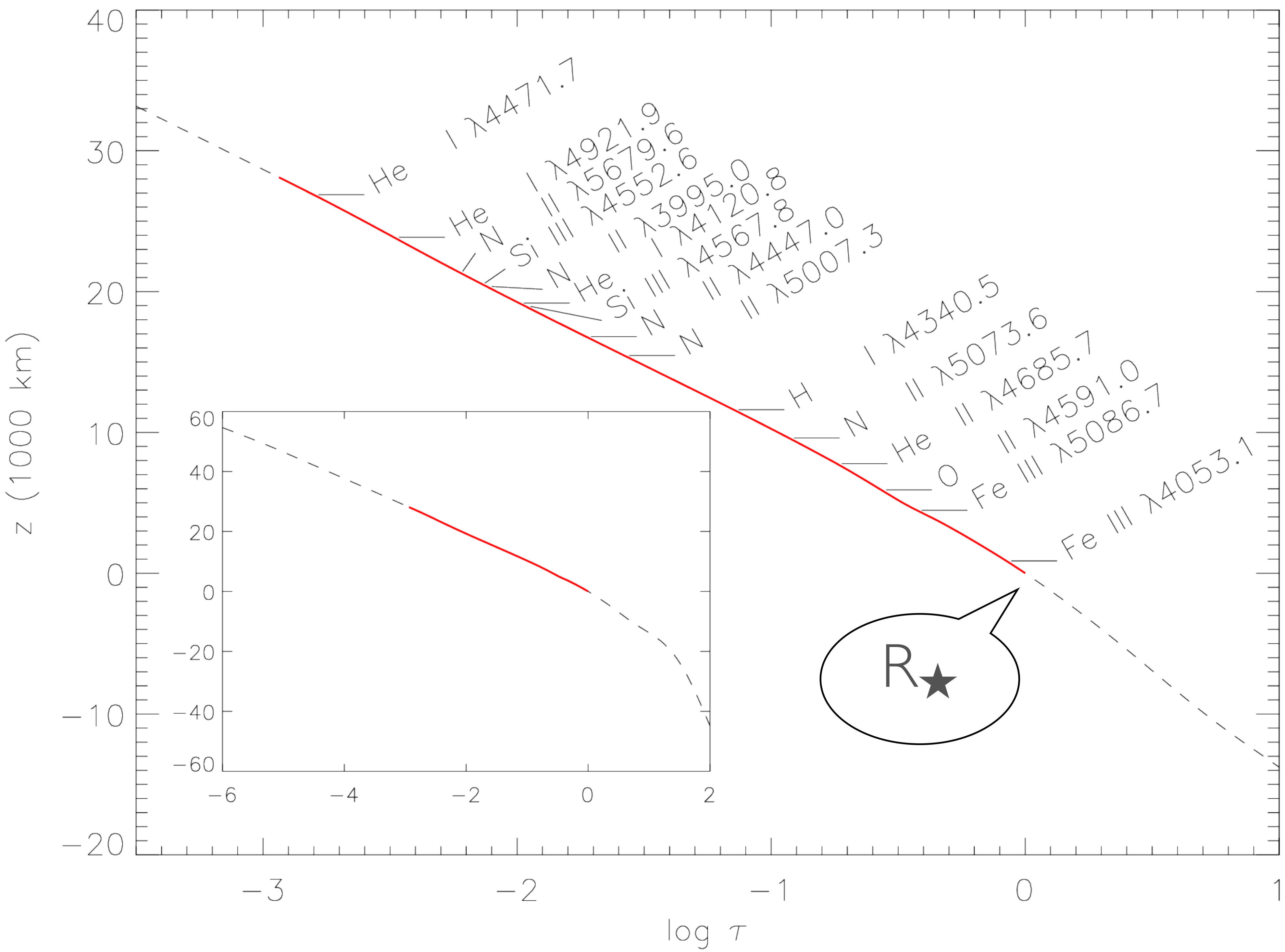
Formal errors: 0.06 - 0.2 km s^{-1}



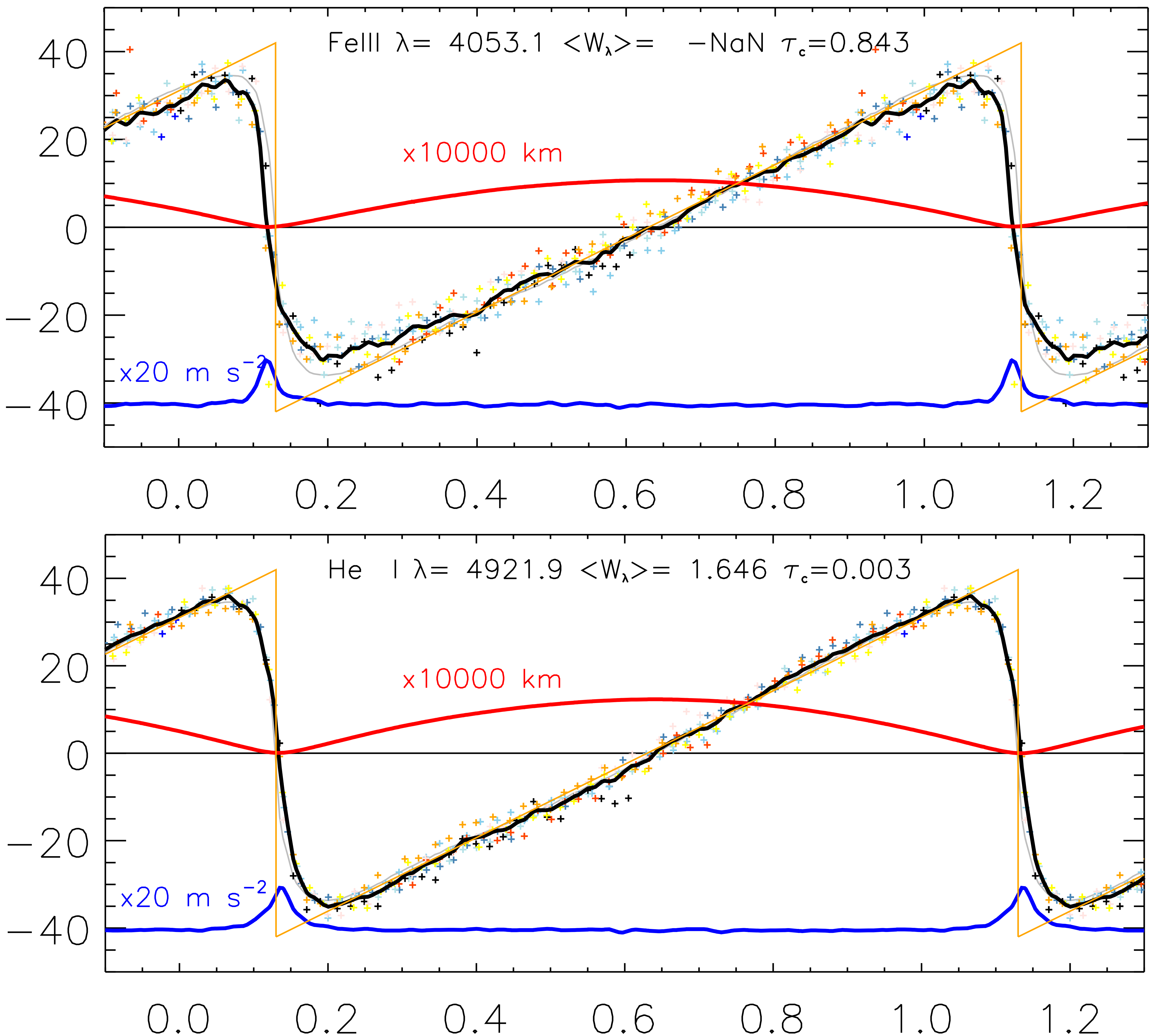


N II λ= 4621.4 <W_λ>= 0.185 τ_c=0.025
x10000 km
radius
radial velocity
x20 m s^-2
acceleration
v (km s^-1)
40
20
0
−20
−40
0.0
0.2
0.4
0.6
0.8
1.0
1.2
ϕ

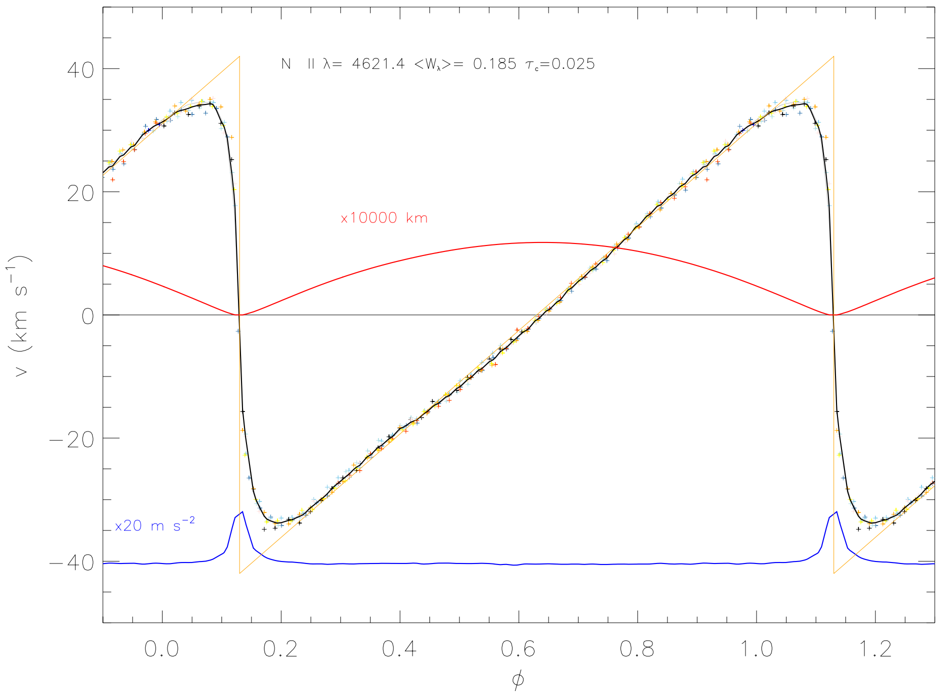

FeII λ= 4053.1 <W_λ>= −NaN τ_c=0.843
FeII λ= 5086.7 <W_λ>= 0.032 τ_c=0.374
O II λ= 4591.0 <W_λ>= 0.054 τ_c=0.271
He II λ= 4685.7 <W_λ>= 0.080 τ_c=0.181
N II λ= 5073.6 <W_λ>= 0.100 τ_c=0.117
H I λ= 4340.5 <W_λ>= 0.410 τ_c=0.071
N II λ= 5007.3 <W_λ>= 0.123 τ_c=0.026
N II λ= 4447.0 <W_λ>= 0.158 τ_c=0.019
SiII λ= 4567.8 <W_λ>= 0.251 τ_c=0.011
He I λ= 4120.8 <W_λ>= −NaN τ_c=0.010
N II λ= 3995.0 <W_λ>= 0.272 τ_c=0.008
SiII λ= 4552.6 <W_λ>= 0.313 τ_c=0.007
N II λ= 5679.6 <W_λ>= 0.384 τ_c=0.006
He I λ= 4921.9 <W_λ>= 1.646 τ_c=0.003
He I λ= 4471.7 <W_λ>= 2.245 τ_c=0.002
x10000 km
x20 m s^-2
v (km s^-1)
ϕ



Position in photosphere at which line cores are formed



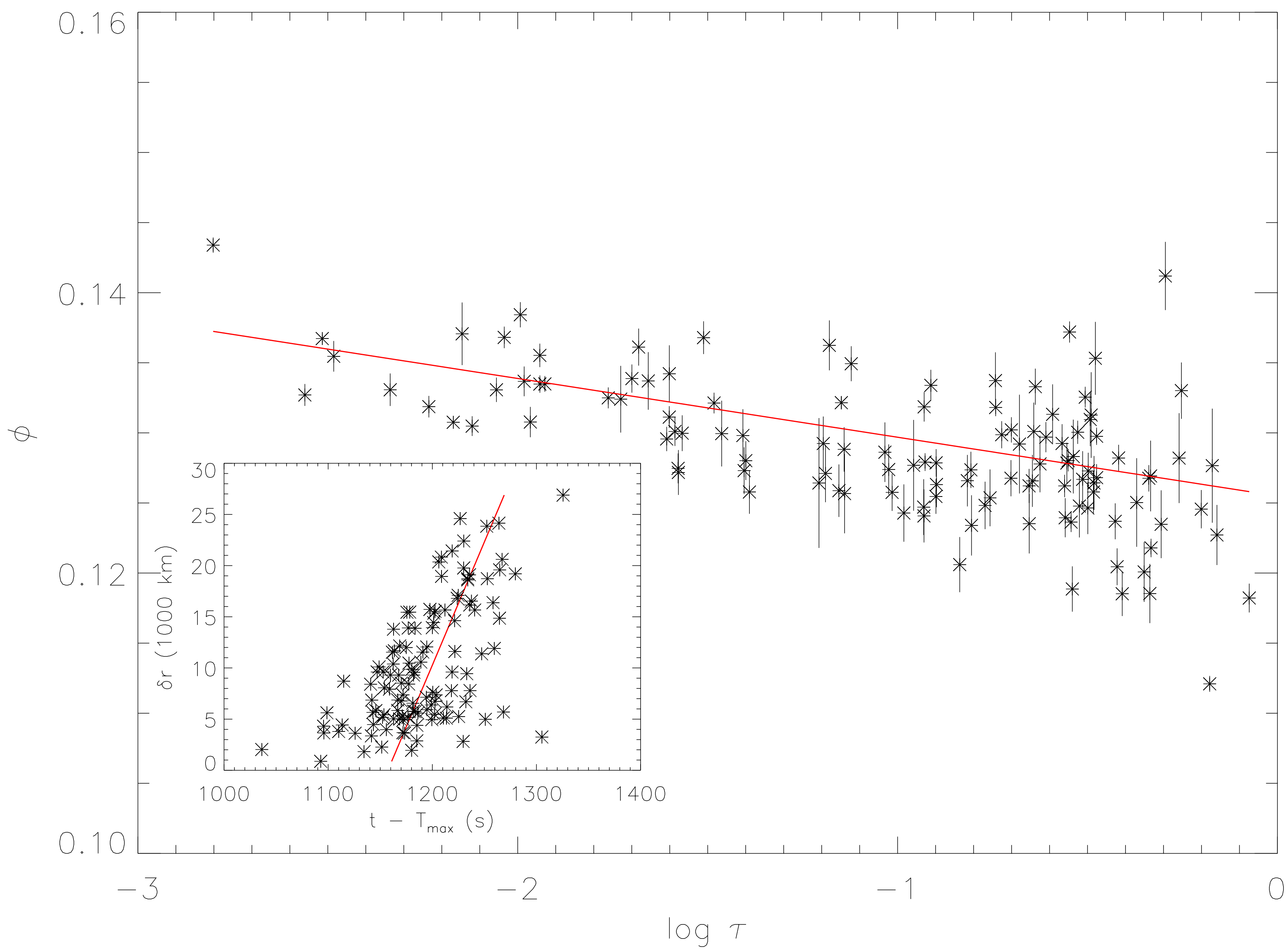
FeIII λ= 4053.1 <W_λ>= −NaN τ_c=0.843
x10000 km
x20 m s^-2
He I λ= 4921.9 <W_λ>= 1.646 τ_c=0.003
x10000 km
x20 m s^-2

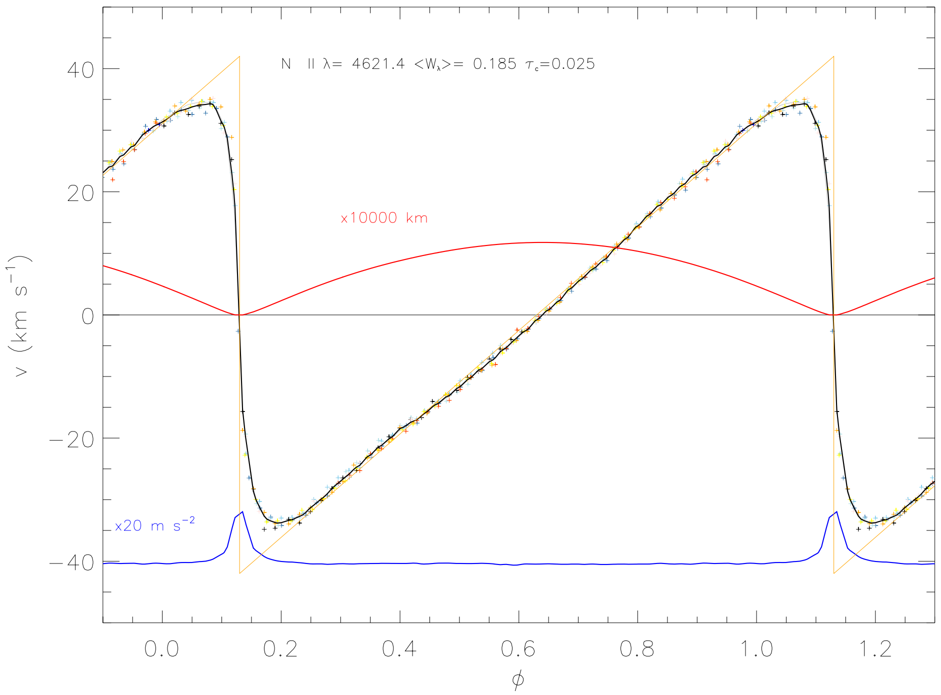


Phase of maximum acceleration as function of depth in photosphere

$\ddot{r}$

$$\ddot{r} = \frac{\mathrm{d}pv}{\mathrm{d}t}$$

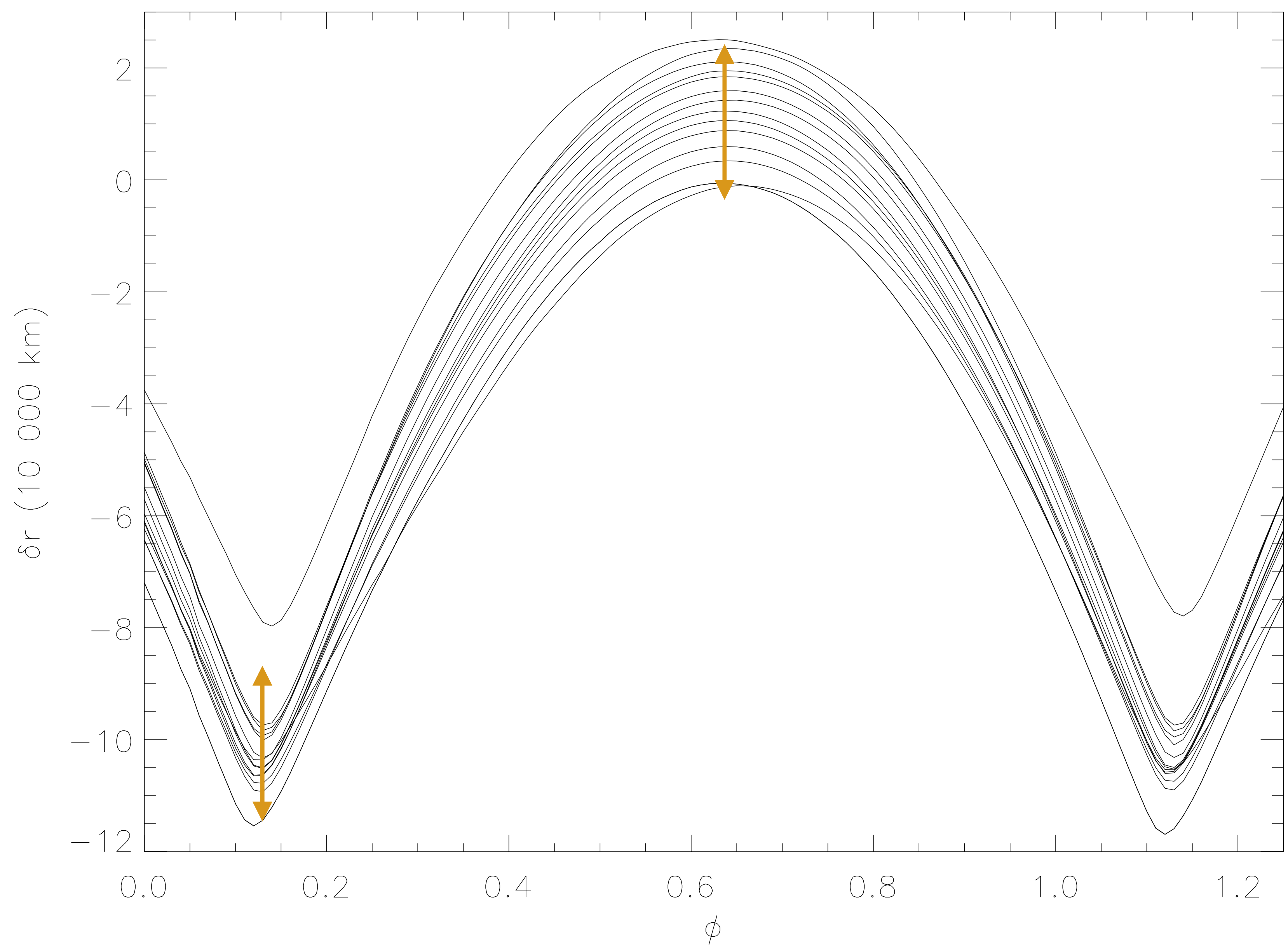


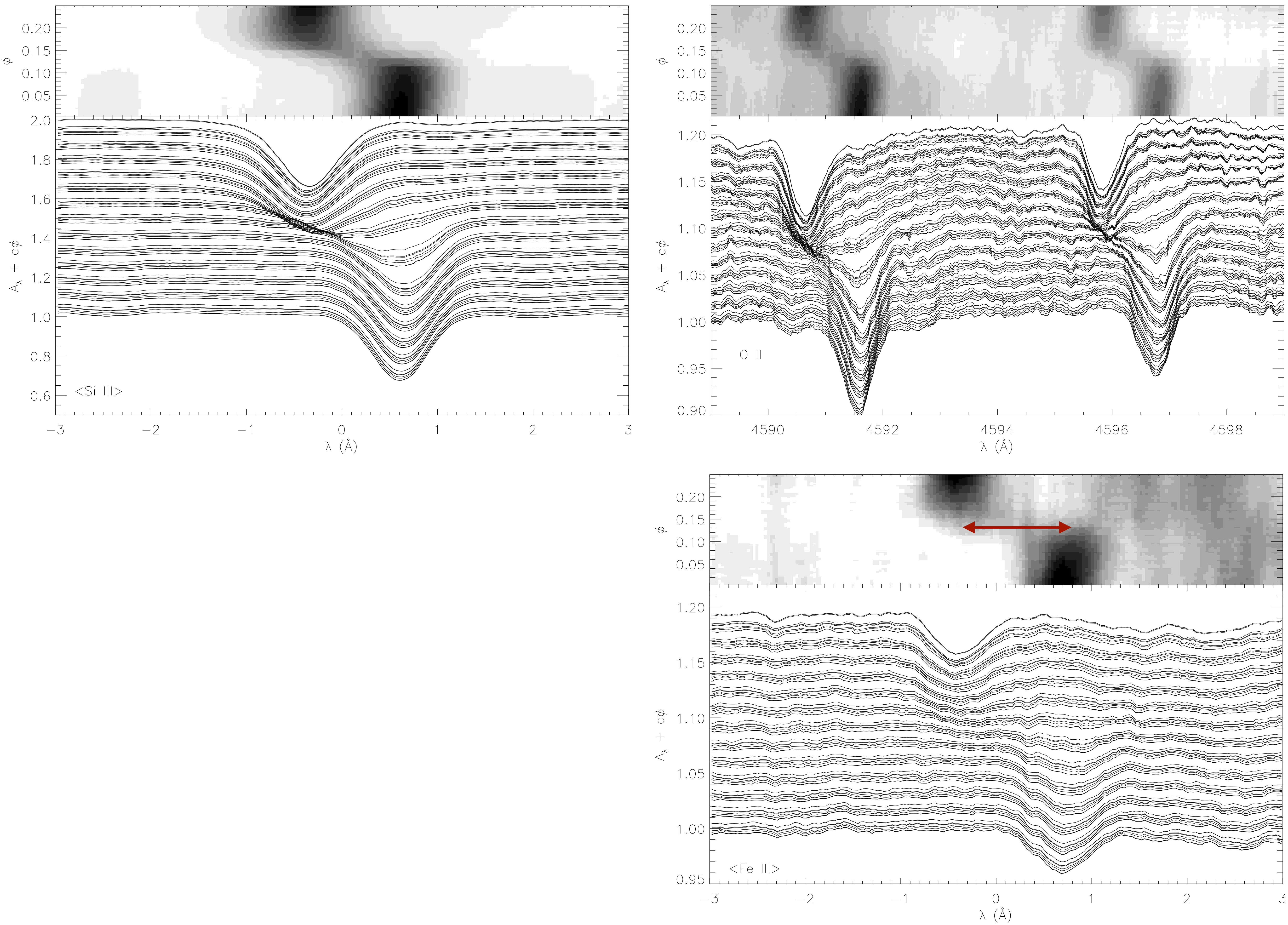


δr

Phase of minimum radius as function of depth in photosphere

$$\delta r = \int p v \mathrm{d}t$$





<Si III>
O II
<Fe III>
ϕ
$A_\lambda + c\phi$
λ (Å)

HYDRO PULSATION MODEL

Montanes-Rodriguez & Jeffery 2002, 2015 - in prep

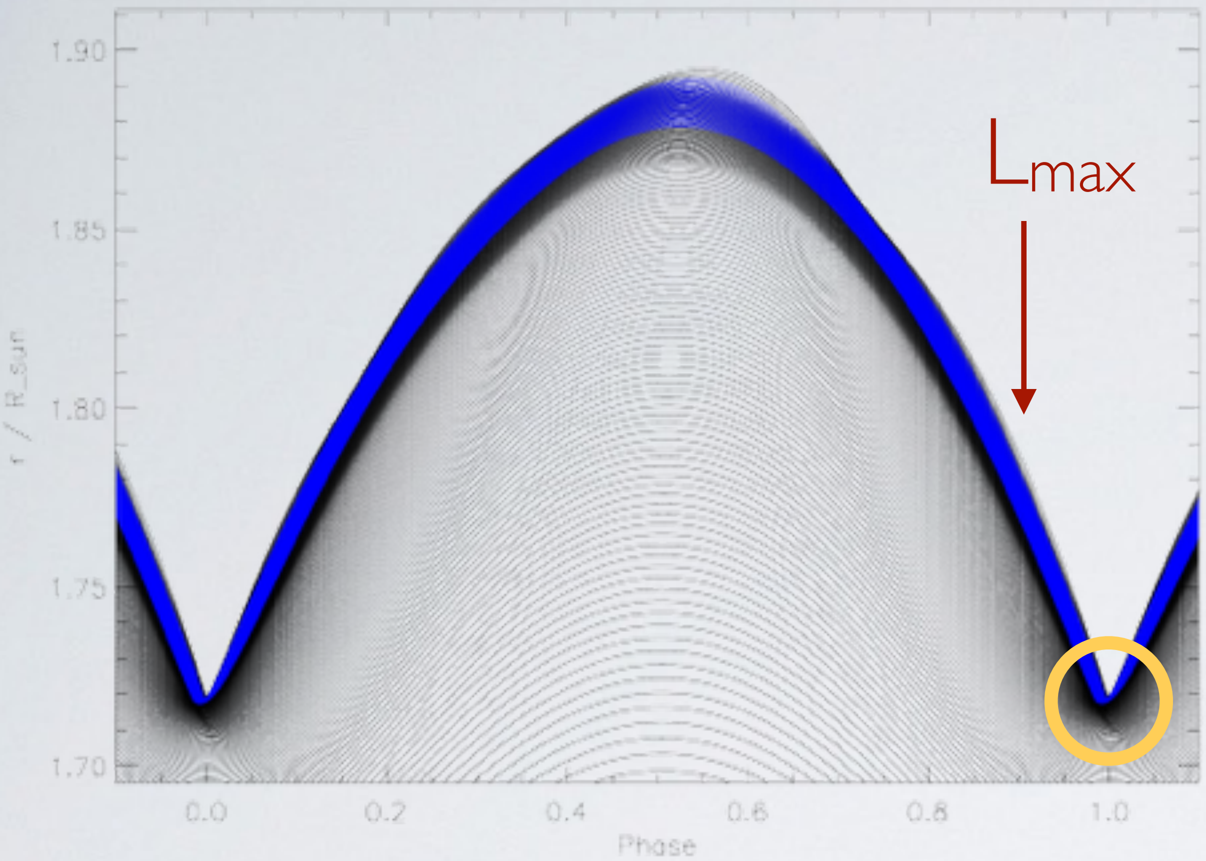
$$\frac{dm}{dr} = 4\pi r^2 \rho$$

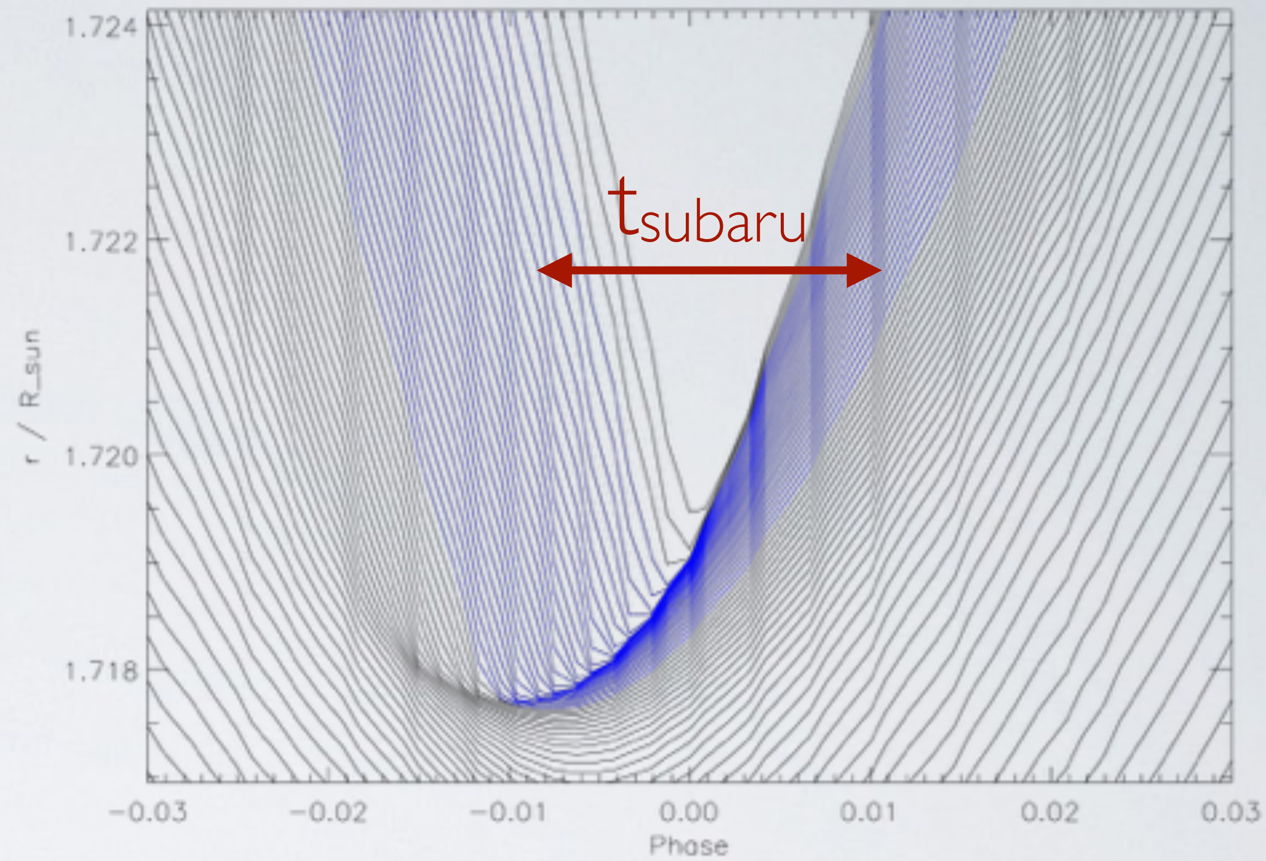
$$\frac{dl}{dr} = 4\pi r^2 \rho \left(\varepsilon - T \frac{\mathrm{d}S}{\mathrm{d}t} \right)$$

$$\frac{dP}{dr} = -\left(\frac{Gm\rho}{r^2} + \rho \frac{\mathrm{d}^2 r}{\mathrm{d}t^2} \right)$$

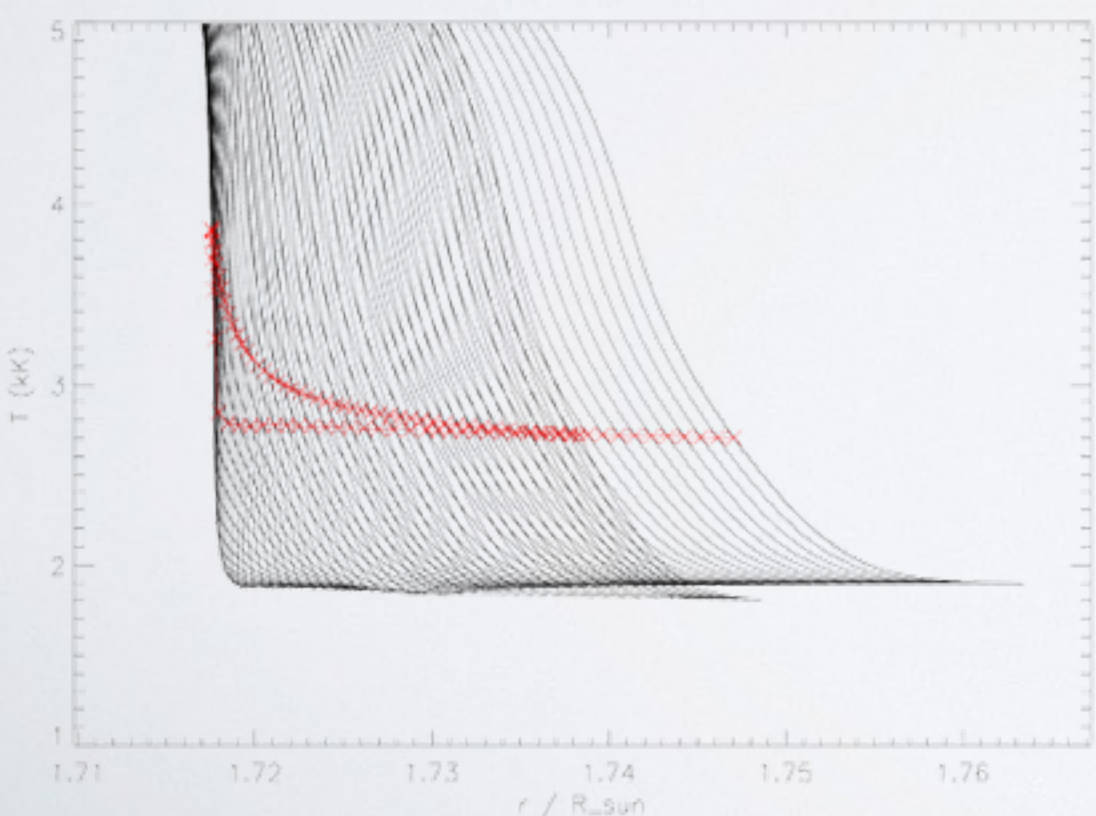
$$\frac{dT}{dr} = -\frac{3\kappa\rho}{4acT^3} \frac{l}{4\pi r^2} \equiv -\frac{Gm\rho}{r^2} \frac{T}{P} \nabla$$

Hydrodynamic pulsation model computed with Christy-type code (Bridger 1984, PhD Thesis St Andrews) for V652 Her.





2015 models with reduced viscosity, more zones, ...

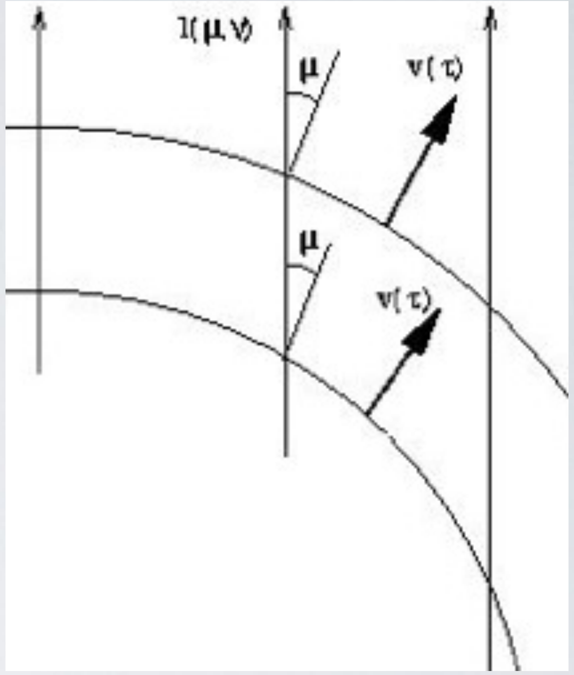


Blue shows line-forming region

$10^{-2} < \tau_0 < 1$

Red tracks temperature of one layer through radius minimum

Modelling line profiles in radially pulsating stars



For a plane-parallel stellar atmosphere, the **total flux** at frequency **ν** is defined by

$F_\nu = 2 \int_0^1 I_{\nu\mu}\, \mu d\mu$ (1)

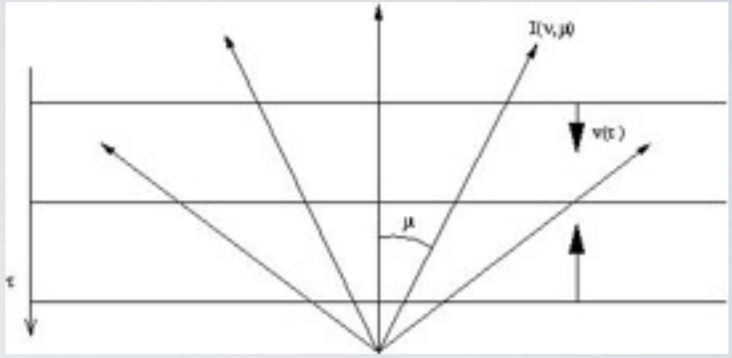
the integral over angle $\mu = \cos\theta$ of the **specific intensity**

$I_{\nu\mu} = \mu^{-1} \int_\infty^0 S_{\tau\nu} \exp(-\tau/\mu)\, d\tau$. (2)

The source function is conventionally written:

$S_{\tau\nu} = (\kappa_{\tau\nu} B_{\tau\nu} + \sigma_\tau J_{\tau\nu}) / (\kappa_{\tau\nu} + \sigma_\tau)$ (3)

with — τ : optical depth, $\kappa_{\tau\nu}$: absorption coefficient, σ_τ : scattering coefficient, $B_{\tau\nu}(T)$: Planck function, $J_{\tau\nu}$: mean intensity



If radial velocity $u(\tau)$ is a function of optical depth τ, then the angle-specific frequency becomes

$$\nu_{\tau\mu} = \nu_0(1 - \mu . u(\tau)/c) \qquad (5)$$

and requires $S_{\tau\nu}$ to be rewritten

$$S_{\tau\nu\mu} = (\kappa_{\tau\nu\mu} B_{\tau\nu} + \sigma_\tau J_{\tau\nu})/(\kappa_{\tau\nu\mu} + \sigma_\tau) \qquad (6)$$

which requires the correctly projected local line opacity

$$\kappa_{\tau l \mu}(\nu) = \kappa_{\tau l}(\nu_0 . (1 - \mu . u(\tau)/c) \qquad (7)$$

and which can again be evaluated and (2) integrated directly:

$$I_{\nu\mu} = \mu^{-1} \int_\infty^0 S_{\tau\nu\mu} \exp(-\tau/\mu) \, d\tau . \qquad (2')$$

COMBINING HYDRODYAMICS WITH RADIATIVE TRANSFER
SPECTRUM - PULS

1. Pulsation model: P, T, r, u … (m,t)

2. Normalise to static model: r/r_0, P/P_0, T/T_0, u ... (m,t)

3. Atmosphere model: $T_\bigstar(\tau)$, $P_\bigstar(\tau)$, ... ⇒ m'(τ): $m' = (M-m)/4\pi r^2$.

4. Interpolate and rescale: $T_\bigstar . T/T_0$, $P_\bigstar . P/P_0$, u, ...(τ,t)

5. Dynamic emergent spectrum: $F_\lambda(t)$

CONCLUSIONS

Line-by-line velocity measurements describe pulsating photosphere as function of optical depth.

Pulse is a running wave, weak shock in deepest layers.

New models developed to exploit depth (v-z-t) information.

Compression, heating at minimum radius by a factor 2.

Methodology? Using new models to interpret data?

New Toys! lots more to play with.

Shorter exposures needed to investigate line splitting.

Simple light curves do NOT imply simple pulsation properties.

Static model atmospheres very risky for pulsating stars.