The Winds of Carbon Stars and the Origin of Carbon Dust

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Outline

- Grid of wind models.
- The sizes of dust grains: does it matter?
- C-star evolution: new mass-loss prescription and new molecular opacities.
- The origin of carbon and carbon dust.
- Carbon and dust yields...

Modelling mass loss

- Hydrodynamics (gas and dust)
- Radiative transfer
- Dust formation

Modelling mass loss

- RHD & dust, conservation laws:

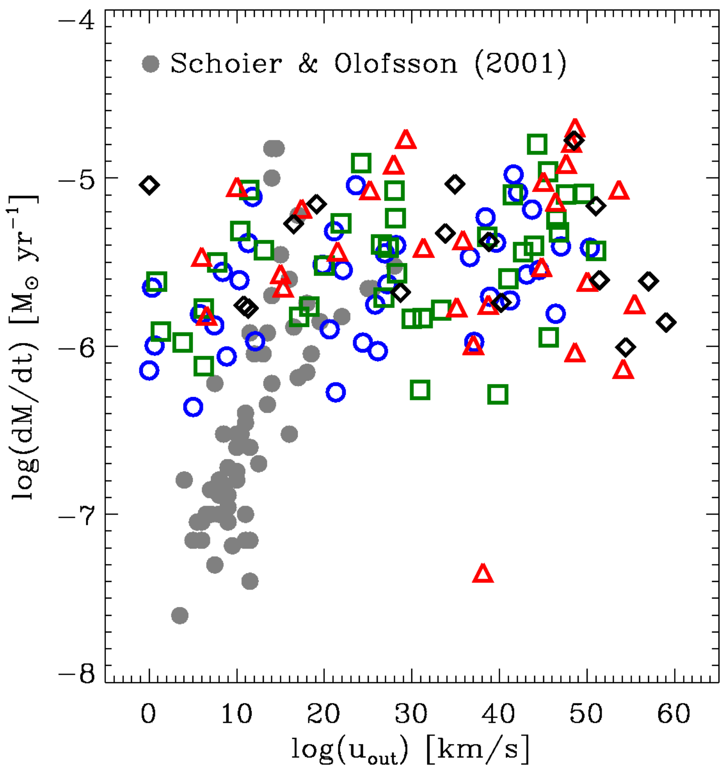
$$\frac{Df}{Dt} \equiv \frac{\partial f}{\partial t} + \nabla \cdot \mathbf{F} = \sum_i \mathscr{S}_i$$

f = mass density, momentum, energy or moments of the grain-size distribution

Modelling mass loss

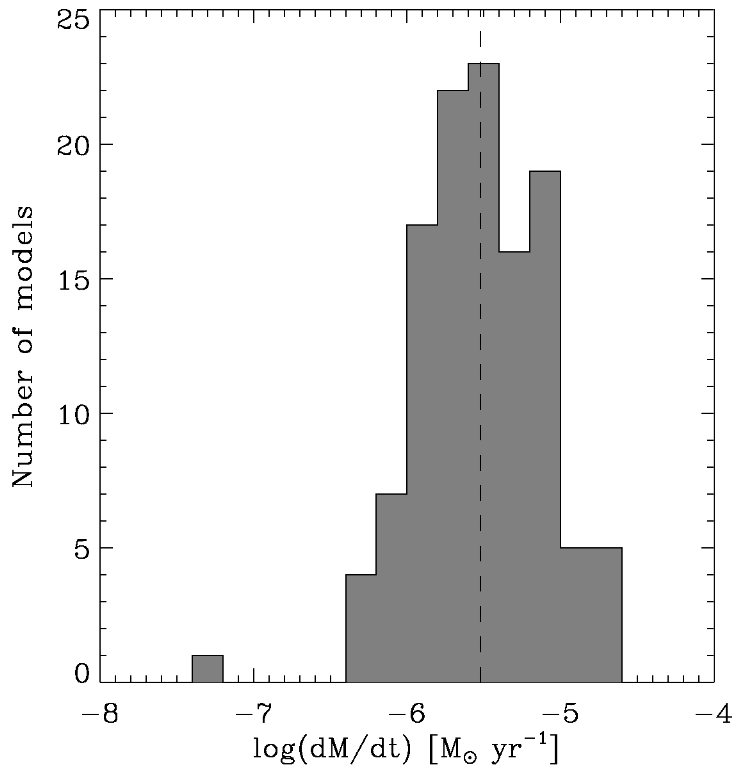
- **We have computed a large grid of dynamical C-star atmosphere models using the frequency-dependent RHD-code with dust formation (Höfner et al. 2003).**
  - The grid of models 900 models with $Z = Z_{\odot}$ implies that the mass loss strongly depends on:
    - The abundance of free carbon.
    - The effective temperatures.
    - The kinetic-energy input from the pulsations.
- **Better mass loss prescription?**

Grid Results



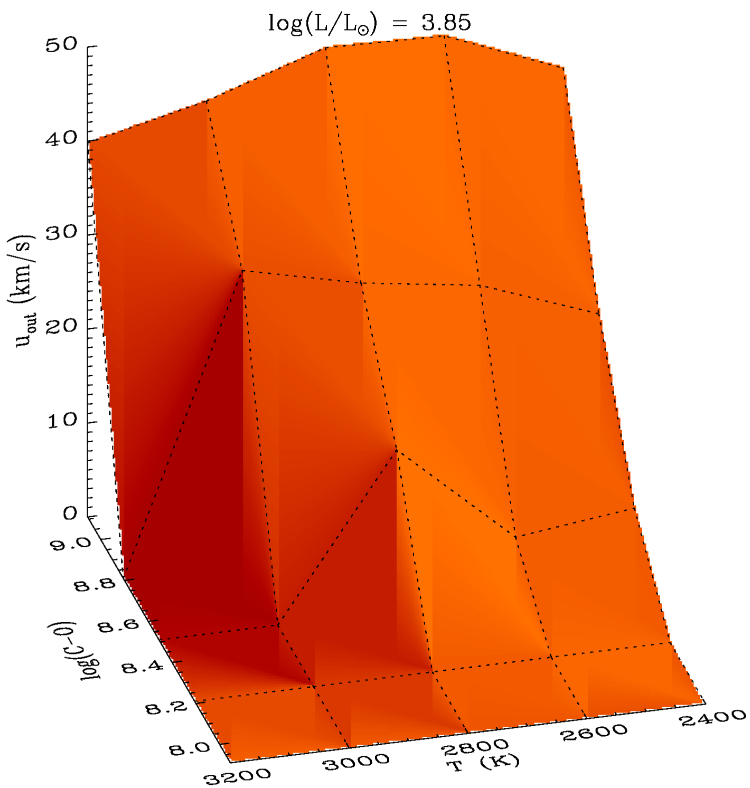
In the right ball park... but...

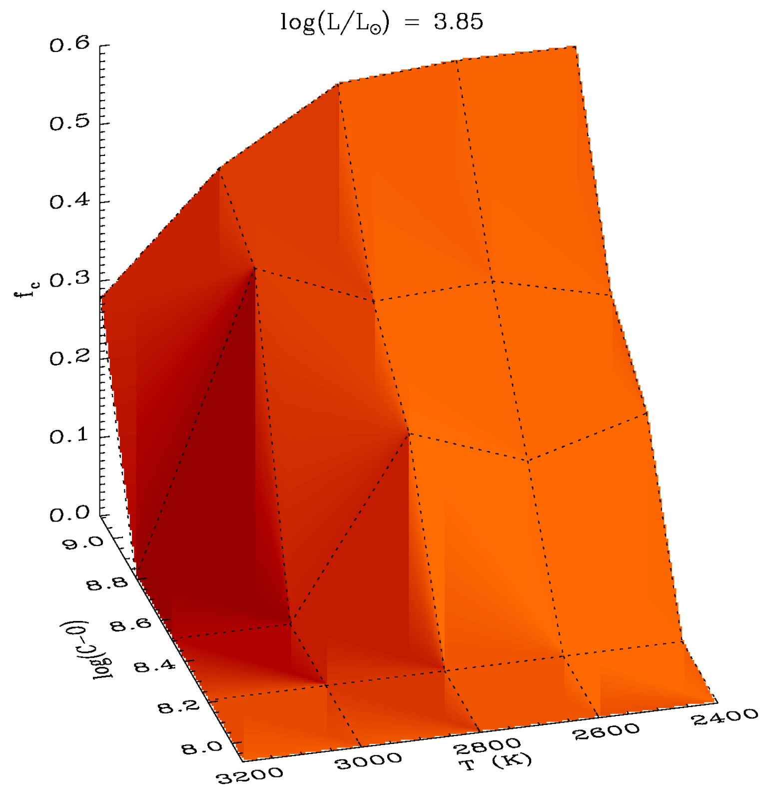
Grid Results



...only quite high mass-loss rates! Why?

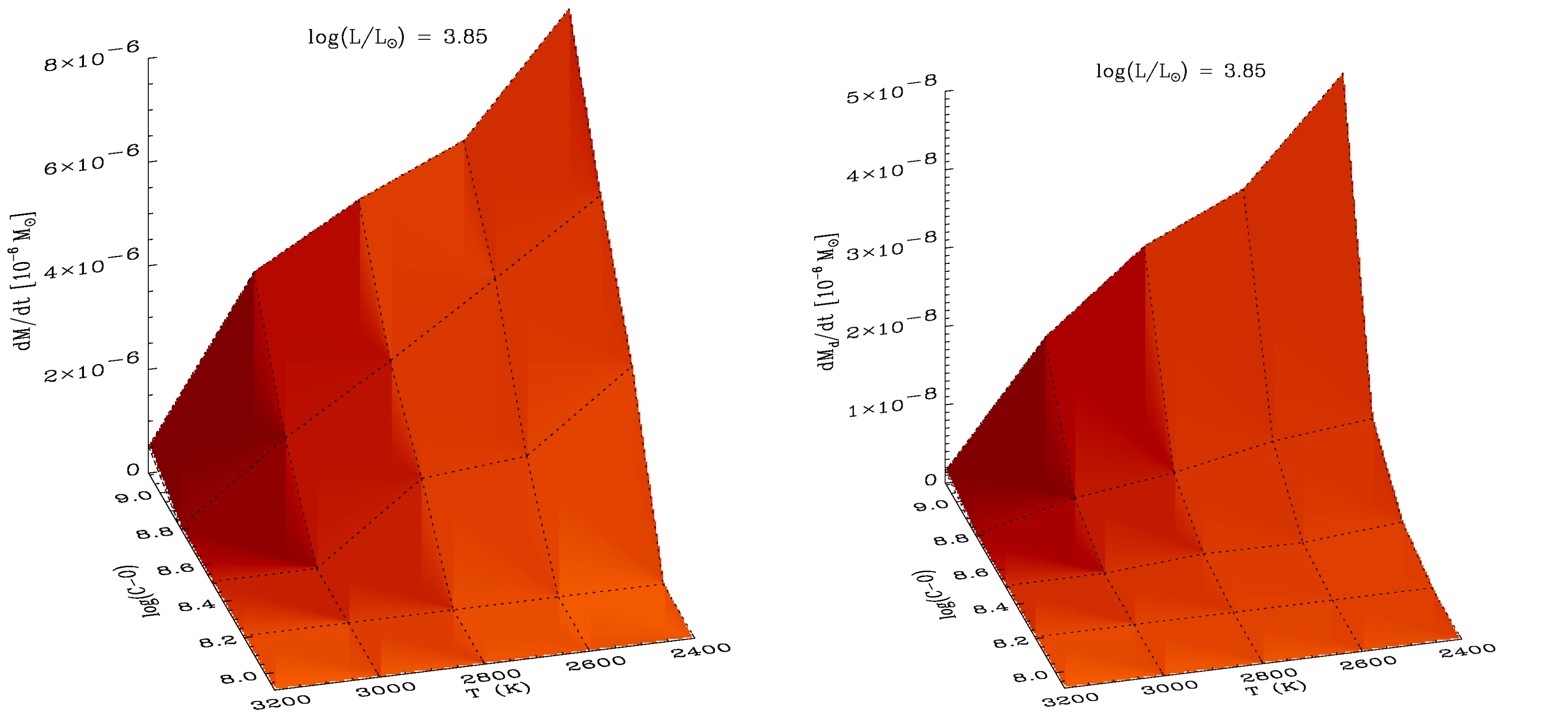
Grid Results





The wind speed is mainly a consequence of the amount of dust.

Grid Results

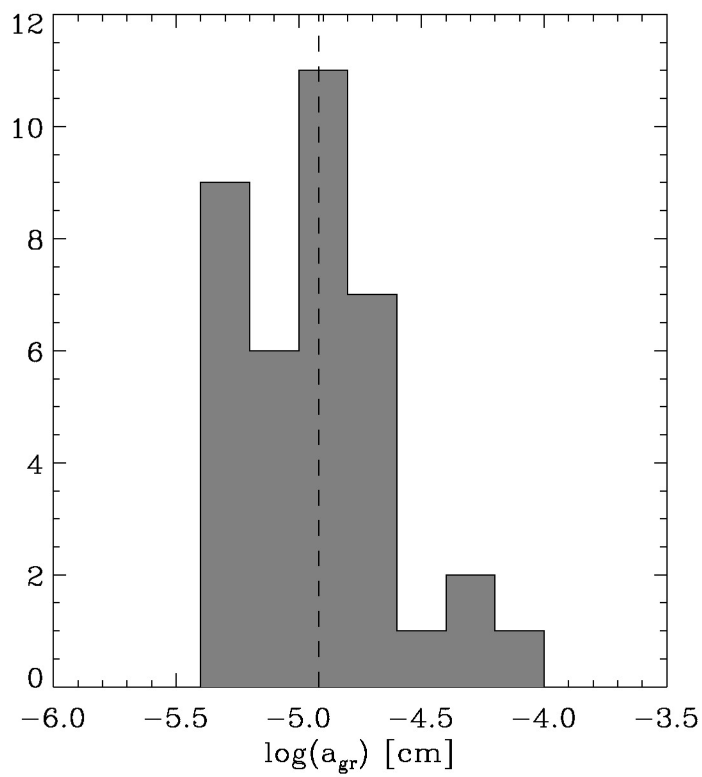


Mass-loss and dust-loss rates seems correlated.

Grain Sizes

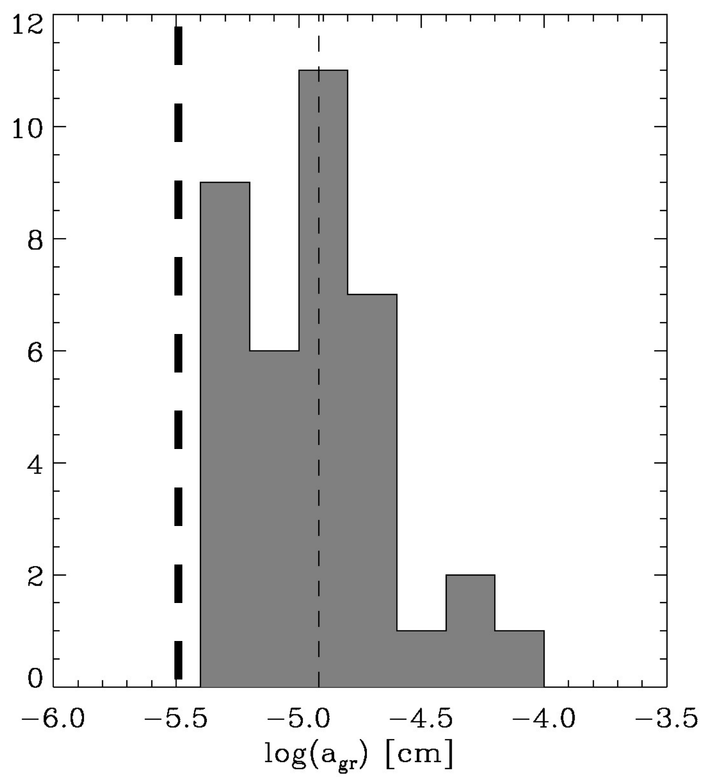
- Small Particle Approximation:
  - All dust grains are small.
  - Their cross-sections are determined by absorption only.
  - The radiation-pressure efficiency factor is proportional to the grain radius (assuming spherical grains).
  - Grain size: proportional to ratio of first and zeroth moment of the grain-size distribution function.

Grain Sizes



The grains are not so small...

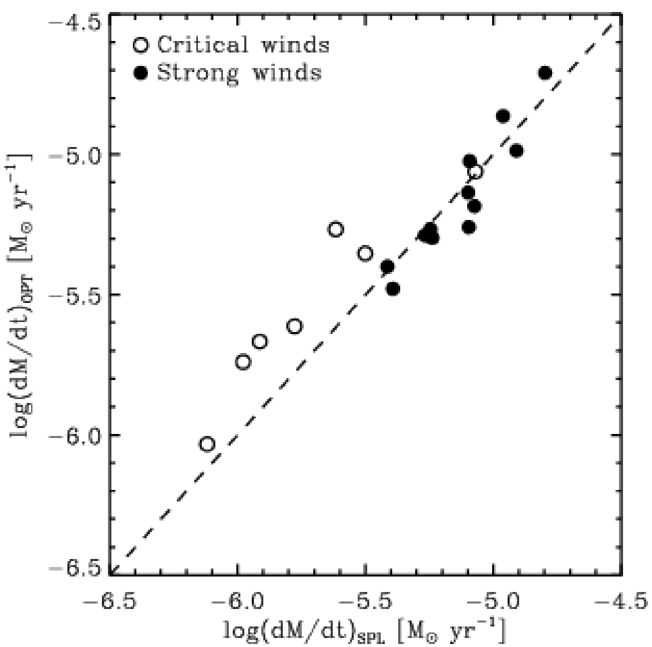
Grain Sizes



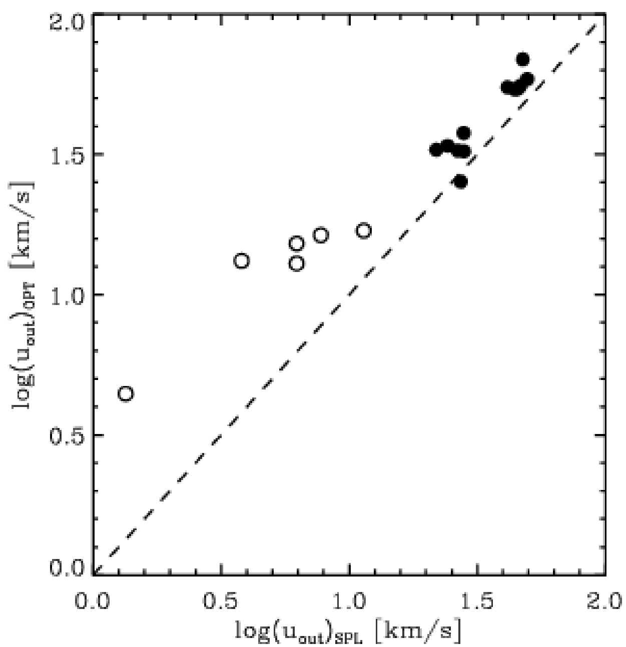
...in fact, the small-particle approximation is not applicable!

Grain Sizes

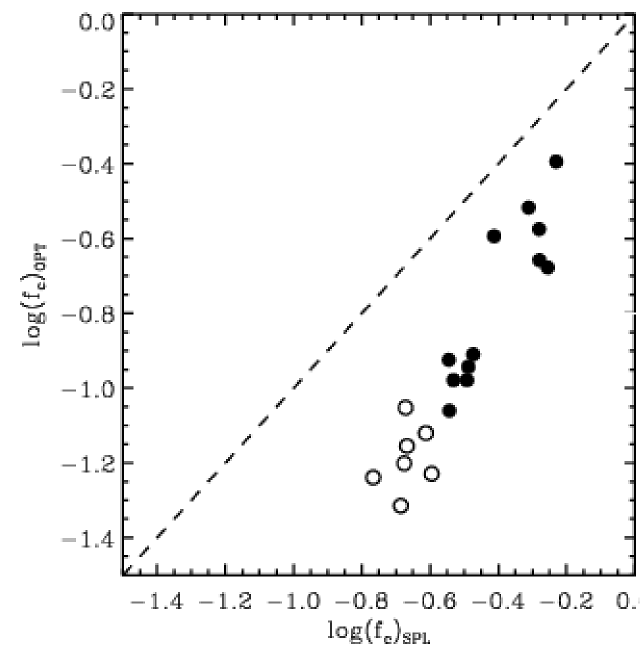
Mass-loss rate:



Wind Speed:



Condensation:

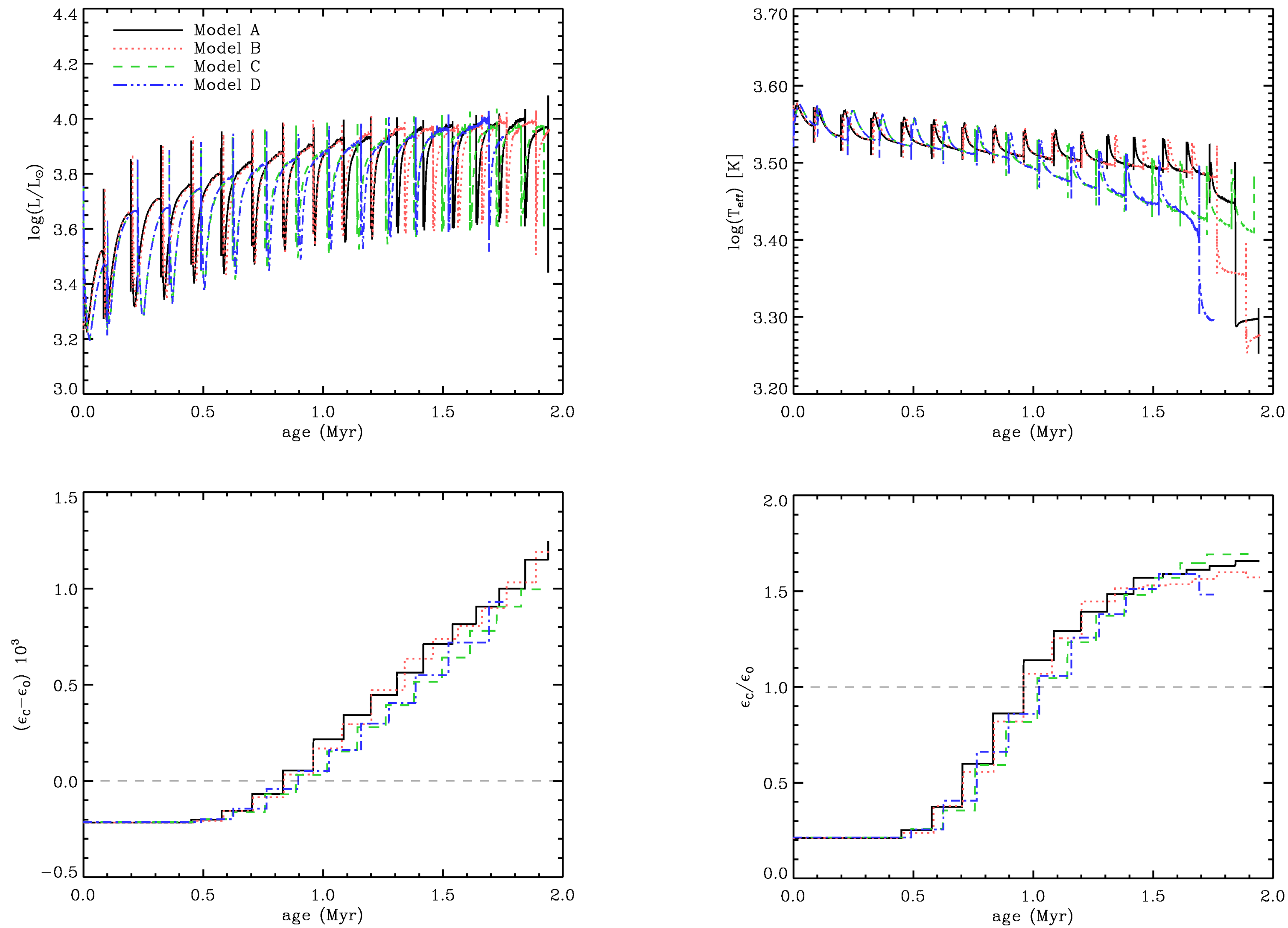


Big grains are big because they stay longer in the dust formation zone!

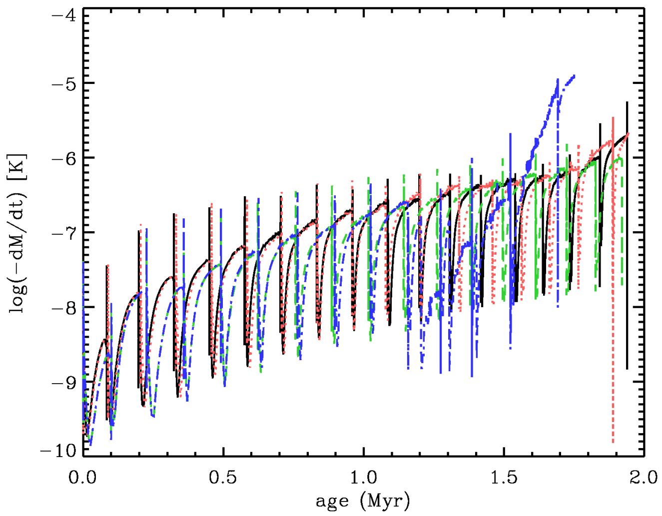
C-star Evolution Model

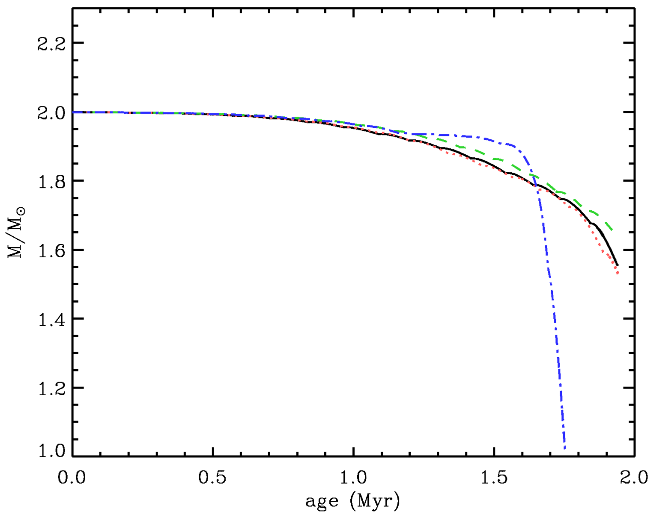
- MESA code, Paxton (2009).
- New ingredients:
  - Inertia term = “some kind of hydro...”.
  - Abundance-dependent molecular opacities.
  - Self-consistent mass-loss model/module.
  - Coded from scratch: modern, fast solvers improve computing times by a factor 10 – 20 !!!

C-star Evolution Model



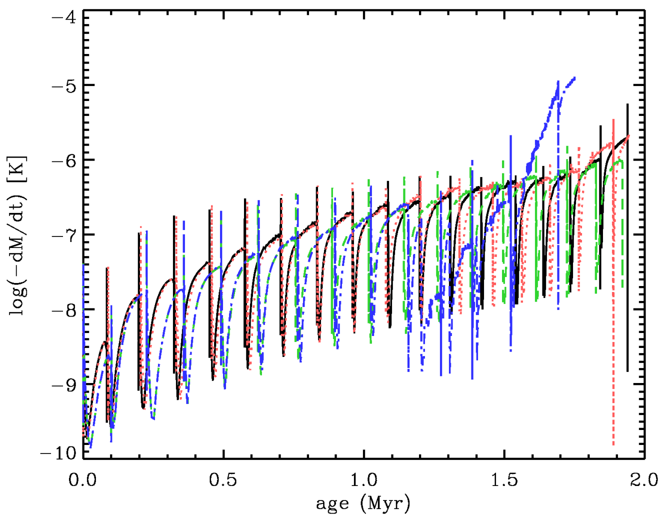
C-star Evolution Model

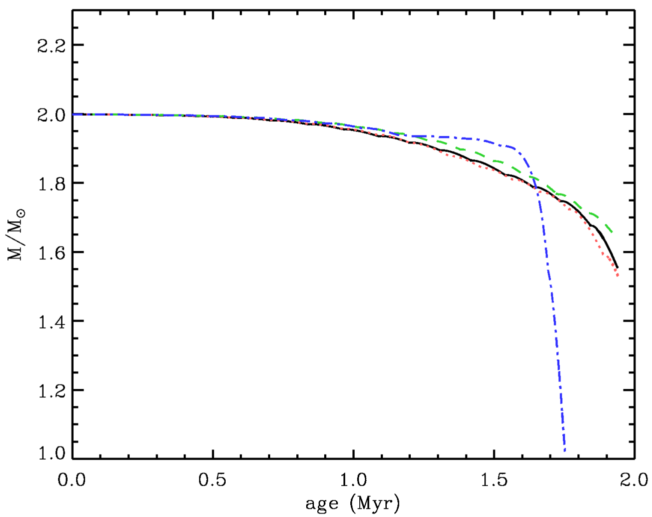


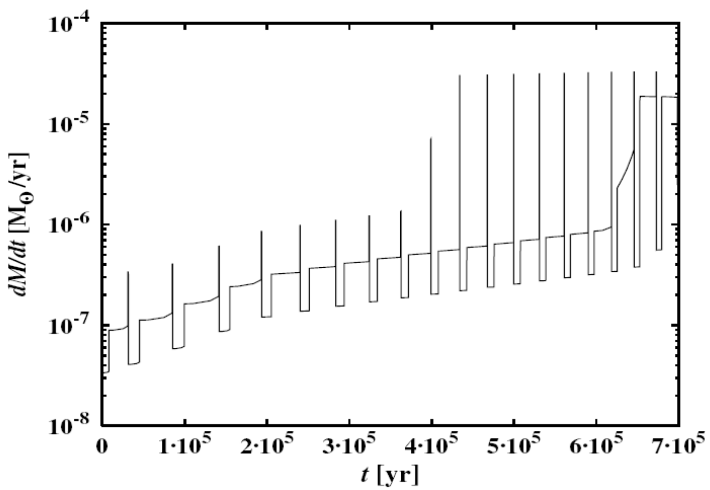


A pronounced superwind develops soon after the starbecomes carbon rich, and it therefore experiences only a few thermal pulses as a carbon star before the envelope is lost.

C-star Evolution Model







Ferrarotti & Gail (2006)

C-star Evolution Model

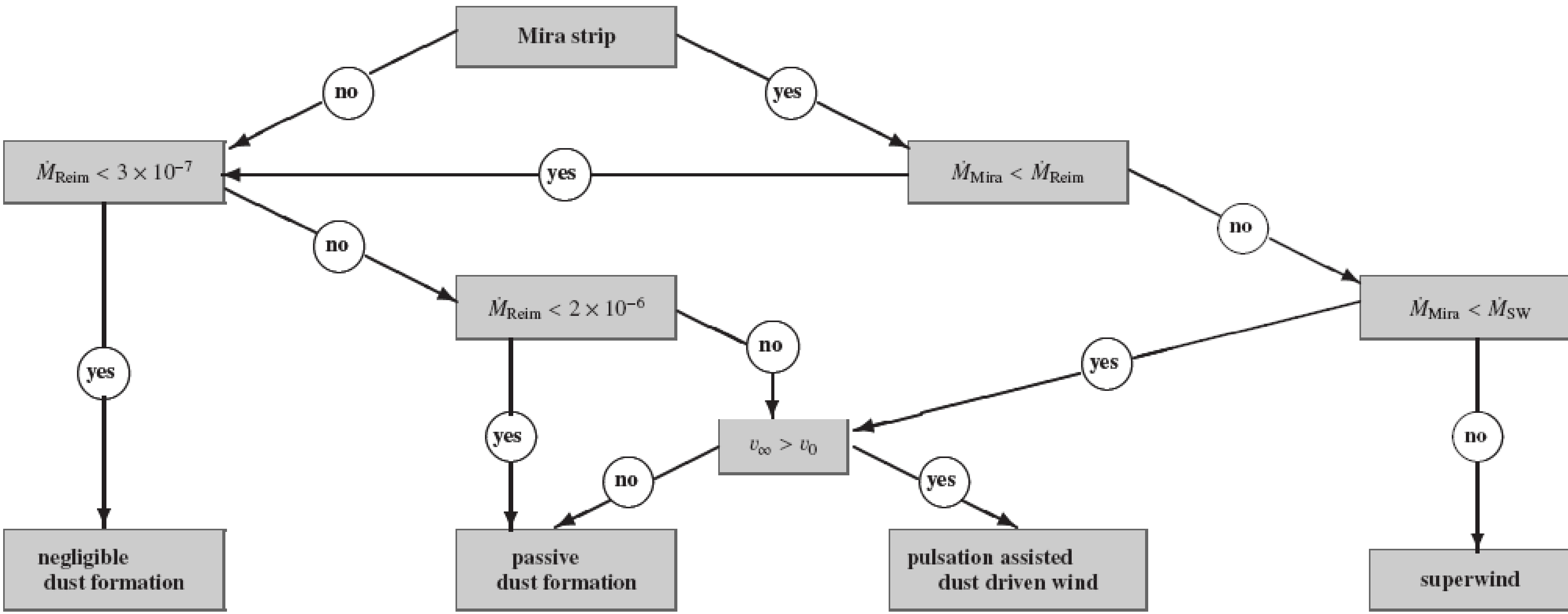
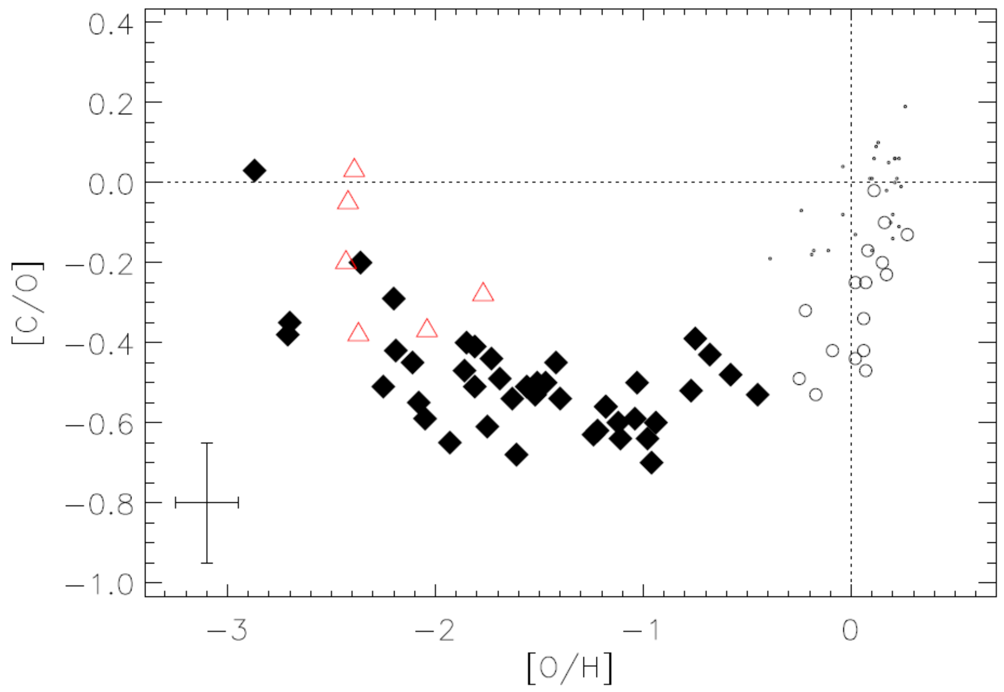


Fig. 3. Decision tree for the different cases of mass-loss prescriptions.

Ferrarotti & Gail (2006)

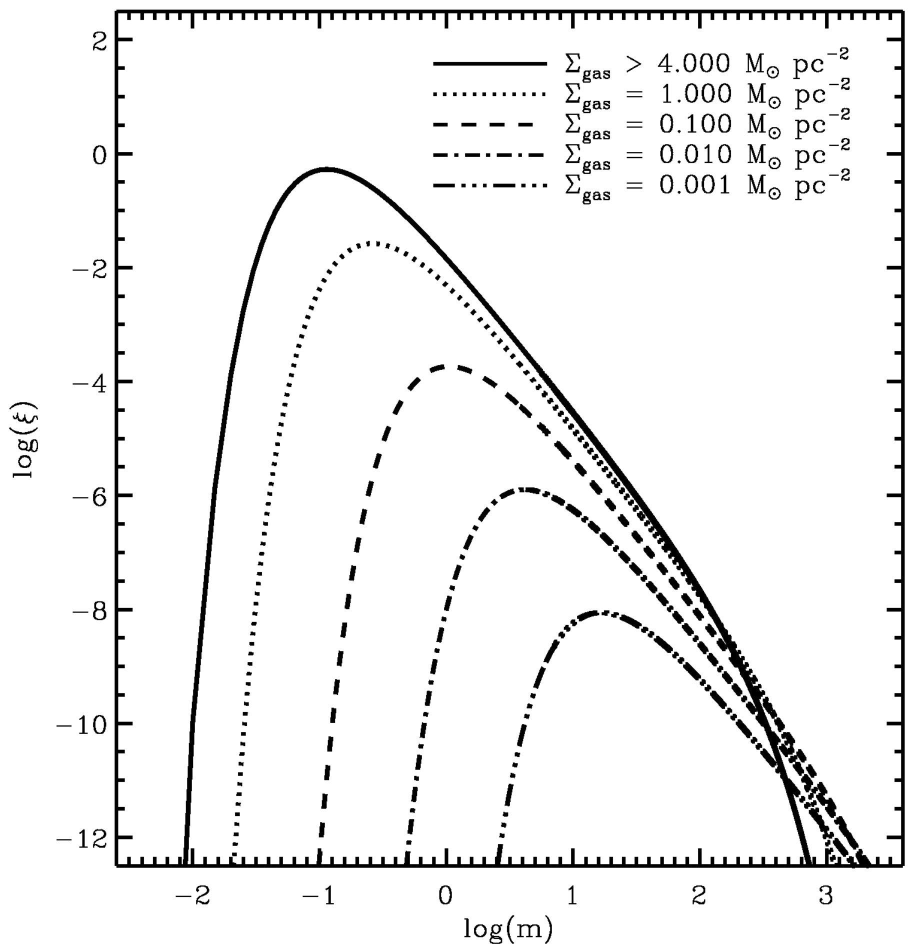
Origin of Carbon

- Carbon stars are probably the main carbon producers.
- High mass stars cannot be excluded, however...
- The C/O trend in the solar neighbourhood at low metallicity can be explained by an evolving IMF!



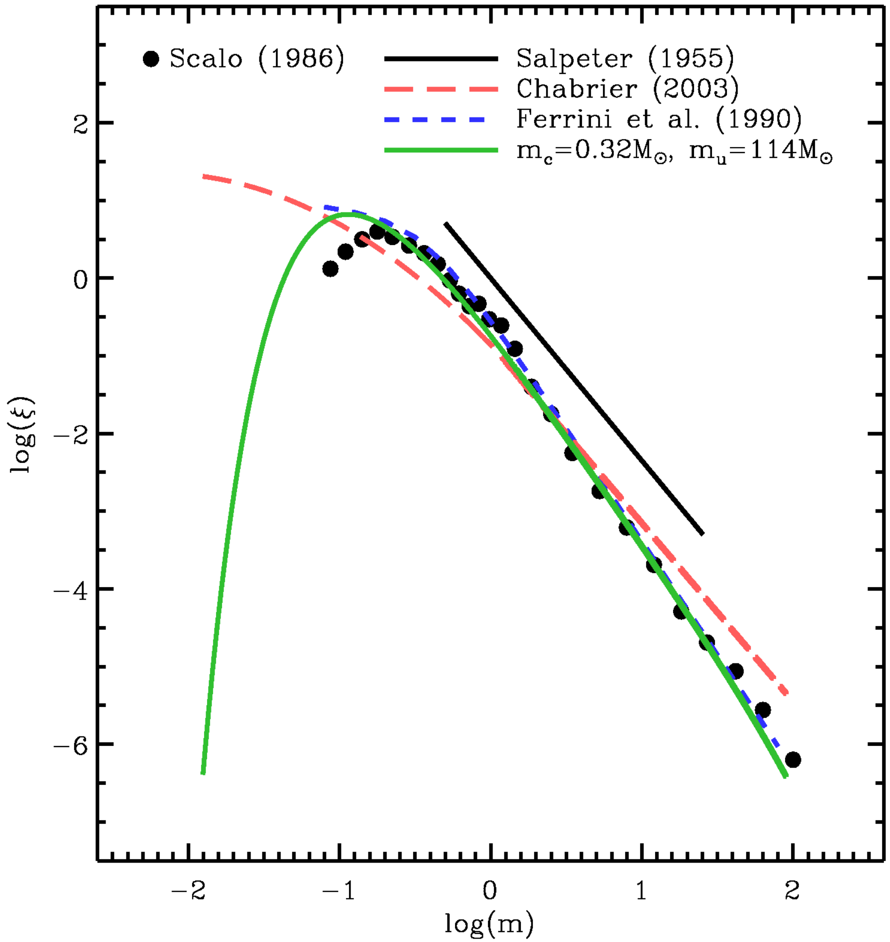
Fabbian et al. (2009)

Origin of Carbon



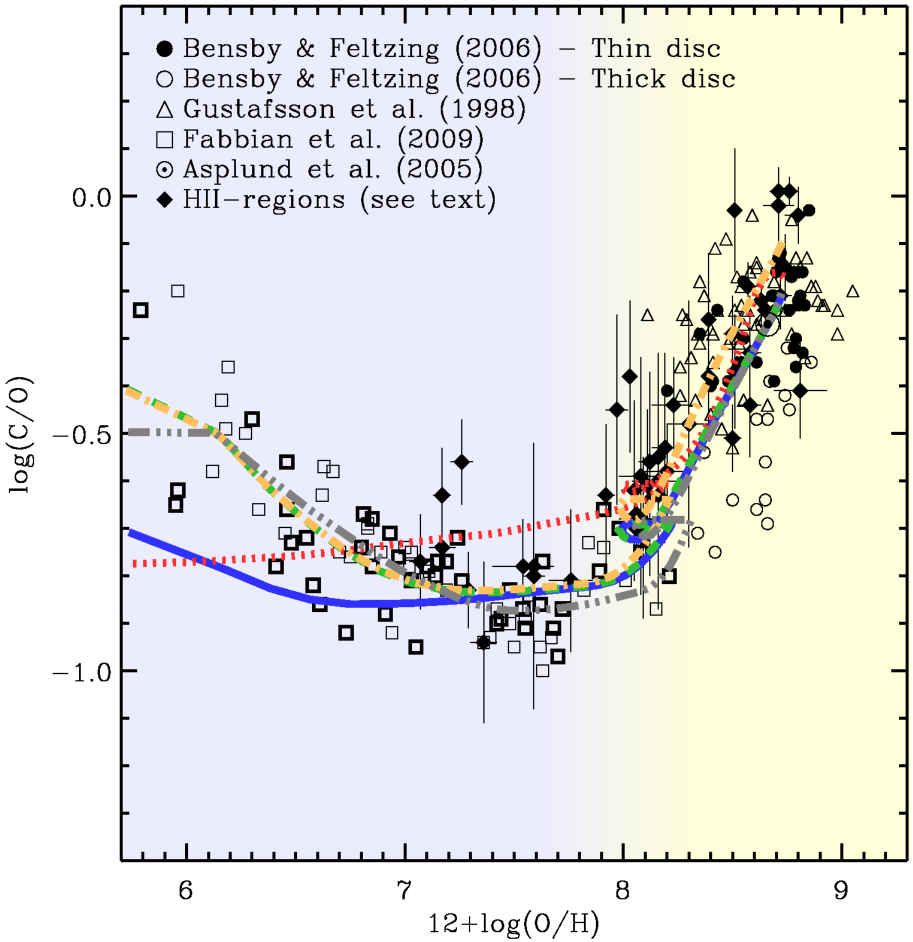
Evolving IMF or yields?

Origin of Carbon



Evolving IMF or yields?

Origin of Carbon



Evolving IMF or yields?

Carbon Dust Yields

- Ferrarotti & Gail (2006) made the first ever complete set of “stellar dust yields”.
- They assume a “fixed” prescription for the mass-loss rate, i.e., no physically consistent wind model was used.
- As we have seen, this may have dramatic consequences for stellar evolution and dust formation as well.
- The “feedback effects” puts a strong upper limit on the carbon-dust yield!
- We need to do the math first, but it seems that Ferrarotti & Gail may have over-estimated the carbon-dust yields... *but we have to do the math!*

Carbon Dust Yields

The dust-to-gas ratio is obtained from the mean degree of dust condensation through the relation

$$X_{\mathrm{d}} \equiv \frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}} = \frac{m_{\mathrm{C}}}{m_{\mathrm{H}} + m_{\mathrm{He}}\varepsilon_{\mathrm{He}}}\,\tilde{\varepsilon}_{\mathrm{C}} f_{\mathrm{c}} \tag{1}$$

where $\tilde{\varepsilon}_{\mathrm{C}}$ is the abundance of condensable carbon in the atmosphere. The dust-loss rate is then obtained as

$$\dot{M}_{\mathrm{d}} = \dot{M}\,\frac{\rho_{\mathrm{d}}}{\rho_{\mathrm{gas}}}. \tag{2}$$

The mass-loss rate and the dust-to-gas ratio (thus also the dust-loss rate) are functions of time, as the star evolves. The dust yield is therefore defined as

$$y_{\mathrm{d}} \equiv m\,p_{\mathrm{d}} = \int_{\tau_1}^{\tau_2} \dot{M}(t)\,(X_{\mathrm{d}} - X_{\mathrm{d,ini}})\,dt, \tag{3}$$

where τ_1, τ_2 denotes the beginning and end of the carbob star phase, respectively, and p_{d} is the relative yield, i.e., the production of dust relative to the initial mass m of the star.

Summary

- Mass loss from carbon stars cannot easily be summarised in a simplistic formula. Thresholds are important.
- Size matters! Relaxing the SPA leads to more efficient momentum transfer.
- Mass loss depends strongly on the carbon excess, which puts an upper limit to the carbon production of “carbon stars”.
- The origin of carbon is still unclear. But carbon stars are more likely?
- But... the strong dependence of the wind on the carbon excess puts an upper limit to how much carbon as well as carbon dust these stars can produce!