Dynamical Atmospheres & Winds of AGB Stars

A Theorist's View

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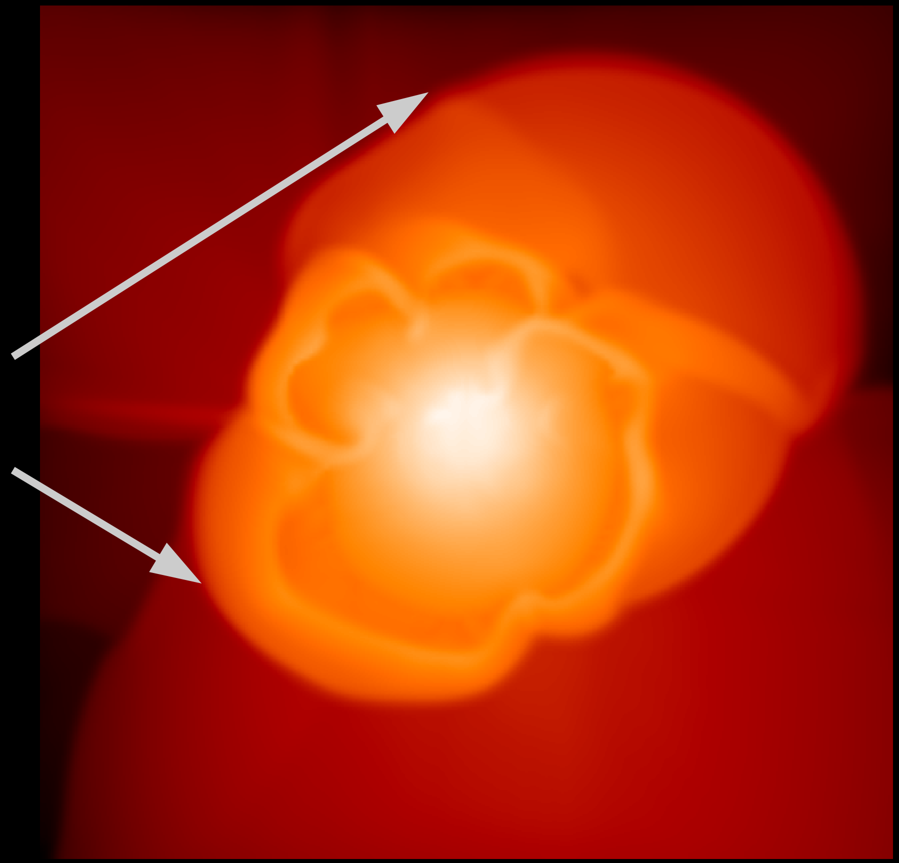
Dynamics of atmosphere & wind

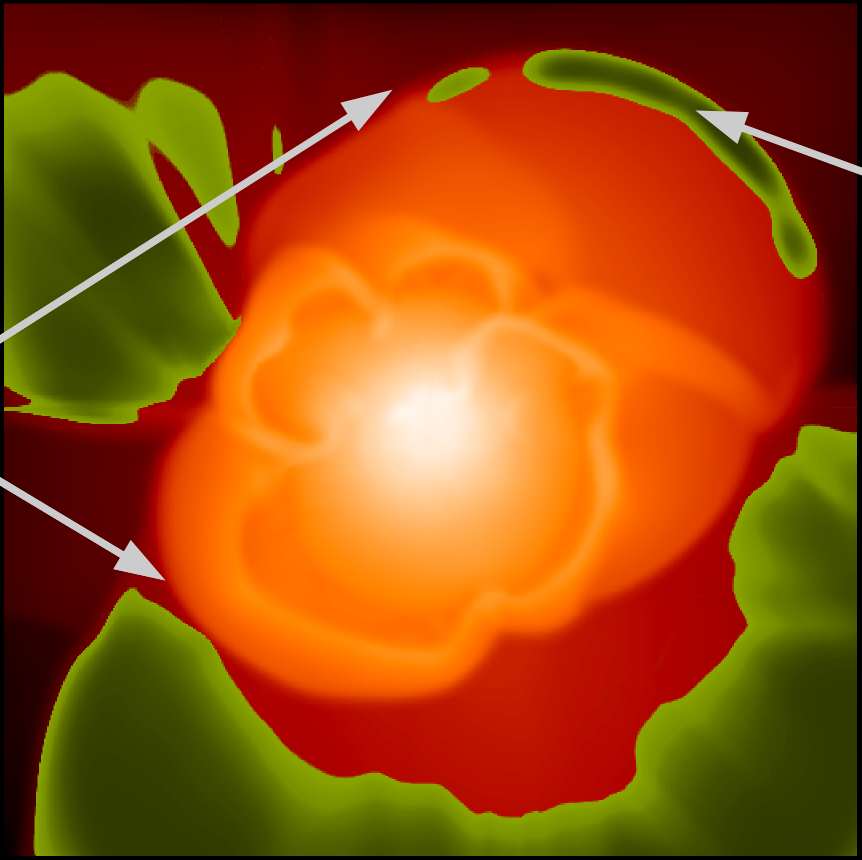
stellar pulsation
& convection
induce strong
shock waves
which propagate
outwards through
the extended
stellar atmosphere



3D star-in-a-box model of an AGB star (Freytag & Höfner 2008)
snapshot of the gas density for a cut through the center of the star

Dynamics of atmosphere & wind

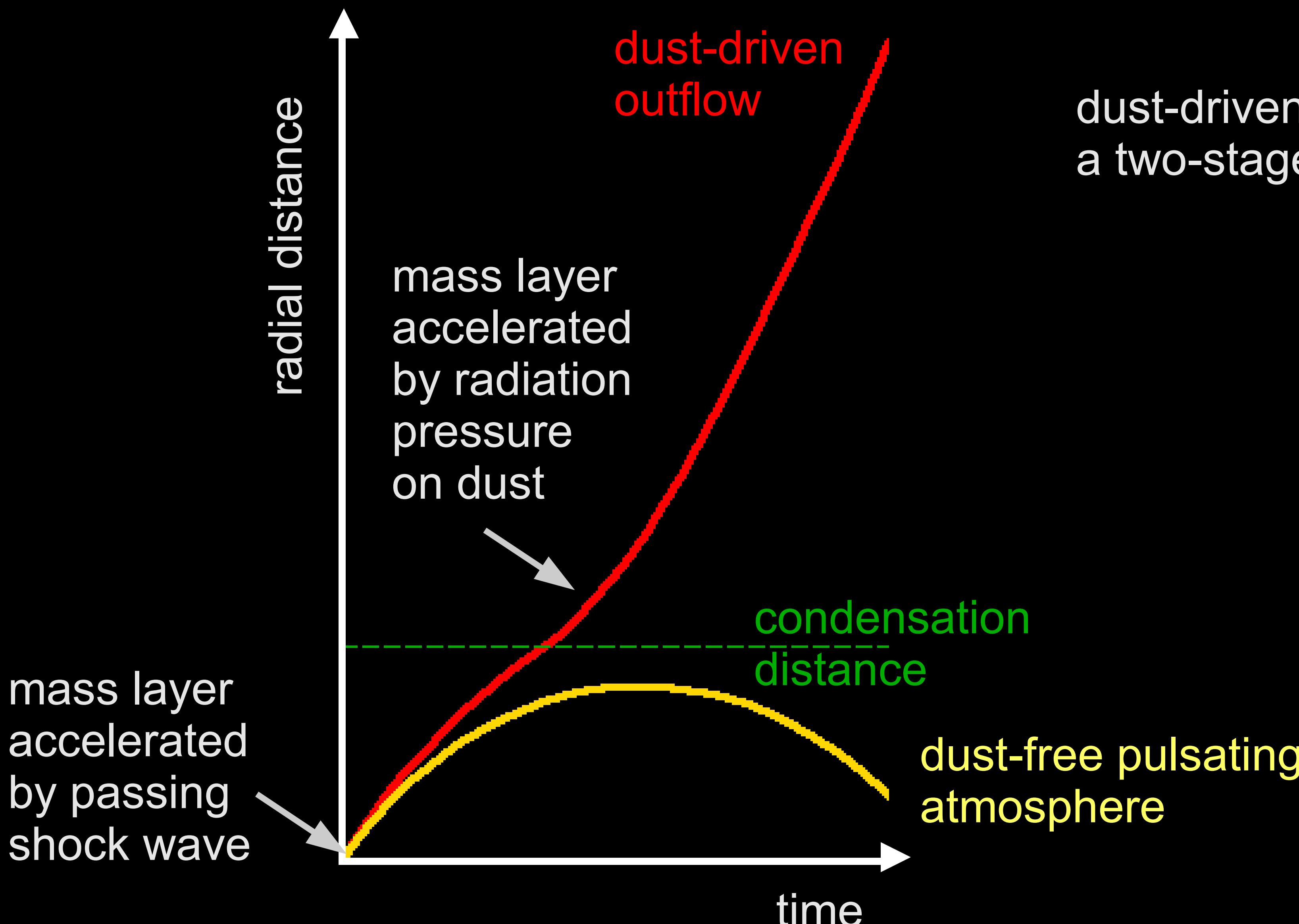
stellar pulsation & convection induce strong shock waves which propagate outwards through the extended stellar atmosphere



dust forms in the wake of the shock at distances of 2-3 stellar radii and is accelerated outwards by radiation pressure triggering a wind

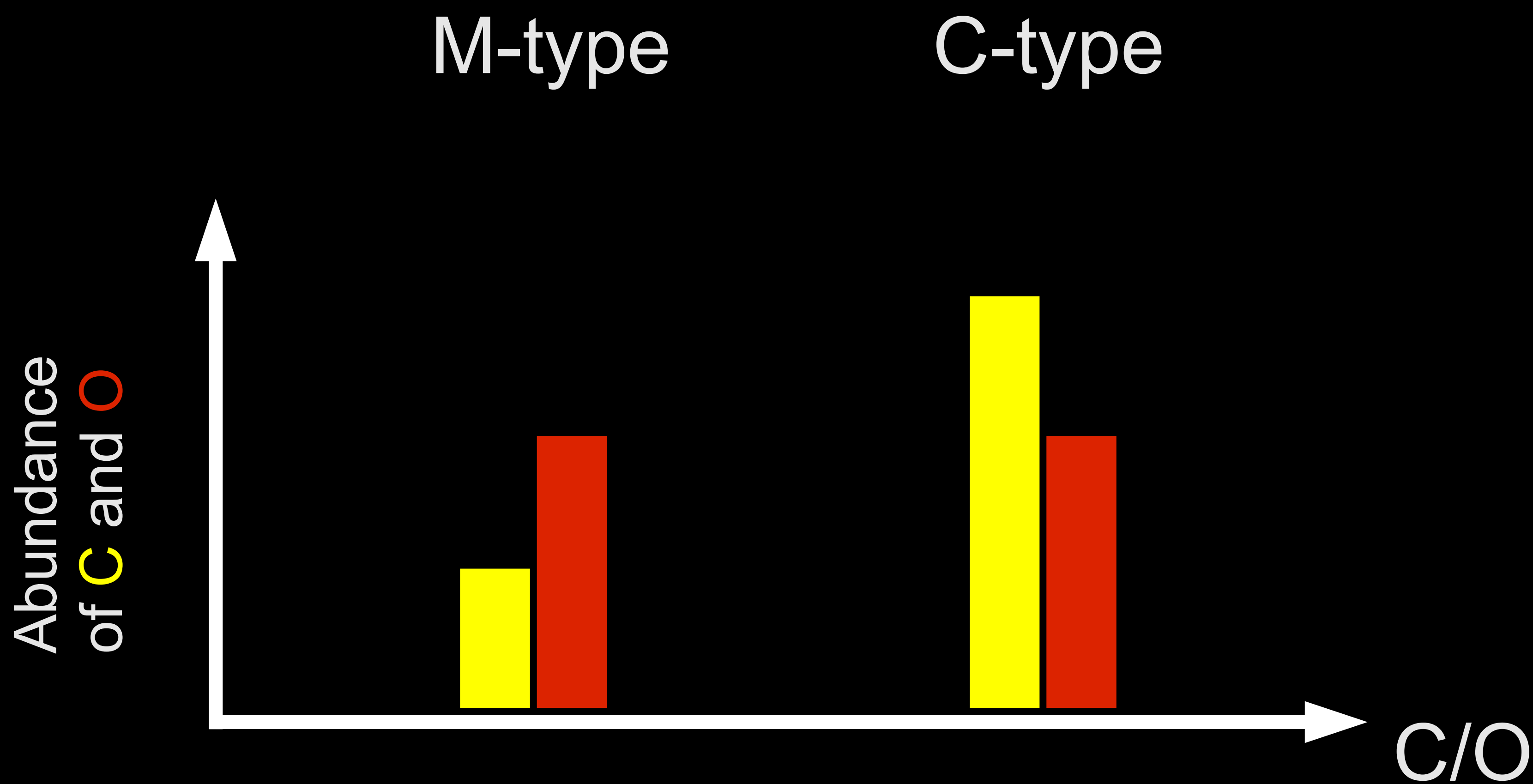
3D star-in-a-box model of an AGB star (Freytag & Höfner 2008)
snapshot of the gas density for a cut through the center of the star
dust distribution shown in green

Dynamics of atmosphere & wind



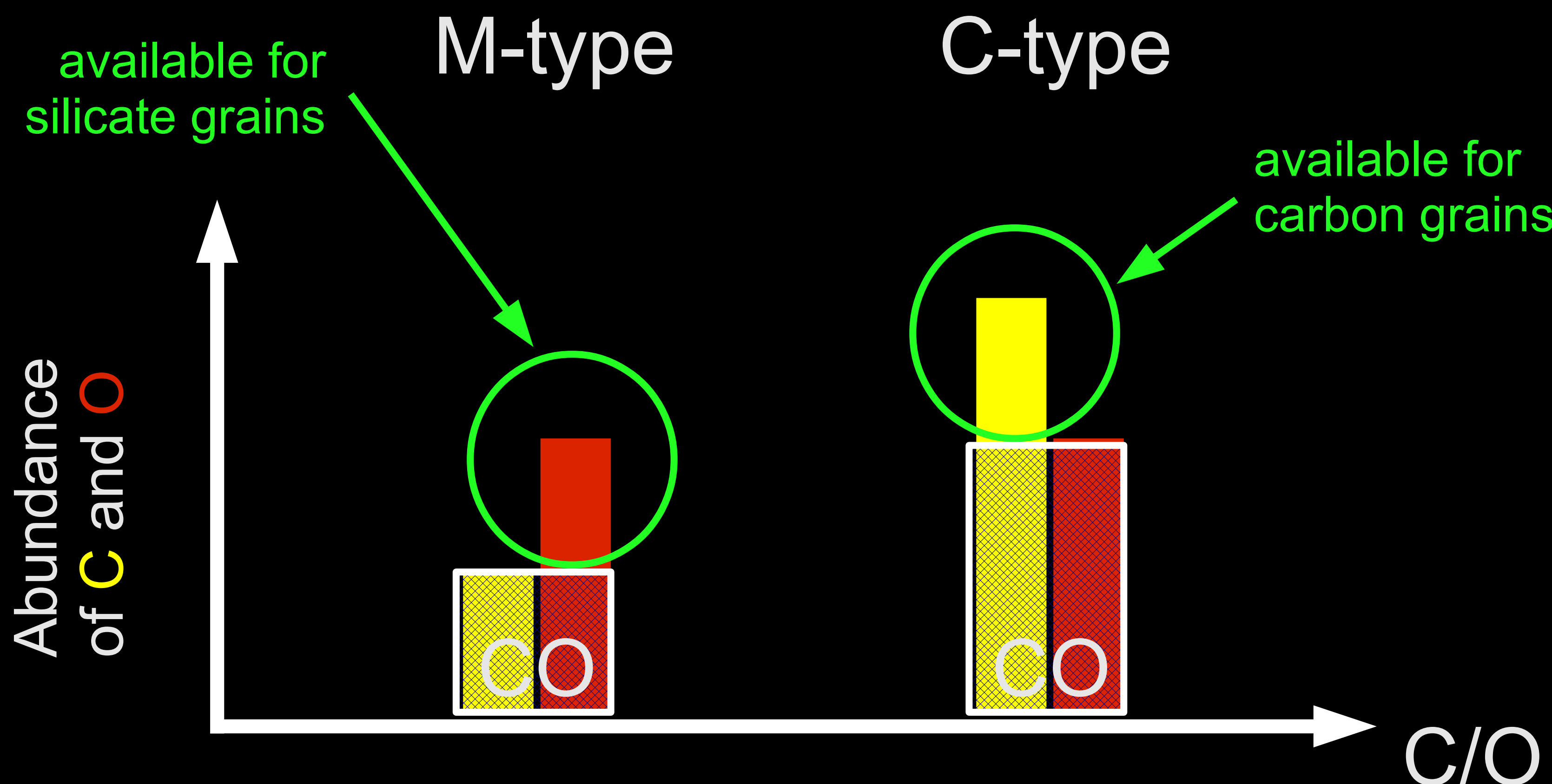
dust-driven wind:
a two-stage rocket

Dust chemistry: the role of C/O



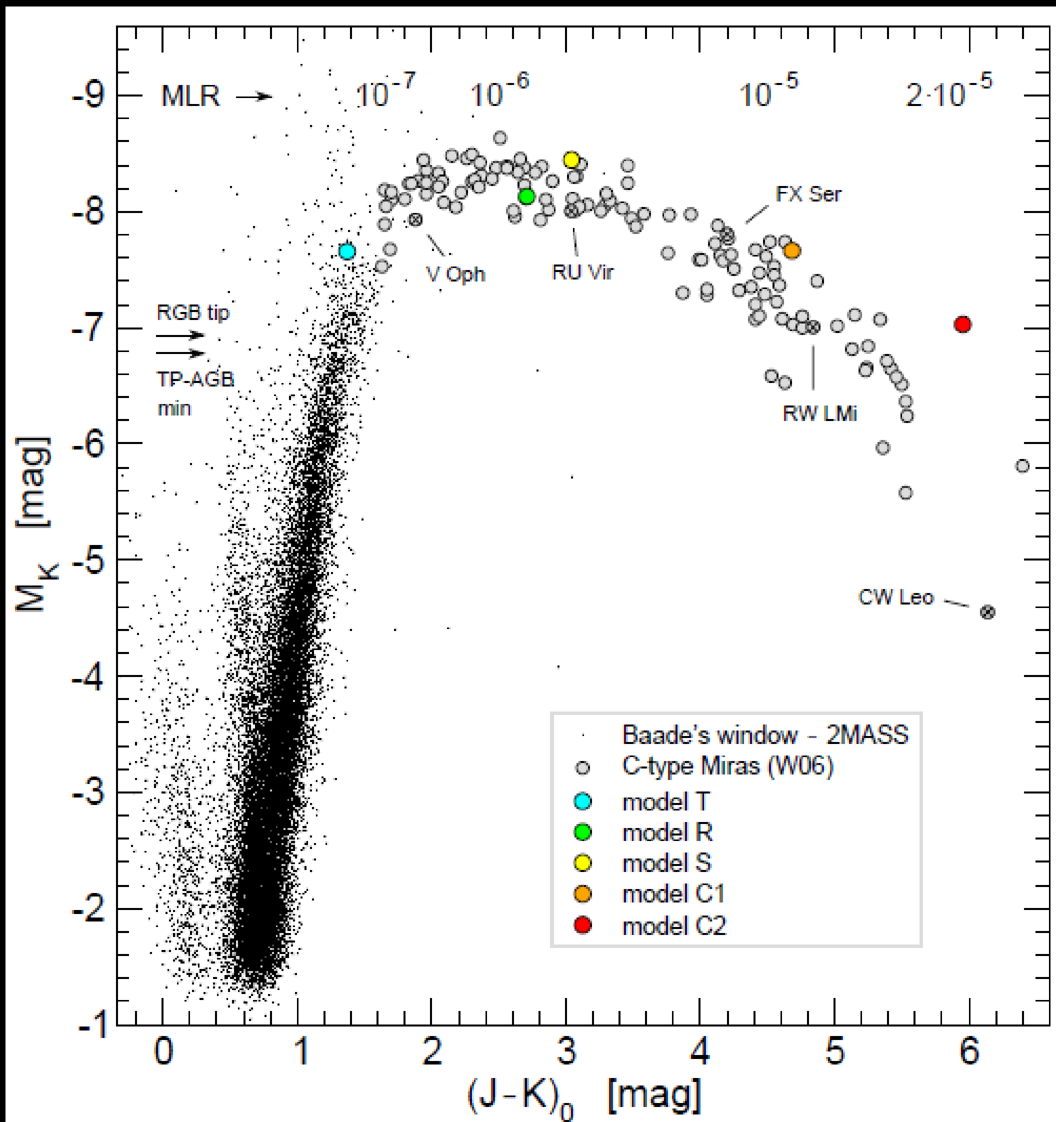
... changes during AGB evolution

Dust chemistry: the role of C/O



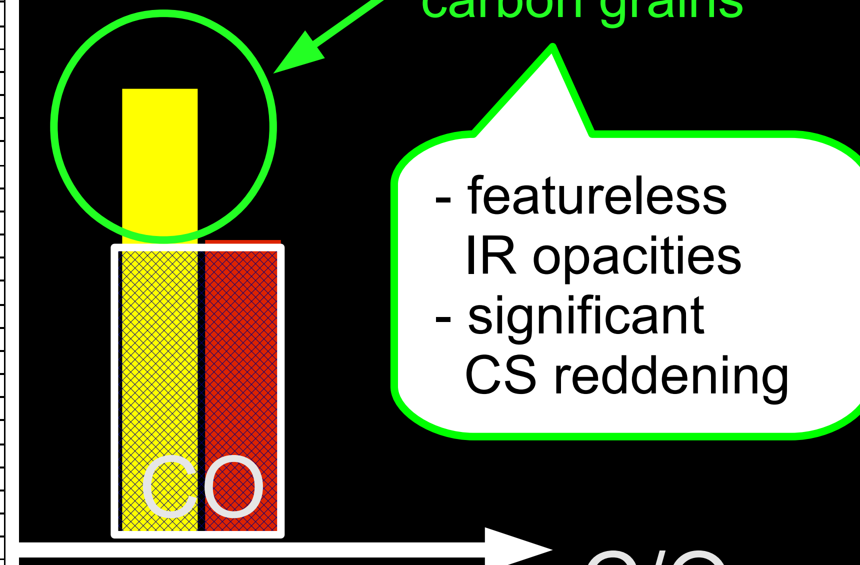
... changes during AGB evolution

Observational constraints on dust



C-type

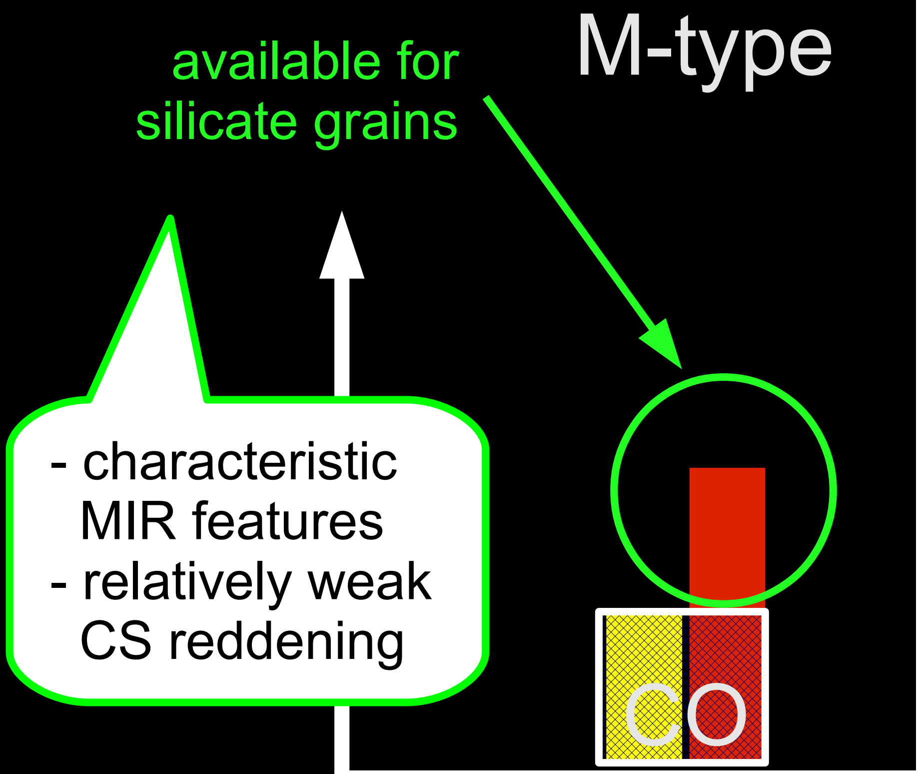
available for carbon grains

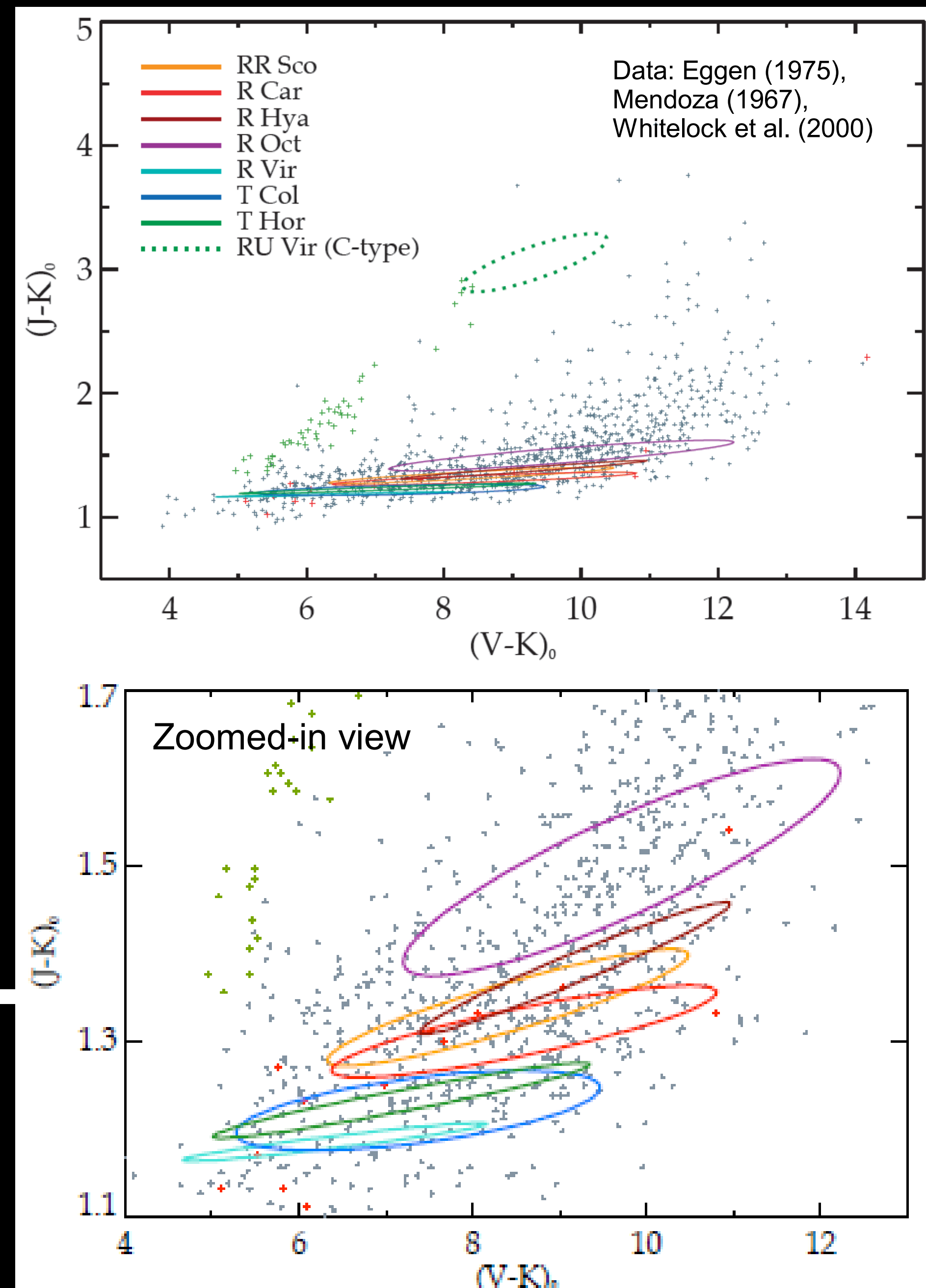


C/O

Dust-driven winds & CS reddening for C-stars (Nowotny at al. 2013)

Observational constraints on dust





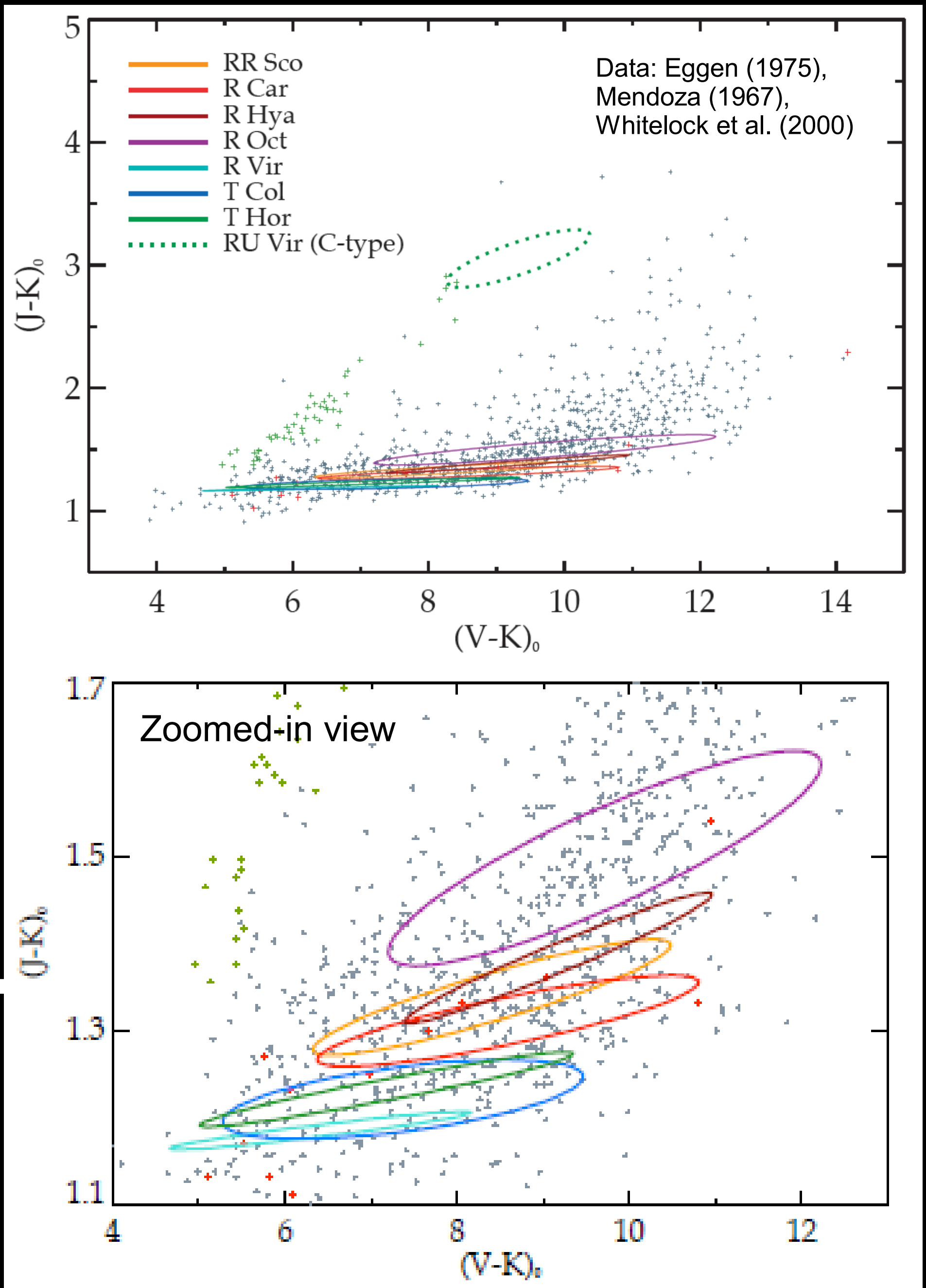
Color variations during pulsation cycle, M-stars (Bladh et al. 2013)

Observational constraints on dust

M-type AGB stars show small variations in J-K and large variations in V-K.

Are these variations of colors with phase caused by dust or molecules?

Does this tell us something about the wind mechanism?



Color variations during pulsation cycle, M-stars (Bladh et al. 2013)

Quantitative dynamic models

Dynamics

- pulsation & convection
- strong shock waves
- stellar wind

Dust

- seed particles
- grain growth
- grain destruction

Radiation

- variable luminosity
- molecular opacities
- dust opacities

Wind properties

- mass loss rates
- wind velocities
- dust yields

Höfner et al. (2003), Höfner (2008)

Synthetic observables

- high-/low-res spectra
- light curves
- interferometric data

Candidates for wind-driving grains

Observations of spectral features
at wavelengths of about 10 and 18 microns
in AGB stars suggest
olivine- and/or pyroxene-type silicates

$Mg_{2x}Fe_{2(1-x)}SiO_4$ $Mg_xFe_{(1-x)}SiO_3$

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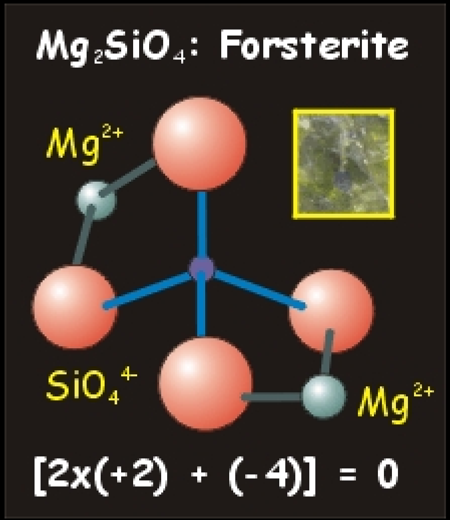

… no strong constraints
from MIR spectra
on the Mg/Fe ratio

X = ?!?

Candidates for wind-driving grains

Mg_2SiO_4 Fe_2SiO_4

Mg-rich $1 \leftarrow X \rightarrow 0$ Fe-rich

low absorption high absorption

at visual and near-infrared wavelengths

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Mg_2SiO_4 $1 \leftarrow X \rightarrow 0$ $Fe_2\,SiO_4$

Mg-rich Fe-rich

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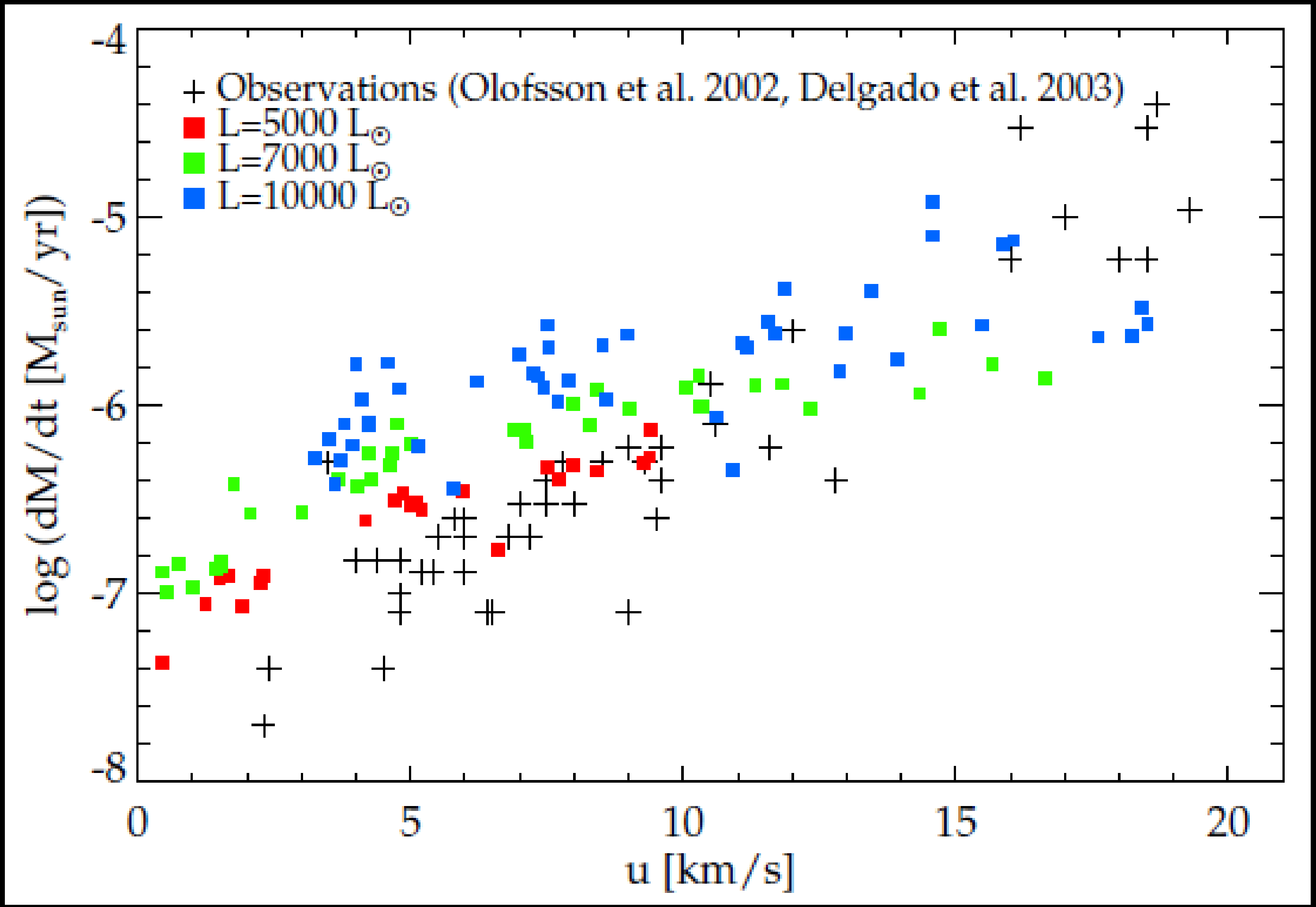
at visual and near-infrared wavelengths

Could drive a wind by scattering if particles are large (0.1-1 μm) …

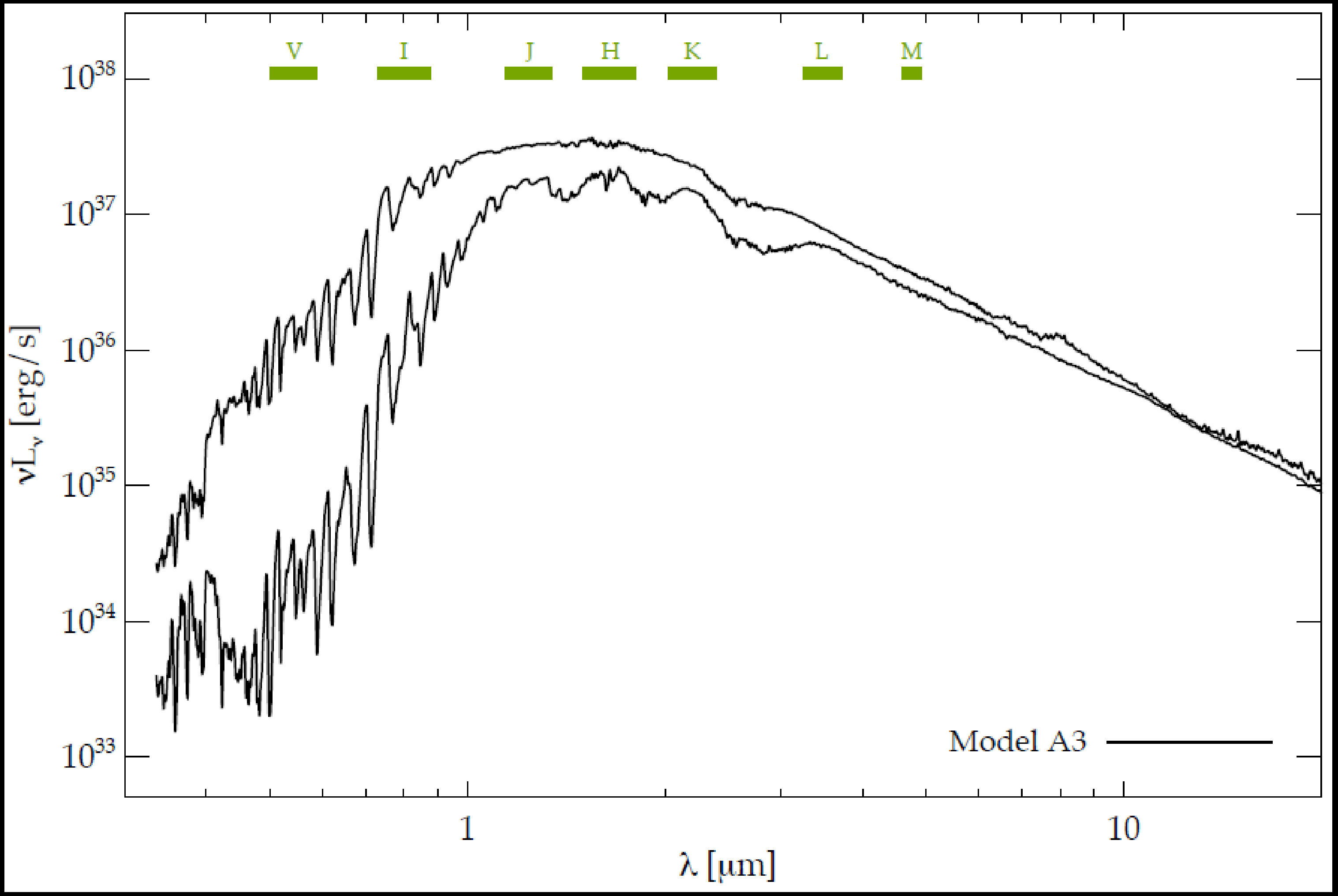
Cannot form sufficiently close to the star to drive a wind !

Dynamic models & observations



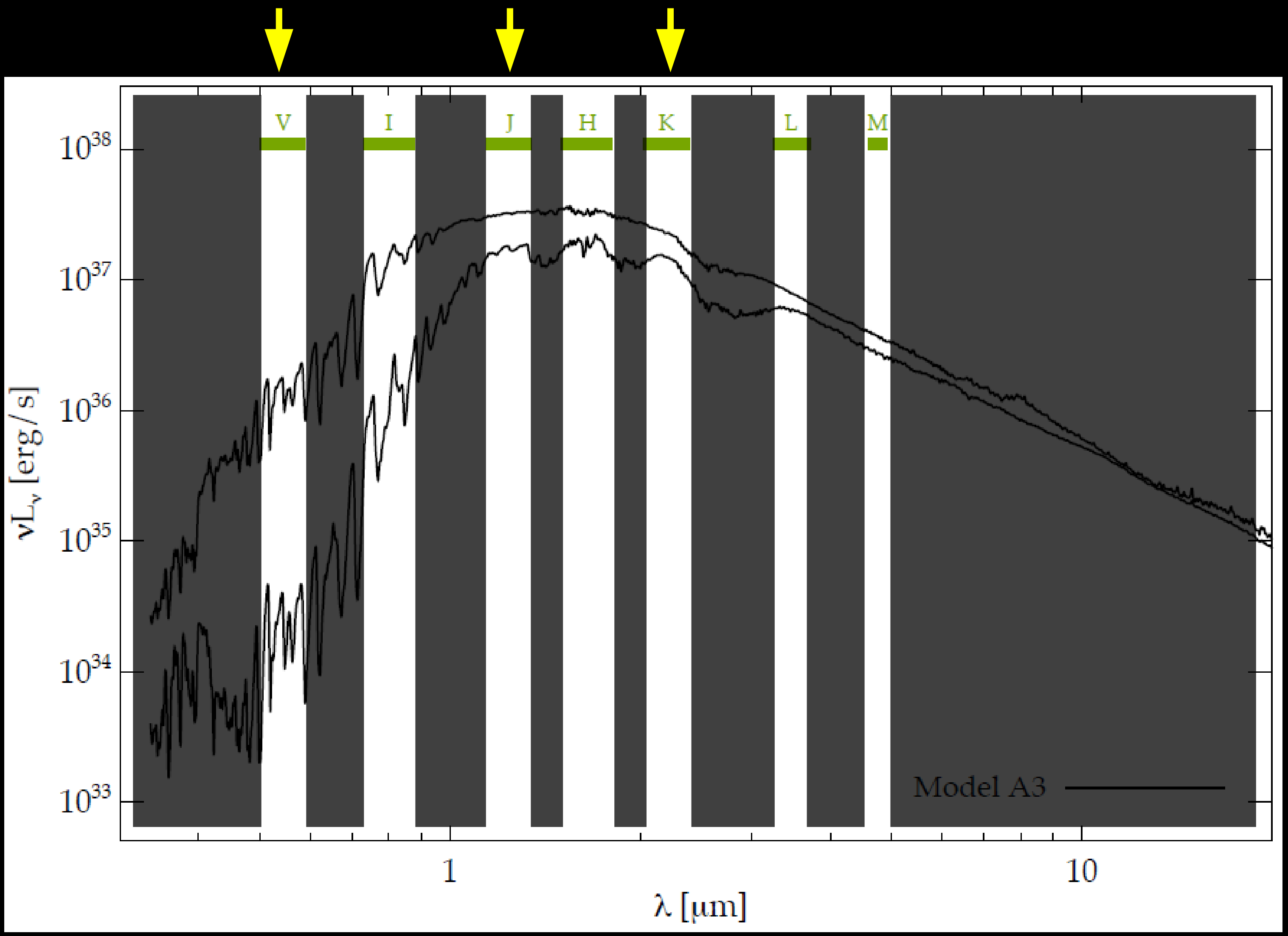
Models of stellar winds driven by photon scattering on Mg_2SiO_4 grains with sizes of 0.1–1 micron show realistic mass loss rates & wind velocities
Höfner (2008), Bladh et al. (2015)

Dynamic models & observations



Spectra: variations during pulsation cycle (Bladh et al. 2013)

Dynamic models & observations



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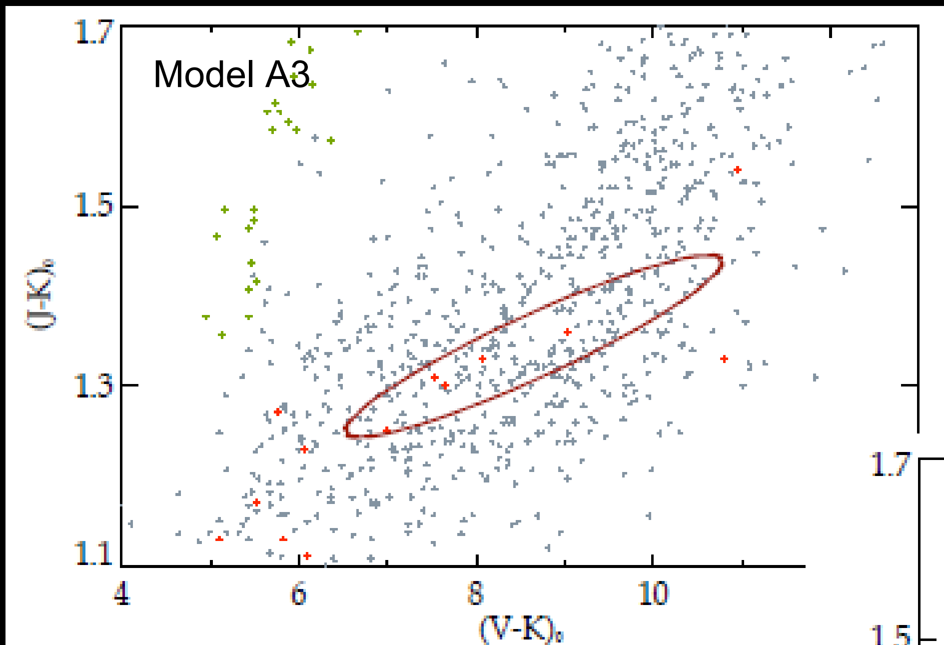
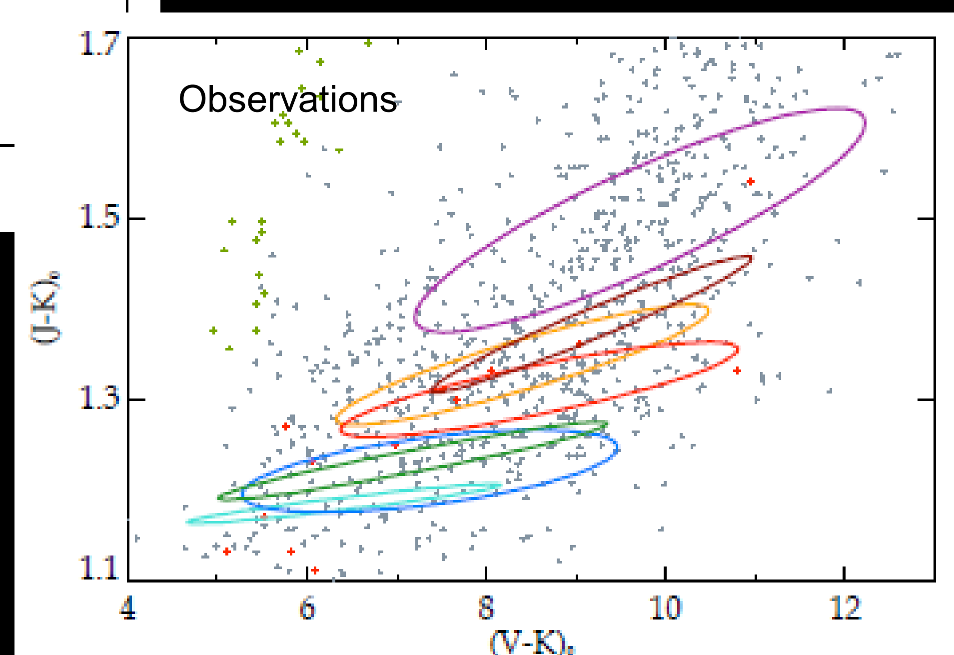


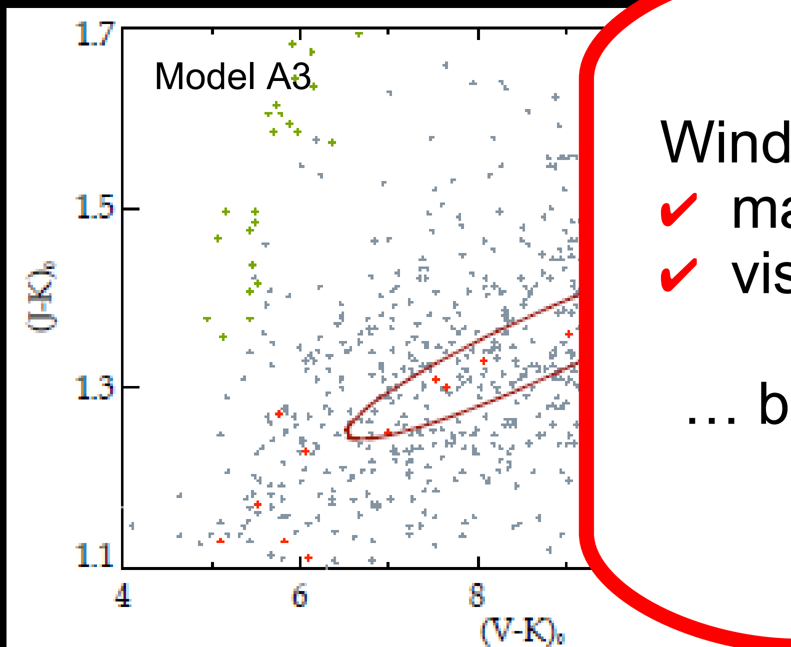
small variation with phase in (J-K)



large variation with phase in (V-K)
due to molecules

Spectra: variations during pulsation cycle (Bladh et al. 2013)

Dynamic models & observations



Winds driven by Fe-free silicate dust match
- ✔ mass loss rates, wind velocities
- ✔ visual and near-infrared fluxes

… but do grains with sizes of 0.1-1 micron actually exist in cool giants ?!?

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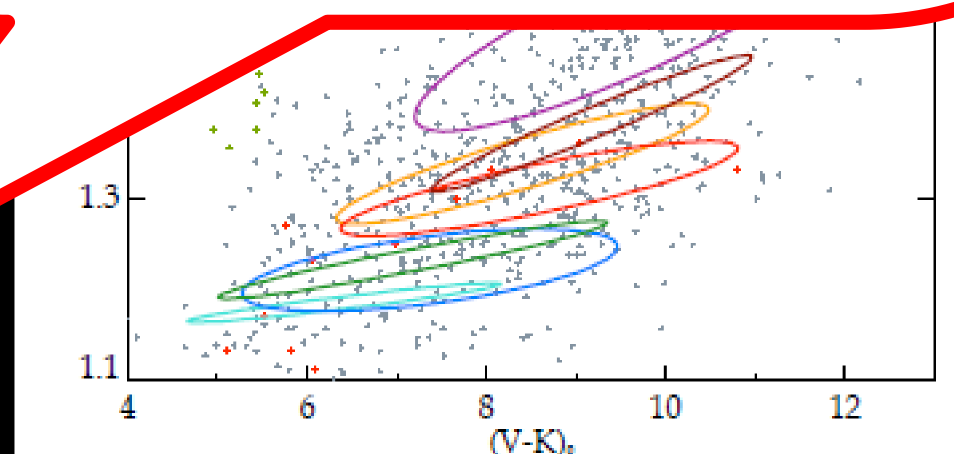
due to molecules



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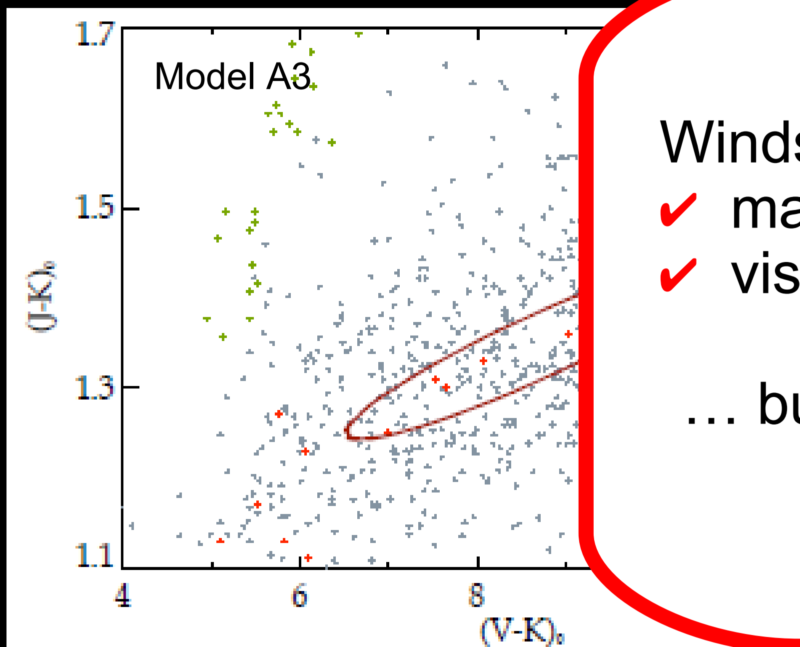

Winds driven by Fe-free silicate dust match
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… but do grains with sizes of 0.1-1 micron actually exist in cool giants ?!?

It would seem so ...

LETTER

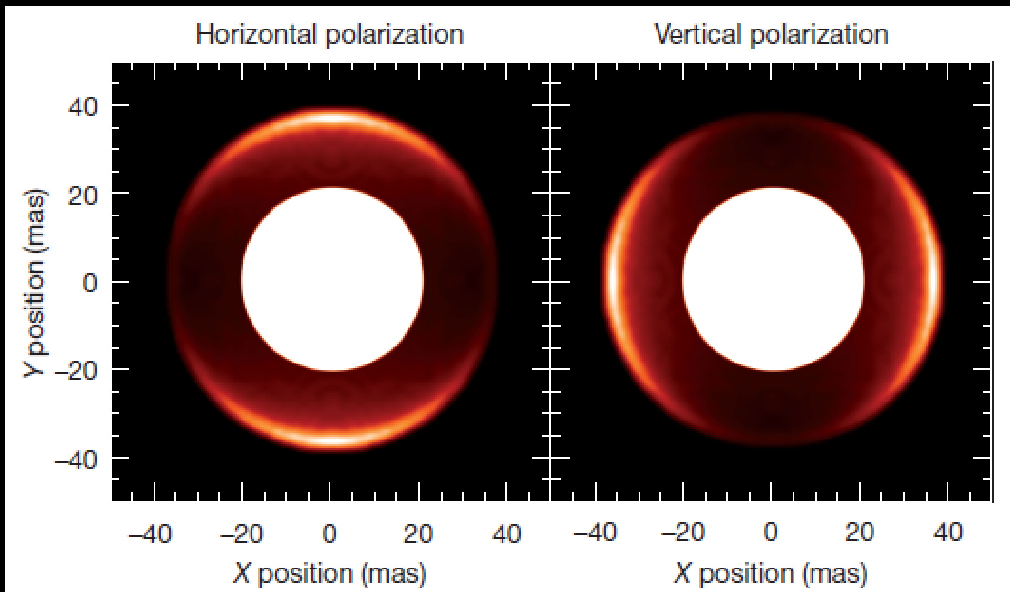
Nature, April 12, 2012

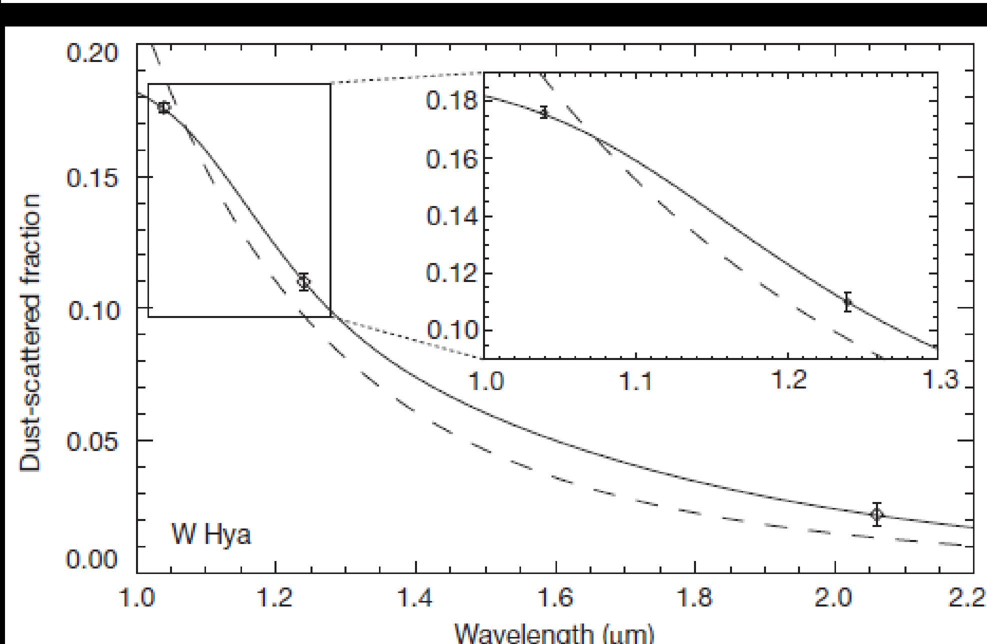
doi:10.1038/nature10935

A close halo of large transparent grains around extreme red giant stars

Barnaby R. M. Norris[1], Peter G. Tuthill[1], Michael J. Ireland[1,2,3], Sylvestre Lacour[4], Albert A. Zijlstra[5], Foteini Lykou[5], Thomas M. Evans[1,6], Paul Stewart[1] & Timothy R. Bedding[1]

Large grains around AGB stars





Combining advanced observational techniques:

Polarimetry
→ identification of starlight scattered by dust

Interferometry
→ spatial scale of dust shell

Multi-wavelength study
→ constraints on grain size

Results for 3 AGB stars:

0.3 μm grains at 2 stellar radii

→ fits nicely with models of Höfner (2008)

Norris et al. (2012)

Dynamic models: ongoing work

- Implementation of more dust species for stars with C/O < 1 (wind driving candidates and materials relevant for spectra)

Dust species of interest

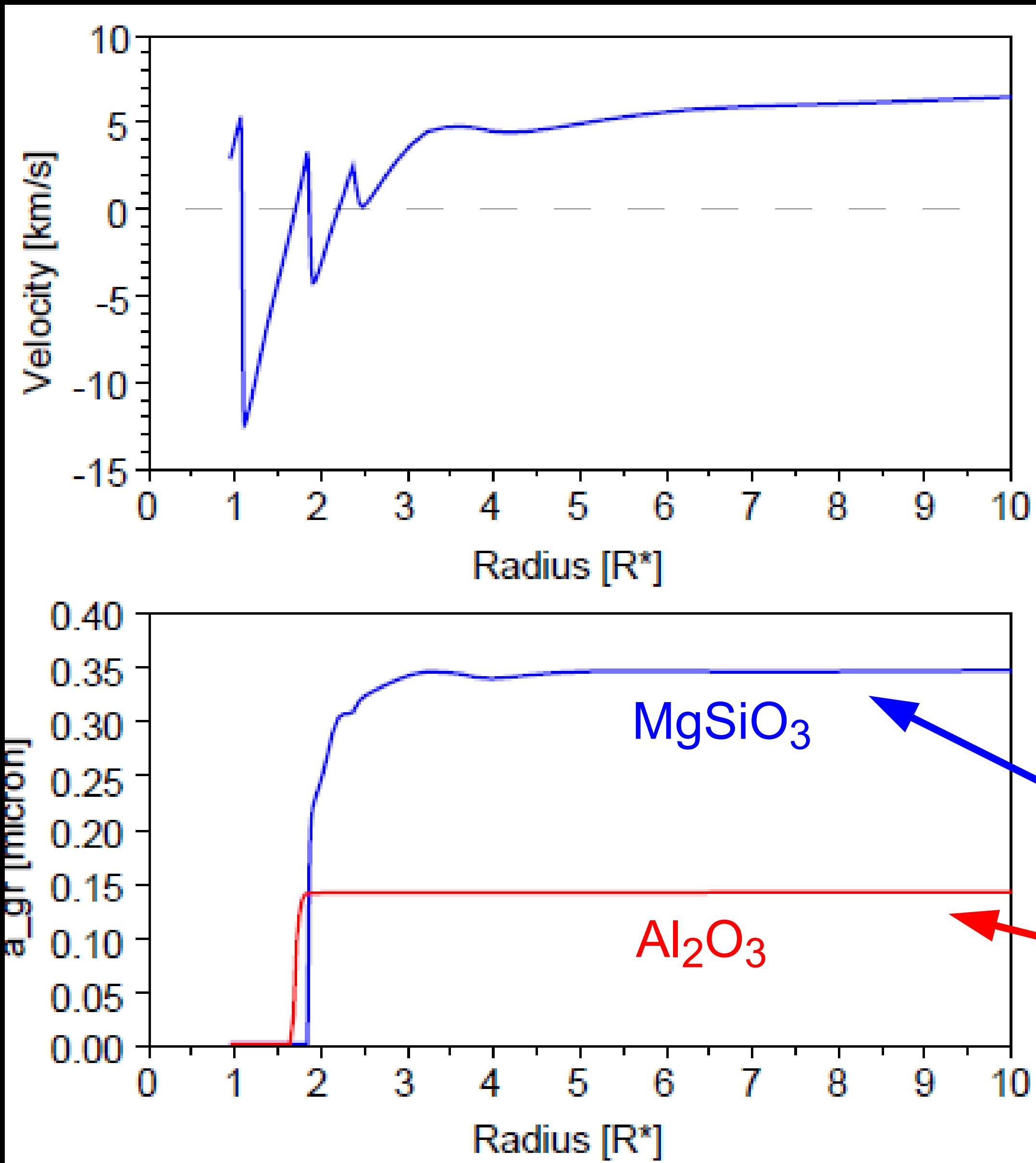
Candidates for wind driving

- Mg_2SiO_4: used in exploratory models (Höfner 2008, Bladh 2013, 2015)
- $MgSiO_3$: under investigation, promising alternative (Höfner et al., in prep.)

Other relevant species (spectra):

- Fe-bearing silicates in the wind (Fe-free grains are too cold to produce emission)
- Al_2O_3: observed close to stellar surface with spectro-interferometry

Dynamic models: grain growth



outflow

infall

wind driven by photon scattering on Fe-free silicate grains

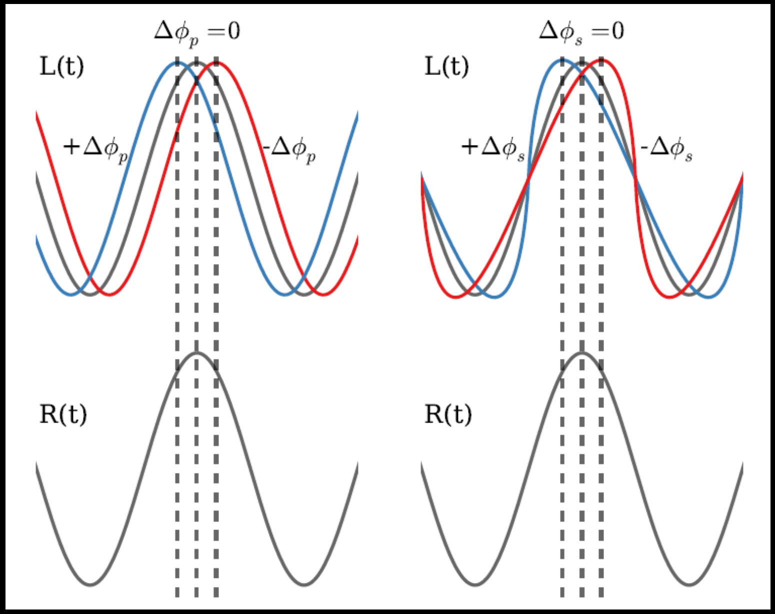
corundum as passive dust species

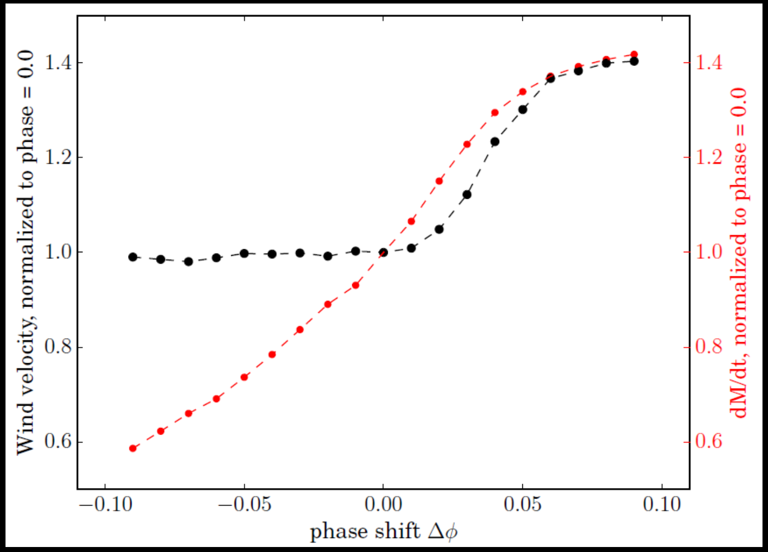
(Höfner et al., in prep)

Dynamic models: ongoing work

- Implementation of more dust species for stars with C/O < 1 (wind driving candidates and materials relevant for spectra)
- Improved description of sub-photospheric dynamics and variable luminosity in the atmosphere & wind models (simulating effects of pulsation and large-scale convective motions), derived from state-of-the-art pulsation and convection models

Variability and mass loss



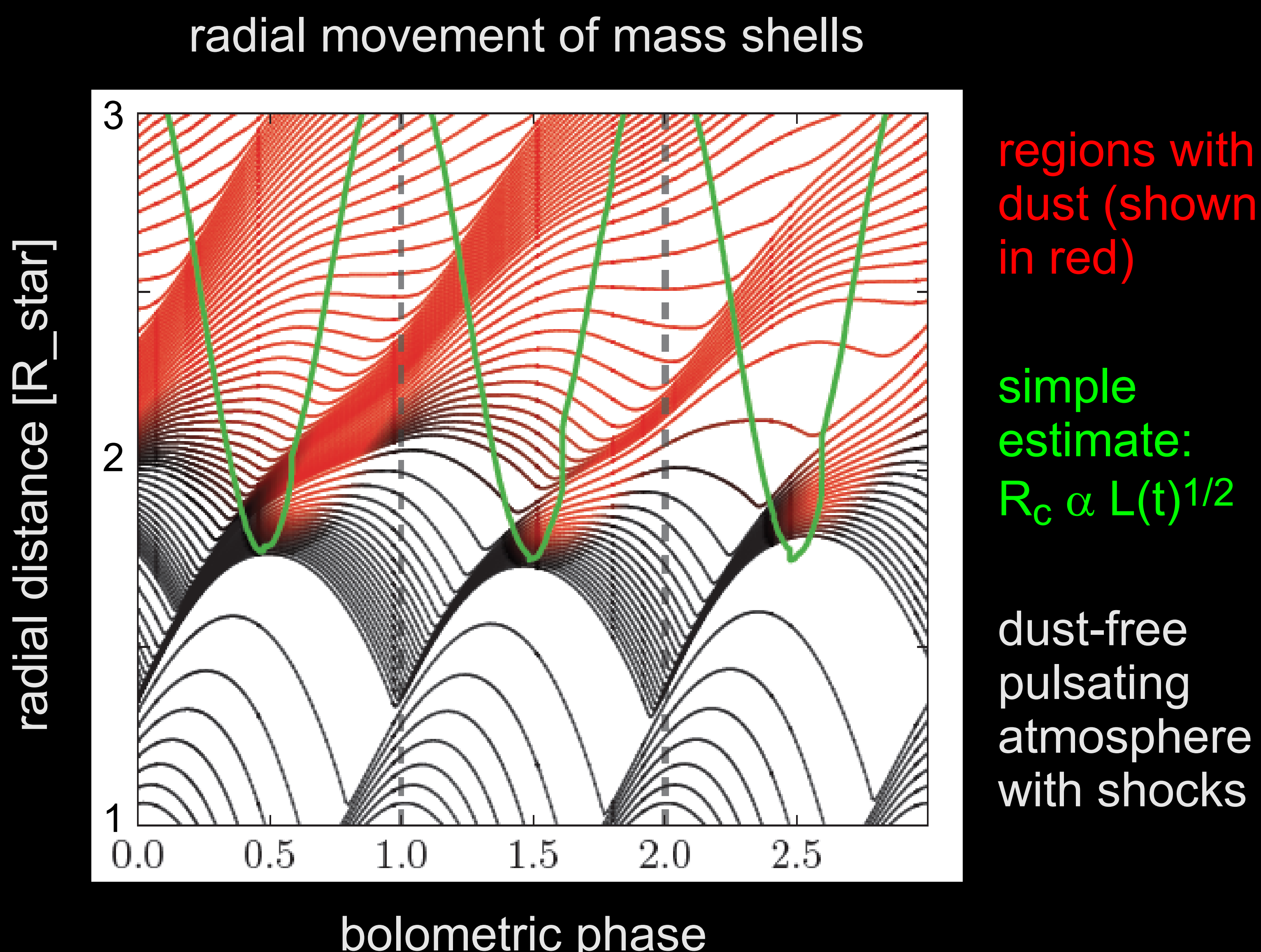


Effects of pulsation and large-scale convection enter wind models as boundary conditions

Small differences in luminosity variations (shape & phase relative to gas velocity and shocks) may have significant effects on dust formation and mass loss

Liljegren et al., in prep.

Variability and mass loss



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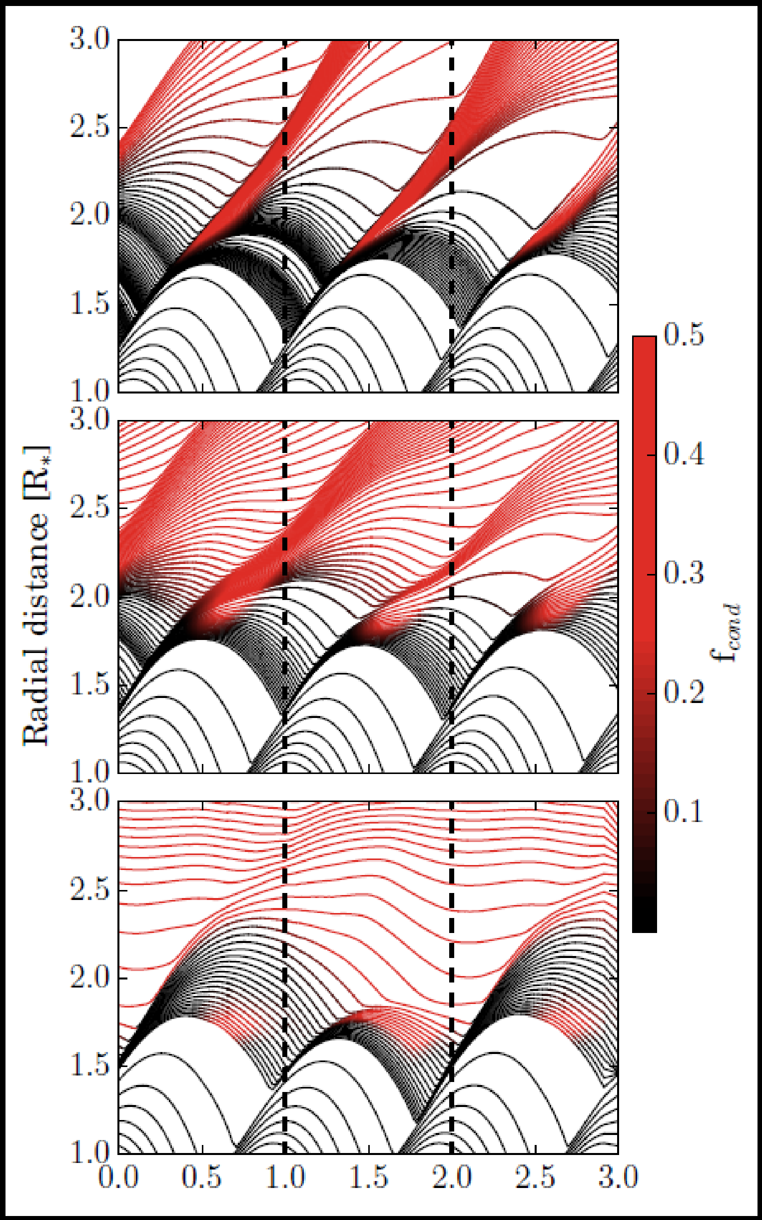

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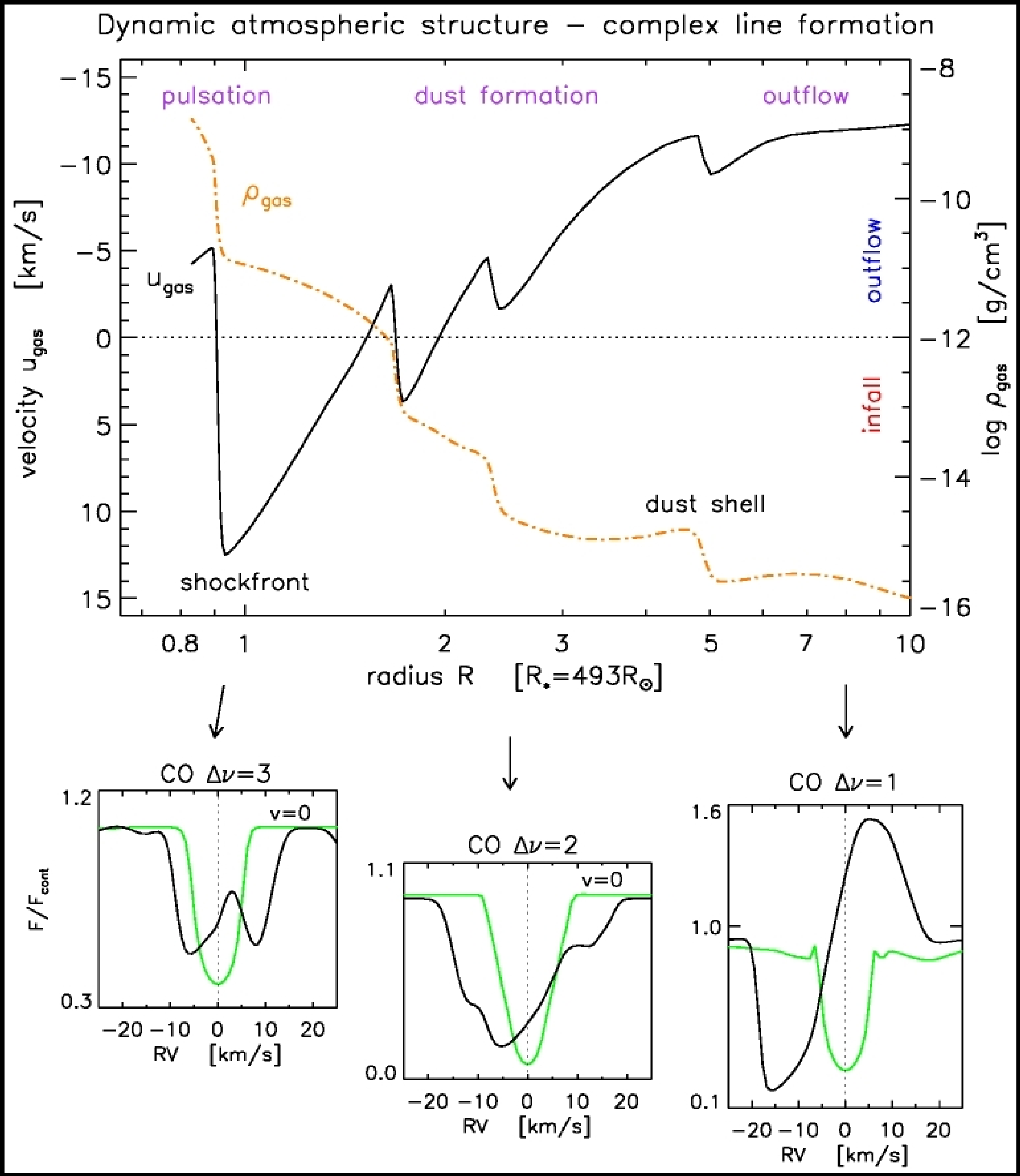
Dynamics of atmosphere & wind



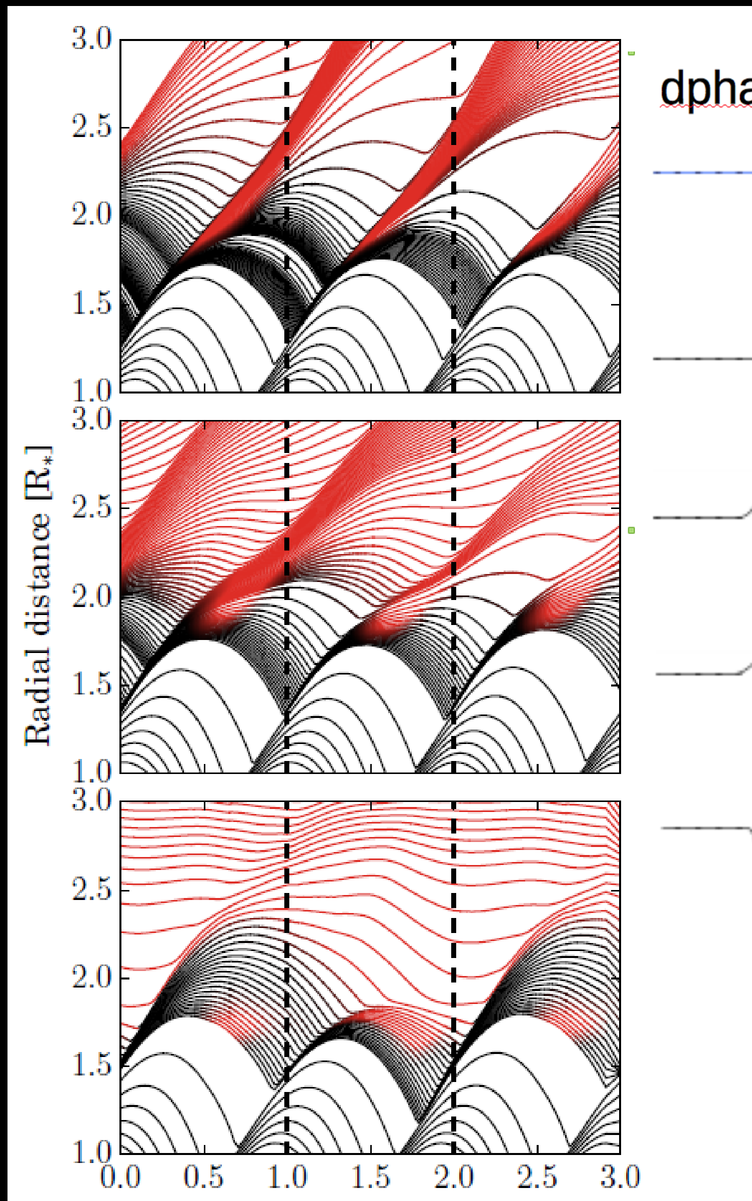
wind model for a pulsating carbon star

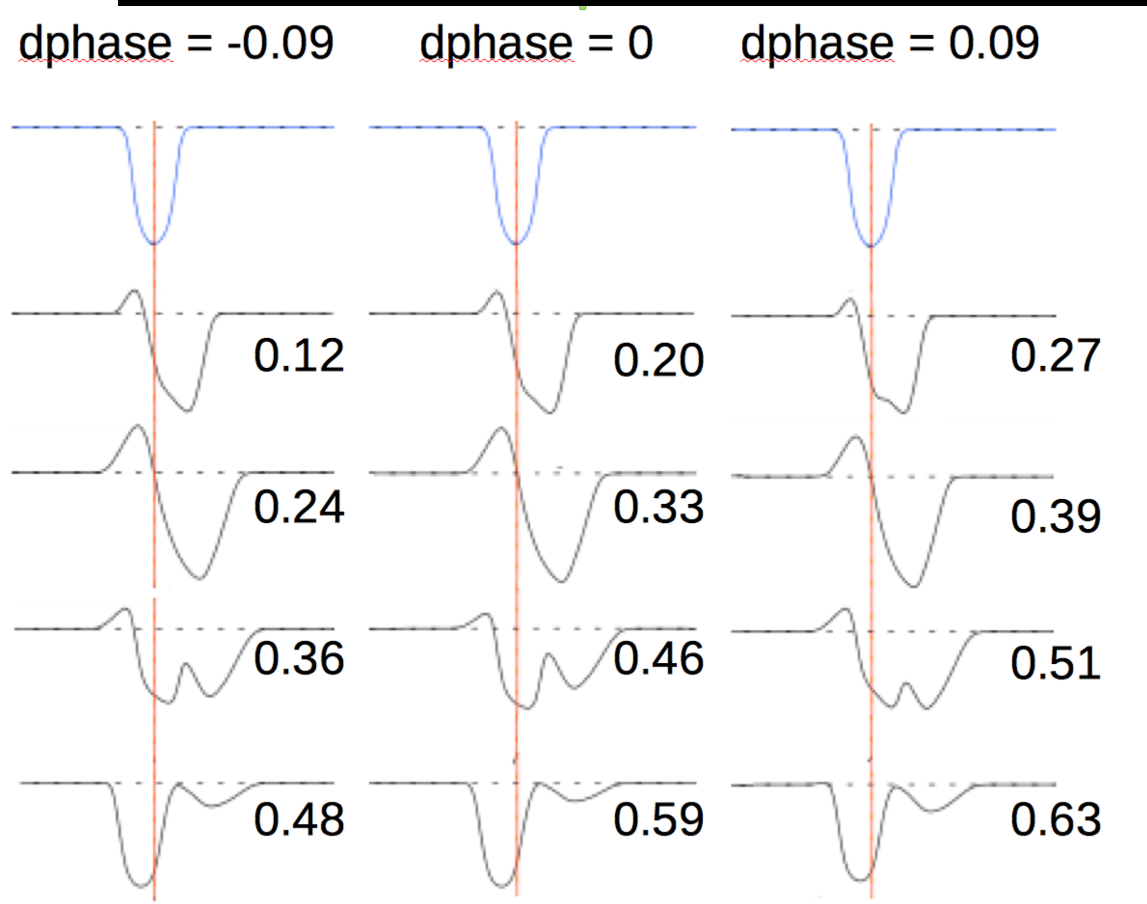
CO vibration-rotation lines in the NIR as probes of atmospheric and wind dynamics

Nowotny et al. (2005, 2010)

complex profiles of second overtone lines (leftmost panel)
due to shock waves passing through the line formation zone

Variability and mass loss



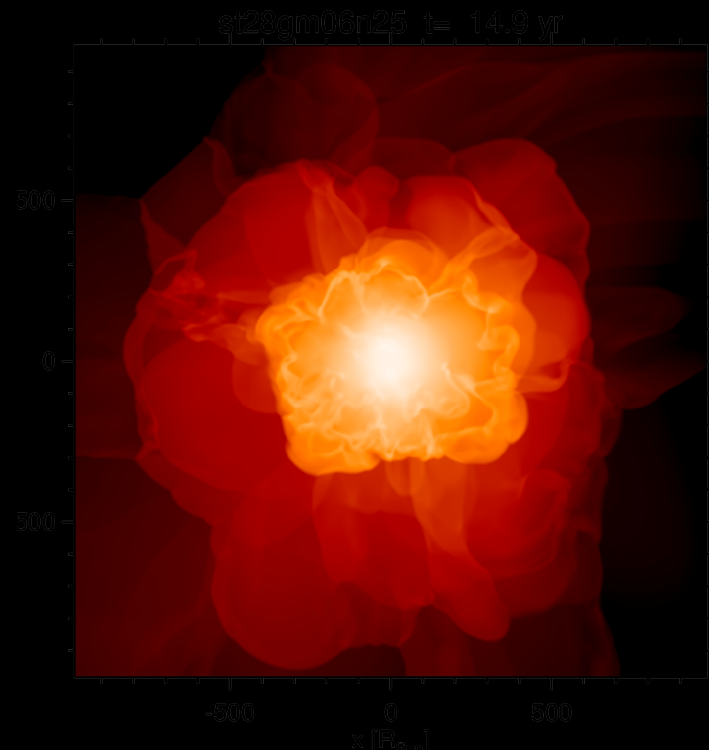


profiles of second overtone lines

Liljegren et al., in prep.

Pulsation, convection and shocks

Freytag & Höfner (2008)



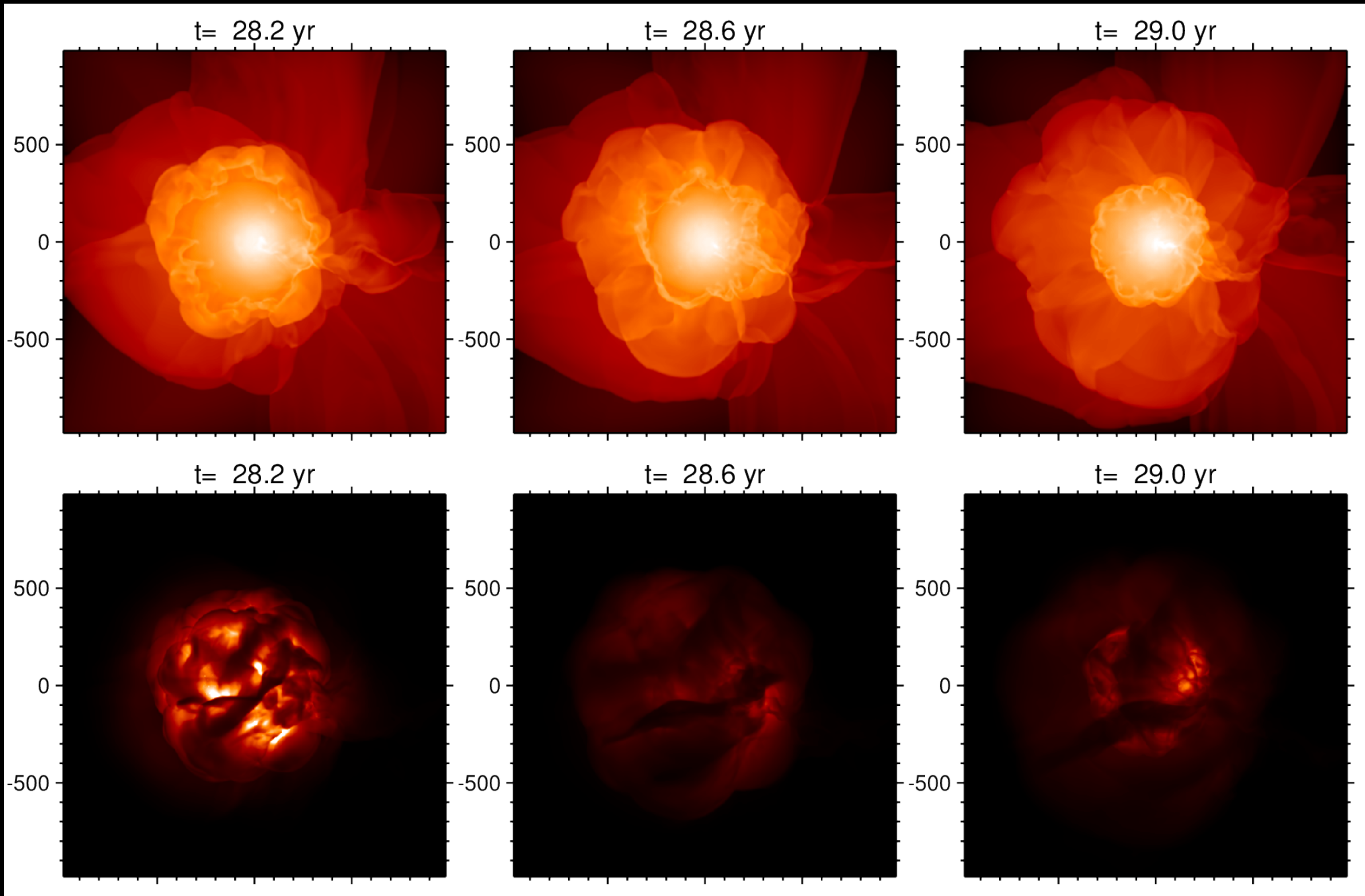
Freytag (2014)

3D star-in-a-box models

snapshots of the gas density (cut through the center of the box) showing giant convection cells and shocks

Work in progress: a small model grid with different stellar parameters

Pulsation, convection and shocks



Time sequences: gas density (top) and surface brightness (bottom)