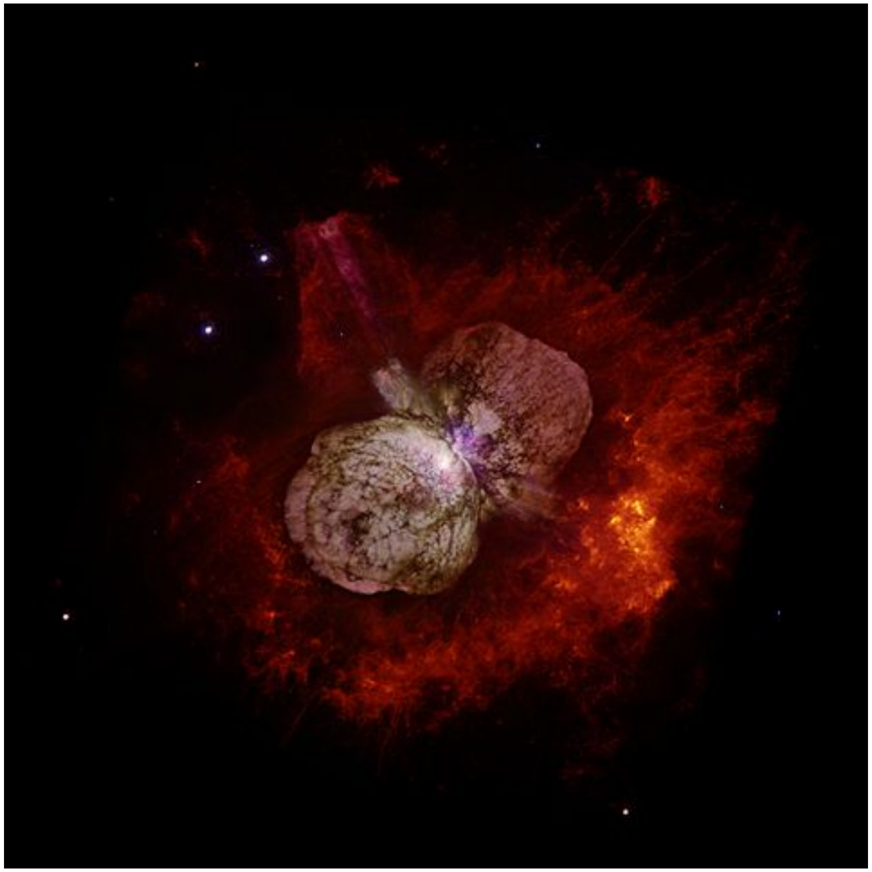
Instability Considerations for Massive Stars



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April 5, 2017

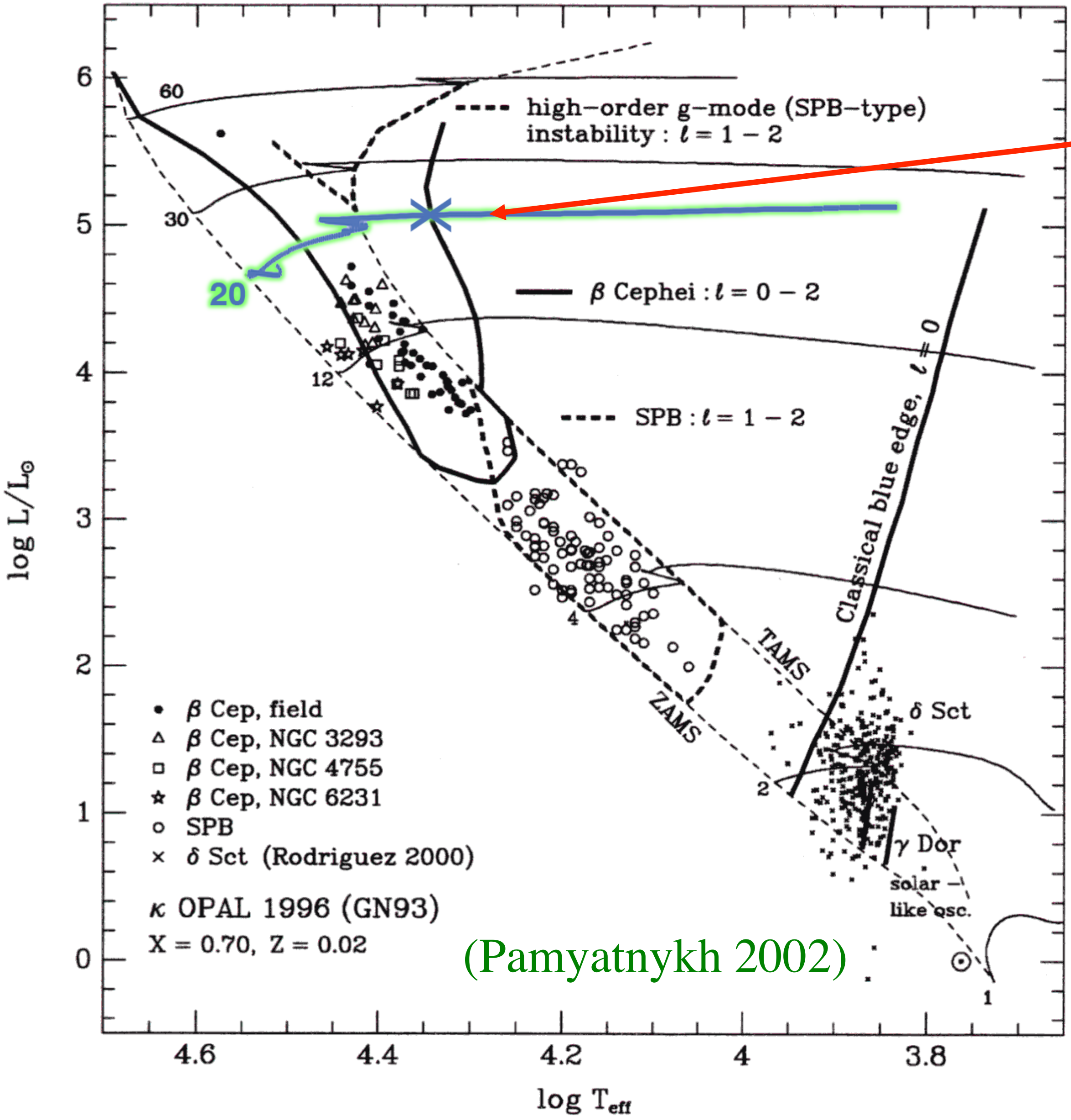
Los Alamos 1-D hydrodynamics calculations 1993 – 2014

Pulsations and Hydrodynamics of Luminous Blue Variable Stars, J.A. Guzik & C. Lovekin, Astronomical Review 7, 13 (2012)

See improved preprint: 2014arXiv1402.0257G

Pulsations as a driver for LBV variability, C.C. Lovekin and J.A. Guzik, MNRAS 445, 1776 (2014)

β *Cephei and SPB stars in the H-R Diagram*

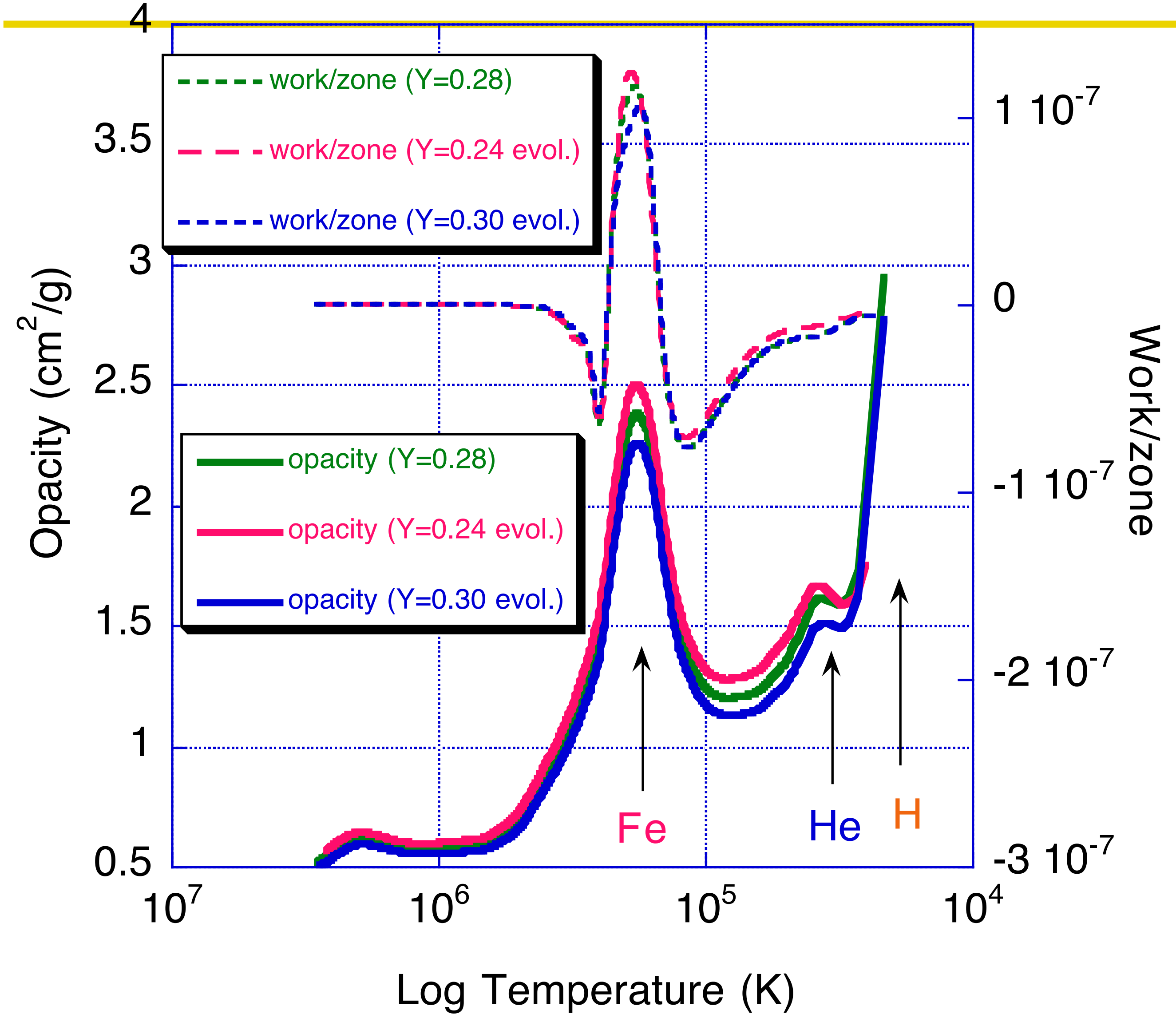


(Pamyatnykh 2002)

Our evolution track with Iben code for (X, Y, Z = 0.70, 0.28, 0.02), X marks ~22,000 K models we studied

20 M$_{sun}$ model radius increases from 6 R$_{sun}$ on ZAMS to 15 R$_{sun}$ before 'blue hook' to 23 R$_{sun}$ after 'blue hook'

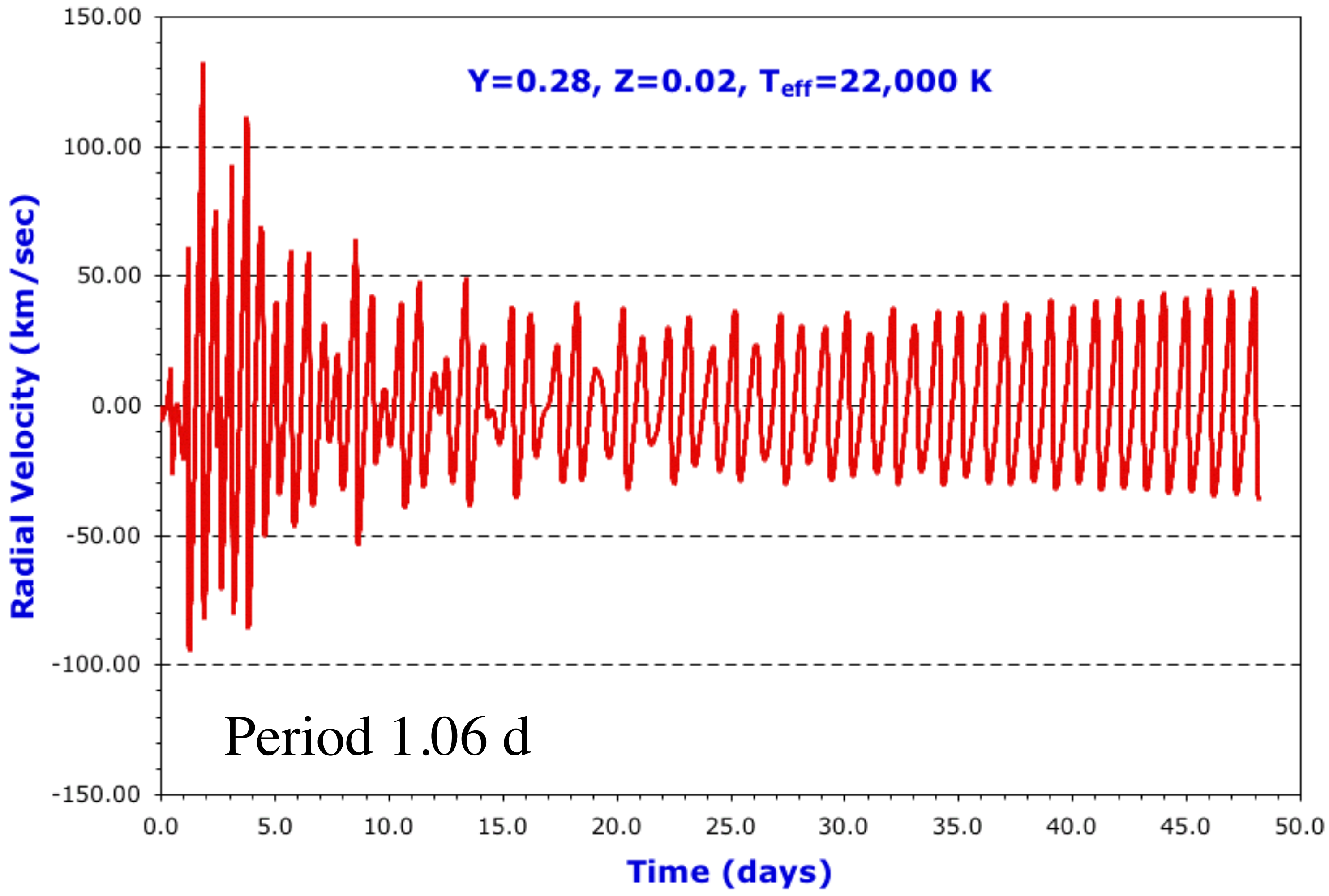
Pulsations driven by Fe-group element opacity bump at about 200,000 K



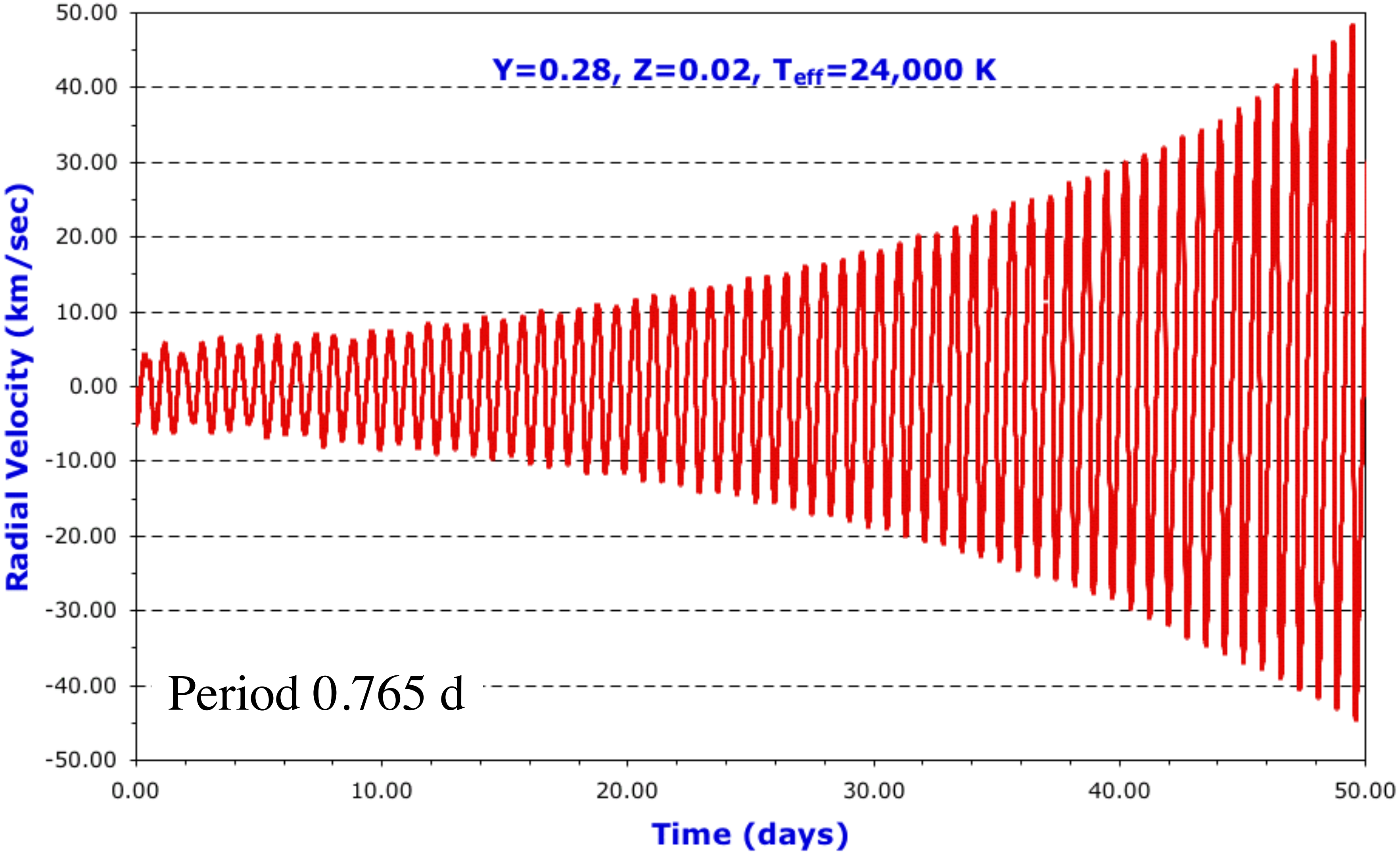
20 M_{sun}
22,139 K

Nonlinear hydrodynamic simulations show radial pulsations

Model initiated in fundamental mode with radial velocity amplitude 5 km/sec.

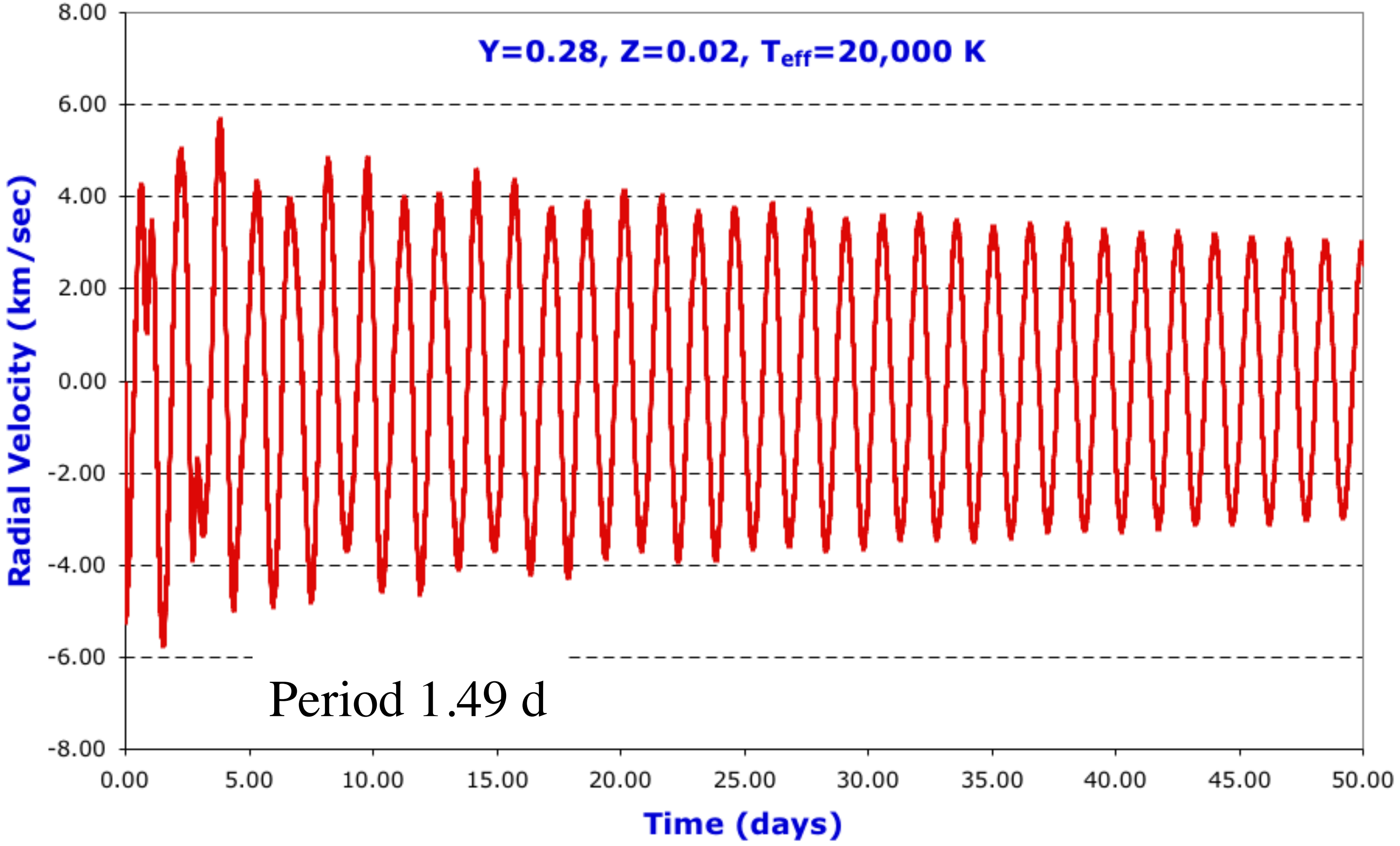


Amplitudes grow rapidly for models with higher T_{eff}



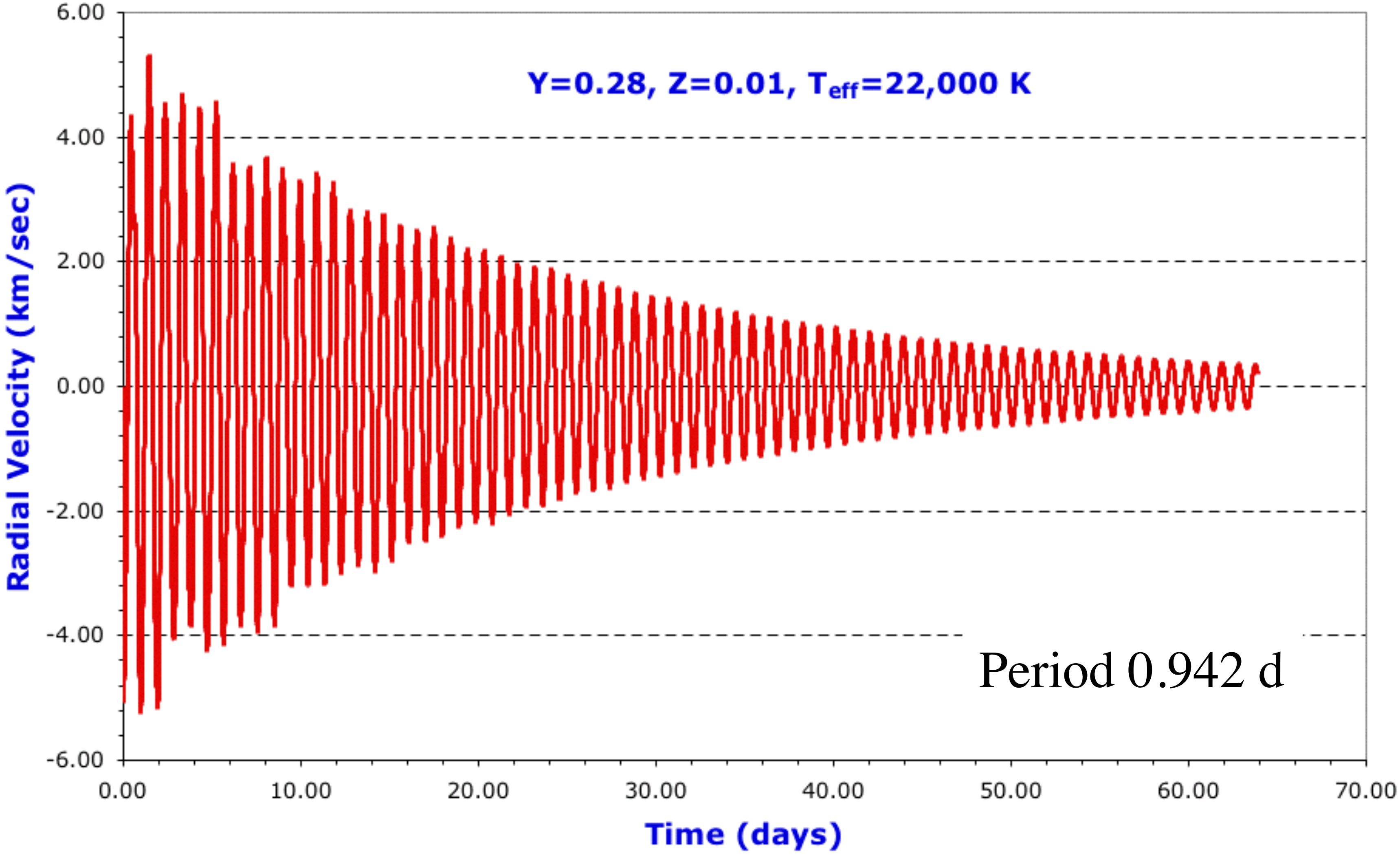
Period 0.765 d

Amplitudes damp with lower T_{eff}



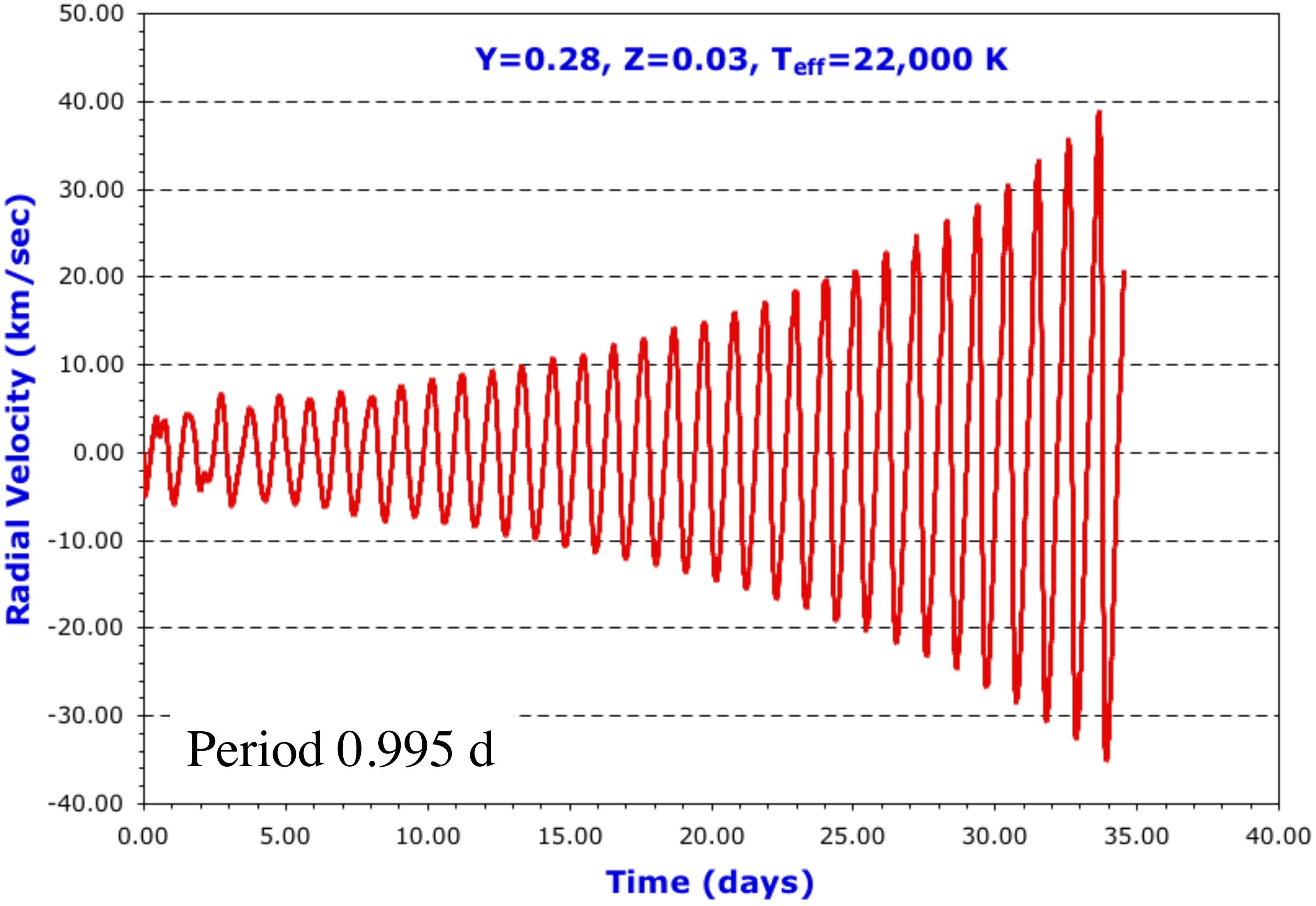
Period 1.49 d

Pulsations damp with decreased Z (Fe) abundance

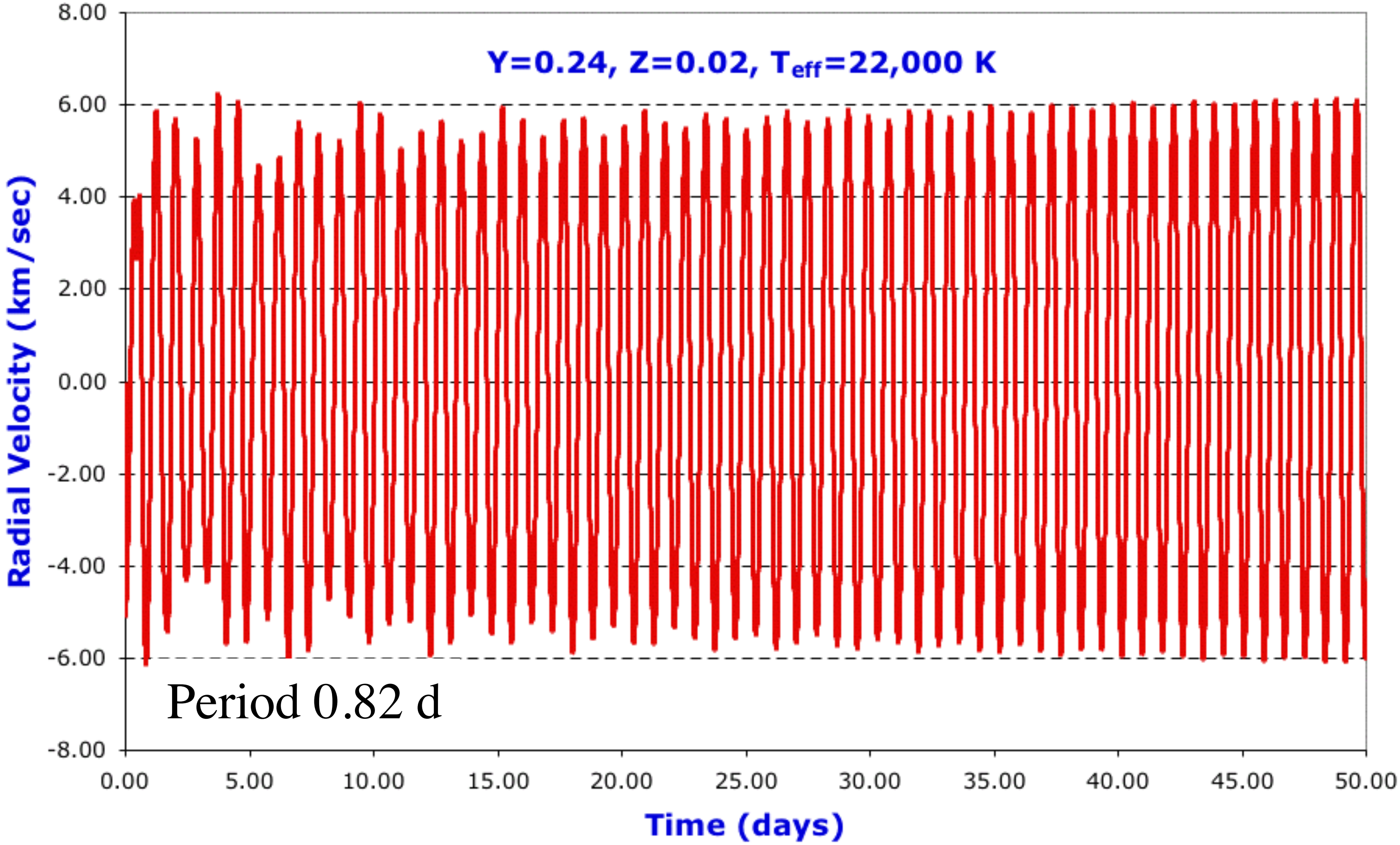


Period 0.942 d

Pulsations grow with increased Z (Fe) abundance

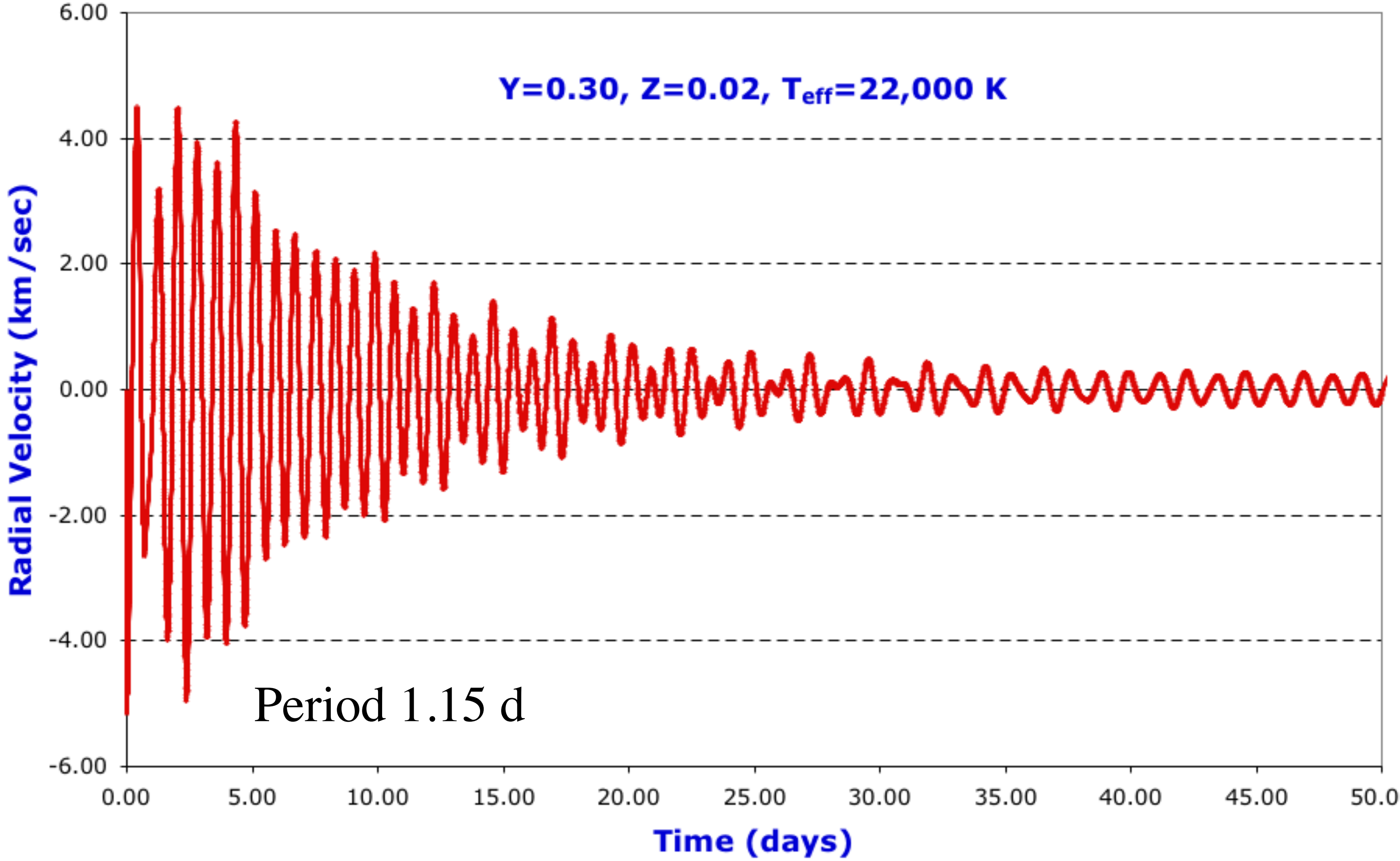


Pulsations grow slowly with decreased He abundance



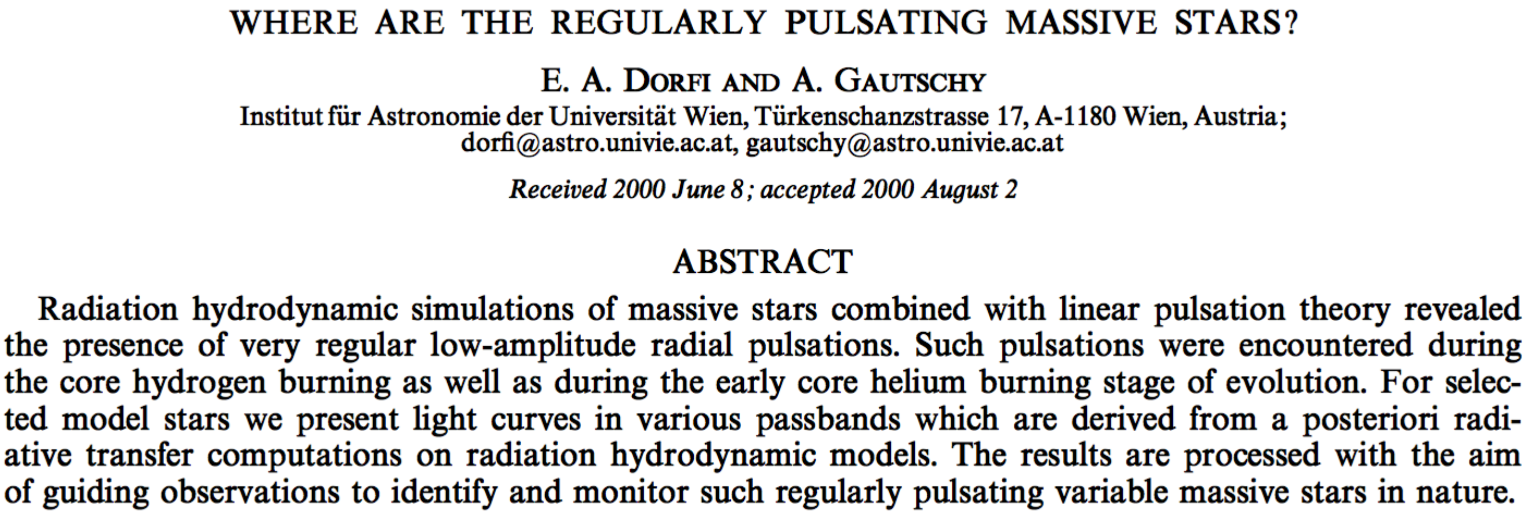
Period 0.82 d

Pulsations damp rapidly with increased He abundance



Period 1.15 d

Do these simulations correspond to observations?



WHERE ARE THE REGULARLY PULSATING MASSIVE STARS?

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ABSTRACT

Radiation hydrodynamic simulations of massive stars combined with linear pulsation theory revealed the presence of very regular low-amplitude radial pulsations. Such pulsations were encountered during the core hydrogen burning as well as during the early core helium burning stage of evolution. For selected model stars we present light curves in various passbands which are derived from a posteriori radiative transfer computations on radiation hydrodynamic models. The results are processed with the aim of guiding observations to identify and monitor such regularly pulsating variable massive stars in nature.

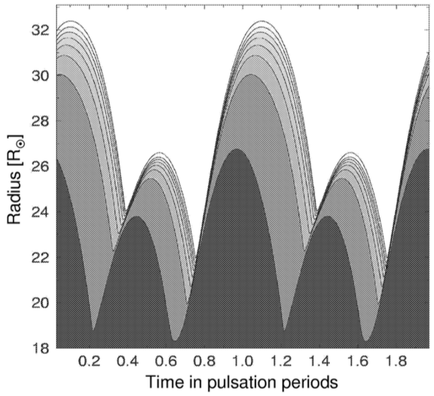
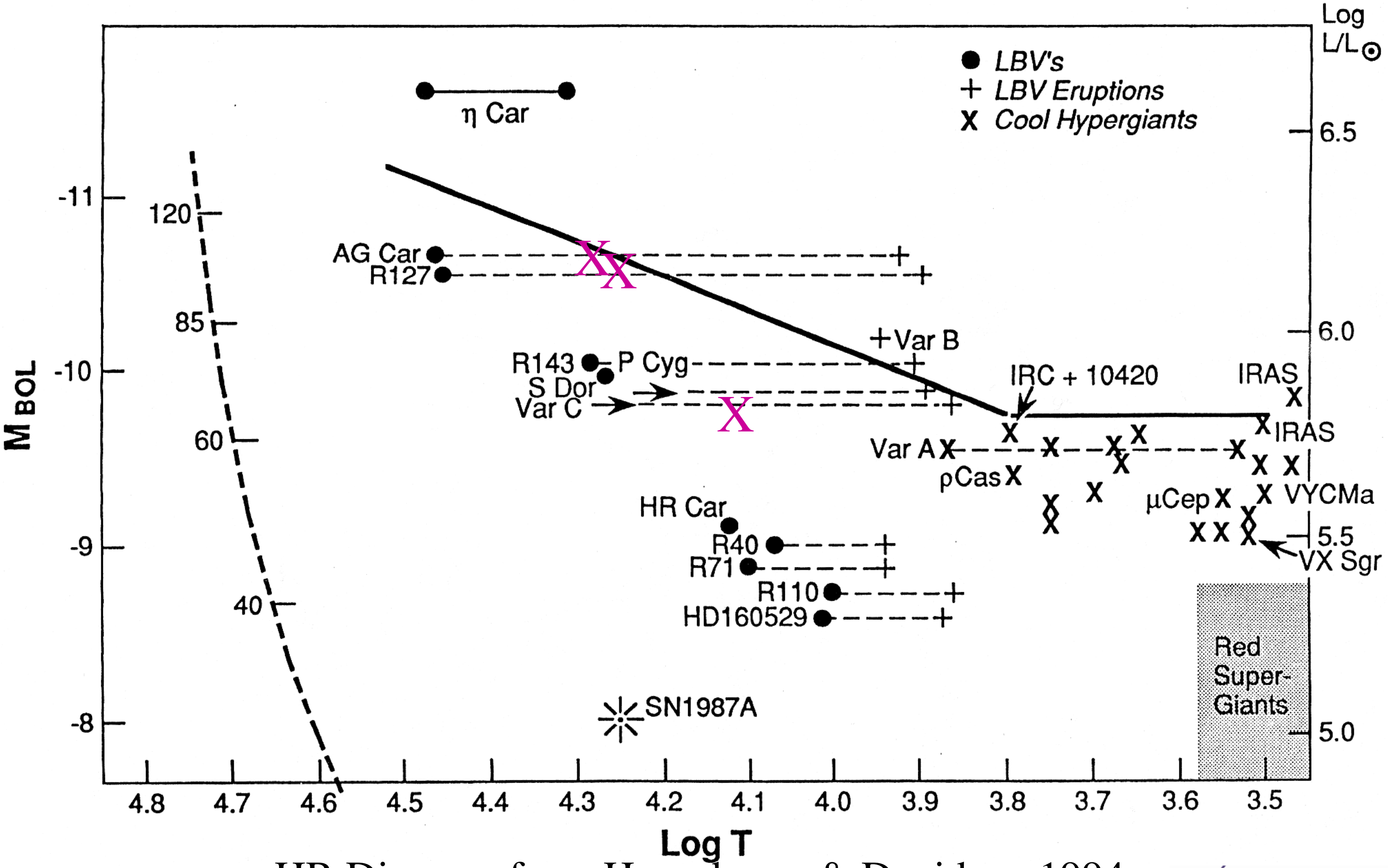


Figure 2: The paths of different mass shells as a function of the pulsation period show the ballistic behavior of the outermost atmosphere ($M = 60\,\mathrm{M}_\odot$, $L = 933\,000\,\mathrm{L}_\odot$, $T_{\mathrm{eff}} = 34\,680\,\mathrm{K}$). For an observer this motion pattern leads to periodic luminosity variations with $P = 1.611$ days whereas the internal pulsation period is close to 0.8 days (see text for more details).

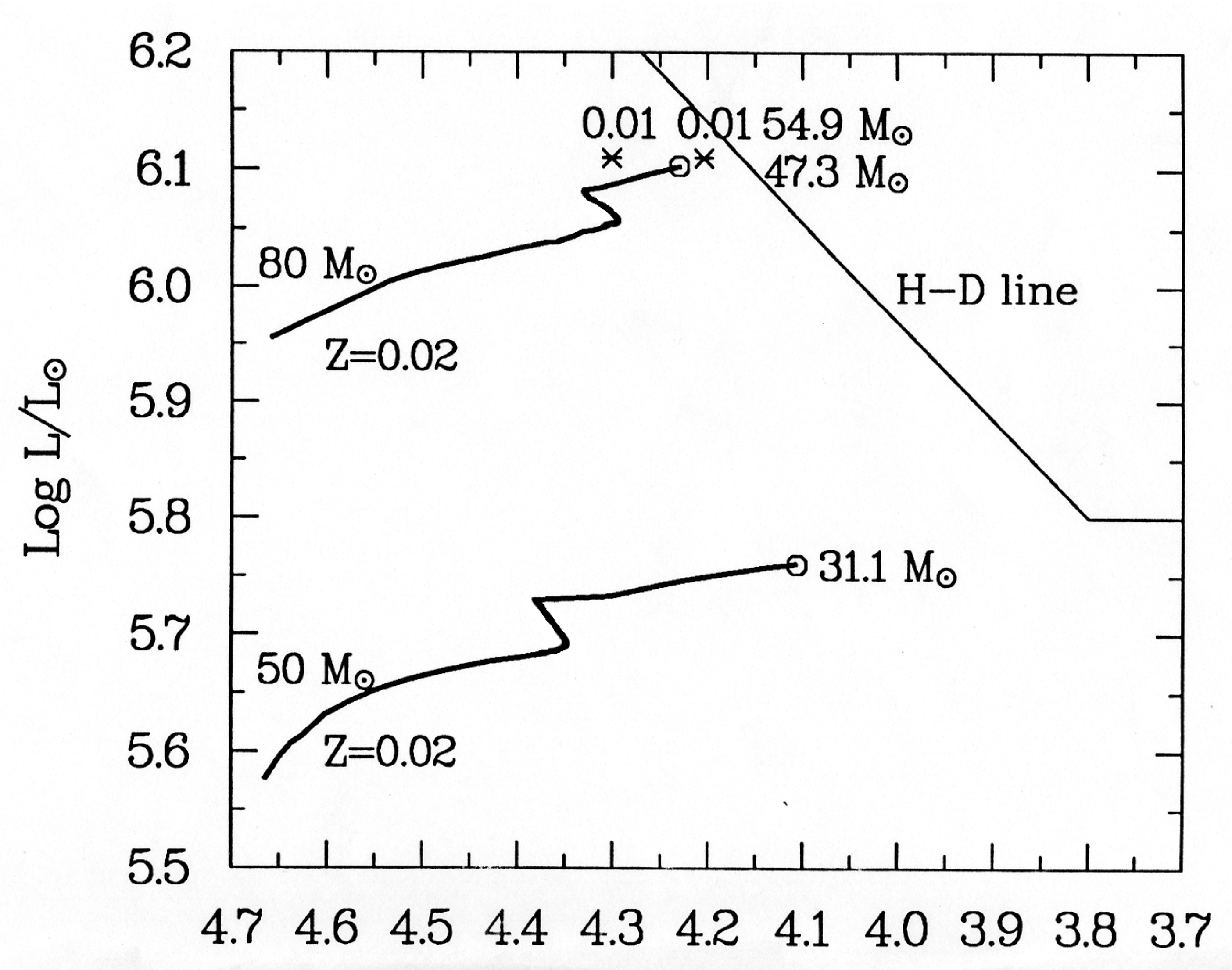
Dorfi and Gautschy, CoAst 2002

LBV stars on HR diagram with Humpreys – Davidson Limit

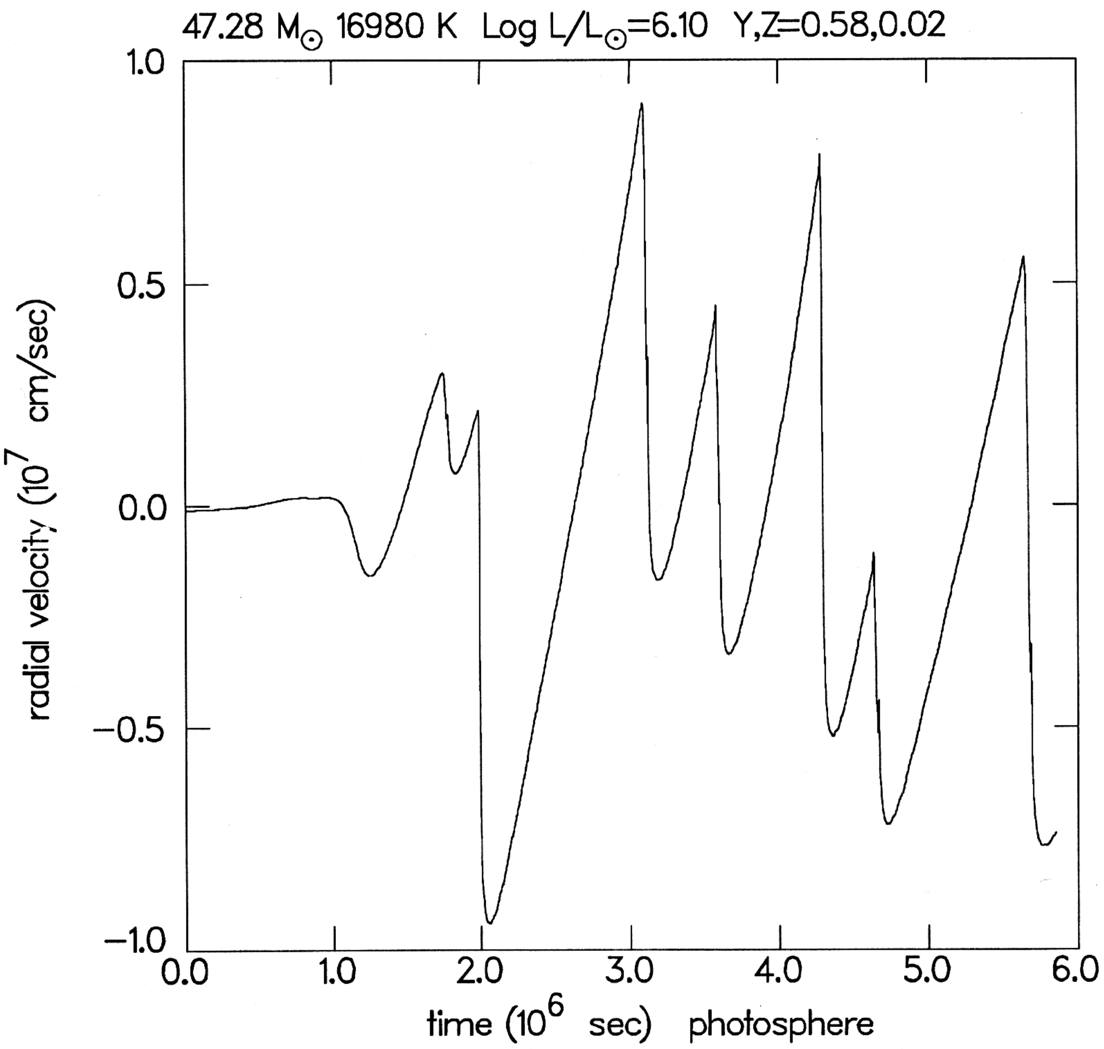


HR Diagram from Humphreys & Davidson 1994

Evolution tracks of 80 and 50 M_{sun} models with mass loss



Model pulsates for surface Y=0.58



M_{init} = 80 Msun
M_{final} = 47.28 Msun

Amplitude ~100 km/sec

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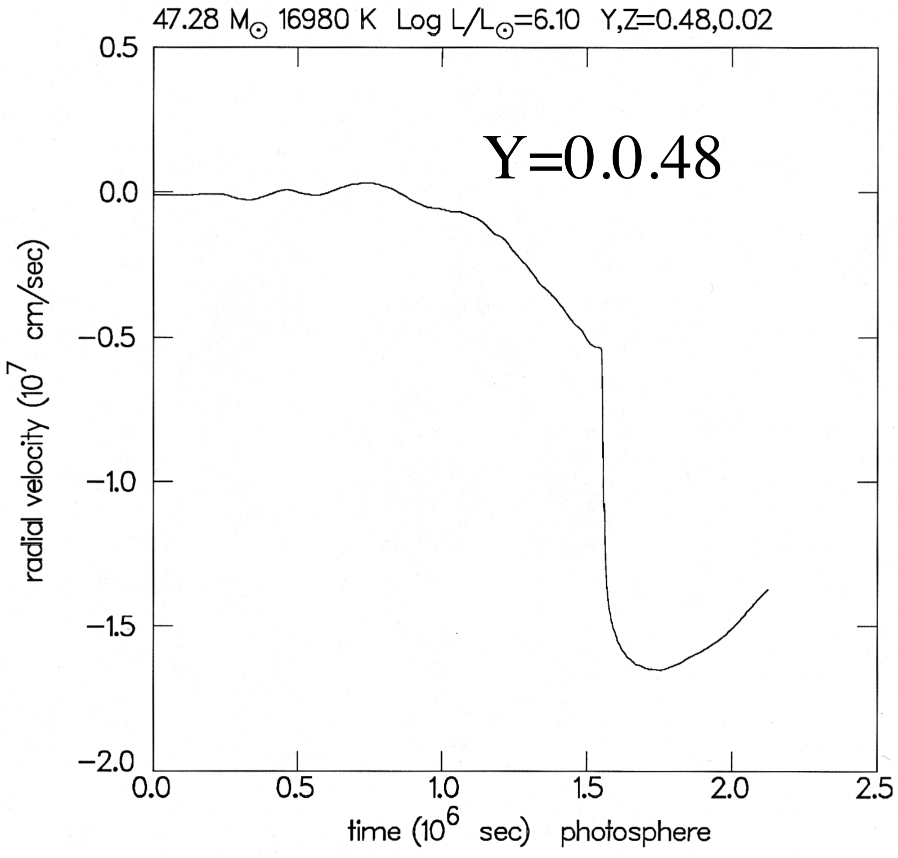
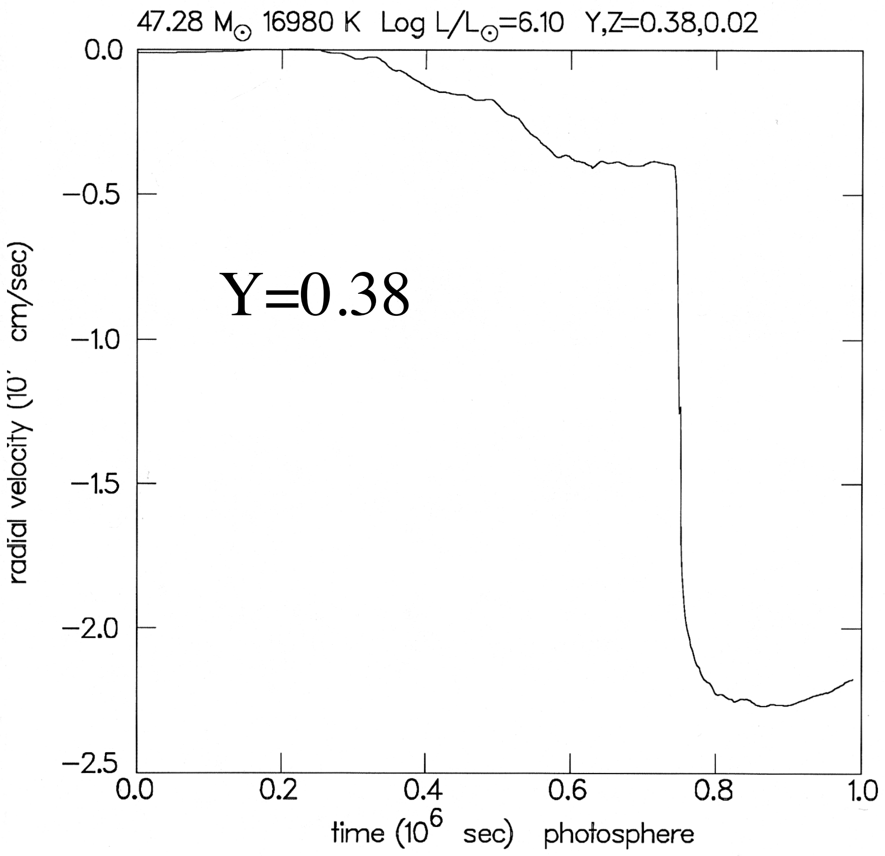
For Y=0.38 and 0.48, models shows large abrupt increase in outward radial velocity





Time-dependent convection and the Eddington limit

- Models show large radial velocity excursions when the ***radiative luminosity*** of ***deep envelope zones*** near pulsation driving region (T>100,000 K) exceeds the ***Eddington luminosity*** for some portion of a pulsation cycle.

Eddington Luminosity = $4\pi GMc/\kappa$

- At this limit, the force due to radiation pressure outward exceeds the force due to gravity.
- In a static non-pulsating model, convection turns on to transport the required luminosity, so the model avoids exceeding the Eddington limit.
- However, in a pulsating model, convection takes some time to turn on during pulsation cycle, so the Eddington limit is periodically exceeded.

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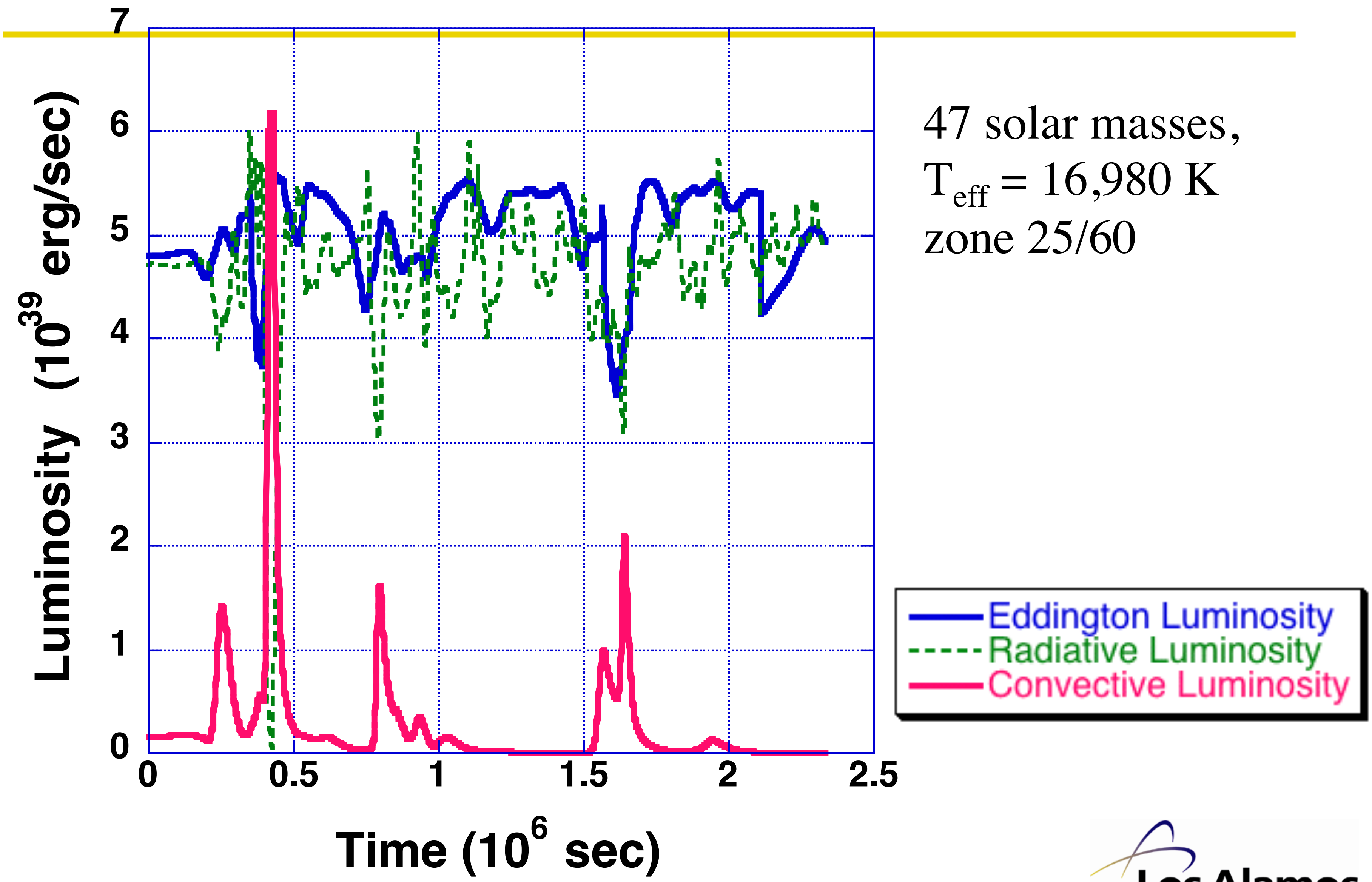
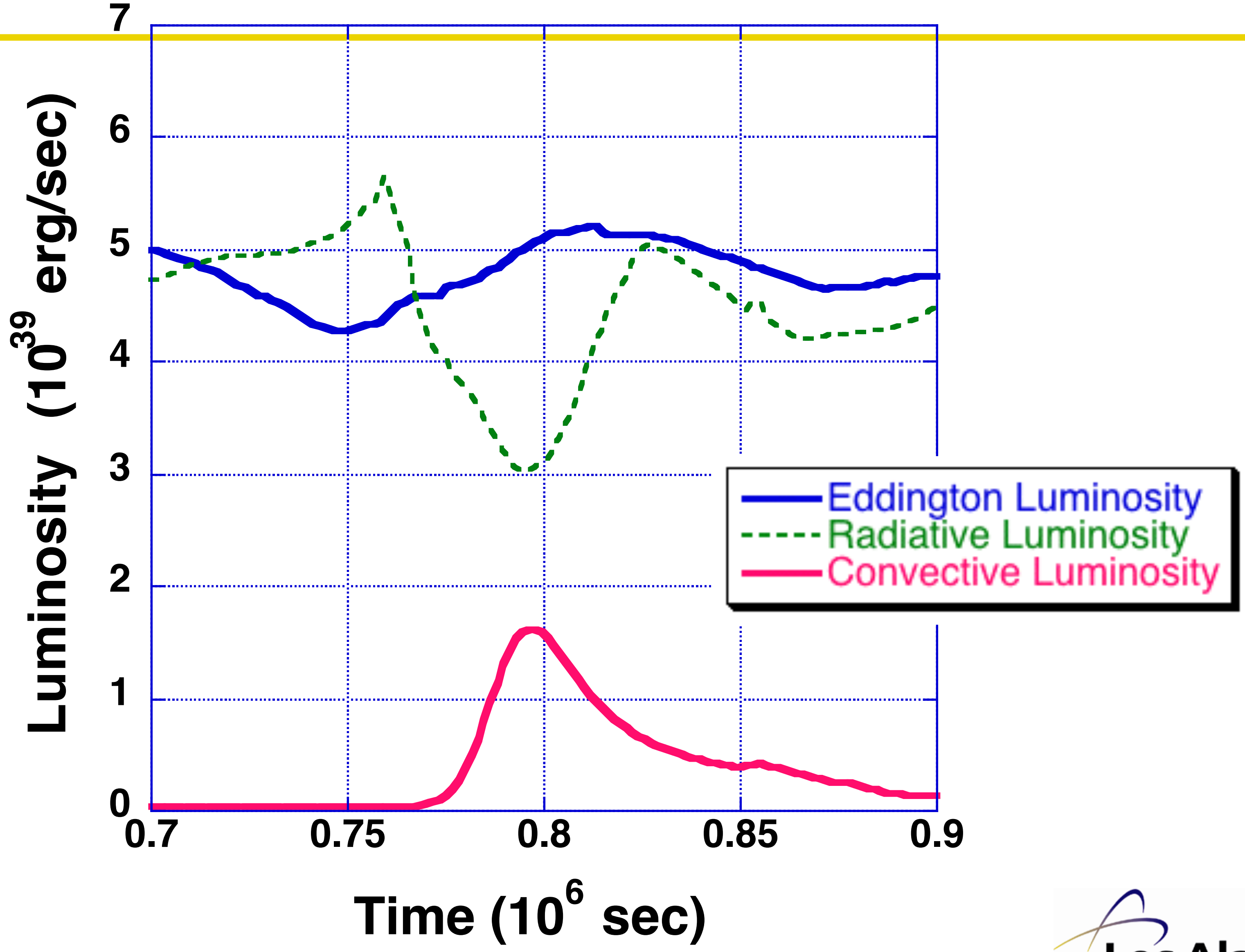
Due to lag in convective luminosity increase during pulsations, deep layers can exceed L_{edd}



47 solar masses,
T_{eff} = 16,980 K
zone 25/60

Radiative luminosity exceeds L_{edd} until convection turns on to transport some luminosity



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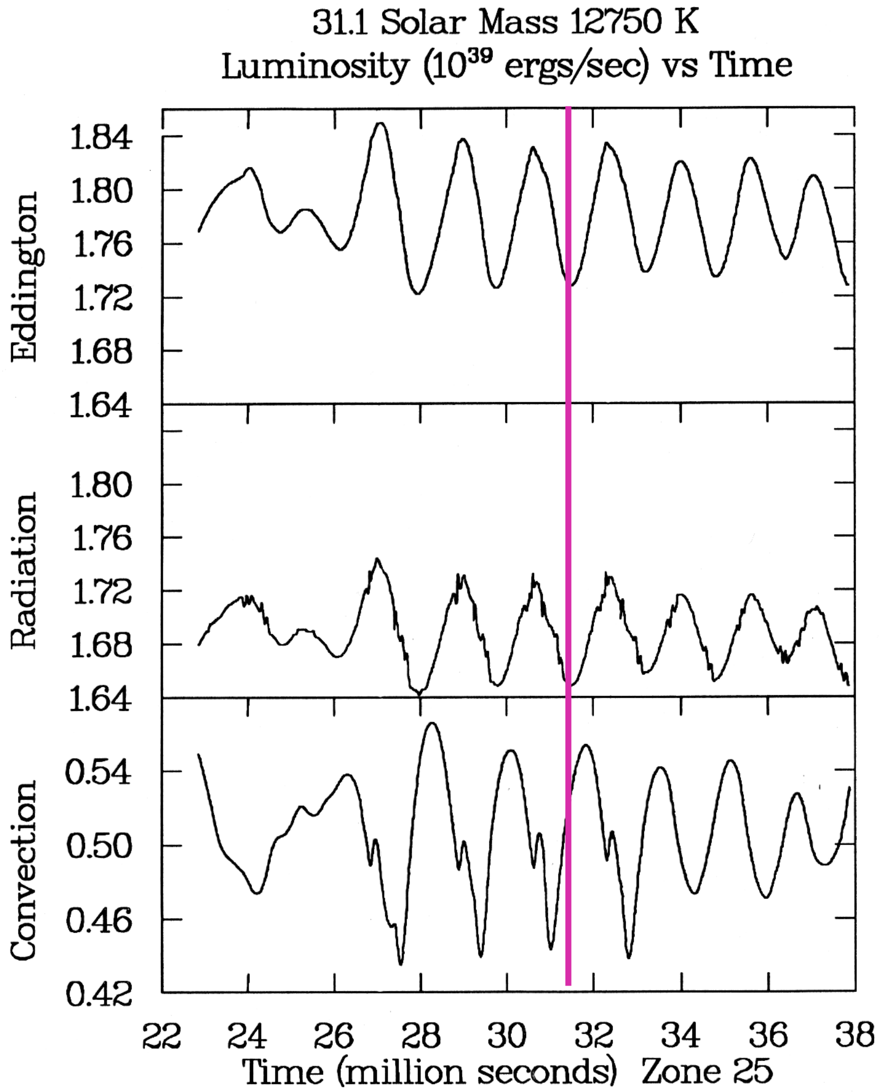
Convective luminosity increase can lag radiative luminosity decrease



Even though for 31 M_{sun} model radiative luminosity is below Eddington luminosity, this model illustrates clearly the lag of convective luminosity increase as radiative luminosity decreases

Summary of hydro model results

For high-mass models near the H-D limit:

•Pulsations grow to large amplitudes (> 100 km/sec)

•Pulsation periods and amplitudes are similar to LBV microvariations (5 to 50 days, ~0.1 mag)

•Convective timescale ~ pulsation period, *so time-dependent convection treatment is needed.*

• When convection cannot compensate to carry luminosity fast enough during a pulsation cycle, layers exceed L_{Edd}.

•Outer layers expand during at least several pulsation cycles.

•An increase in envelope helium abundance (after mass loss) would lower opacity and limit the pulsation amplitudes.

Winds vs. eruptions

- We have shown only that pulsations can cause layers of the stellar envelope to exceed the Eddington limit, leading to envelope expansion.

- Our envelope models encompass only ~10^{-4} solar masses, whereas in observed outbursts much more mass can be lost.
- Considering pulsation period and recovery time, winds produce ~ 4 x 10^{-3} M_{sun}/year (10^{-4} M_{sun} every ~10 days) (neglecting rotation)
- The calculated “outbursts” are generated within a few pulsation cycles (< 1 year) beginning from a near-static configuration.

We have outlined a mechanism for pulsation-enhanced mass loss rather than a mechanism for the rare giant eruptions

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Requirements for giant eruption mechanism

For giant eruptions like those of η Car and P Cyg,

Need a mechanism that:

1) **Ejects a large amount of mass, so origin must be deep-seated**

Envelope has 95% of stellar radius but only contains 10^{-4} M_{sun}

η Car lost ~20 M_{sun} over ~ 20 years (~1 M_{sun}/year)

2) ***Turns on*** suddenly, and then (perhaps after a bounce/rebound) ***turns off*** for hundreds or thousands of years

3) **Generates large amount of energy** (>10^{49} ergs)

Large luminosity, M_{BOL} increase during outbursts

Need energy to lift mass out of deep potential well

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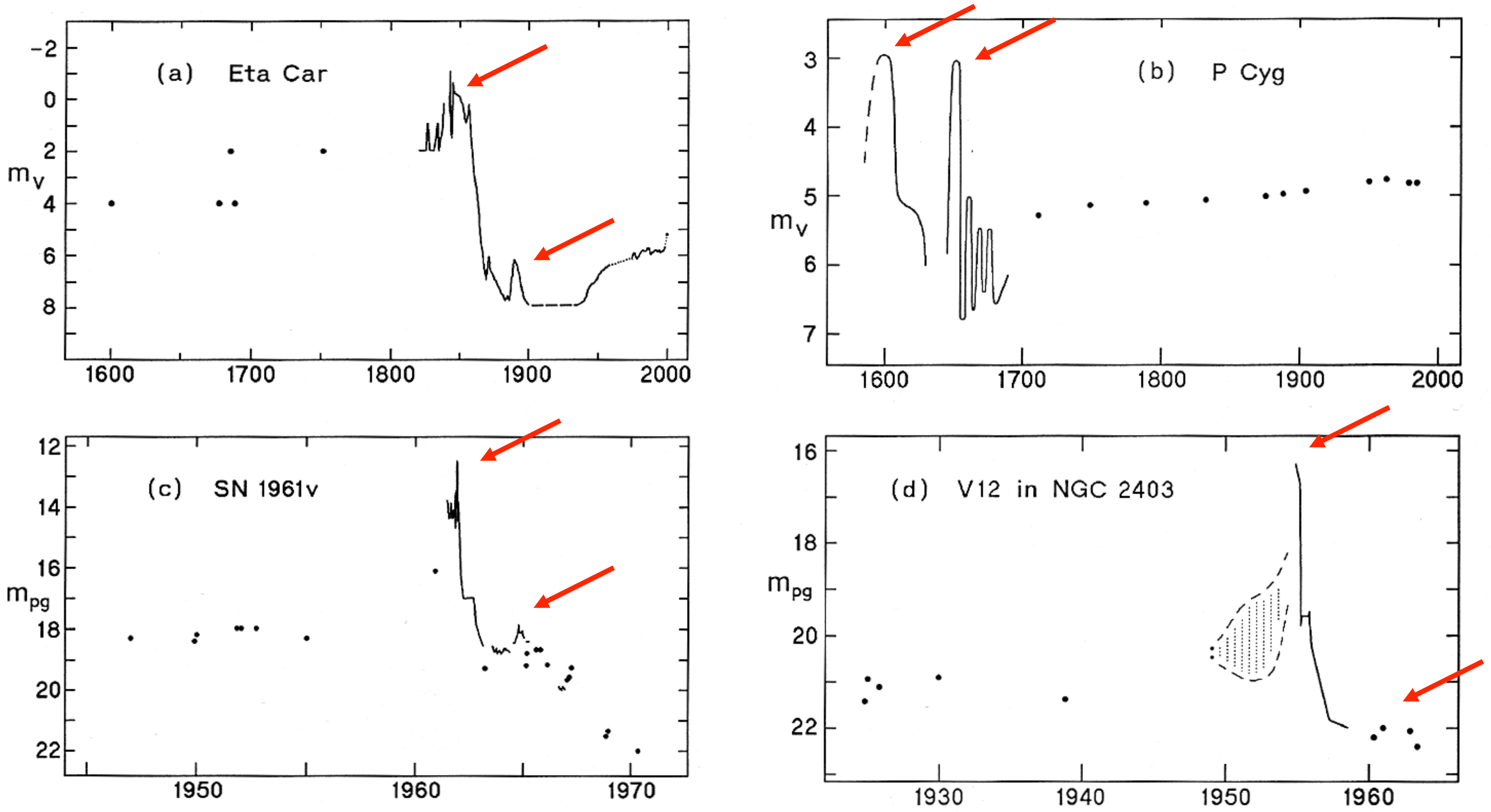
Evidence of ‘rebounds’?

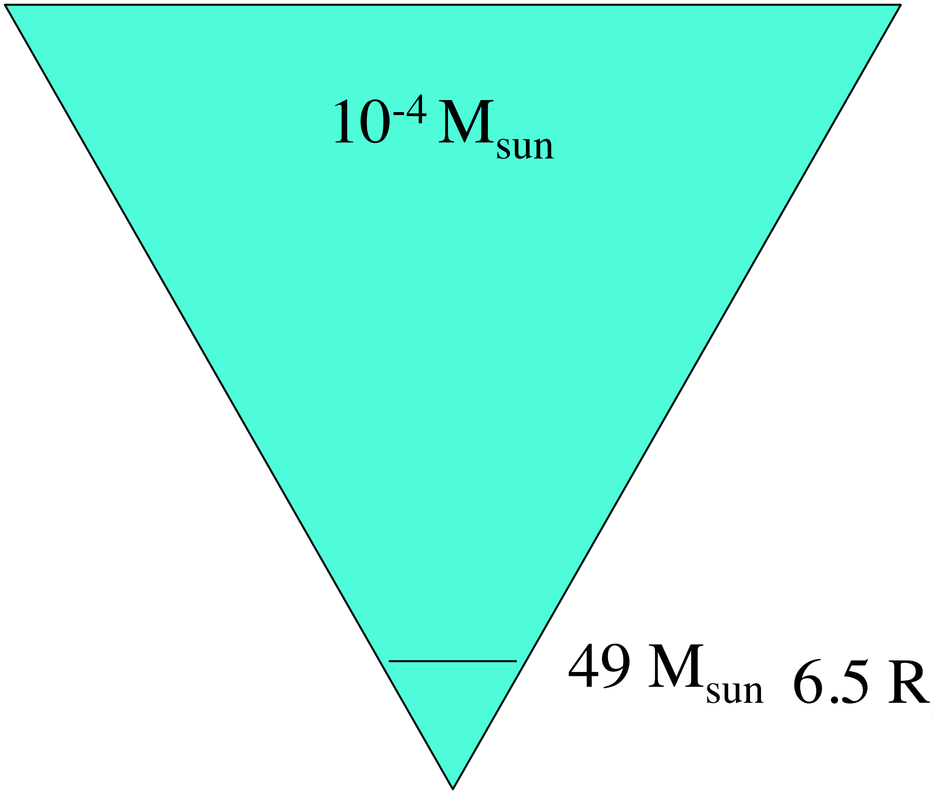


Humphreys, Davidson, and Smith 1999

FIG. 1.—(*a*) The historical light curve of η Carinae based on observations from many sources (see text). (*b*) The historical light curve of P Cygni from de Groot (1988) and Lamers & de Groot (1992), with their permission. (*c*) The light curve of SN 1961v based on Fig. 12 in Doggett & Branch (1985), with permission. (*d*) The light curve of V12 in NGC 2403 based on observations by Tammann & Sandage (1968).

A mechanism causing loss of several solar masses must be deep-seated

49 M_{sun} evolved model (after mass loss) 130 R_{sun}



10^{-4} M_{sun}

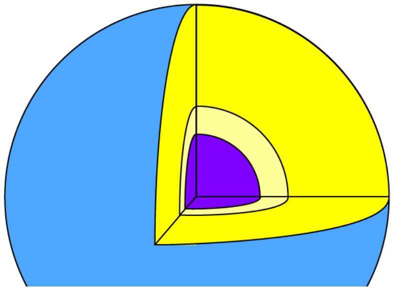
49 M_{sun} 6.5 R_{sun}

Energy required to lift 1 M_{sun} material out of gravitational potential well: 3 x 10^{49} ergs

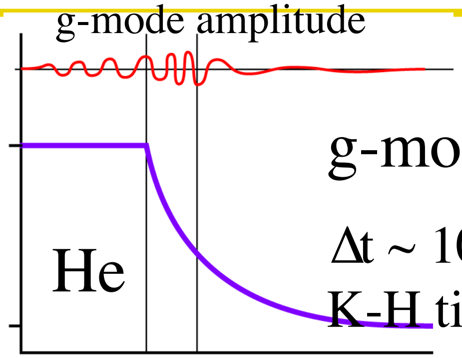
= amount of energy produced by 0.002 M_{sun} hydrogen (a few zones in H-burning shell region in calculation) converted to He

H-burning shell at 20 M_{sun}, 2 R_{sun}, 27 million K

Example outburst mechanism: g-mode mixing in H-burning shell

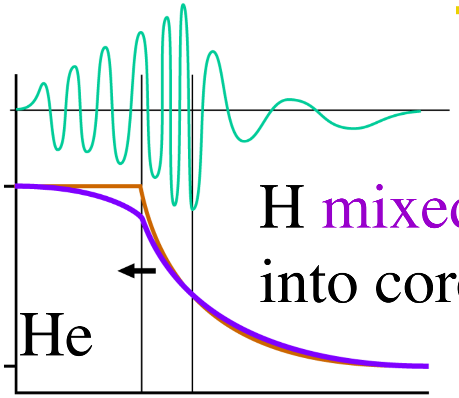


Hydrogen
shell-burning star

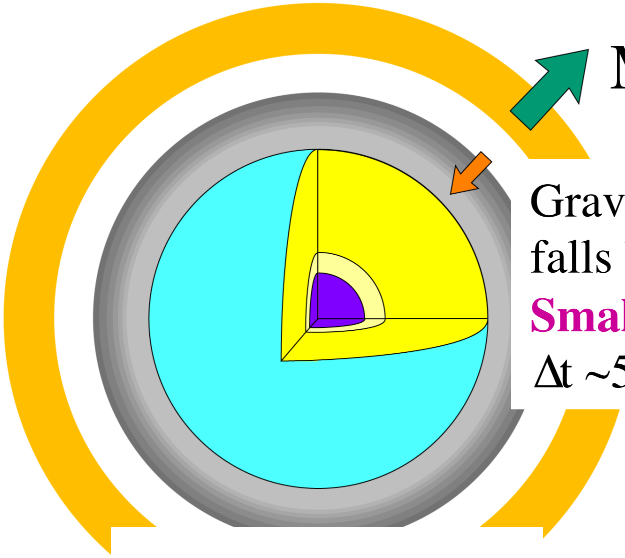


g-modes grow

Δt ~ 100-1000 years
K-H timescale



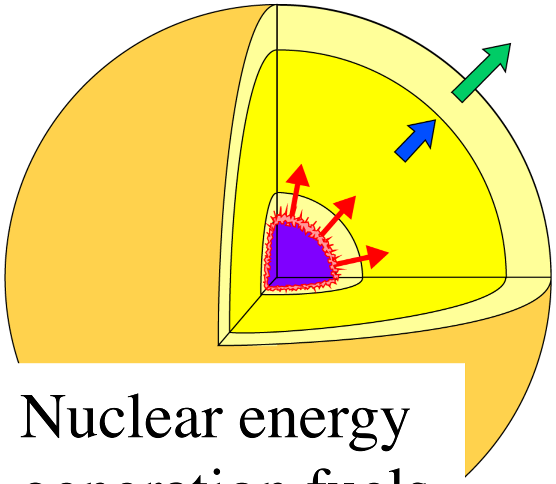
H mixed
into core



Matter ejected

Gravitationally-bound matter
falls back onto star
Smaller rebound after
Δt ~50 years?

Star recovers



Nuclear energy
generation fuels
eruption

Proposed deep-seated mechanisms for instabilities

- Gravity-mode mixing in H-burning shell
- Epsilon mechanism (pulsation driving due to local nuclear energy generation)
- Tidal forcing/flexing effect of binary companion to initiate mixing episodes leading to nuclear burning

- Secular/thermal instability
  - Kelvin Helmholtz (thermal) timescale: $T = GM^2/LR$
  - Instead of normal pulsation analysis that searches for modes on dynamical timescale, find instead modes where star is in hydrostatic equilibrium, but is not in thermal equilibrium

- SASI instability as proposed for Type II supernovae?

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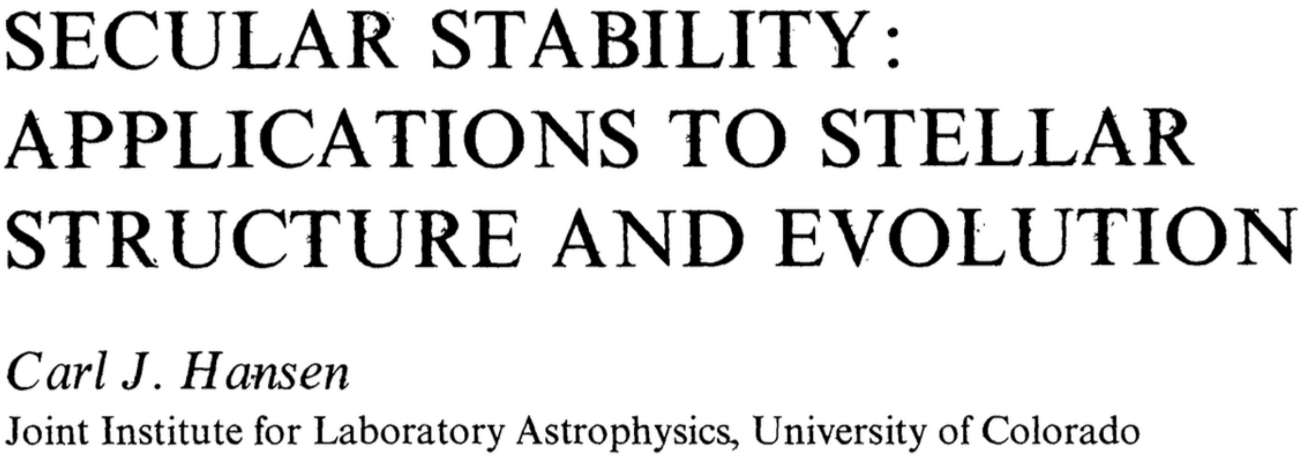
Stellar secular instabilities were a popular subject in 1974-1980



SECULAR STABILITY: APPLICATIONS TO STELLAR STRUCTURE AND EVOLUTION

Carl J. Hansen

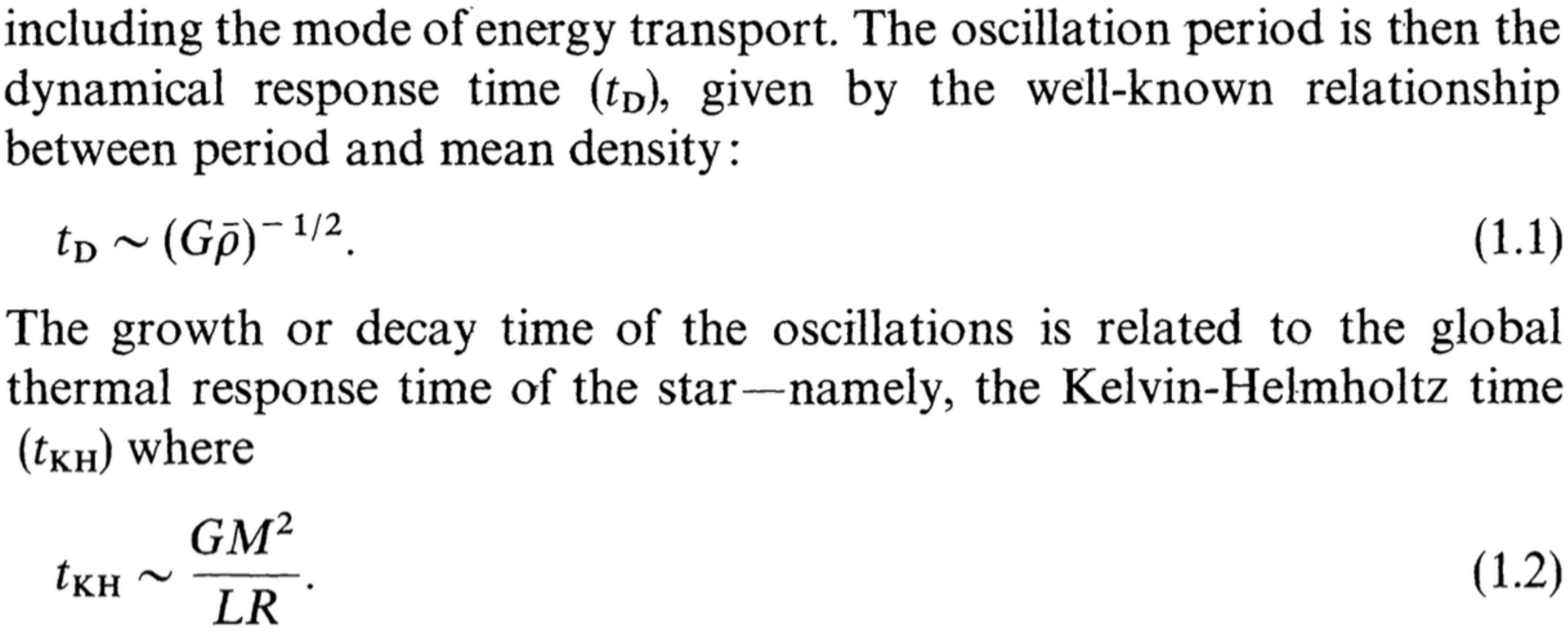
Joint Institute for Laboratory Astrophysics, University of Colorado

ARAA 1978

Secular (thermal) instabilities occur on the *K-H timescale*, longer than the *dynamical timescale*, but smaller than the *nuclear burning* timescale

Investigate what happens when star is in *Hydrostatic* but not in *Thermal* equilibrium

Secular thermal instabilities occur on the KH timescale, longer than the dynamical timescale, but smaller than the nuclear burning timescale



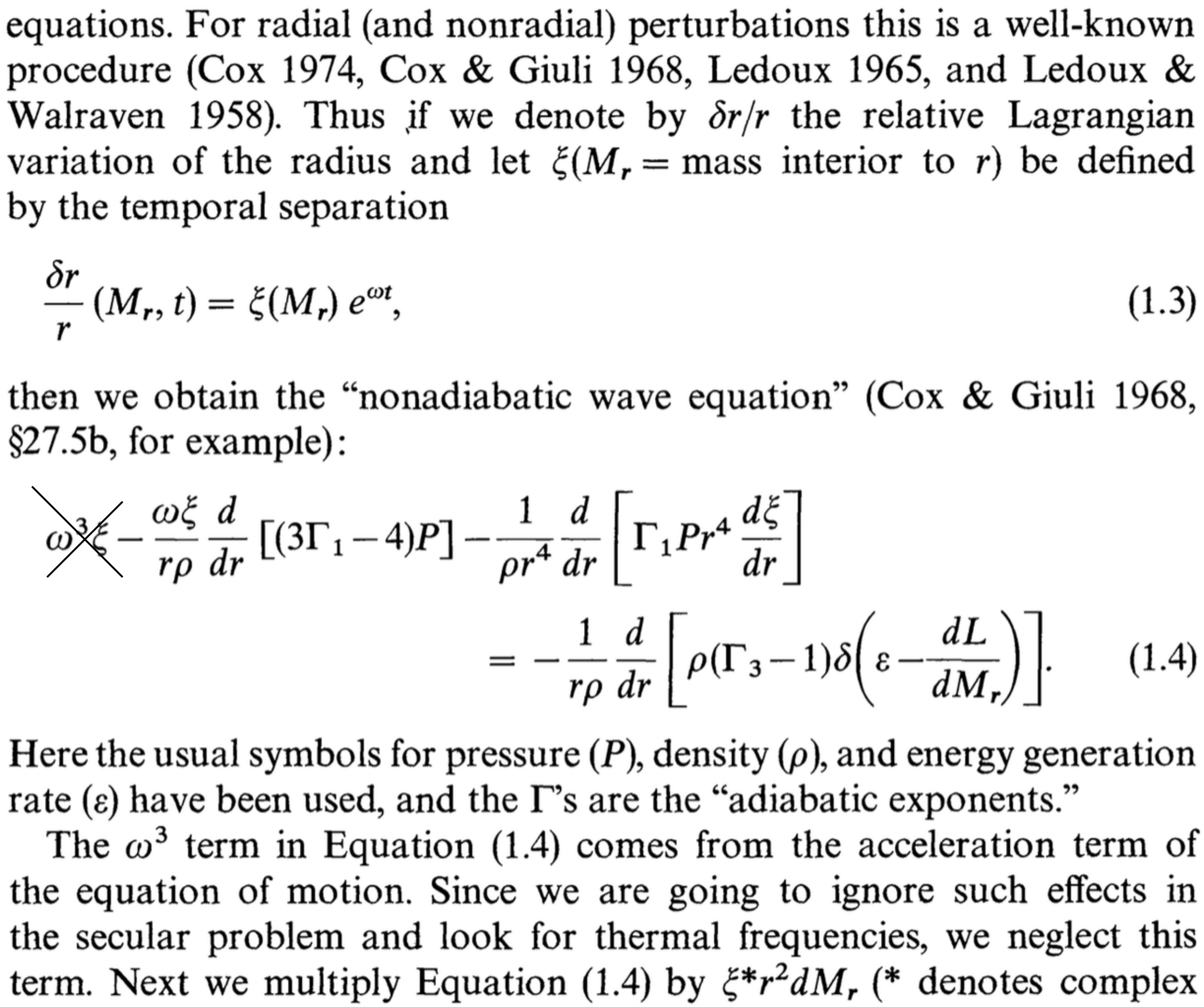
including the mode of energy transport. The oscillation period is then the dynamical response time (t_D), given by the well-known relationship between period and mean density:

$$t_D \sim (G\bar{\rho})^{-1/2}. \tag{1.1}$$

The growth or decay time of the oscillations is related to the global thermal response time of the star—namely, the Kelvin-Helmholtz time (t_{KH}) where

$$t_{KH} \sim \frac{GM^2}{LR}. \tag{1.2}$$

Secular Instabilities are investigated by solving the pulsation wave equation, neglecting the acceleration term



equations. For radial (and nonradial) perturbations this is a well-known procedure (Cox 1974, Cox & Giuli 1968, Ledoux 1965, and Ledoux & Walraven 1958). Thus if we denote by $\delta r/r$ the relative Lagrangian variation of the radius and let $\xi(M_r =$ mass interior to $r)$ be defined by the temporal separation

$$\frac{\delta r}{r}(M_r, t) = \xi(M_r)\, e^{\omega t}, \tag{1.3}$$

then we obtain the "nonadiabatic wave equation" (Cox & Giuli 1968, §27.5b, for example):

$$\cancel{\omega^3 \xi} - \frac{\omega\xi}{r\rho}\frac{d}{dr}\left[(3\Gamma_1 - 4)P\right] - \frac{1}{\rho r^4}\frac{d}{dr}\left[\Gamma_1 P r^4 \frac{d\xi}{dr}\right] = -\frac{1}{r\rho}\frac{d}{dr}\left[\rho(\Gamma_3 - 1)\delta\left(\varepsilon - \frac{dL}{dM_r}\right)\right]. \tag{1.4}$$

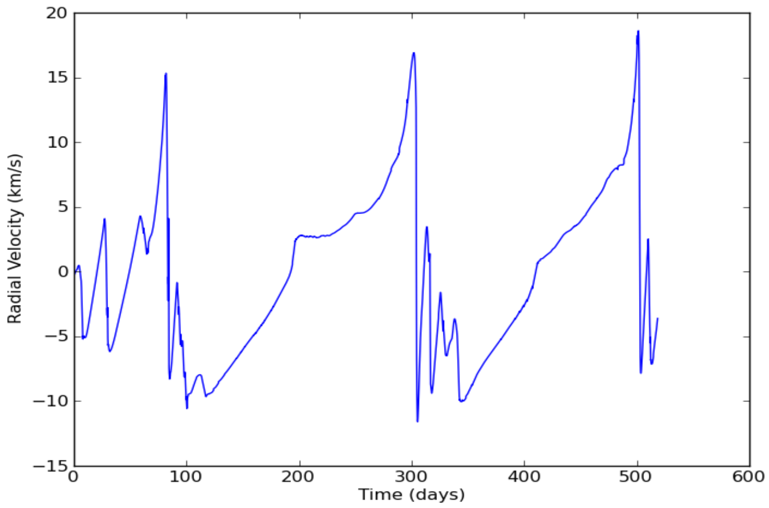
Here the usual symbols for pressure (P), density (ρ), and energy generation rate (ε) have been used, and the Γ's are the "adiabatic exponents."

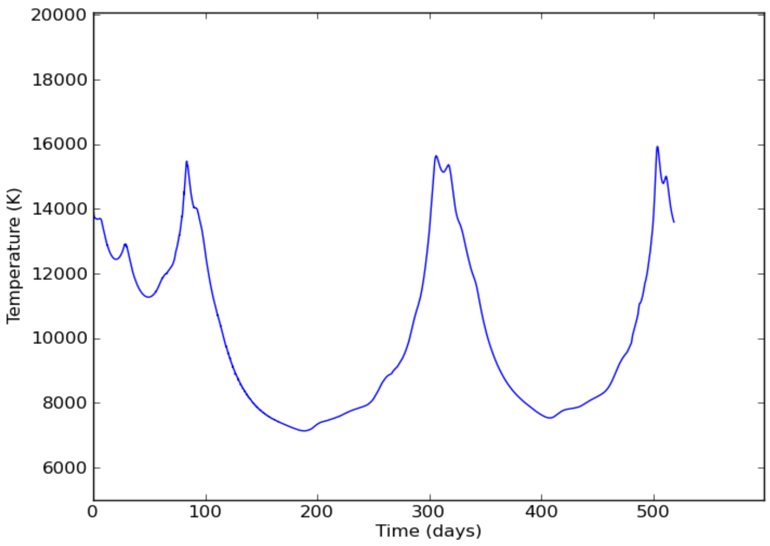
The ω^3 term in Equation (1.4) comes from the acceleration term of the equation of motion. Since we are going to ignore such effects in the secular problem and look for thermal frequencies, we neglect this term. Next we multiply Equation (1.4) by $\xi^* r^2 dM_r$ (* denotes complex

Some questions re. secular instabilities

- Have they already been fully explored for massive stars?
- Are AGB thermal pulses manifestations of secular instability?
- Are pulsation amplitude variations manifestations of secular instability?
- Do we ignore secular instabilities because the timescale is too short for evolution calculations and too long for (pulsation) hydrodynamics simulations?
- Do we assume thermal equilibrium in stellar evolution calculations? (No)
- If we use short-enough evolution code timesteps, would we see effects that could be attributed to secular instability (e.g. He core flash)?

Long Period Models

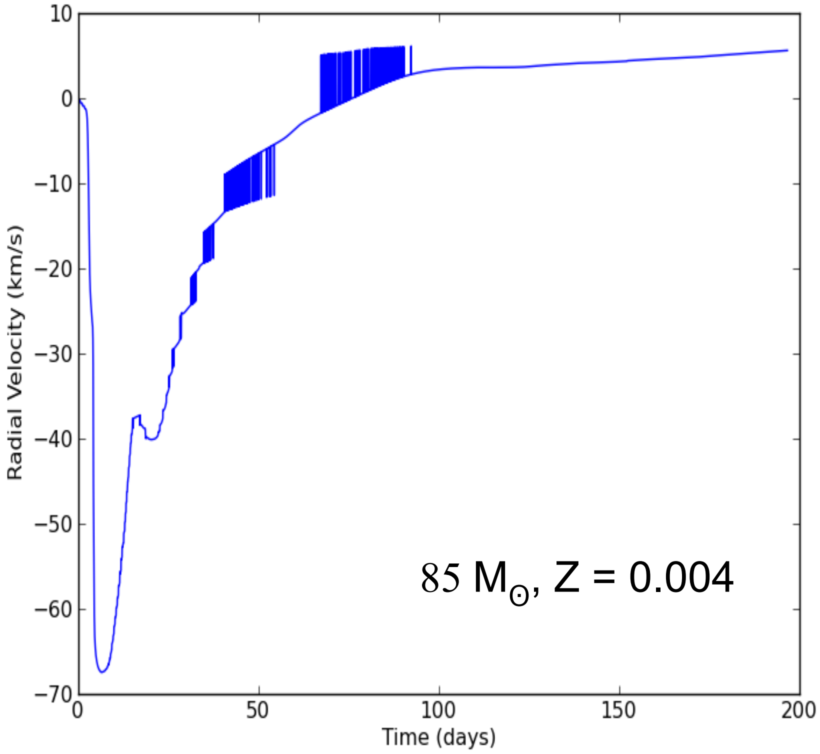




- Long period models tend to have large amplitudes
- Changes in effective temperature can be close to 10 000 K!

85 $M_\odot$, Z = 0.004 – MS model

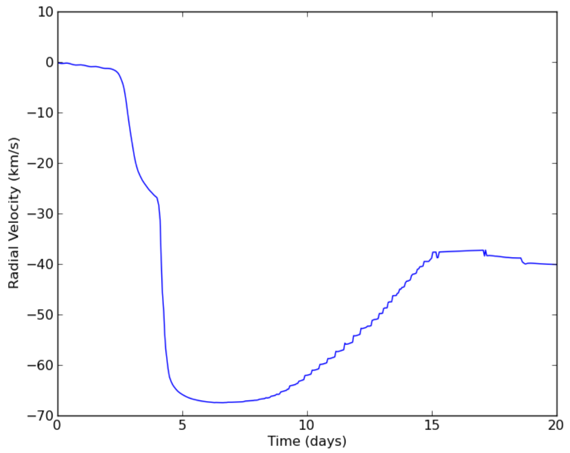
Outbursts

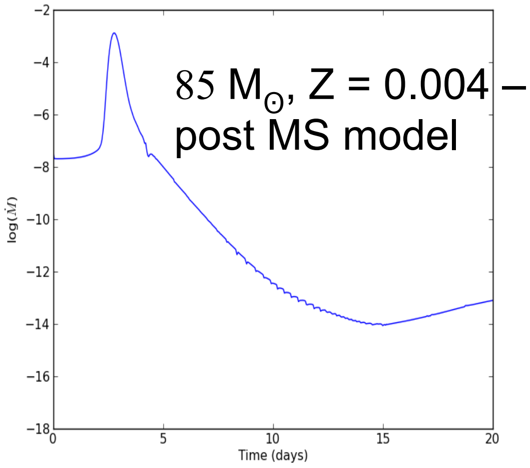


- Some models show outburst-like behaviour
- More common at high mass and low metallicity
- Appears at lower mass as metallicity increases
- Large increase in outward velocity, but slower than the escape speed (neglecting rotation)
- Our models do not include mass loss, so later phases of calculation are unreliable

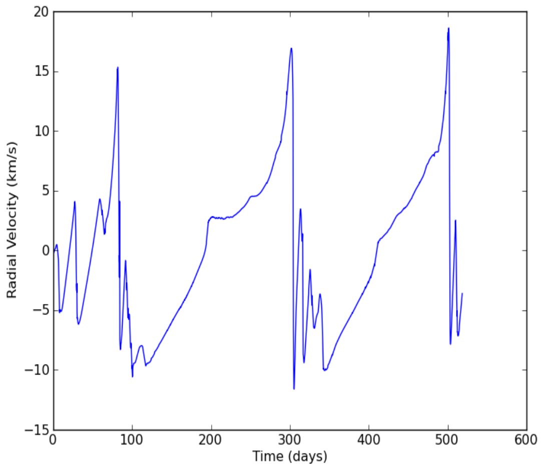
Wind Mass Loss Rates

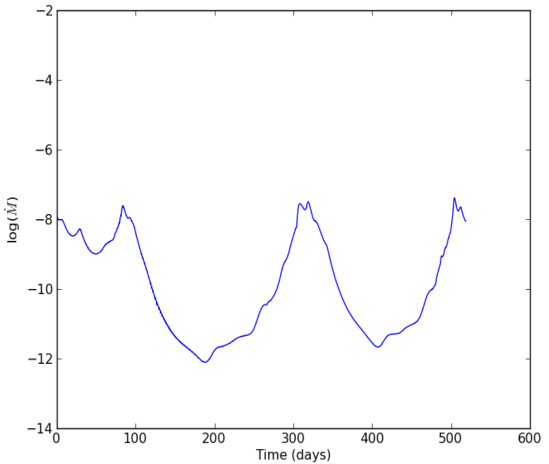
- Outburst-like events can lead to very high mass loss rates
- Peak mass loss of $\sim 10^{-3}$ $M_\odot$/year – more than enough to account for S Dor type episodes
- Mass loss calculated using Vink et al. (2001) mass loss formula





85 $M_\odot$, Z = 0.004 – post MS model





85 $M_\odot$, Z = 0.004 – MS model

- Long period models also have increased mass loss rates over long time scales

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