Time-to-Maximum Studies and Inferred Ionic Charge States in the Solar Energetic Particle Events of 14 and 15 April 2001

W.F.Dietrich[1] and A.J. Tylka[2]
(1) LASR, Enrico Fermi Institute, U. Chicago, Chicago, IL 60637 USA
(2) Code 7652, Naval Research Laboratory, Washington DC 20375-5352 USA

Abstract

We have used data from *Wind*, *ACE*, *IMP8*, and *GOES* to determine the time-to-maximum (TTM) intensity in the solar energetic particle (SEP) events of 14 and 15 April 2001. (The former event was one of the largest impulsive events of Cycle 23, while the later was the largest ground-level event of the Cycle.) From the apparent rigidity-ordering of the TTMs we infer the mean ionic charge state of Fe. In the 14 April event, the analysis indicates that Fe is fully stripped. But in the 15 April event, the charge state increases with energy, in agreement with the observations at ∼1 MeV/nuc and at ∼30 MeV/nuc from *SAMPEX*. This study shows that reliable ionic charge states can be inferred from the TTM method, thus providing a tool for studying charges states at intermediate energies for which no direct measurements are available.

1. Data and Analysis

We have previously discussed our methods for analyzing TTMs [1]. Figure 1 shows the results of our systematic analysis of TTMs in these two events. The plots combine results from eight different instruments (represented by differently shaped symbols, including a proton result from the Climax Neutron Monitor at the bottom right of the 15 April plot) and show eight different species (from H to Fe, and including *ACE*/ULEIS ^{3}He in the small 14 April event.) In these plots, the quantity on the x-axis is $\beta R^{0.5}$, where β is the particle speed in units of light speed and the rigidity R has been evaluated *tentatively assuming the ions to be fully-stripped*. Fe datapoints are shown in red and with larger symbols.

In both plots, the results are reasonably well clustered into a distinct locus of points. The points appear to be more tightly clustered in the 14 April event (left panel), suggesting that the assumption of fully-stripped ions is essentially correct in that event at all energies and for all species. However, this is not the case in the 15 April event (right panel), where the Fe TTMs on the left side of this plot are clearly shorter than those of the other species. As the abscissae increase, the Fe TTMs get closer to the locus of the other species. At the right side of the

pp. 3291–3294

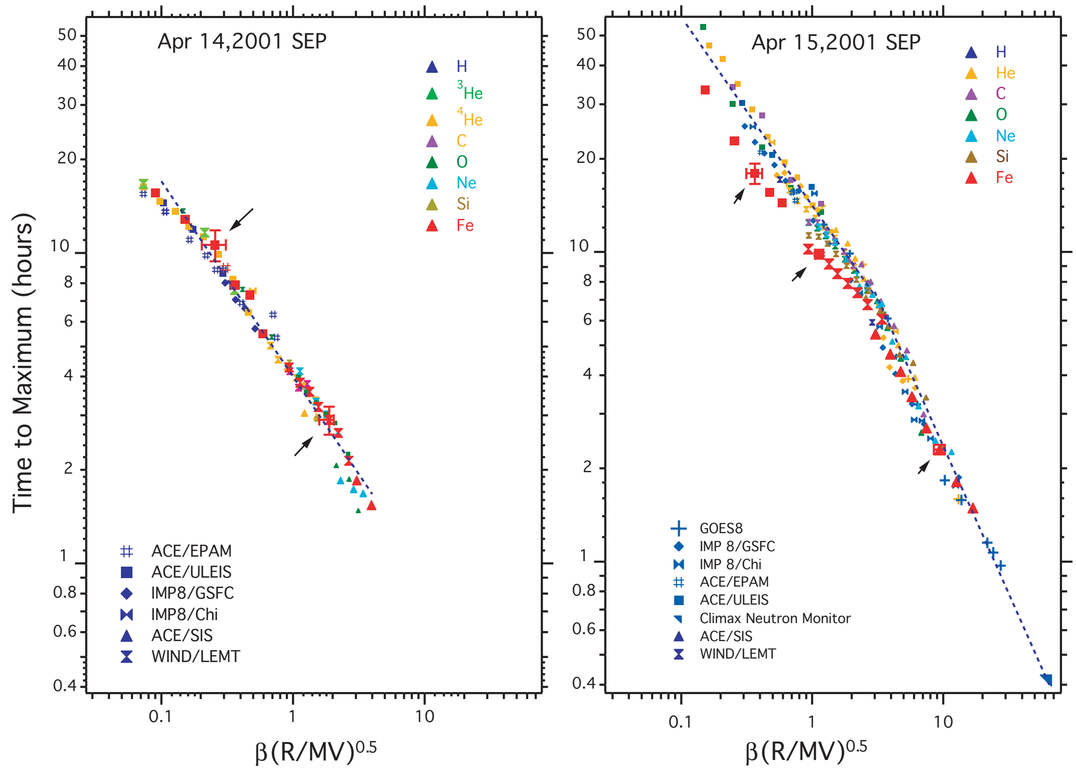
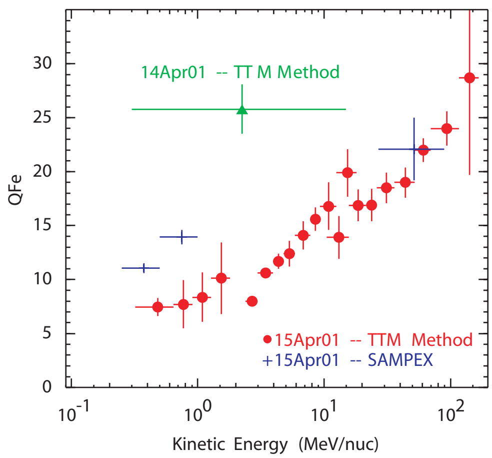


Fig. 1. TTM values vs. $\beta R^{0.5}$ in the 14 April 2001 impulsive event (left) and the 15 April 2001 ground-level event (right). Symbol shape signifies the data source and different colors represent different species, as detailed in the legends. Fe datapoints are larger and in red. In evaluating the rigidity R, all ions are *tentatively* assumed to be fully stripped. Error bars have been suppressed except for the few sample datapoints marked by arrows. The left and right panels contain 92 and 205 datapoints, respectively.

plot, the Fe TTMs coincide with those of the other species. The implication of this systematic drift in the Fe TTMs is that the Fe ions are not fully stripped at all energies in the 15 April event. Instead, the Fe charge states in this event must increase with increasing energy.

To quantify this behavior, for each energy we must find the Fe charge (QFe) that minimizes the separation between the Fe datapoint and the locus formed by the other species in Figure 1. Specifically, for the 14 April event, we fitted the locus of non-Fe points as a simple power-law in $\beta R^{0.5}$; in the 15 April event, we used a broken power-law. (These power-laws are shown as dashed lines in Figure 1. Power-laws were chosen simply because they empirically describe the trend in the data; TTMs are not generally organized as strict power-laws [1].) At each



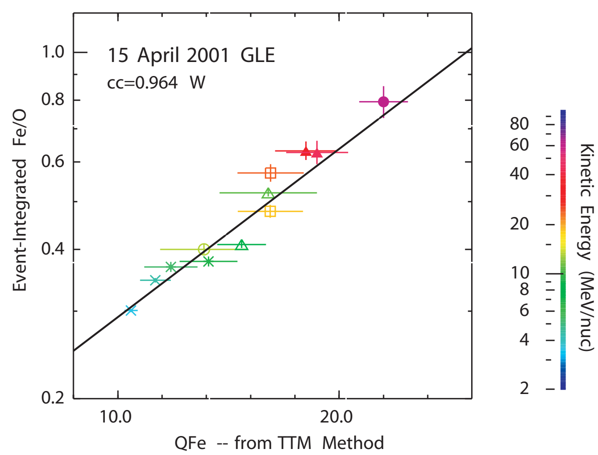


Fig. 2. (left) Inferred QFe (from our TTM analysis) and measured QFe (from *SAMPEX* [2,4]) vs. energy.

Fig. 3. (right) Measured Fe/O [5] vs. QFe from this analysis. Colors indicate the energy, as shown by the key.

energy, we then calculated the value of QFe that moved the Fe datapoint onto the appropriate power-law.

The results of this procedure are shown in Figure 2. In the 15 April event, the inferred QFe is independent of energy below ∼3 MeV/nuc with a mean value of about 8. This value is lower than what is generally observed at these energies in gradual events, but it has been directly measured in other SEP events; it is unusual but not inherently unreasonable. Above 3 MeV/nuc, QFe increases with in energy, reaching QFe ∼26 but not significantly exceeding it.

Figure 2 also shows the result for the 14 April event. In this case, errors are large due to smaller ion statistics. There is no strong energy dependence, as is evident in Figure 1a. We have therefore combined results in a weighted average, giving <QFe> = 25.8 ± 2.3. This value is slightly higher than <QFe>∼20-22 generally reported for impulsive SEP events, perhaps because of the larger x-ray flare (M1.0)in this case.

ACE/SEPICA was not operational during these events, and the 14 April event was too small to be measured by *SAMPEX* instruments. *SAMPEX* results for the 15 April event are also shown in Figure 2. At ∼27-90 MeV/nuc, *SAMPEX*/MAST reports <QFe> = 22.1 ± 2.9 [2], in good agreement with our result of 20.2 ± 0.7, averaged over these same energies. *SAMPEX*/LICA results at 0.25-1.0 MeV/nuc [4] are larger than our values. This discrepancy may be a measure of the limitations of our method below ∼1 MeV/nuc, where the TTM may also be affected by the long duration over which the CME-driven shock generates particles of these energies.

Overall, in both of these events, the TTM method yields plausible QFe values. It should be noted that there is nothing in our methodology that prohibits QFe from taking on "unphysical values", either very low or greatly in excess of 26. The fact that we derive physically reasonable QFe values in these two very different events is a strong indication of the validity of our approach.

2. Discussion

Tylka et al. [6] recently reported the energy dependence of Fe/O in the 15 April 2001 event. Figure 3 correlates those results vs. QFe at ∼3-80 MeV/nuc. The clarity of this trend gives further credence to the reliability of our QFe determinations. A correlation between Fe/O and QFe has been noted before on an event-to-event basis [2]. But this figure demonstrates the correlation in a single event, with both quantities increasing together with energy.

Given an accelerator acting upon a seed population comprising Fe ions with a broad distribution of charge states, the most highly-ionized Fe ions will generally be accelerated preferentially to the highest energies. But it is not clear why this acceleration process should also cause Fe/O to increase with energy. Timing results [7], as well as spectral shapes [6], argue for a single accelerator in the 15 April 2001 event and against a direct flare component. A characteristic of diffusive shock acceleration is that seed particles that start at higher speeds, on average, end up at higher energies. The fact that both QFe and Fe/O increase with energy can therefore be seen as evidence for a two-component seed population [3,5], with lower speeds dominated by solar-wind suprathermals (with Fe/O ∼ 0.1 and <QFe> ∼10) and higher speeds dominated by suprathermals previously accelerated at a flare (with Fe/O ∼ 1 and <QFe> ∼20).

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3. References

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