H TO Zn IONIZATION EQUILIBRIUM FOR THE NON-MAXWELLIAN ELECTRON \( \kappa \)-DISTRIBUTIONS: UPDATED CALCULATIONS

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ABSTRACT

New data for the calculation of ionization and recombination rates have been published in the past few years, most of which are included in the CHIANTI database. We used these data to calculate collisional ionization and recombination rates for the non-Maxwellian \( \kappa \)-distributions with an enhanced number of particles in the high-energy tail, which have been detected in the solar transition region and the solar wind. Ionization equilibria for elements H to Zn are derived. The \( \kappa \)-distributions significantly influence both the ionization and recombination rates and widen the ion abundance peaks. In comparison with the Maxwellian distribution, the ion abundance peaks can also be shifted to lower or higher temperatures. The updated ionization equilibrium calculations result in large changes for several ions, notably Fe\textsc{viii}–Fe\textsc{xiv}. The results are supplied in electronic form compatible with the CHIANTI database.

Key words: atomic data – atomic processes – radiation mechanisms: non-thermal – Sun: corona – Sun: UV radiation – Sun: X-rays, gamma rays

Online-only material: color figures, supplemental data file (tar.gz)

1. INTRODUCTION

One of the most widely used assumptions in the interpretation of astrophysical spectra is that the emitting system is in thermal equilibrium. This means that the distribution of particle energies is at least locally Maxwellian and can be characterized by the Boltzmann–Gibbs statistic which has one parameter, the temperature.

The generalization of the Boltzmann–Gibbs statistic proposed by Tsallis (1988, 2009) results in \( \kappa \)-distributions (e.g., Leubner 2002, 2004a, 2004b; Collier 2004; Livadiotis & McComas 2009) characterized by a parameter \( \kappa \) and exhibiting a near-Maxwellian core and a high-energy power-law tail (Section 2). First proposed by Vasyliunas (1968), \( \kappa \)-distributions are now used to fit the observations of a wide variety of astrophysical environments, e.g., in situ measurements of particle distributions in planetary magnetic environments (e.g., Pierrard & Lemaire 1996; Mauk et al. 2004; Schippers et al. 2008; Xiao et al. 2008; Dialynas et al. 2009) and solar wind (e.g., Collier et al. 1996; Maksimovic et al. 1997a, 1997b; Pierrard et al. 1999; Nieves-Chinchilla & Viñas 2008; Le Chat et al. 2009, 2011; Pierrard 2012), as well as photon spectra of solar flare plasmas (e.g., Kašparová & Karlický 2009; Oka et al. 2013), emission line spectra of planetary nebulae and galactic sources (Nicholls et al. 2012; see also Binette et al. 2012), and even the solar transition region (Dzifčáková & Kulinoňová 2011). A review on the \( \kappa \)-distributions and their applications in planetary magnetic environments can be found, e.g., in Pierrard & Lazar (2010).

In the solar corona, the presence of the \( \kappa \)-distributions, or distributions exhibiting high-energy tails, can be expected due to particle acceleration processes arising as a result of “nanoflare” heating. The nanoflares are an unknown energy release process of impulsive nature, possibly occurring in storms heating the solar corona (e.g., Tripathi et al. 2010; Viał & Klimchuk 2011; Bradshaw et al. 2012; Winebarger 2012). While direct evidence for enhanced suprathermal populations in the solar corona is still lacking (Feldman et al. 2007; Hannah et al. 2010), Pinfield et al. (1999) reported that the intensities of the \textsc{Si} iii transition region lines observed by the \textsc{SOHO}/SUMER instrument do not correspond to a single Maxwellian distribution. Using their data, Dzifčáková & Kulinoňová (2011) showed that the observed intensities can be explained by \( \kappa \)-distributions once the photoexcitation is taken into account. These authors diagnosed \( \kappa = 7 \) in the active region observed on the solar limb. Higher values of \( \kappa \) were diagnosed for the quiet Sun and coronal hole, indicating that the departures from the Maxwellian distribution can be connected to the local magnetic activity. The diagnostic method also works for inhomogeneous plasmas characterized by the differential emission measure. That the \( \kappa \)-distributions can be present in the solar corona is also suggested by their presence in the solar wind (e.g., Pierrard et al. 1999; Vocks & Mann 2003).

Direct diagnostics of \( \kappa \)-distributions in the solar corona using extreme ultraviolet lines observed by the \textsc{Hinode}/EIS spectrometer (Culhane et al. 2007) were attempted by Dzifčáková & Kulinoňová (2010) and Mackovjak et al. (2013). These authors proposed methods for simultaneous diagnostics of the plasma temperature, electron density, and \( \kappa \). However, the majority of the line ratios sensitive to \( \kappa \)-distributions suffer from poor photon statistics, errors in atomic data, and/or plasma inhomogeneities. In spite of this, one of the main results of these works is that the sensitivity to \( \kappa \)-distributions, or to departures from the Maxwellian distribution in general, is enhanced if the line ratios involve lines originating in neighboring ionization stages. This is due to the sensitivity of the line emissivity to the abundance of the emitting ion which depends directly on the ionization equilibrium, which in turn is highly dependent on the type of distribution (e.g., Dzifčáková 2002; Wannawichian et al. 2003; Dzifčáková 2006).

In the past decade, new calculations of the ionization and recombination rates, and ionization equilibrium for the

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Maxwellian electron distribution were published. These are summarized in the continually updated CHIANTI database, currently available in version 7.1 (e.g., Dere et al. 1997, 2009; Landi et al. 2012, 2013). These new calculations of the ionization and recombination rates result in significant differences with respect to the earlier calculations of, e.g., Mazzotta et al. (1998).

The availability of accurate atomic data is of crucial importance in correct determination of the properties of the radiating astrophysical environment, and the solar corona in particular. In this paper, we present up-to-date calculations of the ionization and recombination rates (Section 3) and ionization equilibria (Section 4) for \( \kappa \)-distributions for elements from H to Zn. Such calculations are necessary for diagnostics of the \( \kappa \)-distributions in both the solar transition region and the corona as well as subsequent calculations of the radiative losses (Dudík et al. 2011) or responses of various extreme ultraviolet or X-ray filters (Dudík et al. 2009) used both to model and observe these portions of the solar atmosphere with potential applications to other astrophysical environments.

2. THE NON-MAXWELLIAN \( \kappa \)-DISTRIBUTIONS

The \( \kappa \)-distributions of electron kinetic energies \( \varepsilon \) represent a family of non-Maxwellian distributions characterized by two parameters, \( \kappa \) and \( T \):

\[
 f_{\kappa}(\varepsilon)d\varepsilon = \mathcal{A}_{\kappa} \frac{2}{\pi^{1/2}(k_B T)^{3/2}} \frac{\varepsilon^{1/2}d\varepsilon}{(1 + \frac{\varepsilon}{k_B T})^{(\kappa+1)/\kappa}},
\]

where \( \mathcal{A}_{\kappa} = \Gamma(\kappa + 1)/[\Gamma(\kappa - 0.5)(\kappa - 1.5)^{3/2}] \) is the normalization constant, \( k_B = 1.38 \times 10^{-23} \) J kg\(^{-1}\) is the Boltzmann constant, and \( \kappa \in (3/2, +\infty) \), \( T \in (0, +\infty) \). We note that the definition of \( \kappa \)-distributions in Equation (1) corresponds to the \( \kappa \)-distributions of the second kind (e.g., Livadiotis & McComas 2009).

The shape of the distribution is controlled by the parameter \( \kappa \). The Maxwellian distribution is recovered for \( \kappa \rightarrow +\infty \), while the departures from the Maxwellian increase with \( \kappa \rightarrow 3/2 \). The departures from the Maxwellian distribution with decreasing \( \kappa \) include an increase in the number of particles in the high-energy tail as well as an increase in the relative number of low-energy electrons (Figure 1, top). However, the mean energy \( \langle \varepsilon \rangle = 3/2k_BT \) of the distribution does not depend on \( \kappa \). This allows for the calculation of all quantities depending on the mean energy of the distribution, e.g., pressure (Dzičkáková 2006).

The parameter \( T \) has, in the frame of nonextensive statistics (Tsallis 1988, 2009), a meaning similar to the thermodynamic temperature in the Boltzmann–Gibbs statistic. The reader is referred to, e.g., the work of Livadiotis & McComas (2009, 2010) for details.

While the shape of the \( \kappa \)-distribution differs from the Maxwellian with the same \( T \) at all energies \( \varepsilon \), the core of the \( \kappa \)-distribution can be approximated by a Maxwellian distribution with lower \( T_C = T(\kappa - 3/2)/\kappa \) (Oka et al. 2013). An example for \( \kappa = 5 \) and \( T = 1 \) MK is shown in Figure 1 (bottom), where the approximating Maxwellian distribution has \( T_C = 0.7T \) and has been scaled by the factor \( C \):

\[
 C = 2.718 \frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - 1/2)} \kappa^{-3/2} \left( 1 + \frac{1}{\kappa} \right)^{-(\kappa+1)}/\kappa
\]

(Oka et al. 2013), which is \( \approx 0.84 \) for \( \kappa = 5 \). The difference between \( f_{\kappa}(T) \) and \( f_{\text{Maxwell}}(T_C) \) is then mainly in the pronounced high-energy tail. This shows that the \( \kappa \)-distributions offer a straightforward approximation of situations where a non-Maxwellian high-energy tail is present.

3. IONIZATION AND RECOMBINATION RATES

To calculate the ionization and recombination rates for \( \kappa \)-distributions, we use the atomic data available through the CHIANTI database for astrophysical spectroscopy of optically thin plasmas (Dere et al. 1997; Landi et al. 2013). The analytical functional form of the \( \kappa \)-distributions allows for relatively simple direct integration of the ionization cross sections (Section 3.2). However, the recombination cross sections are not contained in CHIANTI. These then have to be reverse-engineered from the Maxwellian recombination rates using assumptions detailed in Section 3.3.

We note that the CHIANTI database allows for the treatment of non-Maxwellian distributions only if these can be represented by a series of individual Maxwellian distributions (with different \( T_s \)). The technique for the calculation of ionization and recombination rates presented here can in principle be extended for any type of particle distribution, not just for \( \kappa \)-distributions.
3.1. Atomic Data

The CHIANTI atomic database since version 6 (Dere et al. 2009) contains continually updated ionization equilibrium for the Maxwellian distribution. This ionization equilibrium utilizes the cross sections for direct ionization and autoionization, and the corresponding rate coefficients from the work of Dere (2007). Dielectronic and radiative recombination coefficients for the H to Al and Ar isoelectronic sequences are taken from the works of N. Badnell and colleagues, listed.
Figure 3. Changes in the ionization equilibrium with $\kappa$ for iron. Top row: $\kappa = 10$; second row: $\kappa = 5$; third row: $\kappa = 5$; bottom row: $\kappa = 2$. Individual ionization stages are indicated.

(A color version of this figure is available in the online journal.)
at http://amdpp.phys.strath.ac.uk/tamoc/DATA/ (Badnell et al. 2003; Colgan et al. 2003, 2004; Mitnik & Badnell 2004; Badnell 2006; Altun et al. 2005, 2006, 2007; Zatsarinny et al. 2005a, 2005b, 2006; Bautista & Badnell 2007; Nikolić et al. 2010; Abdel-Naby et al. 2012). For the Si to Mn isoelectronic sequences, the recombination rates are based on the works of Shull & van Steenberg (1982), Nahar (1996, 1997), Nahar & Bautista (2001), Mazzotta et al. (1998), and Mazzitelli & Mattioli (2002). The reader is referred to Dere et al. (2009) for details. In the calculations presented in this paper, all atomic data for ionization and recombination correspond to the CHIANTI database. The precision of this approximation is given by the level of error introduced by this approximation is typically several percent, i.e., lower than the error of the atomic data themselves.

The ionization rates have been calculated by a numerical integration of the ionization cross section, $\sigma_i$, available in the CHIANTI database:

$$ R_i = \langle \sigma_i v \rangle = \int_0^\infty \sigma_i \left( \frac{2E}{m} \right)^{1/2} f_a(E) dE, \quad (3) $$

for $\kappa = 2, 3, 5, 7, 10, 25,$ and $33$. Each numerical integral is calculated as a sum of individual integrals split according to the ionization and autoionization energies.

Typical changes in the behavior of direct ionization and autoionization rates with $\kappa$-distributions are shown in Figure 2 for the ions C IV, Fe XII, and Fe XVII formed at the transition region, the quiet corona, and flare conditions, respectively. For lower $\kappa$, the temperature dependence of the ionization rates is much flatter, with lower maxima. Typically, for temperatures lower than those at which the ion abundance peaks (denoted by the arrow in Figure 2; see also Section 4), the $\kappa$-distributions result in a decrease of the ionization rates by up to several orders of magnitude with respect to the Maxwellian distribution. These deviations from Maxwellian ionization rates increase with decreasing $\kappa$.

3.3. Recombination Rates

Since the individual recombination cross sections are not available in CHIANTI, the calculation of the recombination rates for $\kappa$-distributions was performed using the method of Dzifčaková (1992), also used by Wannawichian et al. (2003). This method allows for the calculation of the recombination rates using approximations to the rates for the Maxwellian distribution.

The cross section $\sigma_{RR}$ for the radiative recombination is assumed to have a power-law dependence on energy (Osterbrock 1974):

$$ \sigma_{RR}(E) = C_{RR}/E^{\eta+0.5}, \quad (4) $$

where $C_{RR}$ is a constant and $\eta + 0.5$ is a power-law index. Subsequently, the radiative recombination rate for the $\kappa$-distribution is of the form

$$ R_{RR}^\kappa = \frac{4C_{RR}}{(2\pi m)^{1/2}} \frac{\Gamma(\kappa + \eta - 0.5)(\kappa - 1.5)^\eta}{\Gamma(\kappa - 0.5)} \frac{\Gamma(1.5 - \eta)}{(k_BT)^\eta}, \quad (5) $$

while the radiative recombination rate for the Maxwellian distribution is

$$ R_{RR}^{Maxw} = \frac{4C_{RR}}{(2\pi m)^{1/2}} \frac{\Gamma(1.5 - \eta)}{(k_BT)^\eta}. \quad (6) $$

Therefore, it holds that

$$ R_{DR}^\kappa = \frac{R_{RR}^{Maxw}}{R_{RR}^{Maxw}} \frac{\Gamma(\kappa + \eta - 0.5)(\kappa - 1.5)^\eta}{\Gamma(\kappa - 0.5)}. \quad (7) $$

The level of error introduced by this approximation is typically several percent, i.e., lower than the error of the atomic data themselves.

For the dielectronic recombination, the following approximation has been taken (Dzifčaková 1992):

$$ R_{DR}^\kappa = \frac{A_\kappa}{T^{1/3}} \sum_i \frac{a_i}{(1 + t_i/(\kappa - 1.5)T)^{\kappa+1}}, \quad (8) $$

where parameters $a_i$ and $t_i$ are the same as in similar expressions for the Maxwellian distribution,

$$ R_{DR}^{Maxw} = \frac{1}{T^{1/3}} \sum_i a_i \exp(-t_i/T), \quad (9) $$

where the coefficients $a_i$ and $t_i$ are provided within the CHIANTI database. The precision of this approximation is given by the

![Figure 4. Ionization equilibrium for carbon. Different line styles correspond to different $\kappa$.](A color version of this figure is available in the online journal.)
magnitude of the second-order terms in the expansion of the coefficients $a_i$ and $t_i$ into the series (Equations (37)–(44) in Dzifčáková 1992).

The typical behavior of the total recombination rates ($R_{RR} + R_{DR}$) for $\kappa$-distributions and for the Maxwellian distribution is shown in Figure 2. It can be seen that the radiative recombination rate increases with decrease of $\kappa$. This is a result of increasing number of low-energy electrons for the $\kappa$-distributions (Figure 1), which dominate the recombination processes. The local change of slope of total recombination rate is caused by the contribution of dielectronic recombination. For some ions, e.g., Fe XVII, the contribution of dielectronic recombination is dominant in temperature interval where these ions have a non-negligible abundance.

4. THE IONIZATION EQUILIBRIUM

Calculations of the collisional ionization equilibrium assume that there are no temporal variations in plasma temperature $T$. In the coronal conditions, the resulting relative ion populations are given by the equilibrium between the direct collisional ionization with autoionization and the radiative and dielectronic recombination. Three-body processes can be neglected at low-electron densities typical in the solar corona (Phillips et al. 2008). The radiative field is also usually assumed to be too weak,
i.e., photoionization can be neglected as well. However, we note that photoionization may be important for some transition-region ions with low-ionization thresholds, but the effect will vary depending on the distance from the radiation field (e.g., the solar photosphere).

The ionization equilibrium for $\kappa$-distributions with $\kappa = 2, 3, 5, 7, 10, 25$, and $33$ was calculated for ions of astrophysical interest, ranging from H ($Z = 1$) to Zn ($Z = 30$). Previous calculations by Dzifčáková (1992, 2002) and Wannawichian et al. (2003) involved only the 12 most abundant elements. The current calculations are performed for the same set of temperatures as the calculations in the CHIANTI database in the chianti.ioneq file. That is, the temperature spans the interval of $\log(T/K) \in [4, 9]$ with the step of $\Delta \log(T/K) = 0.05$. The calculations are available in the same format as the chianti.ioneq file and are easily readable using the routines read_ioneq.pro and plot_ioneq.pro available in CHIANTI running under SolarSoft in IDL. More information on the CHIANTI.ioneq file format is provided in the Appendix.

Examples of the current ionization equilibrium calculations for iron are in Figure 3 and for carbon in Figure 4. The typical behavior is that the lower $\kappa$ is, the flatter the ionization peaks are. In addition, ionization peaks can be shifted to lower or higher $T$, depending on $\kappa$, $T$, and the individual ion. This means that a given relative ion abundance can be formed at a wider range of $T$ for a $\kappa$-distribution, with different peak formation temperature. Such behavior was already reported by Dzifčáková (1992, 2002) and Wannawichian et al. (2003). Typically, the shifts of Fe and C ion abundance peaks are to lower $T$ with respect to the Maxwellian ionization equilibrium if $\log(T/K) \lesssim 5.5$. At coronal temperatures, the Fe x–Fe xvi ions are shifted to higher $T$. An interesting example is the ion Fe xvii, whose ionization peak is shifted to lower $T$ for $\kappa \lesssim 3$, but to higher $T$ for $\kappa = 2$ (Figure 3, bottom).

There are a number of differences with respect to the earlier calculations of Dzifčáková (2002), which used the atomic data corresponding to those of Mazzotta et al. (1998). These differences are illustrated in Figure 5. In general, the lower the value of $\kappa$, the greater the differences with respect to the previous calculations. The most conspicuous example is the ion Fe ix, which is shifted to slightly higher $T$ instead of to lower $T$ as in the previous calculations of Dzifčáková (2002). The Fe xii and Fe xiii ions are shifted to higher $T$ (up to 0.1–0.15 dex).

We note that the changes in the ionization equilibria due to the updated atomic data will reflect on, e.g., changes in the total radiative losses (Dudík et al. 2011) and will also modify the proposed diagnostic methods for $\kappa$-distributions (Dzifčáková & Kulinová 2010; Mackovjak et al. 2013).

Ratios of relative abundances of individual ions can be used to diagnose the value of $\kappa$ and simultaneously $T$. Such diagnostics can be applied, e.g., in the solar wind (Owocki & Scudder 1983). An example of diagnostic diagrams is given in Figure 6. We note that such diagrams cannot be directly applied on the observed line intensities unless the additional effect of $\kappa$-distributions on the excitation and de-excitation rates is considered. However, these diagrams provide quantification of the expected changes in ratios of line intensities due to ionization equilibrium. Ratios of lines involving different ionization stages provide better options for determining $\kappa$, as previously noted by Dzifčáková & Kulinová (2010) and Mackovjak et al. (2013).

5. SUMMARY

Collisional ionization equilibrium calculations for $\kappa$-distributions and optically thin plasmas were performed for all ions of elements H to Zn. To do that, the latest available atomic data for ionization and recombinations were used. The calculations are available in the form of ionization equilibrium files compatible with the CHIANTI database version 7.1.

For $\kappa$-distributions, the ionization peaks are in general flatter and can be shifted to lower or higher $T$. This means that for $\kappa$-distributions, individual ions are typically formed in a wide range of temperatures with different peak formation temperatures. Typically, ions formed at transition region temperatures are shifted to lower $T$, while the majority of coronal iron ions are shifted to higher $T$. Comparison to previous calculations is provided. Due to updated atomic data calculations, several ions in the present calculations are shifted to different temperatures.
temperatures with respect to the previous calculations of Dzifčáková (2002). The effect of \( \kappa \) on the ratios of ion abundances is documented.

The present calculations provide an accurate, necessary, and useful tool for the detection of astrophysical plasmas out of thermal equilibrium, where the distribution of particles is characterized by an enhanced power-law tail. The supplied files, compatible with the CHIANTI database and software, should greatly facilitate the synthesis of both line and continuum spectra for optically thin astrophysical plasmas.

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### Table 1

| \( N \) | \( Z_{\text{max}} \) | \( \log(T_1/K) \) | \( \log(T_2/K) \) | \( \log(T_3/K) \) | \( \log(T_4/K) \) | \( \log(T_5/K) \) | \( \log(T_6/K) \) | \( \log(T_7/K) \) | \( \log(T_8/K) \) |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | 1               | \( A_{\text{He}}^{10}(T_1) \) | \( A_{\text{He}}^{10}(T_2) \) | \( A_{\text{He}}^{10}(T_3) \) | \( A_{\text{He}}^{10}(T_4) \) | \( A_{\text{He}}^{10}(T_5) \) | \( A_{\text{He}}^{10}(T_6) \) | \( A_{\text{He}}^{10}(T_7) \) | \( A_{\text{He}}^{10}(T_8) \) |
| 1     | 2               | \( A_{\text{He}}^{11}(T_1) \) | \( A_{\text{He}}^{11}(T_2) \) | \( A_{\text{He}}^{11}(T_3) \) | \( A_{\text{He}}^{11}(T_4) \) | \( A_{\text{He}}^{11}(T_5) \) | \( A_{\text{He}}^{11}(T_6) \) | \( A_{\text{He}}^{11}(T_7) \) | \( A_{\text{He}}^{11}(T_8) \) |
| 2     | 1               | \( A_{\text{He}}^{10}(T_1) \) | \( A_{\text{He}}^{10}(T_2) \) | \( A_{\text{He}}^{10}(T_3) \) | \( A_{\text{He}}^{10}(T_4) \) | \( A_{\text{He}}^{10}(T_5) \) | \( A_{\text{He}}^{10}(T_6) \) | \( A_{\text{He}}^{10}(T_7) \) | \( A_{\text{He}}^{10}(T_8) \) |
| 2     | 2               | \( A_{\text{He}}^{11}(T_1) \) | \( A_{\text{He}}^{11}(T_2) \) | \( A_{\text{He}}^{11}(T_3) \) | \( A_{\text{He}}^{11}(T_4) \) | \( A_{\text{He}}^{11}(T_5) \) | \( A_{\text{He}}^{11}(T_6) \) | \( A_{\text{He}}^{11}(T_7) \) | \( A_{\text{He}}^{11}(T_8) \) |
| 3     | \( + (k+1) \)   | \( A_{\text{He}}^{12}(T_1) \) | \( A_{\text{He}}^{12}(T_2) \) | \( A_{\text{He}}^{12}(T_3) \) | \( A_{\text{He}}^{12}(T_4) \) | \( A_{\text{He}}^{12}(T_5) \) | \( A_{\text{He}}^{12}(T_6) \) | \( A_{\text{He}}^{12}(T_7) \) | \( A_{\text{He}}^{12}(T_8) \) |
| \( Z_{\text{max}} \) + \( (Z_{\text{max}}+1) \) | \( \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) |

**Note.** Explanation of the symbols is given in the text.

### Table 2

**Example of the kappa_05.ioneq File Produced for \( \kappa = 5 \)**

| 101  | 30   |
|------|------|
| \( \ldots \) | 5.80  |
| \( \ldots \) | 5.85  |
| \( \ldots \) | 5.90  |
| \( \ldots \) | 5.95  |
| \( \ldots \) | 6.00  |
| \( \ldots \) | 6.05  |
| \( \ldots \) | 6.10  |
| \( \ldots \) | 6.15  |
| \( \ldots \) | \( \ldots \) |
| 26   | 9    |
| 26   | 10   |
| 26   | 11   |
| \( \ldots \) | \( \ldots \) |
| \( \ldots \) | \( \ldots \) |
| \( \ldots \) | \( \ldots \) |
| \( \ldots \) | \( \ldots \) |

**Note.** The table shows relative abundances of the ions Fe\( \text{ix} \)–Fe\( \text{xi} \).

### APPENDIX

**CHIANTI.ioneq FILE FORMAT**

The .ioneq files, used by the CHIANTI database and software to store data on the ionization equilibrium, are in essence formatted ASCII files. An example of their format is given in Table 1. The file begins with two numbers: \( N \), giving the number of temperature points \( T_i \), \( 1 \leq i \leq N \), and \( Z_{\text{max}} \), denoting the maximum proton number \( Z \) for which the ionization equilibrium is provided. The next line gives the tabulated temperatures \( \log(T_i/K) \). All other lines begin with \( Z \) and a positive integer \(+k\) denoting the roman numeral for the corresponding ion; e.g., 26 and 9 stands for Fe\( \text{ix} \). The line then contains relative ion abundances \( A_{Z_{\text{max}}-1}^{Z}(T_i) \) in floating-point precision for the tabulated temperatures.

A portion of the actual content of the kappa_05.ioneq file is given in Table 2. There, the relative abundances of the ions Fe\( \text{ix} \)–Fe\( \text{xi} \) are listed for \( \kappa = 5 \) and for \( \log(T/K) = 5.80–6.15 \).

**REFERENCES**

Abdel-Naby, S. A., Nikolici, D., Gorczyca, T. W., Korista, K. T., & Badnell, N. R. 2012. **A&A**, 557, A40

Altun, Z., Yumak, A., Badnell, N. R., Colgan, J., & Pindzola, M. S. 2005. **A&A**, 433, 395

Altun, Z., Yumak, A., Badnell, N. R., Loch, S. D., & Pindzola, M. S. 2006. **A&A**, 447, 1165
