# STELLAR WINDS AND MASS LOSS

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BOOK:

"INTRODUCTION TO STELLAR WINDS"

LAMERS + CASSINELLI

CAMBRIDGE UNIV PRESS 1999

PAPERBACK: AMAZON.COM ~~$35.90~~

$69.- $40,-

# LESSON 1

## OBSERVATIONS

WINDS OF HOT STARS

WINDS OF COOL STARS

# WHY ARE STELLAR WINDS IMPORTANT ?

- EVOLUTION OF MASSIVE STARS

$M_i \simeq 60\ M_\odot$

$\tau_{MS} \simeq 4 \times 10^6$ yrs

$\dot{M} \simeq 5 \times 10^{-6}\ M_\odot/yr$

$\Big\} \Delta M_{MS} \simeq 20\ M_\odot$

- END STAGES OF LOW MASS STARS

$M_i = 4\ M_\odot$

$M_{AGB} = 3.6\ M_\odot$

$\dot{M} \simeq 10^{-5}\ M_\odot/yr$

$\tau_{AGB} \simeq 3 \times 10^5$ yrs

$\Big\} M_{FINAL} = 0.6\ M_\odot$

- ENRICHMENT OF ISM

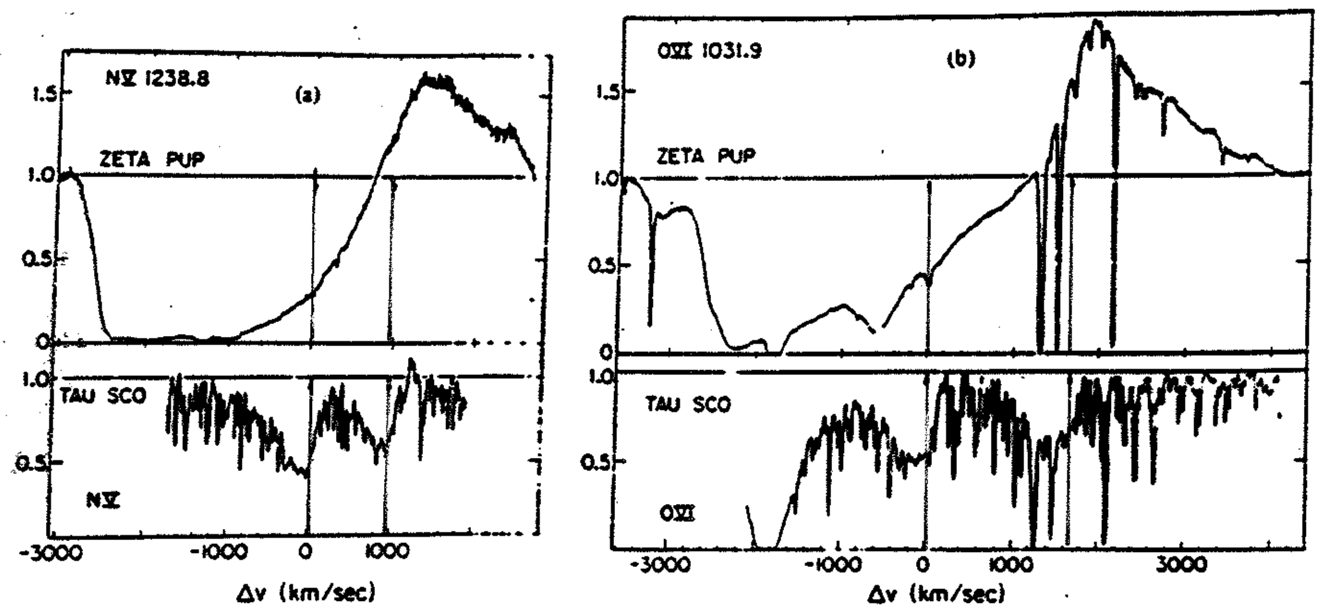
$60\ M_\odot \rightarrow$

| | | |
|---|---|---|
| $20\ M_\odot$ | H | WIND |
| $15\ M_\odot$ | He | WIND |
| $8\ M_\odot$ | N | WIND |
| $10\ M_\odot$ | C | WIND |
| $5\ M_\odot$ | SN | |
| ($2\ M_\odot$ | REMNANT : NS or BH) | |

- DYNAMICS OF ISM

$60\ M_\odot$ : $\Delta M_w \simeq 53\ M_\odot$, $V \simeq 2000$ km/s $\Big\}$ $\frac{1}{2} \Delta M . V^2 \simeq 2 \times 10^{51}$ ERGS

N V O VI




ζ Pup O4 If

τ Sco B0 V

THE WINDS OF HOT STARS ARE "SUPERIONIZED"

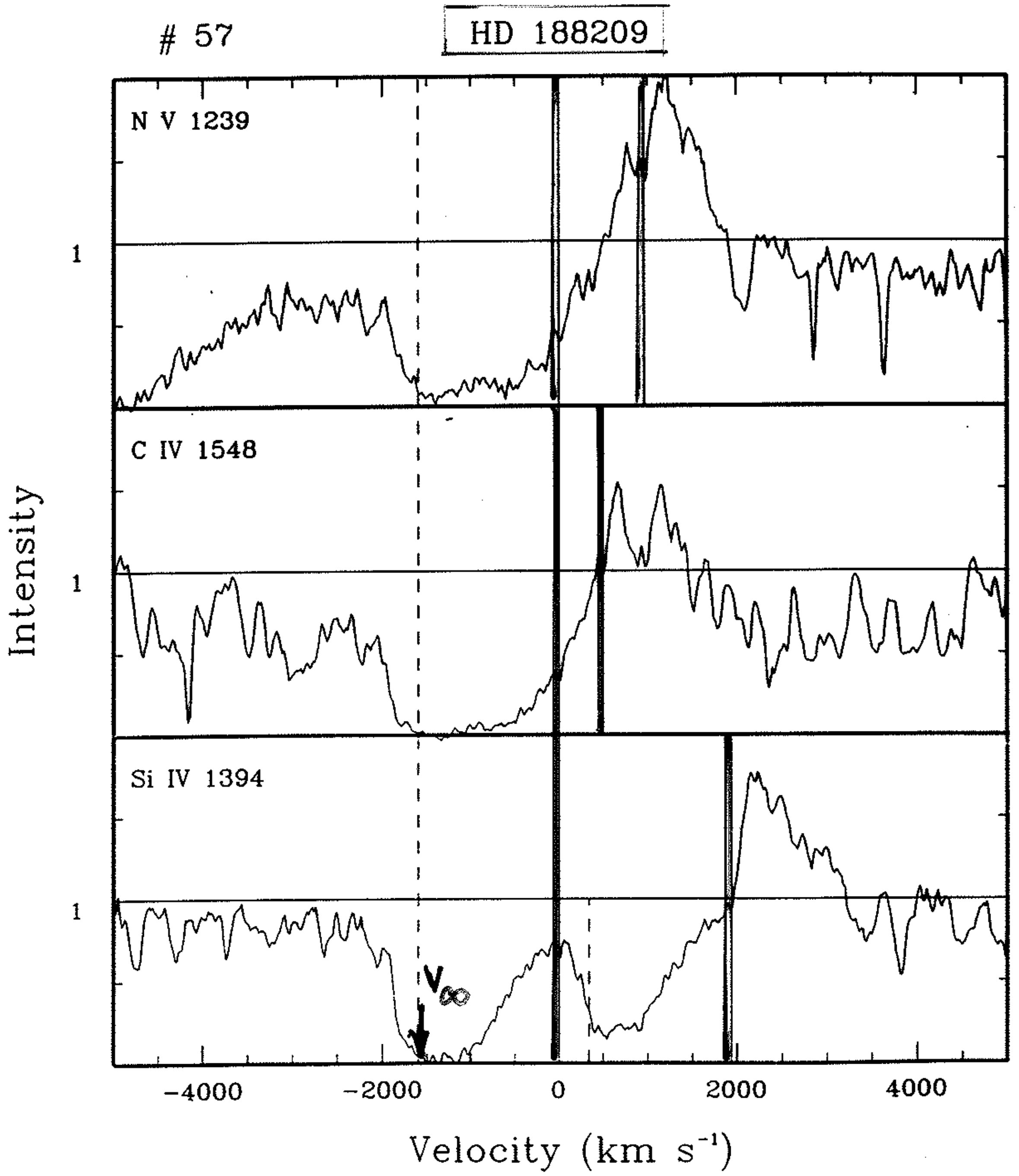
| | | | $T_{EFF}$ |
|---|---|---|---|
| O VI | LINES IN WINDS OF TYPE | O - B0 | (28000 K) |
| N V | | O - B3 | (20000 K) |
| C IV | | O - B8 | (12000 K) |

LAMERS + MORTON + SNOW

1975

P Cygni
Profiles

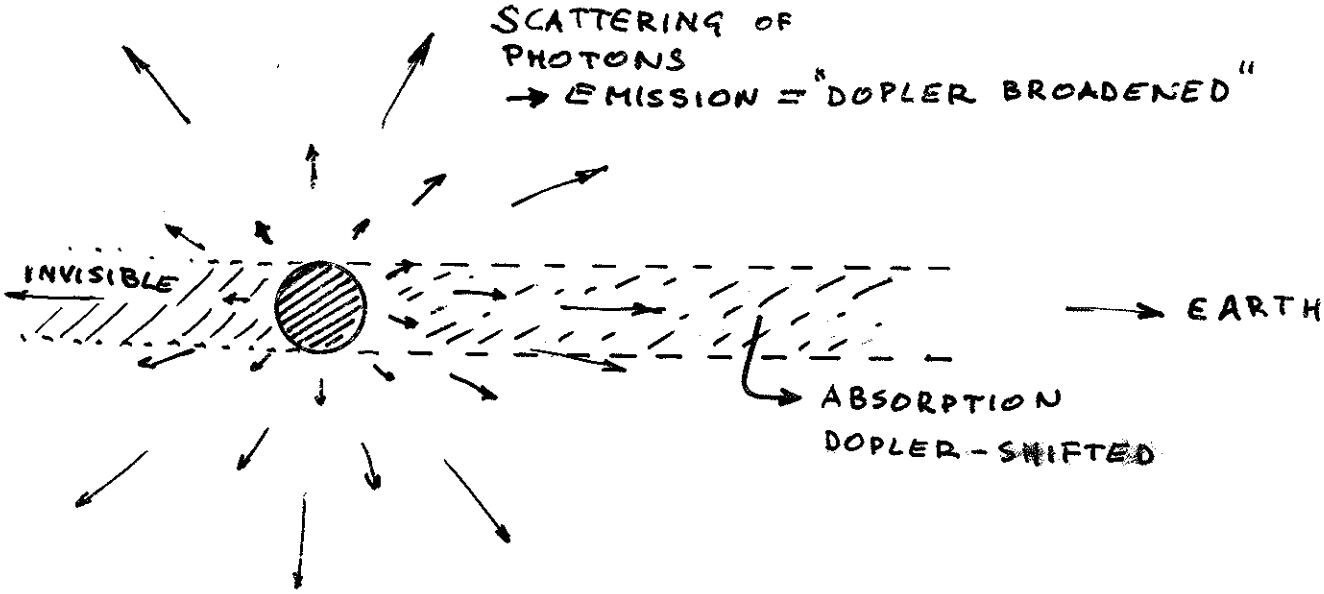
# 57

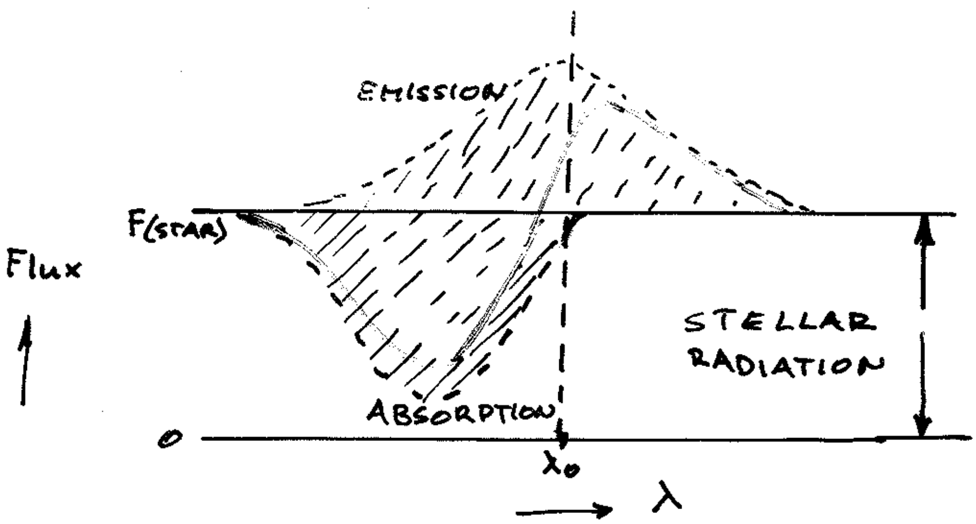



Snow, Lamers, O Dell, Lindholm
1994 ApJ Supl

An Atlas of P Cygni
Profiles

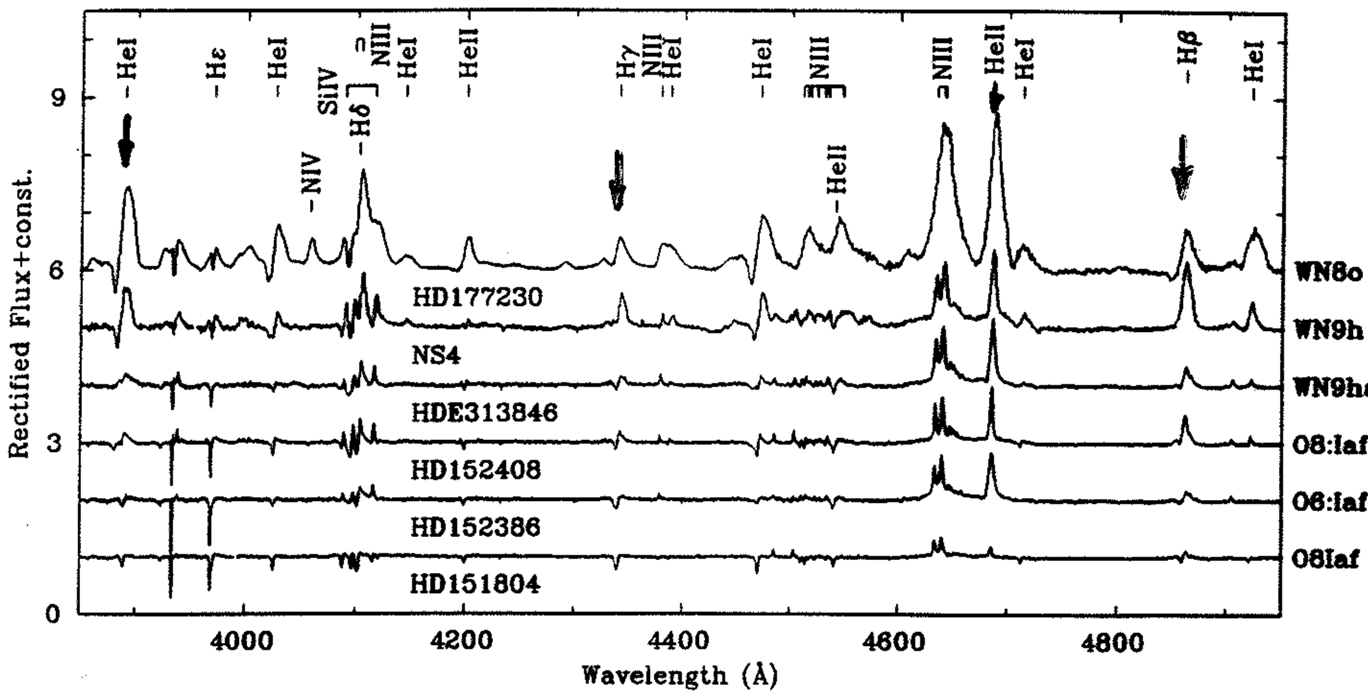
# THE FORMATION OF "P CYGNI PROFILES" BY A STELLAR WIND



# EMISSION LINES FROM WINDS ($\dot{M} \gtrsim 10^{-5}\ M_\odot/yr$)

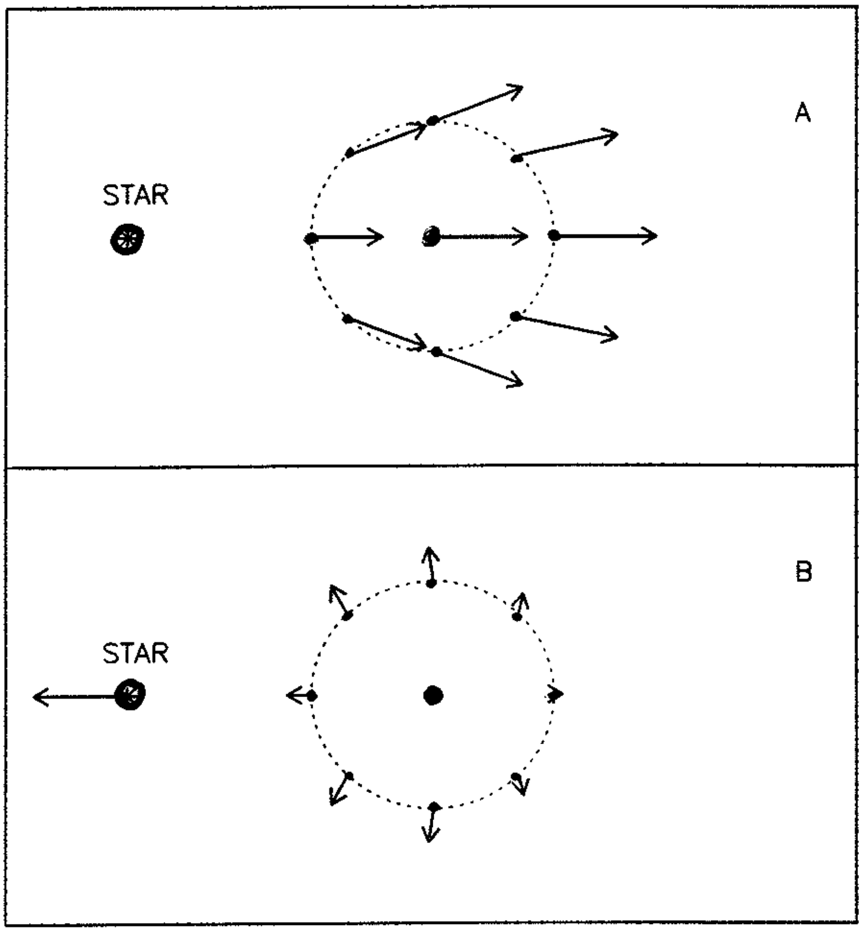
RECOMBINATION
↓
EMISSIVITY $\sim \rho^2$  e.g.: $H_\alpha$ $j_\ell \simeq 3\times10^{-25}\, n_e n_p \left(\frac{T}{10^4}\right)^{-1}$
↓
<u>VERY SENSITIVE TO MASS LOSS</u> !




CROWTHER + WILLIS 1996

| | | |
|---|---|---|
| KLEIN + CASTOR 1978 | } | O STARS |
| LAMERS + LEITHERER 1993 | | |
| PULS ET AL 1995 | | |
| HILLIER 1984 | } | WR STARS |
| HAMANN ET AL 1995 | | |
| CROWTHER ET AL 1996 | | |

EXPANSION VELOCITIES IN THE WIND




WIND VELOCITY RELATIVE TO THE STAR ($\beta$-LAW)

WIND VELOCITY RELATIVE TO A POINT IN THE WIND

GENERAL EXPANSION EVERYWHERE!

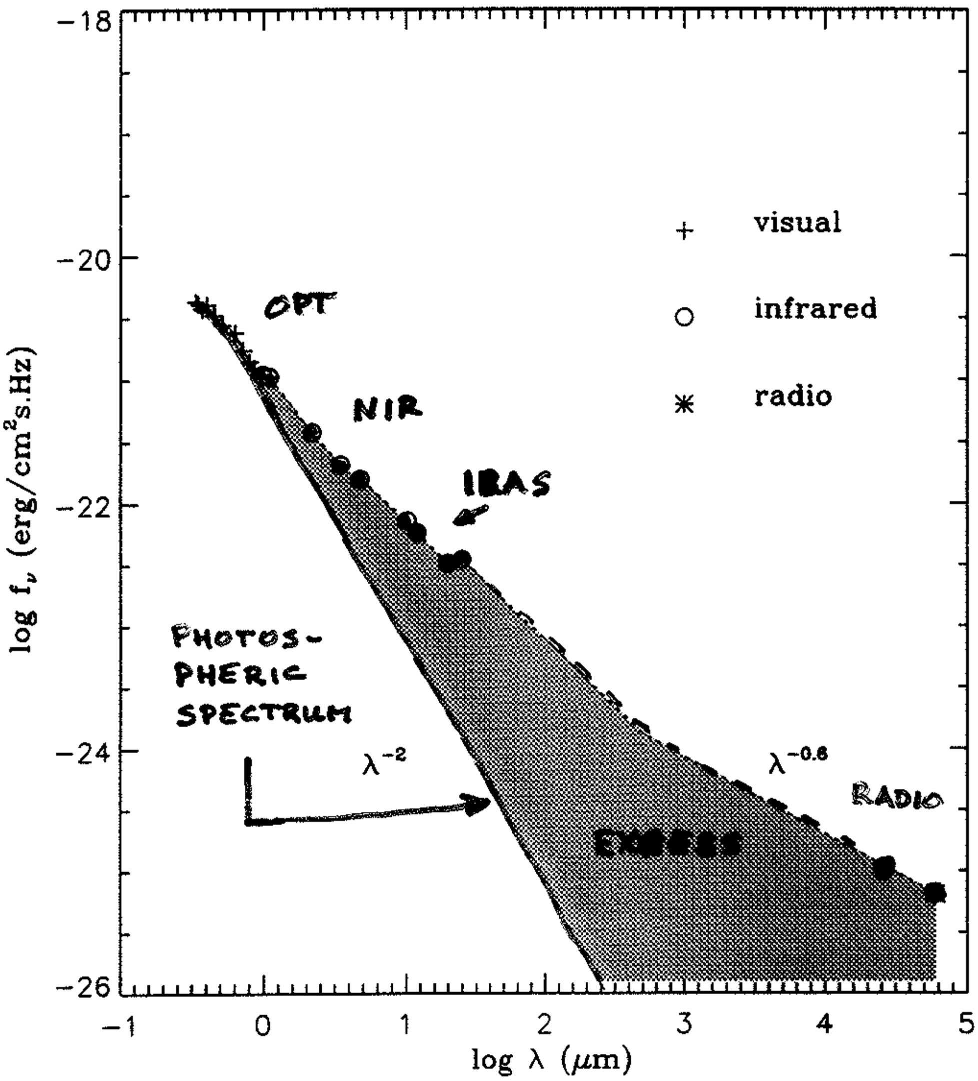
$\Downarrow$

LINE PHOTONS CAN ESCAPE EASILY!

obsexpan.ps

# FREE FREE EMISSION FROM IONIZED WINDS

THE FREE–FREE EXCESS OF P CYGNI

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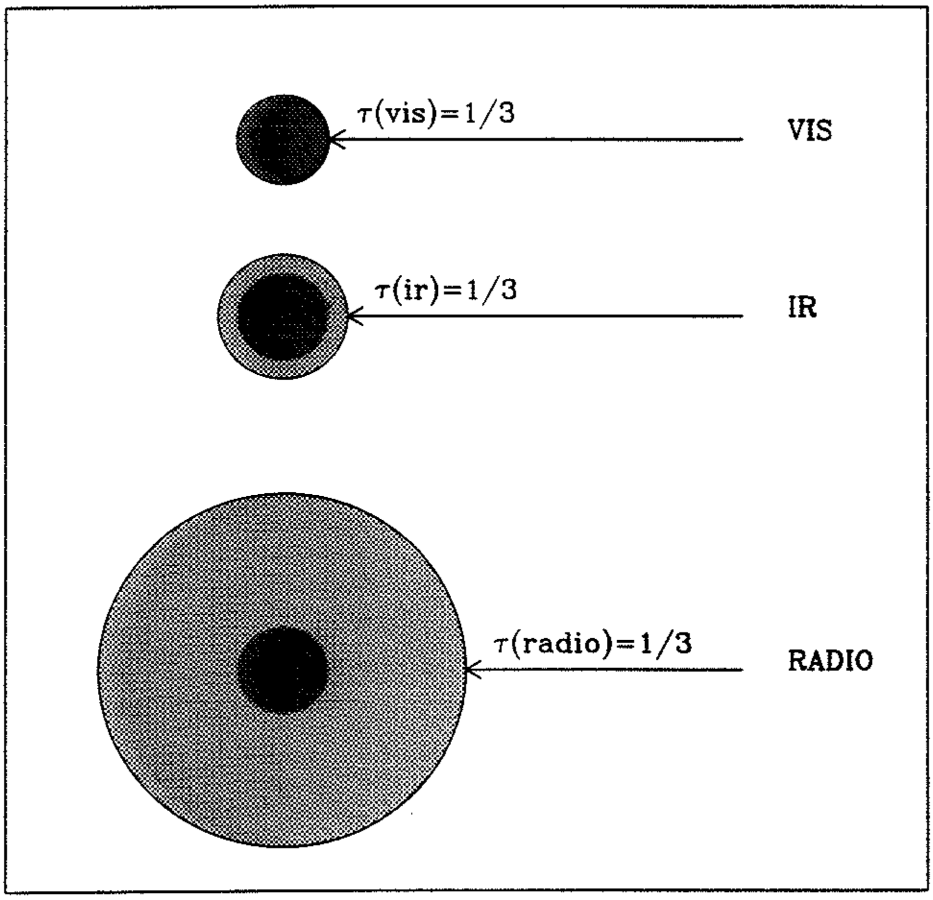
# WHY FREE-FREE EXCESS RADIATION ?

A SCHEMATIC PICTURE OF THE IR AND RADIO EXCESS




(1) ABS COEFF : $\kappa_\lambda \sim \underline{\lambda}^2 \cdot n_e \cdot n_i \cdot f(T)$ FOR FREE-FREE EMISS.

(2) LUMINOSITY : $L_\lambda \simeq 4\pi\, r^2(\underline{\tau_\lambda} \simeq 1/3) \cdot B_\lambda(\underline{\tau_\lambda} \simeq 1/3)$

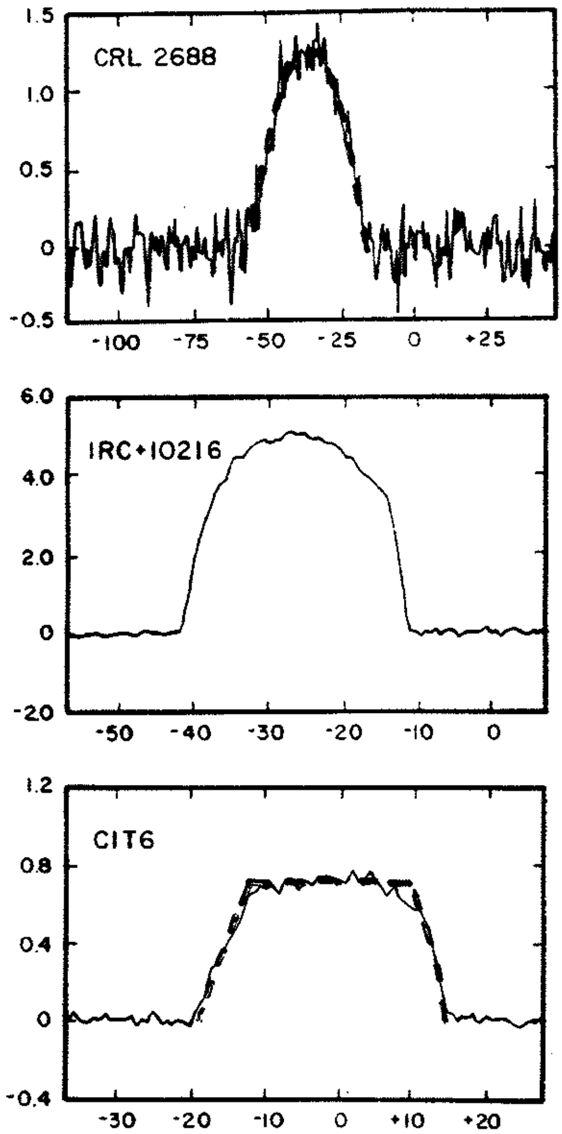
$$\boxed{\frac{L_\lambda}{L_\lambda^*} \simeq \frac{r^2(\tau_\lambda \simeq 1/3)}{R_*^2} \cdot \frac{B_\lambda(\tau_\lambda \simeq 1/3)}{B_\lambda(T_{eff})}}$$

↑ EXCESS ↑ DEFICIENCY

# COOL STARS

## OBSERVED CO 1→0 LINE 2.6 MM

Tant.




PARABOLIC
↓
OPT. THICK

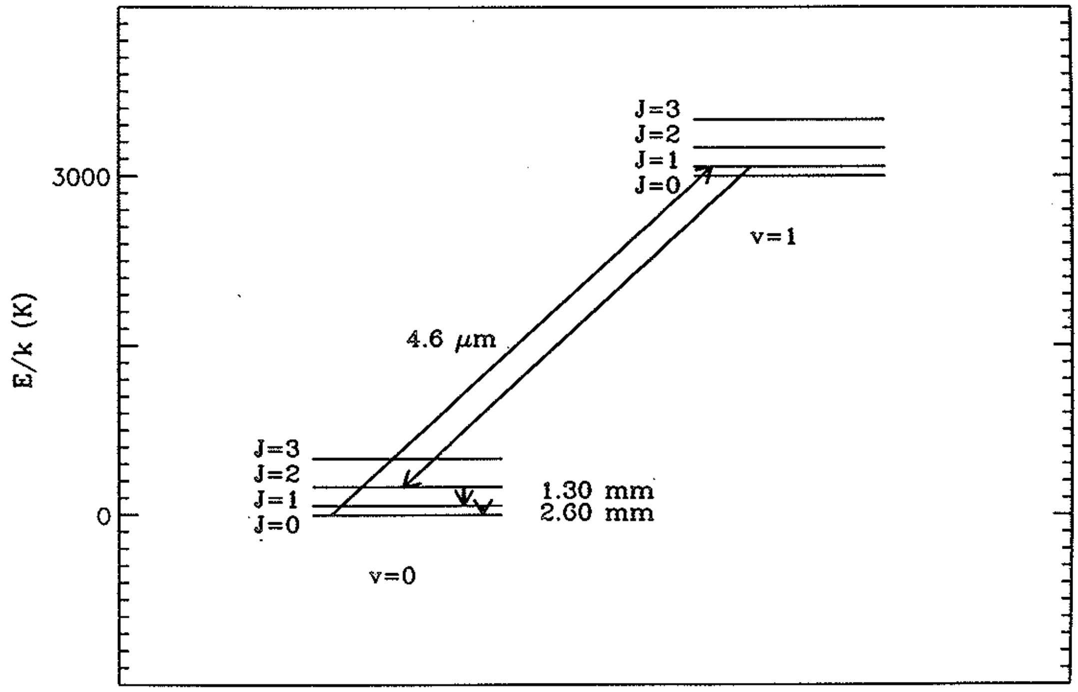
PARTIAL PARABOLA
↓
PARTLY OPT. THICK

FLAT TOPPED
↓
OPT THIN

Figure 1: obscoprf.eps

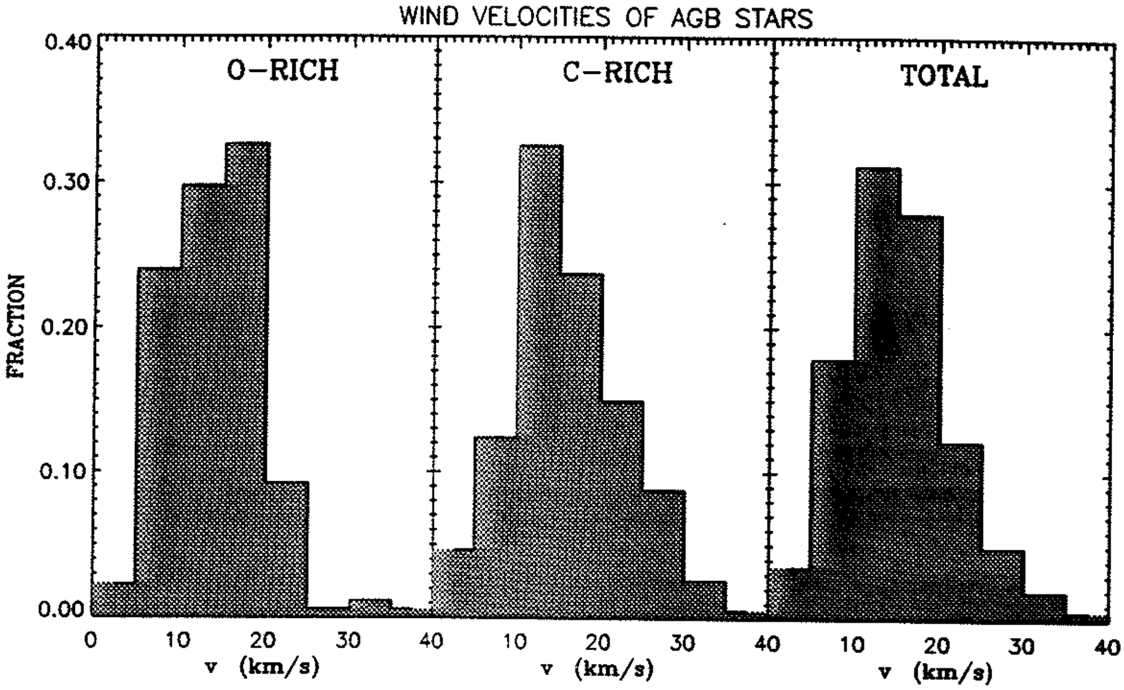
# CO-LINES IN SPECTRA OF COOL STARS

PUMPING OF CO MOLECULES BY INFRARED PHOTONS




1. IR PHOTONS FROM DUST → EXCITE CO-MOLECULES
2. DE-EXCITATION TO V=0, J=2,1 LEVEL
3. DE-EXCITATION OF ROTATIONAL LEVEL TO J=1 OR 0

   → CO MM LINES




cbswind.ps

(2.34)

# ENERGY AND MOMENTUM OF WINDS.

- KINETIC ENERGY LOSS

$$\dot{E}_{KIN} = \frac{1}{2} \dot{M} V_\infty^2 \qquad \dot{E}_{KIN} \lesssim L$$

- POTENTIAL ENERGY LOSS

$$\dot{E}_{POT} = - \dot{M} \times \frac{GM}{R} \qquad \dot{E}_{POT} \lesssim L$$

- MOMENTUM LOSS OF WIND

$$\dot{P} = - \dot{M} V_\infty \qquad \dot{M} V_\infty \approx L/c$$

FOR HOT STARS:

$\dot{E}_{KIN} \simeq 10^{-3} L$

$\dot{E}_{POT} \simeq 10^{-4} L$

$\dot{P} \simeq L/c$ !

FOR COOL STARS (AGB)

$E_{KIN} \lll L$

$\dot{E}_{POT} \lll L$

$\dot{P} \simeq L/c$ !