NON-THERMAL ELECTRON DIAGNOSTICS IN THE CORONA IN VARIOUS WAVELENGTH RANGE

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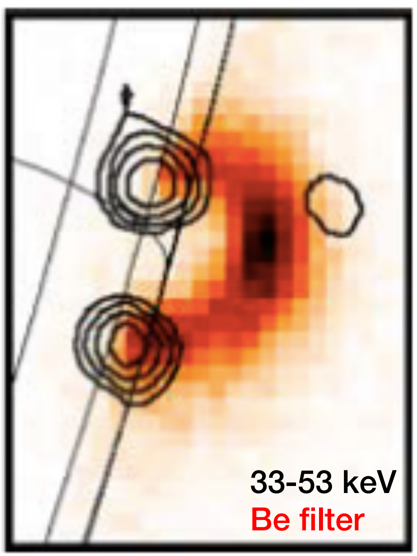
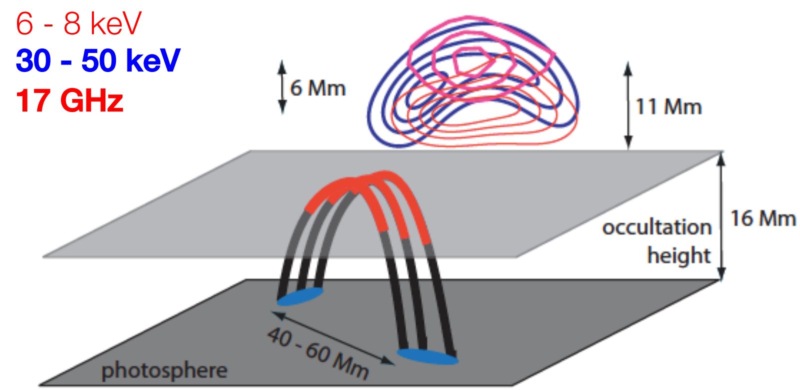
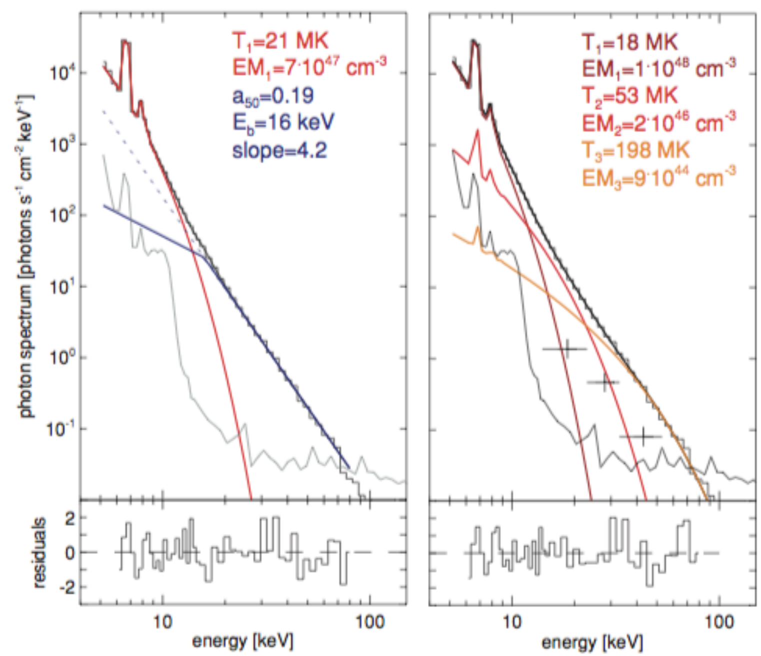
PARTICLE DIAGNOSTICS AROUND THE ENERGY RELEASE REGION

- Observation for the non-thermal particles
  - Hard X-ray (>~10 keV) – electron-ion bremsstrahlung
  - Microwave (~ 10 GHz) - gyrosynchrotron
- Hard X-ray and microwave sources above the soft X-ray loop
  - Acceleration region?
  - Super-hot plasma?



Masuda et al. (1994)





Krucker et al. (2010)

EUV/SXR LINE FORMATION

under the coronal approximation…

excitation is mainly by electron collision,
de-excitation by spontaneous de-exc.

$$I(\lambda_{ij}) = \frac{1}{4\pi d^2} \int_V N_j A_{ji}\, \mathrm{d}V \quad (\mathrm{photons\ cm^{-2}\ s^{-1}\ st^{-1}})$$

$$N_g(X^{+m}) N_e C^e_{gj} = N_j(X^{+m}) A_{jg}$$

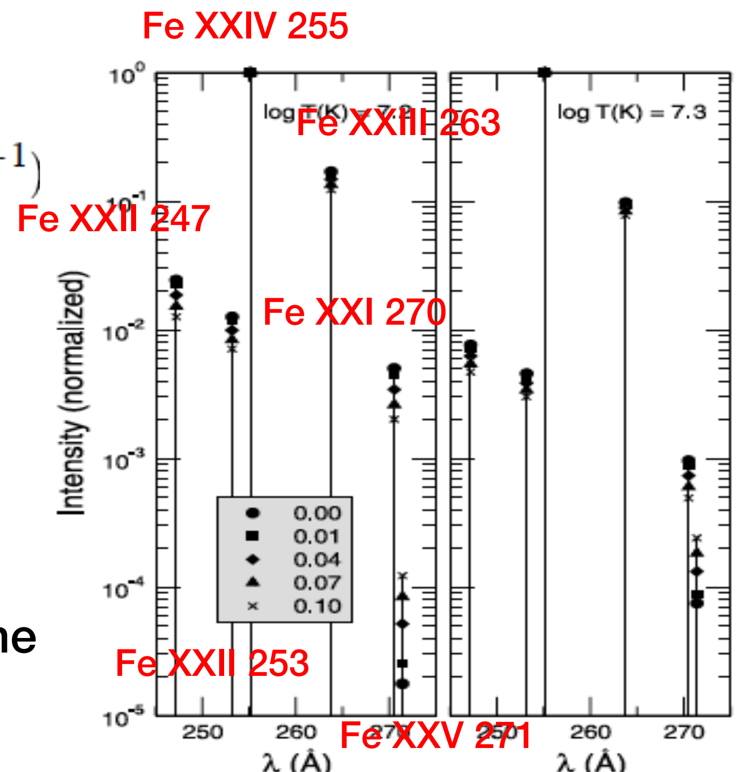
(j : upper level, g: ground level)

A_{ji} – Einstein coefficient
C_{gj} – excitation rate coefficient

C_{gj} is the integration of the collisional cross-section and electron energy distribution over the colliding electron energy

$$C_{gj} = \int_0^\infty v\sigma(v) f(v) dv$$

-> intensity contains information of the electron energy distribution



Feldman et al. 2008

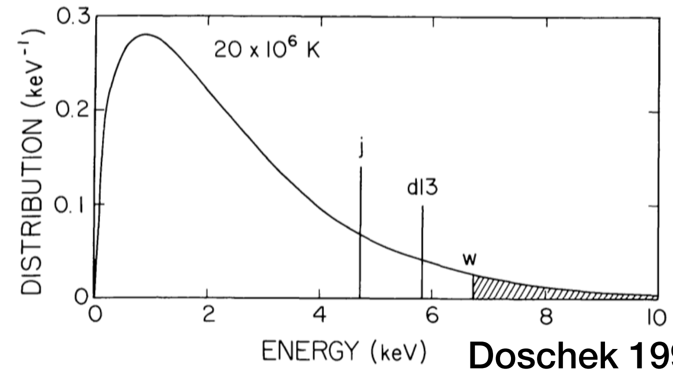
TEMPERATURE (~ELECTRON DISTRIBUTION) DIAGNOSTICS

Intensity without EM term, i.e., without filling factor, is derived from the line ratios (if we can assume the lines are emitted from the same volume)

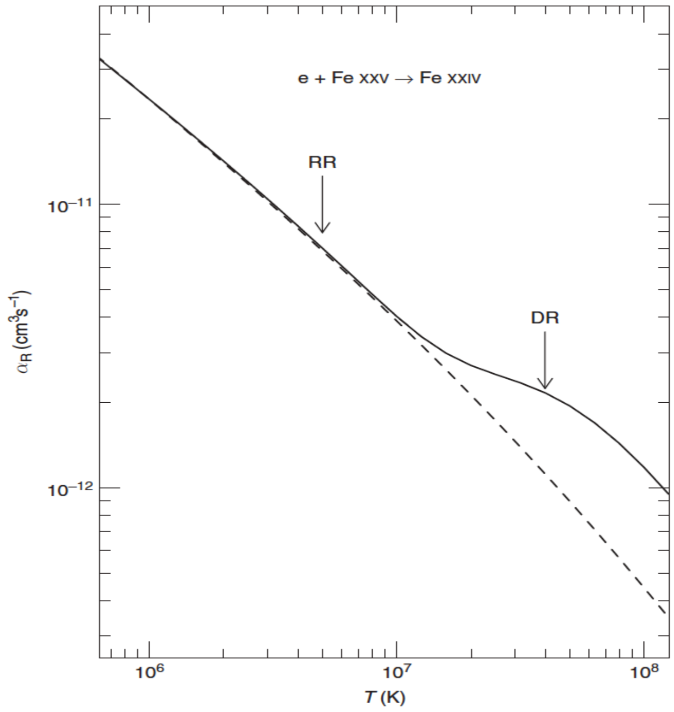
Temperature diagnostics - line pairs whose excitation potentials are significantly different

- with lines with different ionisation stage at EUV wavelength
- with resonance and dielectronic satellite lines at SXR wavelength

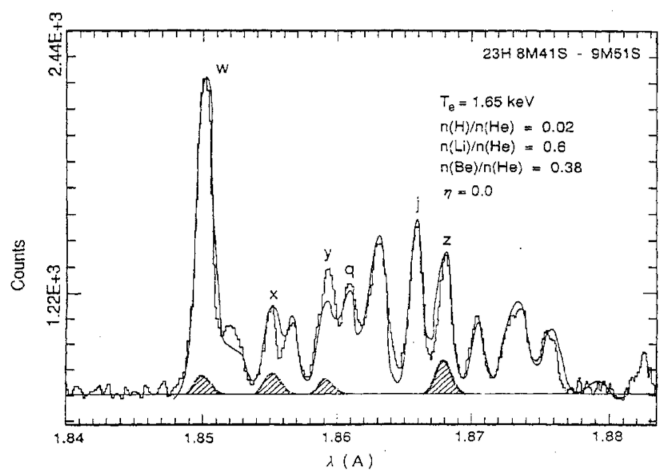
- *Resonance line* - emissivity depends on the population of its ionisation stage
- *Dielectronic satellite line* – emissivity depends on the population of the recombining ion



Doschek 1990



Pradhan&Nahar 2011



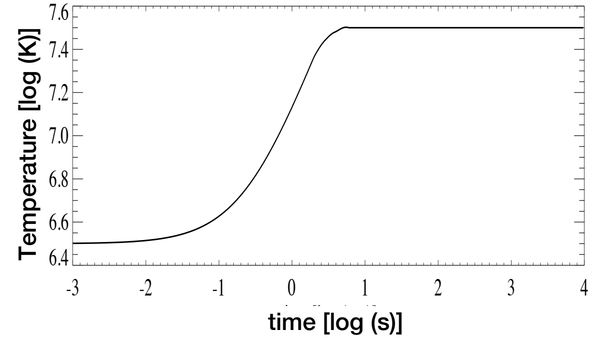
Kato et al. 1997

NON-EQUILIBRIUM PROCESSES

Plasma diagnostics with EUV/SXR lines is, in most cases, assuming the ionisation equilibrium + Maxwellian electron distribution

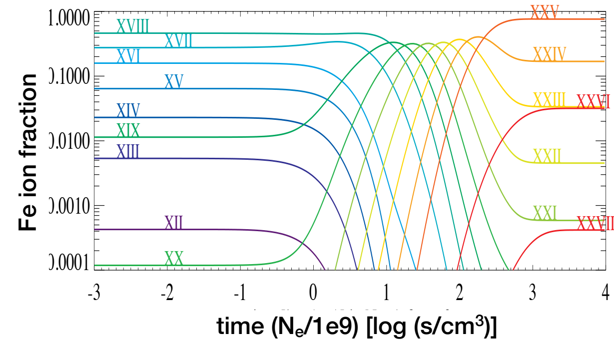
Heating/acceleration timescales

- Electron acceleration ~ 0.1-1 s?
- Chromospheric evaporation ~ 10 s

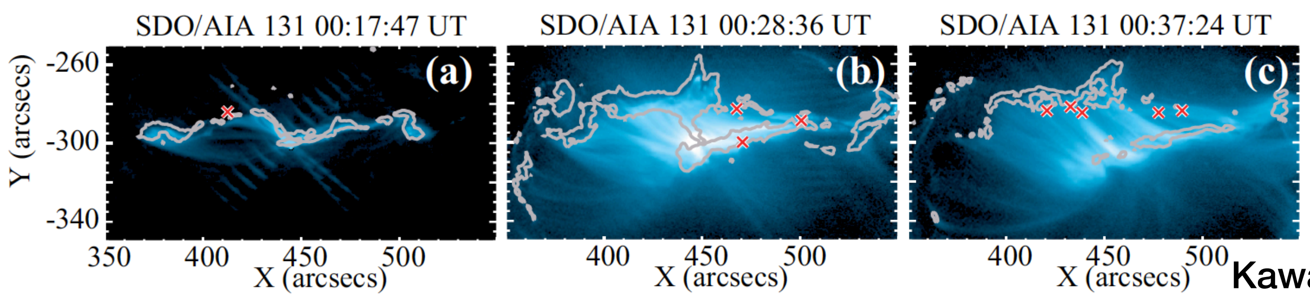


Relaxation timescales

- Radiative de-excitation for allowed lines ~ ps-ns
- Collisional excitation ~ collisional de-excitation ~ ms
- Radiative recombination ~ collisional ionisation ~ 100 s



- Electron precipitation ~ 0.1 s
- Radiative cooling timescale in the corona ~ 1000 s



Kawate et al. (2016)

MOTIVATION OF THIS STUDY

In this study

- perform Numerical examination by solving 1.5D Fokker-Planck equation
- calculate emissivities of HXR/MW as well as EUV/SXR lines under non-Maxwellian electron distribution and non-equilibrium ionisation
- derive the departure from the equilibrium state of SXR/EUV lines to examine the nonthermal electron distribution by using these line ratios

to compare the significance emissivities from the nonthermal electron distribution, and examine capability of detection of nonthermal electron distribution from EUV/SXR line spectroscopy in a dynamic flare loop

NUMERICAL SETUP

1.5D non-stationary Fokker-Planck equation (Lu & Petrosian 1988)

$$\frac{\partial f}{\partial t} = -c\beta\mu\frac{\partial f}{\partial s} + c\beta\frac{d\ln B}{ds}\frac{\partial}{\partial \mu}\left[\frac{1-\mu^2}{2}f\right] + \frac{c}{\lambda_0}\frac{\partial}{\partial E}\left(\frac{f}{E}\right) + \frac{c}{\lambda_0\beta^2\gamma^2}\frac{\partial}{\partial\mu}\left[\left(1-\mu^2\right)\frac{\partial f}{\partial \mu}\right] + S(E,\mu,s,t)$$

- Injection only at t=0 from the looptop with Gaussian spatial distribution
- Symmetric loop with Mirror ratio = 1.6, B_{FP} = 800 G located at the limb
- Loop length = 6 x 10^9 cm
- Initial electron distribution – Maxwellian (T=10^7 K) + κ-distribution (T=10^7 K, δ=3)
- ambient density $n_e = n_i = 10^{10}$ cm^{-3} distributed isotropically in the loop
- Calculation energy range 0.1 ev < E < 10 MeV
- looking at the first 10 sec (to ignore the chromospheric evaporation)

Calculate emissivities of

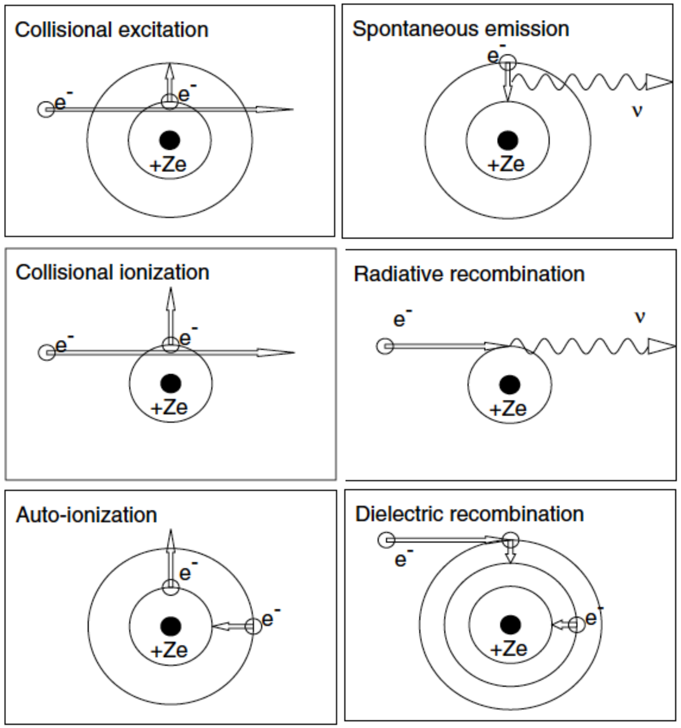
- Thin-target HXR (Bethe-Heitler σ in Koch&Motz 1959)
- Gyrosynchrotron at 17 GHz (assuming single power law in Ramaty 1969)
- Fe XXII 247, Fe XXIII 263, Fe XXIV 255 EUV resonance lines
- Fe XXV 1.85 SXR resonance line
- Fe XXIV 1.85, 1.86 SXR dielectronic satellite lines

EUV/SXR EMISSIONS

Rate equation

$$\frac{\partial n_i}{\partial t} + \nabla \cdot n_i \mathbf{v} = n_e \left[n_{i+1}\alpha_{i+1} + n_{i-1}S_{i-1} - n_i(\alpha_i + S_i) \right]$$

α – recombination rate
S – ionisation rate



Aschwanden 2005

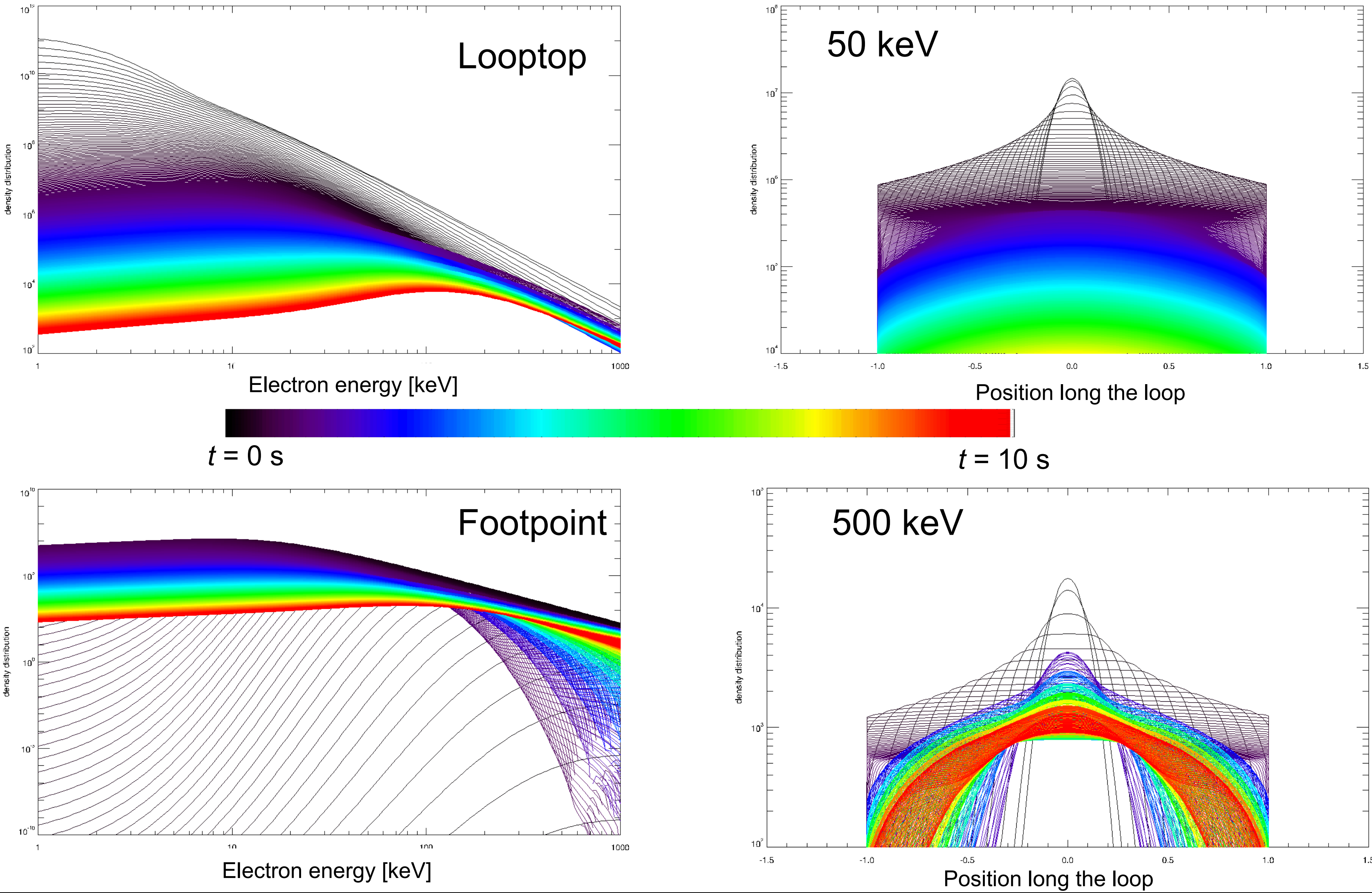
- Solving the balance of populations in ionisation/recombination (radiative + dielectronic) processes
- Assuming ions are excited only by electron collision, and resonance lines are the 2-level process between ground state and excited state

Note: the ionisation/recombination/excitation rates are functions of electron energy distribution, and transition rates are determined at each time step

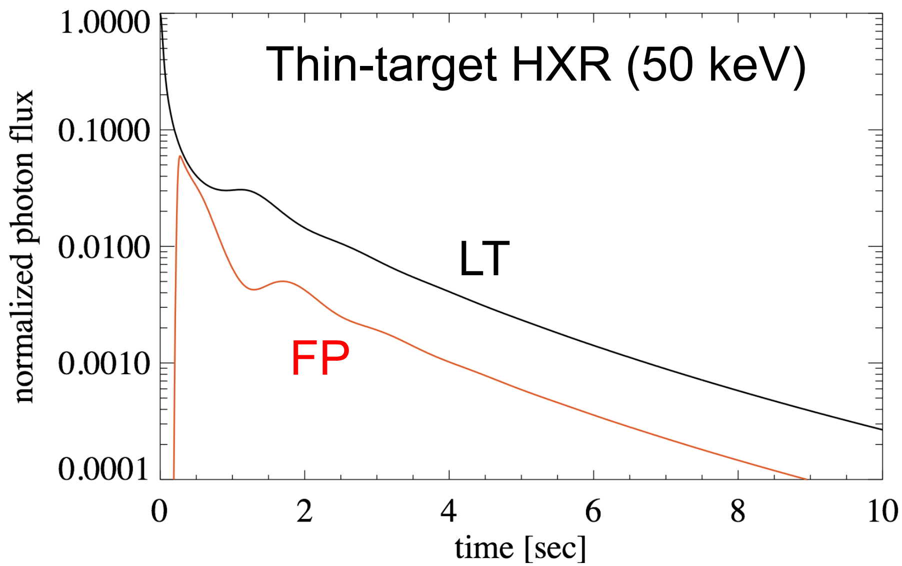
$$\alpha_i = \int_0^\infty v\sigma(v)f(v)dv$$

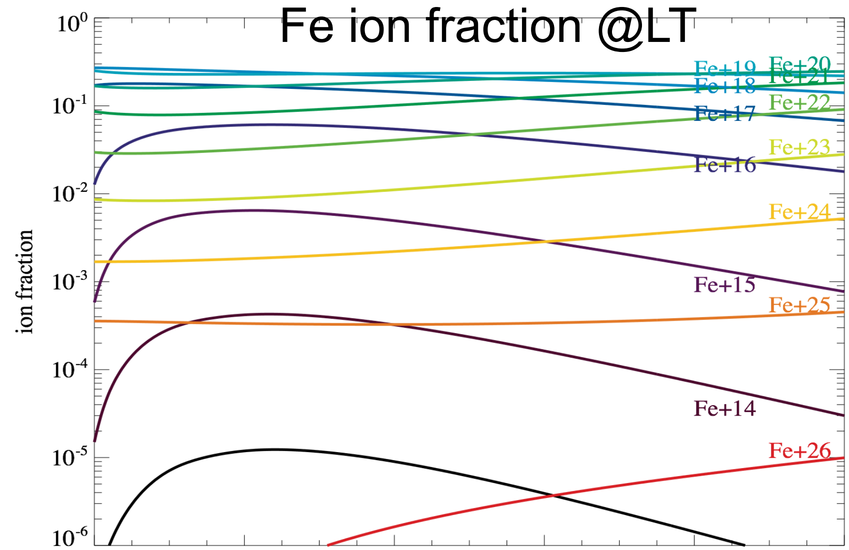
- Initial ionisation balance of $T = 10^{6.5}$ K – Bryans et al. (2009)
- Electron collisional ionisation σ – Dere et al. (2007)
- Radiative recombination σ – derived by photo-ionisation σ in Verner & Yakovlev (1995)
- Dielectronic recombination rate – modifying from the transition rate under the Maxwellian distribution (Bryans 2005)
- Excitation σ of resonance lines - IAEA/ALADDIN Database
- Other transition rates and statistical weight data – CHIANTI v8 and NIST database

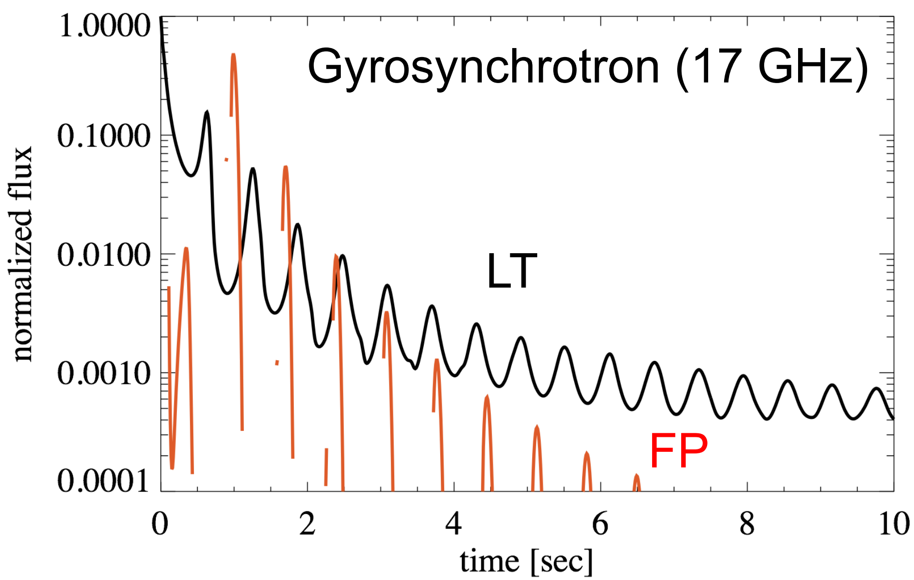
RESULT – ELECTRON DISTRIBUTION

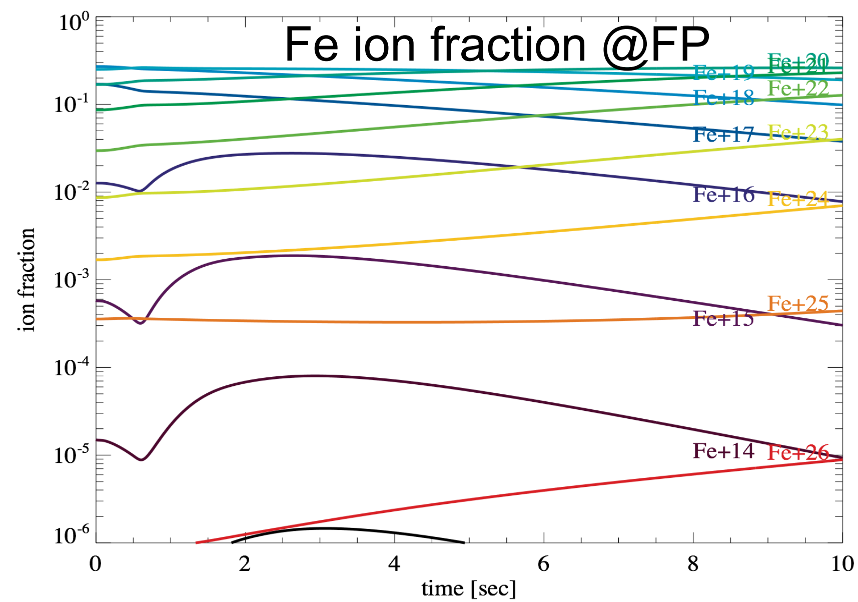


RESULT – HXR/MW/FE ION FRACTION

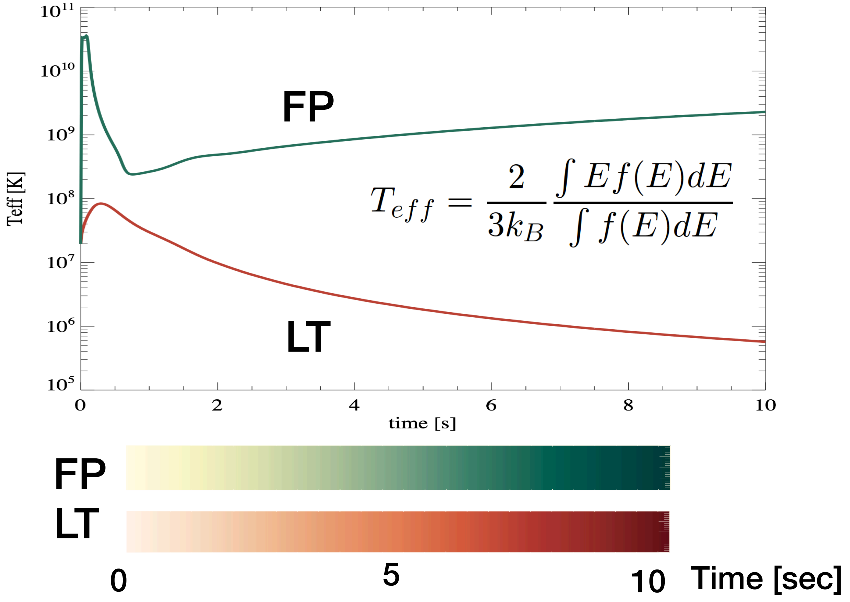


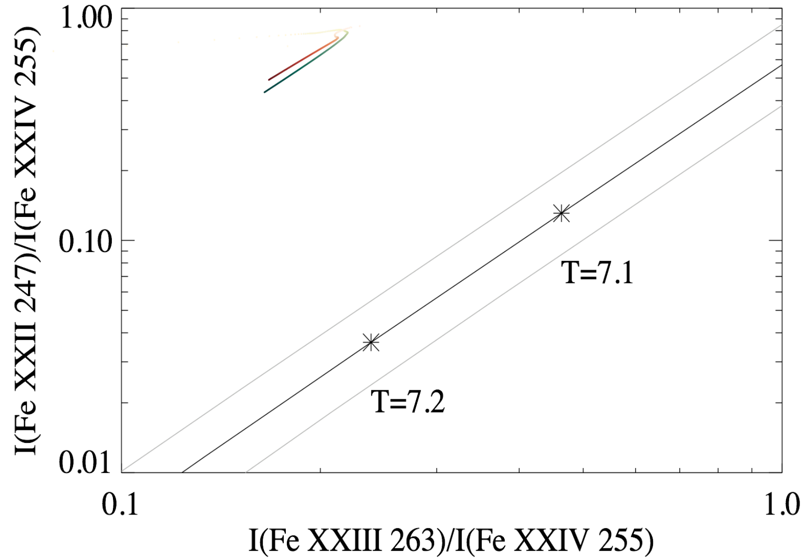


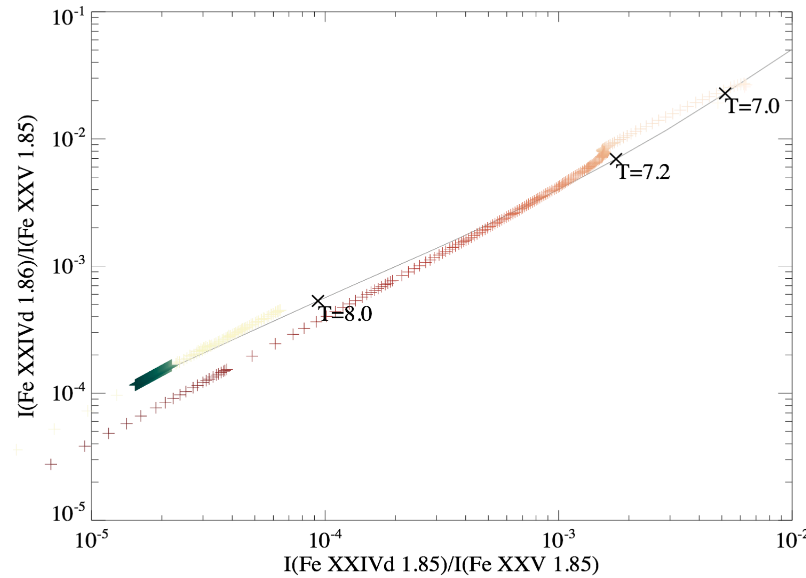




DEPARTURE FROM THE EQUILIBRIUM IN FE SPECTRA







- Fe XXII – Fe XXIV show a significant departure from the equilibrium, but are under-ionised due to the effect of non-equilillbrium ionisation, i.e., highly ionised ions are lower temperature than the electron temperature.
- Fe XXV resonance line and Fe XXIV dielectronic satellite lines show a departure from the equilibrium at the looptop, and an apparent high temperature compared to the effective temperature at the same time of the spectral hardening

SUMMARY

We calculated time- and spatial-dependent electron distribution in a flare loop for 10 sec by the impulsive injection, and derived emissivities of HXR/MW/EUV/SXR

HXR (50keV thin-target) – gradual decay with the electron dissipation

MW (17GHz) – gradual decay, and oscillation due to the electron trapping and transport

EUV resonance lines (Fe XXII 247, Fe XXIII 263, Fe XXIV 255) – shows a departure but under-ionised, i.e., non-equilibrium ionisation affects dominantly

SXR resonance and dielectronic satellite lines (Fe XXV 1.85, Fe XXIVd 1.85, 1.86) – shows departure from the Maxwellian as the hardening of the electron distribution *although errors from observations and atomic data should be taken into account carefully…*

Thank you!