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Systematic Charge-to-Mass-Dependence of Heavy Ion Spectral Breaks in Large Gradual Solar Energetic Particle Events

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We fit the ~0.1-500 MeV nucleon^{-1} H-Fe spectra in 46 large SEP events surveyed by Desai et al. (2015) with the double power-law Band function to obtain a normalization constant, low- and high-energy Band parameters $\gamma_a$and γ_b; and spectral break energy E_B. We also calculate the low-energy power-law spectral slope γ_1. Our results are: 1) γ_a, γ_1, andγ_b are species-independent and the spectra steepen with increasing energy; 2) the low-energy power-law spectral slopes $\gamma_1$are consistent with diffusive acceleration at shocks with compression ratios between ~2 – 4 as predicted by Schwadron et al. (2015); 3) the spectral breaks E_B's are well ordered by Q/M ratio, and decrease systematically with decreasing Q/M, scaling as $(Q/M)^{\alpha}$ with α in most events varying between ~0.2-2, as predicted by Li et al (2009); 4) α is well correlated with Fe/O at ~0.16-0.23 MeV nucleon^{-1}, but not with the ~15-21 MeV nucleon^{-1} Fe/O and the ~0.5-2.0 MeV nucleon^{-1} ^{3}He/^{4}He ratios; 5) In most events: α <1.4, the spectra steepen significantly at higher energy with γ_b–γ_a >3, and O E_B increases with γ_b–γ_a; and 6) Many extreme events (associated with faster CMEs and GLEs) are Fe-rich and ^{3}He-rich, have large $\alpha \geq$1.4, flatter spectra at low and high energies with γ_b–γ_a <3, and E_B that anti-correlates with γ_b–γ_a. In most events, the Q/M-dependence of E_B is consistent with the equal diffusion coefficient condition, while the event-to-event variations in α may be driven by differences in the near-shock wave intensity spectra, which are flatter than the Kolmogorov turbulence spectrum but weaker when compared to extreme events. We interpret these results as being due to weaker turbulence that allows the SEPs to easily escape, resulting in weaker Q/M-dependence of E_B, lower α values, and spectral steepening at higher energies. In contrast for extreme events, the stronger Q/M-dependence of E_B, larger α values, and harder spectra at high and low energy occur because enhanced wave power enables faster CME shocks to accelerate flare suprathermals more efficiently than ambient coronal ions.