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Mean High-Energy Ionic Charge States during the September 2017 Solar Energetic Particle Events Observed by ACE and STEREO

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We have reported mean high-energy ionic charge states of solar energetic particle (SEP) events for Solar Cycles 23 and 24, using the method of Sollitt et al. (2008). The method applies to abundant elements (e.g. N, O, Ne, Mg, Si, and Fe) in SEP events over the energy ranges covered by the STEREO/LET instrument (e.g. 2.7-70 MeV/nuc for Fe) and the ACE/SIS instrument (e.g. 11-168 MeV/nuc for Fe), as well as lower energy measurements by STEREO/SIT and ACE/ULEIS, which provide additional constraints to the charge state calibration. The SEP events of September 2017 were visible at both spacecraft, when STEREO/AHEAD and ACE were separated by ~128 degrees in heliospheric longitude. These events included the September 10 event also detected as a ground level event. The time intensity profiles in some of these events in both the ACE/SIS instrument and the STEREO/LET instrument both show periods of exponential time decay, making the events amenable to charge states analysis using the method of Sollitt et al. (2008). We will report mean ionic charge states for these events using both ACE and STEREO, comparing the measurements to demonstrate longitude-dependence in charge states, if any. We will also compare these results individually with measurements from other SEP events and with previously observed correlation between charge states and abundance ratios.

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1. Introduction

The mean ionic charge states of solar energetic particle (SEP) events generated by flares or coronal mass ejections may reflect the temperatures of the source plasmas, that the SEPs were accelerated out of a seed population stripped in prior SEP events, that SEPs were stripped during transport, or some combination of conditions[1-4] .

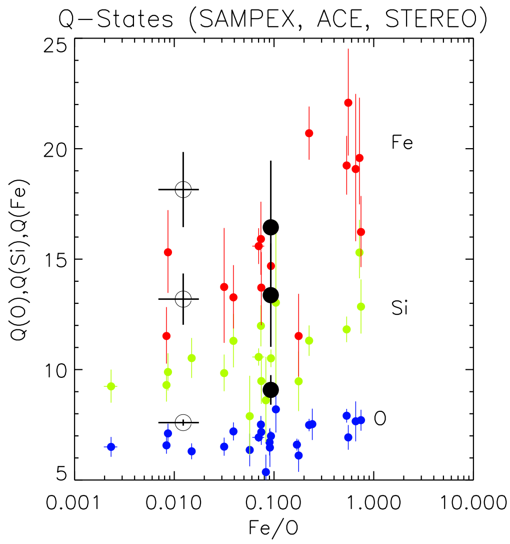


Figure 1: Charge states of O, Si, and Fe vs. Fe/O as measured by SAMPEX/MAST (various SEP events, colored circles), ACE/SIS (solid circles, 3/8/12) and STEREO A (open circles, 9/28/12). SAMPEX Q(Fe) data taken from [6] and later analysis.

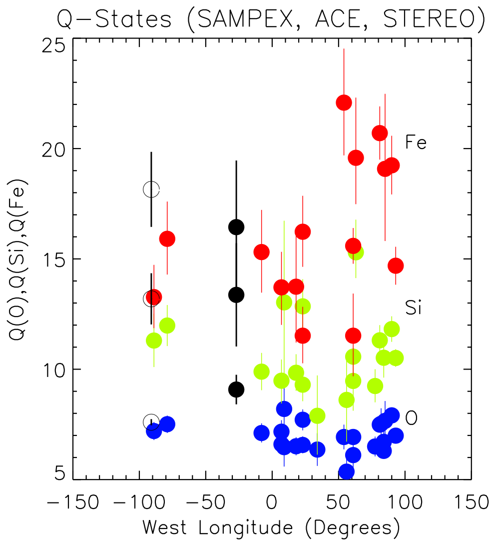


Figure 2: Charge states of O, Si, and Fe as measured by SAMPEX/MAST (various SEP events, colored circles), ACE/SIS (black circles, 3/8/12) and STEREO A (open circles, 9/28/12) vs. source longitude. SAMPEX Q(Fe) data taken from [6] and later analysis. Solar source longitudes taken from [12].

The Mass Spectrometer Telescope aboard the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX/MAST), in polar Earth orbit, used a geomagnetic rigidity cutoff technique to measure mean ionic charge states, and SAMPEX/MAST measurements showed correlation between mean iron charge state (Q(Fe)) and the iron to oxygen ratio (Fe/O) [5,6] (Fig. 1, which also includes ACE/SIS and STEREO A analysis for two events, presented at the AGU Fall Meeting 2017). Similar correlation between Q(Fe) and Fe/O ratio was observed at lower energies by the Solar Energetic Particle Ionic Charge Analyzer (SEPICA) using electrostatic deflection aboard the Advanced Composition Explorer (ACE) [7]. If the enhanced Fe/O ratio were due to bias in favor of mass/charge, we would expect to see an anti-correlation instead, but acceleration from a previously ionized seed population could result in such correlation. Additionally, high Q(Fe) measurements have been observed to be more prevalent in SEP events in which the spacecraft are magnetically well connected to the solar source event, e.g. at high western solar longitudes (Fig. 2) [12].

2. Inferred Ionic Charges – The Method

We use the technique for inferring ionic charge states described by Sollitt et al. [8] with ACE/SIS data, and we have applied this method to use STEREO data [9,10]. The technique models SEP events as filling a magnetic containment volume in the interplanetary medium. After the injection of SEPs into the containment volume is complete, particles diffuse out of the containment volume exponentially vs. time. The escape time decay constant will be energy dependent as well, with higher energy particles escaping faster. Escape time decay constants are measured in intensity vs. time data, during the decay phase of a given SEP event.

In the model, the time decay constant has the form

$$\frac{1}{\tau_X} = \frac{1}{\tau_y} + W(\alpha_X E)^{\gamma} \qquad (1)$$

where τ_X is the time decay constant for a given element X, measured during the decay phase of the SEP event, τ_y is a low-energy decay time due to convection and adiabatic cooling, γ is a constant arising from mean free path rigidity-dependence, and W is a normalization factor. E is energy per nucleon. The parameter α_X is given by

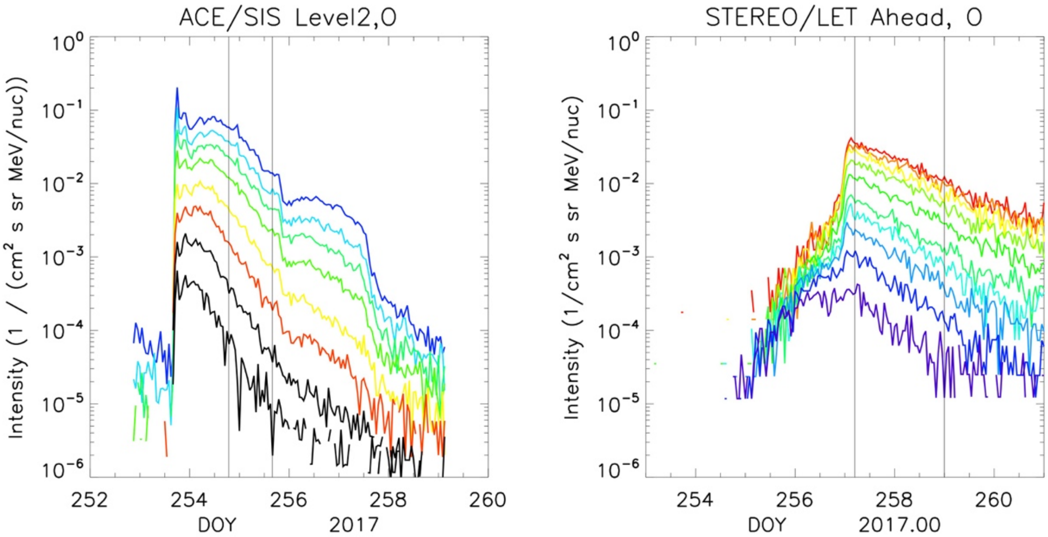
$$\alpha_X = \left[\frac{Q_{cal}}{A_{cal}} \frac{A_X}{Q_X}\right]^{\frac{2\gamma-1}{\gamma}} \qquad (2)$$

where Q and A are mean ionic charge states and mass number for element X and a calibration element of assumed charge and mass. In the ACE analysis, He was used as the primary calibration element (Q_{He}=2, A_{He}=4; α_C=1 fixed), and C was also constrained with Q_C=5.9 and A_C=12 assumed. In the STEREO analysis, incorporation of He from both LET and SIT has not been completed as of this writing. Therefore, C is used as the calibration element for STEREO/LET, with Q_C=5.9 and A_C=12.

With time decays, τ_X, measured for several elements and across several energy bins, the data are then fit to Equation (1). The downhill simplex method ("amoeba") is employed to vary W, γ, τ_C, and all of the α_X's (one each for elements N, O, Ne, Mg, Si, and Fe, when available) in order to find the best fit to Equation (1), by either least squares or maximum likelihood [11]. The final, best-fit values for γ and the α_X's yield charge states Q, and constant contours of maximum likelihood or $\Delta\chi^2$ yield charge state uncertainties, σ_Q.

3. Results

For this work, we have analyzed the 10 September 2017 SEP event in ACE/SIS data and the 12 September 2017 event in STEREO/LET Ahead data, both of which were associated with active region 12673 on the Sun. ACE/ULEIS data for lower energy He decay times have been incorporated into this analysis to aid in the charge states calibration. STEREO/SIT lower energy He data have not yet been incorporated in the STEREO analysis as of this writing.

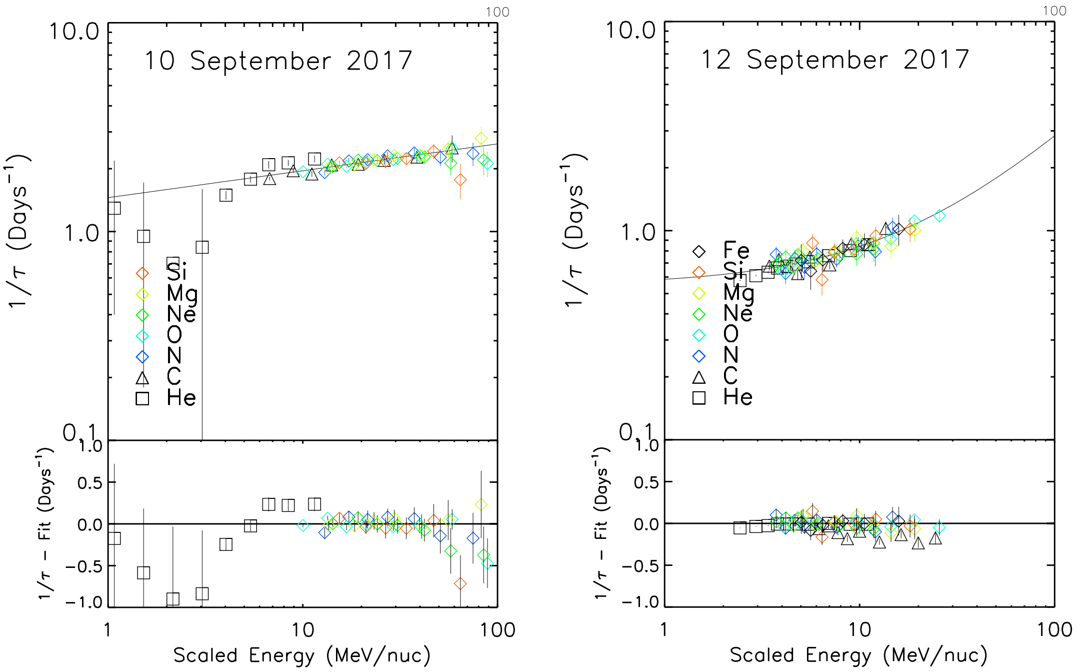


Figures 3 a and b: Oxygen intensity time profiles for the 10 September 2017 (ACE/SIS; 7-10 MeV/nuc top (blue), 64-90 MeV/nuc bottom (black)) and 12 September 2017 (STEREO/LET A; 3.2-3.6 MeV/nuc top (red), 27-33 MeV/nuc bottom (purple)) events. The vertical lines delineate the decay periods used for this analysis.

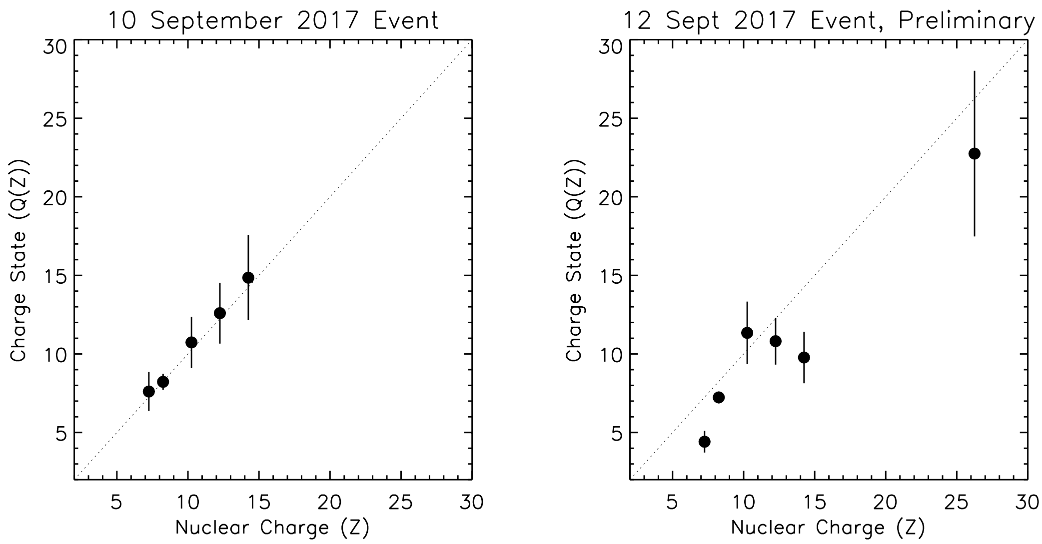
Figures 3 a and b show the intensity vs. time data for Oxygen at various energy ranges in ACE/SIS data (for the 10 September 2017 SEP event) and in STEREO/LET Ahead data (for the 12 September 2017 SEP event). The vertical lines show the start and stop times of the period of exponential decay used in this analysis. For practical simplicity, the start and stop times are selected in common for exponential decay for all elements and energy ranges for each event in each instrument.

Figures 4 a and b show the results of fitting the measured time-decay constants from the intensity vs. time data to the model in Equation 1. The low energy He decay times from ULEIS show large uncertainties and, thus, do not strongly affect the charge states calculation, but the data are left for completeness. For the ACE/SIS data, the Fe decay constants had an energy dependence in reverse of that of the other elements – increasing with increasing energy instead of decreasing – so Fe could not be fit by the model and was excluded from the fit. Interpreting from the model, the Fe may still have been experiencing injection into the magnetic containment volume simultaneous with leakage of other elements, during the time period selected for this analysis; this hypothesis merits further investigation. Similarly, Si at the highest ACE/SIS energy bins also followed Fe, but the lower energies fit the model.

Figures 5 a and b show the inferred mean ionic charge states for the SEP events of 10 September 2017 detected by ACE and 12 September 2017 as detected by STEREO Ahead. The ACE/SIS results are indicative of fully or near-fully stripped ions, which is consistent with an SEP source at western longitudes relative to the instrument (see Figure 2). The September 2017 SEP events were at or just over the west limb of the Sun, as viewed by SIS [13].



Figures 4 a and b: Parameter fits for the 10 September 2017 SEP event (a, left, ACE/SIS and ULEIS) and the 12 September 2017 event (b, right, STEREO/LET A). Scaled energies are element energy (in each instrument energy bin) multiplied by α_X for each element X.



Figures 5 a and b: Inferred ionic charge states for the 10 September 2017 (ACE/SIS and ULEIS) and the 12 September 2017 (STEREO/LET A) events, from this analysis.

The results for STEREO/LET Ahead are more mixed. Q(Ne) and Q(Fe) are consistent with fully or near-fully stripped ions, although the large Q(Fe) uncertainty is also consistent with a lower ionization state. However, the Q(Si) value (as well as the charge states of other elements) are generally consistent with lower ionization states. Lower ionic charge states are consistent with SEP source sites magnetically unconnected to the detecting instrument, with the lower-charged ions more easily traversing across magnetic field lines. At the time, STEREO A was ~128 degrees east of ACE [14], so the SEP source longitude would have been over the east limb relative to STEREO A, magnetically unconnected to the instrument.

The 10 September 2017 event was one of only two ground level enhancement (GLE) events detected during solar cycle 24. Cohen & Mewaldt (2018) note that the composition of the event was nominal except for an Fe/O ratio of 0.10 ± 0.001, which is atypically low compared to non-GLE events from solar cycle 23 [13]. They also note that the proton fluences for this event show a softer spectrum above ~25 MeV than for comparably large, non-GLE events. Low Fe/O ratios in large SEP events are usually associated with low charge states [6], but the charge states for elements up to Si inferred by this analysis are near fully ionized.

Luhmann et al. (2018) suggested via SEPMOD modeling that the 12 September 2018 SEP event may have been magnetically connected to the shock associated with the 10 September 2018 SEP event, and Bruno et al. (2019) also concur via combined ACE and STEREO spectra observations that the 10 September 2018 event at ACE was very broad and observed as the 12 September 2018 event at STEREO, with cross field diffusion and IMF corotation playing major roles [15, 16]. As such, then, these inferred ionic charge state measurements represent the first multispacecraft charge state observations at wide longitudinal separations for a single SEP event. While one might expect a "backside" charge state observation might result in low mean charge states (e.g. see Figure 2), as evidenced by Q(Si) (Figure 5b), the magnetic connectivity found by Luhmann et al. (2018) may also allow for some admixture of higher charge states (e.g. Q(Fe) from Figure 5b).

4. Conclusions

The 10 September 2017 SEP event is the second large SEP event detected at ACE in September 2017, and it was preceded by an SEP event that started ~5-6 September 2017. The event itself is somewhat atypical for a large SEP event, notably in this analysis for having inferred charge states measured by ACE at or near fully ionized while being associated with a low Fe/O ratio. The 12 September 2017 event is the first large SEP event of this period detected at STEREO, followed by another, more intense SEP event that started ~18 September 2017. These charge state measurements are the second set of mulitspacecraft ionic charge state measurements using this method since the 6 December 2006 SEP event, which was measured with SAMPEX/MAST, ACE/SIS, and STEREO/LET, and they are the first at wide longitudinal separation so far. These results may contribute to our understanding overall of the cluster of September 2017 SEP events.

Acknowledgements

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