Particle beams and hydrogen emission in solar flares

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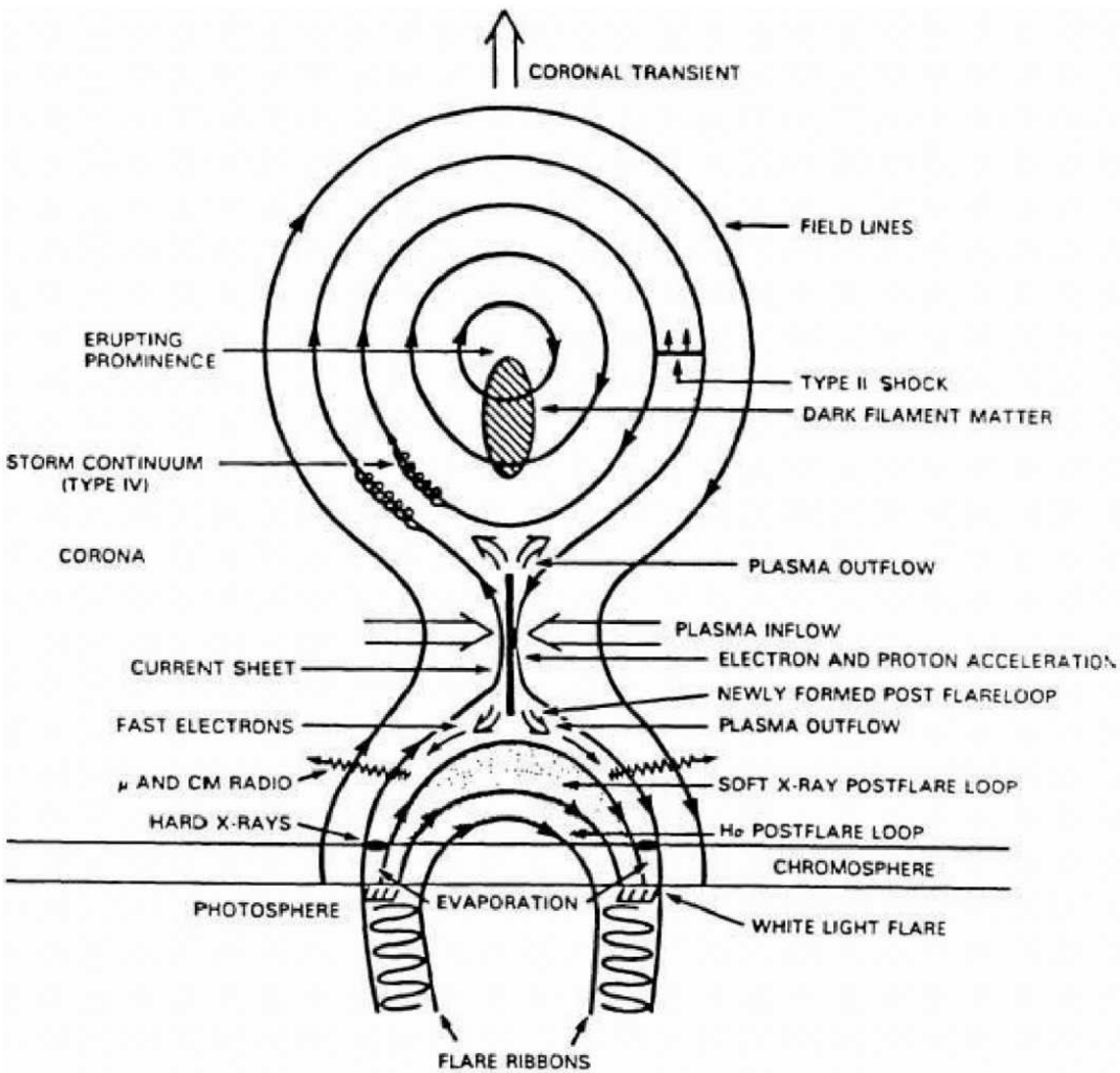
Flare model

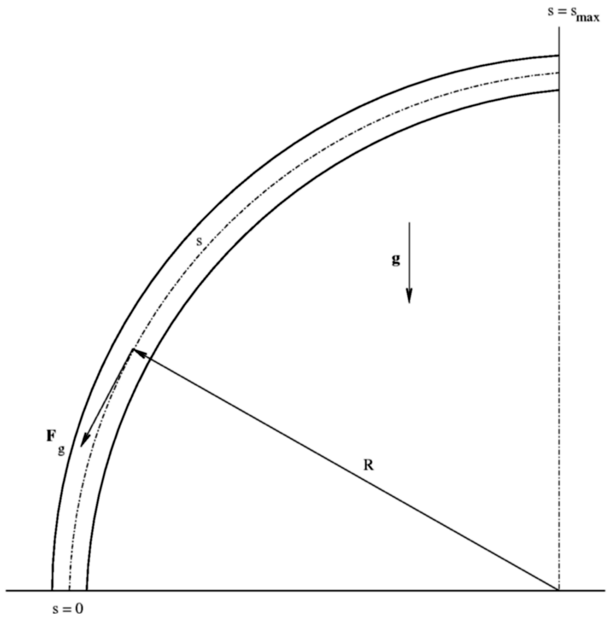


Martens & Kuin, 1989

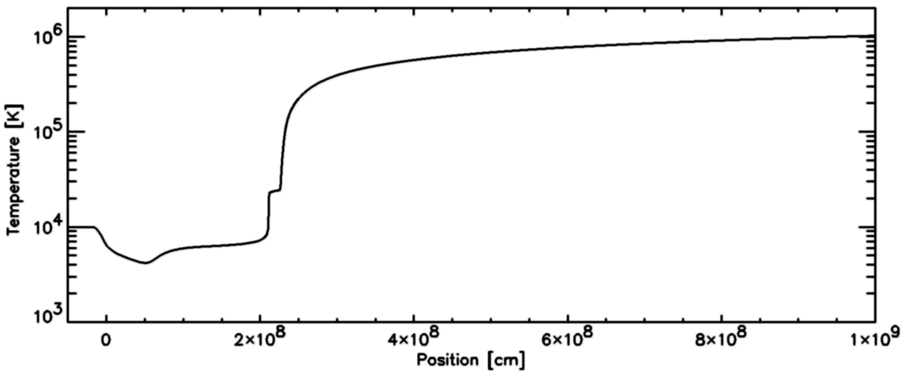
- standard two-ribbon flare
- energy release during mag. reconnection in corona
- plasma heating, particle acceleration
- beams: form of flare energy transport
  - energy loss via Coulomb collision and return current $\Rightarrow$ heating, excitation, ionisation
  - X-ray, radio emission
- increased emission in EUV, UV, optical, IR bands

Problem formulation

- compute time evolution of hydrogen continuum and line profiles
- study influence of particle beams on hydrogen emission
- hydrodynamic and radiative response of solar atmosphere to heating by particle beams: radiative hydro code



- response of hydrostatic VAL C atmosphere to beam heating: HD code
- propagation and energy losses of the beam: test particle code
- ionisation and hydrogen emission: NLTE radiative transfer code

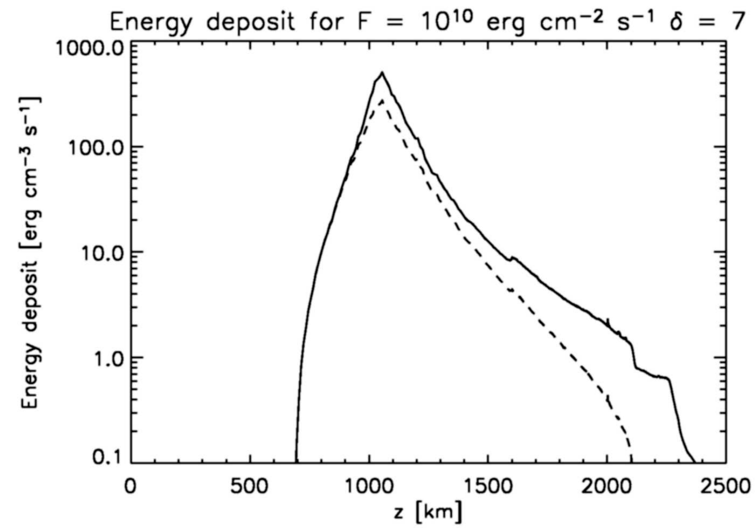


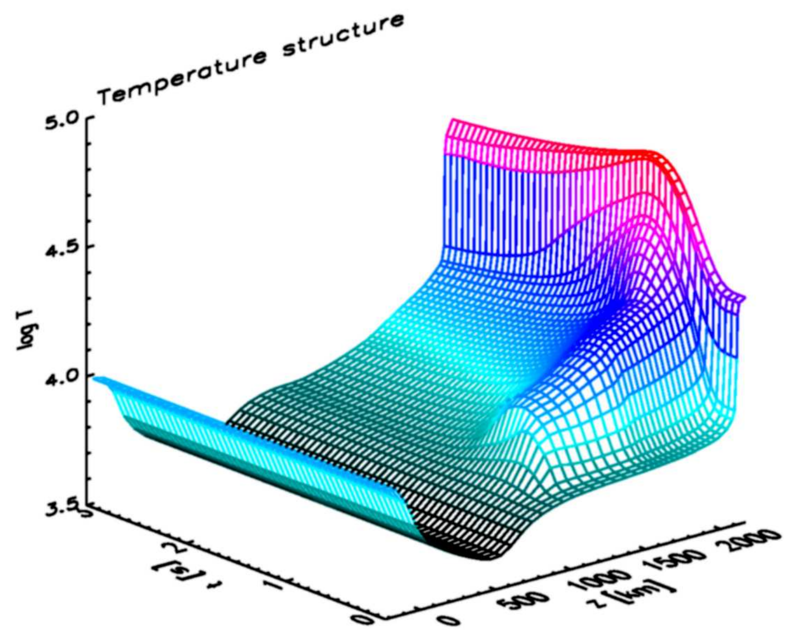
Hydrodynamics (Varady)

- standard set of 1D HD equations in one fluid approximation describes the state and evolution of plasma along magnetic field lines
- included processes
  - thermal conduction (Spitzer's classical approx.)
  - optically thin (Rosner et al., 1978) and thick (Peres et al., 1982) radiative losses (approx. expressions)
  - heating given by beam energy deposit into the atmosphere and return current calculated by a particle code
  - ionisation calculated by a NLTE radiative transfer code
- numerical methods
  - LCPFCT algorithm (for generalised continuity equations)
  - timestep splitting method
  - Crank-Nicholson algorithm for conduction

Particle beam heating (Varady, Karlický, Moravec)

- beam energy deposit is calculated by a test particle code for the instant properties of the atmosphere
- the code includes
  - Coulomb collisions with neutrals and electrons (Emslie, 1978)
  - electron scattering (Bai, 1982)
  - optionally return current (runaway approx., Varady et al., 2005)
- power-law particle beams
  - power-law index $\delta = 3 - 7$
  - low-energy cutoff ≈ 10 keV (MeV) and high-energy cutoff ≈ 100 keV (MeV)
  - time modulation of energy flux $F(t)$
  - properties could be obtained from X-rays





Radiative transfer (Kašparová, Heinzel)

- NLTE radiative transfer for hydrogen is calculated in the lower part of the loop using the instant values of T, n_{H} and the energy deposit to hydrogen E_{H}

- 5-level + continuum model of hydrogen

- time dependent ESE

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

- excitation and ionisation of hydrogen by the particle beam is taken into account by nonthermal collisional rates C_{1j}^{nt} (Fang et al., 1993)

$$C_{1j}^{\mathrm{nt}} = k_{1j} \frac{E_{\mathrm{H}}}{n_1}$$

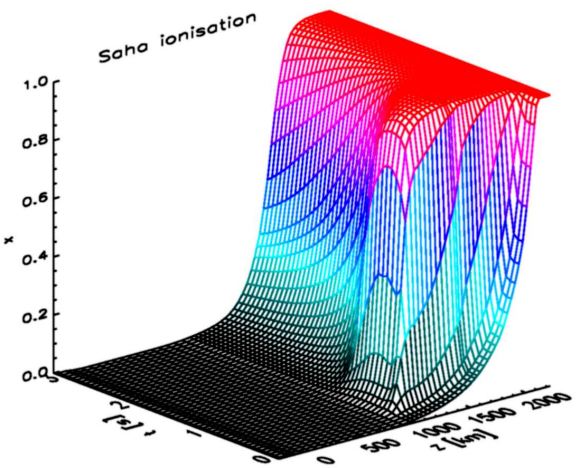
- C_{1j}^{nt} included into transition rates P_{ij}

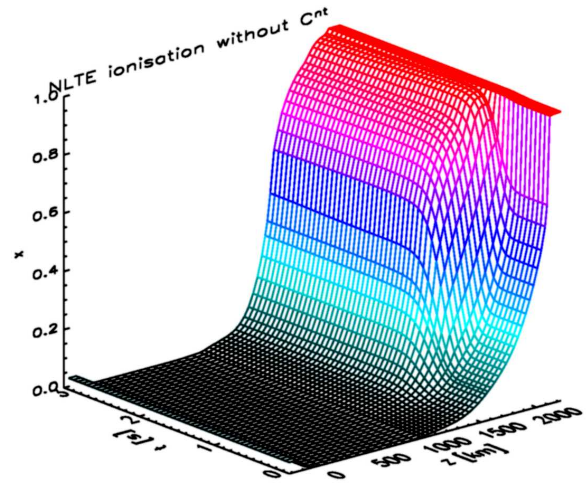
$$P_{1j} = R_{1j} + C_{1j} + C_{1j}^{\mathrm{nt}}$$

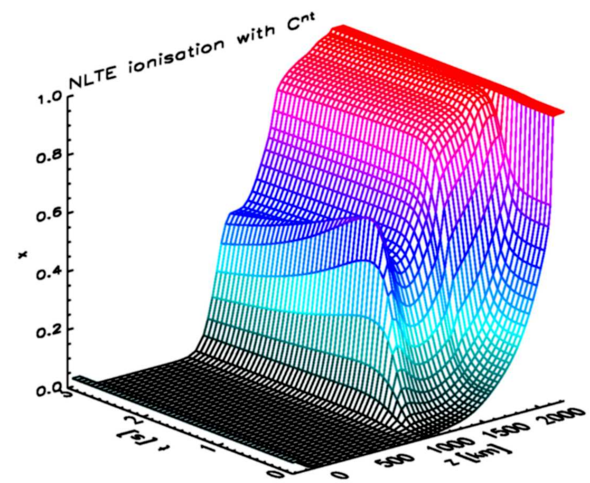
- numerics: MALI, linearisation of ESE, Newton-Raphson, Crank-Nicholson schemes

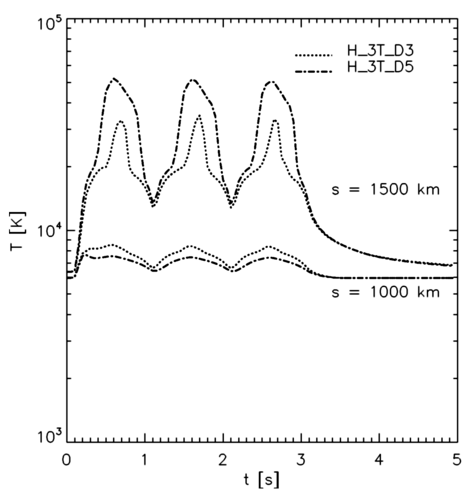
Effects of the $C^{\rm nt}$ - ionisation

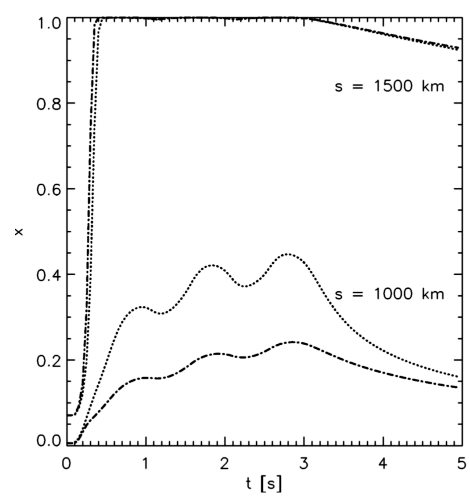
- NLTE ionisation lags behind the time evolution of T due to time evolution of the ratio of the number of recombinations to photoionisations
- $C^{\rm nt}$ increase ionisation ≈ 1000 km where temperature increase itself does not completely ionise the plasma
  - stronger effect for high beam energy flux F and low index δ







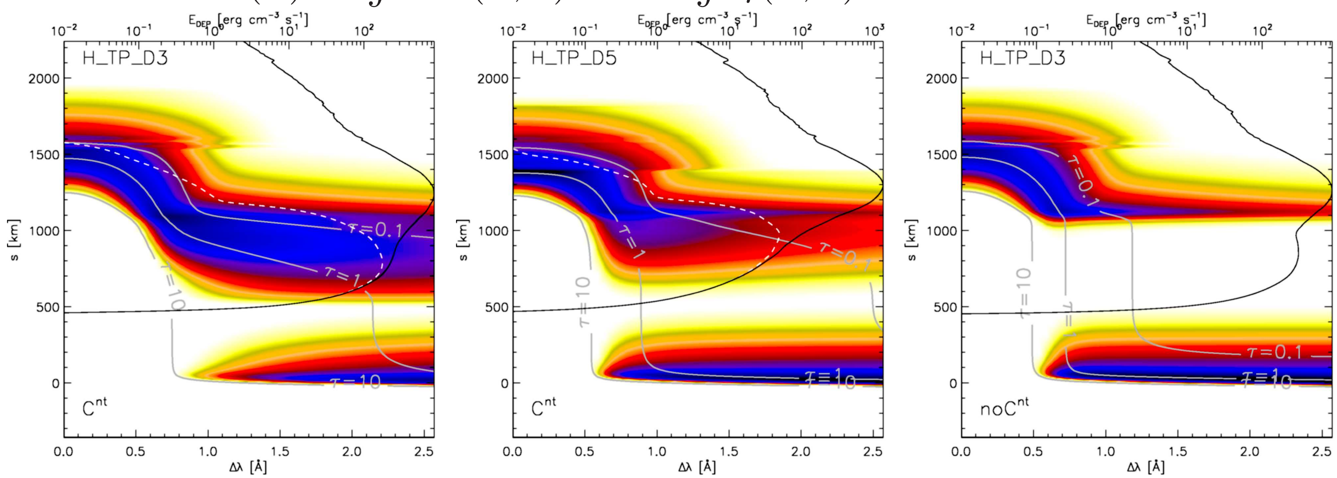




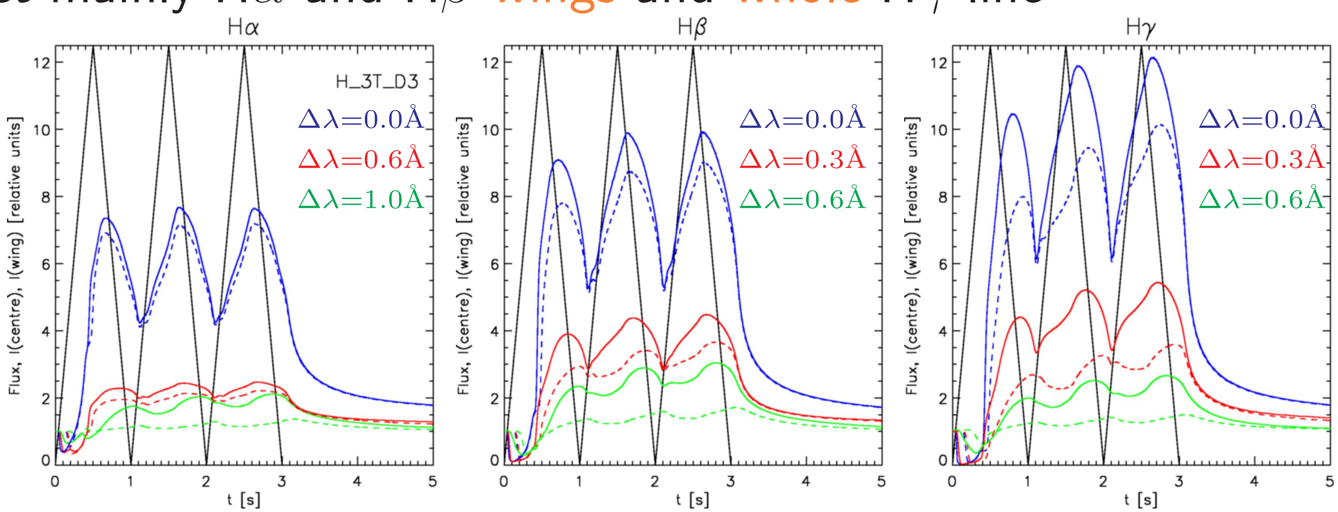
Effects of the $C^{\rm nt}$ - Balmer lines

- $C^{\rm nt}$ influence is strongly linked to $E_{\rm H}$ as a function of height
  - line intensities are affected according to their formation heights

$$I(\lambda) = \int CF(\lambda, s)\ \mathrm{d}s = \int \eta(\lambda, s) e^{-\tau(\lambda, s)}\ \mathrm{d}s$$



- new Hα wing formation region at $E_{\rm H}$ maximum, stronger for lower δ
- $C^{\rm nt}$ affect mainly Hα and Hβ wings and whole Hγ line

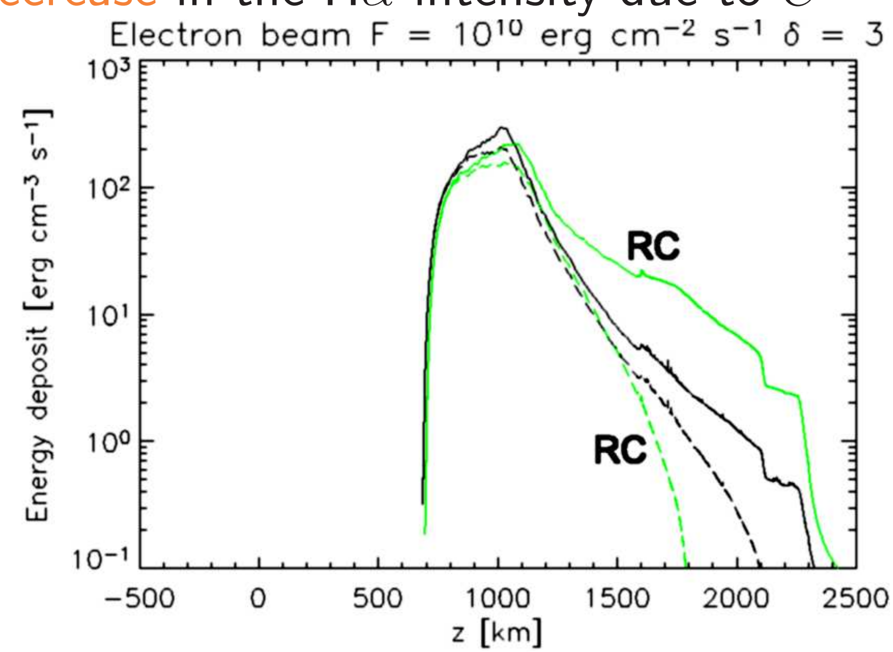


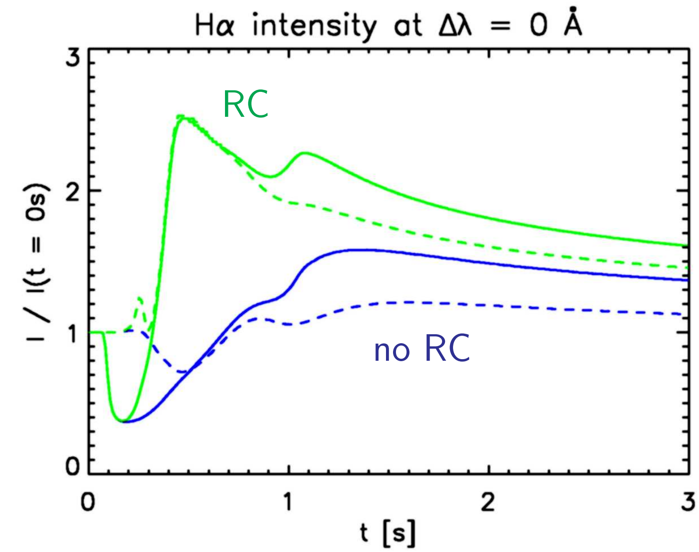
Effects of the return current (RC) - Hα line

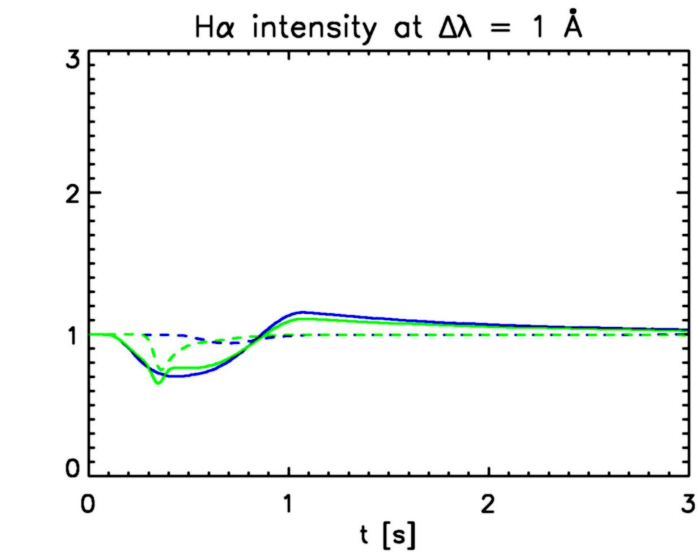
- return current in runaway approximation:

$$j_{\mathrm{b}} = j_{\mathrm{RC}} \qquad \alpha = n_{\mathrm{RC}}/n_{\mathrm{e}} = 0.1$$

- increase in the Hα line centre intensity at $\sim$ 0.4 s
  - result of the higher total energy deposit and subsequent temperature increase at $\sim$ 2000 km
  - C^{nt} again create new formation region at E_{H} peak location
- decrease in the Hα intensity due to C^{nt}

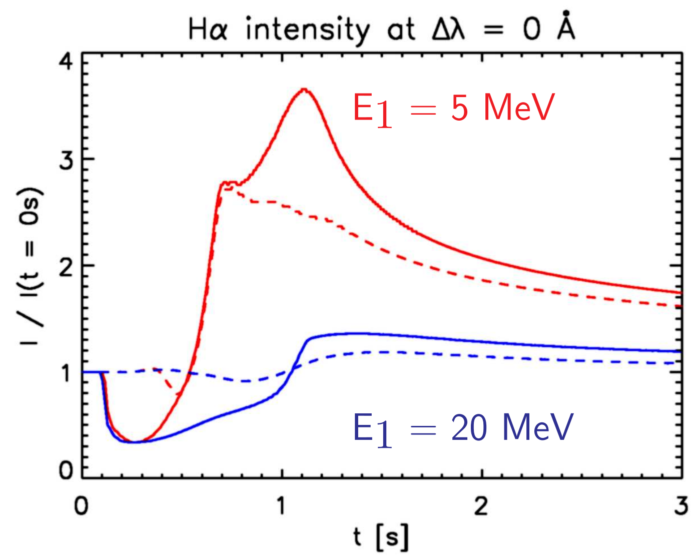


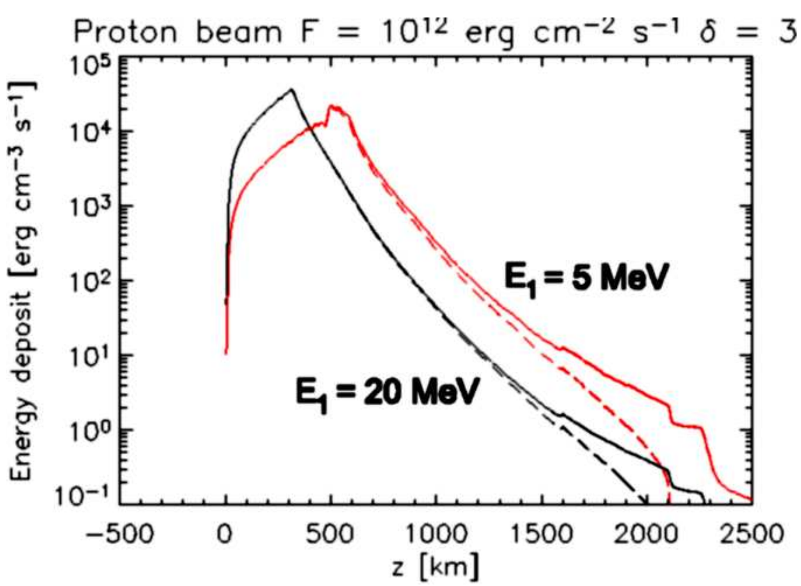


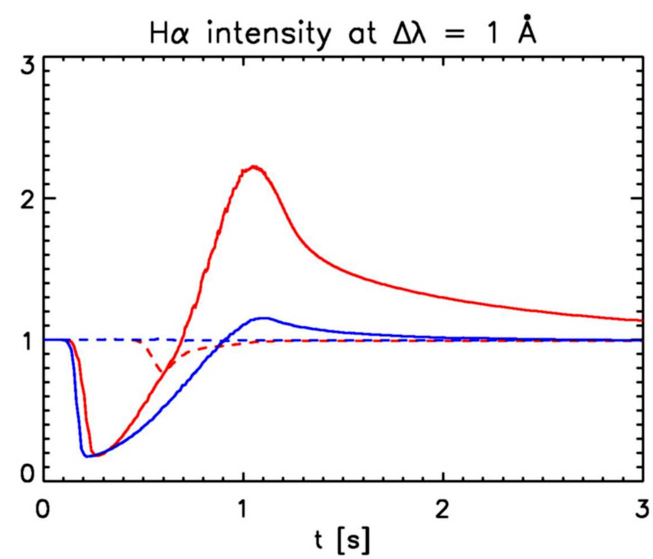


C^{nt} FOR PROTON BEAMS - Hα LINE

- $\delta = 3,\ F = 10^{12}$ erg cm^{-2} s^{-1}
- $E_1 = 5,\ 20$ MeV
  - same hard X-rays as electron beams (deka-MeV protons)
  - higher energy deposit, temperature at $z \geq 500$ km for $E_1 = 5$ MeV



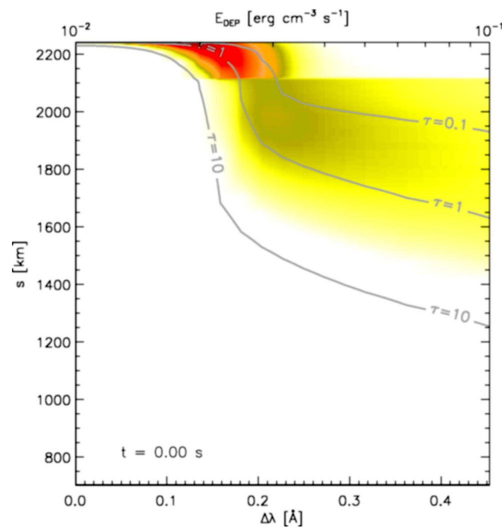


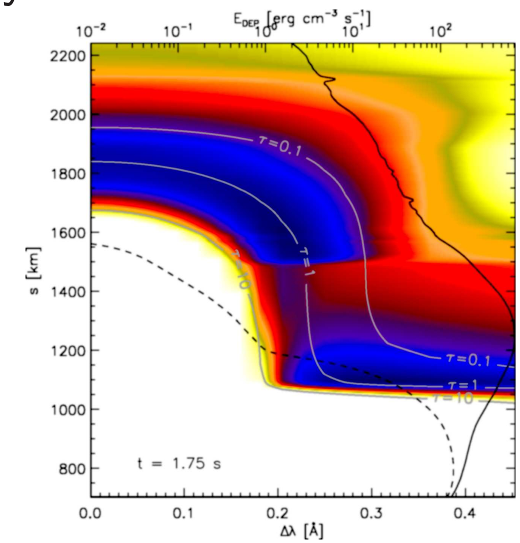


Electron beams - Lyα

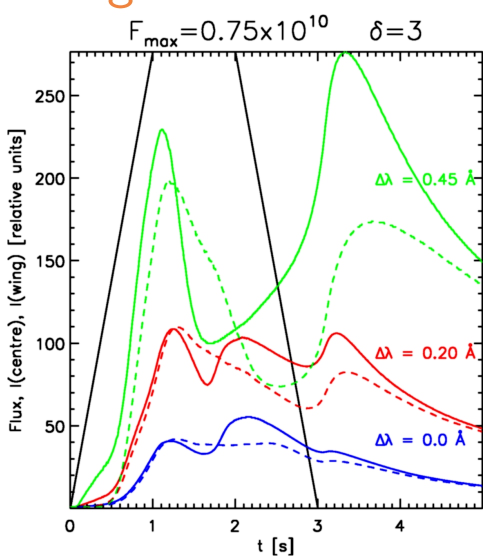
- during heating Lyα is formed in lower atmospheric layers

$CF_t(\lambda, z)$

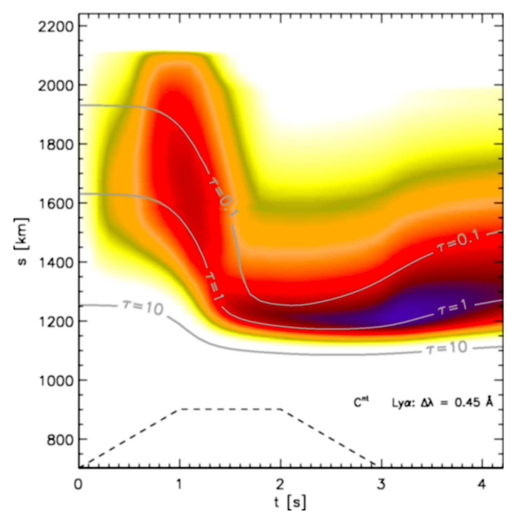




- line wings are more sensitive to $C^{\rm nt}$ (like Balmer lines)



$CF_\lambda(t, z)$

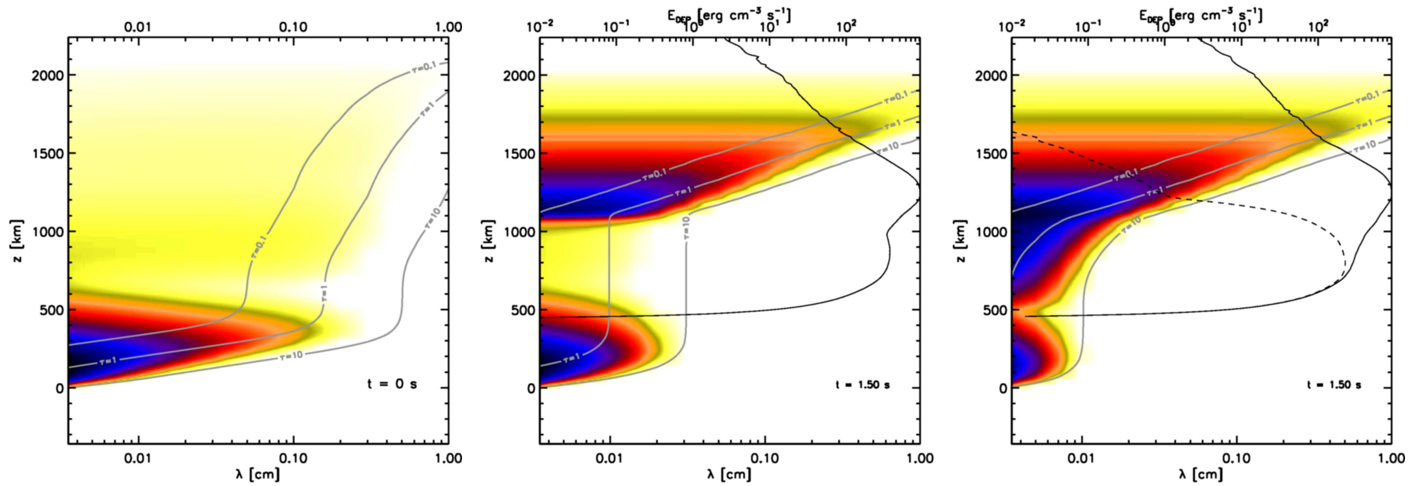


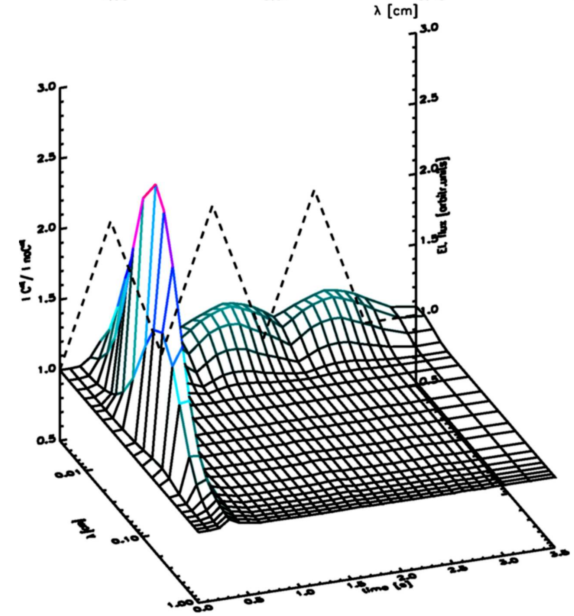
- abrupt drop at $\lambda = 0.45$ Å is due to narrowing of formation region; η, τ decrease due to decrease in n_1, n_2 caused by $C^{\rm nt}$ and heating

Electron beams - far IR and mm continua (35μm - 1cm)

- assumed to be of thermal origin and due to H I and H^- free-free processes
  - Planck source function (LTE), opacity κ_ν calculated using non-LTE populations

$$\kappa_\nu = n_e n_p \; f(T,\nu) + n_e n_H \; g(T,\nu)$$

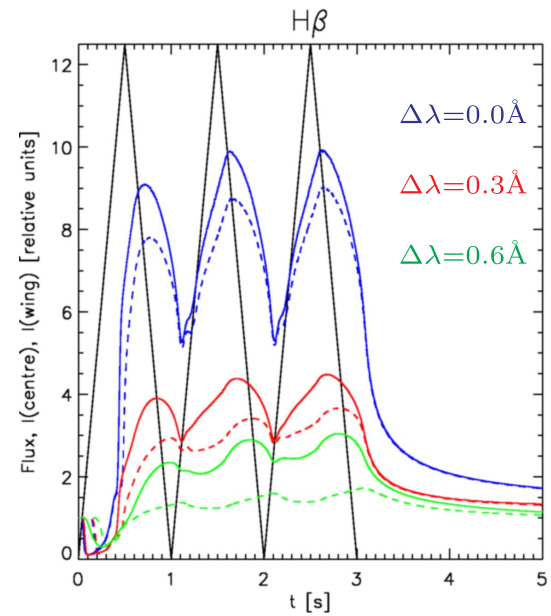


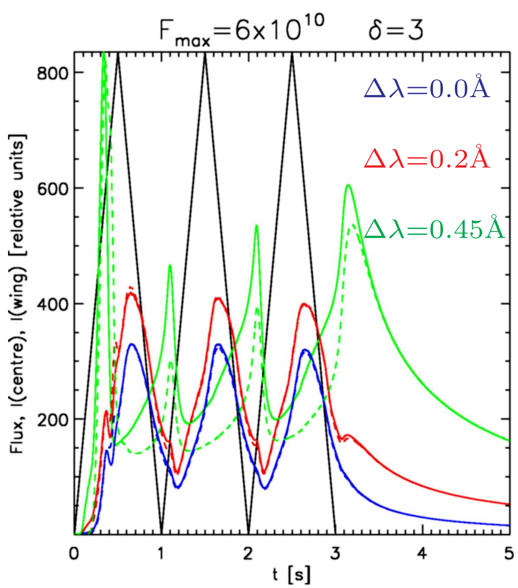


- $C^{\rm nt}$ affect $\lambda < 0.2$ mm since larger λ originates at layers above significant $E_{\rm H}$

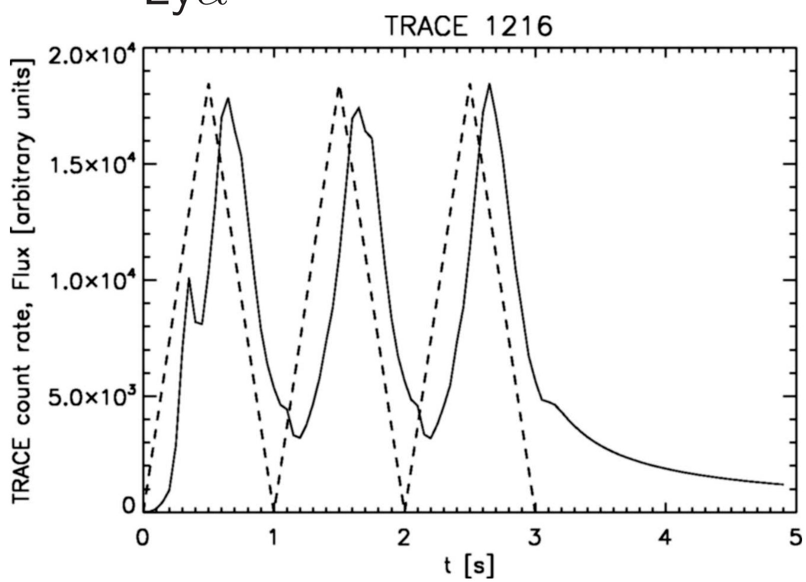
Diagnostic tools - time correlation

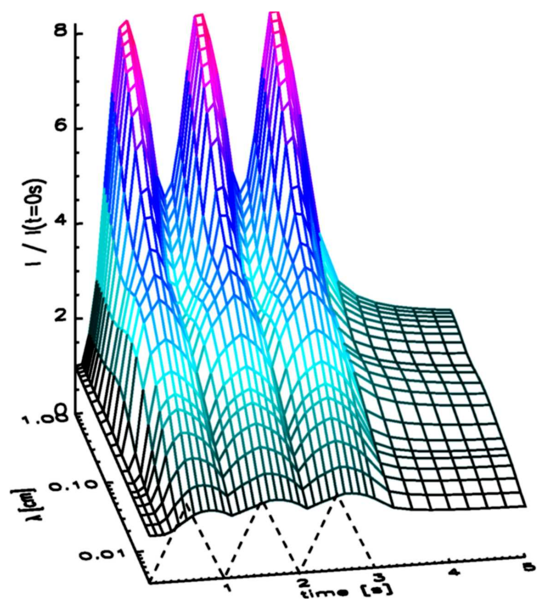
- can we clearly recognise C^{nt} effects in hydrogen emission?
  - fast hydrogen lines/continua variations exhibit a good correlation with beam flux variations
  - Lyα wings show anti-correlation





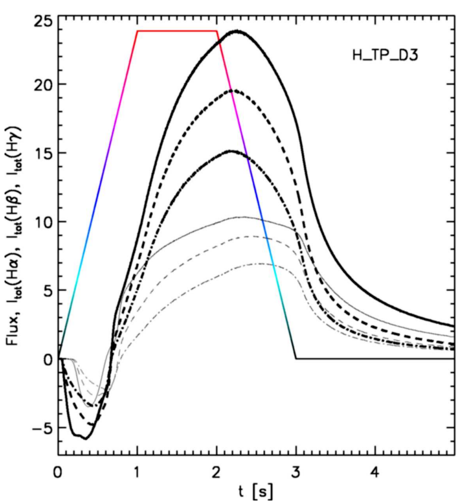
Lyα

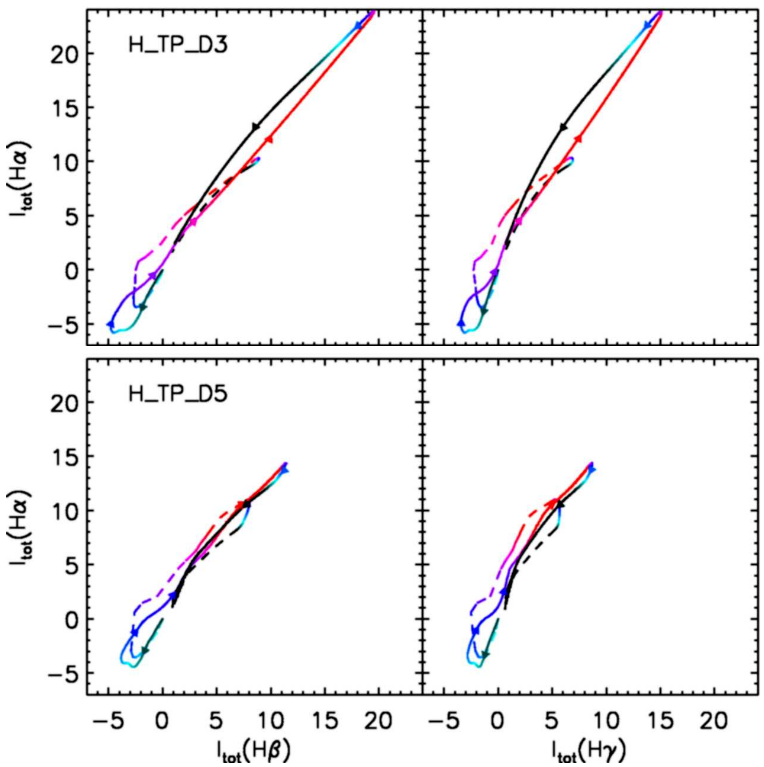


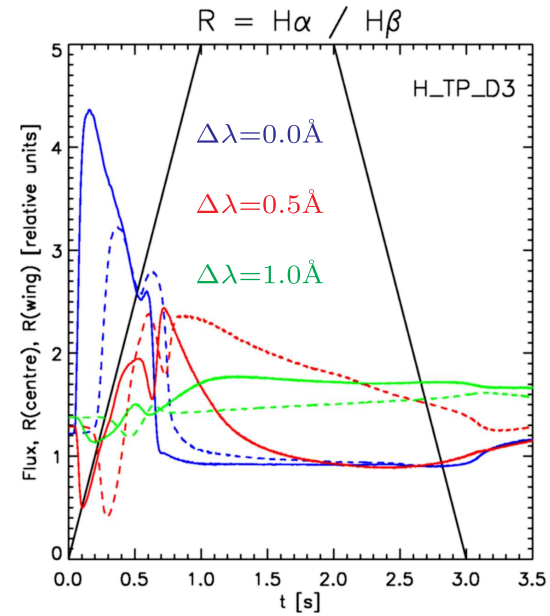


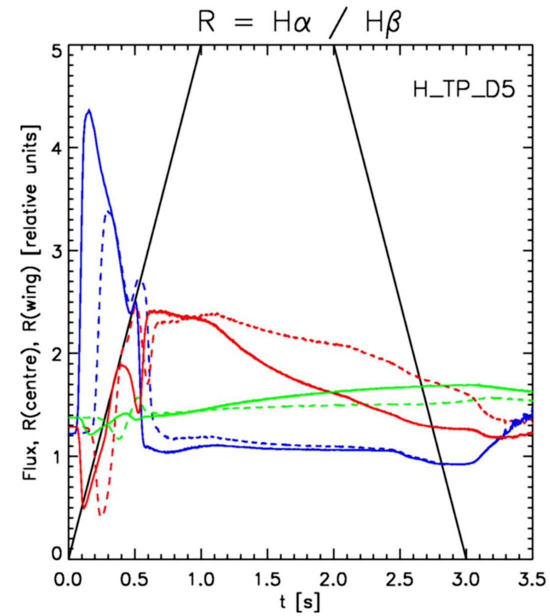
Diagnostic tools - beam parameters

- despite clear influence of C^{nt} on hydrogen emission, unambiguous diagnostic tool has not been found
  - line/intensity ratios R or wavelength-integrated intensity I_{tot} do not exhibit unique and systematic behaviour with beam parameters









Conclusions and future plans

- electron/proton beam heating significantly affects hydrogen emission on time scale of the heating
- correlation of lines/continua variations with hard X-rays presents only an indirect indication of pulse beam heating

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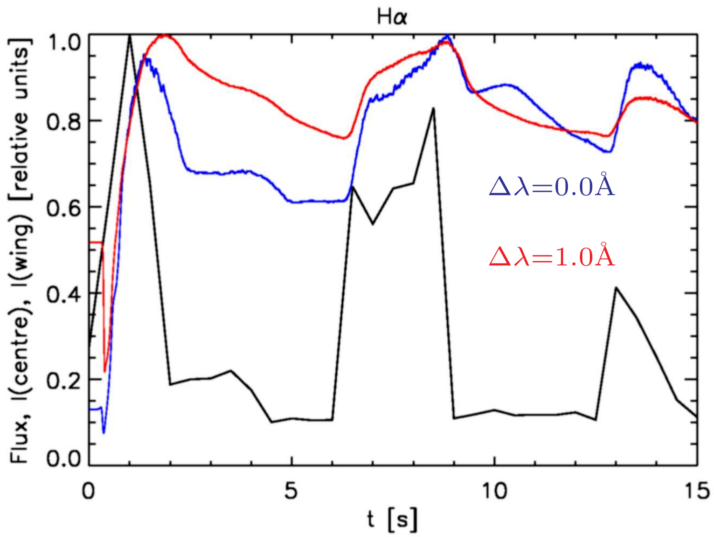
comparison of simulations with observations is needed

- test flare, electron beam parameters from Yohkoh, however no hydrogen data
- more RHESSI flares, Hα data available (Wrocław, Ondřejov)



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