Solar and Stellar Magnetic Fields: Origins and Manifestations
Proceedings IAU Symposium No. 354, 2019
A. Kosovichev, K. Strassmeier & M. Jardine, ed.
doi:10.1017/S1743921320001039

Diagnostics of non-thermal-distributions from solar flare EUV line spectra

Elena Dzifčáková, Alena Zemanová, Jaroslav Dudík, and Juraj Lörinčík

Astronomical Institute of the Czech Academy of Sciences,
Fričova 298, 251 65 Ondřejov, Czech Republic
email: elena.dzifcakova@asu.cas.cz

Abstract. Spectral line intensities observed by the Extreme Ultraviolet Variability Experiment (EVE) on board the Solar Dynamics Observatory (SDO) during 2012 March 9 M6.3 flare were used to diagnose a presence of a non-thermal electron distribution represented by a κ-distribution. The diagnosed electron densities ($\approx 2 \times 10^{11}$ cm^{-3}) are affected only a little by the presence of the non-thermal distribution, and are within the uncertainties of observation. On the other hand, the temperature diagnostics based on the line ratios involving different ionization degrees is strongly affected by the type of the electron distribution. The distribution functions diagnosed from relative Fe line intensities demonstrate the presence of strongly non-thermal distributions during the impulsive phase of the flare and later their gradual thermalization.

Keywords. Sun: flares, Sun: UV radiation, techniques: spectroscopic

1. Introduction

Solar flares are the most energetic manifestations of the solar magnetic activity. The magnetic reconnection transforms the energy of magnetic field mainly into the heating, waves, motions, and particle acceleration (e.g. Priest & Forbes 2000). Typically, a supra-thermal component (high-energy tail of electron distribution) is observed in flares (e.g. Brown 1971, Fletcher *et al.* 2011) and solar wind (Maksimovic *et al.* 1997). Recent theoretical papers (Bian *et al.* 2014) and RHESSI observations of coronal X-ray sources (Kašparová & Karlický 2009, Oka *et al.* 2013, 2015) suggested that the electron distribution function could have a form of κ-distributions. These distributions have a power-law high-energy tail and they are able to approximate an effect of the power-law electron beam on line spectra. The presence of the high-energy tail of the electron distribution during solar flares affects the ionization and excitation state of flaring plasma, and thus the spectrum emitted (e.g. Dzifčáková & Dudík 2013, Dzifčáková & Kulinová 2010). Dzifčáková *et al.* (2018) investigated diagnostics of the κ-distributions from the flare spectra observed by the EVE instrument onboard the Solar Dynamics Observatory (Woods *et al.* 2012) and indicated the presence of the electron distribution with a high-energy tail in the X-class solar flare from 2012 March 7. In this paper, similar diagnostics were applied on EVE spectra of the 2012 March 9, M6.3 flare (03:22 - 03:50 - 04:18 UT).

2. Kappa-distribution and Spectrum Calculation

The expression for the κ-distribution is (e.g. Olbert 1968, Dudík *et al.* 2017):

$$f_\kappa(E)dE = A_\kappa \frac{2}{\pi^{1/2}(kT)^{3/2}} \left(1 + \frac{E}{(\kappa - 1.5)kT}\right)^{-(\kappa+1)} E^{1/2}dE \qquad (2.1)$$

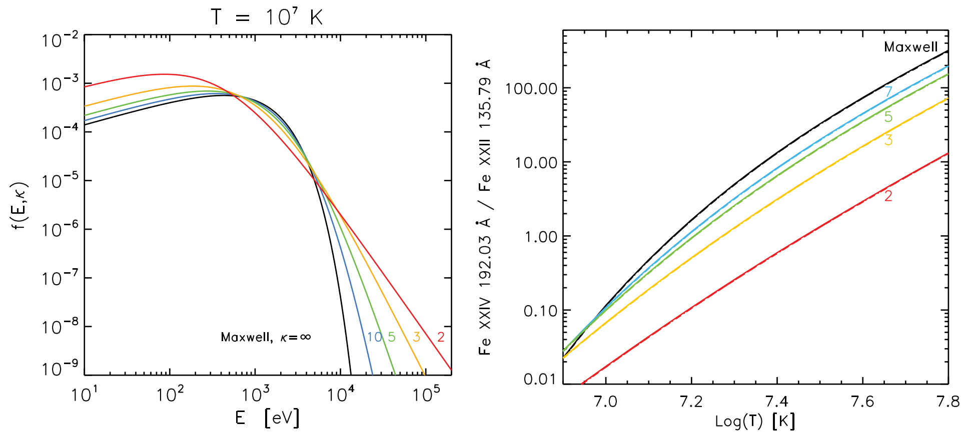

Figure 1. *Left:* Comparison of the Maxwellian distribution (black line) with the κ-distributions for $\kappa = 2$ (red), 3 (orange), 5 (green), and 10 (blue). The mean energies of distributions are the same. *Right:* Ratio of Fe XXIV 192.02 Å to Fe XXII 135.79 Å for the Maxwellian distribution (black line) and κ-distributions with $\kappa = 2$ (red), 3 (orange), 5 (green), and 7 (blue).

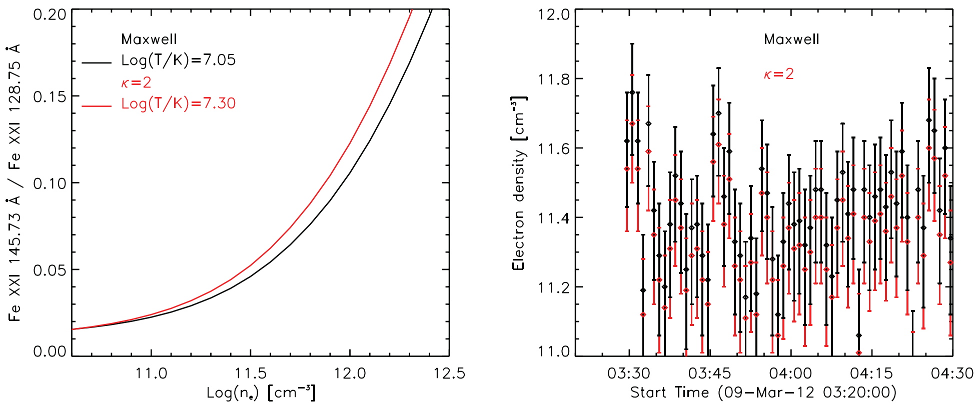

Figure 2. Density sensitive ratio of Fe XXI 145.73 Å to Fe XXI 128.75 Å for the Maxwellian distribution (black line) and the κ-distributions with $\kappa = 2$ (red line). Temperatures correspond to the maxima of the line intensities for these two distributions (*left*). Electron densities and their error-bars diagnosed under the assumption of the Maxwellian distribution are shown in black and for the κ-distributions with $\kappa = 2$ are red (*right*).

where κ is a free patameter, T is temperature, A_κ is normalization constant, m is particle mass and E epresents the particle kinetic energy (Figure 1, *left*). In comparison with the Maxwellian distribution, the κ-distributions have only one extra parameter κ, which models its shape. Strongly non-thermal distribution has $\kappa \to 1.5$ and the Maxwellian distribution corresponds to $\kappa \to \infty$. The mean energy $\langle E \rangle = 3kT/2$ of a κ-distribution is the same as for the Maxwellian distribution.

Synthetic spectra in the SDO/EVE spectral range 60 − 600 Å were calculated for log $(T/\mathrm{K}) = 6.5 - 8.0$, electron densities $10^{10} - 10^{13}$ cm^{-3}, and $\kappa = 2$, 3, 5, 7, 10, and Maxwellian distribution. To do so, we used the KAPPA package (Dzifčáková *et al.* 2015, http://kappa.su.cas.cz) based on the CHIANTI database 7.1. The ionization equilibria for the κ-distributions were taken from Dzifčáková & Dudík (2013). Ratios of synthetic line intensities were used to diagnose physical parameters of the flaring plasma (Figure 1, *right*, Figure 2, *left*).

https://doi.org/10.1017/S1743921320001039 Published online by Cambridge University Press

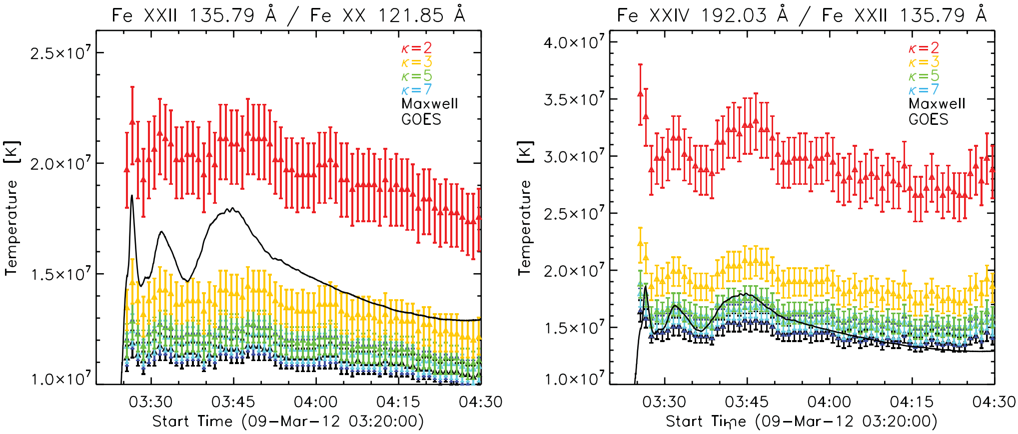

Figure 3. Behaviour of the flare temperature for the Maxwellian distribution (black points with their error bars) and different κ-distributions (collor points with their error bars) derived from Fe XXII 135.79 Å /Fe XX 121.85 Å (*left*) and Fe XXIV 192.03 Å /Fe XXII 135.79 Å (*right*). GOES temperature is shown for a comparison (black line).

3. Results

SDO/EVE provides spectra with relatively low resolution (≈1 Å) and time resolution of 10 s. Spectra observed during the M6.3 flare of 2012 March 9 were averaged over 1 minute for the density and temperature diagnostics, and over 2 minutes for diagnostics of κ to reduce the uncertainty in the determination of the line intensity ratios. After subtraction of preflare spectrum, the spectra observed during 03:27 – 04:30 UT were fitted by XCFIT (SolarSoft) to obtain the line intensities.

Electron densities in flaring plasma were found to be about 2×10^{11} cm^{-3} with local maxima up to 6×10^{11} cm^{-3} (Figure 2, *right)*. During the gradual phase of the flare, the electron density increased slowly. The densities for κ-distribution with $\kappa = 2$ are approximately 0.1 deg lower than those for the Maxwellian distribution. This difference is however smaller than the uncertainties in determination of the electron density.

Diagnosed temperature depends on the line ratio used and as well as on the assumed electron distribution (Figure 3). Local maxima of temperature correspond approximately to the local maxima of the GOES temperature and their timing corresponds also to the maxima of the diagnosed electron density. Different temperatures obtained from different line ratios indicate the presence of the multi-thermal or non-equilibrium plasma. The shift in the diagnosed temperature due to the assumption of the different distributions can be up to a factor of 2 due to the presence of the high-energy tail. This effect shows how important is the diagnostics of electron distribution function for determination of the temperatures and flare energetics.

For diagnostics of the distribution function, the method proposed by Dzifčáková *et al.* (2018) were used. Figure 4 *left* shows the observed line ratios for the whole time interval 03:27 – 04:30 UT. The right panel displays only data from the time interval 03:50–03:55 UT, when the line Fe XX 424.3 Å was visible. The colour coding of points with their error bars corresponds to time, it increases from black, ought blue, green, and orange to red. Observed line ratios from the impulsive phase or from flare maximum (blue points) indicate strongly non-thermal distribution. They are far away from line ratios corresponding to the non-thermal κ-distributions with $\kappa = 2$. This is a signature of strongly non-thermal plasmas, which could also be out of ionization equilibrium. During decay phase, flare emission shows signatures of successive thermalisation with time.

https://doi.org/10.1017/S1743921320001039 Published online by Cambridge University Press

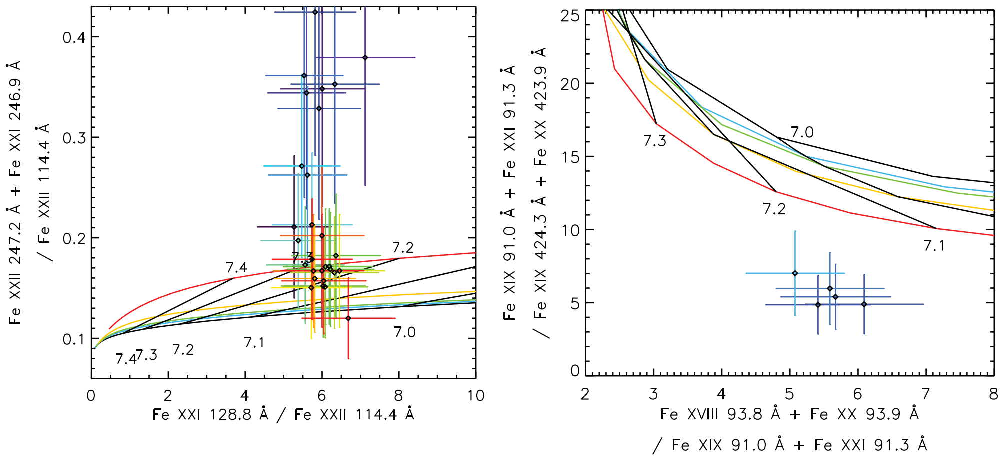

Figure 4. Diagnostics of the distribution function. The theoretical ratio-ratio diagrams are based on the Fe XXI, Fe XXII lines (*left*) and Fe XVIII, Fe XIX, Fe XX lines (*right*). Maxwellian distribution is represented by black lines, while $\kappa = 10$ by blue lines, 5 (green), 3 (orange), and 2 (red). Observed line ratios are shown with their error bars. Thin black lines connect points with the same temperature in different distributions.

4. Acknowledgements

This work was supported by the Grant No. 18-09072S and 17-16447S of the Grant Agency of the Czech Republic, as well as institutional support RVO:67985815 from the Czech Academy of Sciences. This work was also supported by the Charles University, project GA UK 1130218.

References

Bian, N. H., Emslie, A. G., Stackhouse, D. J., & Kontar, E. P. 2014, *ApJ*, 796, 142
Brown, J. C. 1971, *Solar Phys.*, 18, 489
Dudík, J., Dzifčáková, E., Meyer-Vernet, N., *et al.* 2017, *Solar Phys.*, 292, 100
Dzifčáková, E., & Kulinová, A. 2010, *Solar Phys.*, 263, 25
Dzifčáková, E., & Dudík, J. 2013, *ApJS*, 206, 6
Dzifčáková, E., Dudík, J., Kotrč, P., Fárník, F., & Zemanová, A. 2015, *ApJS*, 217, 14
Dzifčáková, E., Zemanová, A., Dudík, J., Lörinčík, J. 2018, *ApJ*, 853, 158
Fletcher, L., Dennis, B. R., Hudson, H. S., *et al.* 2011, *SSRv*, 159, 19
Kašparová, J. & Karlický, M. 2009, *Astron. Astrophys.*, 497, L13
Maksimovic M., Pierrard V., & Lemaire J. F. 1997, *Astron. Astrophys.*, 324, 725
Oka, M., Ishikawa, S., Saint-Hilaire, P., Krucker, S., & Lin, R. P. 2013, *ApJ*, 764, 6
Oka, M., Krucker, S., Hudson, H. S., & Saint-Hilaire, P. 2015, *ApJ*, 799, 129
Olbert, S. 1968, in R. D. L. Carovillano & J. F. McClay (eds.), *in Physics of the Magnetosphere* (Dordrecht: Reidel), p. 641
Priest, E. & Forbes, T. 2000, *Magnetic Reconnection* (Cambridge: Cambridge Univ. Press)
Woods, T. N., Eparvier, F. G., Hock, R., *et al.* 2012, *Solar Phys.*, 275, 115

https://doi.org/10.1017/S1743921320001039 Published online by Cambridge University Press