Astrophysical Dynamics, VT 2010

Stellar Winds: Mechanisms & Dynamics

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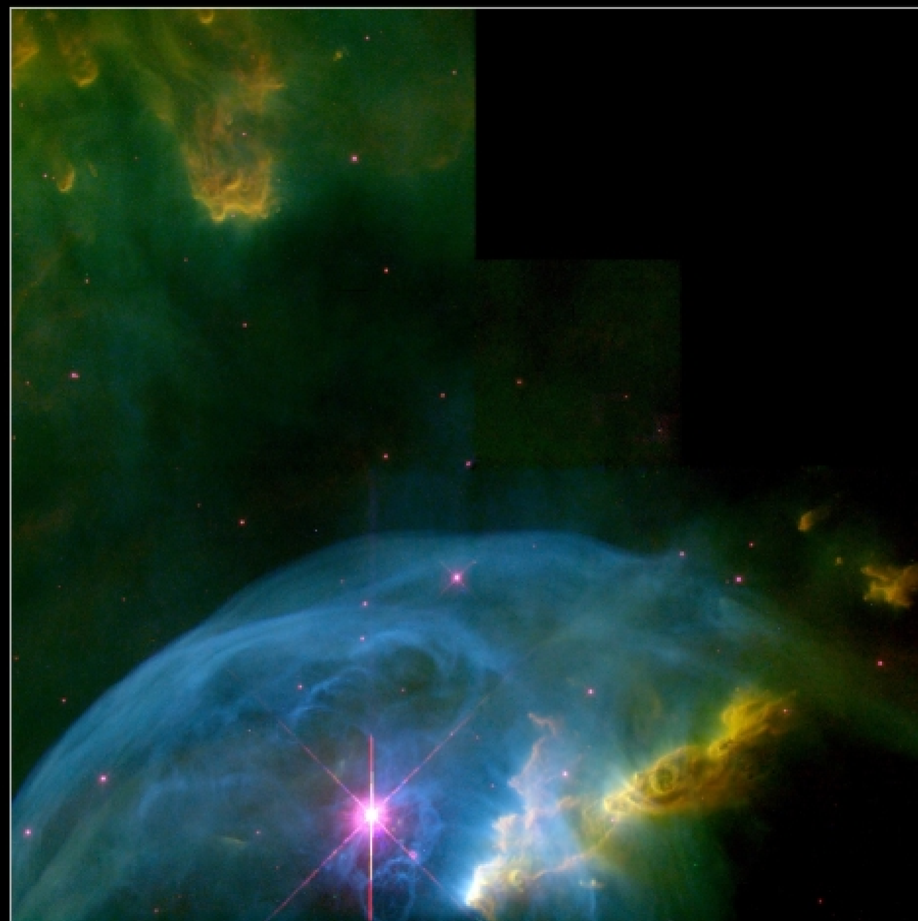
Observations of Stellar Winds: Bubbles



Bubble Nebula • NGC 7635
Hubble Space Telescope • WFPC2

NASA, D. Walter (South Carolina State University) and P. Scowen (Arizona State University) • STScI-PRC00-04

Observations of Stellar Winds: Spectra

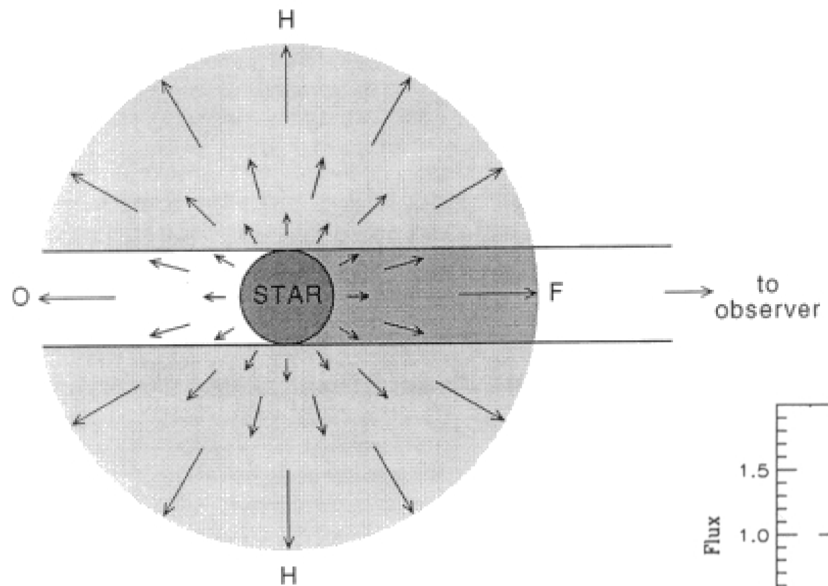
Profiles of spectral lines

- P Cygni profiles
- molecular emission lines

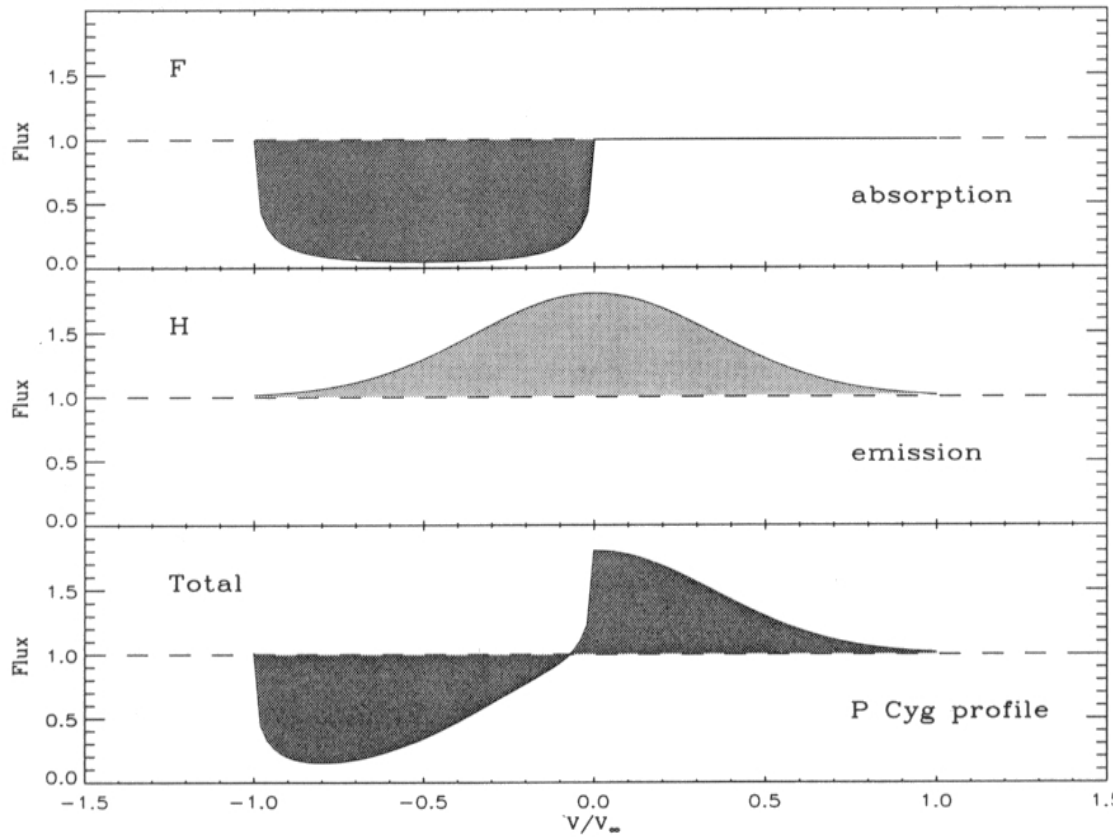
Emission from circumstellar envelopes

- thermal emission from dust
- free-free emission

Spectral Lines: P Cygni Profiles

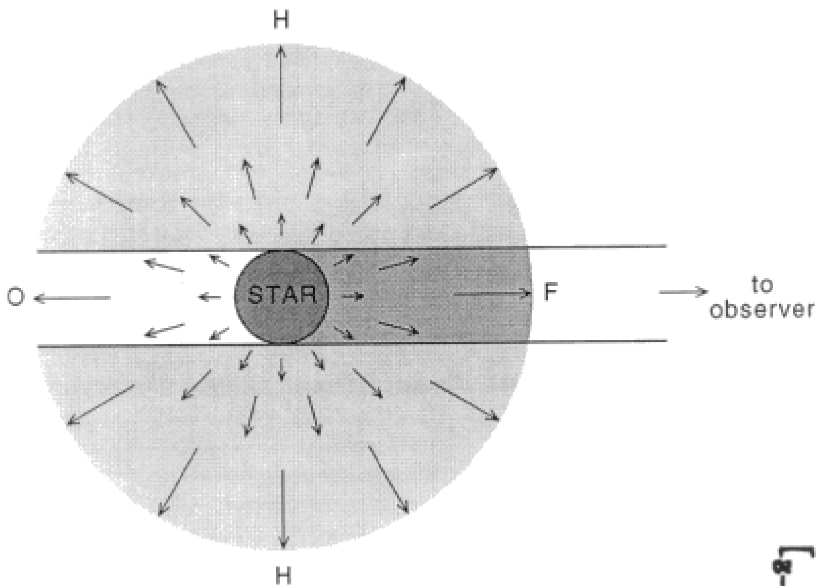


- Doppler shift varying with velocity relative to observer
- emission/absorption according to temperatures along line of sight

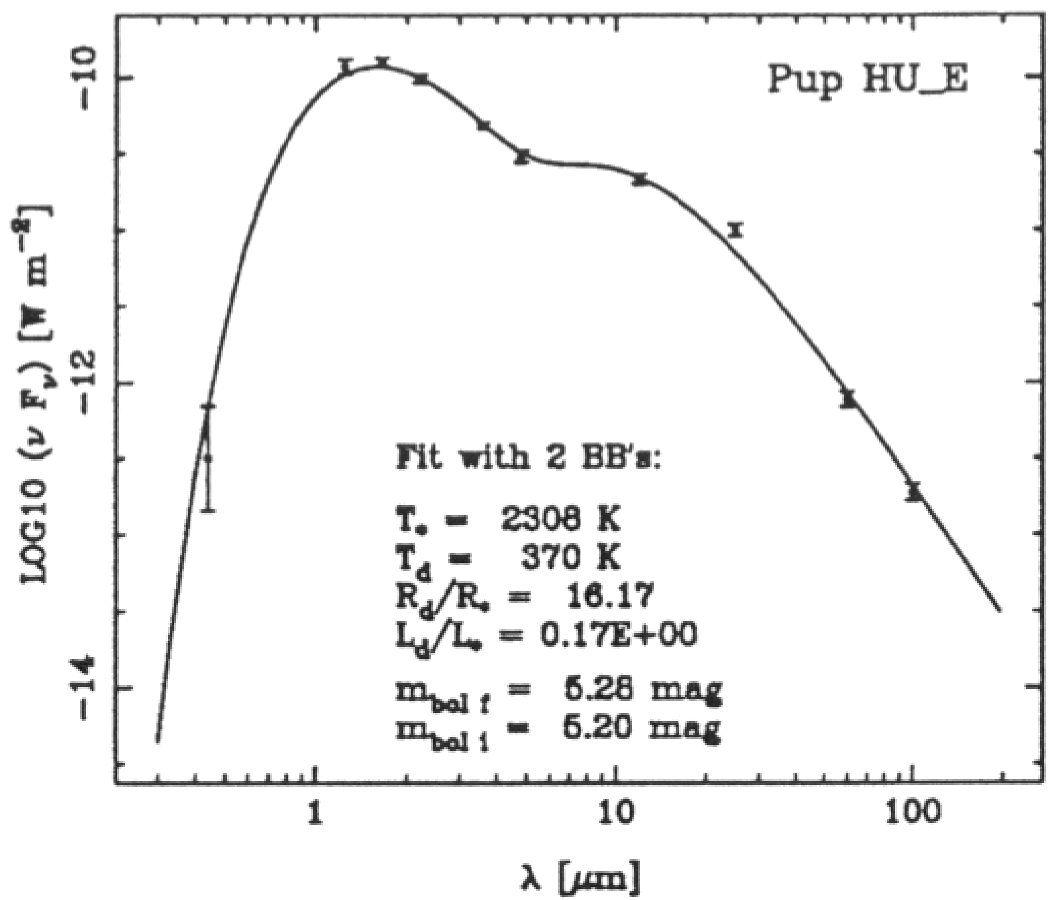


high spectral resolution ⇒

Spectral Energy Distribution: IR Excess



thermal emission of dust grains
in cool circumstellar envelopes causes
excess emission relative to the stellar flux in
the infrared



low spectral resolution $\Rightarrow$

Observations of Stellar Winds: Spectra

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wind velocities & densities
mass loss rates

Stellar Winds: Properties

star	wind velocity [km/s]	mass loss rate [M_{sun}/yr]
sun	400 - 700	10^{-14}
hot giants	1000 - 3000	10^{-5}
cool giants	10 - 30	10^{-5}

no general correlation between
wind velocities and mass loss rates

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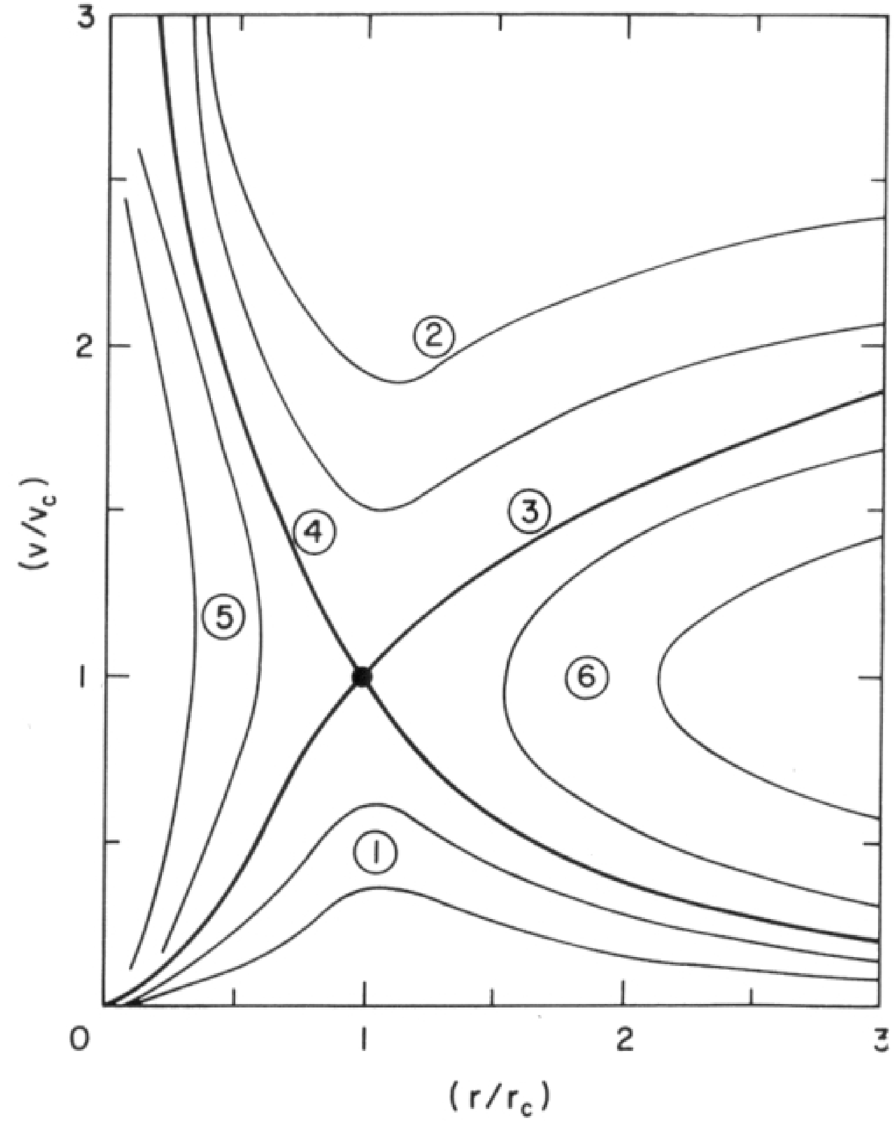
different driving mechanisms

Stellar Winds: Driving Mechanisms

Pressure-driven Winds

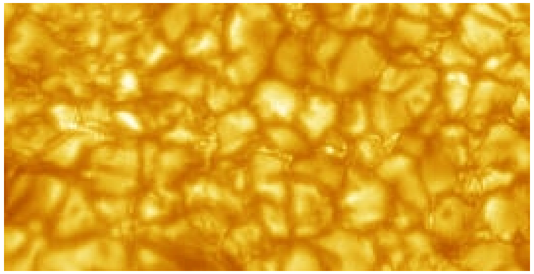
- driving force:
  gradient of thermal
  gas pressure
- source:
  high temperature at base
  of acceleration zone
- properties:
  low mass loss rates

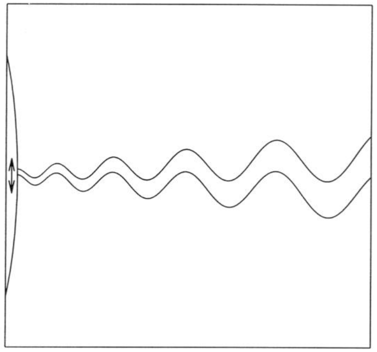


Stellar Winds: Driving Mechanisms

Wave-driven Winds

type	sound waves	Alfven waves
source of waves	surface convection	transverse oscillations at base of magn. flux tube
driving force	dissipation of energy	dissipation of energy
properties		high velocities



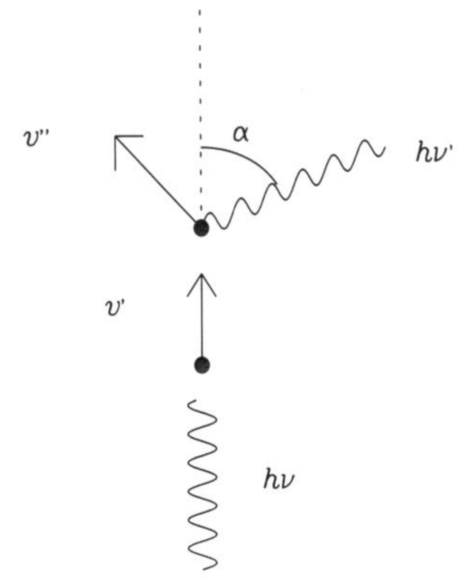


Stellar Winds: Driving Mechanisms

Radiation-driven Winds

driving force:

radiation pressure
(momentum of
absorbed photons)



Stellar Winds: Driving Mechanisms

Radiation-driven Winds

driving force:

radiation pressure
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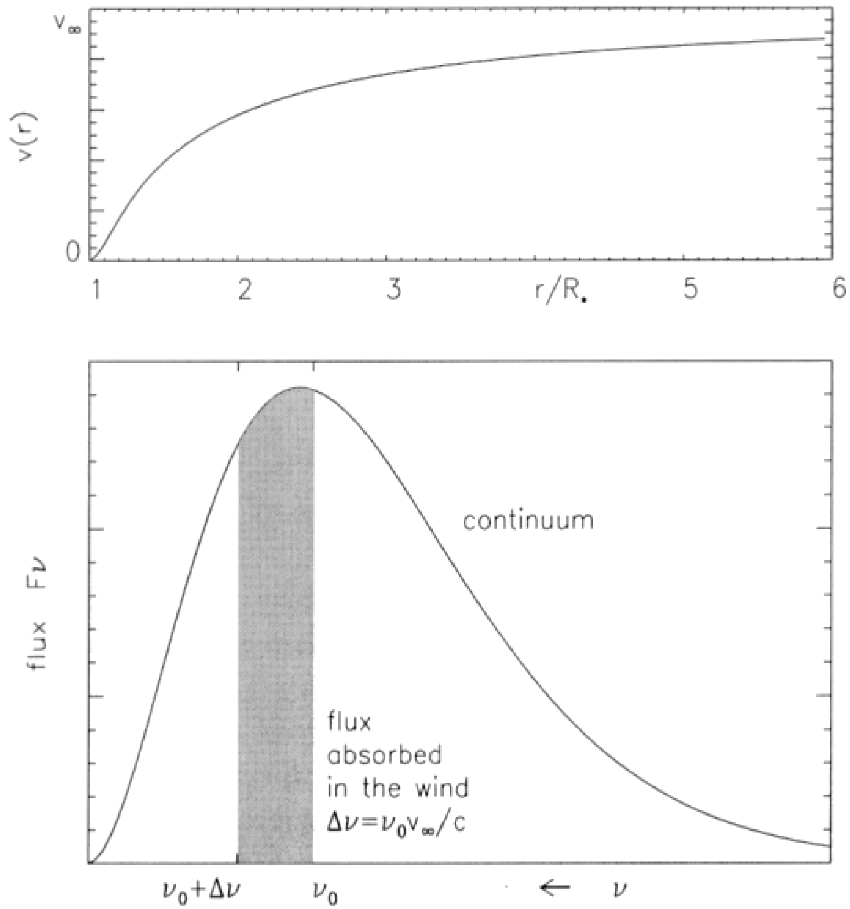
absorbed photons)

	hot stars
absorption by	spectral lines of atoms
properties	high velocities high mass loss



Stellar Winds: Driving Mechanisms

Radiation-driven Winds

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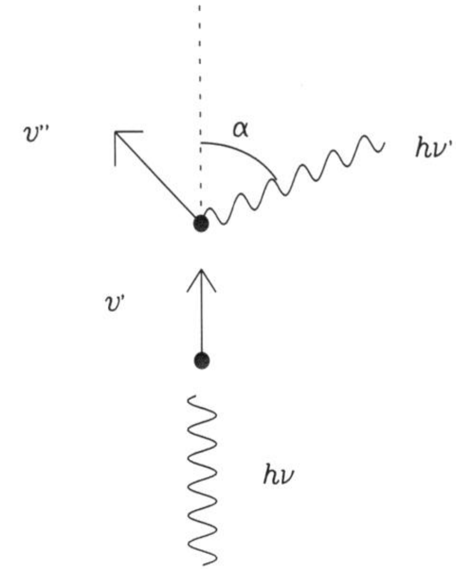
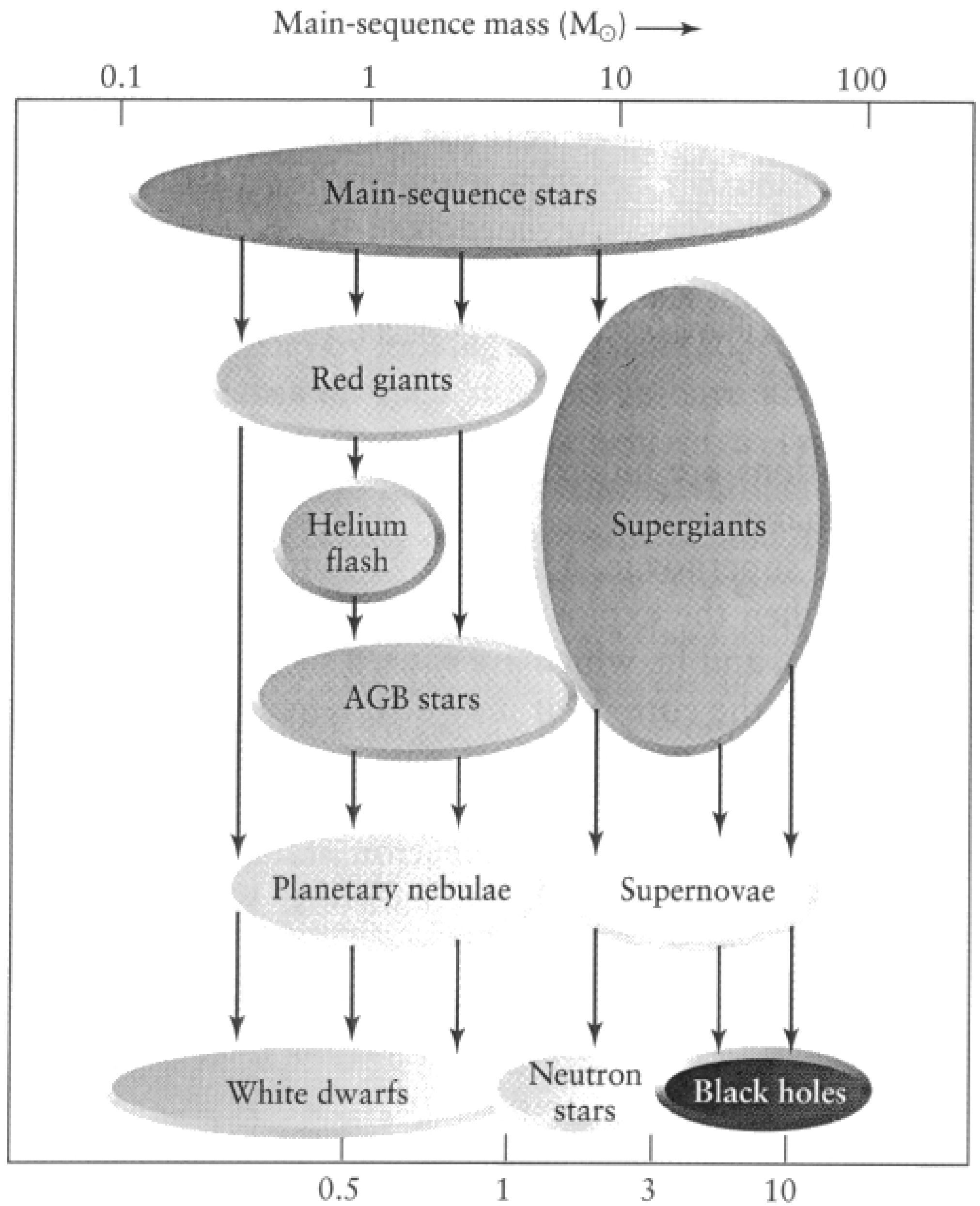
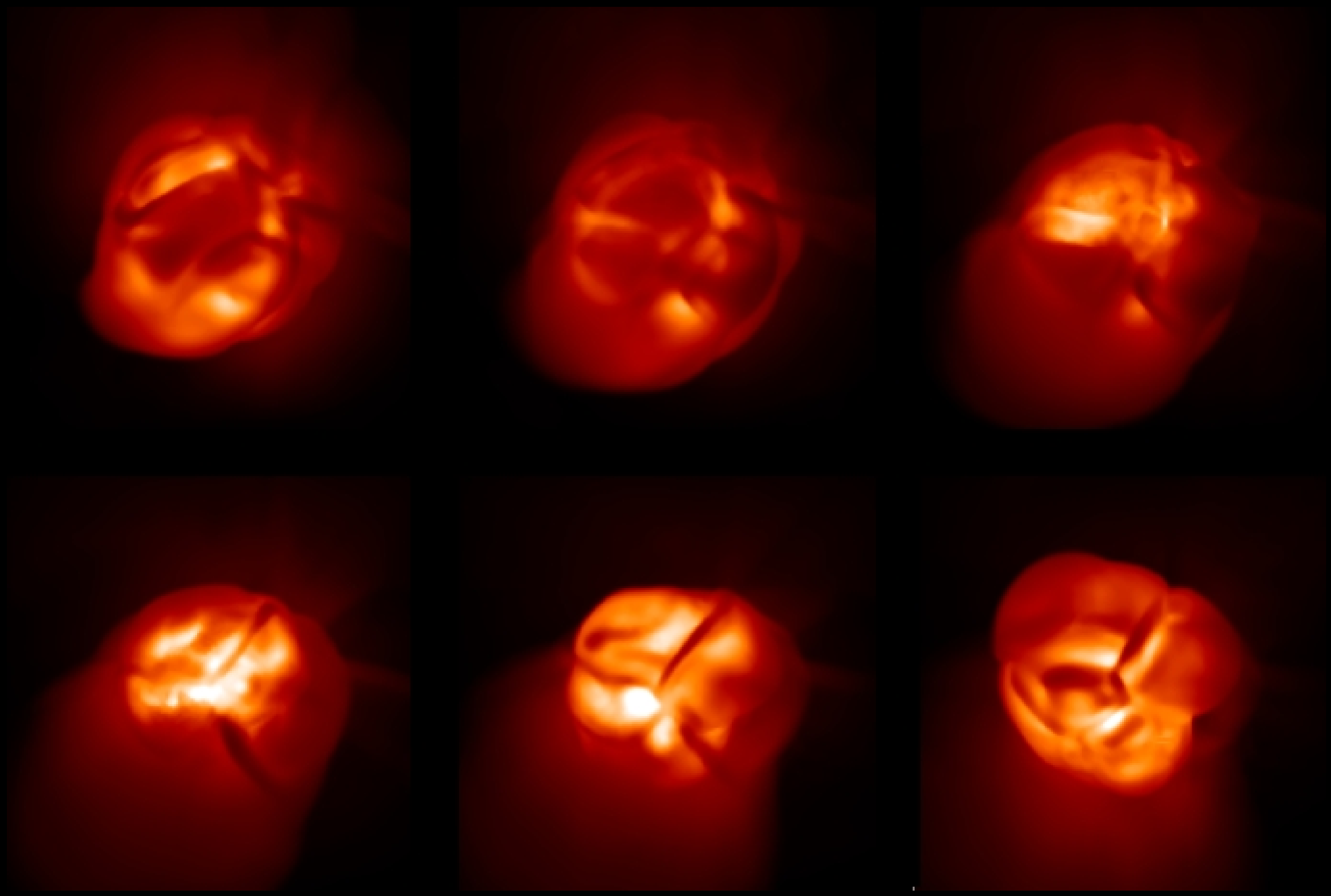


	hot stars	cool stars
absorption by	spectral lines of atoms	molecules and dust grains
properties	high velocities high mass loss	low velocities high mass loss

Stellar Winds: Influence on Evolution



'Star-in-a-box' models of AGB stars

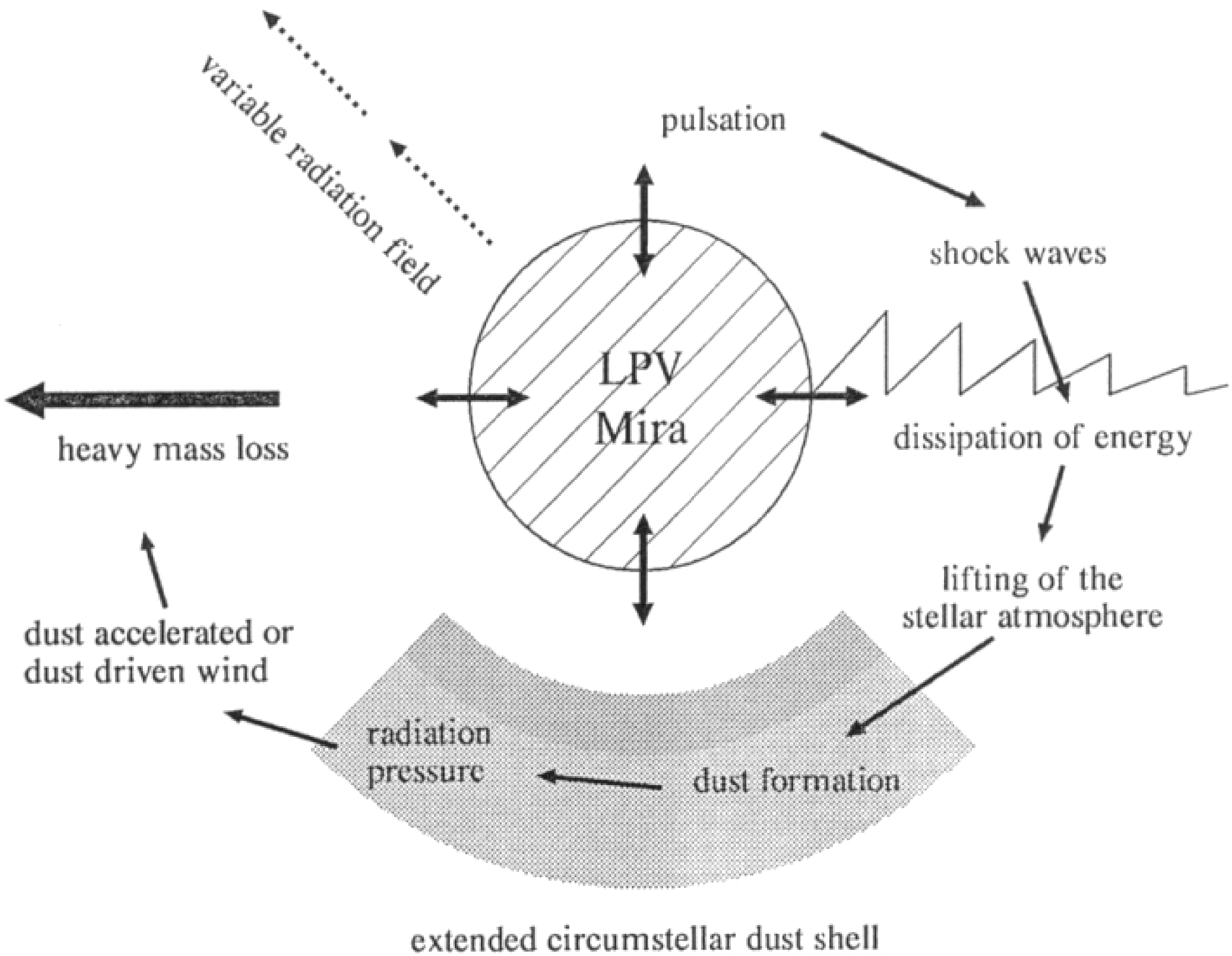


3D star-in-a-box
surface intensity

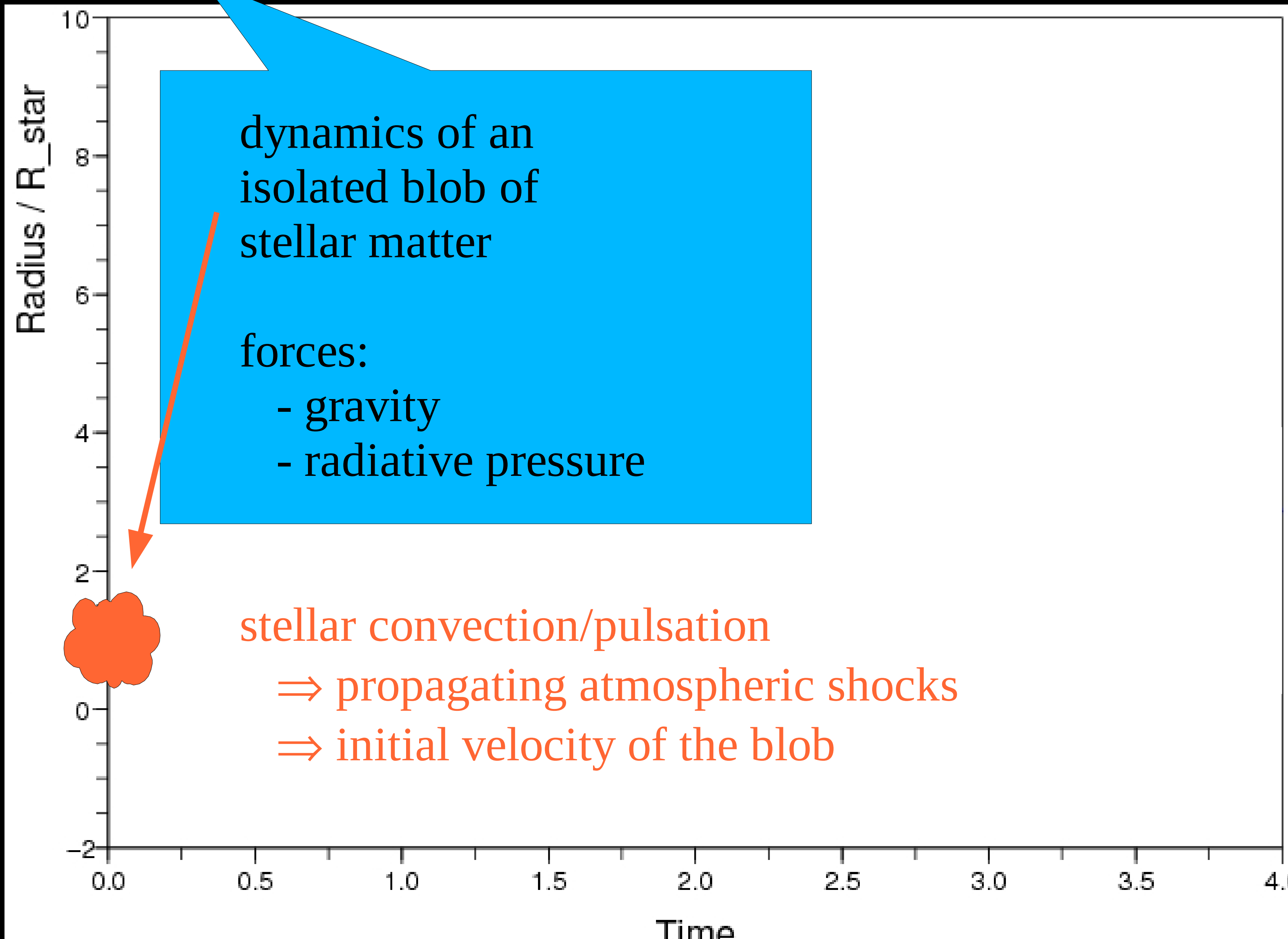
a time series
showing the
development of
giant convection
cells

Freytag & Höfner
(2008)

Dust-Driven Winds: Pulsating Red Giants



A toy model: shocks, dust & wind

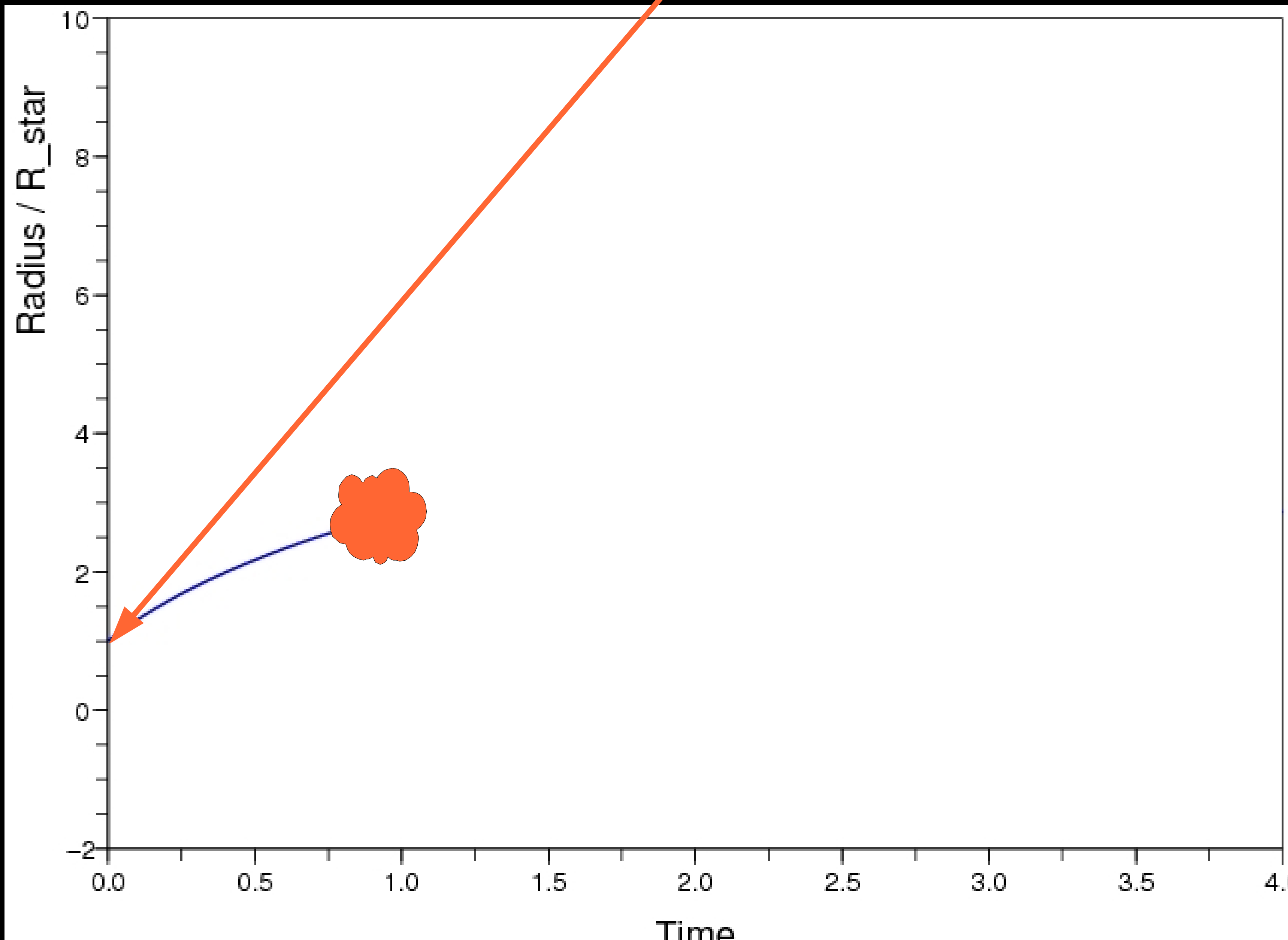


dynamics of an isolated blob of stellar matter

forces:
- gravity
- radiative pressure

stellar convection/pulsation
$\Rightarrow$ propagating atmospheric shocks
$\Rightarrow$ initial velocity of the blob

A toy model: shocks, dust & wind



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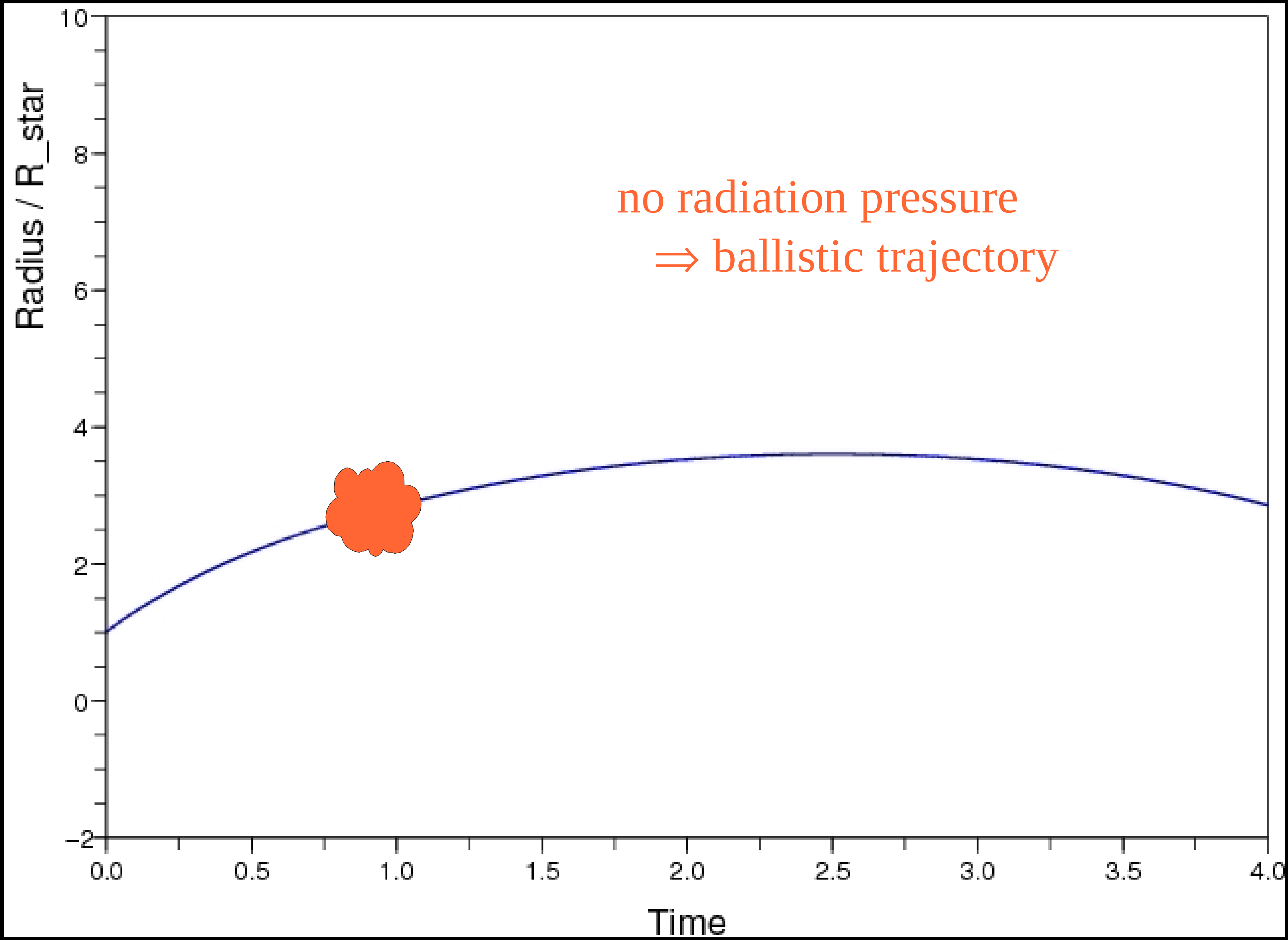

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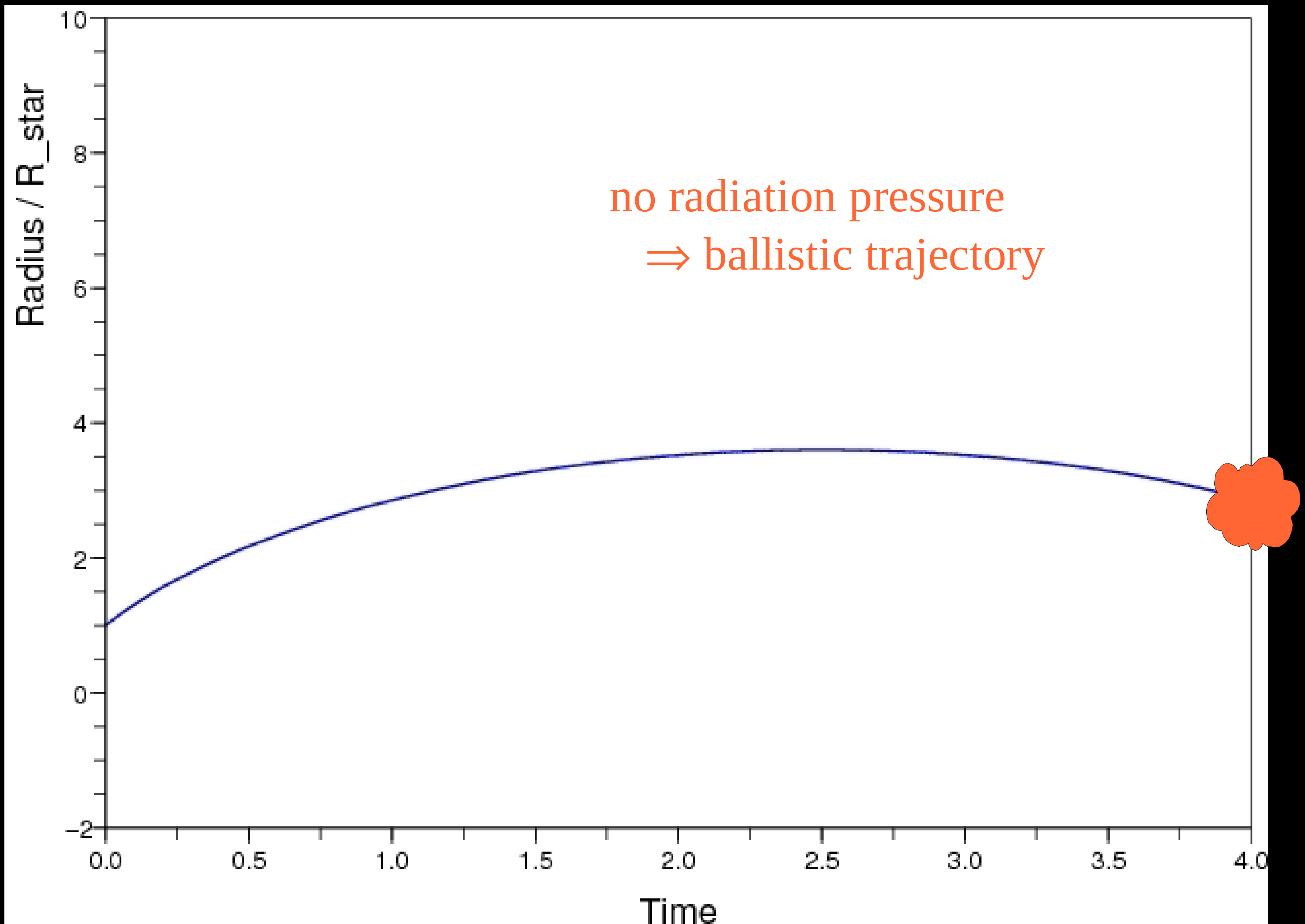

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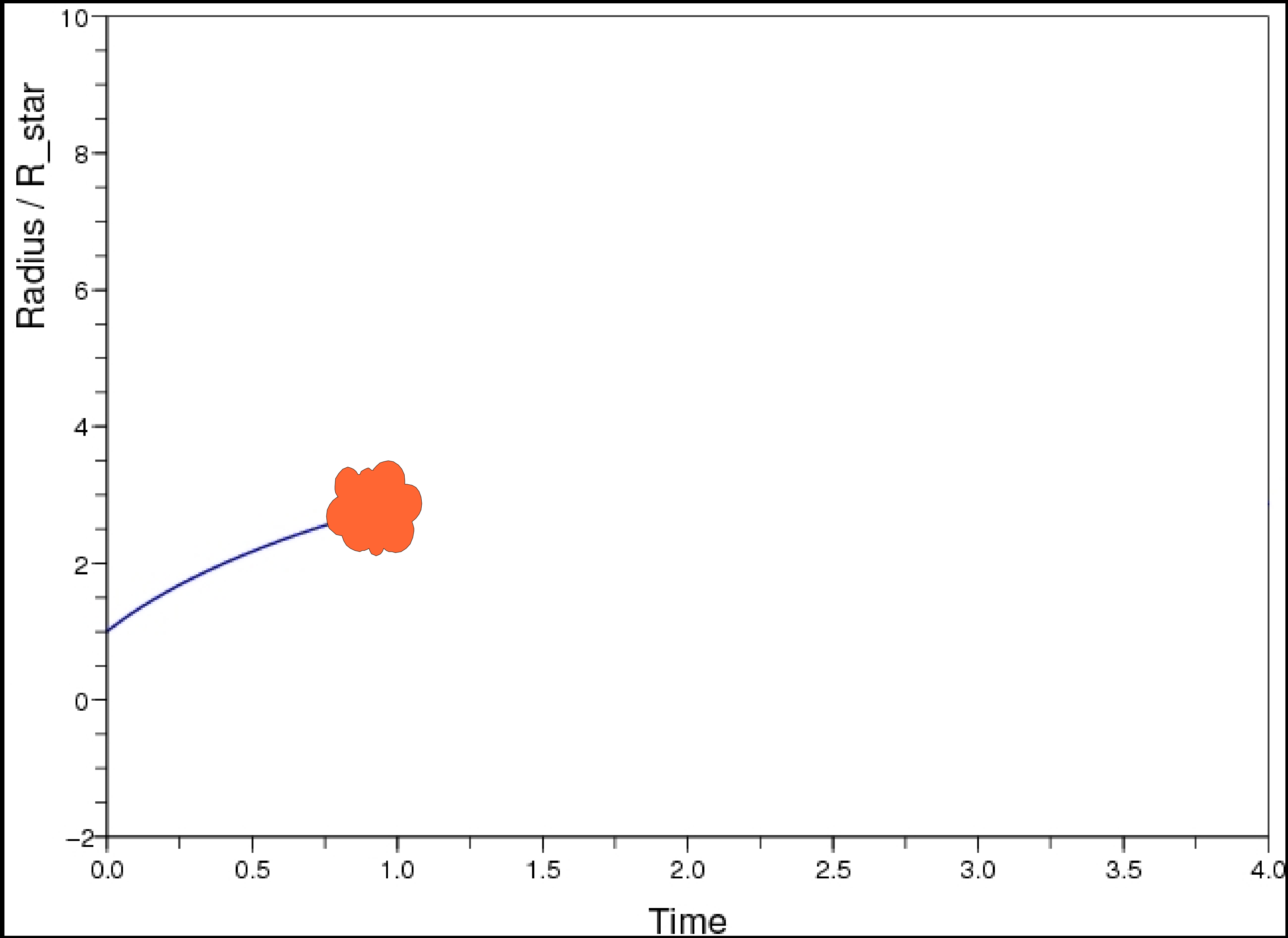

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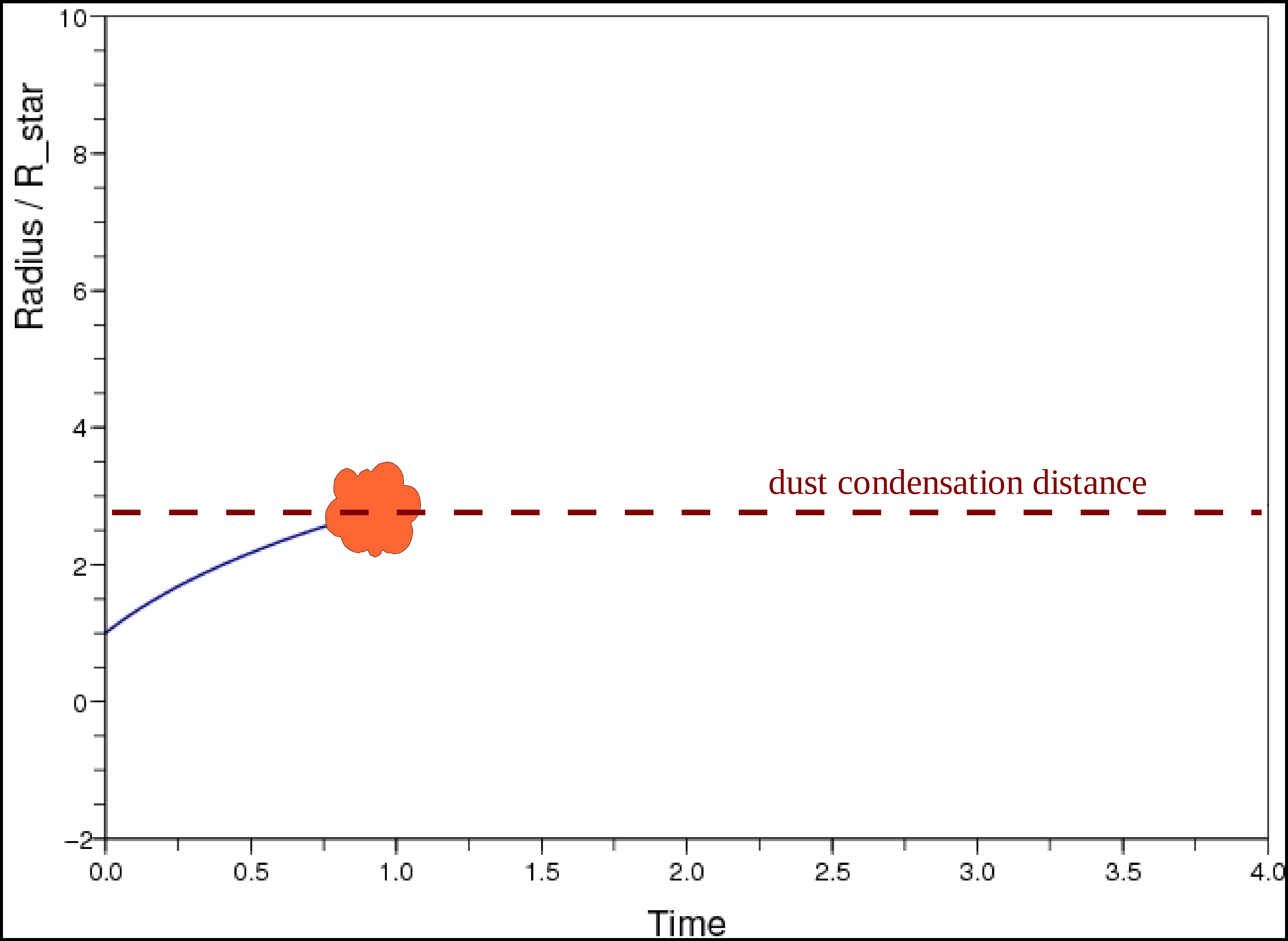

Dust: condensation distance

simple estimate for grain temperature:

- radiative equilibrium
- Planckian radiation field, geom. diluted
- dust opacity approximated by power law

Dust: condensation distance

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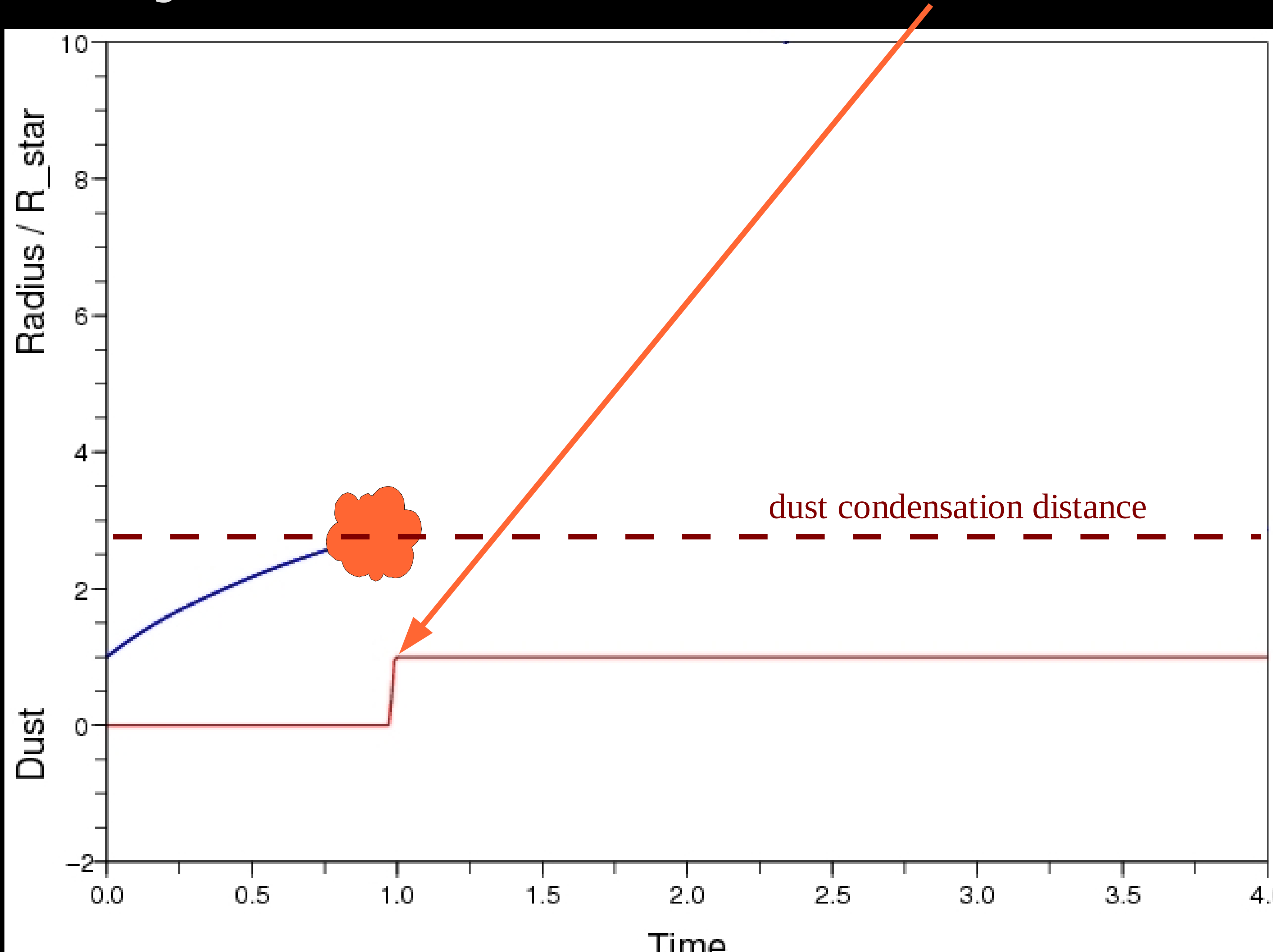
condensation distance: $T_{grain} = T_c$

$$\frac{r_c}{R_*} = \frac{1}{2}\left(\frac{T_c}{T_*}\right)^{-\frac{4+p}{2}}$$

$$\kappa_\lambda \propto \lambda^{-p}$$

condensation
temperature
(material property)

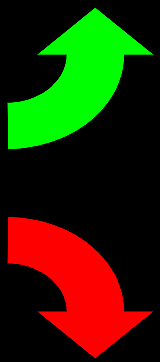
A toy model: shocks, dust & wind



Radiative acceleration: basics

radiative / gravitational acceleration:

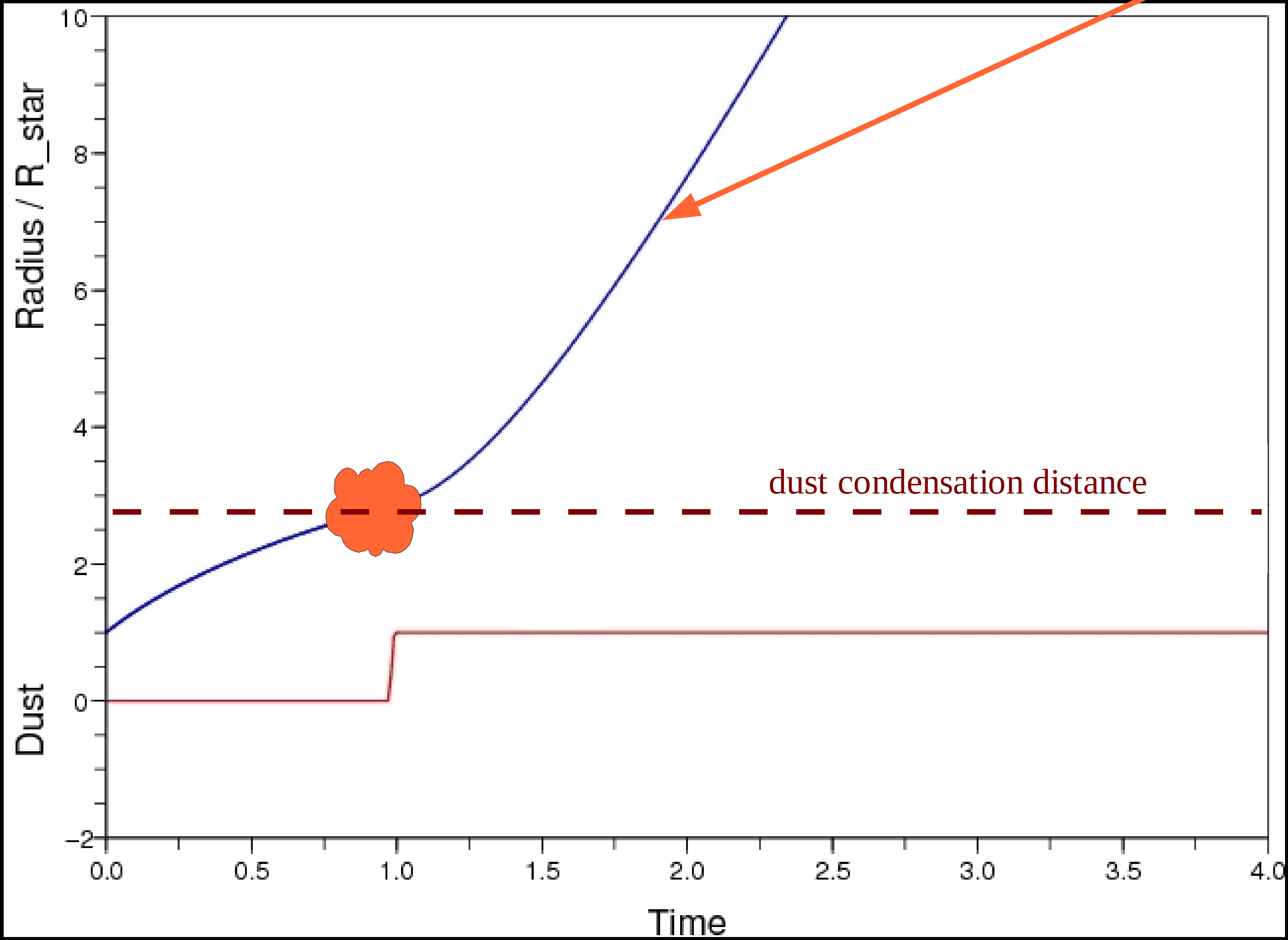
$$\Gamma = \frac{\kappa_H \; L_*}{4 \, \pi \, c \, G \, M_*} \qquad \begin{matrix} > 1 \\ < 1 \end{matrix}$$



critical value = 1 $\Rightarrow$ critical flux mean opacity:

$$\kappa_{crit} = 4 \, \pi \, c \, G \, M_* \, / \, L_*$$

A toy model: shocks, dust & wind



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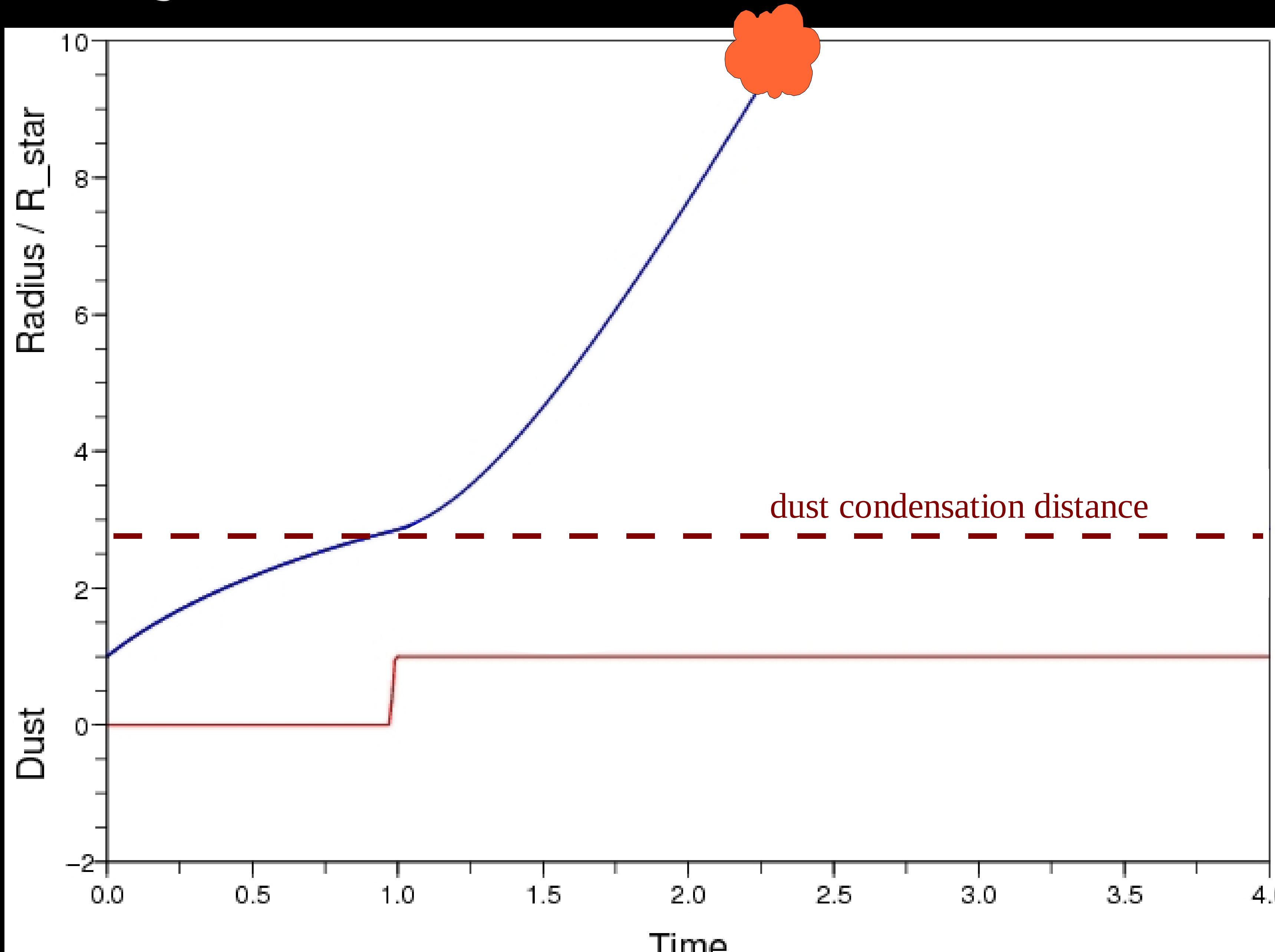

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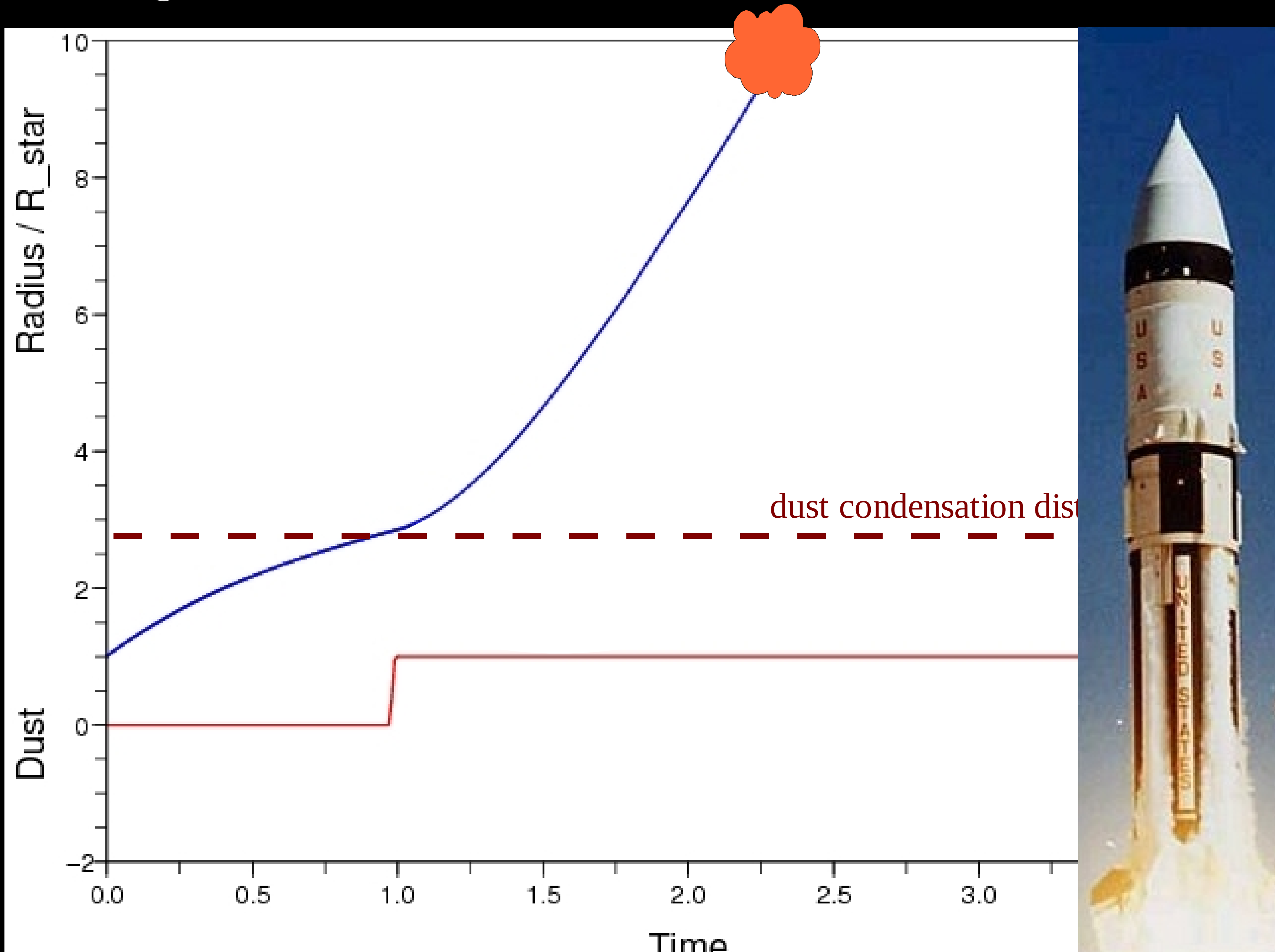


Dust-Driven Winds: Pulsating Red Giants

Dynamical Models

- equations of hydrodynamics
- frequency-dependent radiative transfer
- time-dependent dust formation
- stellar pulsation (simulated by variable inner boundary)

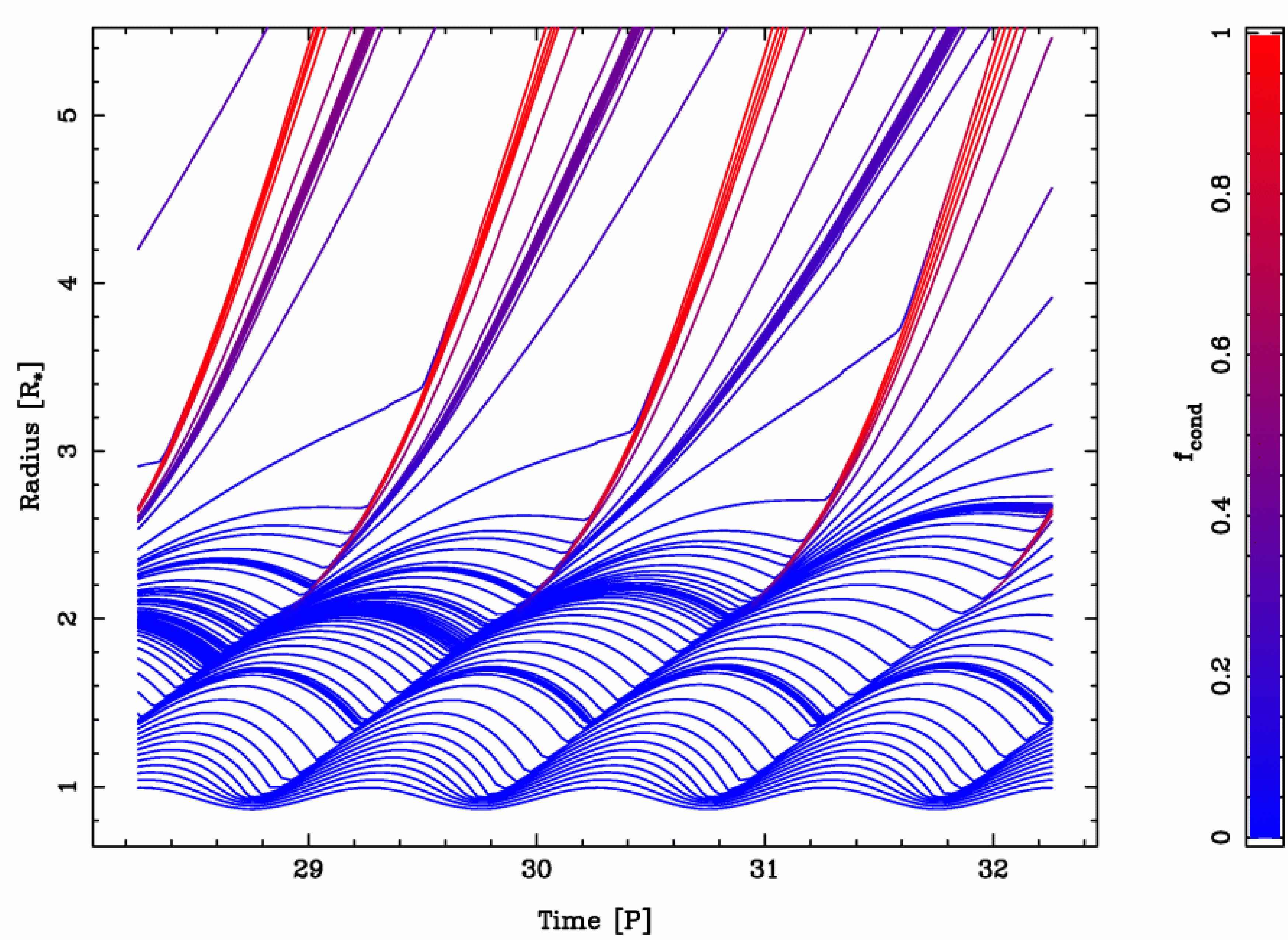
$\Downarrow$

structure of the atmosphere and circumstellar envelope
as a function of time

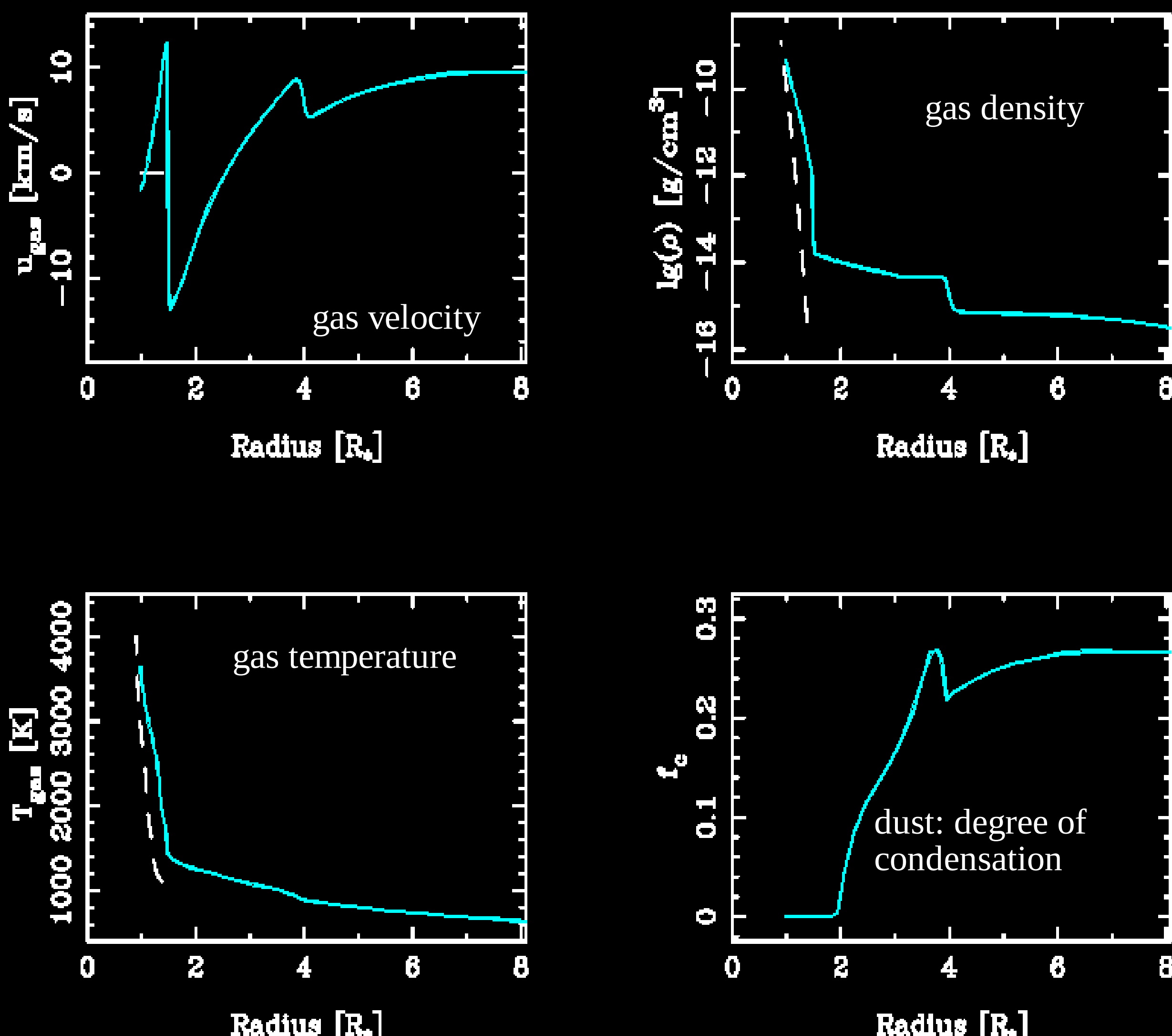
$\Downarrow$

mass loss rate, wind velocity, degree of condensation

Dust-Driven Winds: Pulsating Red Giants



Dust-Driven Winds: Pulsating Red Giants



winds of pulsating carbon stars:

detailed models with frequency-dependent radiative transfer and non-equilibrium dust formation

snapshot of a typical radial structure

Höfner et al. (2003)

Dust-Driven Winds: Pulsating Red Giants

snapshots of the atmosphere and circumstellar envelope

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detailed radiative transfer for given structure

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theoretical predictions of observable properties:

- spectra and variation with phase
- light curves
- spatial intensity distributions
- line profile variations

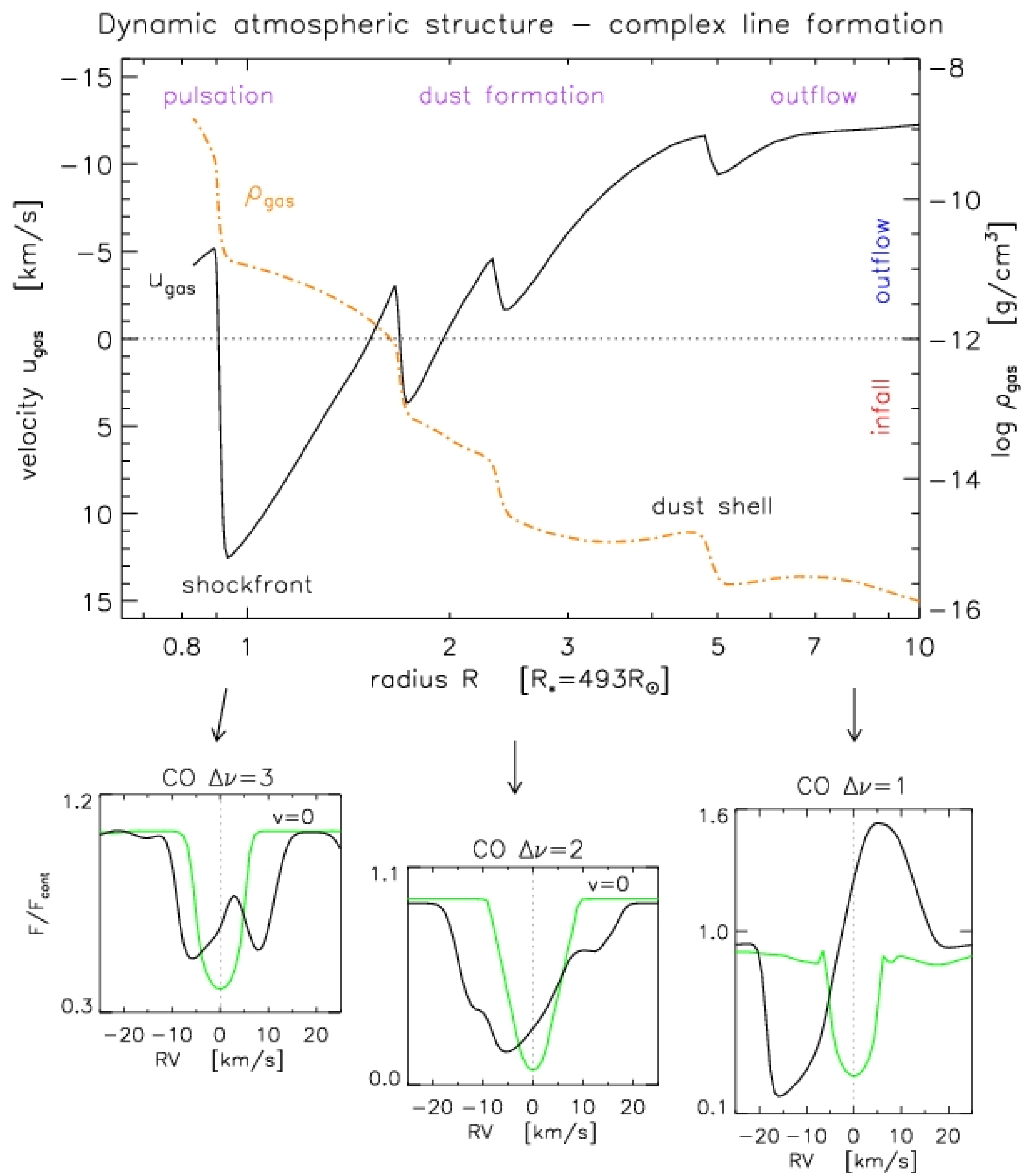
Dust-Driven Winds: Pulsating Red Giants

modelling:

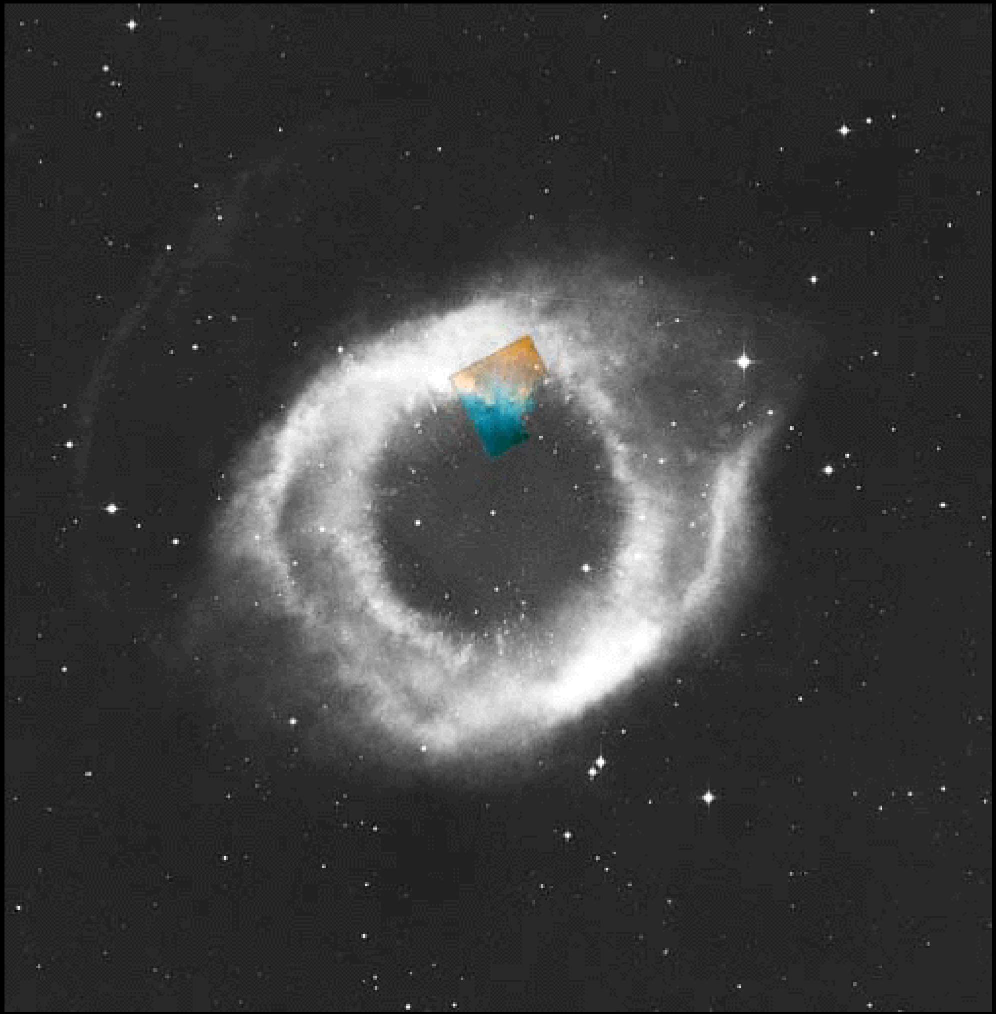
- variations of molecular line profiles due to changes in velocities with pulsation phase

- P Cygni profiles of CO lines

Nowotny et al. (2010)

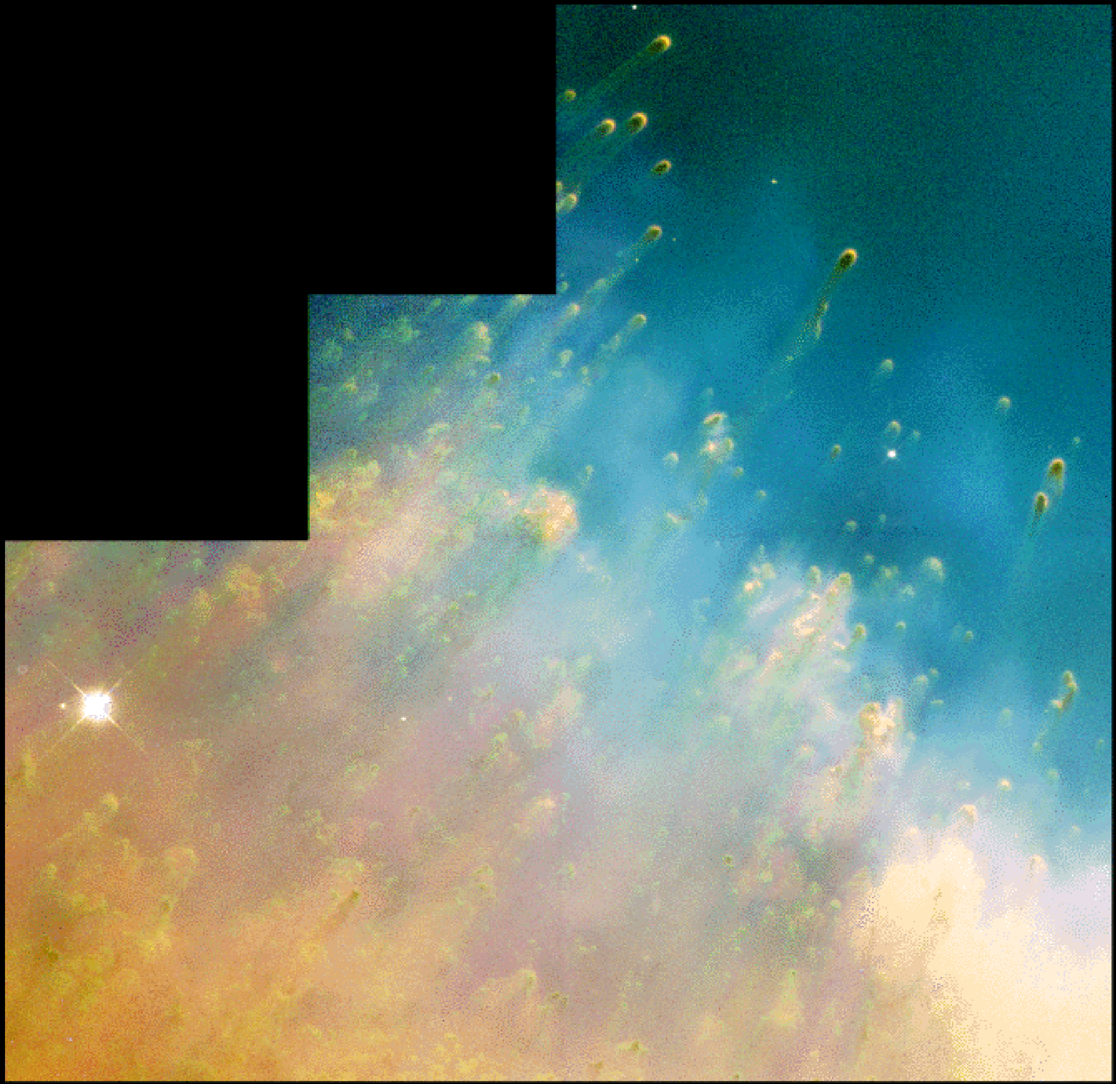


Planetary Nebulae: Hot & Cool Winds



Helix Nebula • NGC 7293 • Las Campanas Observatory and HST
Black & White: J. Bedke (CSC/STScI), Carnegie Institution of Washington
Color Inset: C.R. O'Dell (Rice Univ.), NASA

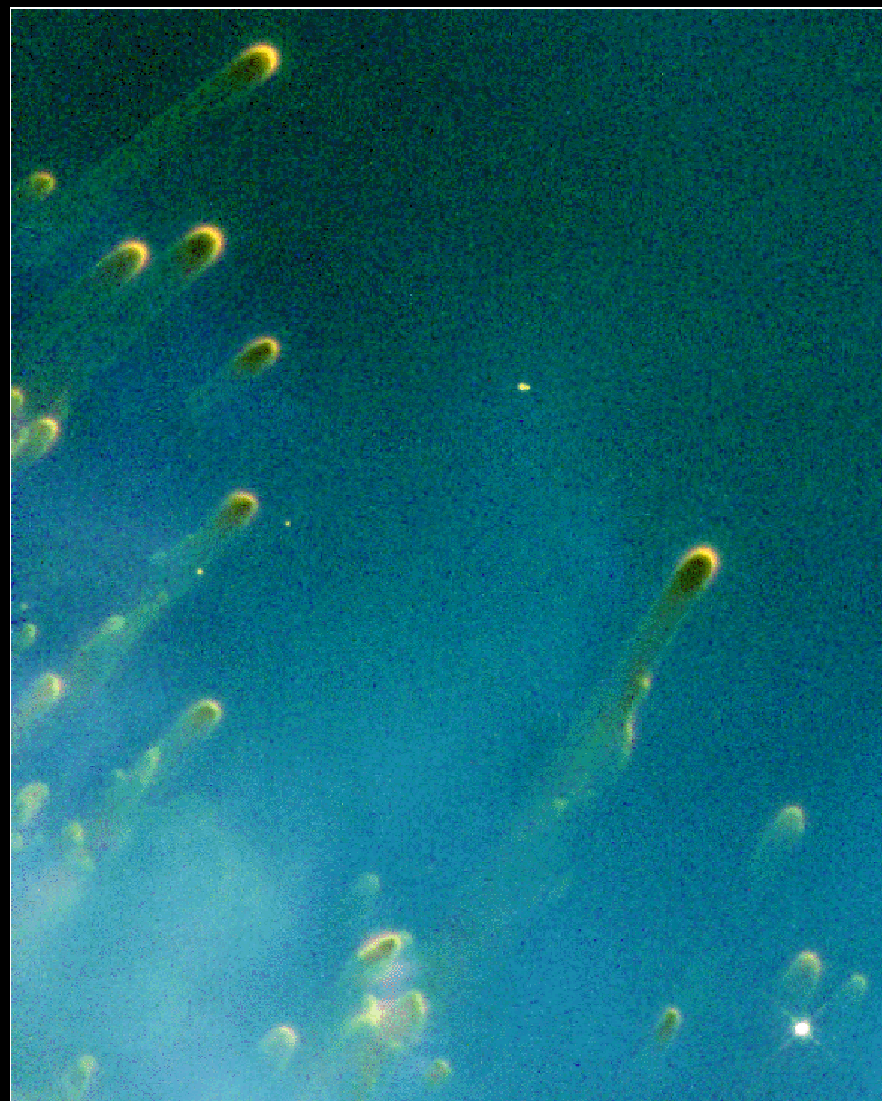
Planetary Nebulae: Hot & Cool Winds



Helix Nebula • NGC 7293 HST • WFPC2

PRC96-13a • ST ScI OPO • April 15, 1996 • C.R. O'Dell (Rice Univ.), NASA

Planetary Nebulae: Hot & Cool Winds



Helix Nebula Detail HST • WFPC2

PRC96-13b • ST ScI OPO • April 15, 1996 • C.R. O'Dell (Rice Univ.), NASA

Stellar Winds: Conclusions

- almost all stars have a stellar wind
- mass loss may increase dramatically during stellar evolution
- radiation pressure is a very efficient driving mechanism
- stars lose a major fraction of their mass through stellar winds
- stellar winds enrich the ISM with heavier elements