Stellar winds

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Outline

- Basic ideas, $\dot{M}$ and v_∞
- Radiation field of stars with different T_{eff}
- Physical processes in the atmosphere
- Line driven winds
- The bi-stability jump
- Vink et al. 2000
- The famous P Cygni profile
- WR stars, cool stars
- What is actually implemented in BEC

Basic ideas, $\dot{M}$ and v_∞

Stellar wind: continuous outflow; stars emit radiation AND particles='wind'

Sun:

- flows driven by gas pressure gradients (1958)
- Alfvén wave driven winds (1965)
- magnetic rotator theory (1967)
- radiation driven winds (1970)

Two main parameters to derive from wind theories (and spectra): $\dot{M}$ and v_∞

- kinetic energy that the wind deposits into the ISM per unit time (→ momentum and energy transfer):

$$\frac{dE_{kin}}{dt} = \frac{1}{2}\dot{M}v_\infty^2 \tag{1}$$

- velocity law: $v(r)$ distribution of the velocity of the wind with radial distance – approximation:

$$v(r) \simeq v_0 + (v_\infty - v_0)\left(1 - \frac{R_*}{r}\right)^\beta \tag{2}$$

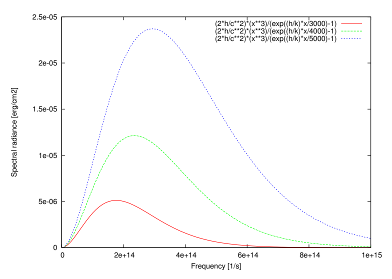
v_0: initial velocity at the photosphere
β: steepness of the law

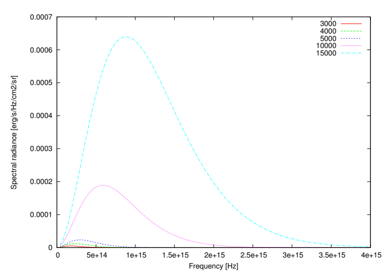
($v_\infty = v(r \to \infty)$)

Radiation field of stars with different T_{eff}

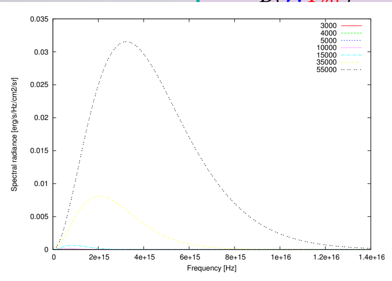
$$B(\nu, T_{eff}) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{k_B T_{eff}}} - 1} \tag{3}$$

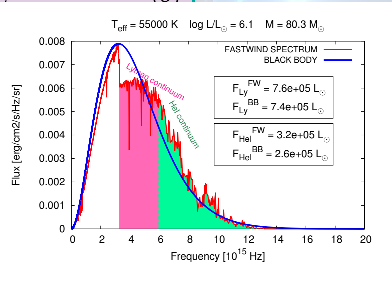
Radiation field of stars with different T_{eff}





$B(\nu, T_{eff}) = \frac{2h}{\ldots 2}$ … $e^{k\ldots}$ (3)





Physical processes in the atmosphere

- line scattering (ground state: resonance scattering → resonance lines)
- recombination → emission (e.g. Hα emission)
- collision → emission
- masering

Spectral lines: photospheric lines ≠ wind lines (Doppler shifted, absorption+emission)

Resonance lines:

- most sensitive indicators of mass loss from hot stars
- scattering:
  - photon emitted by the photosphere is absorbed by an atom →
  - photo-excitation of a ground-state electron →
  - new photon is emitted, but in another direction
- observable, because: abundant elements; oscillator strength of atomic resonance transitions is large
- examples: CIV, NV, SiIV (O-B stars), CII (B-A stars), MgII (B-M stars) – in UV!

Line driven winds

Luminous hot stars: radiation is emitted mainly in UV

+

many absorption lines here (= elements in the atmosphere with potential transitions)

+

Doppler effect: otherwise all radiation would be absorbed in the inner atmosphere...
but outer parts are moving away (redshifted) :)

Momentum and energy transfer from radiation to the gas:

- a bit complicated to calculate all Doppler-shifted transfers of all wavelength...
- and gravity may play a role... and radiation field may be not perfect Black Body...
- and not every gas-component scatters – they must bring everything with them (Coulomb coupling) to reach a steady outflow of plasma...

Sobolev approximation:
treats the 'line' (=small frequency range of the scattering) as a δ-function and the optical depth as a step-function.

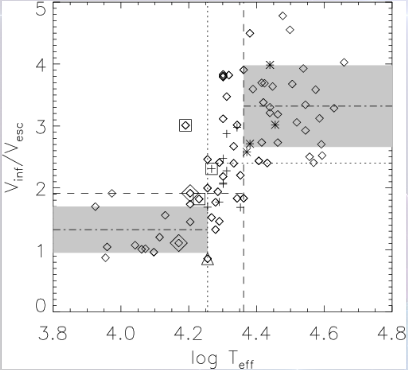
CAK theory (Castor, Abbott, Klein):
a realistic estimate of the radiative force due to lines: computation of the degree of ionization and excitation of large number of energy levels for many different elements

The bi-stability jump

Effective escape velocity (at the stellar surface):

$$v_{esc} = \sqrt{2(1-\Gamma_e)\frac{GM}{R}} \qquad (4)$$

The ratio of v_∞/v_{esc} depends on T_{eff}:



(Markova & Puls 2008)

$21\,000\text{ K} \lesssim T_{eff}$:
C, N, O highly ionized lines in the Lymann continuum

$10\,000\text{ K} \lesssim T_{eff}$:
metal lines in the Lymann and Balmer continuum

$T_{eff} \lesssim 10\,000\text{ K}$:
continuum driven wind (?) dust, molecules (?)

Vink et al. 2000

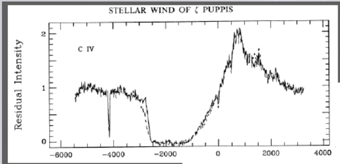
Model atmospheres of stars with different L_*, M_*, T_{eff}, v_∞/v_{esc}

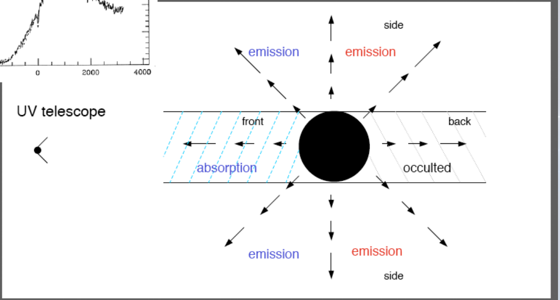
- covering the OB-range of the HRD
- multiple scattering!
- method: total loss of radiative energy is linked to the gain of momentum of the material outflow
- model atmosphere $\rightarrow$ radiative acceleration and $\dot{M}$ are calculated
- $\dot{M}$ as a function of the basic parameters are fitted (= "mass loss recipe"), e.g. for 12 500 K $< T_{eff} <$ 22 500 K:

$$\log \dot{M} = -6.69 + 2.21 \log \frac{L_*}{10^5} - 1.34 \log \frac{M_*}{30} + 1.07 \log \frac{T_{eff}}{20000} - 1.6 \log \frac{v_\infty/v_{esc}}{2.0} \qquad (5)$$

- Vink et al. 2001: metallicity dependence ($+0.85 \log Z$)
- behaviour around the bi-stability jumps
- the calculated $\dot{M}$ match the observations

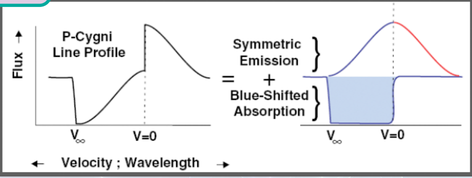
The famous P Cygni profile





violet shifted absorption lines are observable even at low column density; also a symmetric emission component is observable coming from the 'halo' region of the star (recombination)

$\dot{M}$, v_∞ and β can be accurately derived



WR stars, cool stars

Hα line (λ=6562Å$\rightarrow$ optical spectra of OB supergiants):

- emission line, high $\dot{M}$ needed
- widely used to derive parameters

WR stars (Hamann et al. 1995)

- high density strong winds $\rightarrow$ spectrum is dominated by emission lines
- emission comes from recombination $\sim \rho^2 \Rightarrow$ emission comes from lower layers
- problem with radius determination: normally, $R_* = R(\tau = 2/3)$ at the photosphere (where the continuum comes from); but WR wind is optically thick! $\rightarrow$ the 'surface' of the star is somewhere in the wind
- measured radius is different in different wavelength bands ($\tau = \tau(\lambda)$) :)
- mass loss rate for hot stars: derive $\dot{M}$ from radio continuum measurements + v_∞ from P Cygnu profile in UV

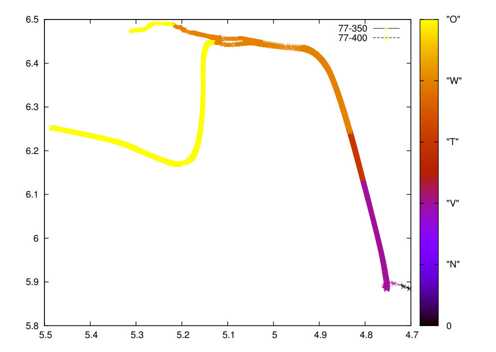
Cool stars (Nieuwenhuizen & de Jager 1990)

- molecular emission lines, e.g. CO, SiO, OH
- additionally: dust!
- dusty winds emit radiation in IR and mm bands, but the energy distribution of dust is typical

What is actually implemented in BEC

- m.dat: MTU=0, MTU=20, MTU=51 etc.
- BEC/CODE/dev/maslos.f

- "N": Nieuwenhuizen & de Jager (1990)
- "V": Vink et al. (2000-2001)
- "T": interpolated
- "W": 0.1 × Hamann et al. (1995)
- "O": ad hoc expression by Sung-Chul (?), see Yoon et al. (2006)



Thank you for your attention!