Non-equilibrium ionization in the solar corona for electron κ-distributions

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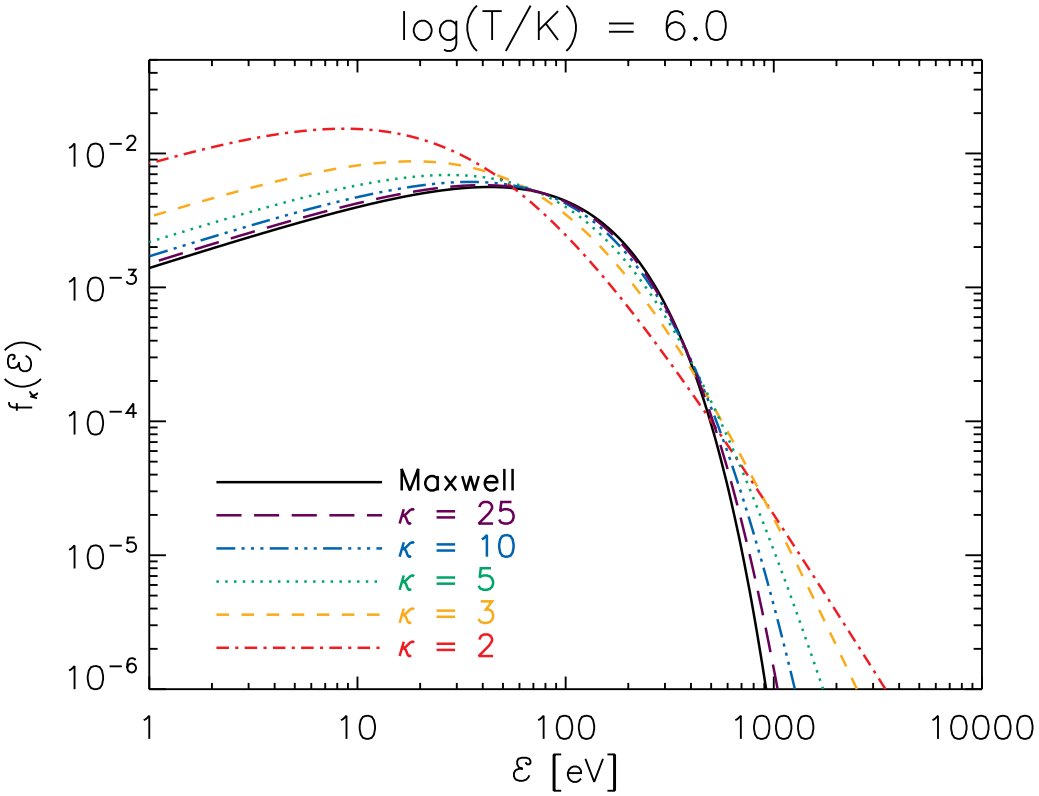
Motivation

- we study the plasma emission – we need to know the microphysics
- Maksimovic et al.(1997): solar wind velocity distribution is well approximated by a κ-distribution
- Dzifcakova & Kulinova (2011): relative intensities of Si III lines in the transition region correspond to the κ-distribution with κ=7-12
- Dudik et al. (2015): diagnostics of the κ-distribution in transient coronal loop
- Collier (2004): if the mean particle energy is not held constant, the entropy is not maximalized by a Maxwellian but a κ-distribution
- supra-thermal component ("high-energy tail") observed in flares
- Bian et al. (2014): formation of κ-distribution accelerated electron population in solar flares
- shape of the distribution affects the ionization and excitation equilibrium
- a distribution with an enhanced high-energy tail can be formed in corona due to heating (e.g. micro flares or waves)

How does the transient high energy tail influence our observations?

Non-thermal Electron κ-distribution

$$f_\kappa(E) = A_\kappa \frac{2E^{1/2}}{\pi^{1/2}(kT)^{3/2}}\left(1+\frac{E}{(\kappa-1.5)kT}\right)^{-(\kappa+1)}$$



$$A_\kappa = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-0.5)(\kappa-1.5)^{3/2}}$$

$$\langle E \rangle = 3kT/2$$

$$p = NkT$$

$$E \to \infty, \quad f(E) \approx const. \times E^{-(\kappa+0.5)}$$

Line intensities

level population

ion abundance

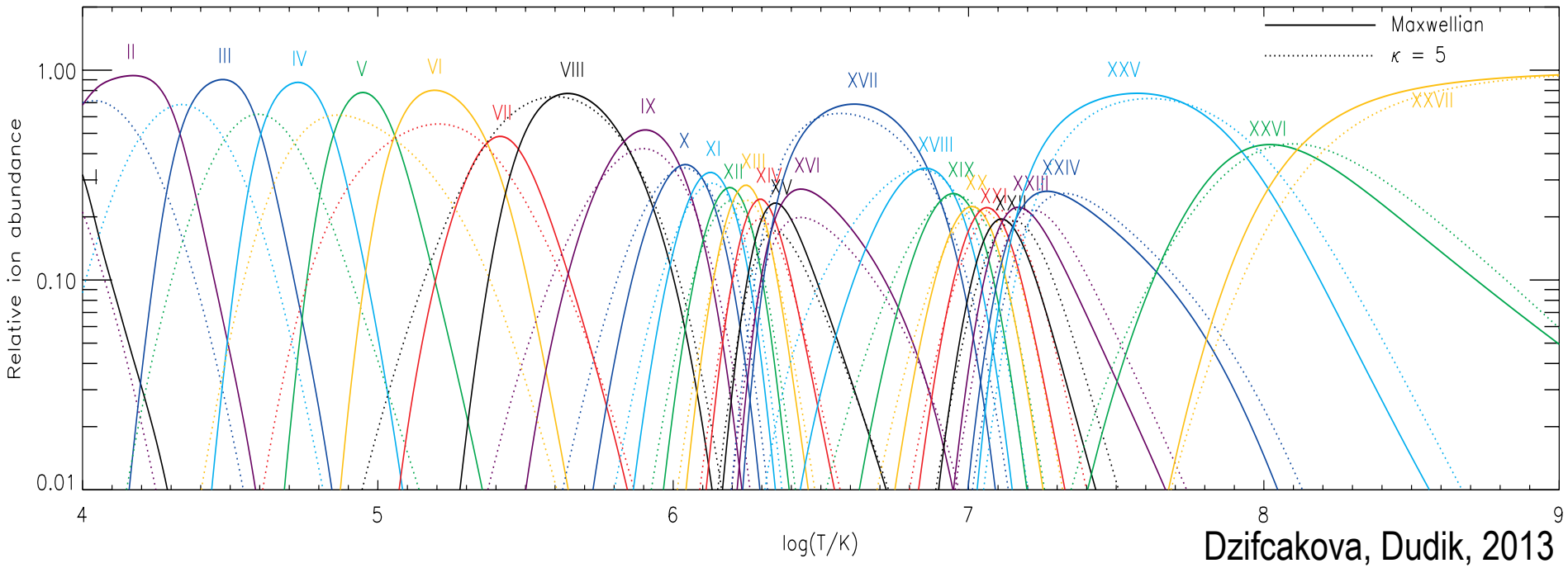
$$I_{ij} = \frac{hc}{4\pi\lambda_{ij}} A_{ij} \int \frac{1}{N_e} \frac{N_{E,\,i}^{+k}}{N_E^{+k}} \frac{N_E^{+k}}{N_E} \frac{N_E}{N_H} \frac{N_H}{N_e} N_e^2 dl$$

Ionization equilibrium

EQUILIBRIUM

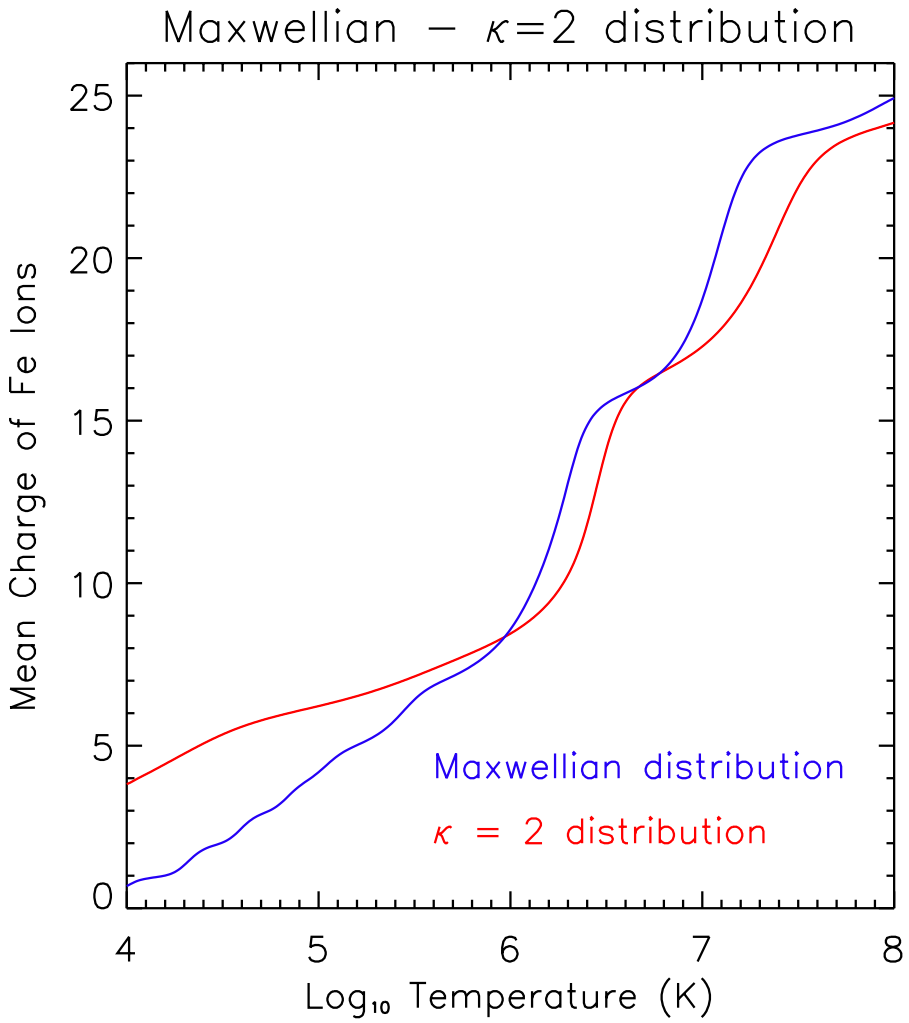
number of ionization of k-times ionized ion = number of recombination from k+1 ionized ion

$$N_k I_{k\to k+1} = N_{k+1} R_{k+1\to k} \qquad \sum_{k=0}^{Z} N_k = 1.$$



Dzifcakova, Dudik, 2013

Mean charge - Fe



Mean charge of ions

- is directly related to temperature
- temperature is different for different distributions
- is used for the estimation of the **ion temperature** during the non-equilibrium ionization

Non-equilibrium ionization

$$\frac{dN_k}{dt} = N_e N_{k+1} R_{i+1\to k} + N_e N_{k-1} I_{k-1\to k}$$

$$- N_e N_k R_{k\to k-1} - N_e N_k I_{k\to k+1}$$

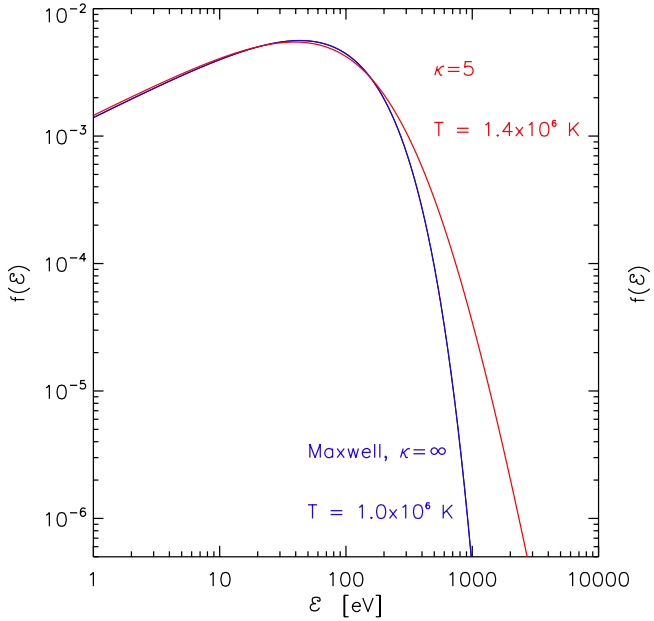
Periodic electron beam

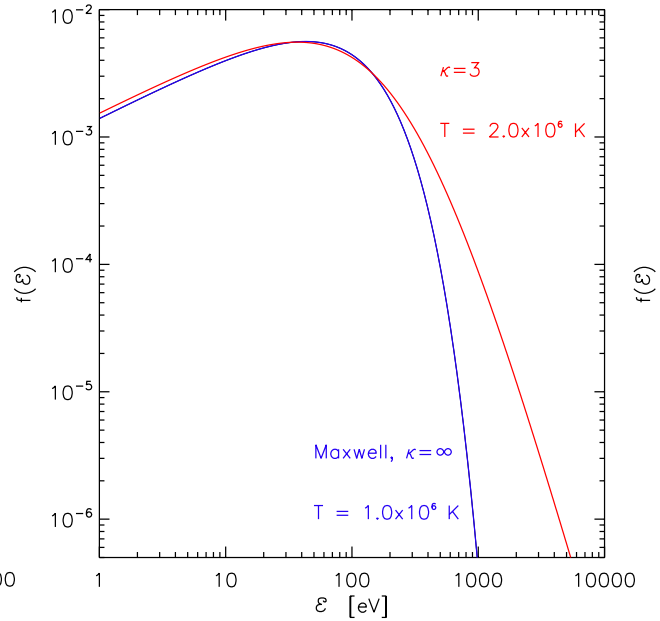
Asumptions:

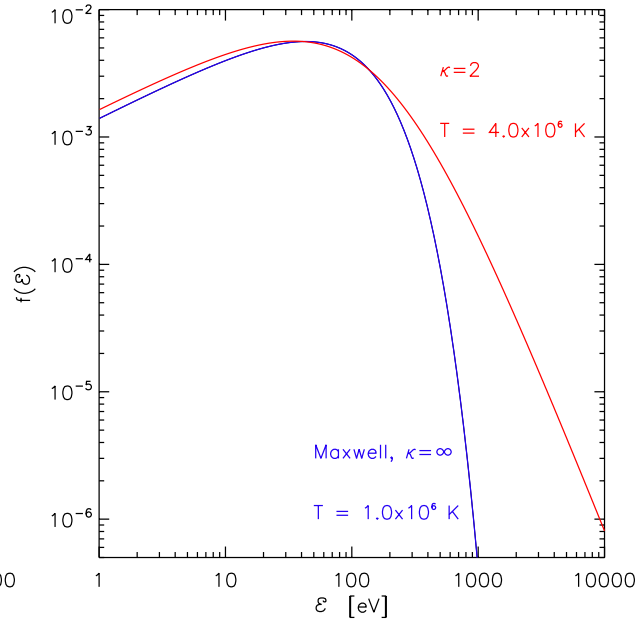
- periodic interaction of plasma with the electron beam (e.g. due to micro-flares) – during interaction the distribution can be described by a κ-distribution, power-law index: κ+0.5
- electron beam (+ ambient plasma, described by a κ-distribution) is during the first half-period and the Maxwellian distribution during the second half half-period
- both distributions have the same low energy part and bulk of distribution and they differ in the high-energy tail and temperature (the mean energy of distribution) only.
- **Advantages of the electron beam**: result of the reconnection, lower energy requirements for plasma ionization, interacts for a short time (travels through the plasma volume), thermalization somewhere deeper in the atmosphere

Periodic Electron Beam Transition Region

κ = 5 - Maxwellian	κ = 3 - Maxwellian	κ = 2 - Maxwellian
Temperature		
1.4×10^4 K - 1×10^6 K	2×10^4 K - 1×10^6 K	4×10^4 K - 1×10^5 K
Tail:		
≈ 15 % particles	≈ 25 % particles	≈ 35 % particles
≈ 30 % energy	≈ 50 % energy	≈ 75 % energy







Periodic Electron Beam Corona

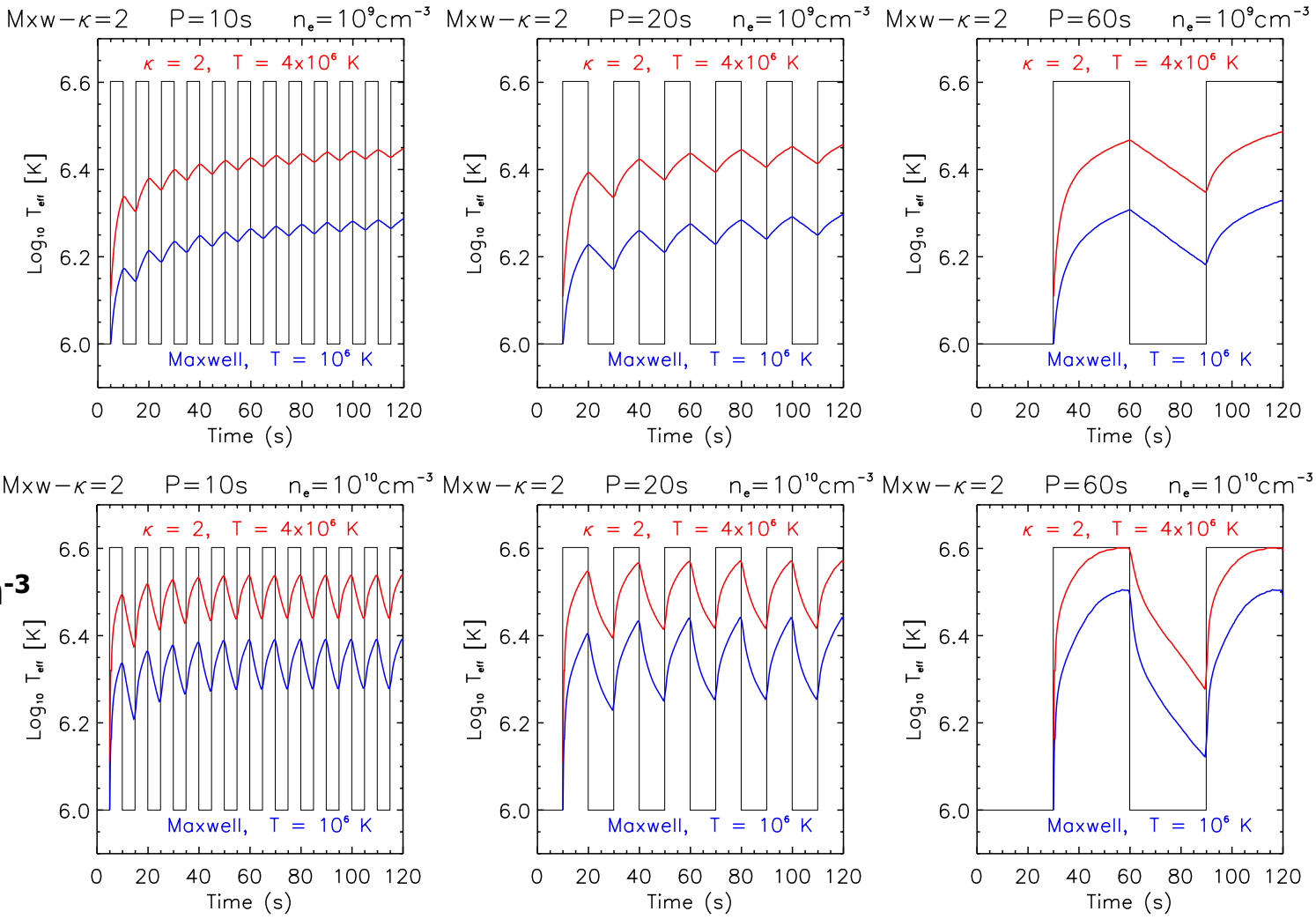
Fe

Maxwell, 10^6 K

↓

κ=2, $4x10^6$ K

N_e: 10^9 - 10^{10} cm^{-3}



Periodic Electron Beam Corona

Fe

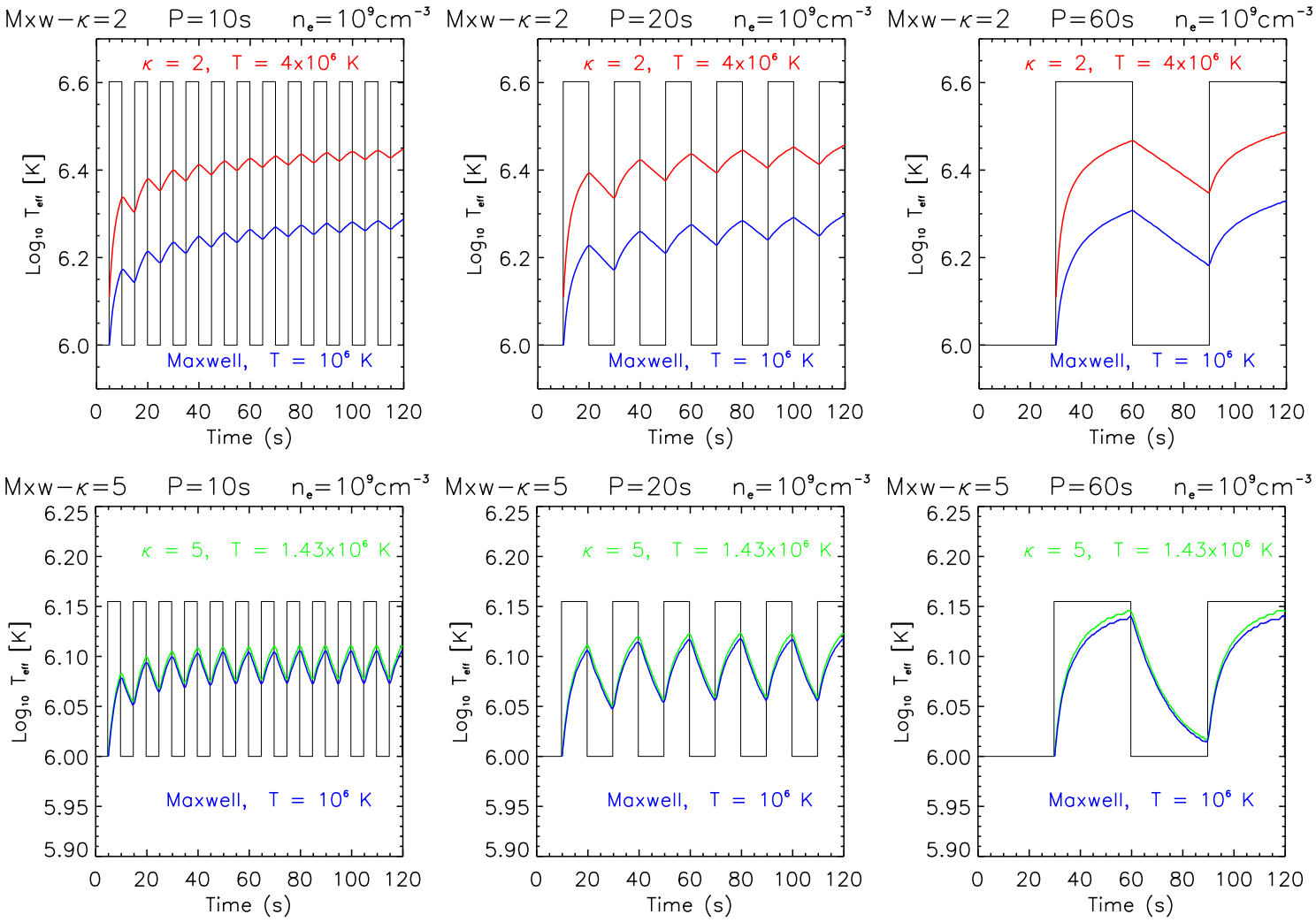
Maxwell, 10^6 K

↓

κ=2, 4.0×10^6 K

κ=5, 1.4×10^6 K

N_e: 10^9 cm^{-3}

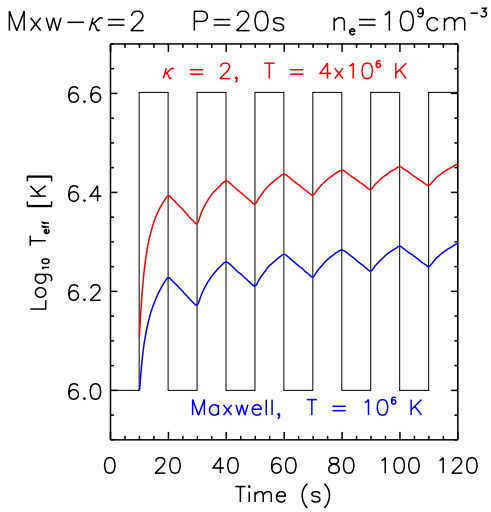


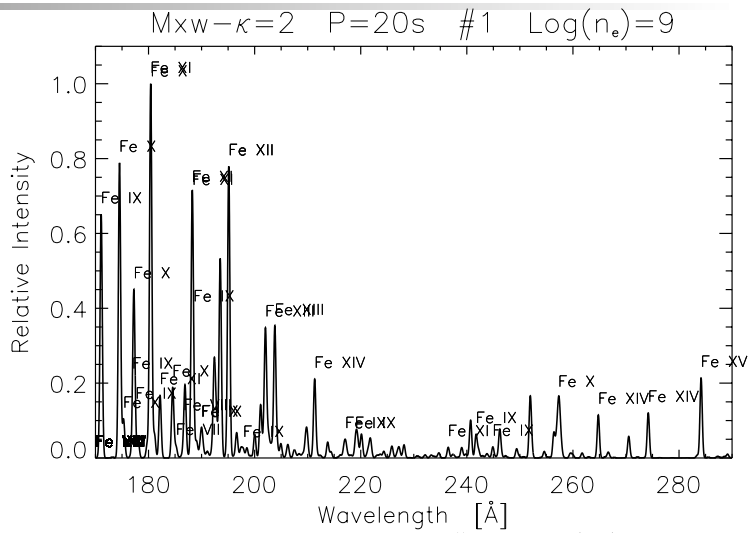
Periodic Electron Beam Corona

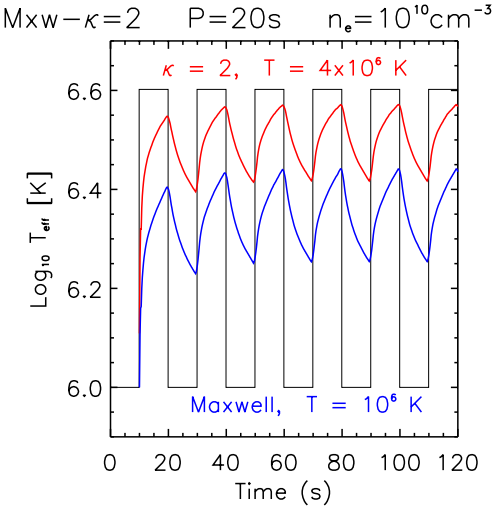
Fe

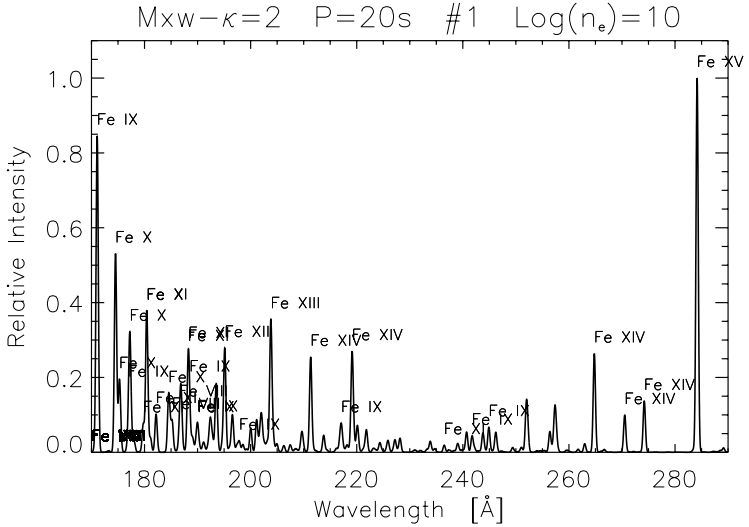
Higher electron densities:

- higher T_{eff}
- higher amplitudes of pulsations
- lower line intensities for the Fe ions in lower ionization degree
- plasma can look multi-thermal due to the non-equilibrium ionization

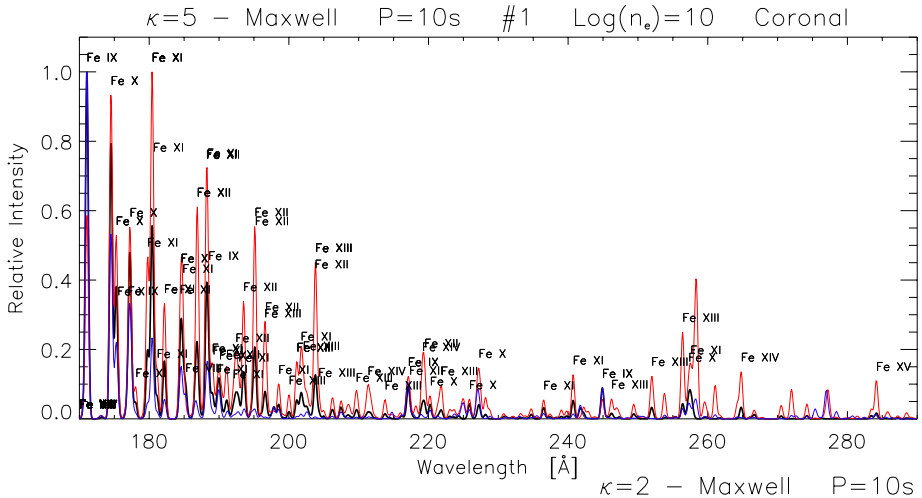


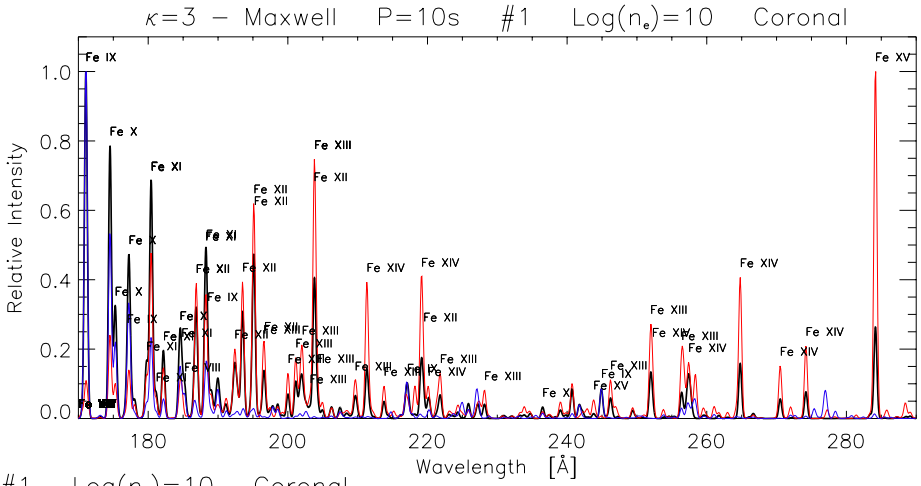


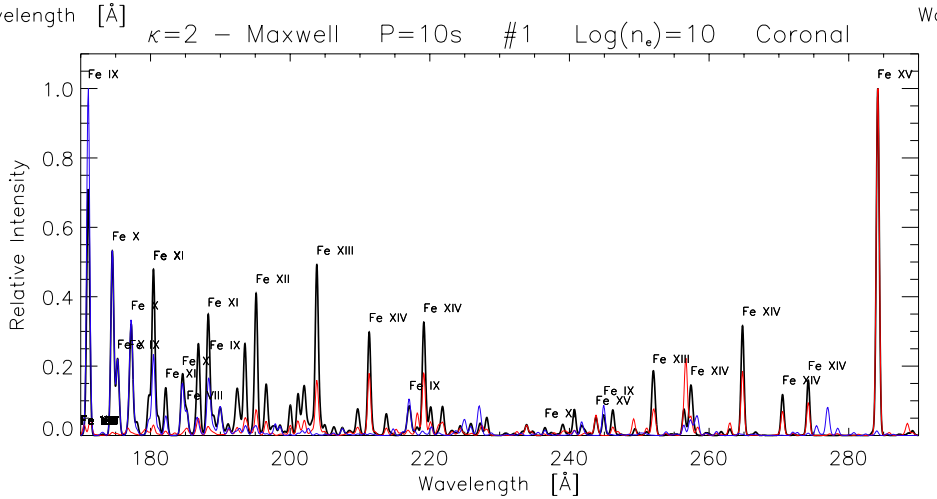




Periodic Electron Beam Corona





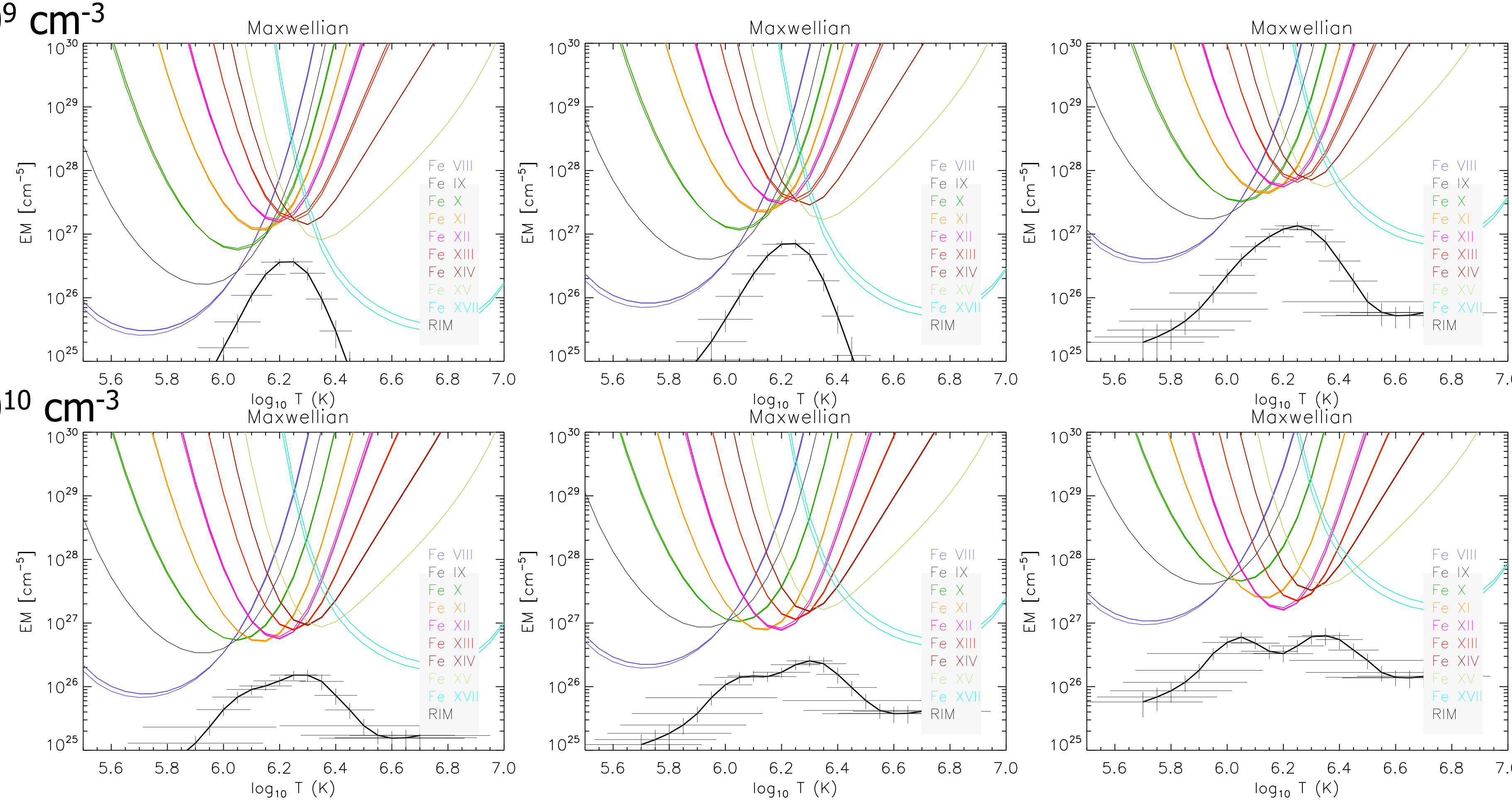


Periodic Electron Beam Corona – DEM

10s 20s 60s

10^9 cm^{-3}

10^{10} cm^{-3}



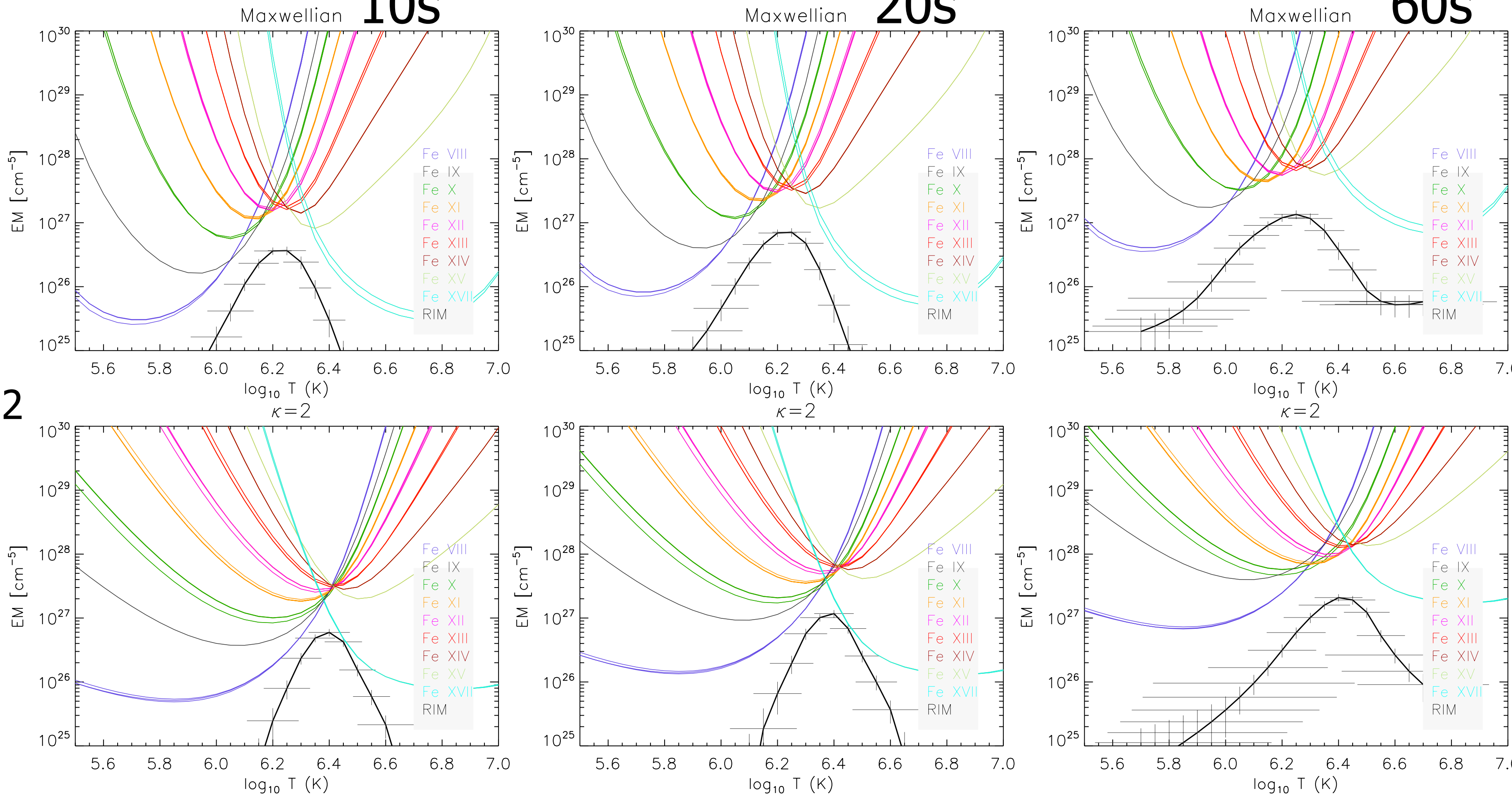
Periodic Electron Beam
Corona - DEM

10^9 cm^{-3}

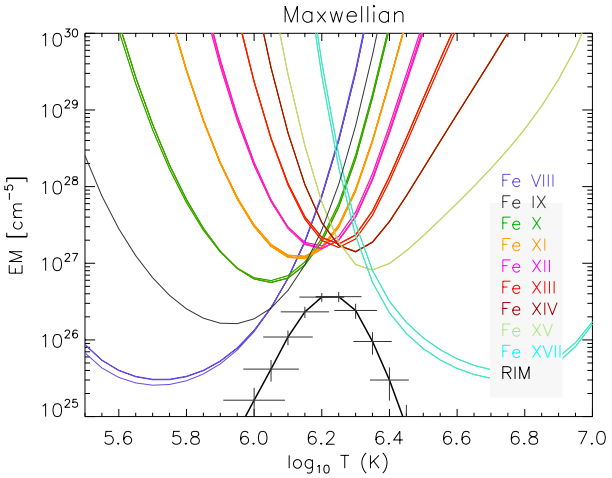
Maxwell

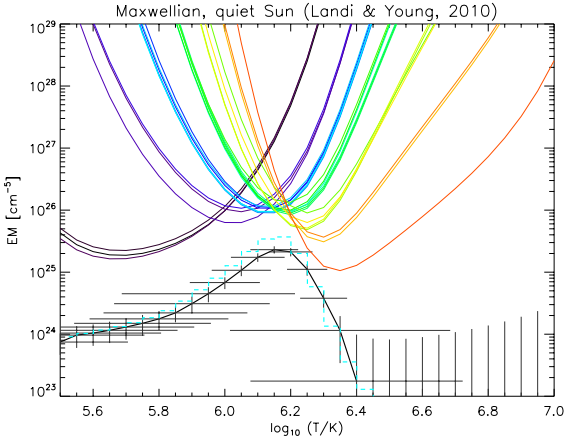
10s 20s 60s

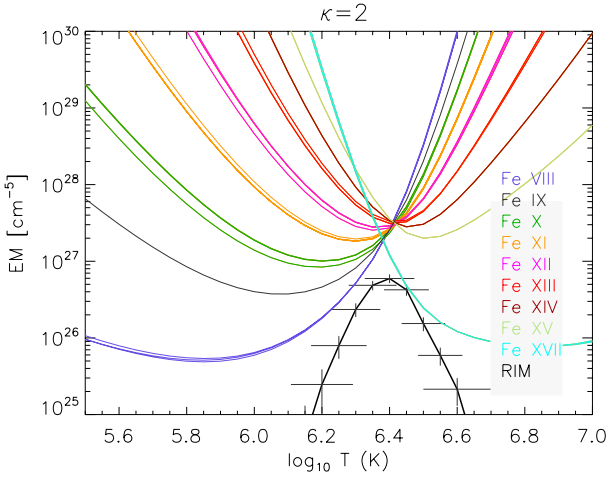
κ=2

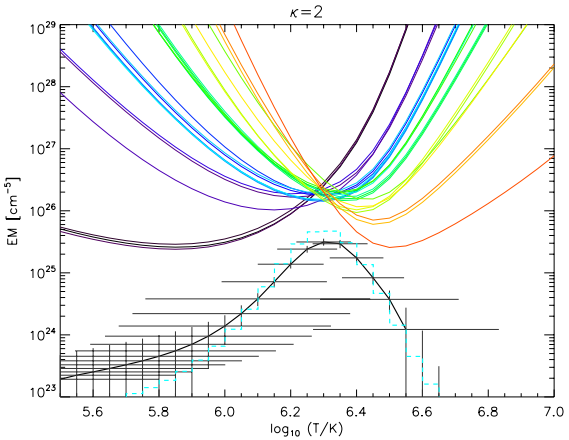


Periodic Electron Beam Corona - DEM Quiet Sun









Summary

- electron beam significantly can affect the ionization state of plasma and line intensities
- the electron distribution influences temperature diagnosed from the line intensities
- non-equilibrium plasma looks like a multi-thermal plasma
- the shape of DEM depends on the electron density, period and parameters of the electron beam


Thank you for your attention!