Coronal Sources of Impulsive Fe-Rich Solar Energetic Particle Events

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ABSTRACT

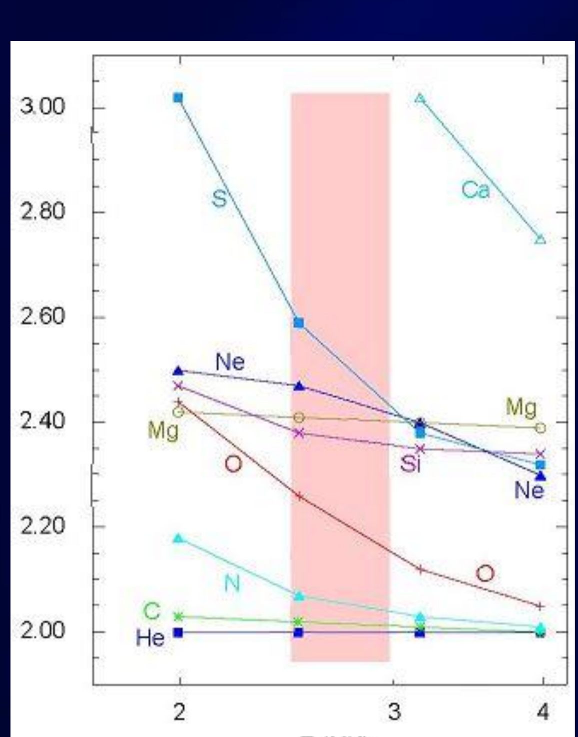
We review recent work on 111 Fe-rich impulsive solar energetic (~ 3 MeV/nuc) particle (SEP) events observed from 1994 to 2013. Strong elemental abundance enhancements scale with A/Q, the ion mass-to-charge ratio, as $(A/Q)^{\alpha}$ where $2 \le \alpha \le 8$ for different events. Most Fe-rich events are associated with both flares and coronal mass ejections (CMEs), and those with larger α are associated with smaller flares, slower and narrower CMEs, and lower SEP event fluences. The narrow equilibrium temperature range required to fit the observed A/Q enhancements is 2.5-3.2 MK, far below the characteristic flare temperatures of ≥ 10 MK. Only a small number of SEP events slightly outside this temperature range were found in an expanded search of impulsive Fe-rich events. Event characteristics are similar for events isolated in time and those occurring in clusters. The current challenge is to determine the solar sources of the Fe-rich events. Ambient coronal regions in the 2.5-3.2 MK range are broadly distributed both in and outside active regions. Acceleration from thermal plasmas at reconnecting current sheets in the context of observed standard and blowout jets may explain the Fe-rich events.

Introduction

Impulsive SEP events are defined primarily by their distinctively non-coronal composition, with up to a 1000-fold increase of $^3He/^4He$ and of heavy elements, such as $(Z \ge 50)/O$. We recently carried out two studies of the abundances of the elements He through Pb in Fe-rich (Fe/O > 0.5) impulsive solar energetic-particle (SEP) events. The Fe-rich event samples were taken from a matrix of Ne/O versus Fe/O ratios at 3 MeV/nuc over 8-hr intervals observed from 1994 to 2013 on the Wind spacecraft, and 111 discrete events with well defined onsets and durations were selected. Their CME, flare, and decametric-hectometric (DH) type III radio burst associations were tabulated (RCK1). We calculated all elemental abundance enhancements of He through Pb at 3-5 MeV/nuc.

Abundance enhancements are organized by elemental A/Q, mass to charge ratios, where Q is temperature dependent. To calculate Q we assumed a coronal range of 2.5-3.0 MK shown as the pink band of Figure 1. The mean enhancements normalized to O are shown in the log-log plot of Figure 2, with a power-law fit with exponent α = 3.6. In RCK1 we found a 69% CME association with the Fe-rich events, nearly all of which were from the western hemisphere. We found:

- Larger O fluences correlate with faster CME speeds.
- A trend for smaller SEP events to correlate with narrower and slower CMEs, consistent with CME associations for all Fe-rich events.
- Median CME speed of 597 km/s and width of 75°.



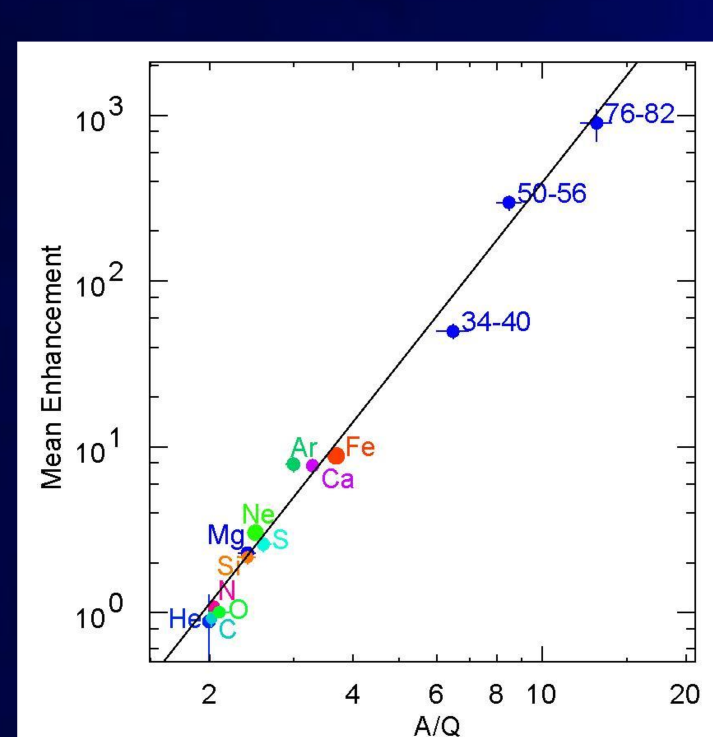
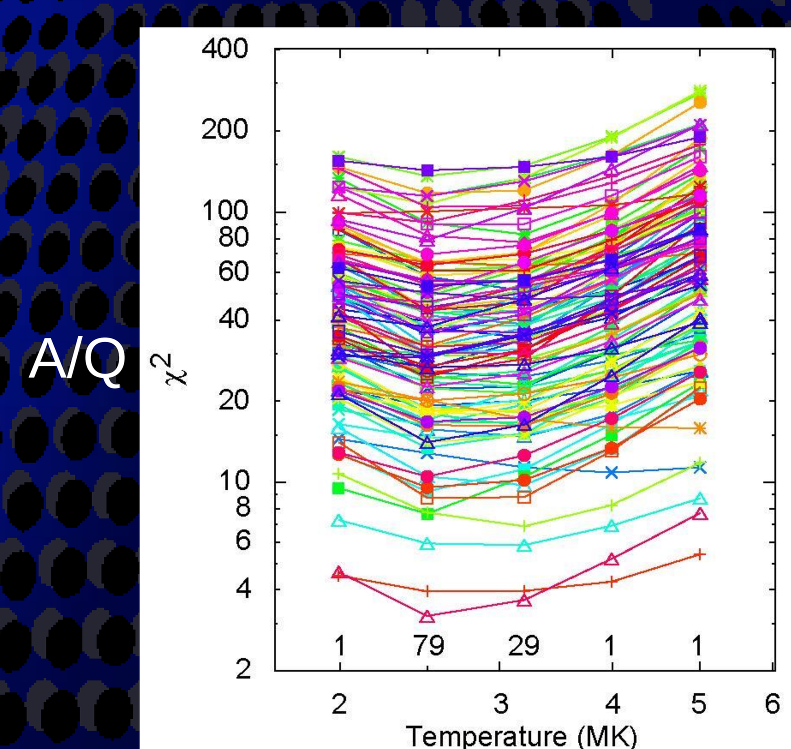


Figure 1 (left). A/Q versus equilibrium temperature in MK for low-Z elements. Only in the pink band of likely temperatures do Si, Mg, and Ne show the observed consecutively increasing A/Q.

Figure 2 (right). Mean enhancements of elemental abundances versus elemental A/Q relative to coronal abundances for the 111 Fe-rich SEP events. Upper data points are elements grouped by atomic numbers Z. The slope α of the best-fit line is 3.64 ± 0.15.

Separating Abundances and Temperatures

The event enhancements are a product of both the source temperature T, which determines the A/Q of each element (Figure 1), and the acceleration mechanism producing a power law of A/Q (Figure 2). To extract the optimum values of T and α, we (RCK2) did χ^2 fits for five assumed T values over the range 1-5 MK for each of the 111 events and selected the minimal fit to determine T (Figure 3). This temperature range is required to obtain *increasing* A/Q and the higher observed abundance enhancements for *decreasing* Z among elements Ne, Mg, and Si (Figure 1). For nearly all events T = 2.5 or 3.2 MK. With the optimal T fit we also derived the associated exponent α for each event.



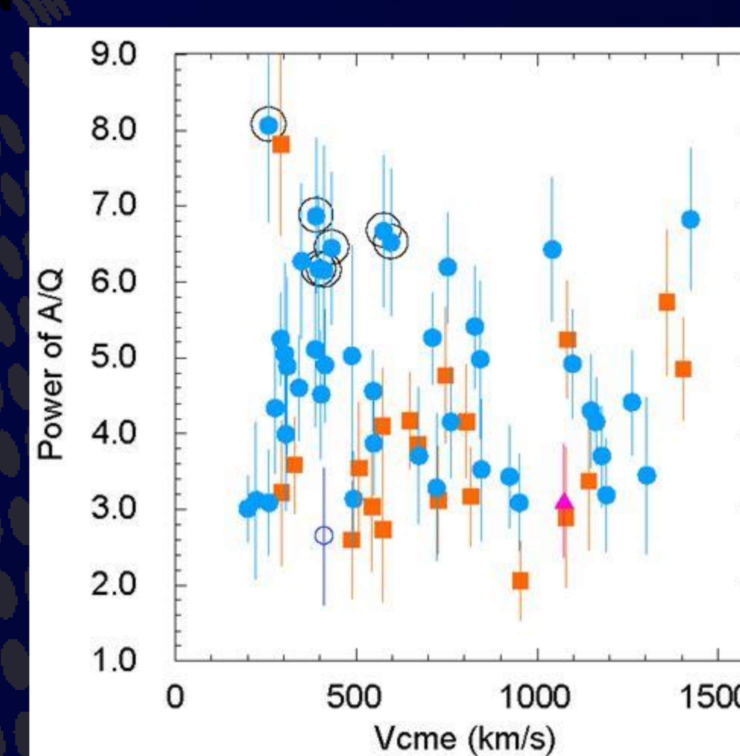


Figure 3 χ^2 vs. T is shown for all 111 impulsive SEP events using different colors and symbols for each event. The number of events with χ^2 minima at each temperature is shown along the bottom of the panel.

Figure 4 The power α versus the associated CME speed. Temperature color coding: 2.5 MK (blue circles); 3.2 MK (red squares). Circled events are those identified as He-poor.

Abundance Enhancements Versus Flares and CMEs.

In Figure 4 we compare α, color-coded for T, of each event with the associated CME speed. The correlations with CME speeds and widths (not shown) are both weak. We also compared α with increasing X-ray flare size and found a trend for decreasing α with increasing flare size. To summarize our (RCK2) statistical comparisons:

- Both T and α vary from event to event.
- The event α decreases with: increasing event O fluences, coronal temperatures, X-ray flare sizes, CME speeds and widths, and flatter O energy spectra.

Recent Work on Fe-rich Events

Using Figure 1 we looked for additional cooler (low He/O) or hotter (S & Si > Ne) impulsive SEP events, but found only 15 new events, all in the 2 to 4 MK temperature range (RCK3). The range of all α values is 2 to 8 with a mean of 4.5 ± 0.74. Seeing that many of the impulsive events tend to cluster in time, we further searched for any systematic differences between clustered and isolated events, but found none.

Implications for Impulsive SEPs

The SEP seed population for the Fe-rich events comes from active region coronal thermal material, not from T > 10 MK flares. Recent modeling of ion acceleration in magnetic reconnection (Drake & Swisdak , 2012, 2014) has shown an A/Q bias, possibly consistent with our results. The CME associations suggest that large-scale coronal blowout jets (Moore et al., 2013), resulting from interchange reconnection, may provide a route for the escape of the SEP ions.

References

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