NLTE wind models of A supergiants

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Stellar wind of A supergiants

- similar properties as stellar wind of OB stars
- accelerated by the absorption of radiation mainly in the resonance lines of C, N, O or Fe
- the domain of A supergiants seems to be overlooked by wind theorists up to now

NLTE models of stellar wind

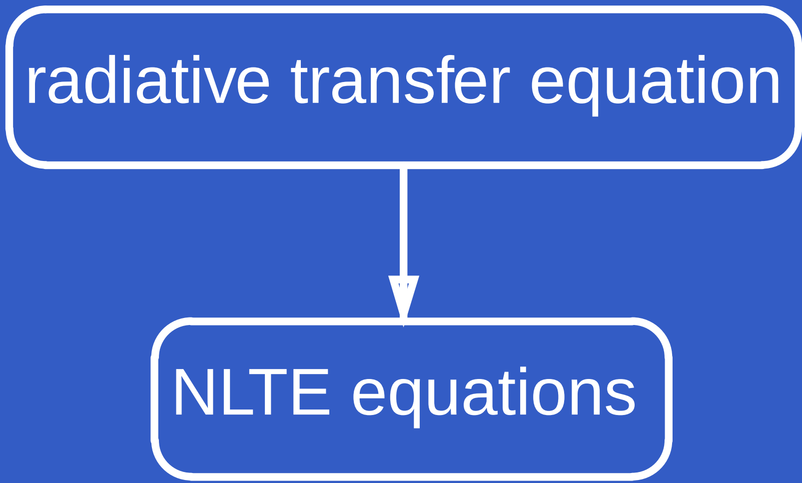
(Krtička & Kubát 2004)

- spherically symmetric stationary wind models
- radiative force calculated using level occupation numbers obtained from the solution of statistical equilibrium equations
- wind density, velocity and temperature calculated as the solution of hydrodynamic equations
- enable prediction of $\dot{M}$, v_∞

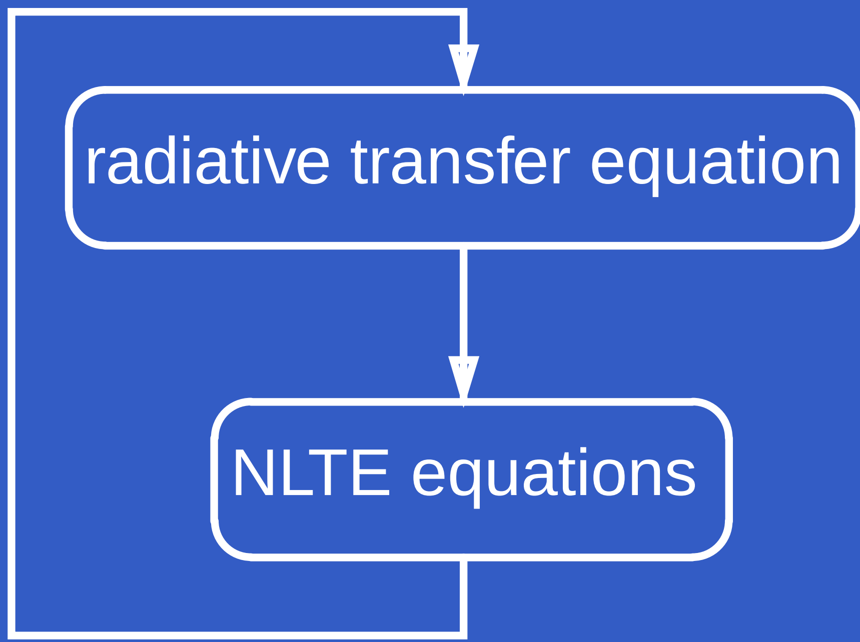
Process of model calculation

radiative transfer equation

Process of model calculation



Process of model calculation



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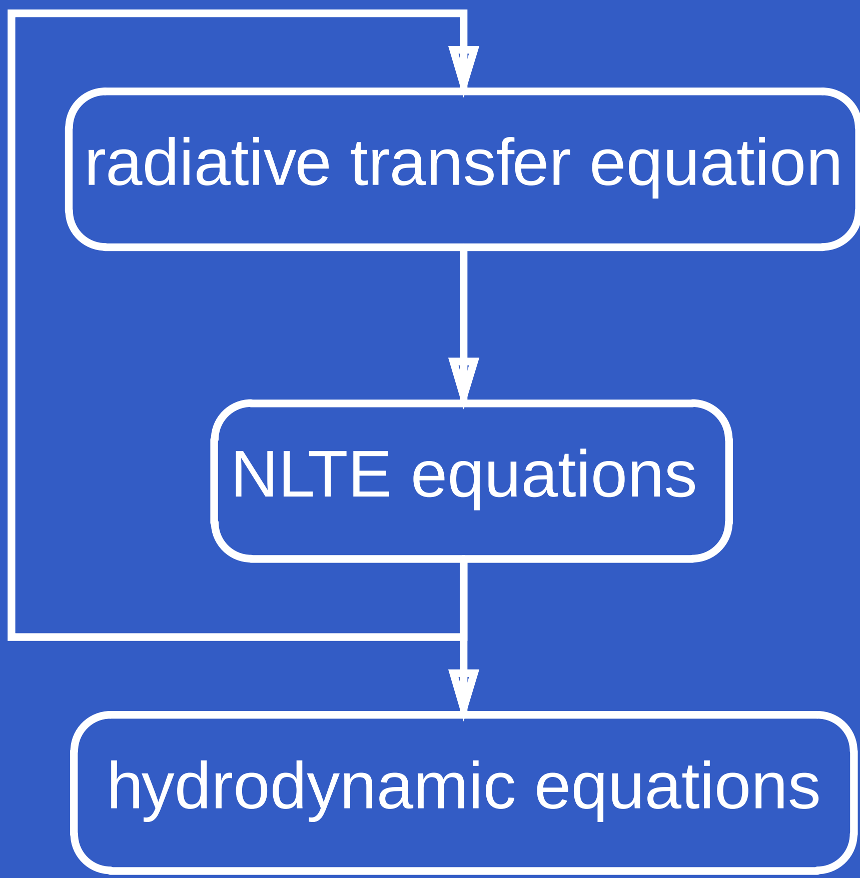
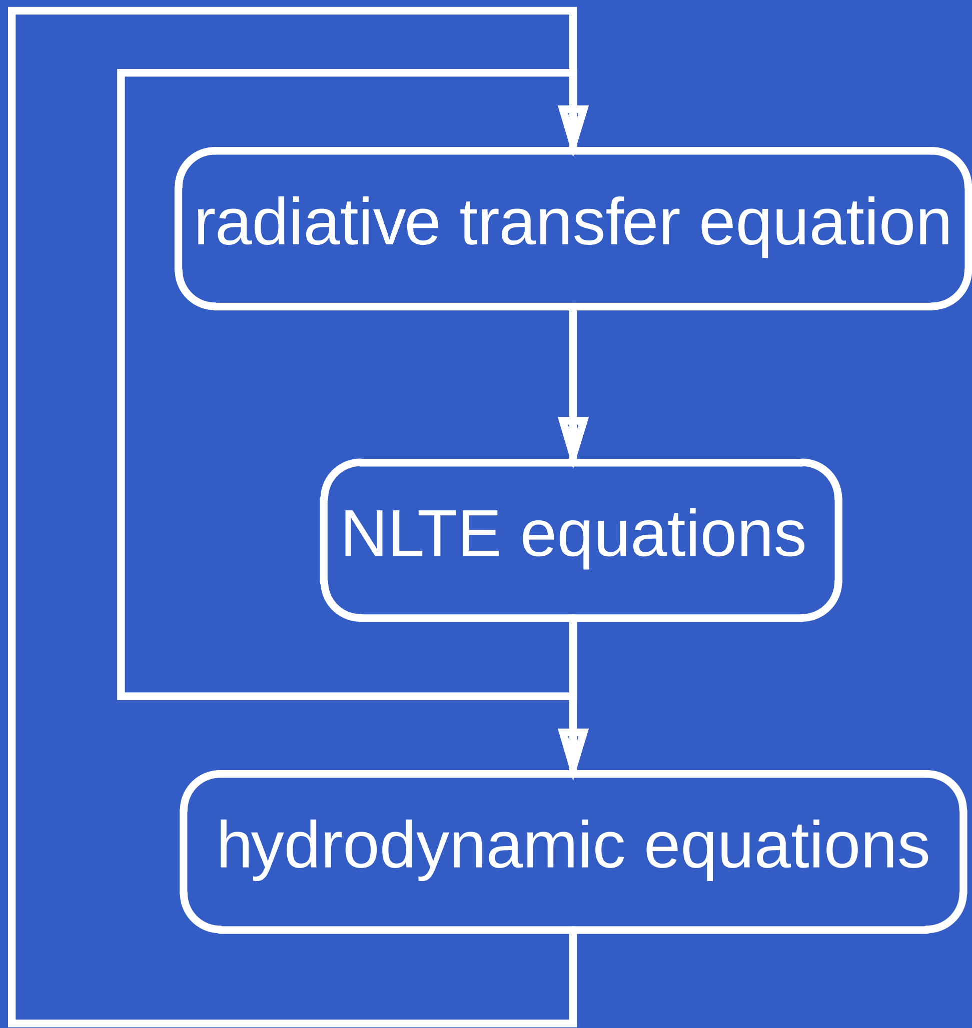


Process of model calculation



Continuum radiative transfer

$$\mu \frac{\partial I(r,\nu,\mu)}{\partial r} + \frac{1-\mu^2}{r} \frac{\partial I(r,\nu,\mu)}{\partial \mu} = \eta - \chi I(r,\nu,\mu),$$

- wind motion neglected
- $I(r,\nu,\mu)$ is the specific intensity of radiation
- $\mu = \cos\theta$ is the direction cosine, ν is the frequency
- $\chi(r,\nu,\mu)$, $\eta(r,\nu,\mu)$ are the emissivity and absorption coefficients
- solution obtained using Feautrier method

Line radiative transfer

Solution using Sobolev approximation

$$\bar{J}_{ij} = (1-\beta)S_{ij} + \beta_c I_c,$$

- $\bar{J}_{ij} = \int_0^\infty \mathrm{d}\nu \int_{-1}^1 \mathrm{d}\mu\, \phi_{ij}(\nu) I(r,\nu,\mu)$ is the mean intensity, $\phi_{ij}(\nu)$ is the line profile
- I_c is the specific intensity of star,
  $\beta = \frac{1}{2}\int_{-1}^1 \mathrm{d}\mu\, \frac{1-e^{-\tau_\mu}}{\tau_\mu}$, $\beta_c = \frac{1}{2}\int_{\mu_*}^1 d\mu\, \frac{1-e^{-\tau_\mu}}{\tau_\mu}$,
  $\mu_* = \left(1 - R_*^2/r^2\right)^{1/2}$,
- source function $S_{ij} = \eta_{ij}/\chi_{ij}$.

Statistical equilibrium equations

Occupation number N_i of atoms in the state i is given by the solution of

$$\sum_{j\neq i} N_j P_{ji} - N_i \sum_{j\neq i} P_{ij} = 0.$$

- P_{ij} are rates of all processes that transfer an atom from a given state i to state j,
- radiative excitation and deexcitation, radiative ionization and recombination and corresponding collisional processes contribute to P_{ij}

Included ionization states

H I-II	He I-III	C I-IV	N I-IV
O I-IV	Ne I-IV	Na I-III	Mg II-IV
Al I-V	Si II-V	S II-V	Ar III-IV
Ca II-IV	Fe II-V	Ni II-V	

- model atoms are taken mostly from TLUSTY code (Hubeny & Lanz 1992, 1995)
- the original set is extended using data from Opacity Project and Iron Project

Hydrodynamic equations

- continuity equation

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\rho v_r\right) = 0 \Rightarrow \dot{M} = 4\pi r^2 \rho v_r = \text{const.}$$

  - ρ is the wind density
  - v_r is the radial velocity

Hydrodynamic equations

- equation of motion

$$v_r \frac{\mathrm{d}v_r}{\mathrm{d}r} = g^{\text{rad}} - g - \frac{1}{\rho}\frac{\mathrm{d}}{\mathrm{d}r}\left(a^2\rho\right)$$

  - g is the gravity acceleration
  - a is the isothermal sound speed
  - $g^{\text{rad}} = g^{\text{rad}}_{\text{lines}} + g^{\text{rad}}_{\text{el}}$ is the radiative acceleration

$$g^{\text{rad}}_{\text{lines}} = \frac{8\pi}{\rho c^2}\frac{v_r}{r}\sum_{\text{lines}} \nu H_c \int_{\mu_c}^{1} \mathrm{d}\mu\, \mu \left(1 + \sigma\mu^2\right)\left(1 - e^{-\tau_\mu}\right)$$

Hydrodynamic equations

- energy equation

$$\frac{3}{2} v_r \rho \frac{\mathrm{d}a^2}{\mathrm{d}r} + \frac{a^2 \rho}{r^2} \frac{\mathrm{d}}{\mathrm{d}r} \left(r^2 v_r \right) = Q^{\text{rad}}$$

  - Q^{rad} is the radiative heating/cooling calculated using the thermal balance of electrons method (Kubát et al. 1999)

Stellar wind of HD 12953

- A1Iae supergiant with parameters $T_{\text{eff}} = 9\,100\,\text{K}$, $R = 145\,\text{R}_\odot$ and $M = 9.7\,\text{M}_\odot$ (Kudritzki et al. 1999)

Stellar wind of HD 12953

- A1Iae supergiant with parameters $T_{\text{eff}} = 9\,100\,\text{K}$, $R = 145\,\text{R}_\odot$ and $M = 9.7\,\text{M}_\odot$ (Kudritzki et al. 1999)
- observed wind mass-loss rate is $\dot{M} = 4.3 \times 10^{-7}\,M_\odot\,\text{year}^{-1}$ and observed wind terminal velocity is $v_\infty = 150\,\text{km}\,\text{s}^{-1}$ (Kudritzki et al. 1999)

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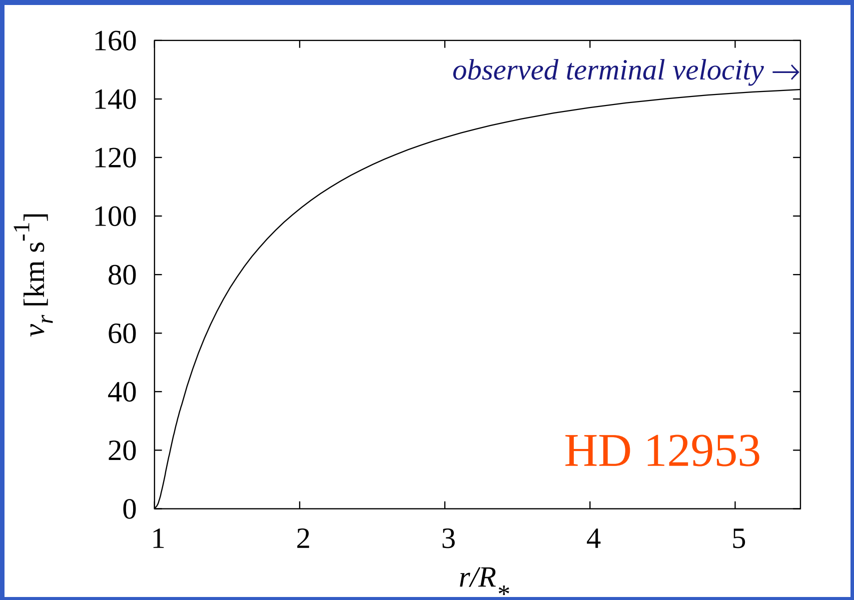
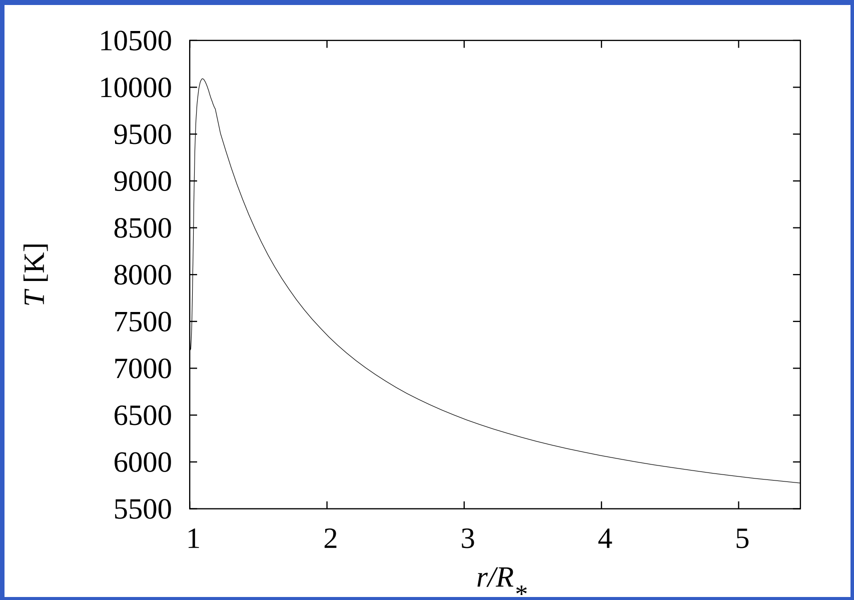
- calculated wind parameters are $\dot{M} = 1.3 \times 10^{-7}\,M_\odot\,\text{year}^{-1}$ and $v_\infty = 140\,\text{km}\,\text{s}^{-1}$

Wind model of HD 12953





Conclusions

- we presented NLTE code which is capable to calculate wind models of A supergiants,
- predicted wind parameters agree relatively well with observed parameters of HD 12953,
- model improvements are necessary (e.g. consistent radiative transfer, inclusion of X-rays, etc.)
- more model testing is necessary.