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Updated calculations of the ionization equilibrium for the non-Maxwellian electron n-distributions in solar flares

Elena Dzifčáková[1] **and Jaroslav Dudík**[1]

[1]Astronomical Institute of the Czech Academy of Sciences,
Fričova 249, 251 65 Ondřejov, Czech Republic
email: elena@asu.cas.cz, jaroslav.dudik@asu.cas.cz

Abstract. The assumption of an equilibrium (Maxwellian) distribution of electron energies cannot explain observed high intensities of the Si XIId satellite lines relative to the Si XIII allowed lines during the flares. However, the presence of n-distribution with a higher and narrower shape than the Maxwellian one is able to explain this behavior. We calculated the ionization equilibrium for the non-thermal n-distributions using the latest atomic data for each element up to the proton number of 30. Significant changes in the shape and maxima of the ion abundance peak occur and can strongly influence the temperature diagnostics.

Keywords. Sun: flares, Sun: corona, Sun: X-rays

1. Introduction

The X-ray spectra in 3.4 - 6 Å spectral range show unusually enhanced intensities of the satellite lines in comparison with Maxwellian spectra. Dzifčáková *et al.*,(2008) explained these high intensities by the presence of the non-Maxwellian n-distributions. The peak of these distributions is higher and narrower compared to the Maxwellian distribution (Fig. 1 left). Their presence in solar flares was suggested by Seely, Feldman & Doschek, (1987). Their occurrence is associated with type III radio bursts (Dzifčáková *et al.*, 2008, Kulinová *et al.*, 2011) and they were also diagnosed in RHESSI spectra (Kulinová *et al.*, 2011). Karlický, Dzifčáková & Dudík (2012) and Karlický (2012) analyzed the physical conditions for formation of the n-distributions and Karlický (2012) showed that they can be formed in the electric double layers.

2. n-distribution

The n-distributions have higher and narrower peaks than the Maxwellian distribution. This is caused by the $(E/kT)^{n/2}$ factor:

$$f(E)dE = B_n \frac{2}{kT\sqrt{\pi}} \left(\frac{E}{kT}\right)^{n/2} exp\left(-\frac{E}{kT}\right) dE, \tag{2.1}$$

where B_n is normalization constant, and n and T are free parameters. The mean energy of the n-distribution is $< E >= \frac{n+2}{2}kT = \frac{3}{2}k\tau$, where τ is the pseudo-temperature, having the same physical meaning as the temperature for the Maxwellian distribution, which is recovered for n=1. The deviation from the Maxwellian distribution rises with rising value of n.

3. Ionization equilibrium

The ionization equilibria for the n-distribution were calculated for Fe (Dzifčáková, 1998), Si and Ca (Dzifčáková & Kulinová, 2005) only and these calculations corresponded

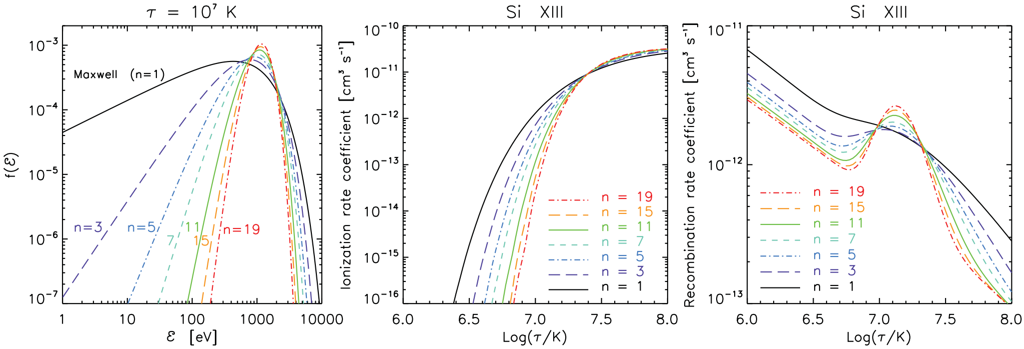

Figure 1. *Left*: The shape of the Maxwellian ($n = 1$) and n-distributions with $n = 3$, 5, 7, 11, 15, and 19. The distributions have the same mean energy. The ionization *(middle)* and recombination rates *(right)* of Si XIII for the Maxwellian (full black lines) and different n-distributions.

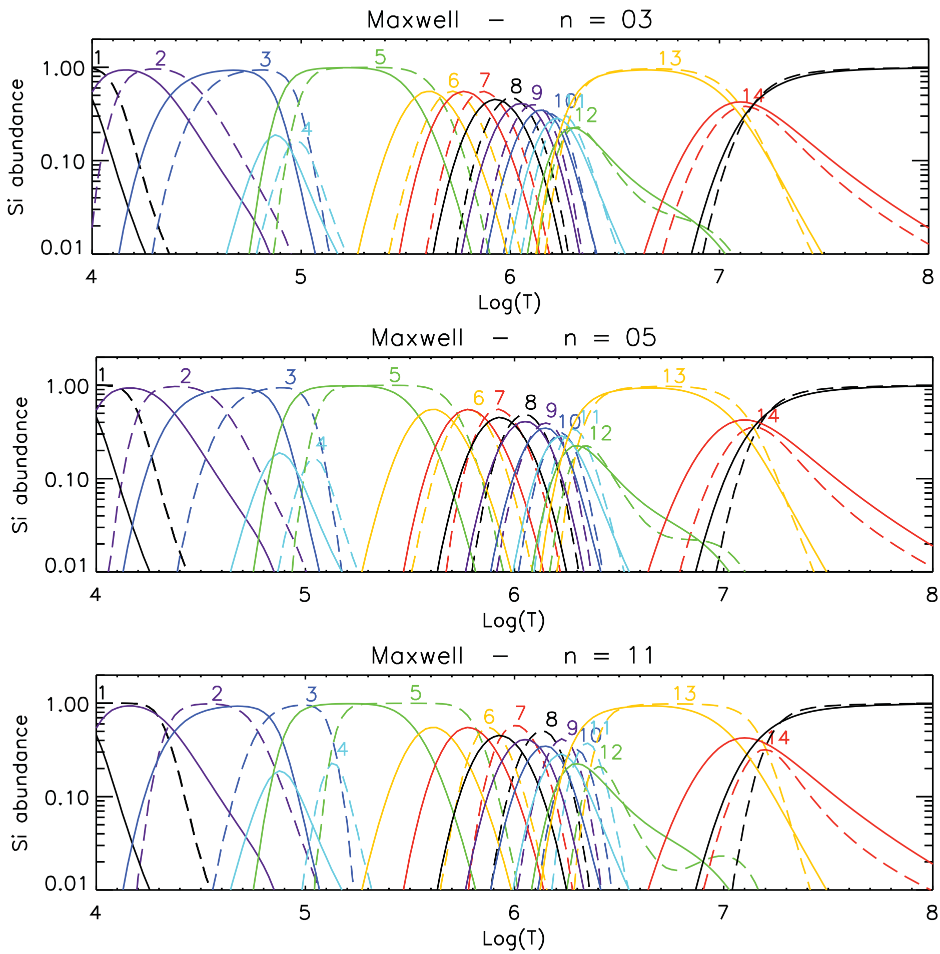

Figure 2. The ionization equilibrium for the Maxwellian (full lines) and n-distributions with different n (dashed lines) for the silicon in the temperature range $10^4 - 10^8$ K. The same color corresponds to the same ions.

to the atomic data of Mazzotta *et al.* (1998). Present calculations are compatible with CHIANTI ionization equilibrium for the Maxwellian distribution. We used ionization cross section included in CHIANTI, version 7.1 (Dere *et al.*, 2009). Atomic data of Dere (2007) from CHIANTI database were used to derive the ionization rates. For the calculation of the recombinatoin rate, we used data of Badnell *et al.* (2003), Colgan, Pindzola, and Badnell (2004), Badnell (2006), Bautista and Badnell (2007), Shull and van Steenberg (1982), Nahar and Bautista (2001), Mazzotta *et al.* (1998). The ionization equilibria for the n-distributions were calculated for the n-distributions with n=1, 3, 5, 7, 9, 11, 13, 15, 17, and 19. These calculations involve all elements from H to Zn.

The typical changes of the ionization and recombination rates are shown for Si XIII in Fig. 1 *middle* and *right*. Ionization rates are steeper with increasing n, while the radiative recombination rates are lower. The contribution of the dielectronic recombination is more peaked and narrower. All these changes are due to the behavior of the distribution at respective energies. The shape of the rates is reflected in the ionization equilibria for the n-distribution. The ionization peaks become narrower and can be shifted (Fig. 2), preferably to higher τ for flare conditions what influences diagnostics of plasma parameters.

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