Modelling of flare processes: comparison of two RHD codes Flarix and RADYN

J. Kašparová[1], M. Carlsson[2], M. Varady[1,3,4], P. Heinzel[1]

[1]Astronomical Institute of the CAS, Ondřejov

[2]Institute of Theoretical Astrophysics, University of Oslo

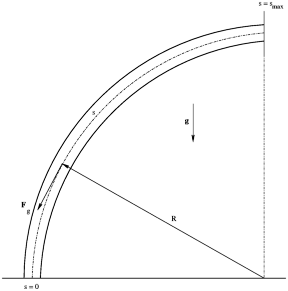
[3]Jan Evangelista Purkyně University in Ústí nad Labem

[4]North Bohemia Observatory in Teplice

15th RHESSI Workshop, Graz, July 26 - 30, 2016

Problem formulation

- hydrodynamic and radiative response of the solar atmosphere to the heating by the particle beams
- 1D scenario
- describe state and evolution of plasma along a single loop
- compute time evolution of continuum and line profiles (H, Ca II, Mg II)



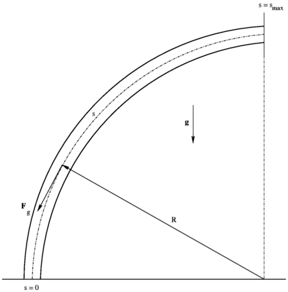
non-LTE RHD codes Flarix and RADYN

Initial hydrostatic atmospheres

- modified VAL C
- atmosphere in radiative equilibrium from RADYN (extra heating at the bottom)

Problem formulation

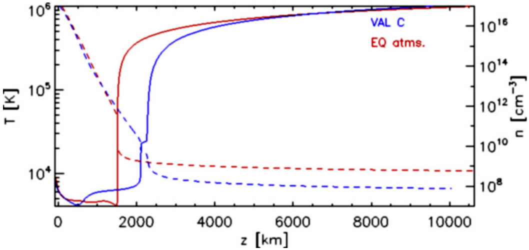
- hydrodynamic and radiative response of the solar atmosphere to the heating by the particle beams
- 1D scenario
- describe state and evolution of plasma along a single loop
- compute time evolution of continuum and line profiles (H, Ca II, Mg II)



non-LTE RHD codes Flarix and RADYN

Initial hydrostatic atmospheres

- modified VAL C
- atmosphere in radiative equilibrium from RADYN (extra heating at the bottom)



Flarix: non-LTE RHD code

- developed at AsI in Ondřejov (Varady et al., 2010)

Hydrodynamics

- standard set of 1D HD equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v_s) = 0 \qquad \frac{\partial(\rho v_s)}{\partial t} + \frac{\partial}{\partial s}(\rho v_s^2) = -\frac{\partial P}{\partial s} + \rho g_s$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial s}(v_s E) = -\frac{\partial}{\partial s}(v_s P) - \frac{\partial}{\partial s}\mathcal{F}_c + \mathcal{S}$$

$$P = n_H(\vartheta + x + \varepsilon)k_B T \qquad E = E_{internal} + \frac{1}{2}\rho v_s^2 \qquad \mathcal{S} = \mathcal{H} - \mathcal{R} + \mathcal{Q}$$

$$\vartheta = 1.1 \qquad \varepsilon = 1.44 \times 10^{-4}$$

- $\mathcal{F}_c$ heat flux (using Spitzer thermal conductivity)
- $\mathcal{H}$ flare heating given by the beam energy deposit
- $\mathcal{Q}$ quiescent heating to assure stability of the initial atmosphere
- $\mathcal{R}$ radiative losses (optically thin + optically thick H, Ca II, Mg II)

Flarix: Flare heating $\mathcal{H}$ through particle beams

Typical beam properties

- power-law flux distribution
- electron, proton or neutral beams
- power-law index $\delta = 3 - 7$
- $E_\mathrm{L} \geq 10$ keV(MeV), $E_\mathrm{H} \leq 500$ keV(MeV)
- prescribed time modulation of the beam flux

Two approaches

- analytic beam energy deposit (Hawley & Fisher, 1994)
- the test particle approach (Varady et al., 2014)
  - Coulomb collisions with neutrals and electrons (Emslie, 1978)
  - electron scattering (Bai, 1982)
  - consistent with Fokker-Planck approach (MacKinnon & Craig, 1991)
  - the return current (runaway approx. optional)
  - secondary re-acceleration by electric fields (optional)
  - beam hard X-ray emission and its directivity

Flarix: Flare heating $\mathcal{H}$ through particle beams

Typical beam properties

- power-law flux distribution
- electron, proton or neutral beams
- power-law index $\delta = 3 - 7$
- $E_L \geq 10$ keV(MeV), $E_H \leq 500$ keV(MeV)
- prescribed time modulation of the beam flux

Two approaches

- analytic beam energy deposit (Hawley & Fisher, 1994)
- the test particle approach (Varady et al., 2014)
  - Coulomb collisions with neutrals and electrons (Emslie, 1978)
  - electron scattering (Bai, 1982)
  - consistent with Fokker-Planck approach (MacKinnon & Craig, 1991)
  - the return current (runaway approx.,optional)
  - secondary re-acceleration by electric fields (optional)
  - beam hard X-ray emission and its directivity

Flarix: Flare heating $\mathcal{H}$ through particle beams

Typical beam properties

- power-law flux distribution
- electron, proton or neutral beams
- power-law index $\delta = 3 - 7$
- $E_{\rm L} \geq 10$ keV(MeV), $E_{\rm H} \leq 500$ keV(MeV)
- prescribed time modulation of the beam flux

Two approaches

- analytic beam energy deposit (Hawley & Fisher, 1994)
- the test particle approach (Varady et al., 2014)
  - Coulomb collisions with neutrals and electrons (Emslie, 1978)
  - electron scattering (Bai, 1982)
  - consistent with Fokker-Planck approach (MacKinnon & Craig, 1991)
  - the return current (runaway approx.,optional)
  - secondary re-acceleration by electric fields (optional)
  - beam hard X-ray emission and its directivity

Flarix: non-LTE radiative transfer

- 1D plane parallel atmosphere in the lower part of the loop
- instant values of T and n_{H} along the loop
- atoms important for radiative losses are treated in detail (H, Ca II, Mg II)
- time dependent equations of statistical equilibrium (ESE)

$$\frac{\partial n_i}{\partial t} = \sum_{j \neq i} n_j P_{ji} - n_i \sum_{j \neq i} P_{ij}$$

  - non-thermal collisional rates can be included into P_{ij}
- radiative transfer equation

$$\mu \frac{\partial I_{\mu\nu}}{\partial \tau_\nu} = I_{\mu\nu} - S_\nu \qquad \mathrm{d}\tau_\nu = -\chi_\nu \mathrm{d}z \qquad S_\nu = \eta_\nu / \chi_\nu$$

- particle and charge conservation equations

$$\sum n_i = n_{\mathrm{atom}} \qquad n_{\mathrm{e}} = n_{\mathrm{p}} + \varepsilon n_{\mathrm{H}}$$

Flarix: non-LTE radiative transfer

- 1D plane parallel atmosphere in the lower part of the loop
- instant values of T and n_{H} along the loop
- atoms important for radiative losses are treated in detail (H, Ca II, Mg II)

- time dependent equations of statistical equilibrium (ESE)

$$\frac{\partial n_i}{\partial t} = \sum_{j \neq i} n_j P_{ji} - n_i \sum_{j \neq i} P_{ij}$$

  - non-thermal collisional rates can be included into P_{ij}

- radiative transfer equation

$$\mu \frac{\partial I_{\mu\nu}}{\partial \tau_\nu} = I_{\mu\nu} - S_\nu \qquad \mathrm{d}\tau_\nu = -\chi_\nu \mathrm{d}z \qquad S_\nu = \eta_\nu / \chi_\nu$$

- particle and charge conservation equations

$$\sum n_i = n_{\mathrm{atom}} \qquad n_{\mathrm{e}} = n_{\mathrm{p}} + \varepsilon n_{\mathrm{H}}$$

Comparison with RADYN

- 1D non-LTE RHD code (Carlsson & Stein, 1997)

RADYN	Flarix
• adaptive spatial grid	• fixed fine spatial grid

• implicit scheme to solve linearised equations
  ◦ Newton-Raphson iteration
	• explicit scheme for HD equations
	  ◦ LCPFCT alg. (convection)
	  ◦ Cranck-Nicholson alg. (conduction)

• ALI techniques (radiative transfer)	• ALI, linearisation of ESE (radiative transfer)
• advection term in ESE	
• analytical formula or Fokker-Planck approach (beam heating)	• analytic. formula or test-particle approach (beam heating)
• more atoms in detail (He)	• return current, re-acceleration
• XEUV heating	• beam HXR emission

Comparison with RADYN

- 1D non-LTE RHD code (Carlsson & Stein, 1997)

RADYN

- adaptive spatial grid
- implicit scheme to solve linearised equations
  - Newton-Raphson iteration
- ALI techniques (radiative transfer)
- advection term in ESE
- analytical formula or Fokker-Planck approach (beam heating)
- more atoms in detail (He)
- XEUV heating

Flarix

- fixed fine spatial grid
- explicit scheme for HD equations
  - LCPFCT alg. (convection)
  - Cranck-Nicholson alg. (conduction)
- ALI, linearisation of ESE (radiative transfer)
- analytic. formula or test-particle approach (beam heating)
- return current, re-acceleration
- beam HXR emission

Comparison with RADYN

- 1D non-LTE RHD code (Carlsson & Stein, 1997)

RADYN

- adaptive spatial grid
- implicit scheme to solve linearised equations
  - Newton-Raphson iteration
- ALI techniques (radiative transfer)
- advection term in ESE
- analytical formula or Fokker-Planck approach (beam heating)
- more atoms in detail (He)
- XEUV heating

Flarix

- fixed fine spatial grid
- explicit scheme for HD equations
  - LCPFCT alg. (convection)
  - Cranck-Nicholson alg. (conduction)
- ALI, linearisation of ESE (radiative transfer)
- analytic. formula or test-particle approach (beam heating)
- return current, re-acceleration
- beam HXR emission

Comparison with RADYN

- 1D non-LTE RHD code (Carlsson & Stein, 1997)

RADYN

- adaptive spatial grid
- implicit scheme to solve linearised equations
  - Newton-Raphson iteration
- ALI techniques (radiative transfer)
- advection term in ESE
- analytical formula or Fokker-Planck approach (beam heating)
- more atoms in detail (He)
- XEUV heating

Flarix

- fixed fine spatial grid
- explicit scheme for HD equations
  - LCPFCT alg. (convection)
  - Cranck-Nicholson alg. (conduction)
- ALI, linearisation of ESE (radiative transfer)
- analytic. formula or test-particle approach (beam heating)
- return current, re-acceleration
- beam HXR emission

Comparison with RADYN

- 1D non-LTE RHD code (Carlsson & Stein, 1997)

RADYN

- adaptive spatial grid
- implicit scheme to solve linearised equations
  - Newton-Raphson iteration
- ALI techniques (radiative transfer)
- advection term in ESE
- analytical formula or Fokker-Planck approach (beam heating)
- more atoms in detail (He)
- XEUV heating

Flarix

- fixed fine spatial grid
- explicit scheme for HD equations
  - LCPFCT alg. (convection)
  - Cranck-Nicholson alg. (conduction)
- ALI, linearisation of ESE (radiative transfer)
- analytic. formula or test-particle approach (beam heating)
- return current, re-acceleration
- beam HXR emission

Comparison with RADYN

- 1D non-LTE RHD code (Carlsson & Stein, 1997)

RADYN

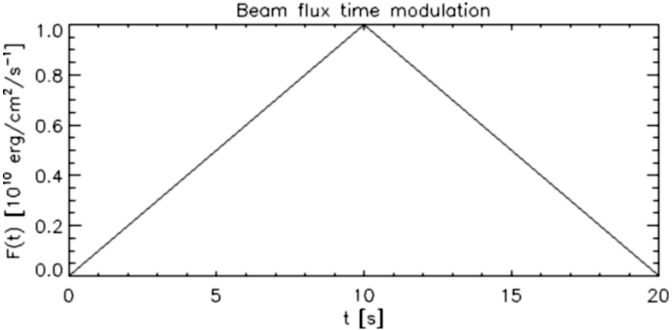
- adaptive spatial grid
- implicit scheme to solve linearised equations
  - Newton-Raphson iteration
- ALI techniques (radiative transfer)
- advection term in ESE
- analytical formula or Fokker-Planck approach (beam heating)
- more atoms in detail (He)
- XEUV heating

Flarix

- fixed fine spatial grid
- explicit scheme for HD equations
  - LCPFCT alg. (convection)
  - Cranck-Nicholson alg. (conduction)
- ALI, linearisation of ESE (radiative transfer)
- analytic. formula or test-particle approach (beam heating)
- return current, re-acceleration
- beam HXR emission

Initial settings for comparison

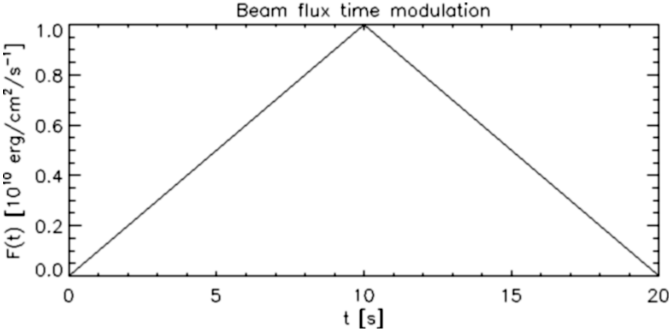
- analytical heating by an electron beam
  - $\delta = 3$, $F_{\max} = 10^{10}$ erg cm^{-2} s^{-1}
  - moderate heating, triangular time modulation
  - 20 s duration, integrated beam flux: 10^{11} erg cm^{-2}



- identical initial atmosphere (VAL C)
- only H and Ca II computed in detail

Initial settings for comparison

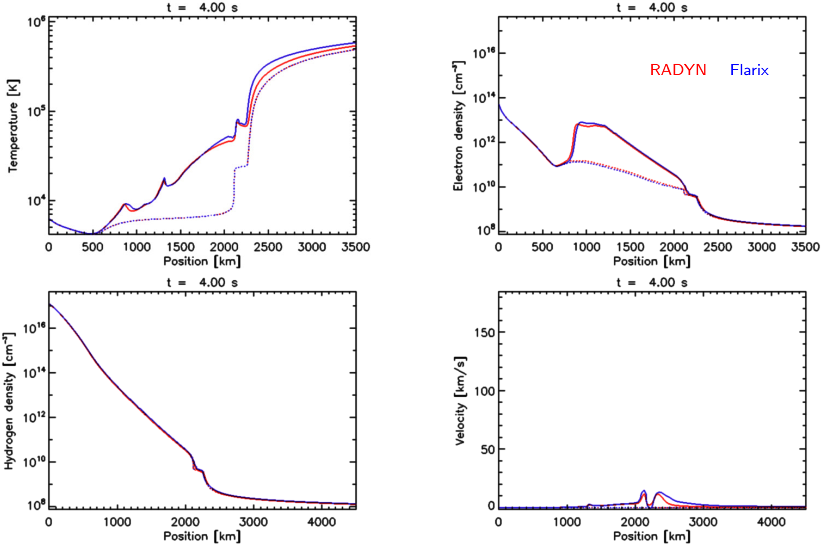
- analytical heating by an electron beam
  - $\delta = 3$, $F_{\text{max}} = 10^{10}$ erg cm^{-2} s^{-1}
  - moderate heating, triangular time modulation
  - 20 s duration, integrated beam flux: 10^{11} erg cm^{-2}



- identical initial atmosphere (VAL C)
- only H and Ca II computed in detail

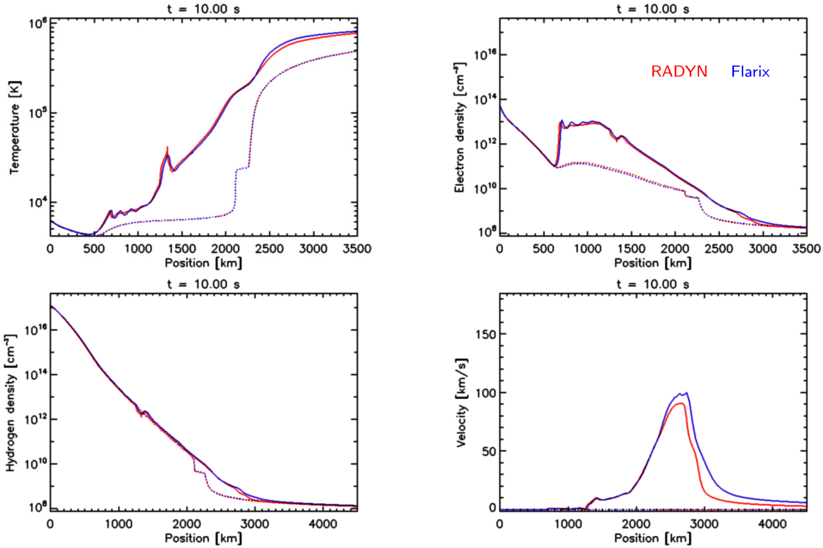
Results of the test model - atmosphere structure

- reasonably good agreement

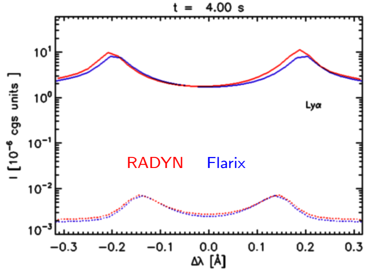


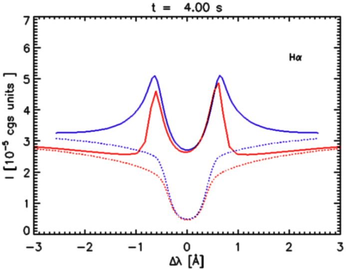
Results of the test model - atmosphere structure

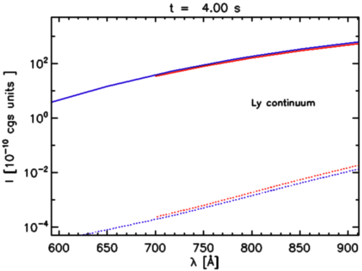
- reasonably good agreement



Results of the test model - spectral lines and continua

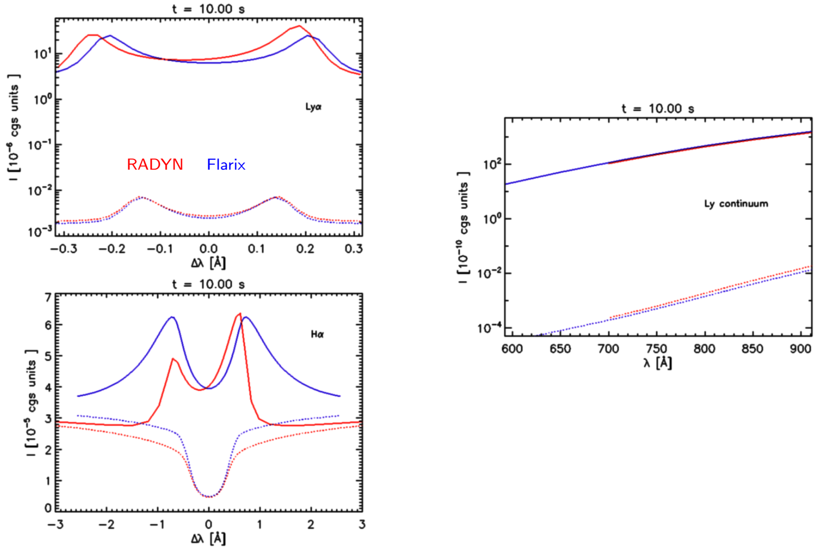






- order of magnitude agreement
- differences due to velocity term, different hydrogen collisional rates

Results of the test model - spectral lines and continua



- order of magnitude agreement
- differences due to velocity term, different hydrogen collisional rates

Summary

- comparison of two independent non-LTE RHD codes was presented
- a simplified model of moderate beam heating was used
- RADYN and Flarix results are in a good agreement despite different concepts of the codes
- there are some discrepancies in the results but the general trends are the same

$\Downarrow$

RADYN and Flarix give comparable results