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Ion Composition Properties in Interplanetary Coronal Mass Ejection (ICME) and Post-CME Current Sheet (CS)

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14. ABSTRACT
Coronal mass ejections (CMEs) are among the most energetic solar events. Solar energetic particles (SEPs) are accelerated at a CME shock. The SEPs, when reaching Earth, can cause severe space weather effects such as satellites, navigation, communication, and Humans in space. We investigate the heating inside interplanetary coronal mass ejections (ICMEs) using variations of ion composition with Kappa (?) electron velocity distributions, which represent supra-thermal populations. The ion compositions are calculated by using a time-dependent ionization model with various ? values along a post-CME current sheet (CS) as CME erupts. In this work, we investigate 1) what causes the variations in ion charge composition in ICMEs and how they are related to the physical conditions at the magnetic reconnection site 2) What the range of ? values can explain the observed ion charge composition structure inside ICMEs and what will be the most probable heating and acceleration process to satisfy the observed ion
composition structure inside ICMEs. This work impacts the increase of knowledge for supra-thermal particle populations in the solar-terrestrial environment and leads to learning the more proper interpretation of the physical process of heating and acceleration of erupting plasma.

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ABSTRACT

Coronal mass ejections (CMEs) are among the most energetic solar events. Solar energetic particles (SEPs) are accelerated at a CME shock. The SEPs, when reaching Earth, can cause severe space weather effects such as satellites, navigation, communication, and Humans in space. We investigate the heating inside interplanetary coronal mass ejections (ICMEs) using variations of ion composition with Kappa (κ) electron velocity distributions, which represent supra-thermal populations. The ion compositions are calculated by using a time-dependent ionization model with various κ values along a post-CME current sheet (CS) as CME erupts. In this work, we investigate 1) what causes the variations in ion charge composition in ICMEs and how they are related to the physical conditions at the magnetic reconnection site 2) What the range of κ values can explain the observed ion charge composition structure inside ICMEs and what will be the most probable heating and acceleration process to satisfy the observed ion composition structure inside ICMEs. This work impacts the increase of knowledge for supra-thermal particle populations in the solar-terrestrial environment and leads to learning the more proper interpretation of the physical process of heating and acceleration of erupting plasma.

I. Accomplishments

1. Research Objectives

- To investigate the heating inside interplanetary coronal mass ejections (ICMEs) using variations of ion composition with Kappa electron velocity distributions
    - To investigate the nonequilibrium properties of a current sheet observed 2017 September 10 using a time-dependent ionization equation with various kappa distributions
    - To investigate source region temperatures of impulsive SEP events with various kappa distributions

2. Research Content

2.1 Nonequilibrium properties of a current sheet observed 2017 September 10

2.1.1 Introduction

- A flux rope eruption event of 2017 September 10 on the solar west limb provides unique observations of the current sheet underneath the rising flux rope (Figure 1).
- The current sheet is possibly in a nonequilibrium state in terms of both nonequilibrium ionization (Thermodynamical time scale ≪ ionization or recombination time scale) and non-Maxwellian electron distribution ($\kappa \ll \infty$).
- We apply a time-dependent ionization equation to the observed current sheet with various Kappa (κ) values representing the non-Maxwellian electron distribution.

- During the first half of September 2017, 27 M-class, four X-class flares, three SEP events were produced from Active Region 12673. The third SEP event was produced by the X8.2 flare associated with the flux rope eruption on September 10.
- The STEREO A (Solar-Terrestrial Relations Observatory A) was located at the heliocentric longitude of ~144° while the flare was produced at the solar west limb. The observed third shock was likely produced by the passage of the eastern flank of the shock associated with the September 10 event (Bruno et al. 2019). A long-duration high speed stream was also observed several hours later. Thus, it is difficult to constrain the ion fractions at the low corona with the ICME observations for this event.

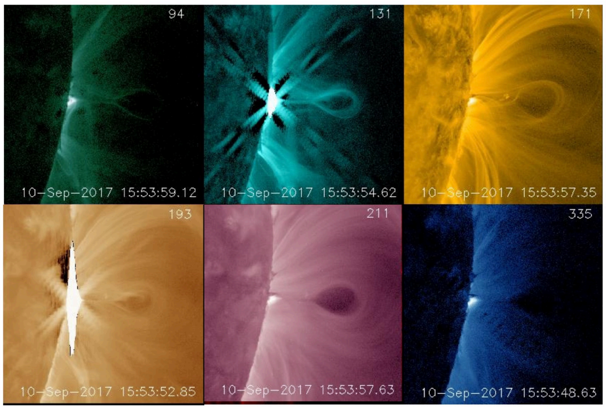


Figure 1. Flux rope eruption on 2017 September 10

2.1.2 Analysis

2.1.2.1 Tracking of current sheet propagation

- We track a current sheet blob by finding height information using a time-space plot using a slit along with the current sheet (Figure 2).
- We assume that the blobs propagate with the same speed and select the blobs seen at least three passbands (131, 193, and 211Å) of the AIA observations.

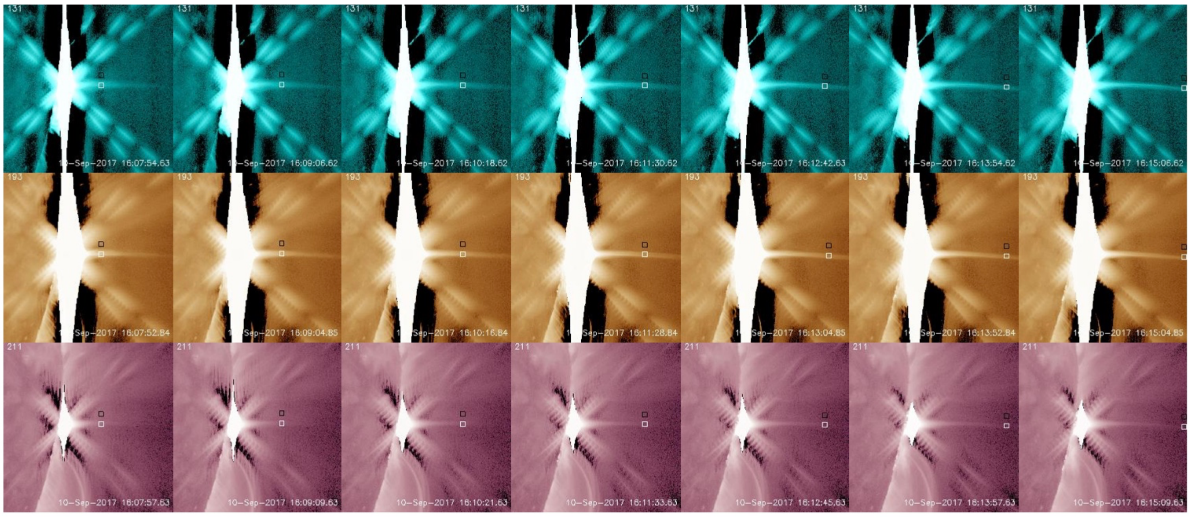


Figure 2. Tracking of current sheet propagation. whit box: current sheet blob, black box: background

2.1.2.2 Time-dependent ionization model

- We find the ion fractions using a time-dependent ionization model (Shen et al. 2015).
- The model pre-computes the ionization and recombination rates, and the rates are saved into tables. Using the pre-computed tables, the ion fractions are calculated with the time-dependent ionization equation,

$$\frac{df_i}{dt} = n_e[C_{i-1}f_{i-1} - (C_i + R_i)f_i + R_{i+1}f_{i+1}],$$

where f_i is ion fraction, n_e is density and t is time. C_i and R_i are ionization and recombination rate coefficients.

- **The C_i and R_i are calculated with various kappa values** (Cui et al. 2019).
- Firstly, we practice the ionization model with a rapid heating model (Lee et al. 2019) (Figure 3). The ion fractions vary with the κ values and temperatures.

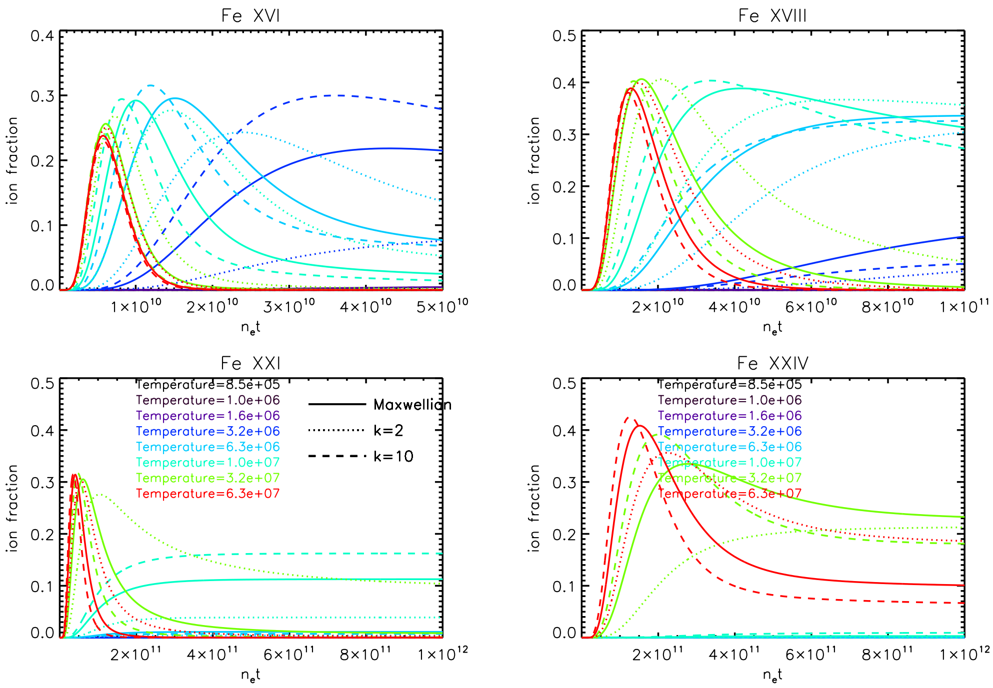


Figure 3. Ion fractions with κ=2(dotted), 10(dashed), and Maxwellian electron distributions(solid) using a rapid heating model by Lee et al. 2019.

2.1.2.3 Temperature and density history of the traced blobs to calculate the ion fractions

- We estimate the temperature and emission measure by differential emission measure (DEM) analysis. The DEMs are calculated using 131, 171, 193, and 211Å, assuming equilibrium (ionization equilibrium and Maxwellian electron distribution) at each discrete time.
- We use the estimated temperatures and densities as input parameters to calculate the ion fractions using a time-dependent ionization model.

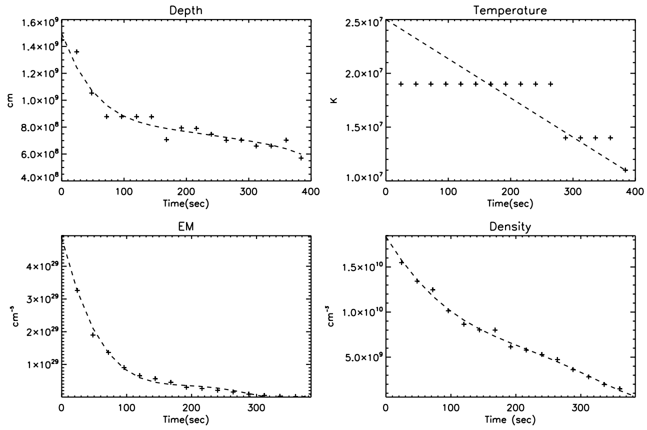


Figure 4. Temperature and density history of the traced blobs to calculate the ion fractions

2.1.2.4 Heating rate and temperature history with parameterized heating

- Cooling by adiabatic expansion.
  - $T_2 = T_1 (\frac{n}{n_1})^{\gamma - 1}$, where γ is 5/3.
- Additional continuous heating decreasing along the current sheet with rapid heating
- Decreasing rates: MHD simulation of current sheet

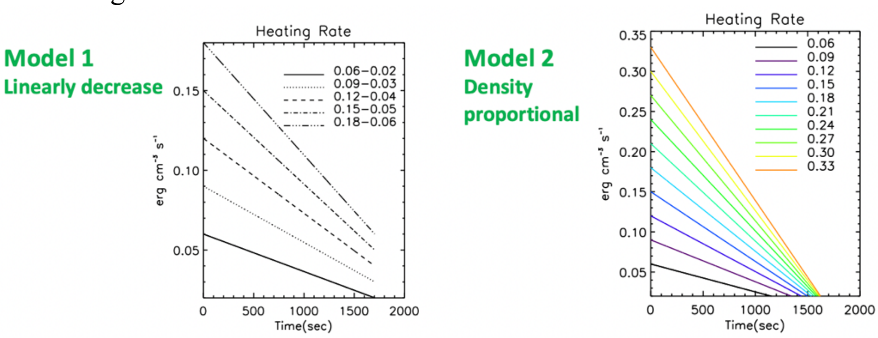
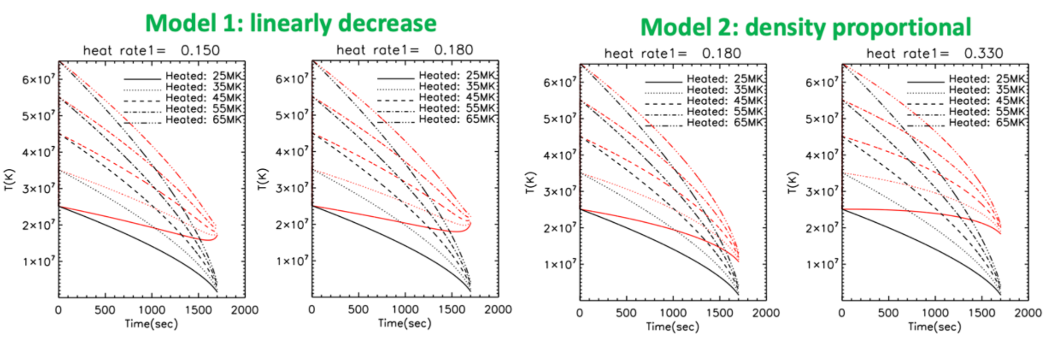


Figure 5. Heating rates for additional continuous heating



- Black: no continuous heating
- Red: continuous heating (decrease along the current sheet)

Figure 6. Temperature history using the heating rates in Figure 5.

2.1.2.5 Comparisons of the synthesized and observed DNs

- DN = R(T, hr, T_h, $\boldsymbol{\kappa}$) EM
  - EM = $\langle n_e \rangle^2$ dl
  - R(T, hr, T_h, $\boldsymbol{\kappa}$) – Temperature responses

$$R(T,\ \kappa, band) = \sum_{Z}\sum_{z} Resp(Z, z, T, band) \times AB(Z) \times f(Z, z, T,\ n_e, \boldsymbol{\kappa}),$$
$$+ \text{continuum},$$

  - dl – Line of sight depth, hr: heating rates, T_h: heated temperature
  - AB(Z) is abundance of Z element, and f(Z,z,T,n_e,$\boldsymbol{\kappa}$) is the ion (z) fraction calculated using the time-dependent ionization model.

2.1.3. Results

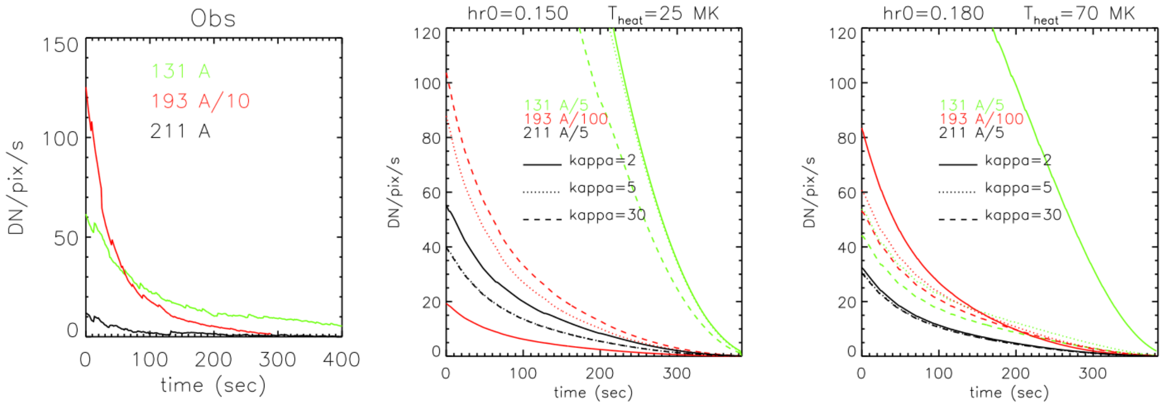


Figure 7. Observed and synthesized DNs with Model 1 in Figure 6.

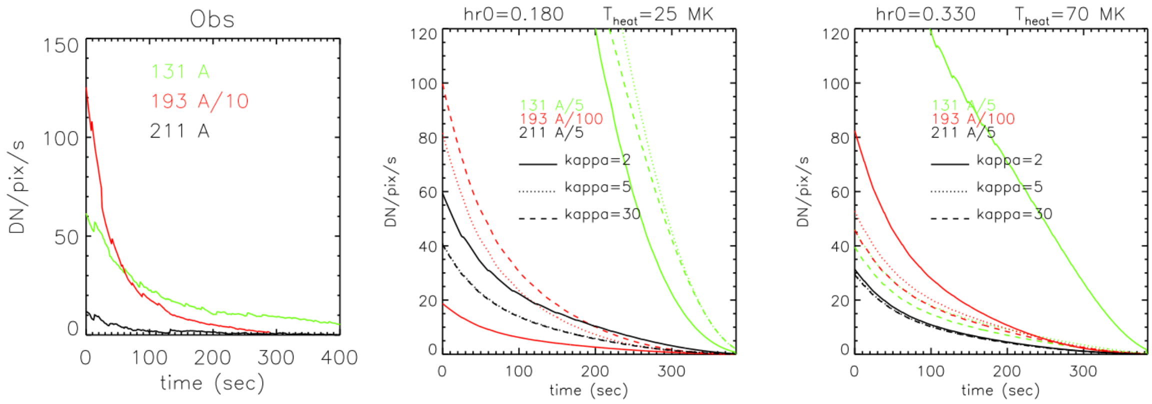


Figure 8. Observed and Synthesized DNs by Model 2 in Figure 6.

- We investigate whether the calculated DNs from ion fractions considering both nonequilibrium ionization and non-Maxwellian electron distribution could explain the observed current sheet DNs on 2017 September 10.
- With given models, the models are hard to match the observations. The models predict the larger DNs than the observations.
- We find that a higher heated temperature and heating rates and larger Kappa values are required to satisfy the observed DNs for 131 Å and 211 Å. In comparison, relatively lower heated temperature and smaller kappa values are required for 193 Å.
- The heating rates in this analysis are larger than those in the analysis of CME plasma observed at 2.4 $R_\odot$ (Lee et al. 2009) and those of erupting loop in EUV (Lee et al. 2017).

2.2 A study of source region temperatures of impulsive SEP events with various kappa values

2.2.1 Introduction

- Impulsive solar energetic particle (SEP) events generate tremendous enhancements in the abundances of ^{3}He and the heaviest elements. The impulsive SEPs are believed to be accelerated in solar jets by a mechanism that causes a mass-to-charge (A/Q) dependence of the elemental abundance.
- It is important to understand the source region properties since the accelerated particles in the impulsive SEP events could become the seed population that could be reaccelerated by a coronal mass ejection shock, then produce gradual SEP events.
- The temperatures of the source region of the impulsive SEPs is known to be about 1~3 MK derived by fitting the SEP abundance power-law distribution vs A/Q which depends on the electron temperature. These are consistent with recent studies based on EUV observations in the solar corona.
- In this work, we examine whether the temperature estimation from the A/Q would differ with various kappa values in a kappa function representing high-energy tails deviating from a Maxwellian velocity distribution. We use the KAPPA package recently upgraded with the CHIANTI 10 atomic database to calculate the averaged charge states of each element, assuming ionization equilibrium.

2.2.2 Analysis

- Mass to charge (A/Q) dependence of the elemental abundance
- The temperature of the source region of the impulsive events: 1~3 MK derived by fitting the SEP abundance vs A/Q.
  - $(A/Q)_{Ne} > (A/Q)_{Mg} > (A/Q)_{Si}$
  - Opposite direction from mass (A)
- We examine whether the temperature estimation from the A/Q would differ with various kappa values.
- κ-distributions represents a high-energy tails deviating from a Maxwellian velocity distribution (**κ** → ∞ : Maxwellian).
- We calculate the mass to charge (A/Q) using a KAPPA package with CHIANTI Version 10 (Dzifčaková et al. 2021).
  - A: mass of the elements
  - Q: charge state depends on the electron temperatures and various **κ** values.

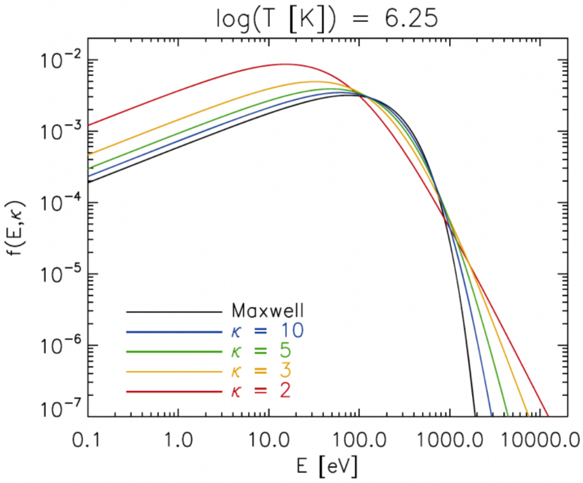


Figure 9. The κ-distributions, plotted for a constant coronal temperature of log(T [K]) = 6.25. The values of κ are indicated by colors. (Dzifčaková et al. 2021)

2.2.3 Results

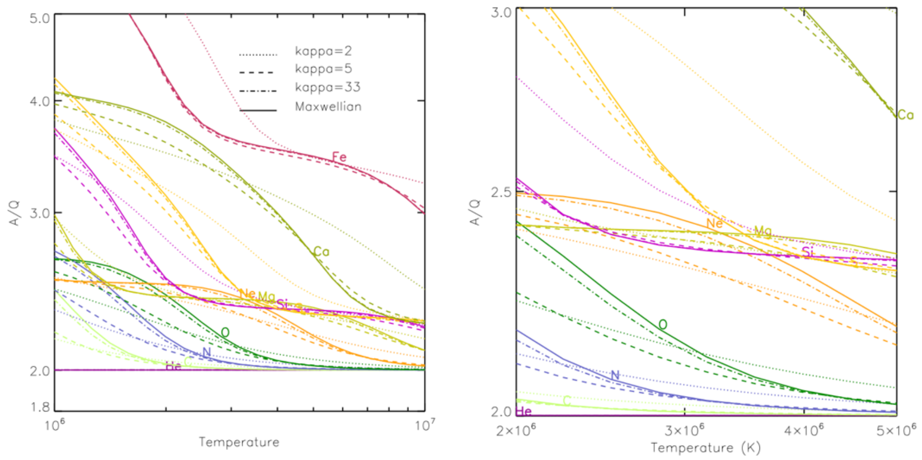


Figure 10. Temperature vs. A/Q with κ values. Right: Close view in narrow temperature range in left.

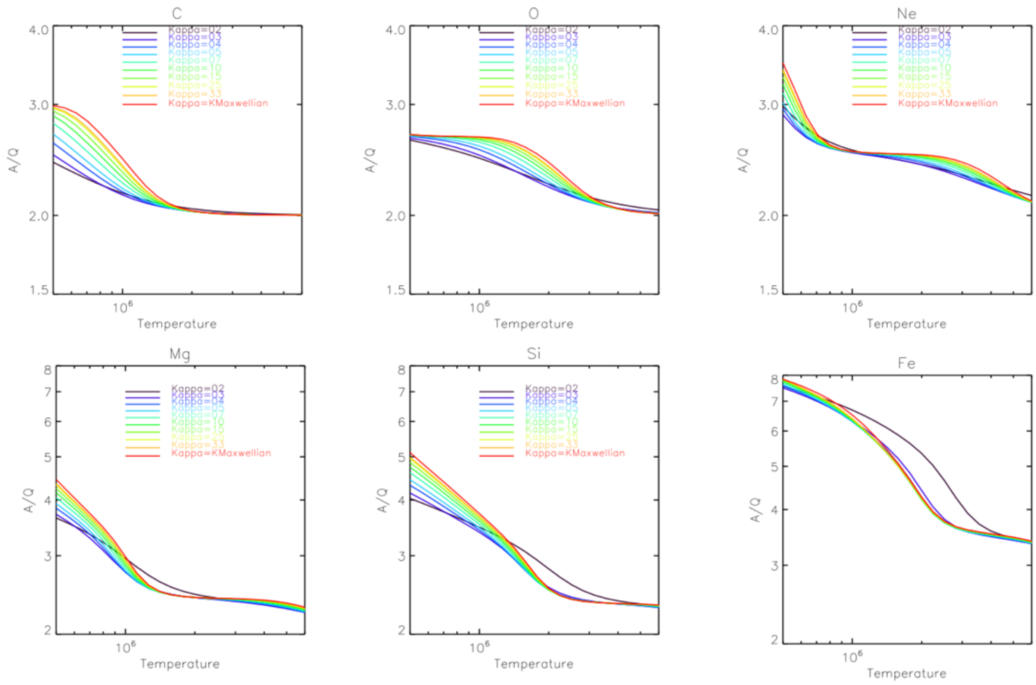


Figure 11. Temperature vs. A/Q with κ values of C, O, Ne, Mg, Si, and Fe elements

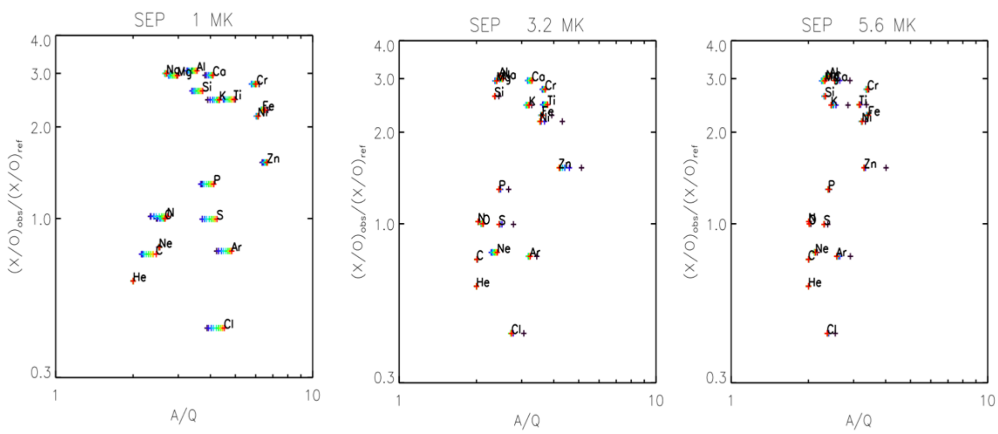


Figure 12. A/Q with κ values vs. observed abundances of SEP (Reames 2020). The reference abundances are from the photosphere, and all abundances are normalized at O

- The differences in the A/Q between a Maxwellian and an extreme ***κ*** distribution are only about 10-20%.
- Therefore, the derived source region temperature is not significantly affected whether or not the electron velocity distribution deviates from a Maxwellian, i.e., thermal, distribution.

3. Research Publications

- Title: Plasma heating along a current sheet in nonequilibrium ionization and non-Maxwellian electron velocity distribution
  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim
  - *In preparation*
- Title: Charge states and abundance enhancements of solar energetic particle events
  Authors: Jin-Yi Lee, Stephen Kahler, Yuan-Kuen Ko, and John C. Raymond
  - *In preparation*

4. Research Presentations

- **Korean Space Science Society Fall Meeting, 28-30 Oct 2020, Jeju, Republic of Korea**

  Title: Nonequilibrium Properties in the Plasma Sheet Observed on 2017 September 10

  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim
- **American Geophysical Union Fall Meeting, 1-17 December 2020, Virtual Meeting**

  Title: Nonequilibrium Properties in the Plasma Sheet Observed on 2017 September 10

  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim
- **Korean Space Science Society Spring Meeting, 28-30 April 2021, Yeosu, Republic of Korea**

  Title: Investigation of a current sheet using a time-dependent ionization equation with various Kappa distributions

  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim
- **Korean Astronomical Society Fall Meeting, 13-15 October 2021, Jeju, Republic of Korea**

  Title: Simple modeling to explore temperatures, heated temperature, and Kappa values of a current sheet observation
  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim
- **American Geophysical Union Fall Meeting, 13-17 December 2021, New Orleans and Online**

  Title: Investigation of a current sheet using a time-dependent ionization equation with various Kappa distributions

  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim
- **Korean Space Science Society Spring Meeting, 27-29 April 2022, Samcheok, Republic of Korea**

  Title: Plasma heating along a current sheet in nonequilibrium ionization and non-Maxwellian electron velocity distribution

  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim

- **International Astronomical Union General Assembly (IAUGA) 2-11 August 2022, Samcheok, Republic of Korea**

  Title: Plasma heating along a current sheet in nonequilibrium ionization and non-Maxwellian electron velocity distribution

  Authors: Jin-Yi Lee, John C. Raymond, Katharine K. Reeves, Chengcai, Shen, Yuan-Kuen Ko, Stephen Kahler, Yong-Jae Moon, Yeon-Han Kim

- **The 3rd Korea Geoscience Union Meeting 17-19 August 2022, Pyeongchang, Republic of Korea**

  Title: A study of mass-to-charge ratio with various kappa values in impulsive SEP events

  Authors: Jin-Yi Lee, Stephen Kahler, Yuan-Kuen Ko, John C. Raymond

5. References

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Shen et al. 2015, Astronomy & Computing, 12, 1

II. Impacts

- Increase of knowledge for supra-thermal particle populations in the solar-terrestrial environment
- Increase of knowledge for heating and acceleration of erupting plasma through magnetic reconnection in the current sheet.
- Increase of knowledge for source region temperature of solar energetic particle events

III. Changes

- None

IV. Technical Updates

- The first study on heating of current sheet using both nonequilibrium ionization and non-Maxwellian electron distribution
- The first study on mass to charge ratio with non-Maxwellian electron distribution