Is it possible to diagnose the non-thermal distributions from EUV spectra?

E. Dzifčáková[1,2], A. Kulinová[1,2]

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

[2] Faculty of Mathematics, Physics and Informatics, Comenius University
842 48 Bratislava, Slovakia

Motivation

- The EUV Imaging Spectrometer (EIS/HINODE) is a new powerful instrument to investigate mainly the coronal heating, transient phenomena in the transition region and solar corona, and energy transfer from the photosphere to the corona. Spectral bands: 163 - 209 Å, 242 - 289 Å. Dispresion - 0.0223 Å / CCD pixel.
- SPIRIT/CORONAS-F was lanched on 2001, July to study the dynamics of active Sun and the diagnostics of plasma parameters of the non-stationary solar events . Spectral bands: 177 - 207 Å, 285 - 335 Å. Dispresion - 0.03 Å / CCD pixel.
- Observed intensities of the EUV lines can be used for the diagnostics of the plasma parameters.
- Physical conditions in the solar corona and transition region can affect the electron distribution function in the solar corona and the transition region and thus the intensities of the EUV spectral lines.
- How the non-thermal electron distributions influence intensities of (EUV) spectral lines and the diagnostics of the basic plasma parameters (electron density, temperature) using these lines?
- Is it possible to diagnose the non-thermal electron distributions from EUV spectra?

Non-thermal electron distribution - κ-distribution

The non-thermal electron distribution with the enhanced number of particles in the high energy tail is κ-distribution with the free parameter κ. The κ -distribution becomes a strong non-thermal distribution for $\kappa \to 1.5$ and it is equal to Maxwellian one for $\kappa \to \propto$:

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

where

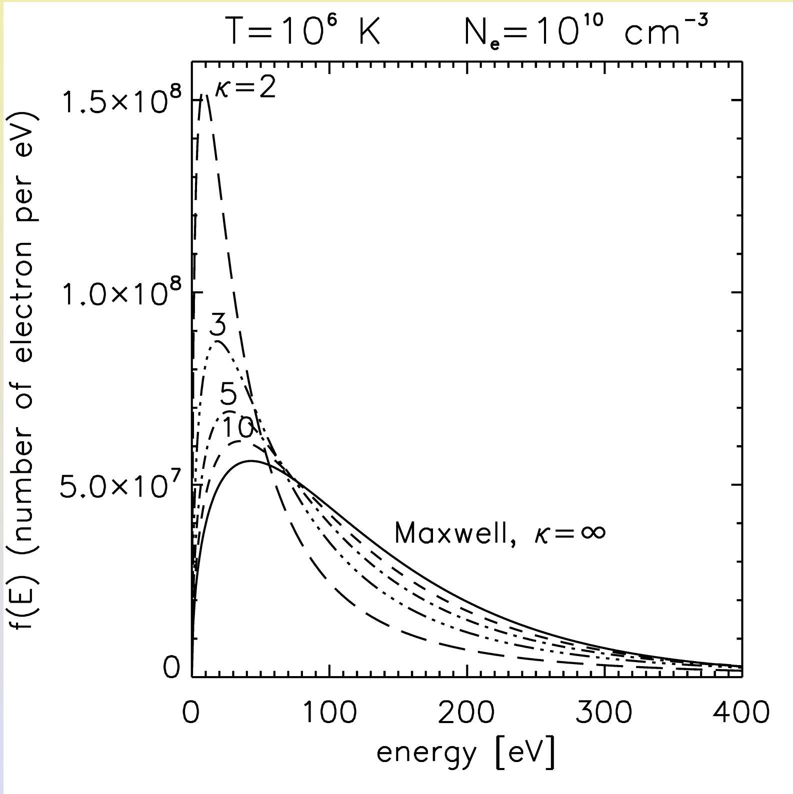
$$A_\kappa = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa - 0.5)(\kappa - 1.5)^{3/2}} \;.$$

The mean energy of the κ-distribution is

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

and pressure is

$$p = NkT\;.$$



The comparison of the Maxwellian distribution with the $\boldsymbol{\kappa}$*-distribution for* $\boldsymbol{\kappa}$ *= 2, 3, 5 and 10.*

Ionization and excitation equilibrium

- The non-thermal electron distributions change the both ionization and recombination rates what leads to changes in the ionization and excitation equilibrium.
- The ionization equilibrium for the κ-distributions and the power distributions has been calculated by Dzifčáková (1992) and Dzifčáková (2005).
- The original modification of CHIANTI* software and database has been used for computation of the synthetic spectra. We have used the last correction of Fe XIII splups file for our computation.
- The modified software and extended database now allows the computation of the excitation equilibrium and synthetic spectra under the assumption of non-thermal distributions and involves computation of satellite line intensities.

CHIANTI is a collaborative project involving the NRL (USA), RAL (UK), MSSL (UK), the Universities of Florence (Italy) and Cambridge (UK), and George Mason University (USA). The software is distributed as a part of SolarSoft.

Diagnostics of the κ-distributions

We have concentrated on Fe ions in our preliminary analysis. Thermal FWHM ~ 0.023 Å is for Fe ions, λ=200 Å and T=2x10^6 K (T=2x10^7 K, FWHM ~ 0.072 Å).

Instrument	**EIS**	**SPIRIT**
Spectral bands	**163 - 209 Å, 242 - 289 Å**	**177 - 207 Å, 285 - 335 Å**
Dispersion	**0.0223 Å / CCD pixel**	**0.03 Å / CCD pixel**

Observed FWHM for flares:

EIS	**0.09 - 0.12 Å**	(G. del Zanna, 2008, A&A, **481**, L69)
SPIRIT	**0.12 - 0.21 Å**	(Shestov et al., 2008, Astronomy Letters, **34**, 33)

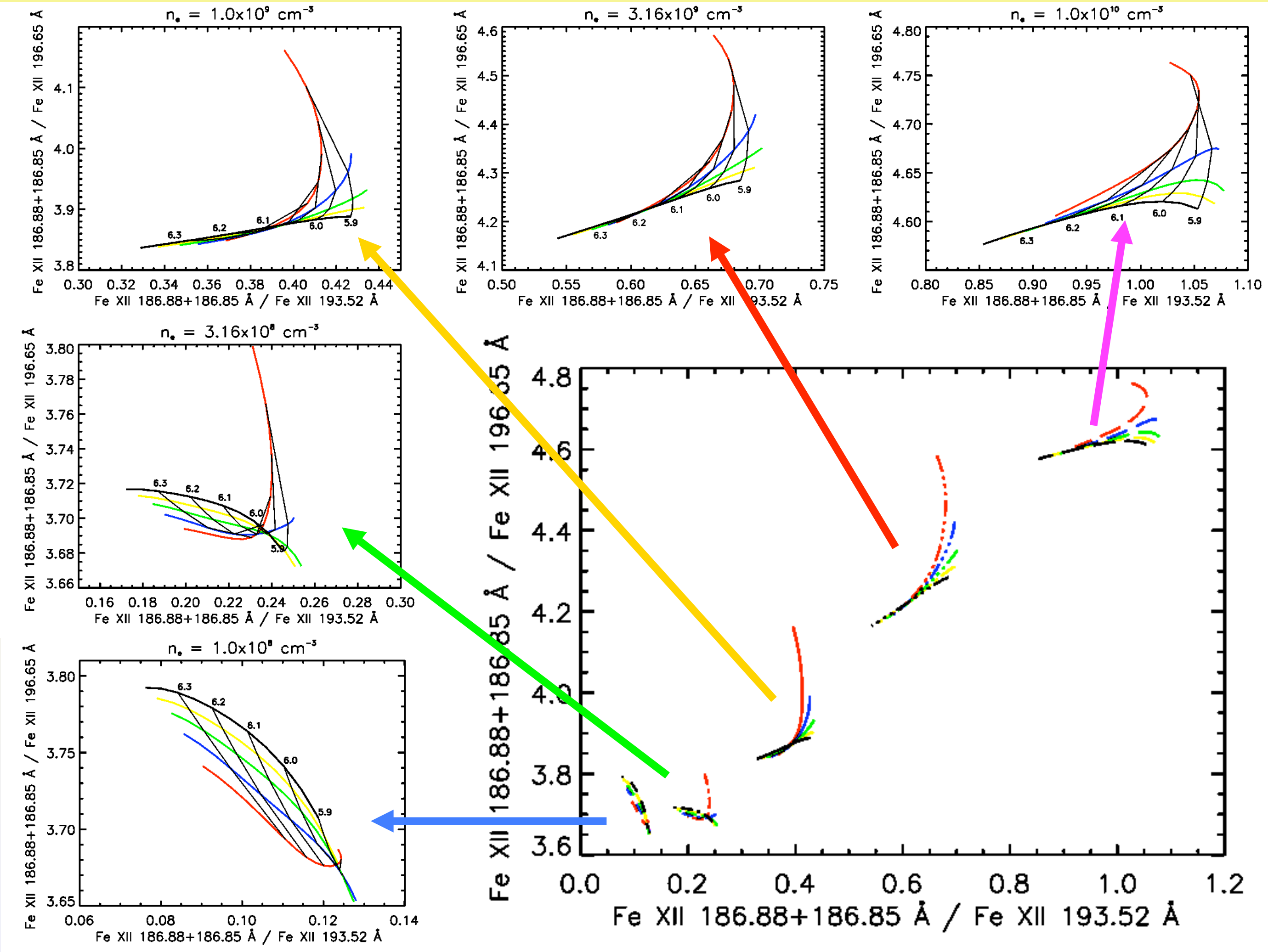
Diagnostics has been proposed for two different cases:

1. we can resolve spectral lines which differ in λ more than 0.03 Å. List of lines for EIS has been used in this case.

2. we have used lines (with their blends) observed during flares. Data of G. del Zanna (2008) and Shestov et al. (2008) have been used in this case.

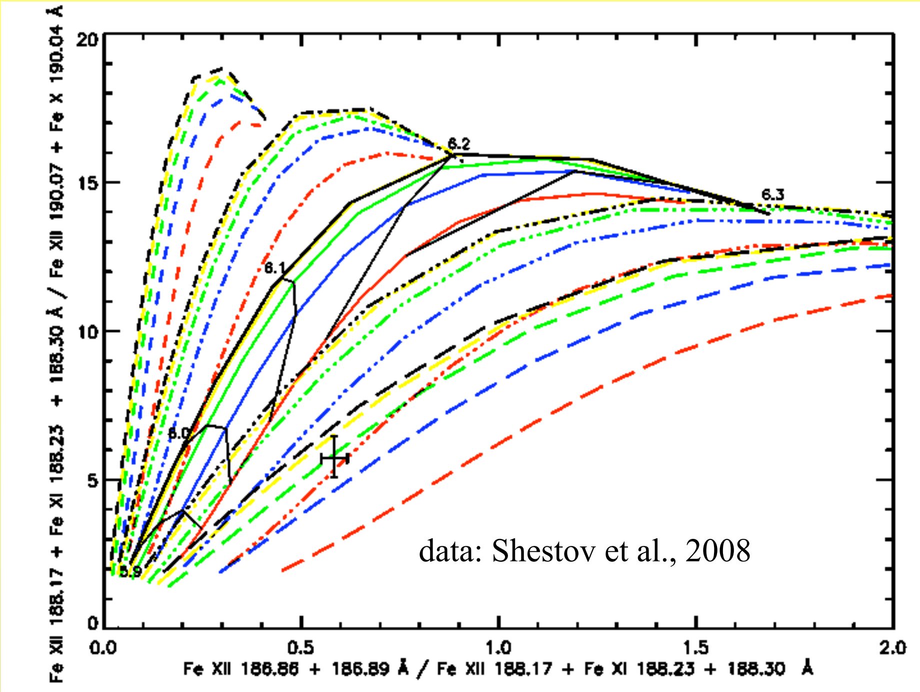
Generally, the Fe VIII - Fe XVI lines observed in spectral bands of EIS or SPIRIT do not give good possibility to diagnose the shape of the electron distribution function from lines of one ion due to the high sensitivity of their ratios on the electron density.

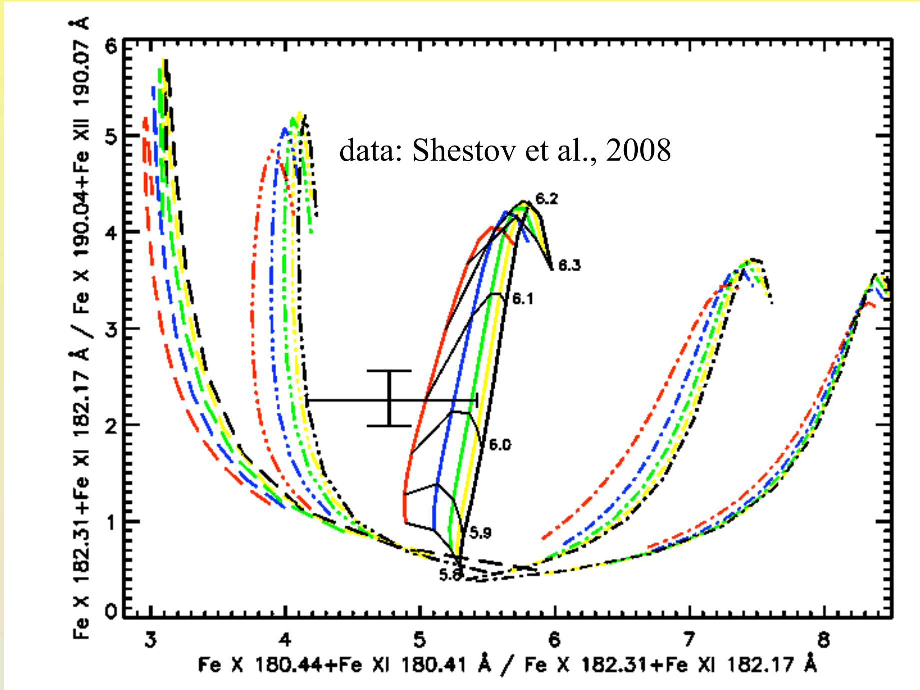
Diagnostics - 1st case

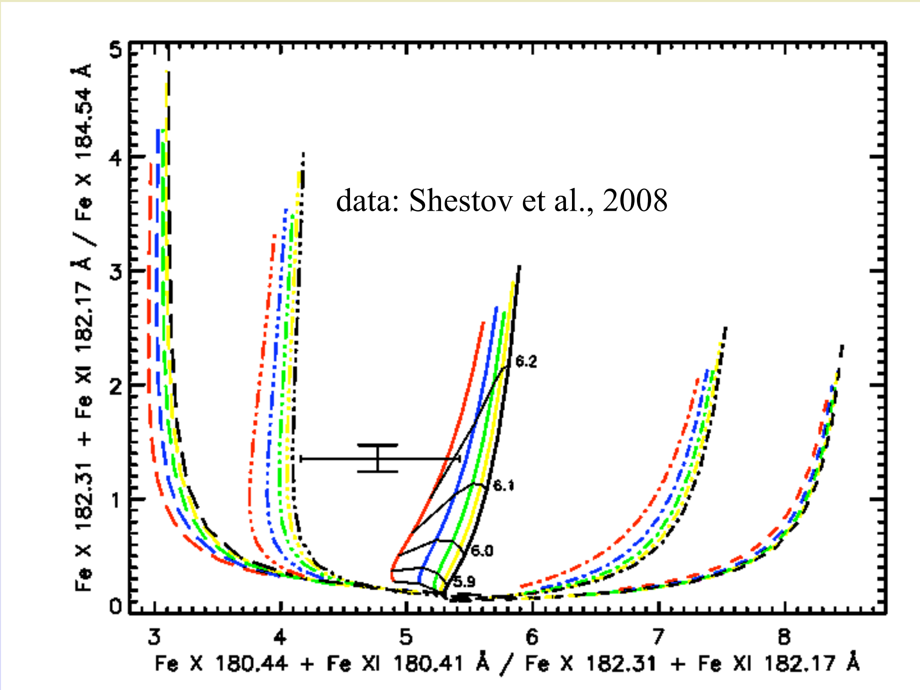


The dependence of Fe XII 186.88+186.85/196.65 on Fe XII 186.88+186.85/193.52 for different densities (dashed lines: 10^8 cm^{-3}, dot-dashed lines: 3.16x10^8 cm^{-3}, full lines: 10^9 cm^{-3}, dotted lines: 3.16x10^9 cm^{-3}, and dot-dot-dot-dashed lines: 10^{10} cm^{-3}), for Maxwellian distribution (black lines) and different κ-distributions with κ = 10 (yellow lines), κ = 5 (green lines), κ = 3 (blue lines) and κ = 2 (red lines). Smaller figures show details of dependence on the different distributions for given n_e.

Diagnostics - 2nd case



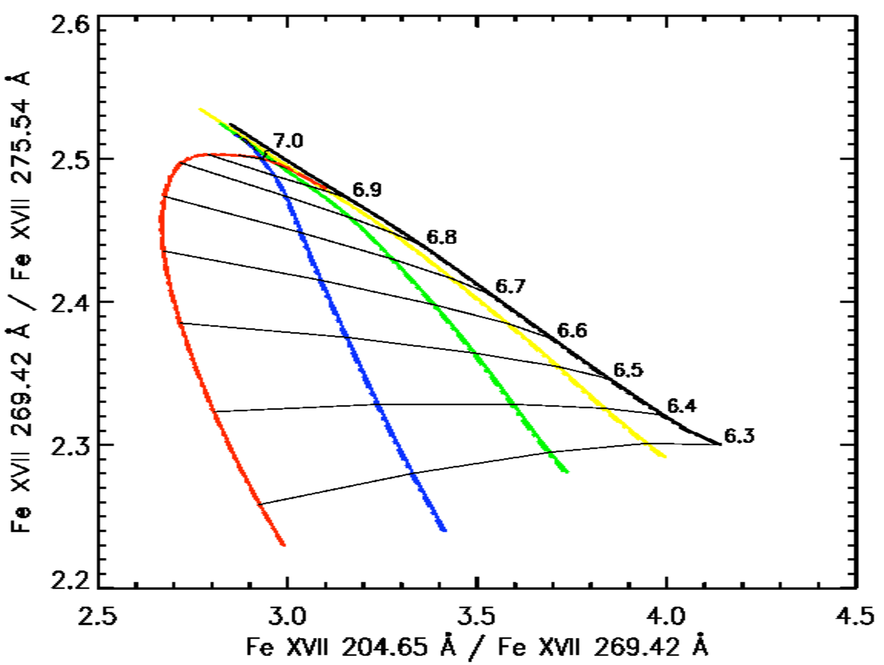


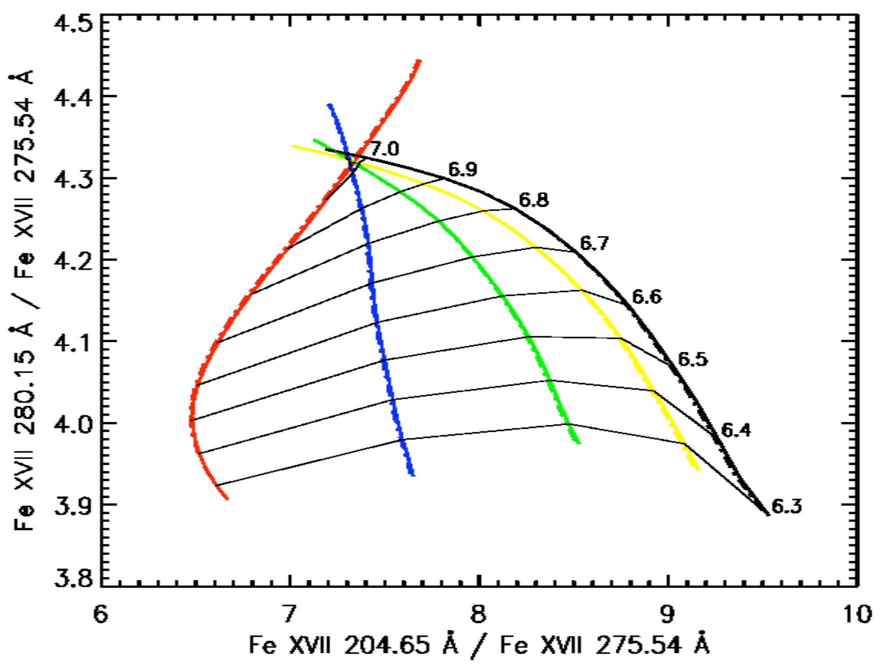


Diagnostics of the κ-distribution from blended lines of Fe ions for different densities (dashed lines: 10^8 cm^{-3}, dot-dashed lines: 3.16×10^8 cm^{-3}, full lines: 10^9 cm^{-3}, dotted lines: 3.16×10^9 cm^{-3}, and dot-dot-dot-dashed lines: 10^{10} cm^{-3}), for Maxwellian distribution (black lines) and different κ-distributions with κ = 10 (yellow lines), κ = 5 (green lines), κ = 3 (blue lines) and κ = 2 (red lines). Black crosses with errors bars show observed line ratios (Shestov et al., 2008).

Diagnostics

The best possibility to diagnose the shape of the electron distribution function from lines of one ion provides Fe XVII. The line ratios for this ion are practically independent on the electron density. This ion is formed at higher T and its lines are suitable to the study of solar flares but only particular lines are suitable for non-thermal diagnostics. Figs. show two examples of such line ratios that can be observed in EIS spectral bands. It is bad success that suitable lines of Fe XVII are blended in SPIRIT spectral bands.





The dependence of Fe XVII 269.42/275.54 on Fe XVII 204.65/269.42 (left) and Fe XVII 280.15/275.54 on Fe XVII 204.65/275.54 (rigth) for different densities (unresolved), for Maxwellian distribution (black lines) and different κ-distributions with κ = 10 (yellow lines), κ = 5 (green lines), κ = 3 (blue lines) and κ = 2 (red lines). Thin black lines connect points with the constant log(T) and they are labeled by the value of log(T).

Diagnostics of the electron density

It becomes clear that when one wants to diagnose the non-thermal distribution using the lines of any Fe ions, the electron density needs to be determined as much precisely as it is possible. The precision of electron density determination is important and one also needs to know how the particular lines are sensitive on temperature and how the non-thermal distribution function affects the density diagnostics.

P. Young (*http://solar.bnsc.rl.ac.uk/~young/solarb_eis/eis_emission_lines.html*) has proposed strong lines with good sensitivity to electron density as lines suitable for diagnostics of the electron density:

Fe XIII 203.83Å/202.04Å
Fe XIII 196.54Å/202.04Å
Fe XII 186.88Å/195.12Å

The other density diagnostics proposed by him are:

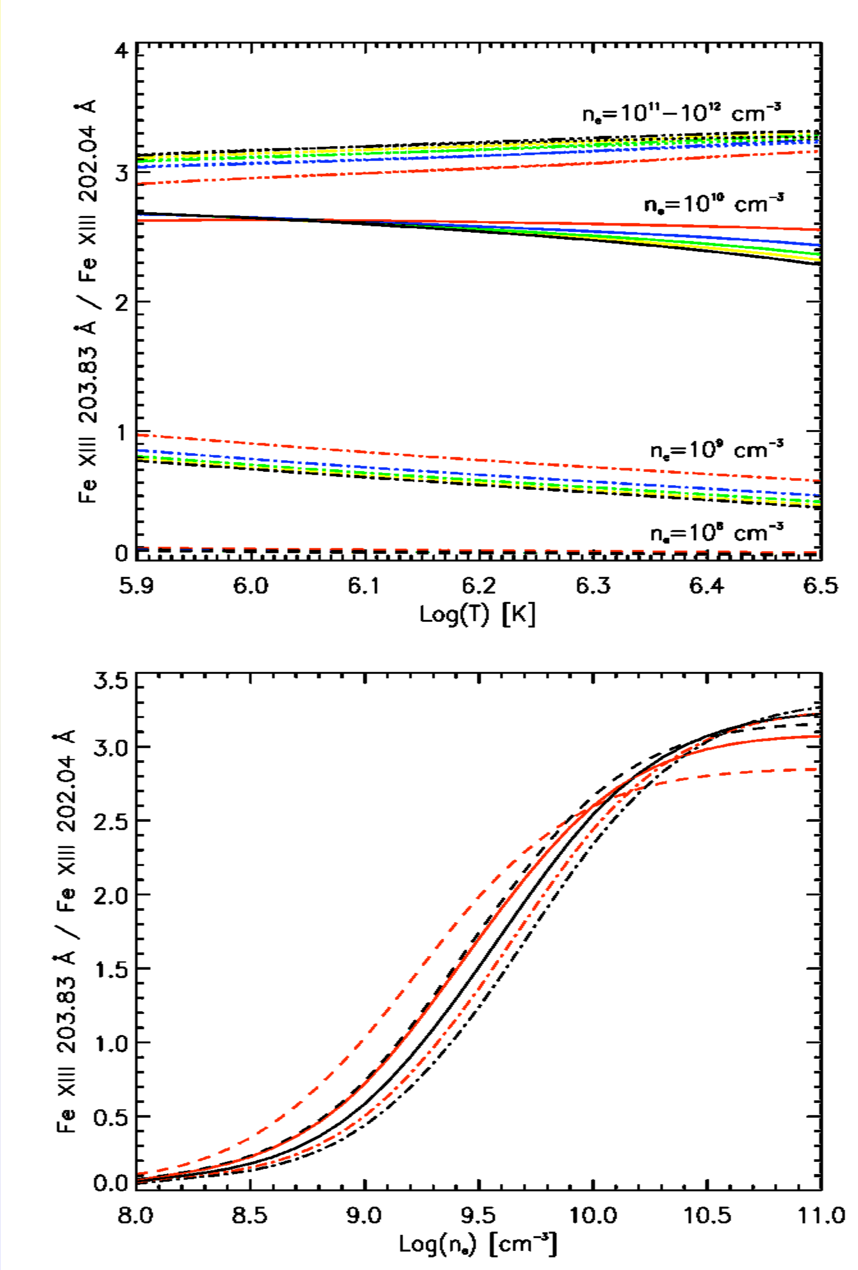
Fe X 257.26Å/184.54Å
Si X 258.37Å/261.04Å
Fe XI 182.20Å/188.23Å
Fe XIV 264.78Å/274.20Å

We must point out that *Fe XIII 203.83* line is self-blended with *Fe XIII 203.80 Å* line, *Fe XII 186.88 Å* with *Fe XII 186.85 Å* line, and *Fe XII 195.12 Å* with *Fe XII 195.18 Å* line. *Fe 186.88 Å* is also partially blended with *S XI 186.84 Å* line. This blending can be assessed by taking the *S XI 191. 27 Å* line (*S XI 186.84 / S XI 191.27* = 0.195 for all T, densities and distributions).

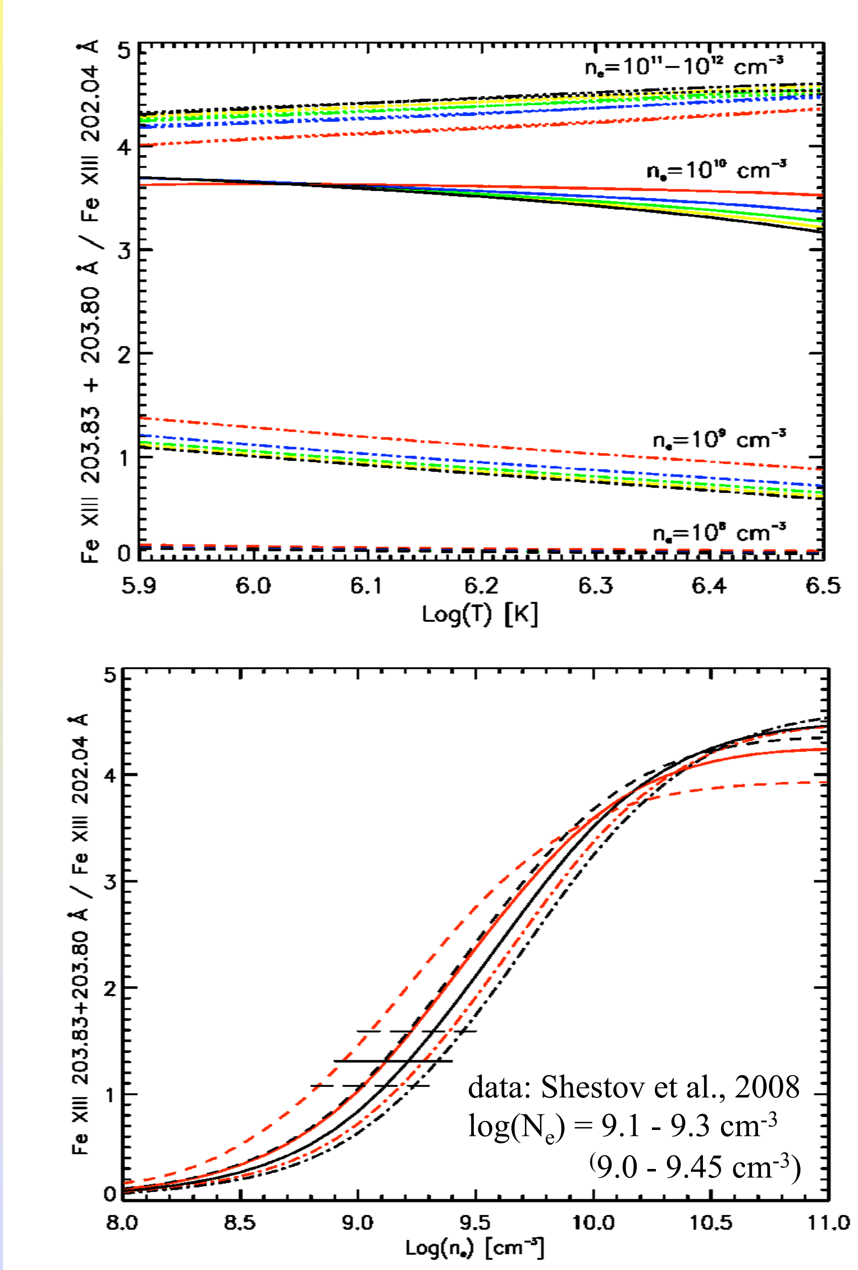
The ratios of all the above proposed lines have been computed for the Maxwellian and non-thermal distributions. All line ratios are slightly temperature dependent.

Fe XIII 203.83 Å / 202.04 Å $\log(T_{max}) = 6.2$ K

1st case, non-blended

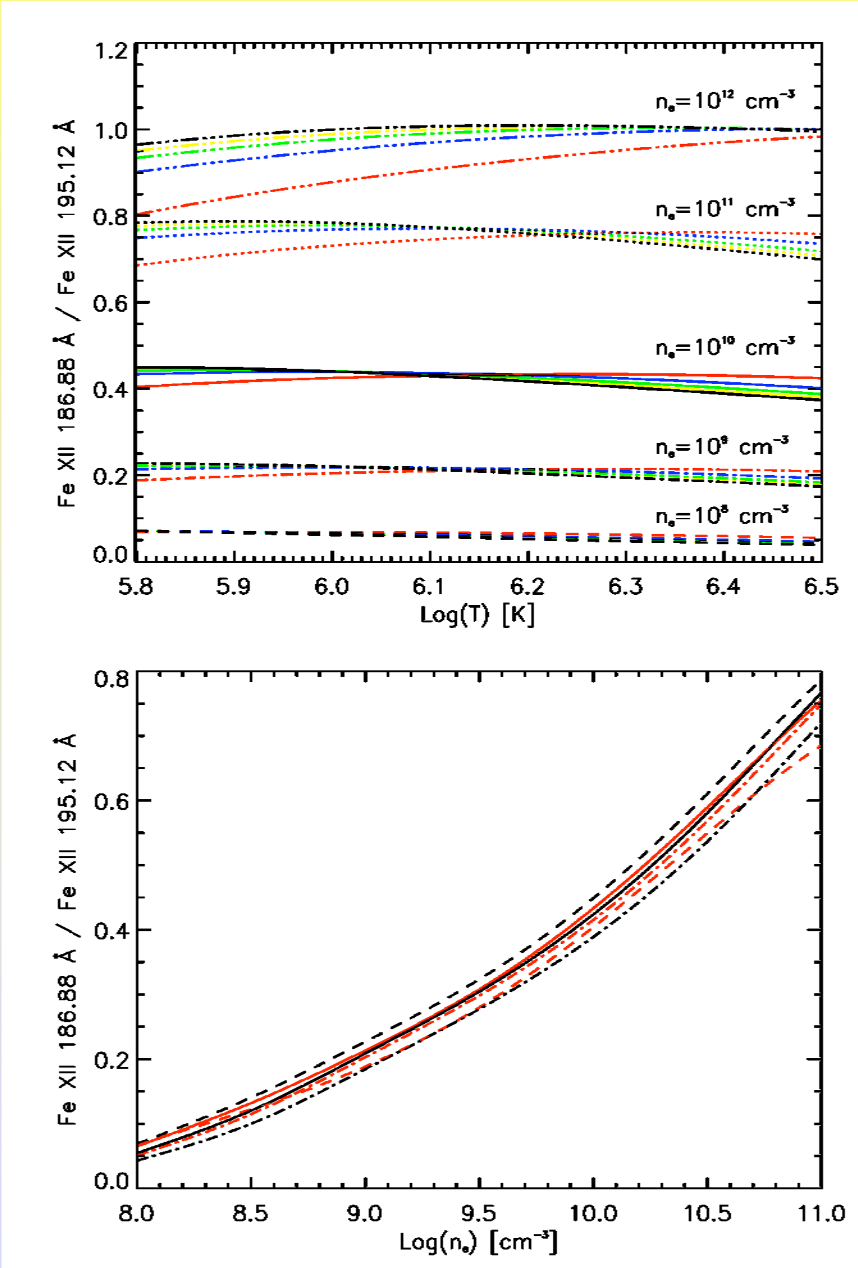


2nd case, blended

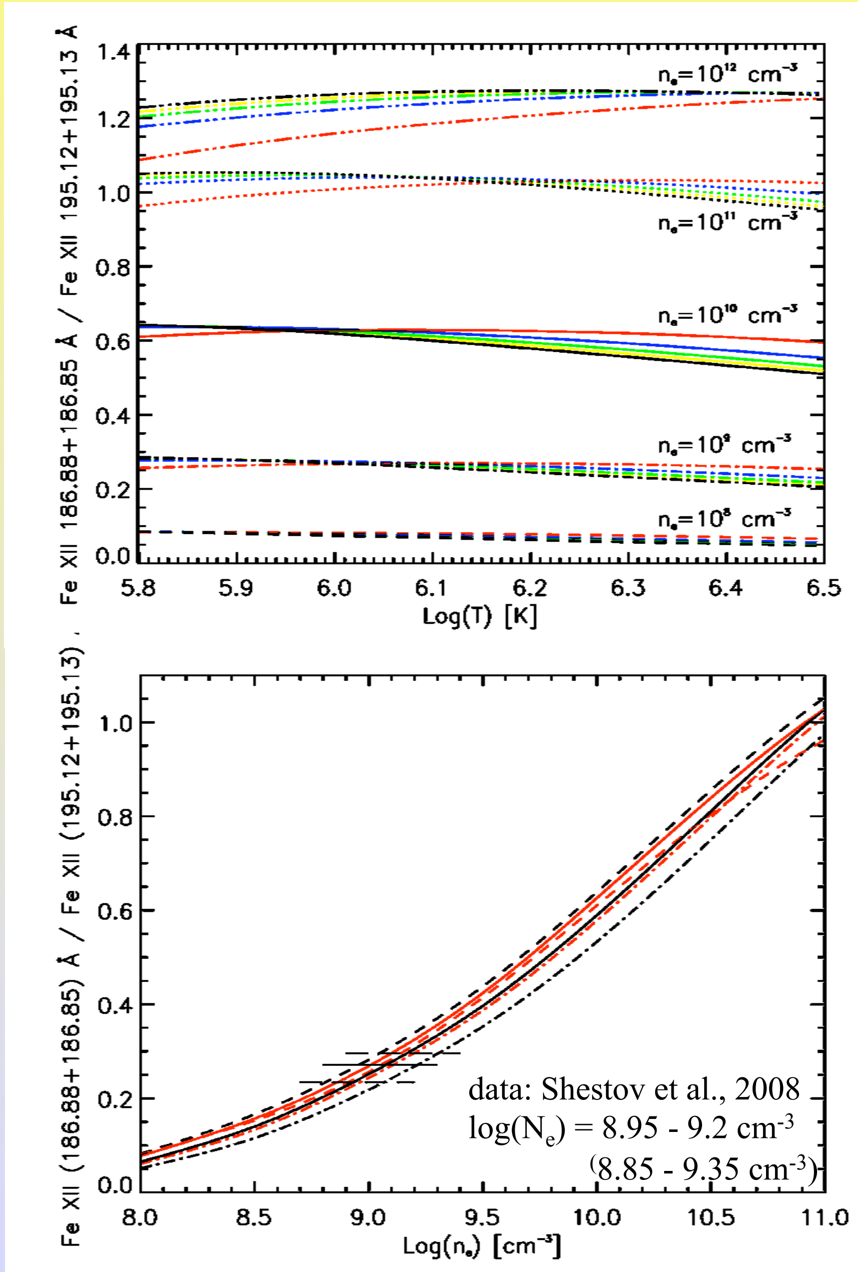


Fe XII 186.88 Å / 195.12 Å   log(T_{max})= 6.15 K

1st case, non-blended

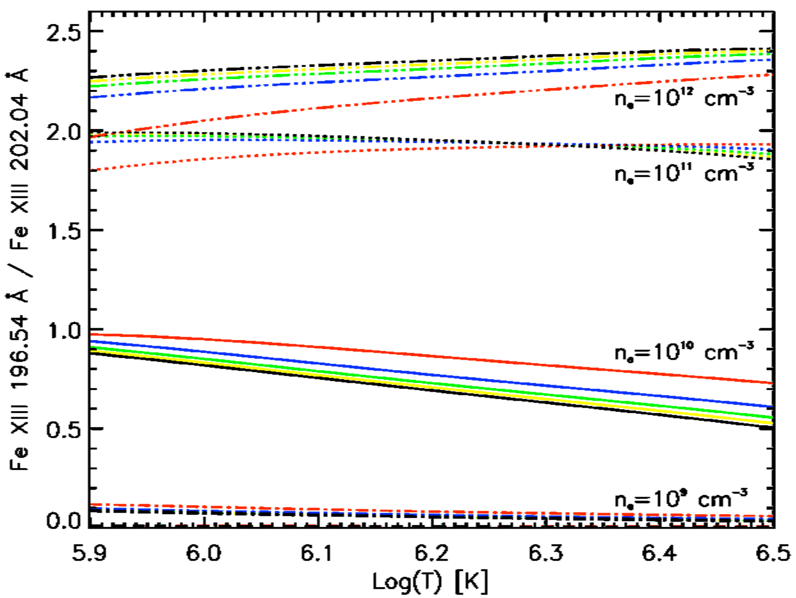


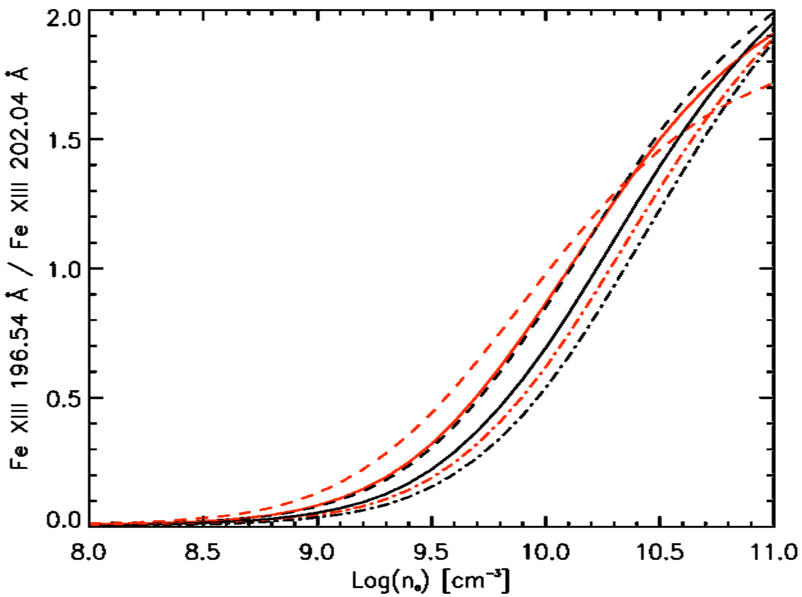
2nd case , blended



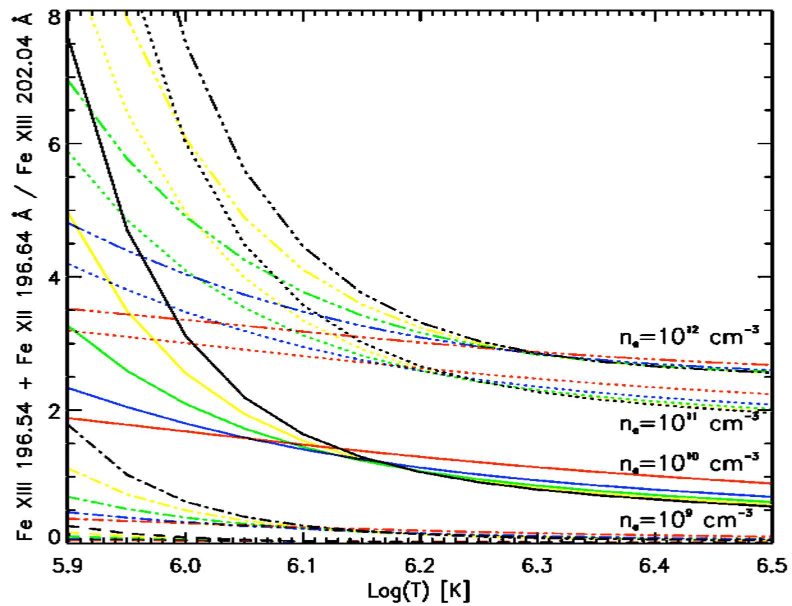
Fe XIII 196.54 Å / 202.04 Å   log(T_{max})= 6.2 K

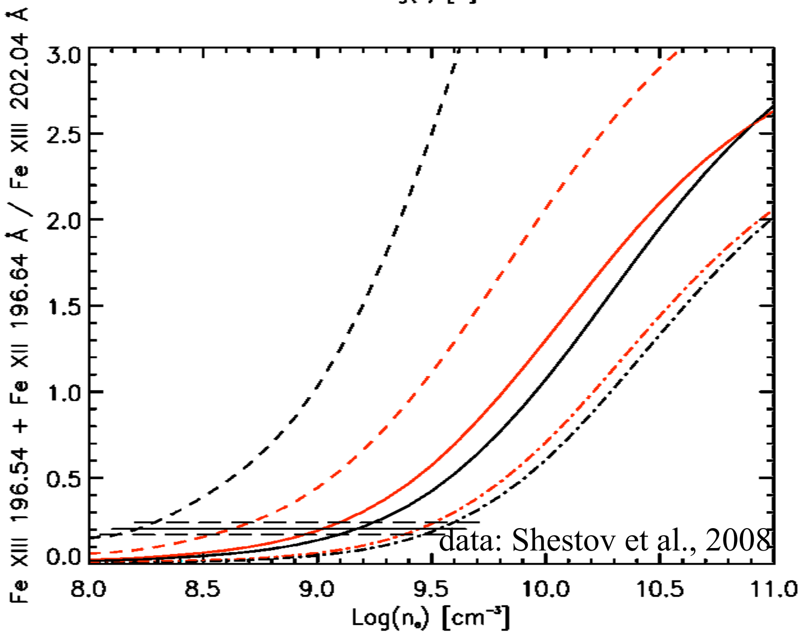
1st case, non-blended





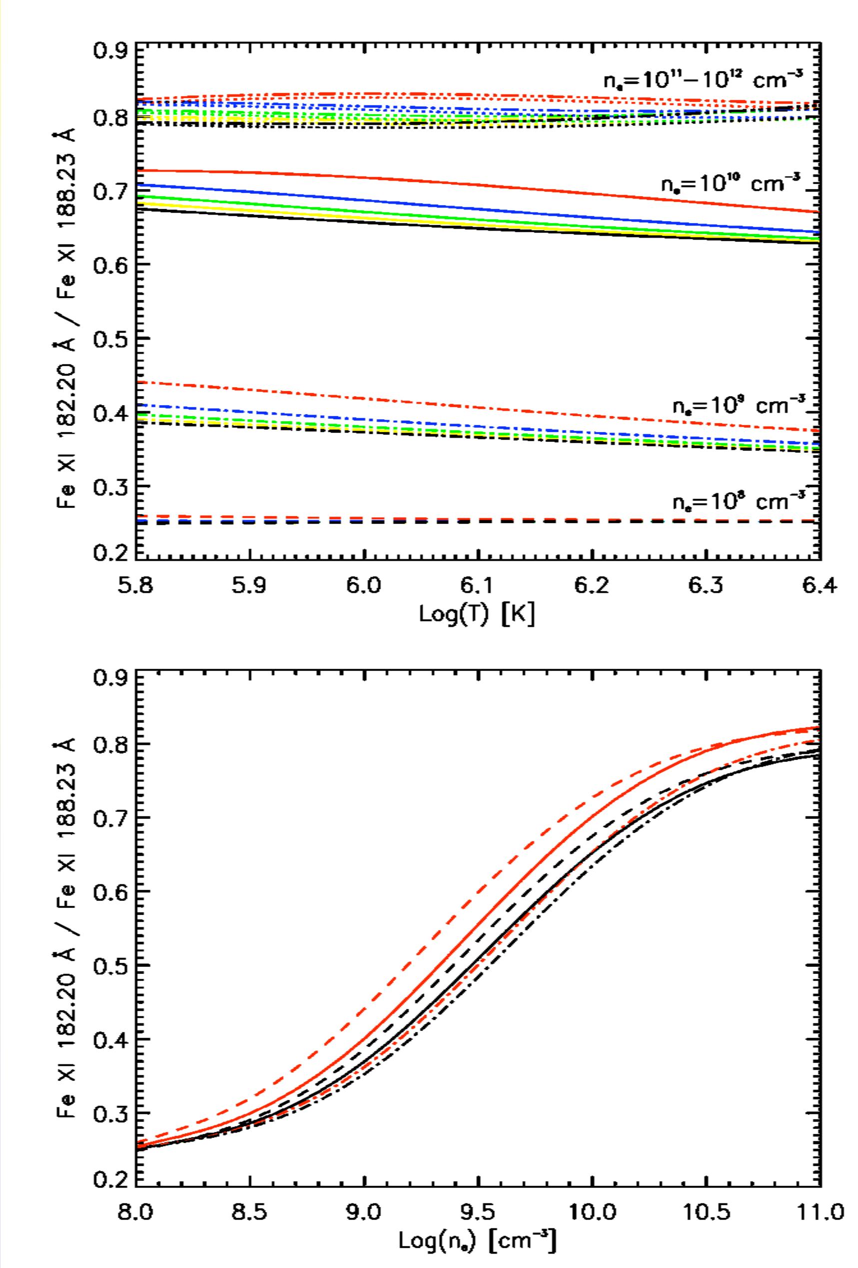
2nd case , blended



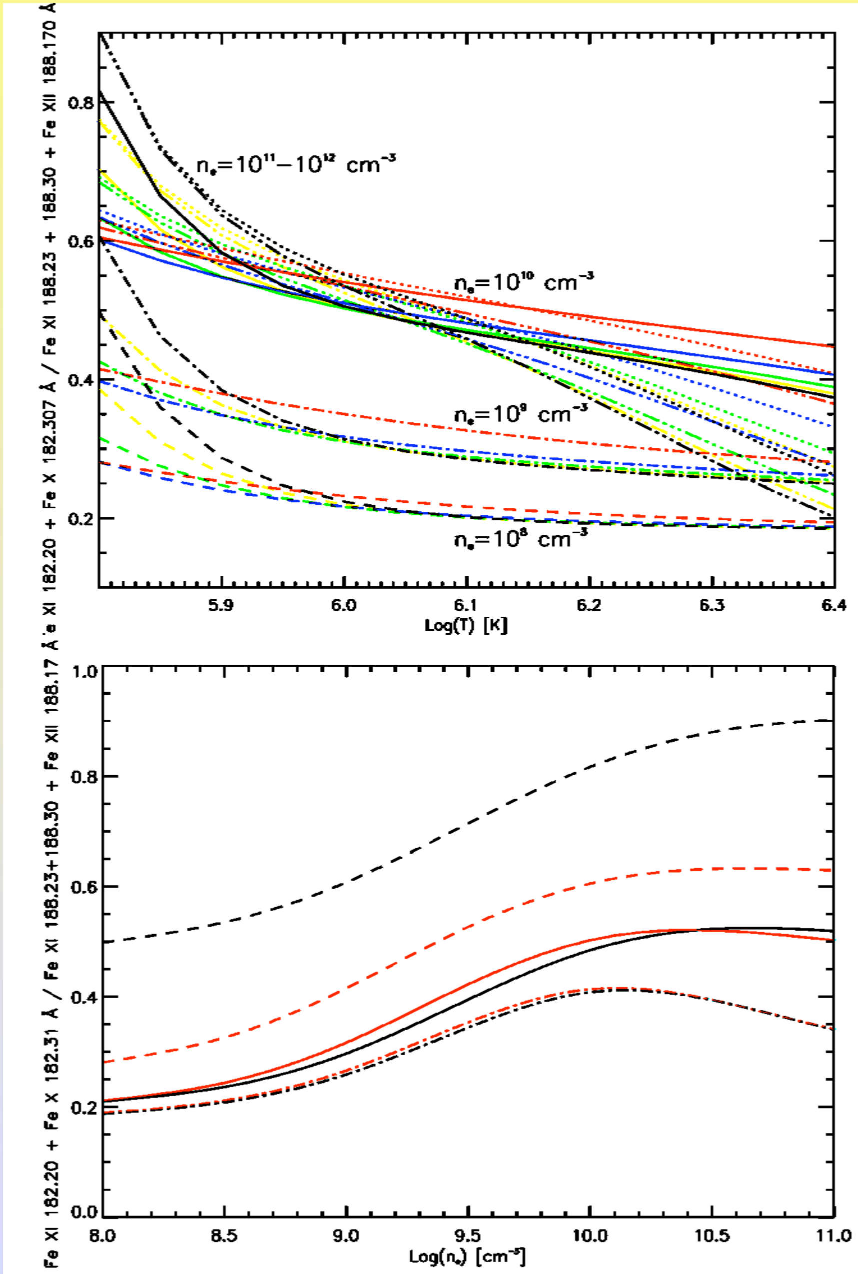


Fe XI 182.20 Å / 188.23 Å $\log(T_{max}) = 6.1$ K

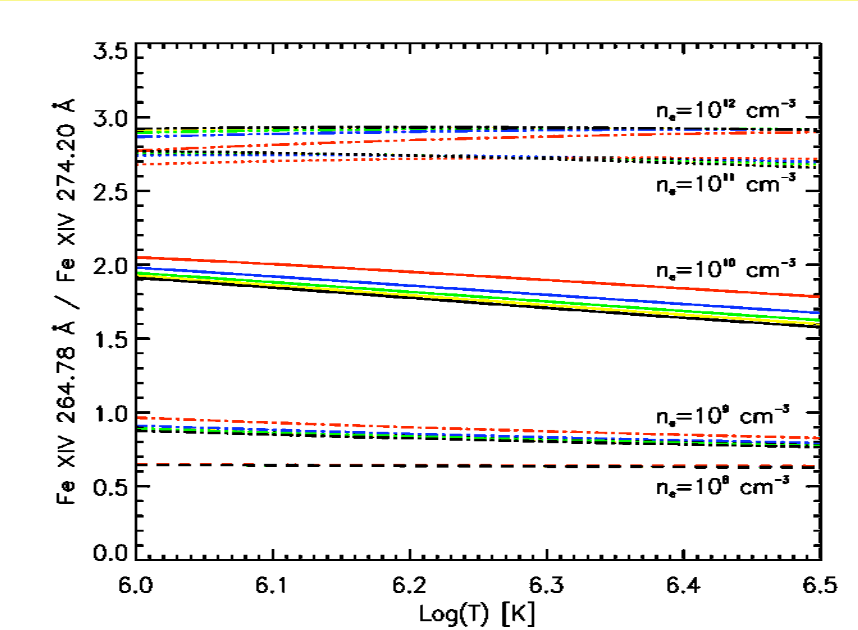
1st case, non-blended

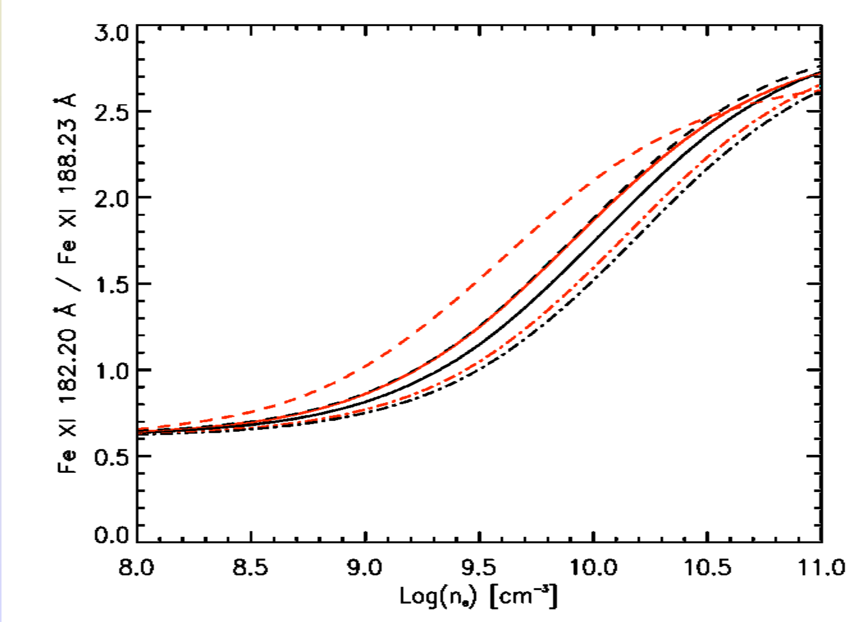


2nd case , blended

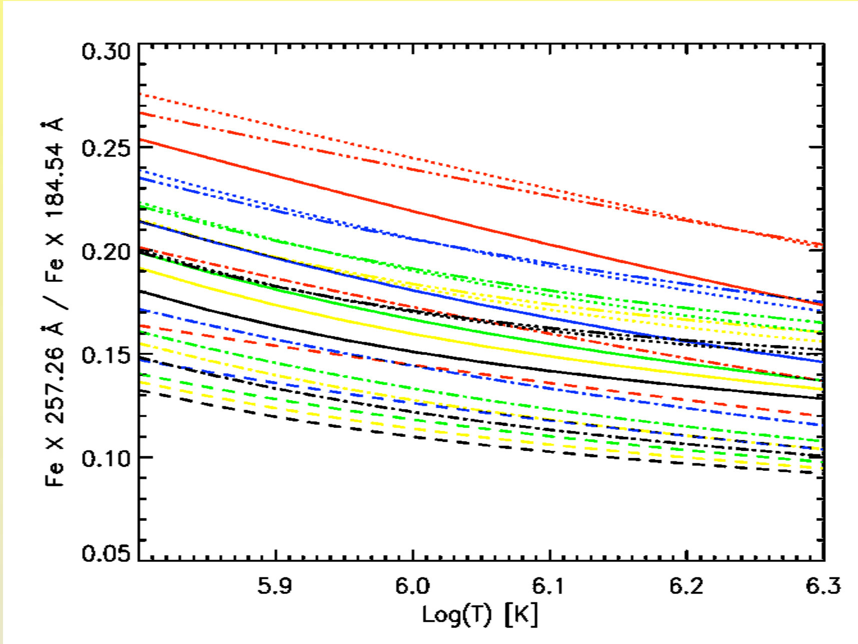


Fe XIV 264.78 Å / 274.20 Å
log(T_{max})= 6.3 K





Fe X 257.26 Å / 184.54 Å
log(T_{max})= 6.0 K



The line ratio *Fe X 257.26 Å / 184.54 Å* is unusuable for density diagnostics for non-thermal electron κ-distributions.

Diagnostics of the electron density

• The temperature dependence of the ratios allows us to determine log(ne) with maximum precision about ±0.1 for the Maxwellian distribution. If we use full black lines which correspond to log(T) of the maximum line emissivity of given ion then the dashed and dot-dashed lines can represent possible error in determination of $\log(n_e)$. The dashed and dot-dashed lines correspond to log(T) where emissivity reaches approximately 1/100 of its maximum value.

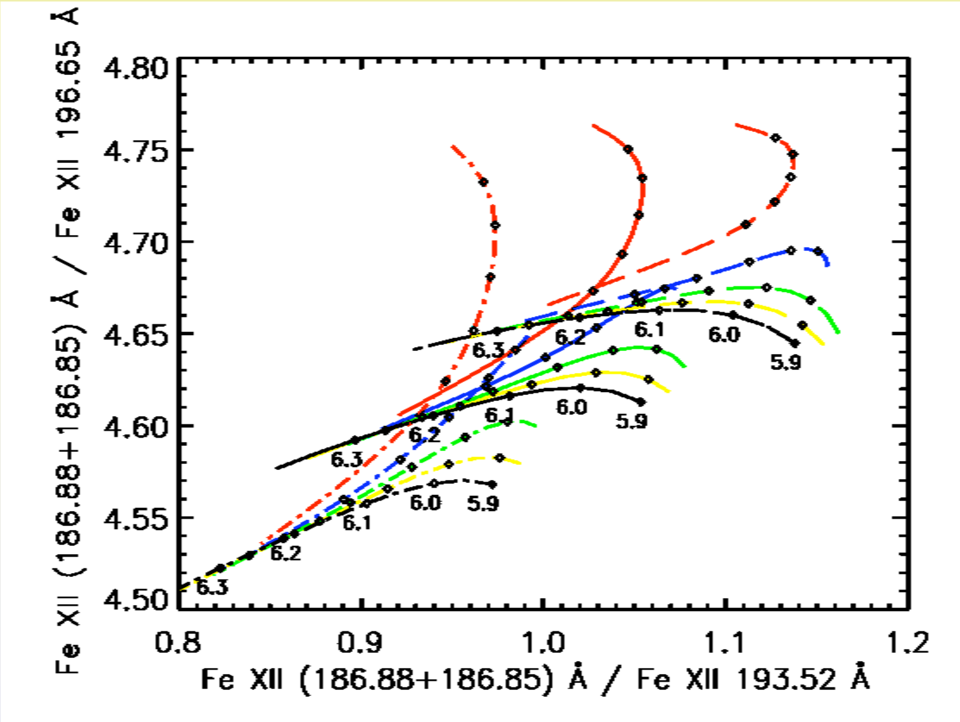
• The presence of the non-thermal κ-distribution has usually only a small effect on density diagnostics from the ratios of non-blended lines but it makes the error in determination of $\log(n_e)$ slightly higher for the all proposed line ratios.

• The only exception is the ratio Fe *X 257.26/184.54 Å*. This line ratio is strongly influenced by the non-thermal electron distribution so it is not suitable for density diagnostics.

• Only the *Fe XIII 203.83 + 203.80 Å / 202.04 Å* and *Fe XII 186.88 + 186.85 Å / 195.12 + 195.13 Å* can be used for density diagnostics from blended lines. The other blended lines are not usefull for this purpose.

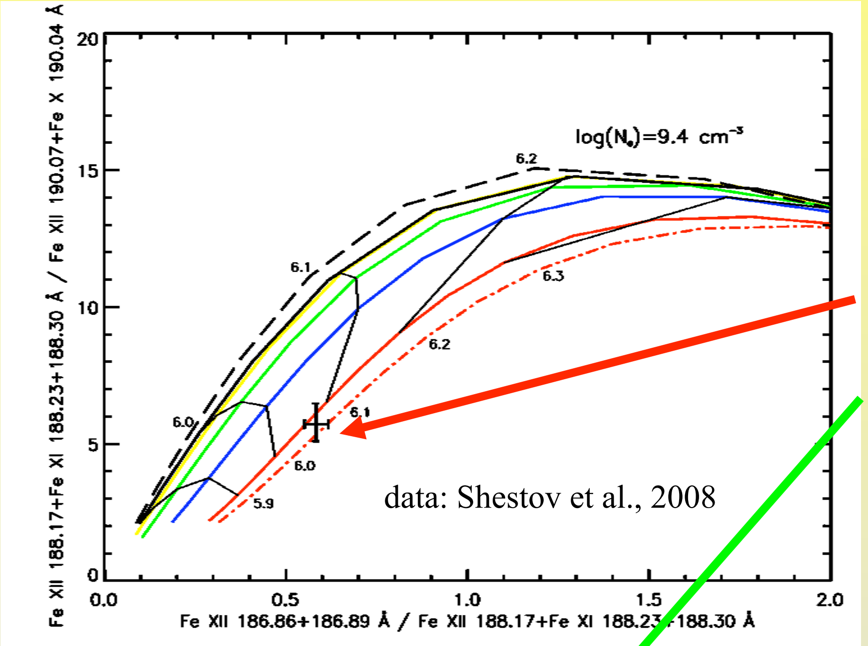
Diagnostics - 1st case

An error ±0.1 in determination of $\log(n_e)$ leads to large error in determination of the shape of the electron distribution. The example of the problems with non-thermal diagnostics for the density sensitive ratio of Fe XII lines is in Fig. Thus, if we know log(ne) with the precision of ±0.1 then we are able to say that very high ratio of *Fe XII (186.88+186.85)/196.65* corresponds only to the non-thermal distribution with low κ.



The dependence of Fe XII (186.88+186.85)/196.65 on Fe XII (186.88+186.85)/193.52 for 3 densities differ in log(ne) by 0.1 (dot-dashed lines: $10^{9.9}$ cm^{-3}, full lines: 10^{10} cm^{-3}, dashed lines: $10^{10.1}$ cm^{-3}), for Maxwellian distribution (black lines) and different κ-distributions with κ = 10 (yellow lines), κ = 5 (green lines), κ = 3 (blue lines) and κ = 2 (red lines).

Diagnostics of the distribution



Now we can try to diagnose the distribution for the known density log(N_e) = 9.1 - 9.4 cm^{-3} from SPIRIT data. The best possibility is *Fe XII 186, Fe XII+Fe XII 188, Fe XII+Fe X 190*:

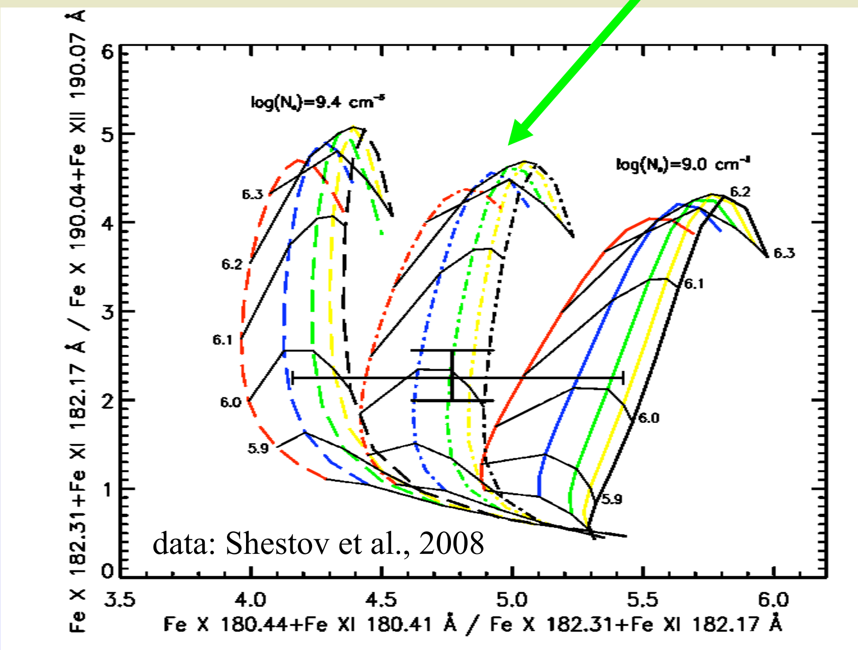
log(N_e) = 9.4 cm^{-3}, **κ**=2 and log(T) ~ 6.1 K.

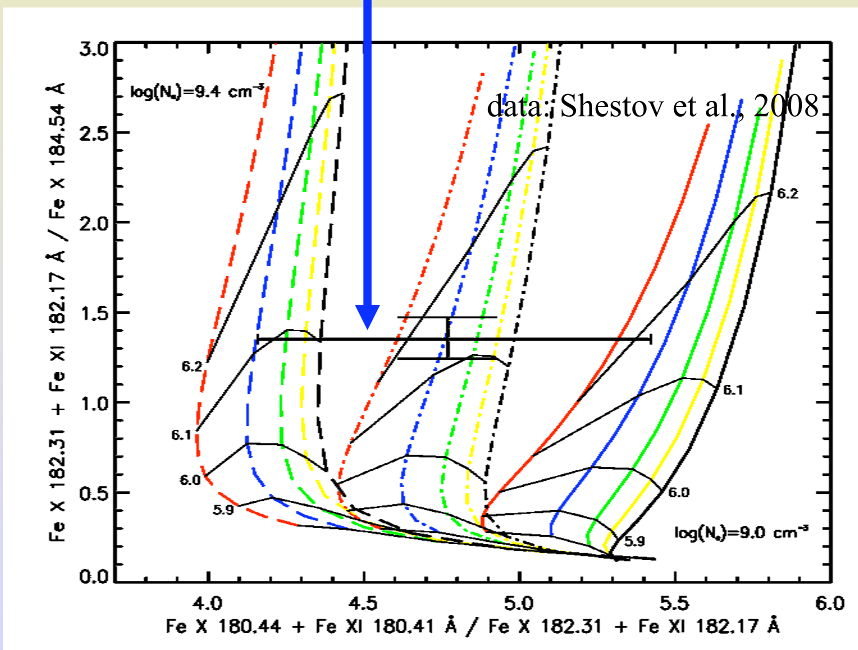
Fe X+Fe XI 180, Fe X+Fe XI 182, Fe X+Fe XI 190:

log(N_e) = 9.0 - 9.4 cm^{-3}, log(T) ~ 6.0 - 6.1 K, any distribution.

Fe X+Fe XI 180, Fe X+Fe XI 182, Fe X 184:

log(N_e) = 9.0 - 9.4 cm^{-3}, log(T) ~ 6.1 -6.2 K, any distribution.





Diagnostics of the κ-distributions

G. del Zanna (2008, A&A, **481**, L69) measured the intensities of the flare lines from Hinode EIS spectra. He presented the intensities of the four Fe XVII lines: 204.65 Å, 254.88 Å, 269.42 Å and 280.15 Å. Although these lines are not sufficiently suitable for diagnostics we have tried to use them. The observed line ratios are marked by asterisk in the Fig. and it corresponds to strongly non-thermal κ-distribution with $\kappa = 2$.

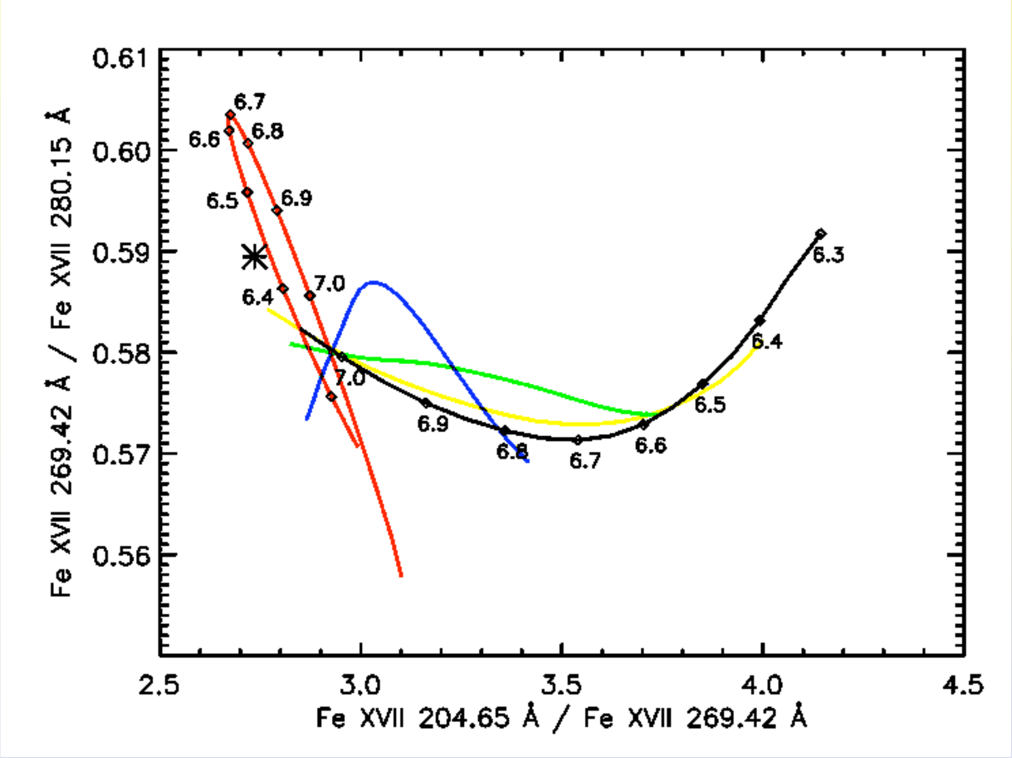


Fig. 5. *The dependence of Fe XVII 269.42/280.15 on Fe XVII 204.65/269.42 for Maxwellian distribution (black lines) and different κ-distributions with κ = 10 (yellow lines), κ = 5 (green lines), κ = 3 (blue lines) and κ = 2 (red lines). Thin black lines connect points with the constant log(T) and they are labelled by the value of log(T). An asterisk marks observed line ratio.*

Conclusion

- EUV coronal Fe lines are generally not very suitable to diagnose non-thermal distributions due to their high sensitivity to electron density. It is desirable to use more lines of one ion to reduce possible errors. For the diagnostics of the distribution it is better to use lines belonging to ions in different degree of ionization. However, it can be a source of the other errors.
- The Fe XVII lines are the exception. Their ratios have no sensitivity to electron density and therefore they can be used for the diagnostics of the presence of the non-thermal distributions in solar flares.
- The lines recommended for density diagnostics allow to diagnose electron density with precision up to ±0.1 $\log(n_e)$ due to their small temperature sensitivity.
- The non-thermal distribution has small effect on density diagnostics from non-blended lines but it can increase the error of log(ne) determination approximately two times. The ratio *Fe X 257.26/184.54 Å* is unusuable for density diagnostics for non-thermal distributions.
- The smallest influence of the presence of the non-thermal κ-distributions on the line ratio shows *Fe XII 186.88/195.12 Å*.
- We can used blended *Fe XIII 203.83+ 203.80/Fe XIII 202.04 Å* and *Fe XII 186.88+ 186.85/195.12 Å* for density diagnostics only. The other pairs of blended lines can not be used for this purpose.
- It must be pointed that the presented results can be influenced by many other errors (mainly plasma inhomogeneities and atomic data errors).

Is it possible to diagnose the non-thermal distributions from EUV spectra?

Yes, but it is not easy. We must properly consider all possible sources of errors and their values to be sure what we really diagnose.


Thank you very much for
your attention