LESSON 4

DUST-DRIVEN WINDS OF COOL STARS

- DUST TEMPERATURE
- RADIATION PRESSURE ON DUST
- MOMENTUM EQUATION
- THE ROLE OF PULSATION

TWO KINDS OF DUST : O-RICH , C-RICH

		EMISSION BANDS
• SILICATE (O-RICH)	SiO , SiO_2 , ...	9.7 μm , 20 μm
• GRAPHITE (C-RICH)	 $C-C-C-$ with H , PAH	3.3 μm , 11.3 μm
AMORPHOUS CARBON (C-RICH)		3.·· μm

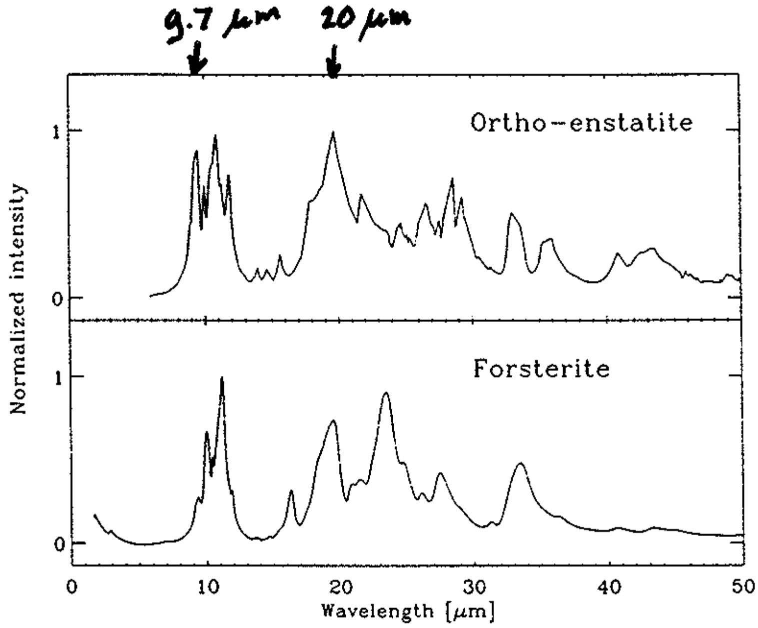
O > C ALL C is IN CO

REMAINING O → SILICATE DUST

C > O ALL O IS IN CO

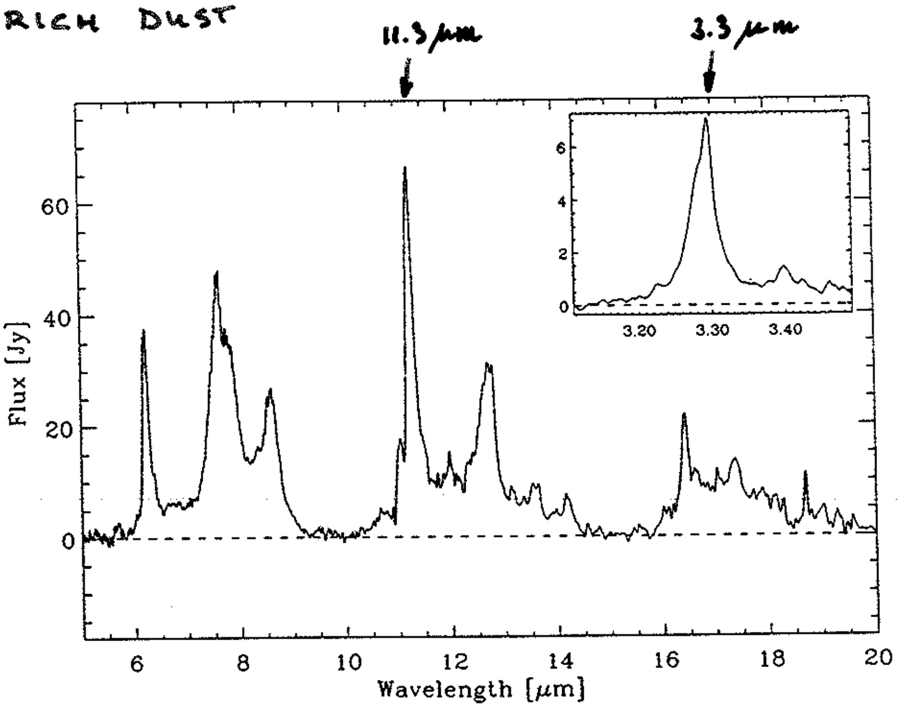
REMAINING C → CARBON DUST

O-RICH DUST



LABORATORY SPECTRA

C-RICH DUST



PAH = POLYCYCLIC AROMATIC HYDROCARBON
IN STAR CD-42° 11721

ROBERT VOORS
THESIS 1999

ISO SPECTRUM OF B[e] STAR HD 45677

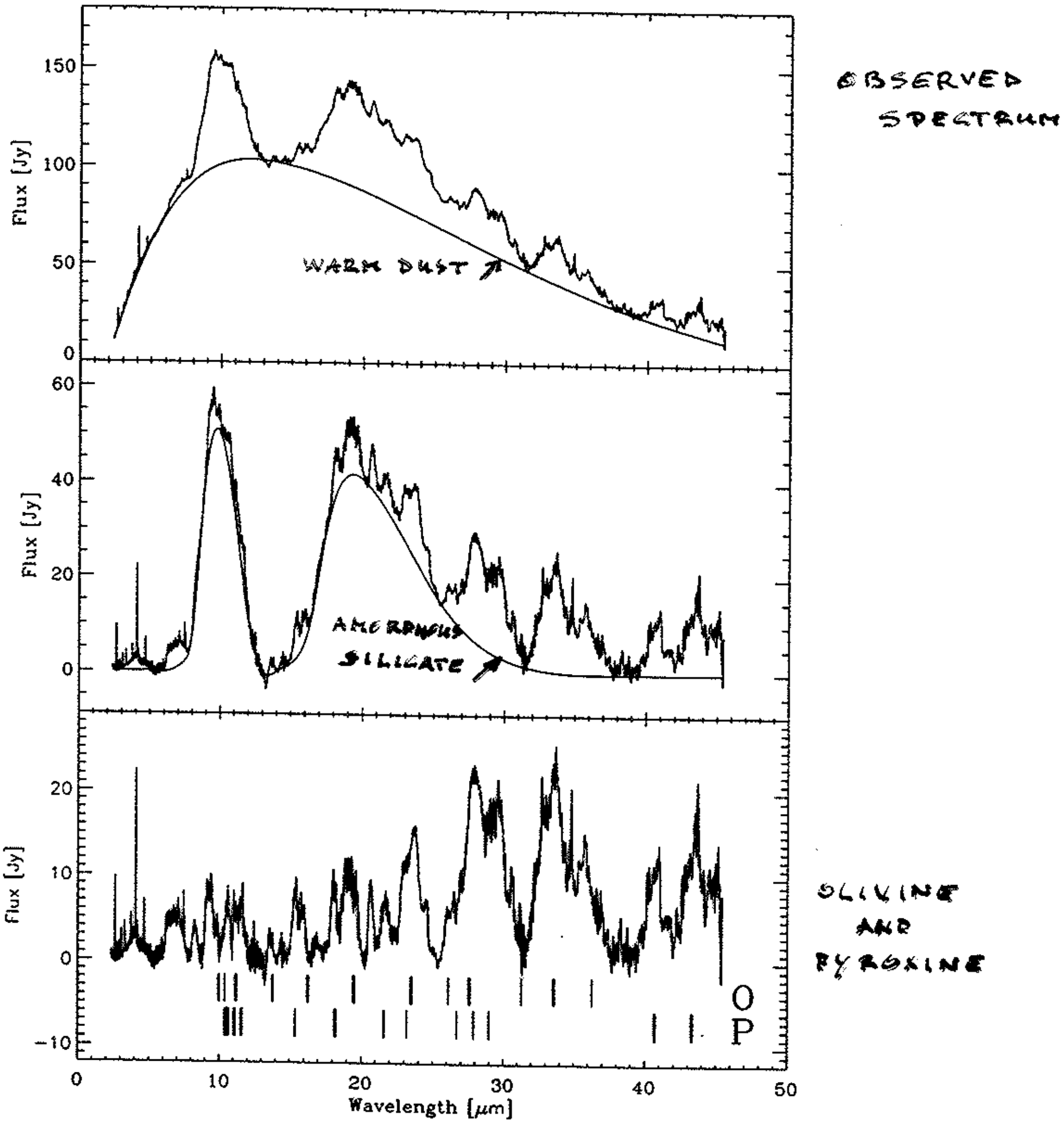


Figure 6.20: *The SWS spectrum of HD 45677. The upper panel shows the SWS spectrum with the smooth underlying continuum. The middle panel shows the SWS spectrum with the smooth continuum subtracted and the contribution of the amorphous components. The lower panel shows the SWS spectrum with both components subtracted. Indicated are the identifications of the strongest olivine (O) and pyroxene (P) bands. Thick tick marks indicate strong bands in the laboratory spectra of Jäger et al. (1998) and Koike & Shibai (1998).*

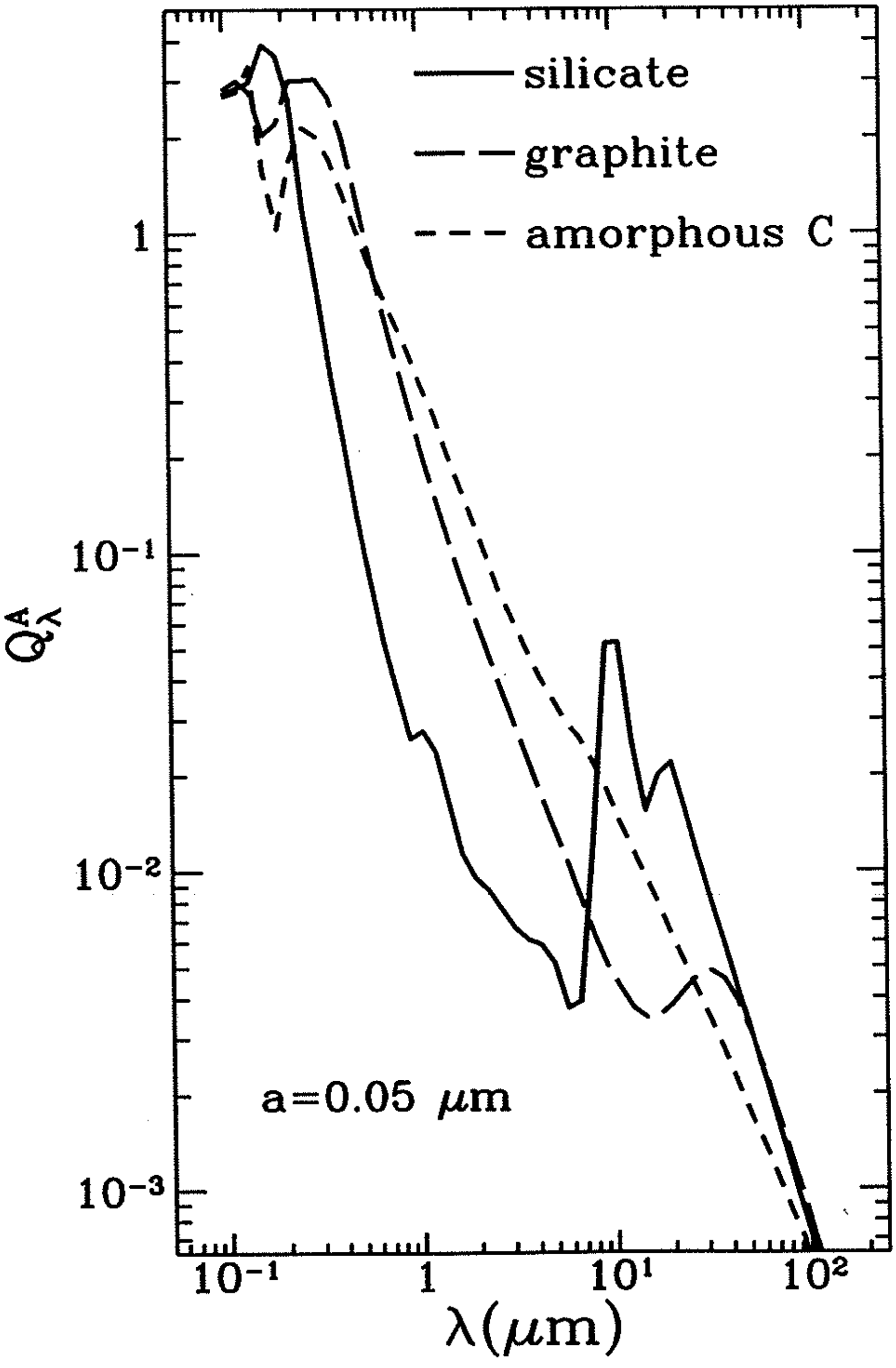
OPACITIES + CROSS-SECTIONS + EFFICIENCIES

$$\kappa_\lambda \, (\mathrm{cm}^2/\mathrm{cm}^3) = n_d \times Q^A_\lambda \cdot \pi a^2$$

$$\sigma_\lambda \, (\mathrm{cm}^2/\mathrm{cm}^3) = n_d \times Q^S_\lambda \cdot \pi a^2$$

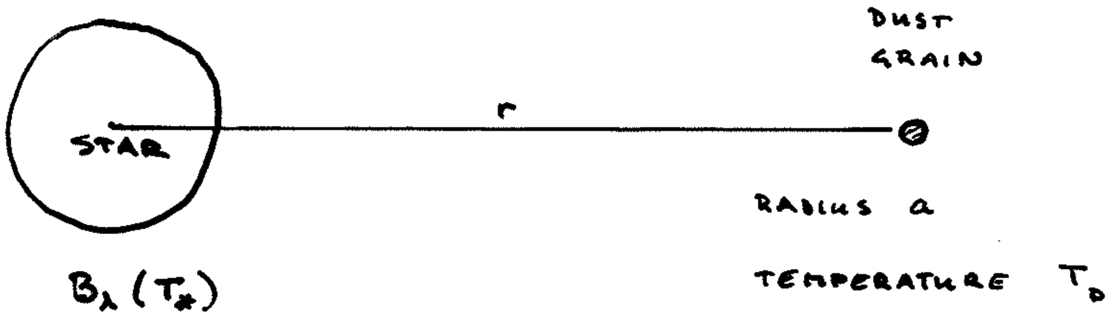
$$\kappa_\lambda + \sigma_\lambda = n_d \left(Q^S_\lambda + Q^A_\lambda \right) \pi a^2 = Q^T_\lambda \, \pi a^2$$

Q DEPENDS ON λ AND ON SIZE OF DUSTGRAINS



THE TEMPERATURE OF DUST GRAINS

$$L_* = 4\pi R_*^2 \sigma T_*^4$$



ABSORBED ENERGY:

$$\frac{L_*}{4\pi r^2} \times \pi a^2 = \frac{\text{FLUX}}{\text{cm}^2} \times \text{CROSS-SECTION}$$

EMITTED ENERGY

$$4\pi a^2 \times \sigma T_D^4 = \text{SURFACE} \times \text{EMISSION PER cm}^2$$

EQUILIBRIUM DUST TEMPERATURE

$$\frac{4\pi R_*^2 \sigma T_*^4}{4\pi r^2} \times \pi a^2 = 4\pi a^2 \times \sigma T_D^4$$

$$T_D^4 = \frac{1}{4} \frac{R_*^2}{r^2} T_*^4$$

$$T_D(r) \approx \sqrt{\frac{R_*}{2r}} \cdot T_*$$

IF YOU TAKE INTO ACCOUNT : $K(\lambda)$ THEN

$$T_D(r) \simeq \left(\frac{R_*}{2r}\right)^{2/5} \cdot T_*$$

WHERE DOES DUST FORM ?

DUST CAN EXIST WHERE $T_d < T_{CONDENSATION}$

$$T_{COND} \simeq 1500\ K$$

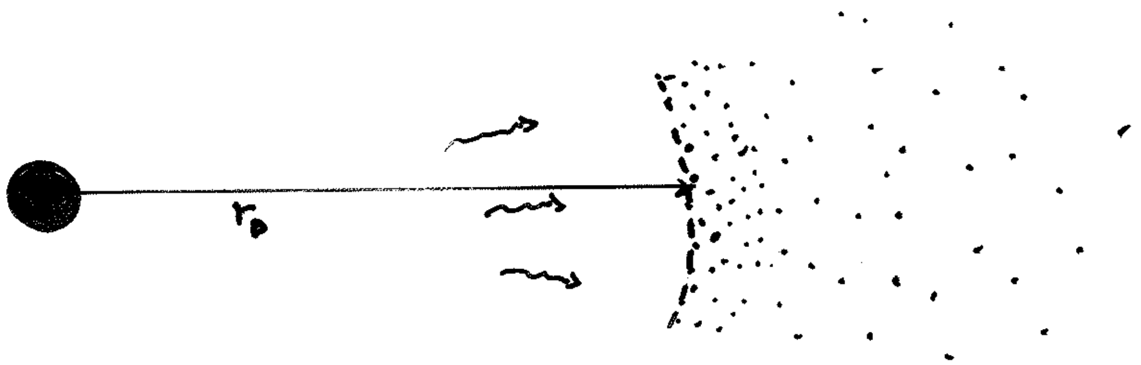
$$\left.\begin{array}{l} T_d(r) \simeq \left(\dfrac{R_*}{2r}\right)^{2/5} T_* \\ \\ T_d < T_{COND} \end{array}\right\} r > r_{COND} = R_* \cdot \frac{1}{2}\left(\frac{T_*}{T_c}\right)^{5/2}$$

THE CONDENSATION RADIUS : $(T_c \simeq 1500\ K)$

T_*	SILICATE r_c/R_*	GRAPHITE r_c/R_*	AMORPHOUS CARBON r_c/R_*
3000	2.99	4.03	3.42
2500	1.85	2.34	2.12
2000	1.15	1.29	1.24

DUST DRIVEN WINDS

WIND DRIVEN BY RADIATION PRESSURE DUE TO DUST



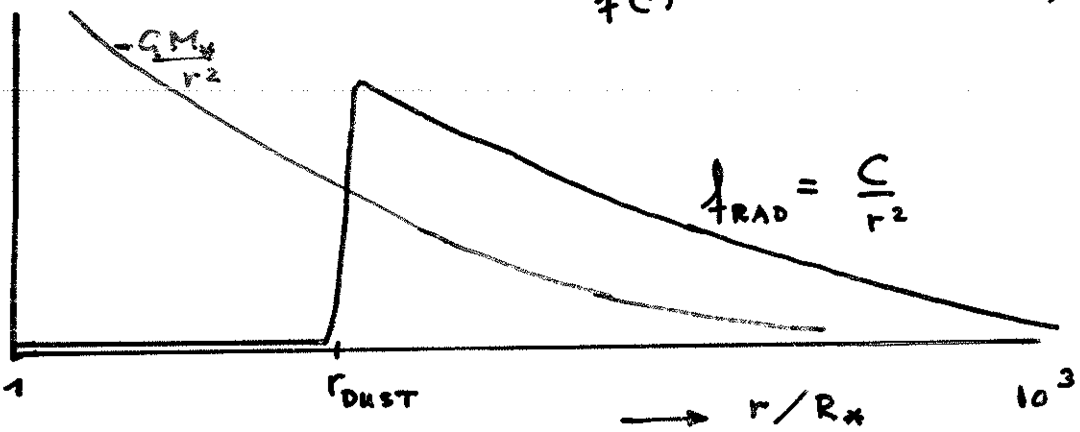
$$F(r) = \frac{L}{4\pi r^2}$$

$$f_{RAD} \sim \frac{1}{r^2}$$

DUST IS FORMED AT RADIUS r_D

→ EXTRA FORCE : $f(r) = \frac{C}{r^2}$ $\quad r \geq r_D$

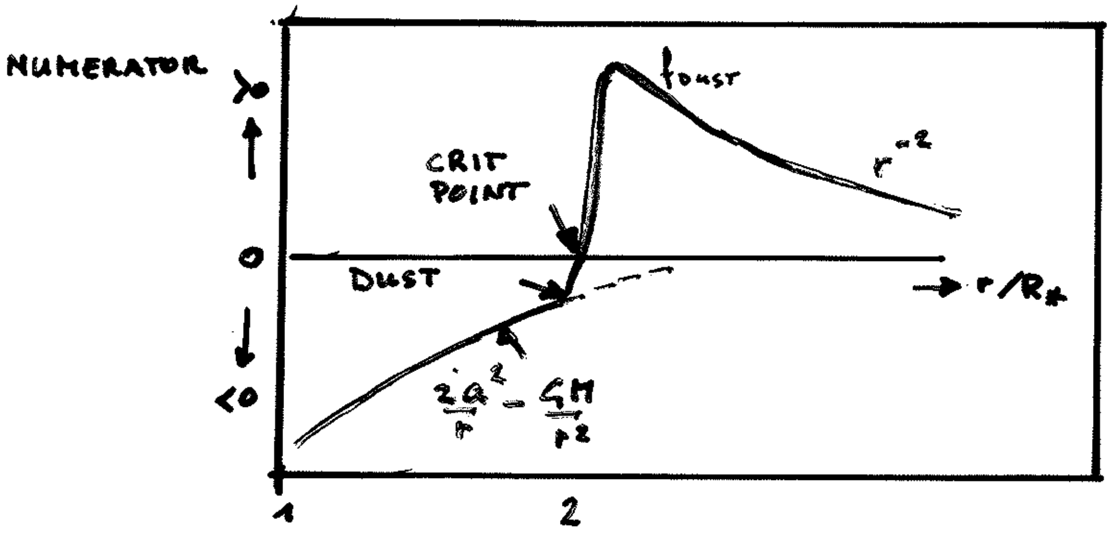
$f(r) = 0$ $\quad r < r_D$



DUST DRIVEN WINDS

MOMENTUM EQUATION

$$\frac{1}{v}\frac{dv}{dr} = \frac{+\frac{2a^2}{r} - \frac{GM_*}{r^2} + f_{DUST}}{v^2 - a^2} \qquad \left(f_{DUST} \sim \frac{1}{r^2}\right)$$



AT CRITICAL POINT : $V = a$

NUMERATOR $= 0$ → $r_c \simeq r_{DUST}$

MASS LOSS RATE :

$$\dot{M} \simeq 4\pi\, r_{DUST}^2 \cdot a \cdot \rho_0 \cdot e^{-\frac{(r_D - R_*)}{H}}$$

r_D = RADIUS WHERE DUST IS FORMED

SIMPLE ESTIMATE FOR AGB STAR

$$\left.\begin{aligned} M_* &= 2\,M_\odot \\ T &= 2200\ \mathrm{K} \\ R_* &= 300\ R_\odot \\ g &= 0.6\ \mathrm{cm/s^2} \end{aligned}\right\} \quad \mathcal{H} = \frac{RT}{\mu g} = 6 \cdot 10^{-3}\ R_*$$

$$r_{DUST} \simeq 1.5\ R_*$$

$$r_{DUST} - R_* = 0.5\,R_* = 83\ \mathcal{H}$$

$$\rho \simeq \rho_0 \times e^{-83} = 10^{-37}\,\rho_0 \ !$$

$$\dot{M}_{DUST} \simeq 4\pi\, r_D^2\, a\, \rho_0 \cdot 10^{-37} \longrightarrow \text{VERY SMALL !!}$$

$$\approx 10^{-45}\ M_\odot/yr$$

So :

THE HIGH MASS LOSS RATES OF DUST DRIVEN WINDS REQUIRE :

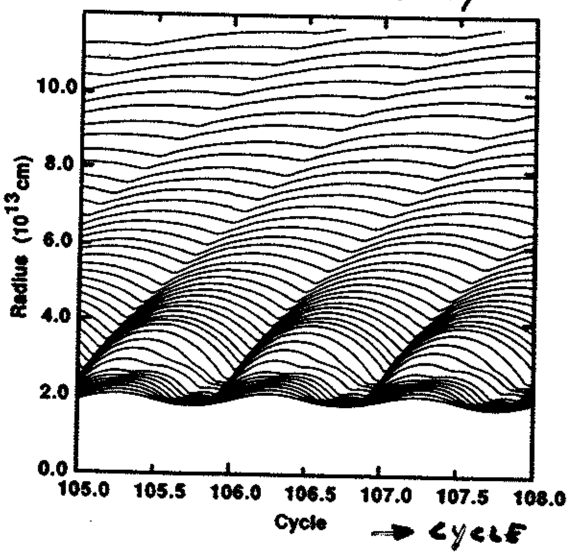
LARGER SCALE HEIGHT IN SUBSONIC REGION !

$$\Downarrow$$

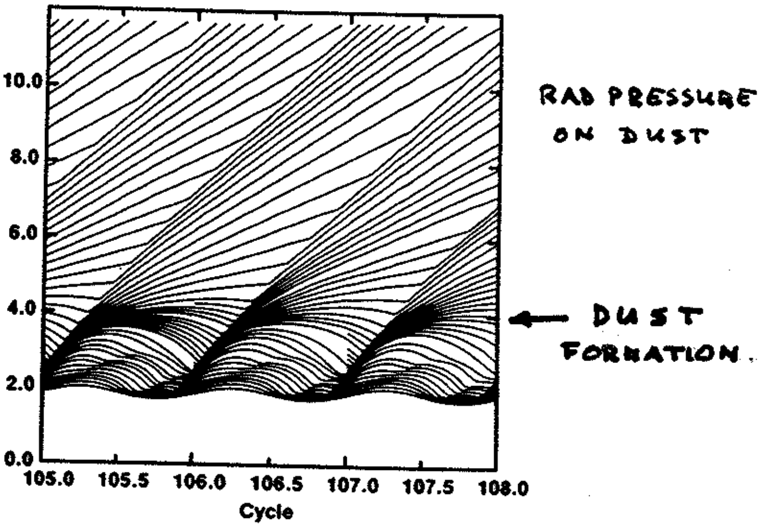
PULSATION

PULSATION + DUST DRIVEN MASS LOSS OF AGB STARS

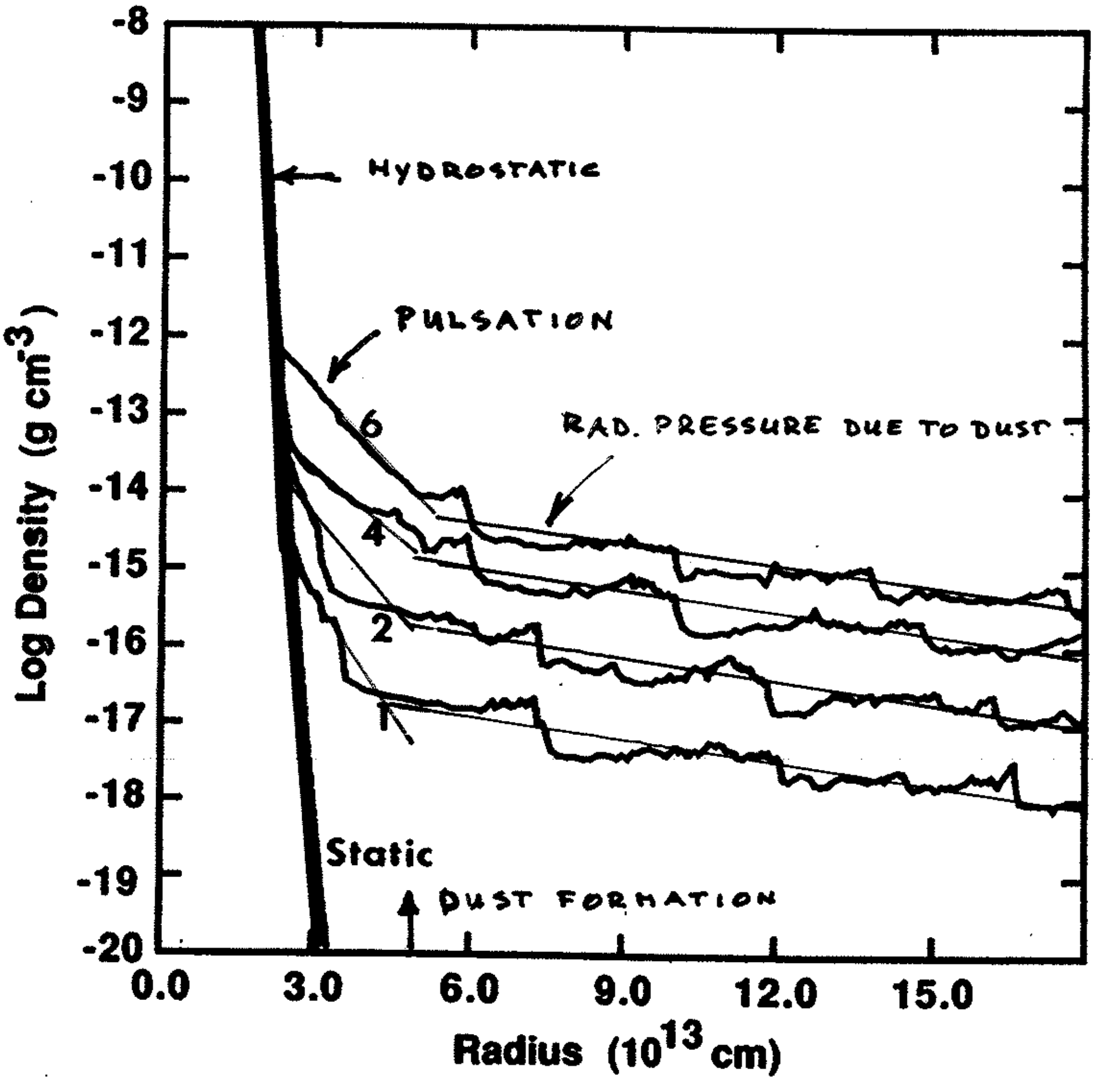
PULSATION ONLY



PULSATION + DUST



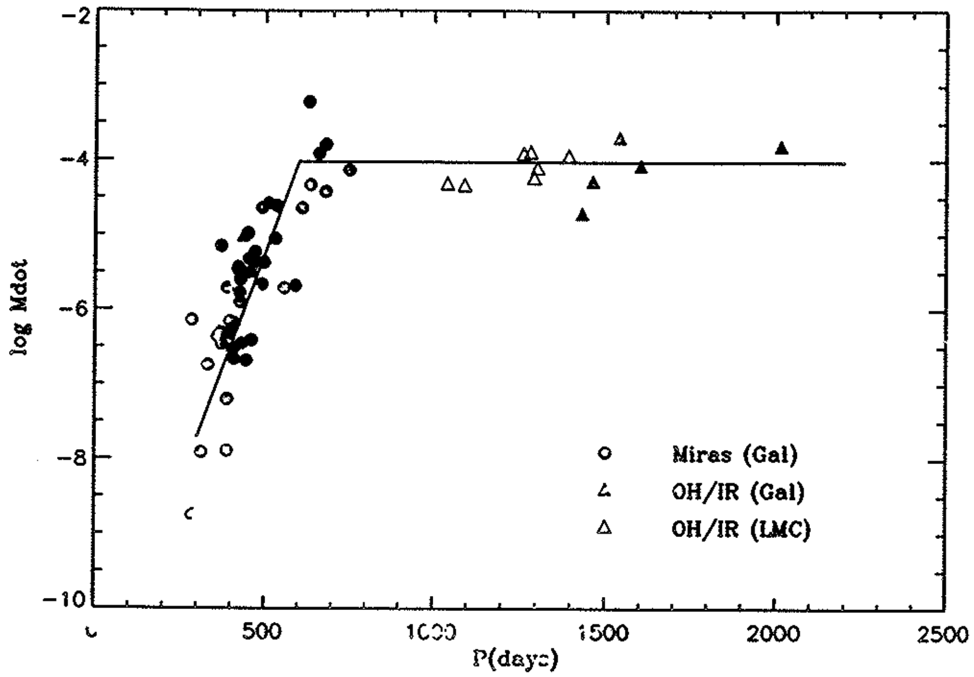
DENSITY STRUCTURE DUE TO PULSATION



BOWEN 1988

WILLSON 2000

MASS LOSS RATES OF
MIRAS
AGB STARS



VASSILIADIS + WOOD 1993

1. MASS LOSS RATE DEPENDS ON PULSATION PERIOD
2. "SATURATION" AT P ≳ 700 DAYS

TERMINAL VELOCITIES ≃ 10 - 20 KM/S !

CONCLUSIONS

- COLD STARS ($T_* \lesssim 2500$ K) = AGB STARS, MIRA'S HAVE DUST DRIVEN WINDS

  = RADIATION PRESSURE ON DUST GRAINS

  DUST GRAINS COLLIDE WITH MOLECULES (H_2, CO) AND SO: <u>ALL</u> MATERIAL IS ACCELERATED: GAS + DUST

- RADIATION PRESSURE ON DUST ALONE CANNOT EXPLAIN HIGH OBSERVED MASS LOSS RATES ($10^{-5} - 10^{-4}$ $M_\odot$/YR)

- PULSATIONS ARE NEEDED TO PRODUCE A LARGE SCALEHEIGHT BETWEEN PHOTOSPHERE AND DUST FORMING REGION

- PREDICTED MASS LOSS RATE

$$\dot{M} \simeq 2 \times 10^{-9} \left(\frac{M_*}{M_\odot}\right)^{0.6} \left(\frac{R_*}{R_\odot}\right)^{0.8} \left(\frac{T_*}{2000}\right)^{0.5} \left(\frac{\Delta V}{4 \text{ km/s}}\right)^{4} \left(\frac{T_D}{T_*}\right)^{7.5}$$

TYPICAL AGB-STAR

$M_* = 2 M_\odot$ $\quad L_* = 9 \times 10^3 L_\odot$
$R_* = 500 R_\odot$ $\quad T_W = 2000$ K
$T_* = 2500$ K $\quad T_c = 1500$ K
PULSATION VELOCITY: $AV \approx 4$ km/s

$\dot{M} \simeq 2 \times 10^{-6} M_\odot$/YR

$V_\infty \simeq 20$ km/s