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# The charge-to-mass dependence of solar energetic particle spectral breaks

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**Abstract:** Measurements of the energy spectra of SEP events over a broad energy range (~0.1 to 100 MeV/nuc) show that all large SEP events have spectral beaks organized by the charge-to-mass ratio (Q/M) of the ions. In this paper we present preliminary results of a multi-spacecraft study of the Q/M-dependence of spectral breaks in 11 SEP events and investigate whether the deduced Q/M dependence is correlated with other characteristics of the events.

## Introduction

A new generation of instruments during solar cycle 23 made it possible to measure solar energetic particle (SEP) energy spectra for many species over a broad energy interval (~0.1 to ~100 MeV/nuc). These observations revealed that most large SEP events have power-law spectra below a few MeV/nuc with rather hard spectral indices, followed by spectral breaks at higher energies. The spectral breaks are ordered by species -- the spectra of lighter elements break at higher energy/nuc than those for heavier species. In previous studies Tylka et al. [1], Cohen et al. [2] and Mewaldt et al. [3, 4] found the break energies scaled as a power of the charge-to-mass ratio (Q/M) ranging from ~0 to ~2. According to the model of Li, et al. [5], for parallel shocks the break locations (in energy/nuc) relative to protons should depend on $(Q/M)^b$, with $b \approx 2$.

In Figure 1 we show spectra measured during a 6-hour time period on Oct. 29 following the arrival of the shock from the Oct. 28, 2003 event. Break energies were identified by fitting the spectra with the Ellison-Ramaty (ER) spectral form [6]:

$$dJ/dE = KE^{-g} \exp(-E/Eo), \quad (1)$$

where E is kinetic energy/nuc and K, g, and Eo are constants. During this time period the Q/M-dependence is similar to that expected by Li et al.

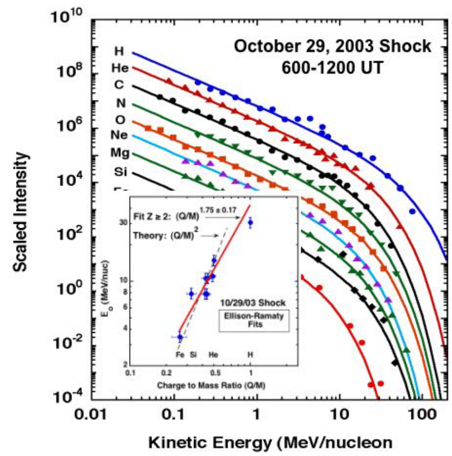


Figure 1: Energy spectra following the arrival of a shock on Oct. 29, 2003 are fit with the ER spectral shape [7]. The inset shows the Q/M-dependence of the e-folding energies.

However, fits to a shock on October 30, 2003 events (~1 day later) gave $b \approx 1$, suggesting that some critical condition(s) had changed.

In this paper we fit fluence spectra from ~0.1 to ~100 MeV/nuc using H to Fe data from ACE, SAMPEX and GOES. Combining the break locations with Q/M data from SAMPEX, we compare the resulting Q/M-dependence of the break energies with other characteristics of these events to investigate their origin.

This initial study focuses on events with clear spectral breaks that allow for accurate determination of the break energies. These initial results are for fluence spectra integrated over the events. Preliminary results are presented for 11 events, while the analysis of additional events is proceeding. The Q/M dependence of three of the 11 events was analyzed earlier for $6 \leq Z \leq 26$ [8] and for H and He [3]. This study includes all abundant species from H to Fe.

## Sources of Data and Fitting Procedure

The spectral data used in this study come from ACE (EPAM, ULEIS and SIS), GOES 8 and 11, and SAMPEX (PET). For additional information on these data sets see [3, 4, 9].

Cohen et al. [2, 8] have shown that in many events the spectra of all species are similar in shape if they are shifted in energy by an appropriate amount. In order to determine the energy shift for species with $6 \leq Z \leq 26$ we followed the procedure described in Cohen et al. [2], including many of the same SEP events. Data for H and He were fit with the ER shape to determine the low-energy power law slope (g) and the e-folding energy, Eo. The oxygen spectra were also fit with the ER shape in order to normalize the H and He data to the heavier species. To date, proton data have been obtained for 10 of the 11 events and He data are included for 7 events. It is intended to fill in H and He data for all events.

There are mean charge-state (<Q>) measurements for a number of SEP events from instruments on SAMPEX and ACE. This preliminary study makes use of ~20 to ~80 MeV/nuc <Q> measurements from SAMPEX [10] whenever there were measurements for Fe (3 events). In all other events we have used the nominal SEP charge states adopted by Cohen et al. [8]. The Q/M values assume solar system isotropic composition.

In Figure 2 we plot the Eo values versus Q/M for four of the 11 events. For those three events where there are <Q> measurements we have included the reported uncertainties. The typical uncertainties on the H and He Eo values are <5%; Typical uncertainties for the heavy ions are ~10%. Also shown in Figure 2 are unweighted least-squares fits to the Q/M dependence of Eo. In the first three events all species are generally consistent with a single power-law. In the October 28, 2003 event it appears that the proton Eo value is inconsistent with the extrapolated behavior of the heavier ions, which also occurred in two other events. We are presently ignoring these differ; if we fit the Z > 2 data alone the values of the Q/M-exponent change by 0.18 to 0.35.

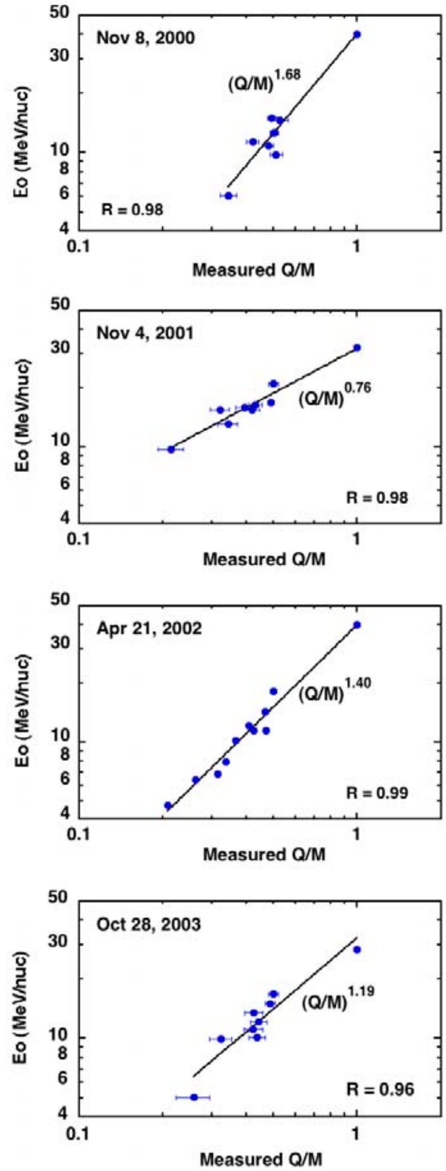


Figure 2: Plots of the e-folding energy (Eo) versus Q/M for four SEP events. The best-fit values of the power-law index (b) are shown. Correlation coefficients are also indicated.

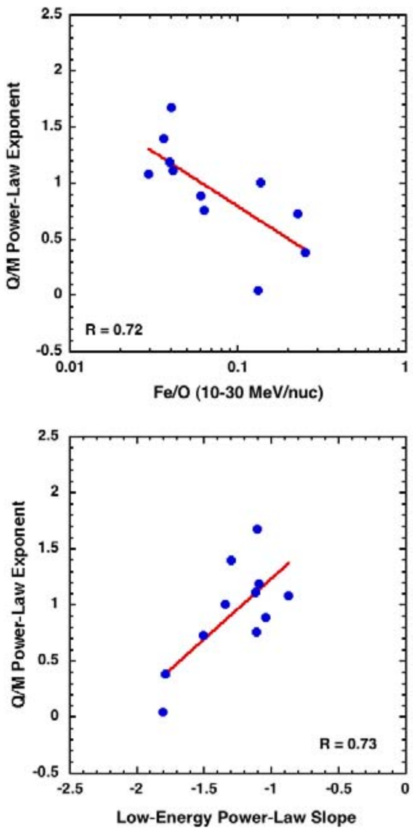


Figure 3: Best-fit values of the Q/M power-law exponent (b) are plotted vs. Fe/O (top) and the power-law slope (g) of the low-energy spectra for all 11 events (bottom). Correlation coefficients are also shown.

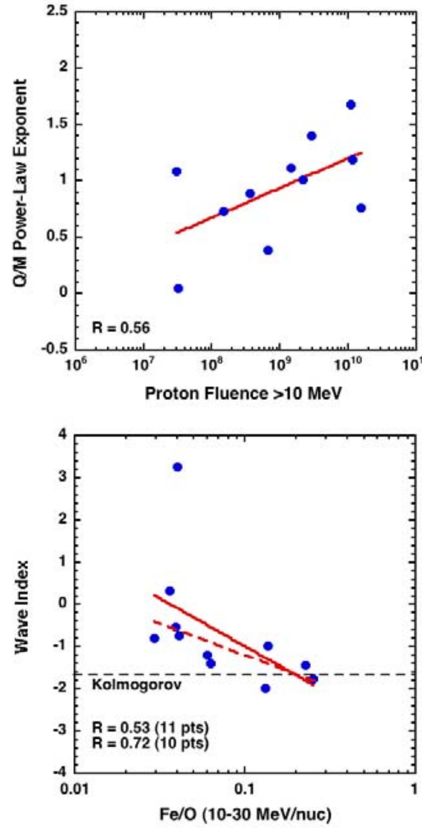


Figure 4: (Top): Plot of the Q/M power-law index vs. the >10 MeV proton fluence. (Bottom): Plot of the deduced interplanetary wave index (see text) vs. Fe/O. Correlation coefficients are also shown.

In Figures 3 and 4 we plot the best-fit values of b versus three other relevant quantities: the high-energy Fe/O ratio, the slope of the low-energy spectrum (g), and the proton fluence. All appear to be correlated with b to varying degrees. However, we do not find significant correlations for b versus CME speed (R = 0.18) or flare longitude (R = 0.28). The positive correlations of b with Fe/O and g suggest that Fe/O and g are correlated, and they are found to be (R = 0.83). The lower panel of Figure 4 is discussed below.

## Discussion

All of the SEP events in this study had break-energies that were organized by the Q/M ratio of the ions. In most cases fits to the break-energies vs. Q/M are reasonably compatible with a single power-law; in three events (see Oct. 28, 2003) the proton Eo values appear to be inconsistent with the trend of the heavier ions. These differences do not seem to be due to uncertainties in the <Q> values. There was no obvious commonality among the three events – one was among the largest of solar cycle 23 while another was ~500 times smaller. In general, there is considerable scatter, possibly due to uncertainties in the <Q> values (note that the mean charge states are energy-dependent in many SEP events [11]).

The correlation plots in Figures 3 and 4 suggest that the Q/M-dependence of the spectral breaks is correlated with both composition and the low-energy spectral slope. Among other possibilities, a correlation with composition is possible if: (1)

there are two or more components contributing to, for example, Fe-rich events [12, 13], or (2) if the acceleration process differs in some way (e.g., if the shock geometry is different for Fe-rich events [14]).

Cohen et al. [8] suggested that the location of spectral breaks in fluence spectra observed at 1 AU is governed by diffusion processes, such as escape upstream from the shock, in which case the breaks should occur at the same value of the diffusion coefficient. Assuming a diffusion coefficient that scales like $(Q/M)^{\alpha}$, they found $\alpha = 0.8$ to 2.7 for five events. Cohen et al. related $\alpha$ to the interplanetary turbulence spectrum (assumed to be a power-law in wave number, $k^q$ [15]). They found that the SEP spectra were organized by wave spectra ranging from q = -1.2 to q = 0.7, significantly flatter than a Kolmogorov spectrum (q = -5/3), suggesting a source of turbulence near the shock where the ions were accelerated. Cohen et al. [8] (see also [3]) note that proton-amplified Alfven waves [16, 17] can produce broad features in the wave spectra with $q \geq 0$.

For these 11 events (3 of which are in common with Cohen et al. [8]), we deduce q values ranging from about -2 to +3, as shown in the bottom panel of Figure 4 as a function of Fe/O. It is interesting that there is a correlation with Fe/O – those events that are most Fe-rich have wave indices more or less consistent with a Kolmogorov spectrum, while it is the Fe-poor events that have somewhat harder wave spectra, indicating an additional source of turbulence. [Note that the November 8, 2000 event (top panel of Figure 3) appears as an outlier because in the above approximation the deduced wave index approaches infinity as the Q/M power-law index approaches 2. For this reason we show the best-fit correlation with and without this event included.]

The Fe-poor events in the bottom panel of Figure 4 that provide evidence for an additional source of turbulence also happen to include some of the largest SEP events of solar cycle 23 (as can be deduced from the top panel of Figure 4). Thus, these results provide support for the idea that the enhanced wave power is occurring in those events with the largest proton intensities.

In future work we plan to include more events and also concentrate on analyzing Q/M-dependent breaks in shock spike events (like in Figure 1), when there can be a more direct comparison with theoretical models.

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