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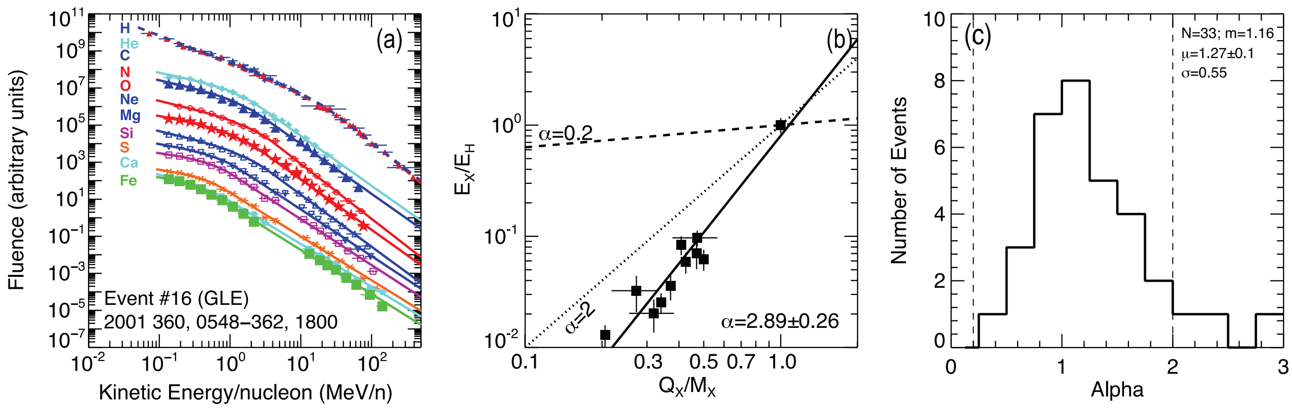
Q/M-Dependence of Heavy Ion Spectral Breaks in Large SEP events

Heavy-ion energy spectra in large gradual solar energetic particle (SEP) events associated with coronal mass ejections (CMEs) are often represented by two broken power-laws with distinct low and high-energy spectral slopes. We fit the ~0.1-500 MeV per nucleon H-Fe spectra in 46 large SEP events with the double power-law Band function to obtain a normalization constant, low- and high-energy parameters γ_a and γ_b, and spectral break energy E_B, and derive the low-energy spectral slope γ_1. We use the power-law slopes and the location of the transition or break energies to infer the seed populations and conditions under which the SEPs are accelerated by near-Sun CME shocks.



***Left panel**: Event-integrated differential fluences versus energy of ~0.1-500 MeV per nucleon H-Fe nuclei (offset for clarity) with Band-function fits (solid lines) during a large gradual SEP event that also produced a ground level enhancement (GLE). Data are from ACE/EPAM, ACE/ULEIS, SoHO/ERNE, GOES/EPS, SAMPEX/PET, and ACE/SIS. **Middle panel**: Break energy E_X of species X normalized to the proton spectral break energy $\boldsymbol{E_H}$ vs. the ion's charge-to-mass (Q/M) ratio. Solid line is the fit to the data with the linear function $\log(E_X/E_H) = \log(n_0) + \propto \log(Q_X/M_X)$; dashed line is $\propto = 0.2$; dotted line is $\propto = 2$. **Right panel**: Distribution of $\propto$ in 33 large gradual SEP events.*

Our results show that: 1) γ_a, γ_1, and γ_b are species-independent and the spectra steepen with increasing energy (left panel); 2) E_B's decrease systematically with decreasing Q/M scaling as $(Q/M)^\alpha$ (middle panel); 3) In 33 events, α varies between ~0.2-3 (right panel) and is well correlated with the ~0.16-0.23 MeV nucleon^{-1} Fe/O; 4) In most events, $\alpha < 1.4$, $\gamma_b - \gamma_a > 3$, and the O E_B increases with $\gamma_b - \gamma_a$; and 5) In many extreme events (associated with faster CMEs and GLEs), the Fe/O and $^3He/^4He$ ratios are enriched, $\alpha \geq 1.4$, $\gamma_b - \gamma_a < 3$, and E_B decreases with $\gamma_b - \gamma_a$.

The species-independence of γ_a, γ_1 and γ_b and the Q/M dependence of E_B within an event, and the α values suggest that double power-law SEP spectra occur due to diffusive acceleration by near-Sun CME shocks rather than scattering in interplanetary turbulence. Using γ_1 we infer that the average compression ratio for 33 near-Sun CME shocks is 2.49±0.08. In most events, the Q/M-dependence of E_B is consistent with the equal diffusion coefficient condition and the variability in α is driven by differences in the near-shock wave intensity spectra, which are flatter than the Kolmogorov turbulence spectrum but weaker than the spectra for extreme events. In contrast, in extreme events, enhanced wave power enables faster CME shocks to accelerate impulsive suprathermal ions more efficiently than ambient coronal ions. For further details see, Desai et al., *Astrophysical Journal, Vol. 828, 106, 2016; doi:10.3847/0004-637X/828/2/106*.

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