Electron kappa-distributions and non-equilibrium ionization in the solar corona and transition region

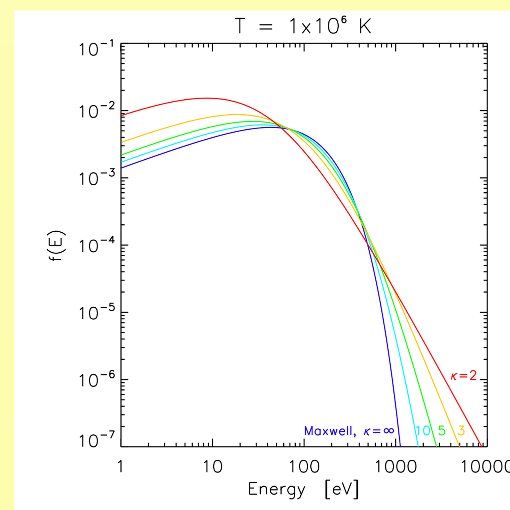
Elena Dzifčáková[1], Jaroslav Dudík[1], Šimon Mackovjak[2]

[1] Astronomical Institute of the Academy of Sciences of the Czech Republic 251 65 Ondrejov, Czech Republic

[2] ISDC – Data Centre for Astrophysics, Astronomy Department, University of Geneva, Chemin d'Escognia 16, 1290 Versoix, Switzerland

Non-thermal κ-distribution

- is equilibrium distribution under many conditions in space plasma (Tsallis, 1988, 2009)
- has a power-law high-energy tail
- supra-thermal component is observed in flares and solar wind (Maksimovic *et al.*, 1997)
- the shape of the distribution affects the ionization and excitation equilibrium (e.g. Dzifčáková & Dudík, 2013, Dzifčáková & Kulinová, 2010)
- explains Si III line intensities in the transition region (Dzifčáková & Kulinová, 2011)
- can be formed in corona by coronal heating (e.g. by micro flares or waves)
- it is easy to use it to simulate the effect of the electron beam on the plasma emission in the solar corona and transition region, for $E \rightarrow \propto$: $f_\kappa(E) \approx E^{-(\kappa+0.5)}$
- has a small affect on the ionization times, significant efffect on the **recombination times: ≈10-times shorter** than for the Maxwellian distribution!



Experssion:

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

where

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

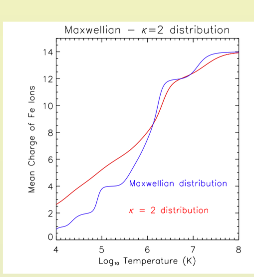
Two independent parameters, κ and $\boldsymbol{T}$.
$\kappa \rightarrow 1.5$ – distribution is strongly non-thermal,
$\kappa \rightarrow \propto$ – Maxwellian distribution
Mean energy of the κ−distributions is the same as for the Maxwellian distribution: $\langle E \rangle = 3kT/2$

Periodic interaction of the electron beam with plasma

Assumptions:

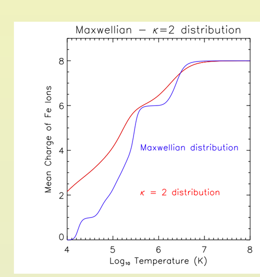
- **Electron beam** is a result of the reconnection and its presence is a common signature e. g. of the coronal heating
- It interacts for a short time (travels across the plasma volume) and can be thermalize somewhere deeper in the atmosphere.
- **Beam + plasma distribution** can be modeled by a **κ-distribution.**
- Periodic interaction of the beam with plasma: **κ-distribution** during **first half-period; Maxwellian distribution** during **second half-period**
- Both distributions have **the same low energy part and bulk**, they **differ in the high-energy tail** and temperature **only**
- The effective ion temperature, $\mathbf{T_{eff}}$, **is the temperature corresponding to the mean charge of ions during the non-equilibrium** and is **different for the Maxwellian and κ-distribution**

Transition region – Si, O

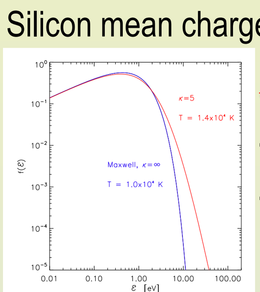


Silicon mean charge

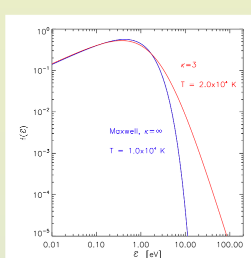
The Maxwellian distribution with T=10^4 K is assumed before the interaction. Then, it periodically changes from Maxwellian to a κ−distribution. Parameter κ can be 5, 3, and 2 (*left* to *right*), giving the magnitude of the electron beam. The electron beam (tail of the κ−distribution) contains 15%, 25%, and 35 % of the total number of the particles and carries 30%, 50%, and 75% of energy.



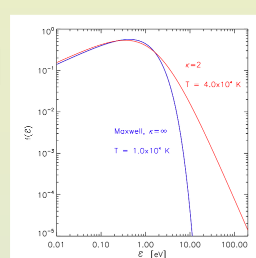
Oxygen mean charge



κ = 5 ↔ Maxwell
T: 1.4x10^4 ↔ 1x10^4 K
Tail: ≈ 15% particles
≈ 30% energy



κ = 3 ↔ Maxwell
T: 2x10^4 ↔ 1x10^4 K
Tail: ≈ 25% particles
≈ 50% energy

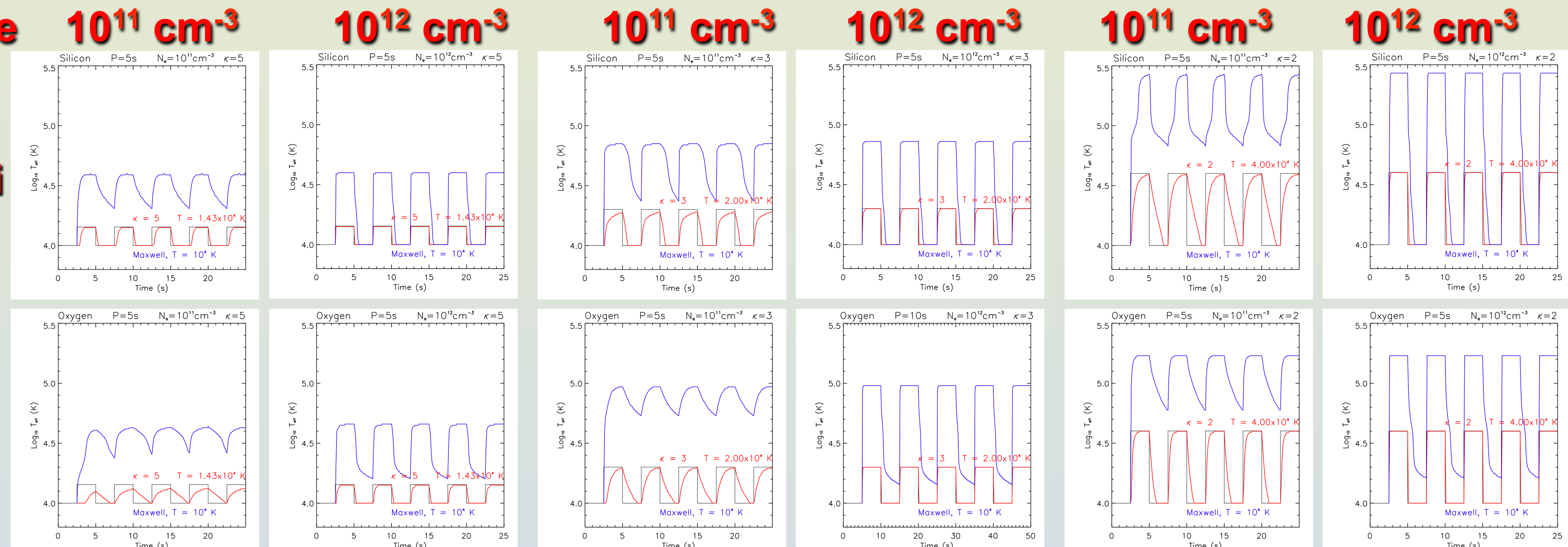


κ = 2 ↔ Maxwell
T: 4x10^4 ↔ 1x10^4 K
Tail: ≈ 35% particles
≈ 75% energy

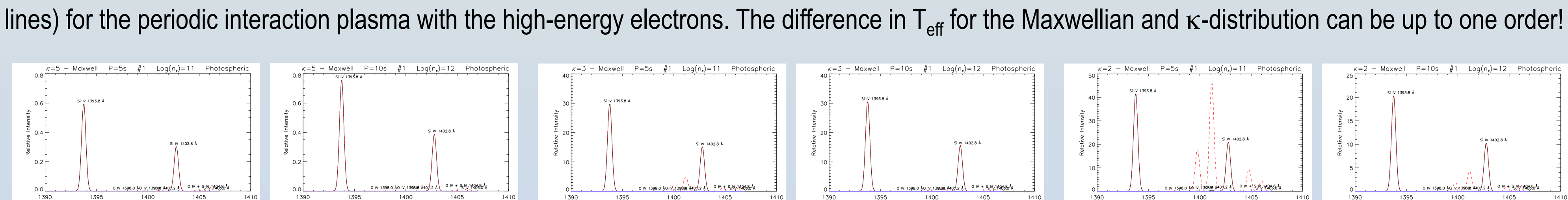
P = 5 s

Ne | 10^{11} cm^{-3} | 10^{12} cm^{-3} | 10^{11} cm^{-3} | 10^{12} cm^{-3} | 10^{11} cm^{-3} | 10^{12} cm^{-3}

Si, **O**



T_{eff} from the mean charge of Silicon and Oxygen (blue lines for the Maxwellian and and red lines for κ=5, 3, 2) and the distribution temperature (thin black lines) for the periodic interaction plasma with the high-energy electrons. The difference in T_{eff} for the Maxwellian and κ-distribution can be up to one order!



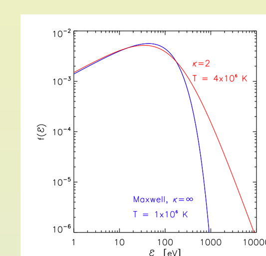
The synthetic EUV spectra averaged over the first period (black lines) for the interaction plasma with the high-energy electrons. Dashed red spectra correspond to the κ-distribution with T = 1.4x10^4, 2x10^4, and 4x10^4 K and κ=5, 3, and 2. There are no oxygen lines in the synthetic non-equilibrium spectra!

Conclusions – transition region:

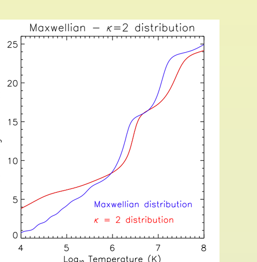
•**Temperature** derived from the observation strongly depends on the assumed distribution, it can be **different by an order of magnitude for κ=2.** The effective temperature is different for different ions.
•**Non-equilibrium plasma can form IRIS spectra with no oxygen lines**. The line intensities depend on the period, electron density and κ.
•The **beam energy** required to ionize the plasma to the observed degree of ionization can **be much lower than the thermal energy.**

Corona - Fe

The Maxwellian distribution with T=10^6 K is supposed before the interaction. The distribution periodically changes from Maxwellian to κ−distribution, κ=2. The temperature from the mean charge for the κ−distribution are higher than for the Maxwellian distrubution. Averaged spectra look multithermal.



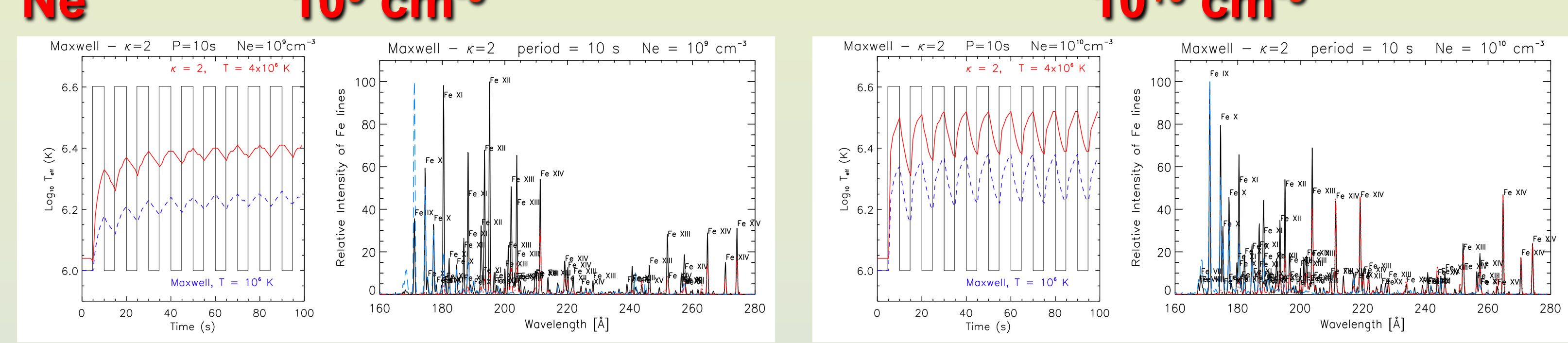
κ = 2 ↔ Maxwell
T: 4x10^6 ↔ 1x10^6 K
Tail: ≈ 35 % particles
≈ 75 % energy



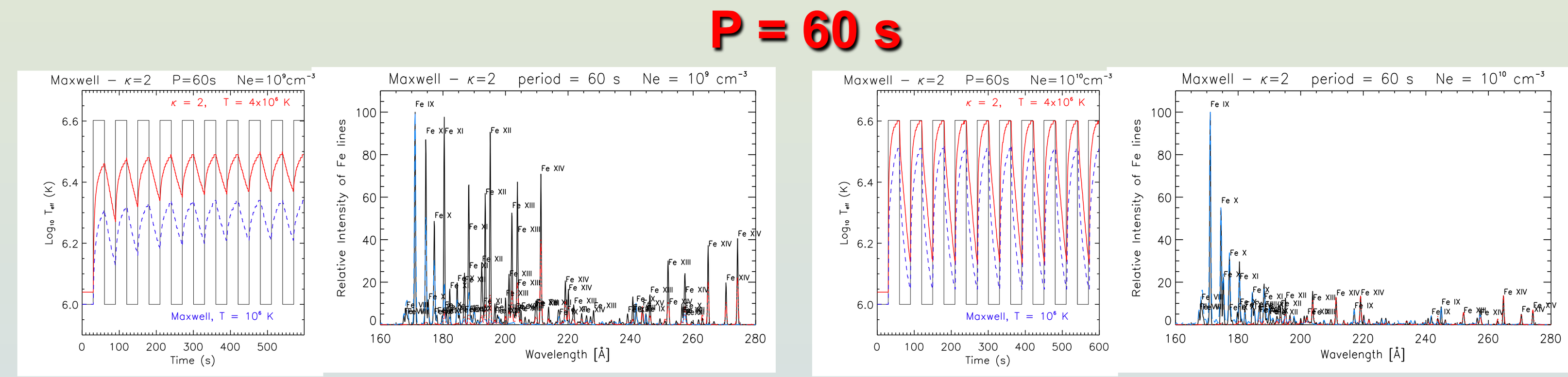
Fe mean charge vs. T for the Maxwellian (blue) and κ=2 distribution (red).

P = 10 s

Ne | 10^9 cm^{-3} | 10^{10} cm^{-3}

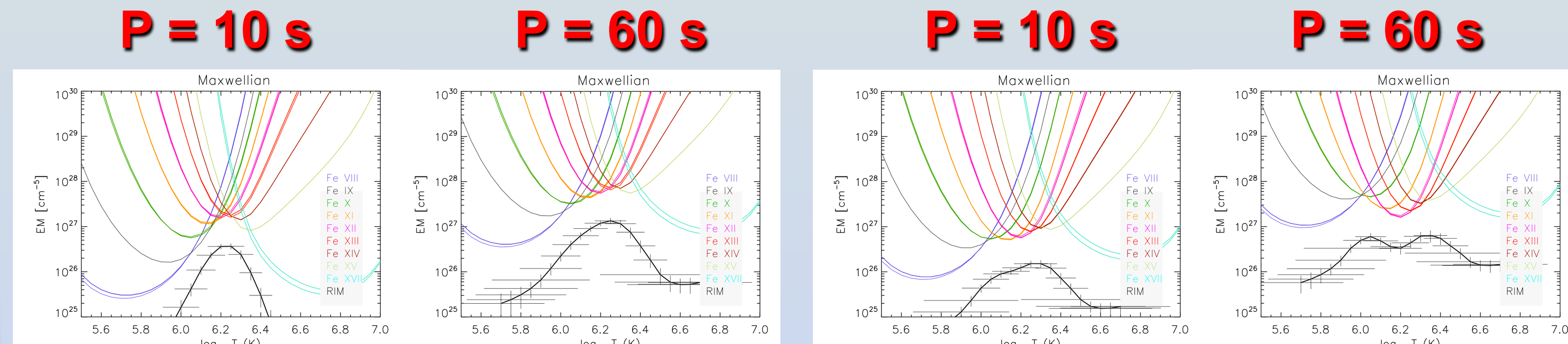


P = 60 s



T_{eff} from the mean charge of Fe (dashed blue lines for the Maxwellian and red lines for κ=2), the distribution temperature (thin black lines), and synthetic EUV spectra averaged over one period (black lines) for the periodic interaction plasma with the high-energy electrons. The difference in T_{eff} for the Maxwellian and κ-distribution is about 10^6 K. Blue lines in spectra correspond to the Maxwellian spectrum with T = 10^6 K and red ones to the κ-distribution with T = 4x10^6 K and κ=2.

P = 10 s | **P = 60 s** | **P = 10 s** | **P = 60 s**



DEM calculated from averaged synthetic EUV spectra under the assumption of the Maxwellian distribution.

Conclusions - corona:

- **Temperature** derived from from the observation depends on the assumed distribution function, **differences** in its estimation can **be up to 10^6** K.
- **Non-equilibrium plasma looks multi-thermal** and the shape of DEM depends on the period, electron density, and, of course, on the value of κ.

ACKNOWLEDGEMENTS

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