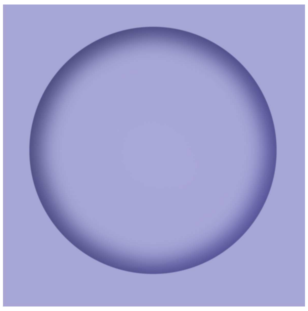
Macroclumping in winds of massive stars

Lidia M. Oskinova & Wolf-Rainer Hamann
Universität Potsdam, Germany



Clumping: micro versus macro

The "microclumping" approximation:
(included in various codes: CMFGEN, PoWR, Munich codes ...)

Assumptions

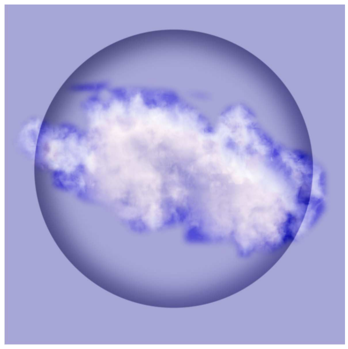
- Clumps are *optically thin at all frequencies*
- For frequencies of large opacity, this implies unrealistically small scales of the clumps
- In the winds of O- and WR stars, high opacities occur especially
  - in the resonance lines
  - in the X-ray domain (K-shell absorption)

Photon mean free path
maximum size for opt. thin clumps
Example: ζ Puppis model
at typical point in the wind (at $\frac{1}{2}v_\infty$)

C IV resonance line	$4*10^{-4}$ R_*
P V resonance line	0.1 R_*
He II 1 - 2 at 304 Å	$3*10^{-6}$ R_*
K-shell edges (X-ray)	$2*10^{-4}$ R_*

An approach to macroclumping (Oskinova, Hamann & Feldmeier 2007)

- A large number of clumps are statistically distributed
- At a given frequency and location, all clumps have the optical diameter $\tau_{\rm clump}$
- Macroclumping reduces the effective opacity by a factor $\frac{1-e^{-\tau_{\rm clump}}}{\tau_{\rm clump}}$
- For $\tau_{\rm clump} \gg 1$, this implies a drastic reduction by a factor of $\tau_{\rm clump}$!
- The reduction of opacity is already significant for moderate $\tau_{\rm clump} \approx 1$
- Specification of the clump size:
  - Clumps are conserved entities (→eq. of continuity)
  - the average separation of clumps is, with a parameter L_0 , $L(r) = L_0 \left(r^2 \frac{v(r)}{v_\infty}\right)^{1/3}$
- Realistic choices for L_0 are of the order of 1 R_*
  - from 1-D hydro (Feldmeier et al. 1997): radial shells launched on $\lesssim$ dynamical timescale → $L_0 \lesssim 1\,R_*$)
  - from *Line Profile Variability* in WR stars: $\gtrsim 10^4$ clumps launched per hour (Lépine & Moffatt 1999) → $L_0 \approx 0.25\,R_*$
  - from modeling X-ray line profiles (Oskinova et al. 2006): $L_0 \lesssim 1\,R_*$



Macroclumping can mask higher mass-loss rates

Implementation in the *Potsdam Wolf-Rayet* (PoWR) code

- Macroclumping only accounted in the *Formal Integral*
- *Effective opacity*, reduced due to macroclumping effect
- Non-LTE source function as from microclumping model, i.e. feedback of macroclumping effects on population numbers neglected

Macroclumping can solve the mass-loss rate discrepancy

- The P V resonance line gives >10 times smaller O-star mass-loss rates than Hα and radio free-free emission ! (Fullerton, Massa & Prinja 2006)
- Accounting only for *microclumping* → incredibly small filling factors to reconcile the ρ^2 diagnostics (Hα line, radio free-free emission) with such small mass loss
- Accounting for *macroclumping* effect → weaker P V resonance line, reconciling it with the ρ^2 diagnostics without a reduction of the mass-loss rate

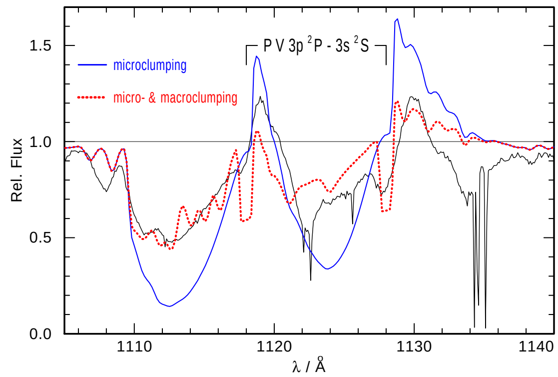
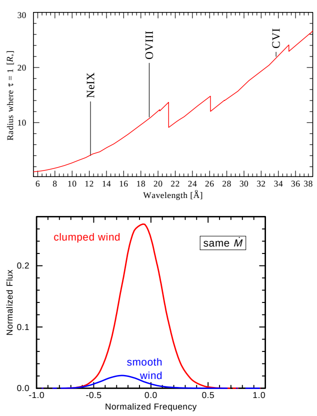


Figure: Observation of ζ Pup and two synthetic profiles from the same model, but with and without macroclumping effect, respectively



Macroclumping explains how X-rays from massive-star winds escape

- In soft X-rays, stellar winds should be opaque due to K-shell absorption (*left Figure, upper panel:* radius of optical depth unity for a ζ Pup model)
- From the X- ray line widths ($\frac{1}{2}v_\infty$, typically) and from hydrodynamical models, X-rays are expected to be produced in the lower part of the wind
- The reduction of the effective opacity by *macroclumping* can explain how a signicant fraction of the X-rays can emerge (*left Figure, lower panel*)
- When clumps are optically thick, the effective opacity becomes *grey*; this can explain the observed similarity between different X-ray line profiles
- Observed *symmetric* X-ray line profiles can be reproduced best with macroclumps that are flat like pancakes ("broken-shell model", *right Figure*) Oskinova et al. 2004