(Abundances), Atmospheric Structure, and the Mass Loss Process in Miras

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AGB – major mass loss phase for low mass stars

AGB mass loss rates ~10^{-6} $M_{\odot}$ yr^{-1}.

White dwarf initial mass to final mass relation –

by end of Mira phase

>0.5 $M_{\odot}$ lost

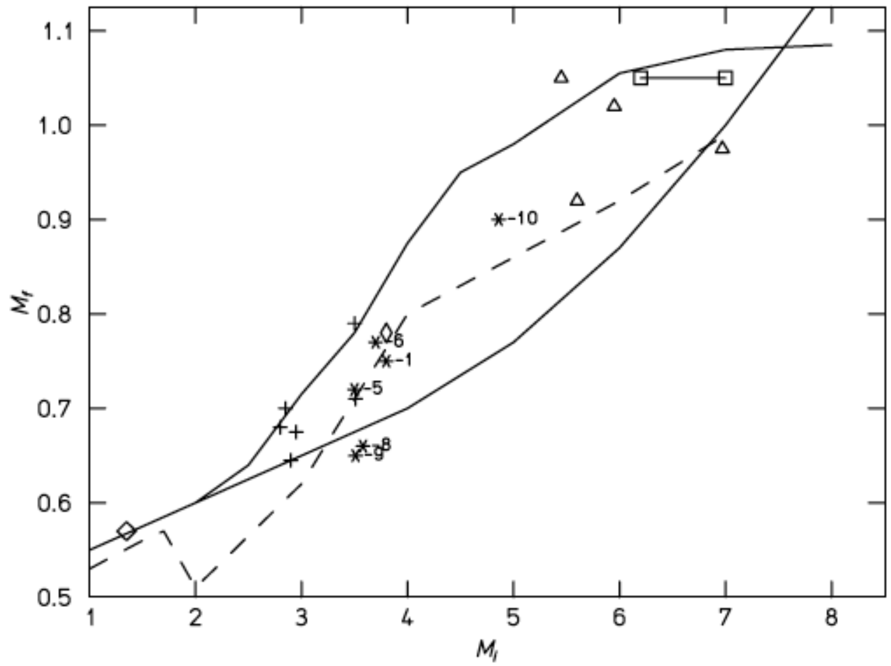


Fig. 2. Semi-empirical data for final masses, and M_i/M_f relations +: Hyades, ∗: NGC3532, rhombus: PG 0922+162A, triangles: NGC2516, squares: Pleiad, diamond: M67. Long dashed line: 1.TP relation of Herwig & Blöcker (priv. comm), full lines: semi-empirical M_i/M_f relations by Weidemann 1987 (below) and Herwig 1995 (above)

Weidemann 2000 AA 363 647

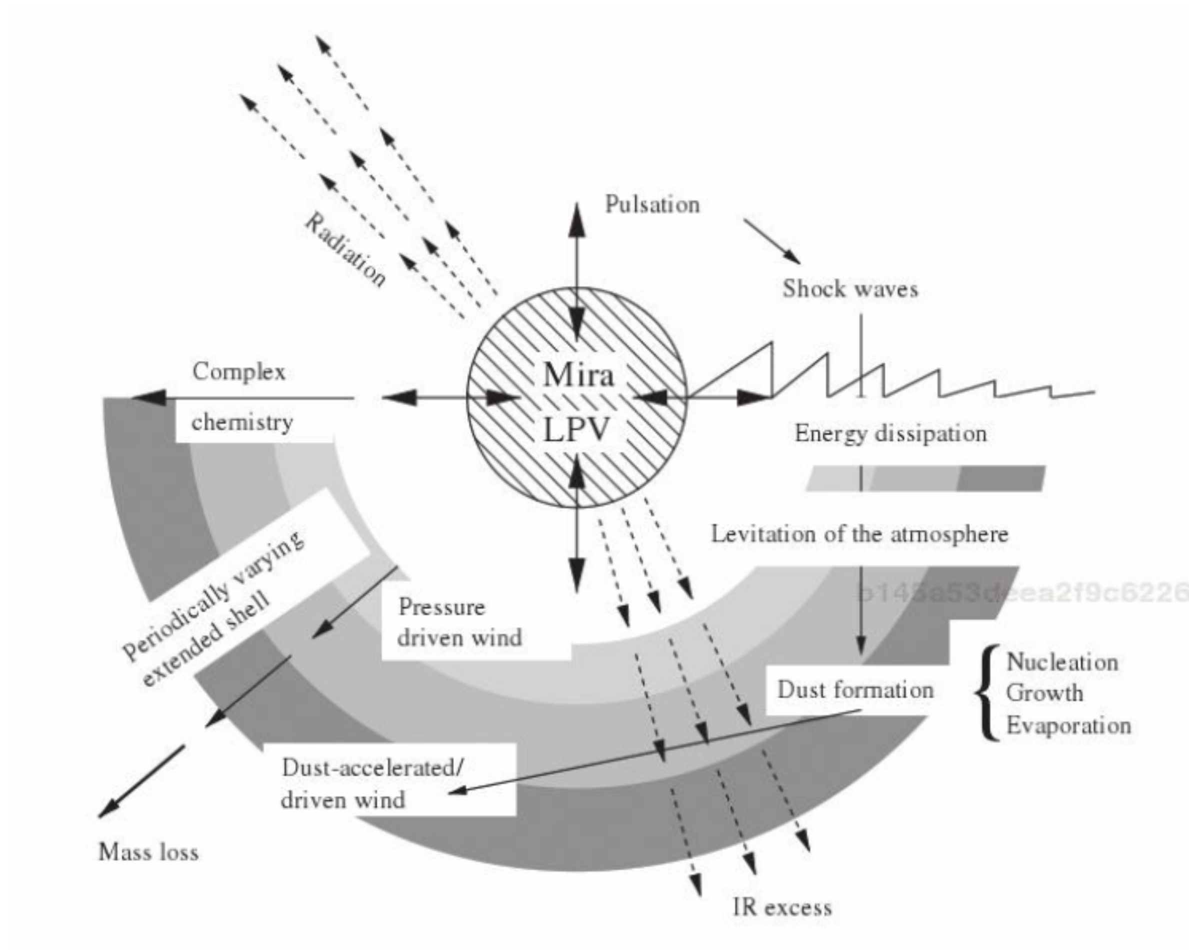
Table 3. Revised Initial-to-Final Mass Relation

M_i	1	2	2.5	3	4	5	6	7
M_f	0.55	0.60	0.63	0.68	0.80	0.88	0.95	1.02

What is the mass loss mechanism?

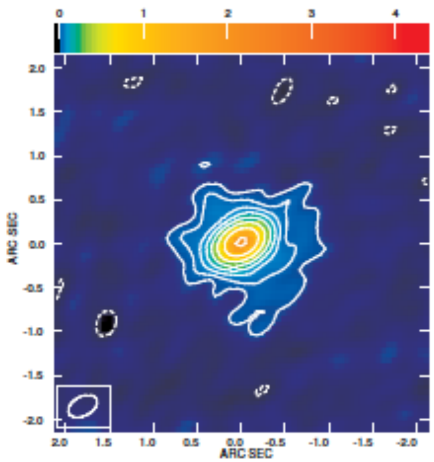
Text book model of Mira extended atmosphere

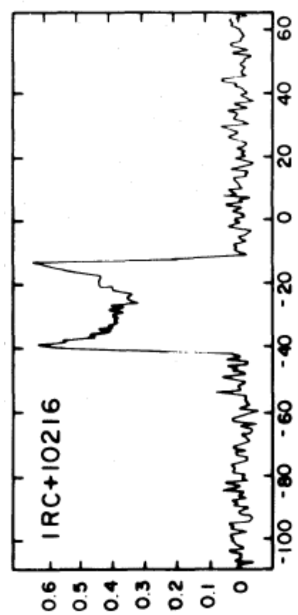
Clear overall picture but many details remain unkown

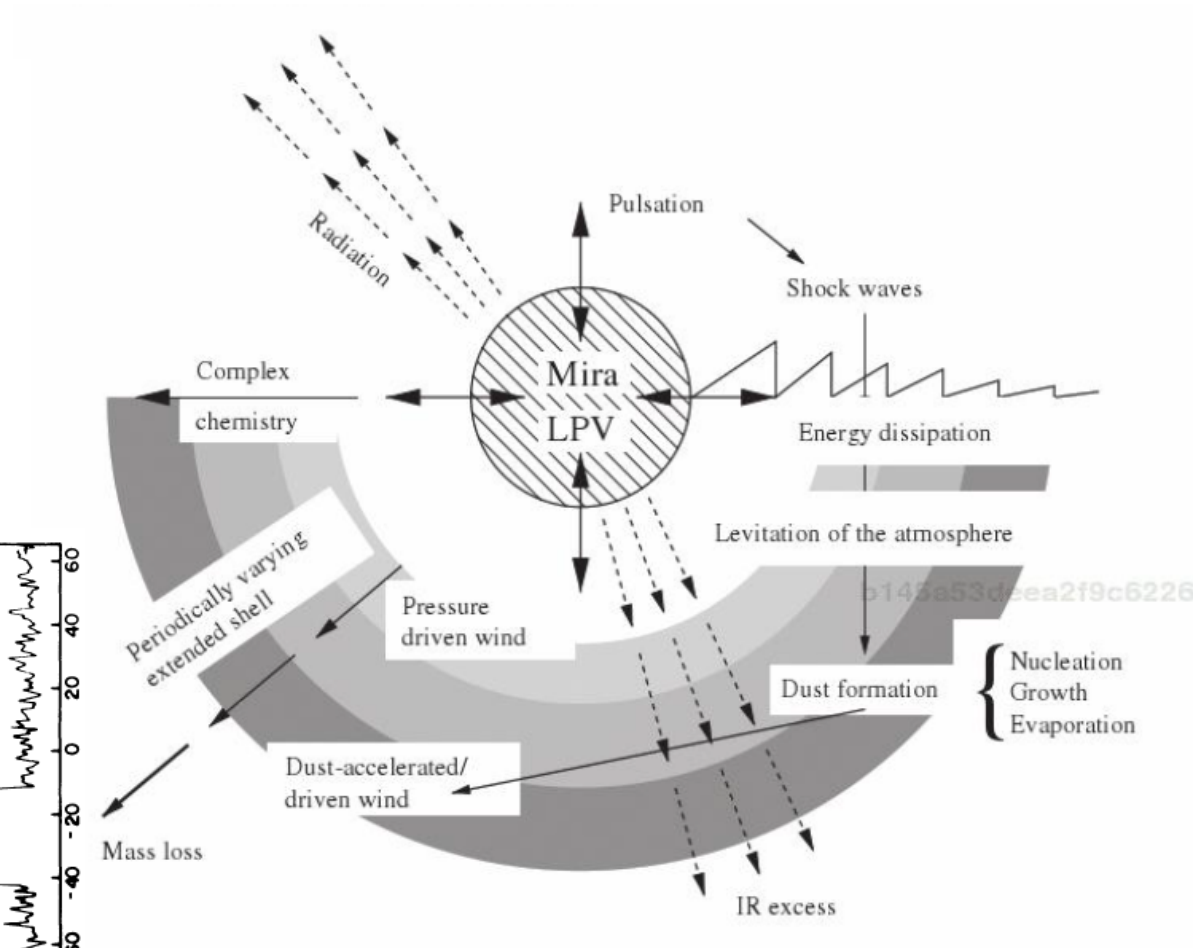


Gail & Sedlmayr 2014,'Physics and Chemisty of Circumstellar Dust Shells, (Cambridge Univ. Press), Chapter 16.

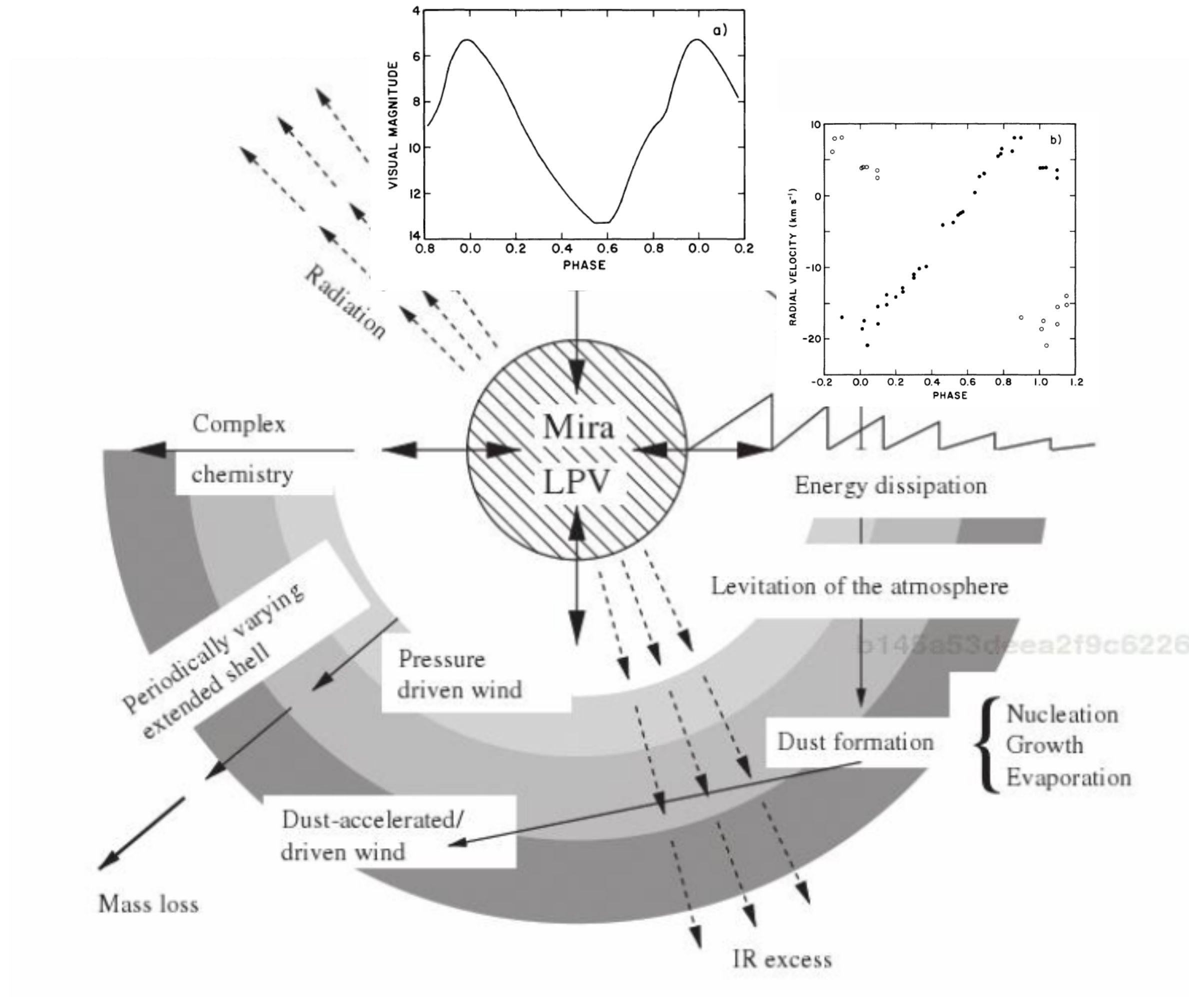
Expanding Circumstellar Shell



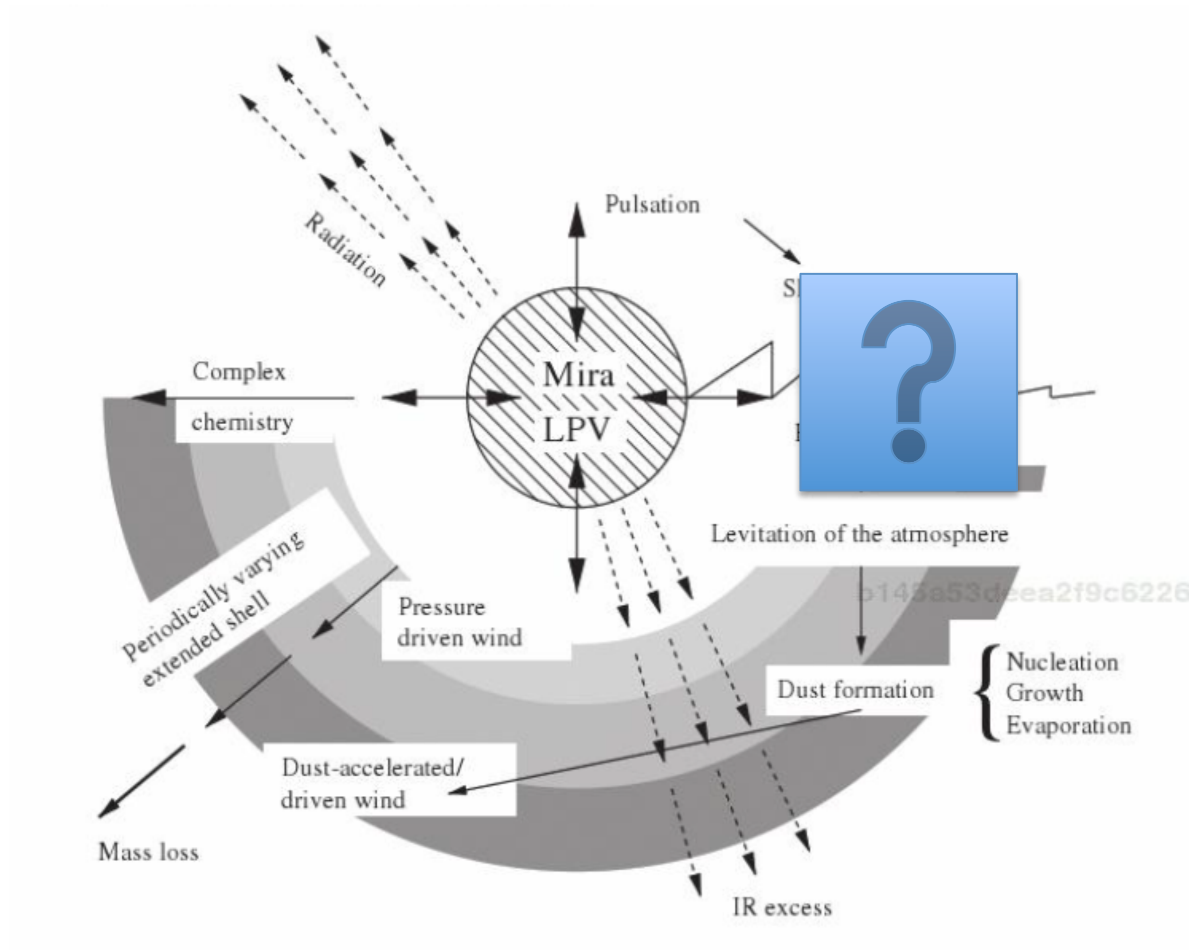




Stellar Pulsation



Photospheric – Circumstellar connection



How do we explore the inner-circumstellar/ extended photospheric region?

- Masers – Images, especially SiO
- Interferometry – near-IR/radio sizes and images
- IR Spectroscopy

Low excitation 2-0 CO lines and H_2O lines in Miras are asymmetric

Tsuji named the region probed by these lines the "MOLsphere" (ApJ 540 L99)

Tsuji's work limited to non-variable stars

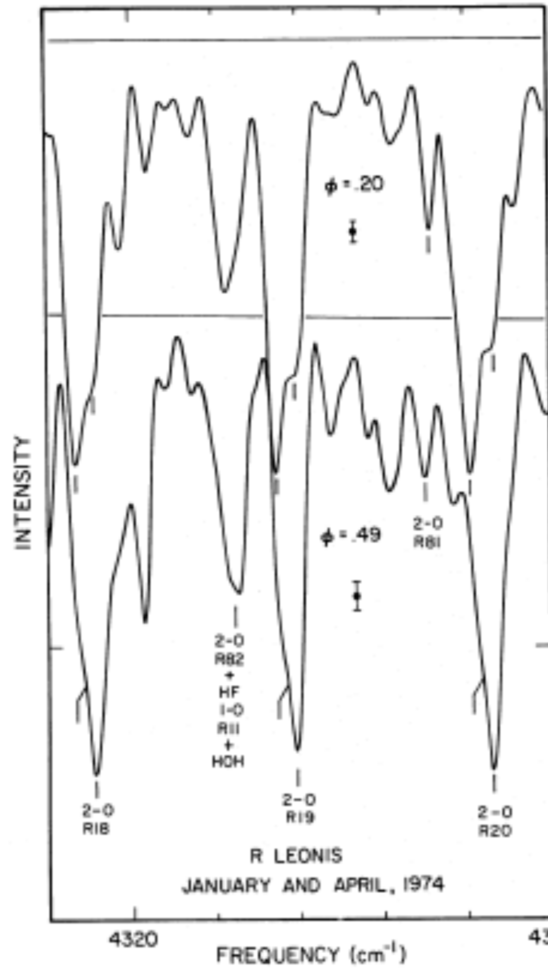


FIG. 9.—The spectrum of R Leo from 4319 to 4325 cm^{-1} at two postmaximum phases. The ordinate, continuum, and error bars are as in Fig. 2. The deepest part of the $^{12}C^{16}O$ 2–0 *R*(18), *R*(19), and *R*(20) lines are not at the same velocity as the high-excitation lines, represented here by 2–0 *R*(81). Only a few very weak telluric features are present in this origin.

Hinkle 1978, ApJ, 220, 210

A long time series of Infrared observations of the S-type Mira χ Cyg suggested a quasi-stationary MOLsphere

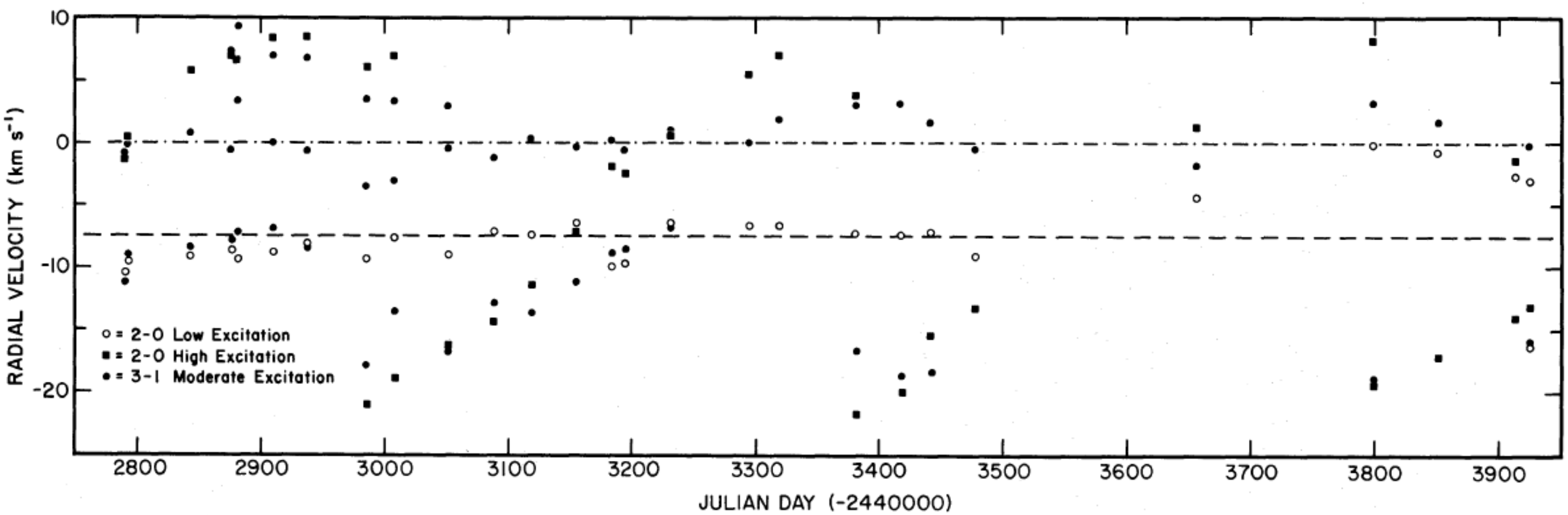


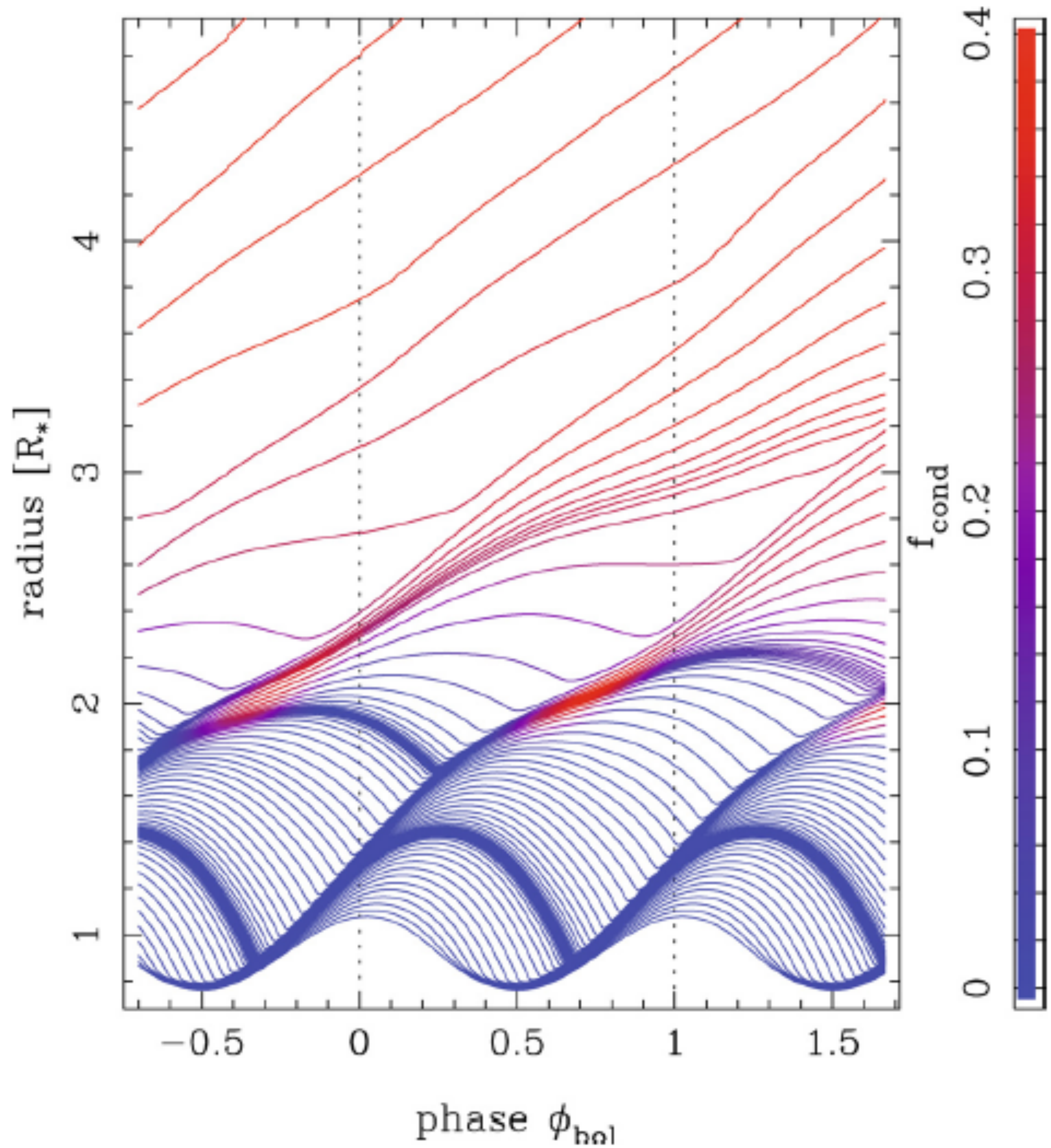
FIG. 14.—CO first overtone velocities for three different groups of lines plotted as a function of JD number. *Dashed line*: center of mass velocity (Dickinson *et al.* 1978). *Dot-dashed line*: mean visual region "photospheric" velocity given by Wallerstein (1975).

Filled symbols = photosphere, open symbols = MOLsphere

Hinkle et al. 1982, ApJ, 252, 697

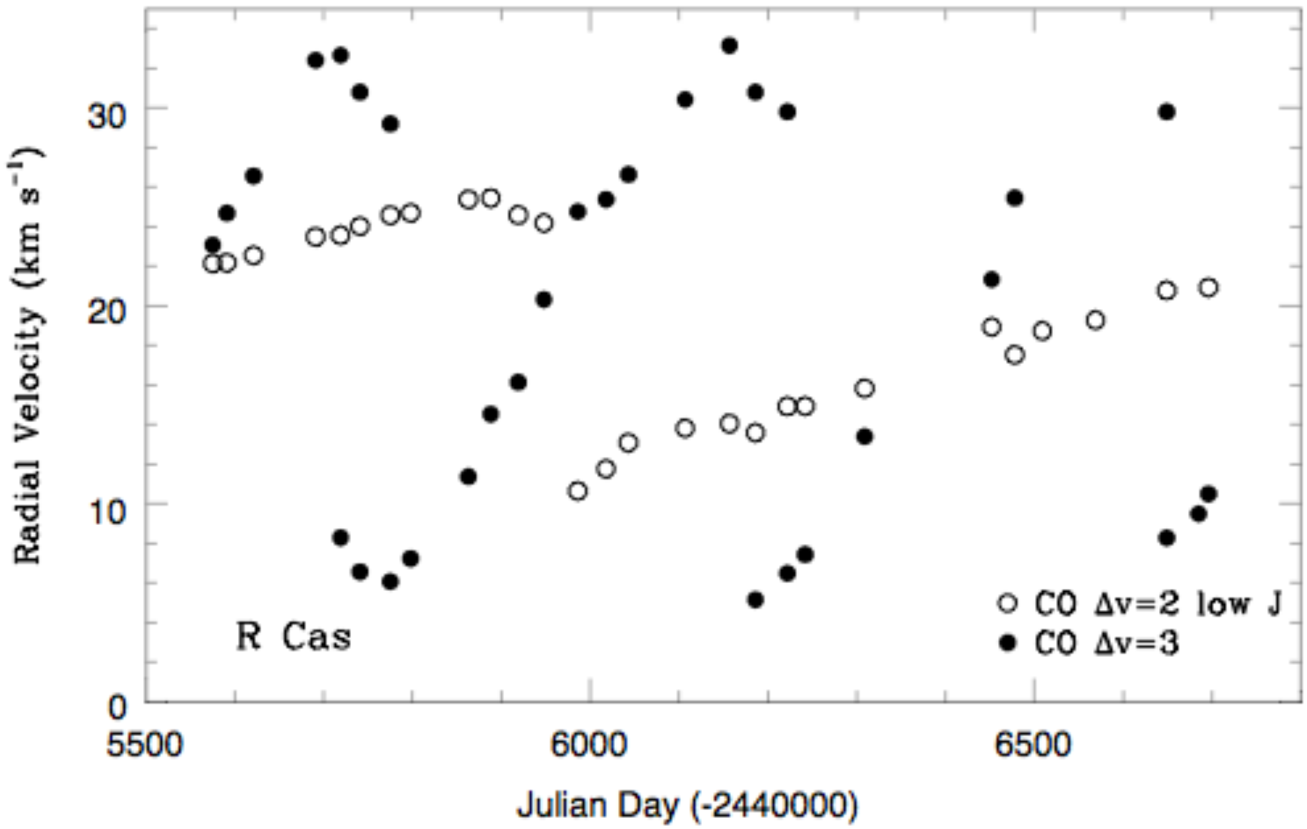
Stellar pulsation models

Stationary MOLsphere is at many R_*



Nowotny, Höfner, & Aringer 2010, AA, 514 A35

3 year velocity time series for the Mira R Cas



Moving MOLsphere Period ≠ pulsation period

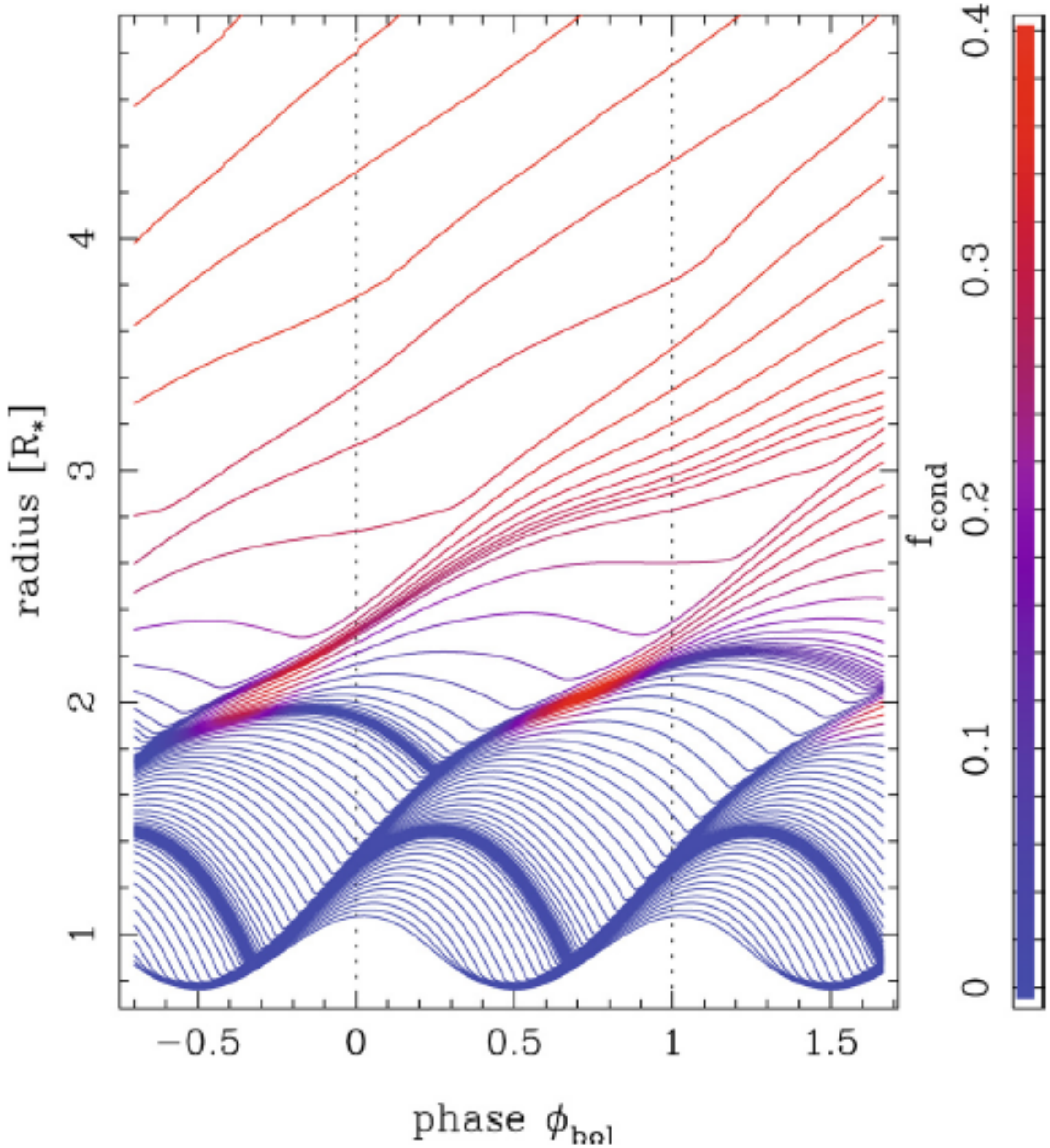
Optical period = 430 days,
solid symbol = photosphere
open symbol=MOLsphere

Radius changes due to pulsation

High excitation lines – periodic velocity changes, 1 R_*

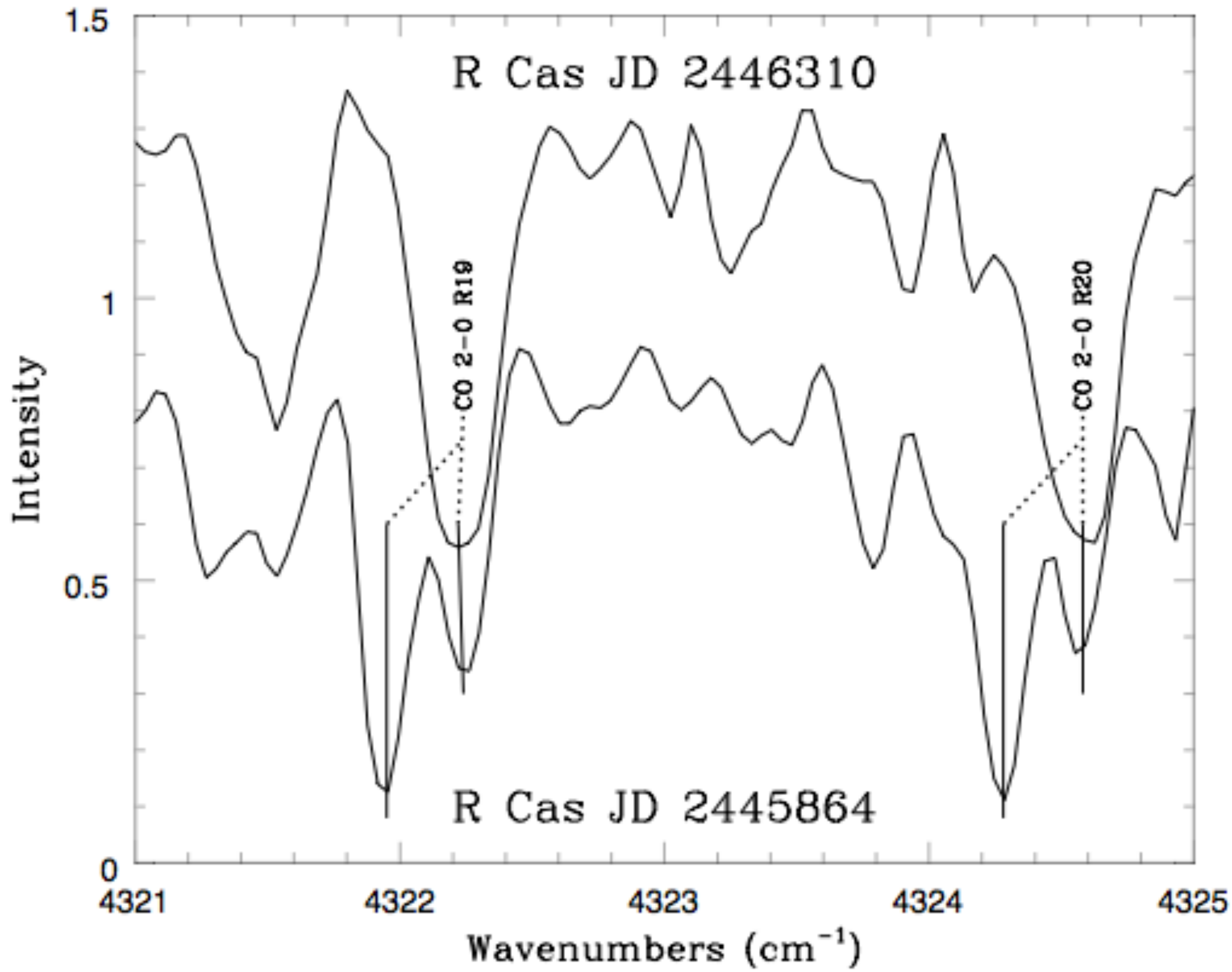
Low excitation lines – aperiodic, >2 R_*

Nowotny, Höfner, & Aringer 2010, AA, 514 A35



Low excitation line profile change with time

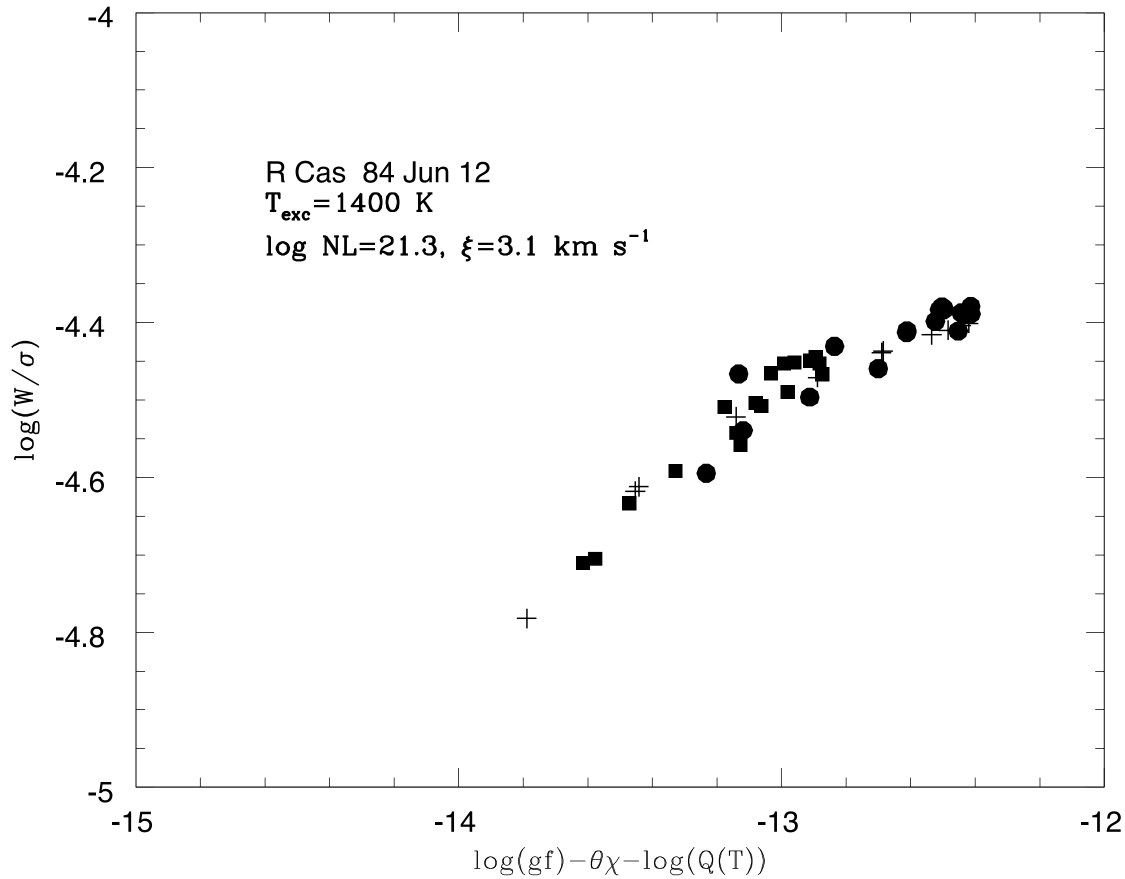
Lines usually blended but occasionally separated—
allows measurement of MOLsphere lines



Curve of Growth Analysis

Empirical determination of temperature

+ = plane parallel model



1000 K gas = 2 – 3 R_*

Models – Gas temperature and dust condensation vs radius

➔CO observed would be at about 2 R_*

➔Dust condensation at about 3 R*

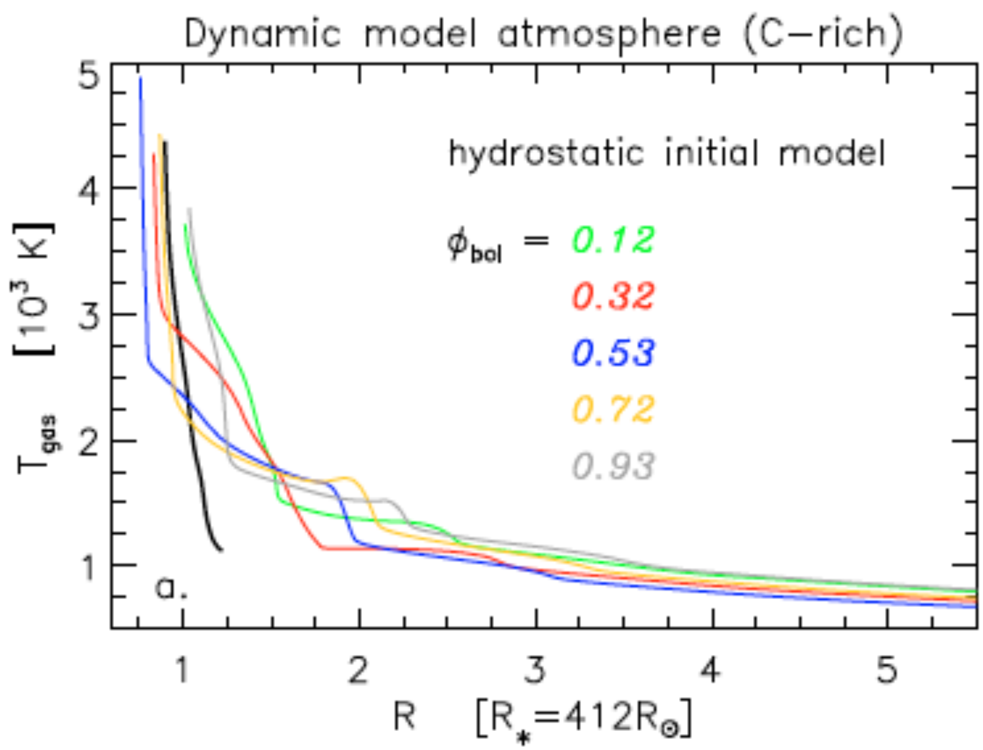
(Nowotny et al. 2010, Reid & Menten 1997, ApJ, 476 327)

Interferometry - radius of the cool molecular layer

➔ **2.2 R_***

FLOUR/IOTA 2.2 µm observations

(Perrin et al. 2004 AA 426 279)

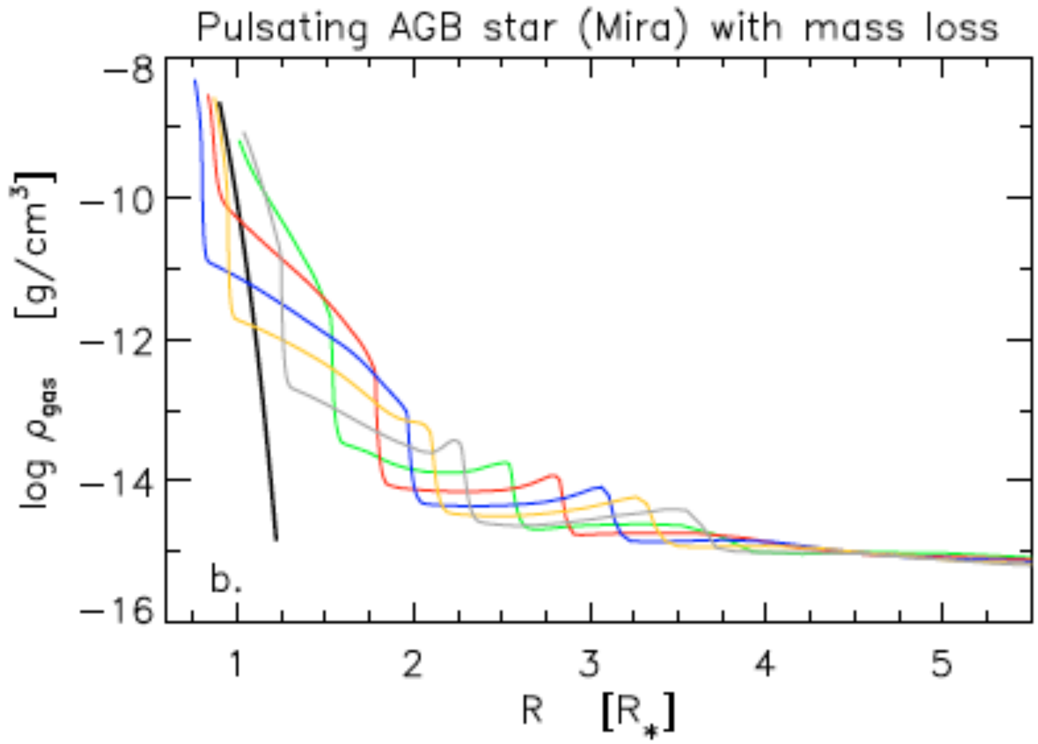


Mass of the shell

- Curve of growth well fit by plane-parallel model – suggests thin layer
- Assuming:
  - $R_{shell} = 2R_{mira}$
  - R_{mira}=400 $R_{\odot}$
  - Spherical symmetry
  - Solar abundances
- $M_{shell} = 3 \times 10^{-5}\ M_{\odot}$

Models provide density

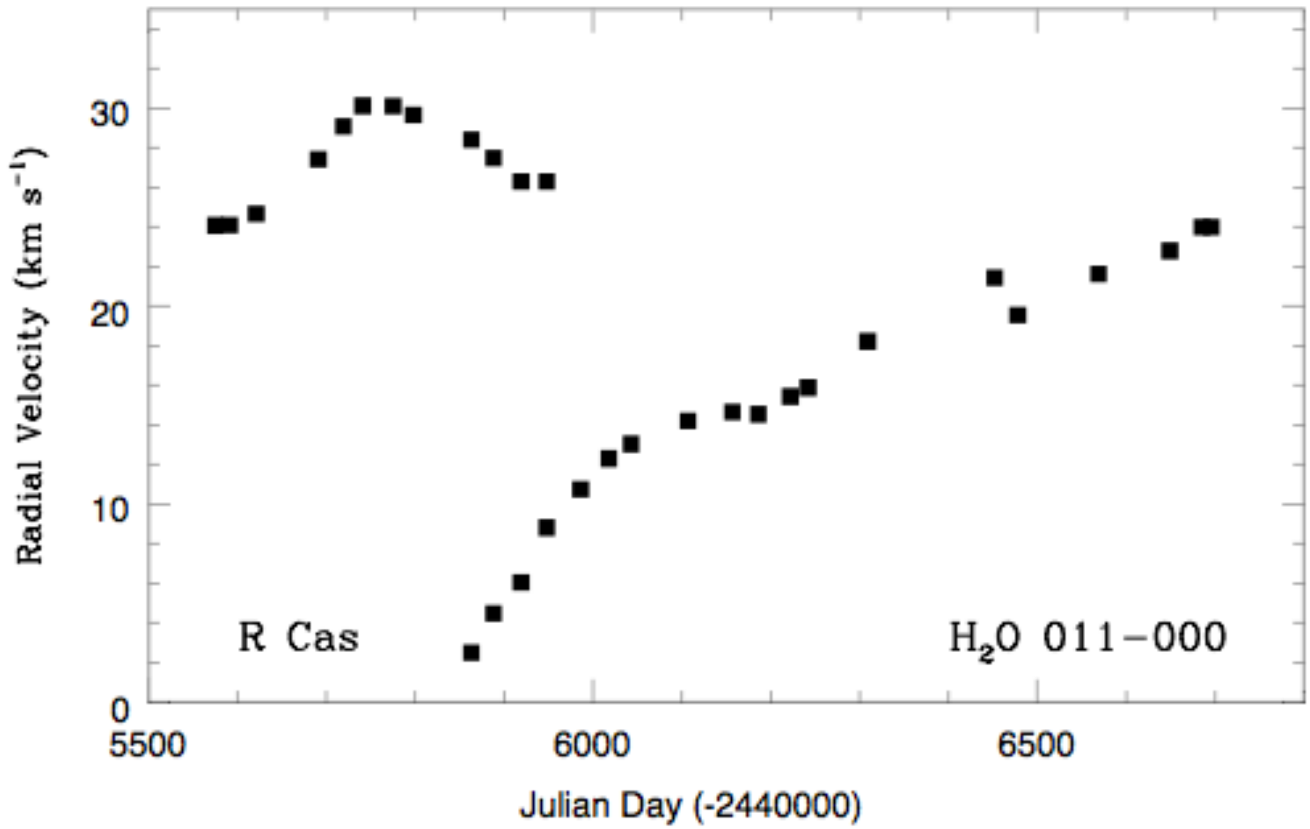
Nowotny et al. (2010)



Assuming $\rho = 10^{-13}$ g cm^{-2} at 2 R$_*$, log NL(CO) =21.3 results in a shell >1000R$_\odot$ thick.

The thinner shell suggested by the observations requires density 10 – 100 x lower.

H_2O lines present



Similar velocity changes to CO but not identical

Probes velocity structure

1000 K – gas consists largely of CO and H_2O -- abundances

Mira MOLsphere

- Temperature ~ 1000 - 1400 K
- Density ~10^{-15} g/cm^3
- Models suggest radius 2-4 R_*, atmosphere extended by stellar pulsation
- Dust condensation zone
- Interferometry suggests radius 2 R_*
- MOLsphere mass ~ 10^{-5} M
- Time variable – episodic mass loss

Rich photospheric spectrum in the IR

Isotopic lines:

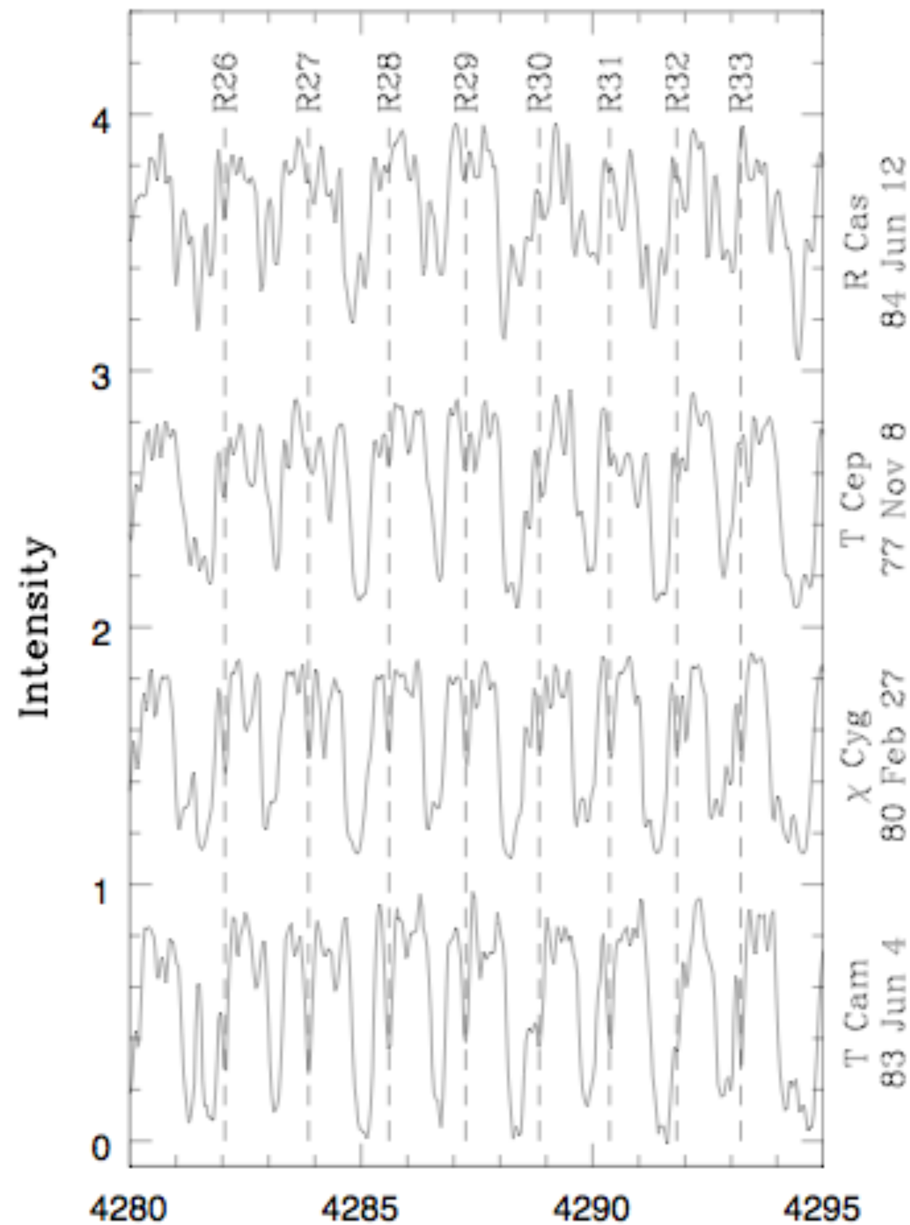
^{12}CO

^{13}CO

$C^{16}O$

$C^{17}O$

$C^{18}O$



Surface isotopic ratios altered by dredge-ups

2^{nd} and 3^{rd} dredge-ups depend on mass

	1^{st} dup	RGB extra-mixing	2^{nd} dup	3^{rd} dup	HBB
$^{12}C/^{13}C$	⬇	⬇	⇩	⬆	⬇
$^{16}O/^{17}O$	⬇	⇩	⇩		⇩
$^{16}O/^{18}O$	⬆	⇧	⇧		⬆

1^{st} dredge-up on RGB. CNO cycle material mixed to surface results in large changes in isotopic ratios.

2^{nd} dredge-up takes place for stars of mass > 4 $M_{\odot}$ during the early AGB.

3^{rd} dredge-up during late AGB. Products of He burning mixed to surface.

- More mixing for stars undergoing strong thermal pulses.
- Low mass stars do not experience strong thermal pulses.
- Thermal pulses are also weaker in the most massive AGB stars
- Hot Bottom burning occurs for massive AGB stars

Straniero et al. 2006 Nuclear Physics A, 777, 311

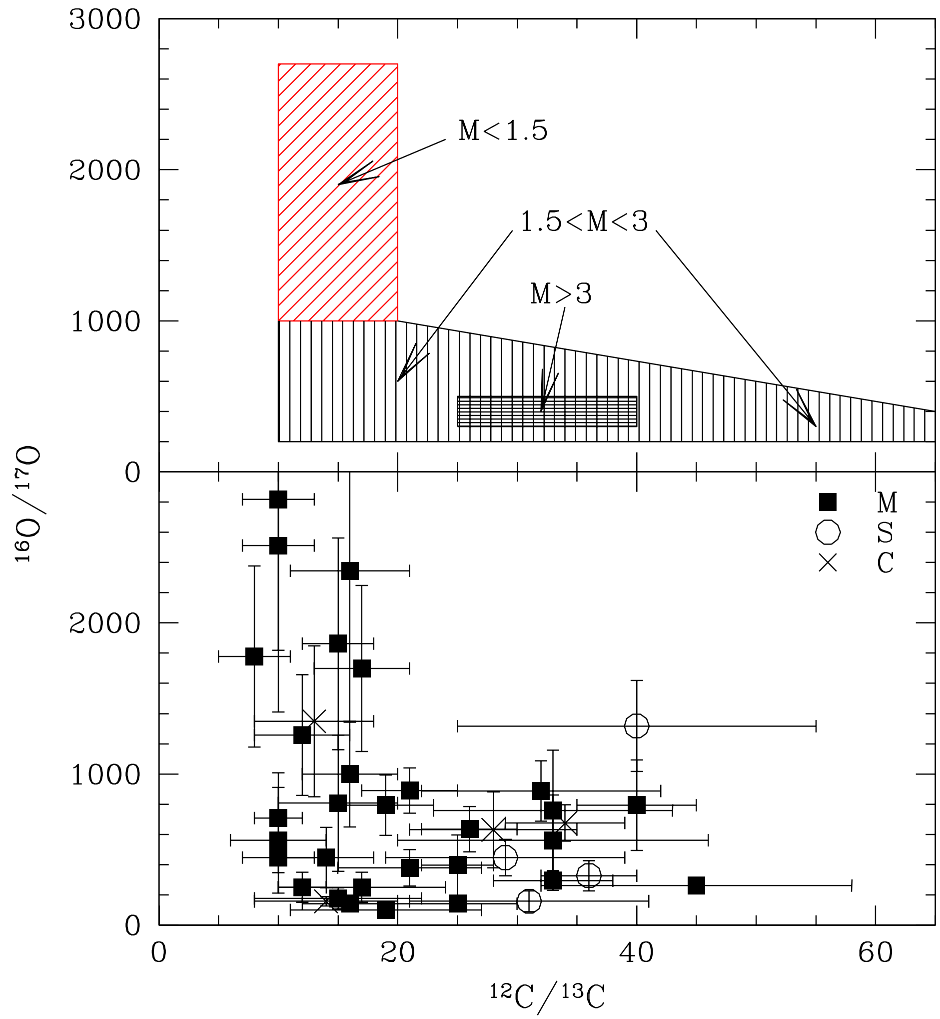
$^{12}C/^{13}C$ and $^{16}O/^{17}O$ depend on initial mass

Model predictions for solar composition are in top panel

Measured parameters are in bottom panel. Note symbols for different classes of AGB stars.

M stars with large $^{16}O/^{17}O$ have not experienced 3rd dredge-up and have masses below 1.5 $M_{\odot}$.

The sample was limited to bright Miras mostly picked randomly from the field so is dominated by oxygen rich (M-type) Miras.



Presolar silicon carbide dust grain - AGB star material in the lab

- Grains are isolated from matrix material of meteorites.
- Near-all oxygen rich grains originate in AGB star winds.
- Abundances can be derived from the grains.
- Time Capsule

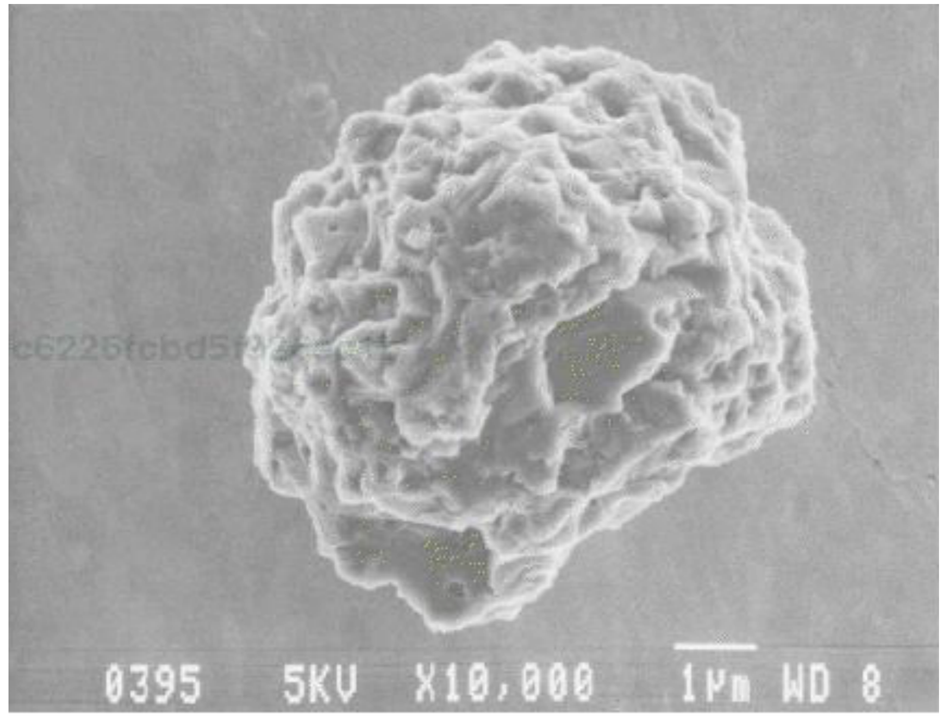


Image: Gail and Sedlmayer, Physics and Chemistry of Circumstellar Dust Shells 2013

Mira and grain isotopic abundances

Filled circles = Miras

Open squares = grains

Shift to right results from increasing ^{17}O and ^{18}O abundances due to galactic chemical evolution (GCE) over the last 4 Gyr.

AGB star abundances are predicted to populate the central dense region.

The large spread in the Mira values in the $^{18}O/^{16}O$ axis results from difficulties in measuring the ^{18}O and in an increasing spread of initial ^{18}O abundances due to GCE.