Pulsation in Massive Stars

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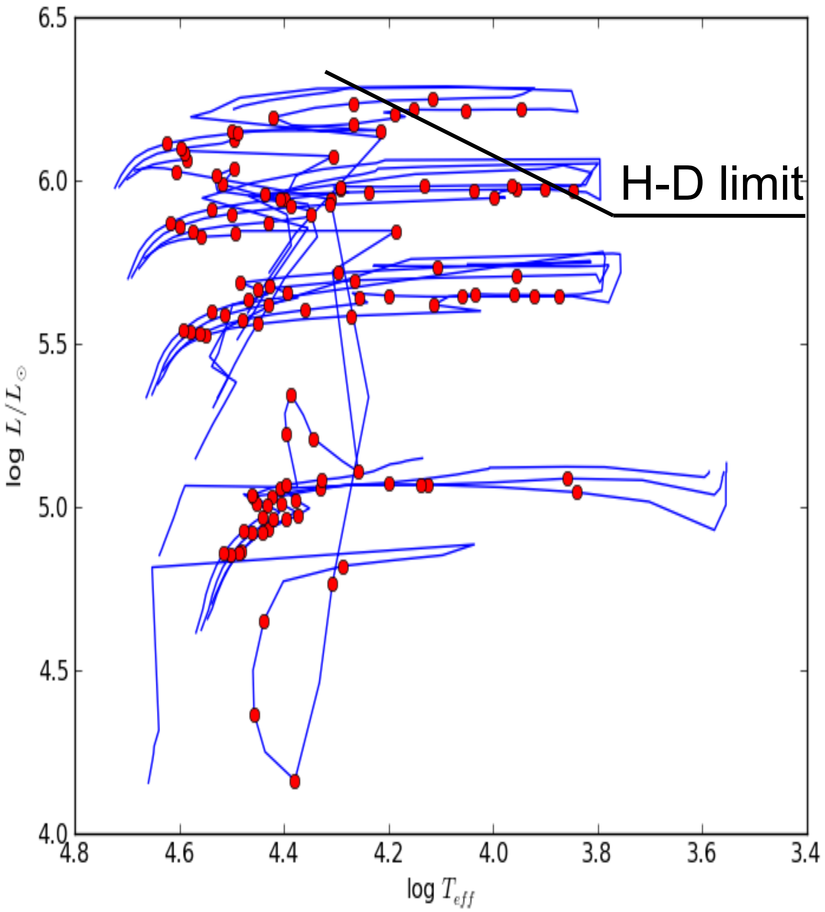
Massive stars are known to pulsate at many stages of evolution. Among the most spectacular are the Luminous Blue Variables (LBVs), in which pulsation is one possible origin for the S Dor type outbursts. This phase of evolution is poorly understood. The driving mechanisms for the variability are not known, and there are even questions as to how this phase connects with other evolutionary phases. Some recent evidence shows that these stars may undergo supernovae explosions, producing Type IIn events.

In this work, we present the radial pulsations of stars with initial masses of 20, 40, 60 and 85 solar masses using both linear and non-linear pulsation codes. The pulsations can then interact with time-dependent convection, which increases the luminosity until the Eddington limit is exceeded locally, potentially driving mass loss and S Dor outbursts. We consider models at various stages of evolution and metallicity, covering the observed properties of the majority of the observed LBVs and LBV candidates. Preliminary results characterizing the pulsations as functions of Y and Z are presented.

A few of our models show outburst-like events. Unfortunately, our models cannot follow mass loss, so once the event begins, our simulations are ended. Based on our results, it is not clear that pulsations can drive the levels of mass loss seen during S Dor outbursts. However, the expansion of the star could lead to increased radiatively driven mass loss. We present preliminary calculations for wind-driven mass loss rates for the outbursting models.

Stellar Models



- Evolution sequences taken from Meynet et al. 1994
- Models include mass loss, but not rotation
- Z = 0.004, 0.008, 0.02 and 0.04
- M = 20, 40, 60 and 85 solar masses

Pulsation Models

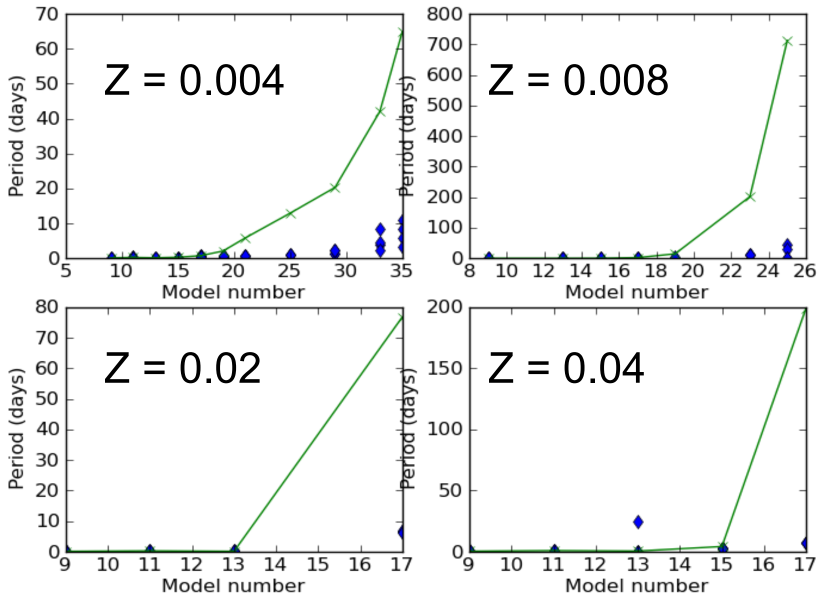
- Find pulsation frequencies using linear, non-adiabatic pulsation code
    - Calculate envelope model containing outer 3-7% of stellar mass, which gives T ~ 2 million K at the bottom – ensures model includes Fe ionization zone (T ~ 200 000K)
    - Pulsation frequencies calculated for first 4 harmonics of radial oscillation
- Linear periods used as input for hydrodynamic models – initialized in a given mode with a velocity of 1 km/s
    - Hydrodynamic models include nonlocal time-dependent convection treatment, which interpolates the convective velocity over the previous two time steps and also weights convective properties of adjacent zones

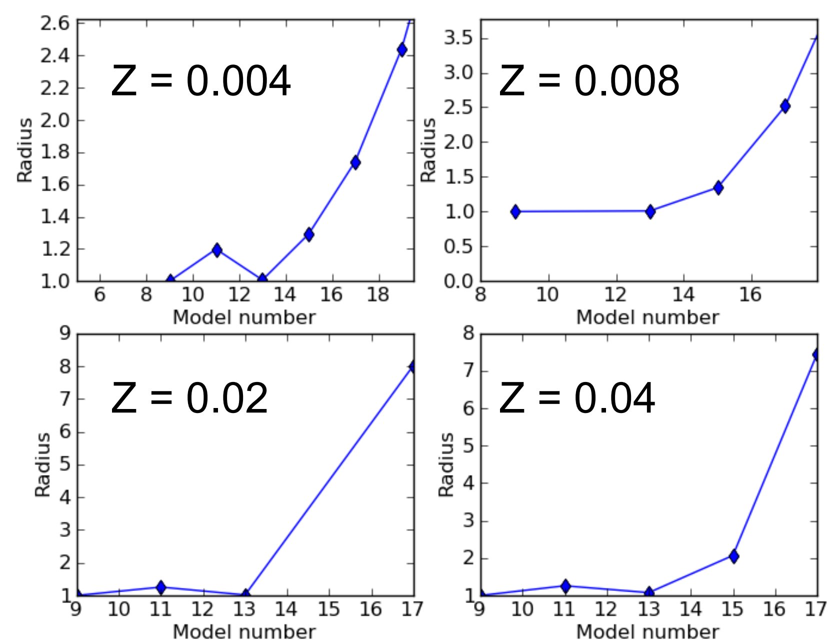
Time Dependent Convection

- During pulsations, convective layers become more or less efficient at transporting luminosity due to changing temperature, density and opacity conditions
- Convective timescale (mixing length/convective velocity) is a significant fraction of the pulsation period
- When luminosity increases locally during a pulsation cycle, convection cannot adapt instantaneously to transport the excess luminosity
- These layers (~100 000-200 000 K) may exceed the Eddington limit, driving expansion or mass loss

Q - Parameter

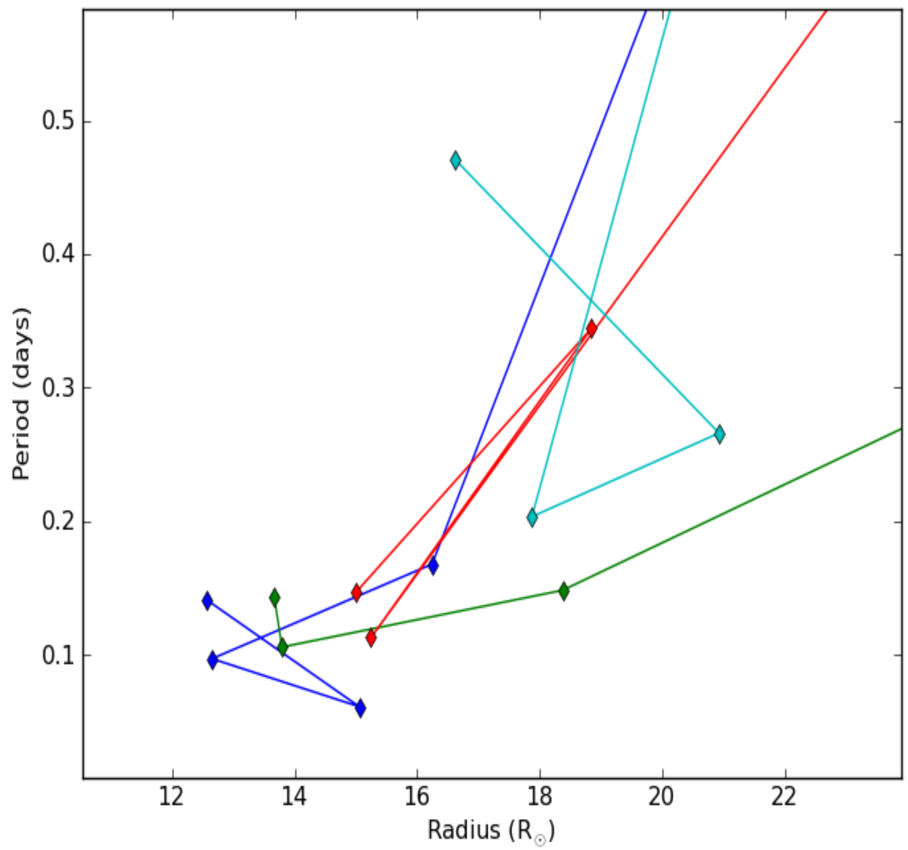
- Define Q = Πρ (period x mean density)
- Q remains ~ constant for stars of similar structure
- Model number is used as a proxy for age





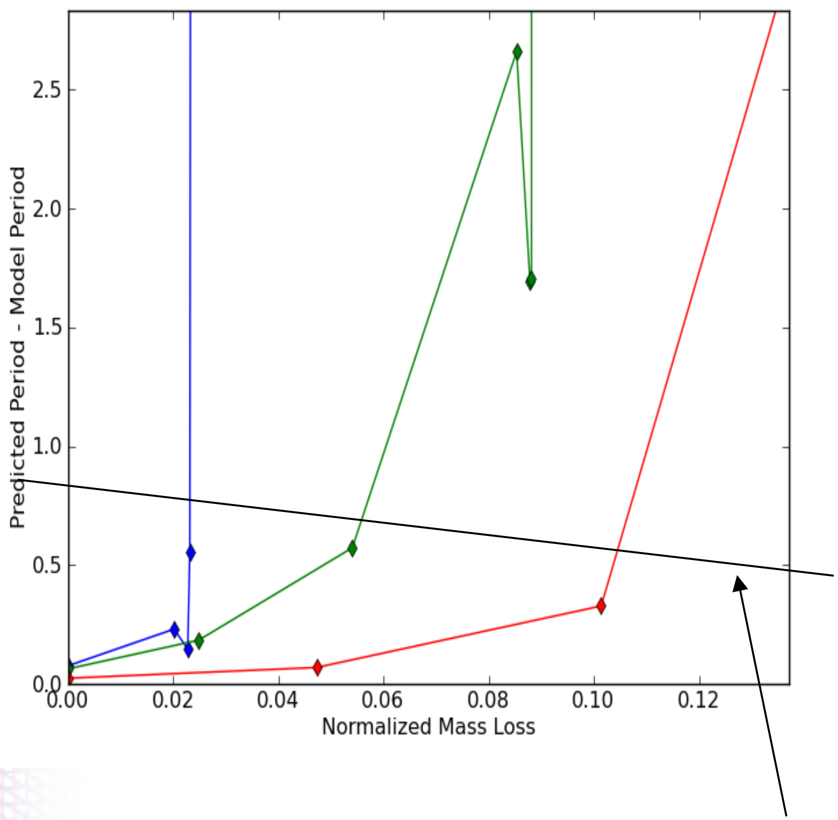
- Q is a good predictor of fundamental period until radius doubles
- At 20 $M_{\odot}$, mass loss is negligible and photospheric helium abundance does not change

Metallicity Effects



- Figure shows non-linear periods for 20 $M_\odot$ models, at Z = 0.004 (blue), 0.008 (green), 0.02 (red) and 0.04 (light blue)
- For main sequence and subgiant models, metallicity has little effect on periods

Changes in Mass

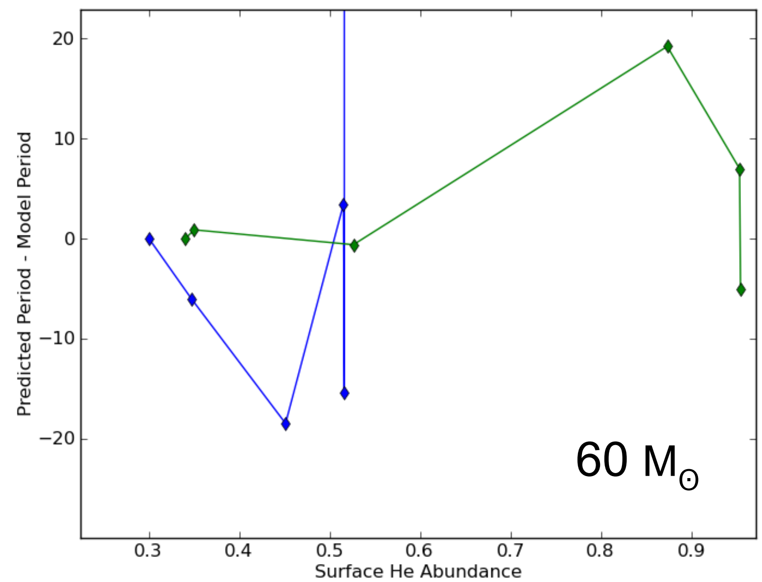


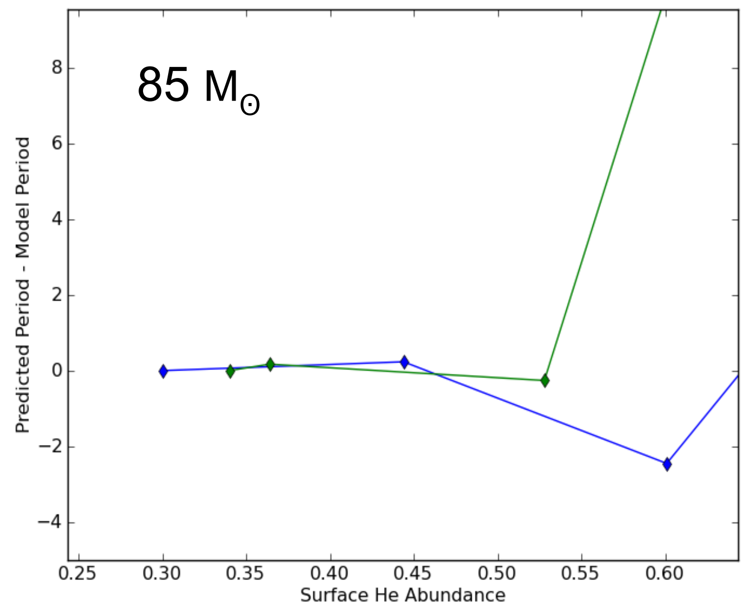
Radius ~ doubles beyond this point

- 40 $M_\odot$ models start to lose significant amounts of mass, but surface He remains constant
- Mass loss has a significant effect on fundamental period when model mass changes by ~5%
- Differences get larger as more mass is lost
- Blue: Z = 0.004, green: Z = 0.008, red: Z = 0.02

Changes in Surface Y

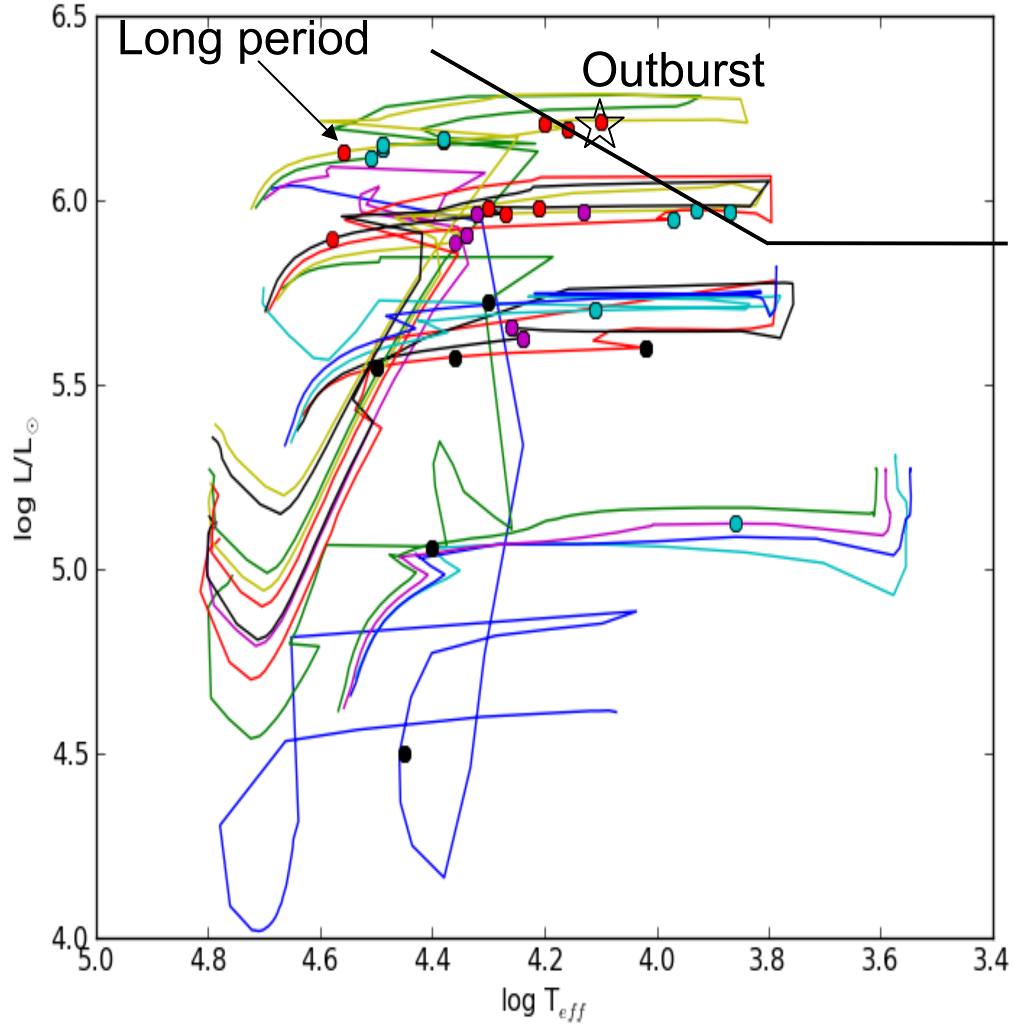
- Increase in surface He abundance increases fundamental periods relative to predictions from Q
- This effect is typically an order of magnitude or more larger than the effects of mass loss
- Also appears to dominate the effects of increasing metallicity
- blue: Z = 0.02; green: Z = 0.04



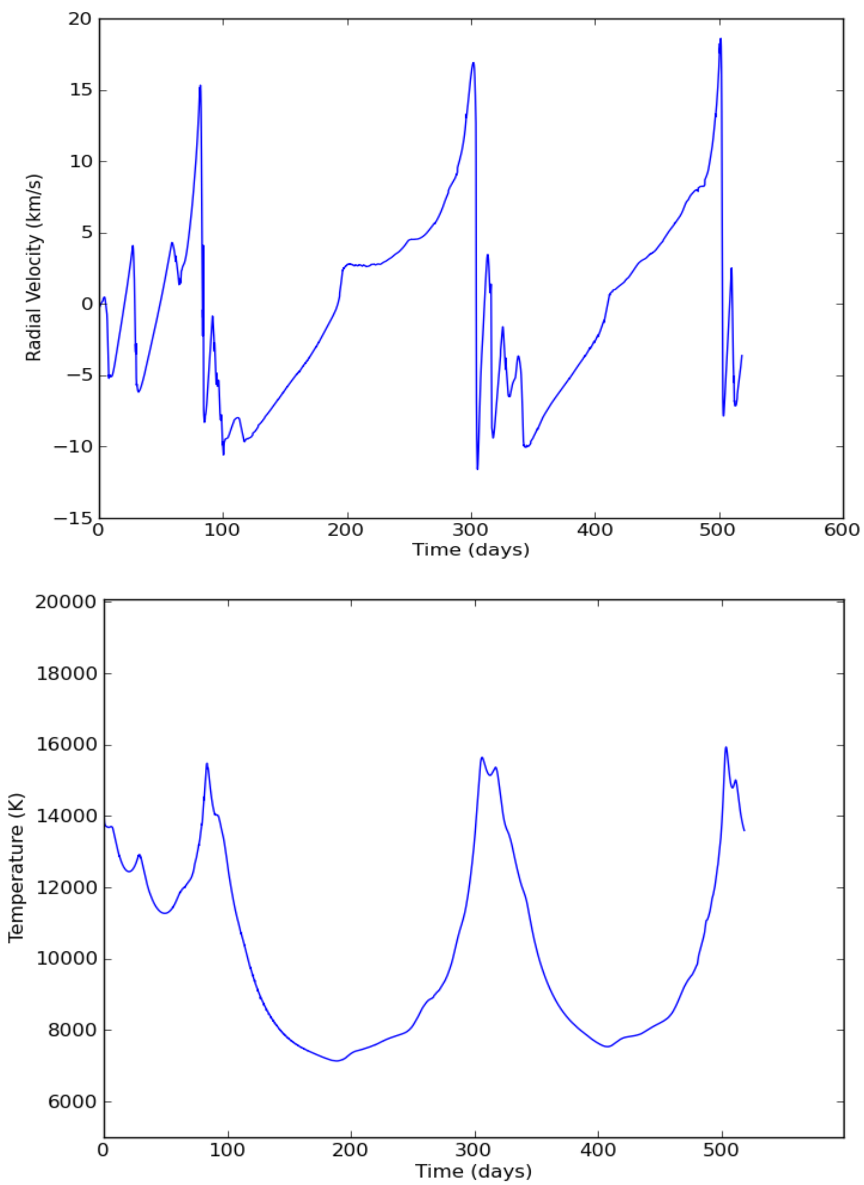


Long Period Models

- High mass, low metallicity models show long periods (> 20 d)
- Many of these models have large amplitudes
  - Z = 0.004 - red
  - Z = 0.008 – light blue
  - Z = 0.02 - purple
  - Z = 0.04 - black



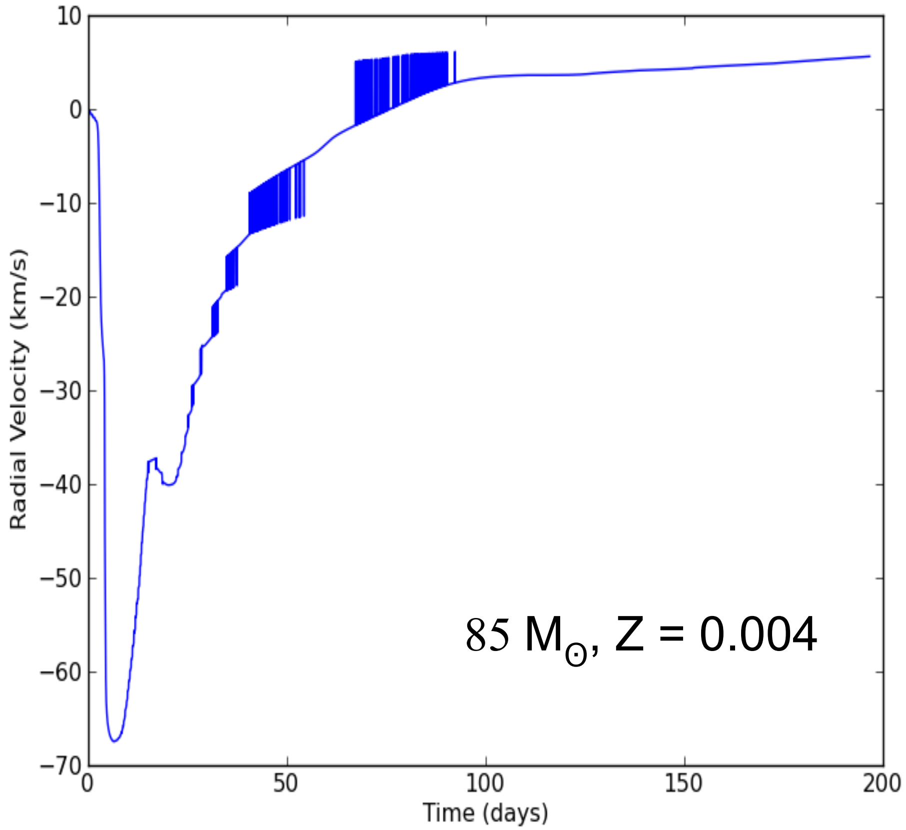
Long Period Models



- 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

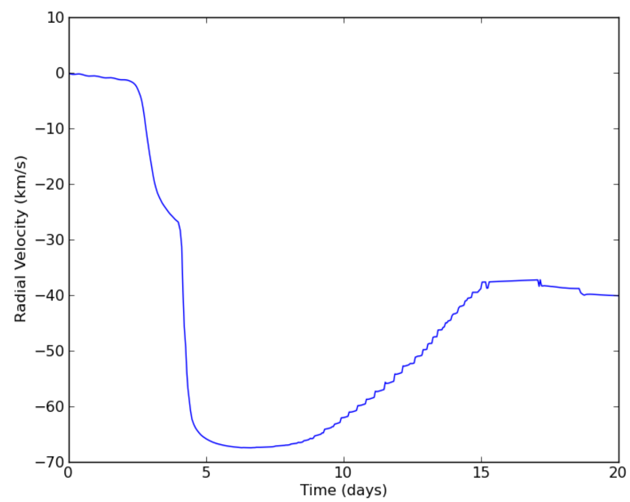
Outbursts

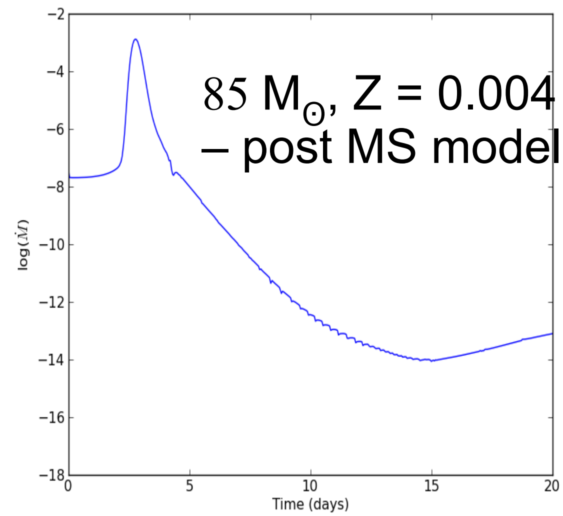


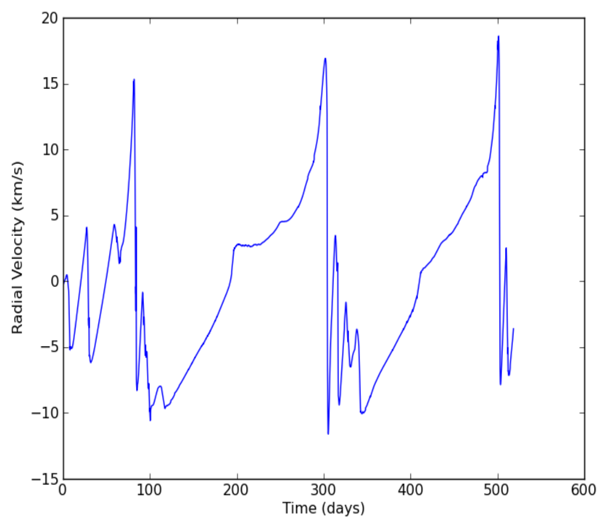
- Some models show outburst-like behaviour
- More common at high mass and low metallicity
- Appears at lower mass as metallicity increases
- Large increase in outward velocity, but slower than the escape speed (neglecting rotation)
- Our models do not include mass loss, so later phases of calculation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

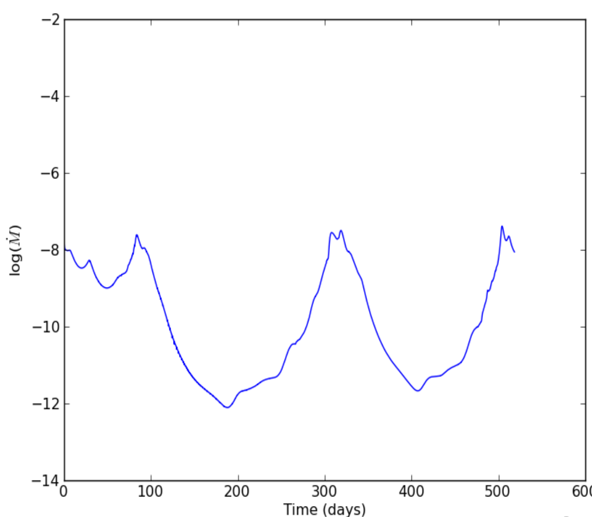
Wind Mass Loss Rates

- Outburst-like events can lead to very high mass loss rates
- Peak mass loss of ~ 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 – MS model

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

Conclusions

- Q works well to predict periods in models with little mass loss (< ~ 5%) until the radius doubles. Another Q value fits later evolutionary stages
- Metallicity has little effect on the periods
- Change in mass of more than 5% decreases periods relative to predictions from Q parameter
- Increasing surface He abundance increases periods relative to predictions from Q – dominates over other effects (metallicity, mass loss)
- Some models are so unstable that when pulsation is initiated, outburst-like event appears
- Changes in surface properties due to pulsation can produce huge changes in mass loss rates