Solar Energetic Particle Spectral Breaks

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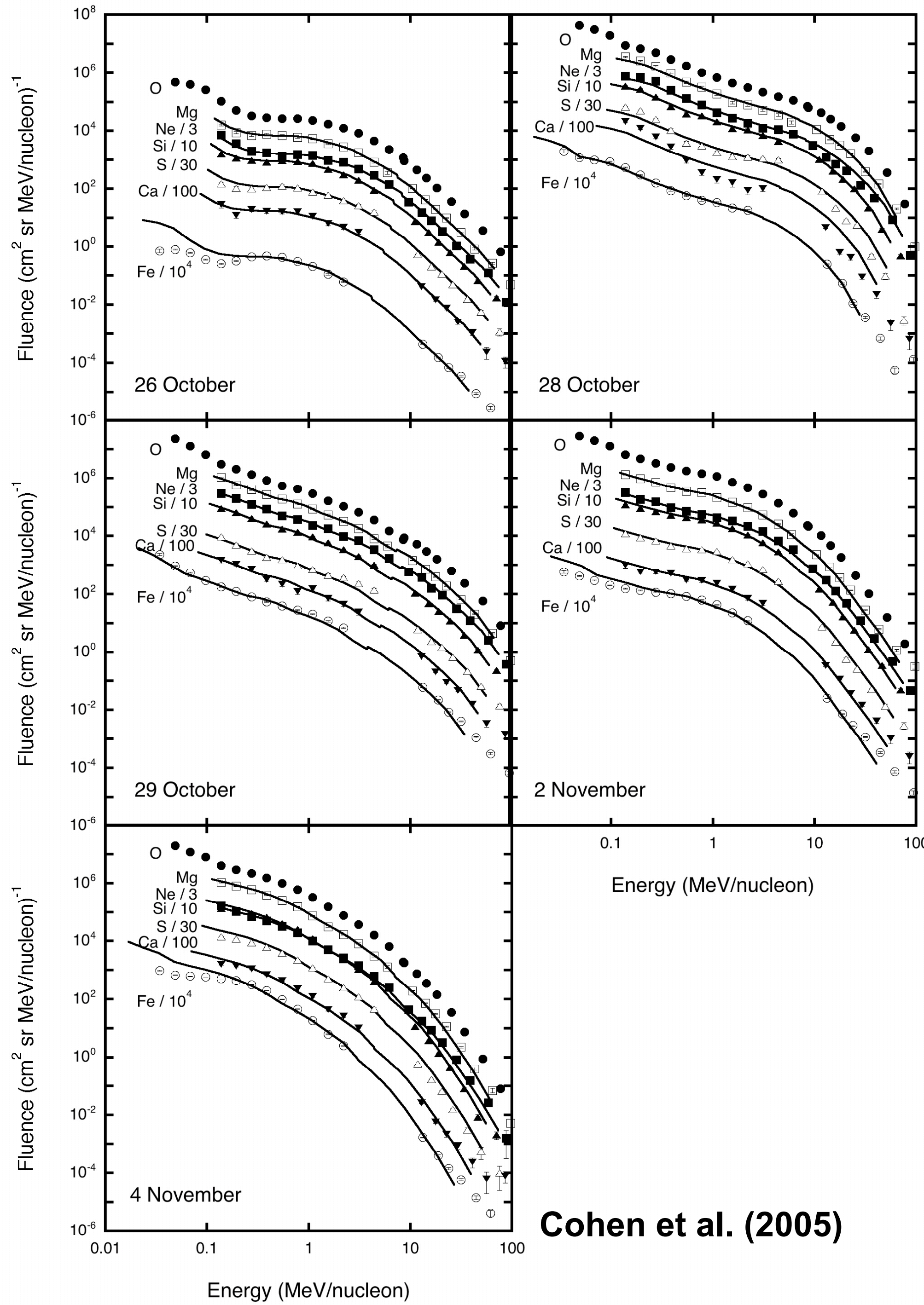
Determining Spectral Breaks - Approach #1

The heavy-ion fluence spectra for the five Oct-Nov 2003 events are organized by Q/M. When the O spectra are shifted in energy and fluence they match up with the spectra of other elements (Cohen et al. 2005; see also Tylka et al. 2000). The size of the energy shift is then plotted versus Q/M

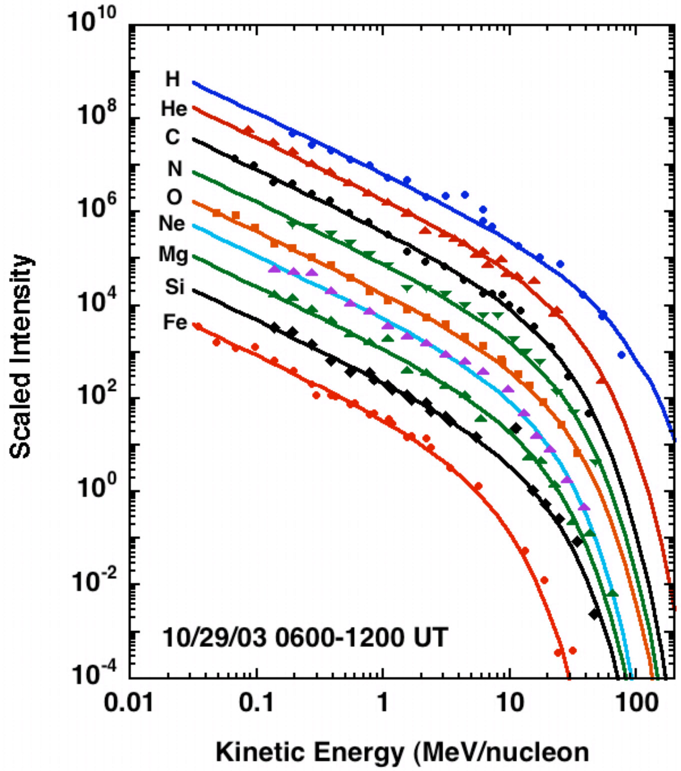
Measured charge states from SAMPEX have been used when available - for other events average charge states were used.

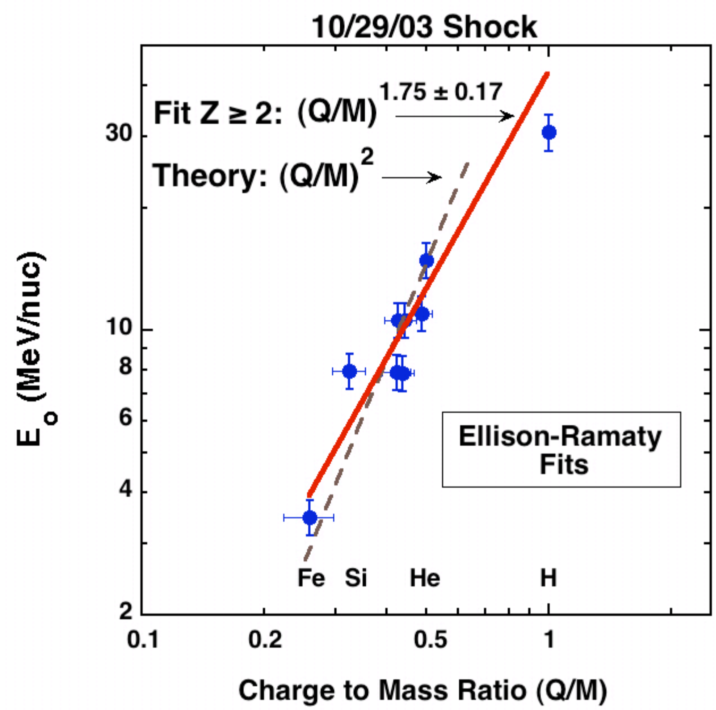


Cohen et al. (2005)

Determining Spectral Breaks - Approach #2

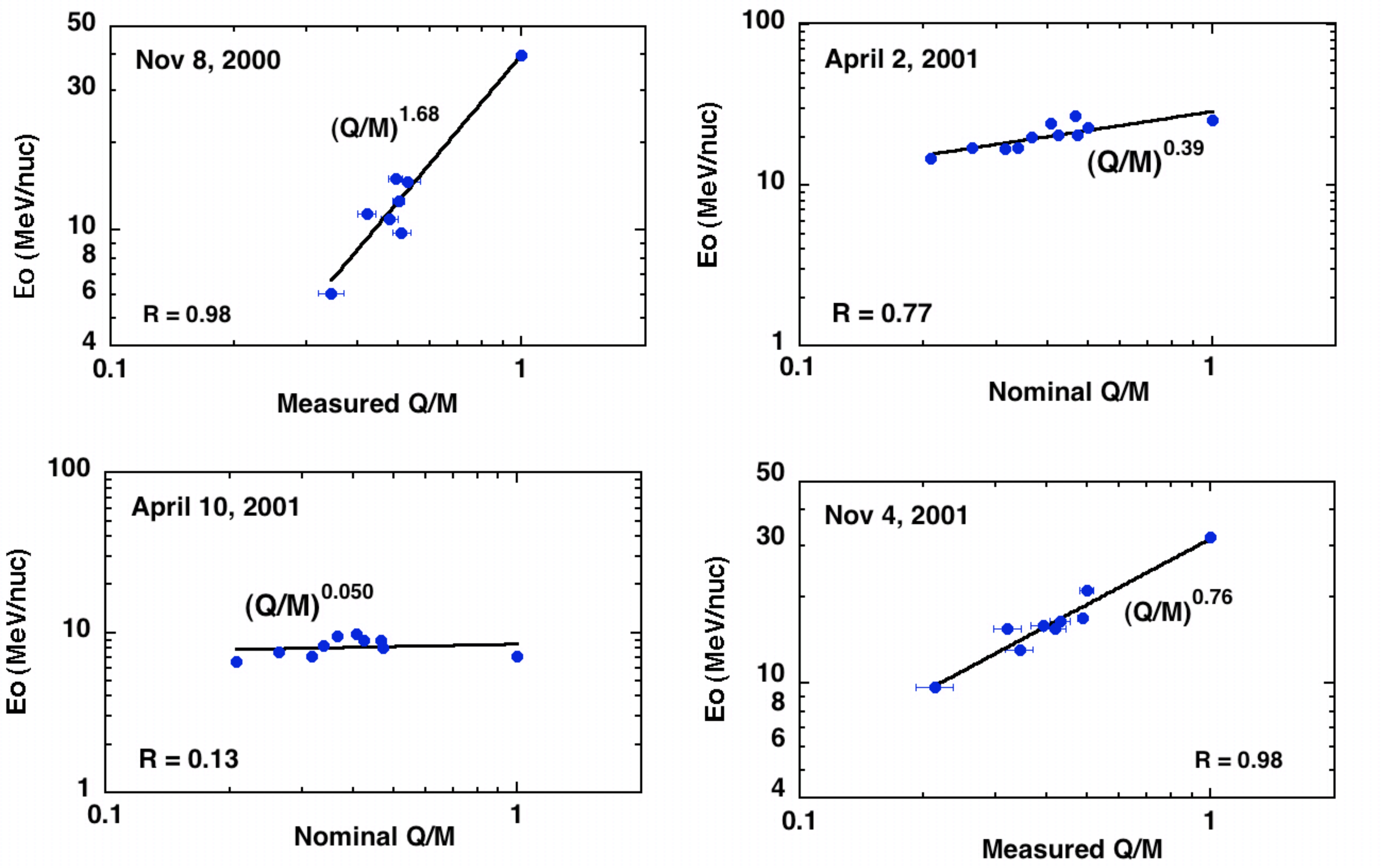
These spectra were obtained following the arrivial of a strong shock on 10/29/03. They are fit with an Ellison-Ramaty spectrum (power-law times an exponential) to determine the break energies (Eo) and low-energy spectral slopes (γ). The Q/M measurements are from SAMPEX.

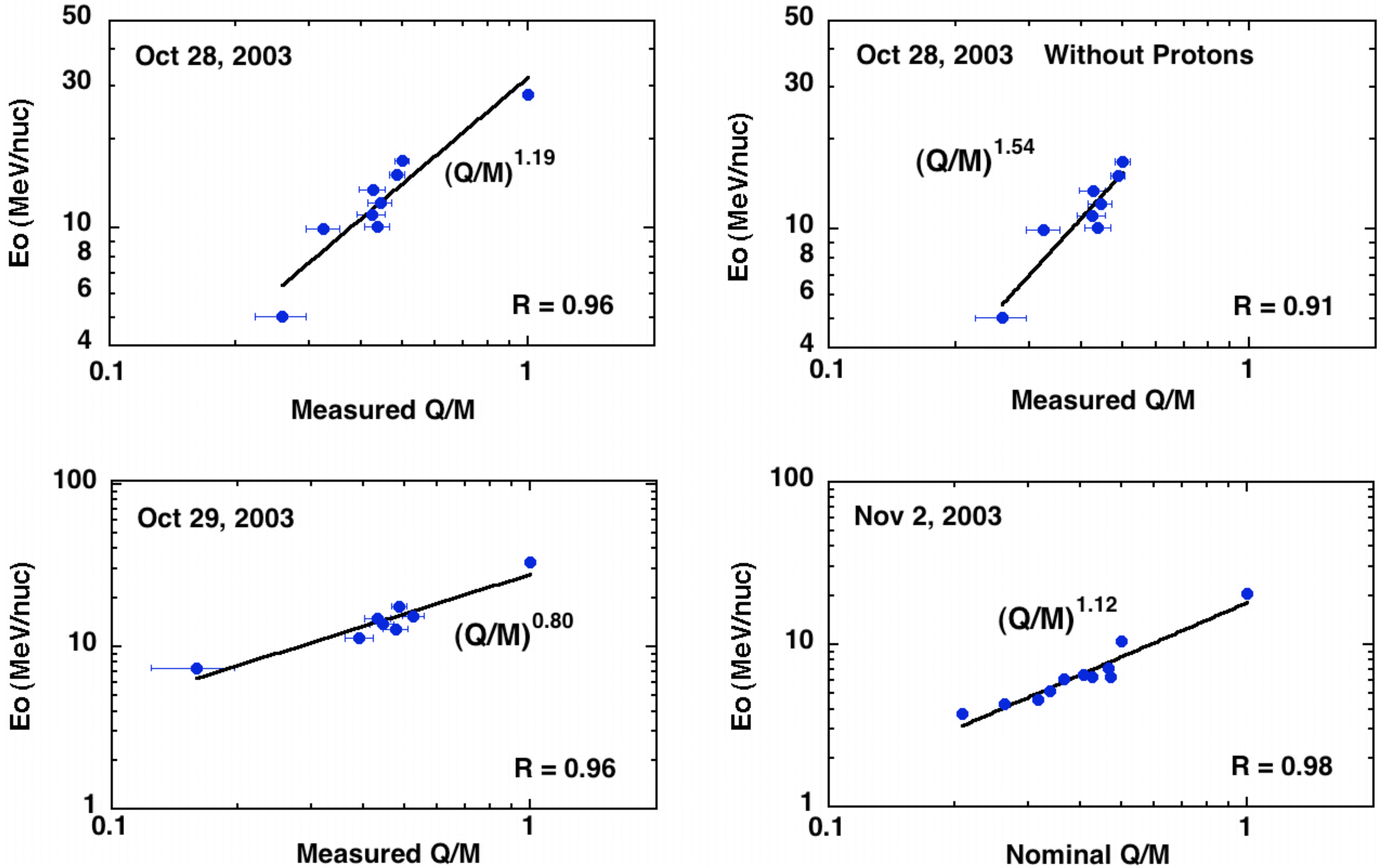




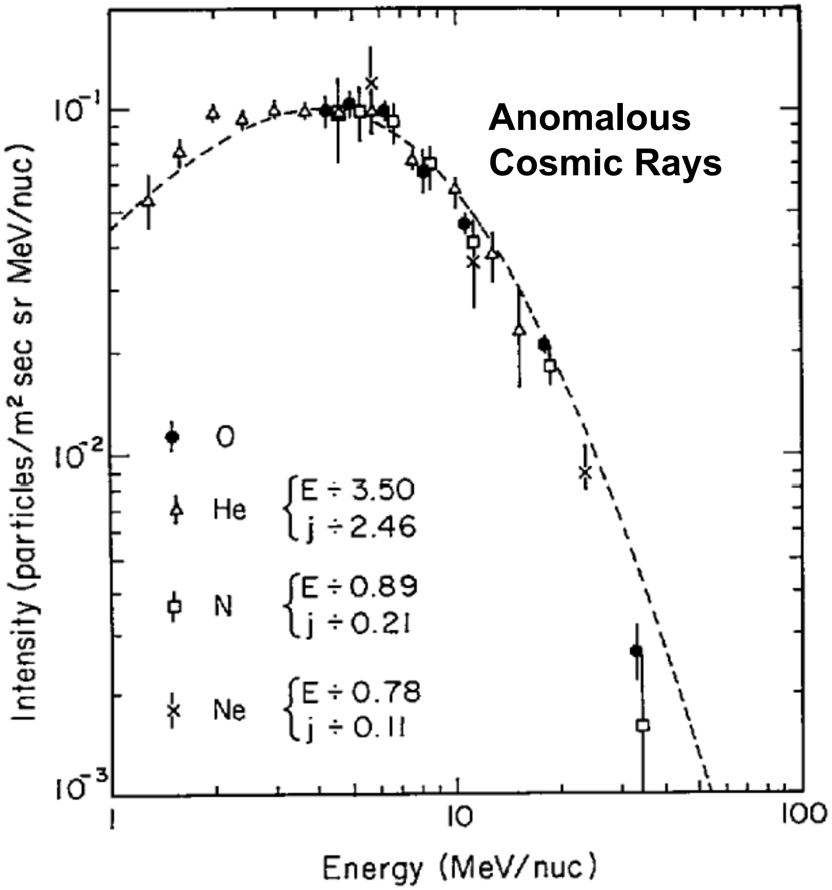
The observed break locations for Z ≥ 2 following the arrival of the 10/28/03 shock scale as $(Q/M)^{1.75 \pm 0.17}$ (Mewaldt et al. 2005). However, the breaks following the 10/29/03 shock arrival scaled as $(Q/M)^1$.

Plots of the E-folding energies or spectral shifts vs Q/M





Oct 28, 2003
(Q/M)^1.19
R = 0.96
Eo (MeV/nuc)
Measured Q/M
Oct 28, 2003 Without Protons
(Q/M)^1.54
R = 0.91
Eo (MeV/nuc)
Measured Q/M
Oct 29, 2003
(Q/M)^0.80
R = 0.96
Eo (MeV/nuc)
Measured Q/M
Nov 2, 2003
(Q/M)^1.12
R = 0.98
Eo (MeV/nuc)
Nominal Q/M



Cummings, Stone & Webber found that ACR features occur at the same diffusion coefficient

Interpretation

Cohen et al. (2005) suggest that the spectral breaks in fluence spectra are most likely related to diffusion effects such as escape from the shock region (see Li et al. 2005).

In this case, the position of the breaks should scale according to their diffusion coefficients,

$\kappa = 1/3\ v\ \lambda$

Assuming λ is a power law in rigidity,

$\kappa \sim (M/Q)^{\alpha}(E)^{(\alpha+1)/2}$

If the spectral breaks occur at the same value of κ, then the energy shifts are related by $E_1/E_2 = [(Q/M)_1 / (Q/M)_2]^{2\alpha/(\alpha+1)}$

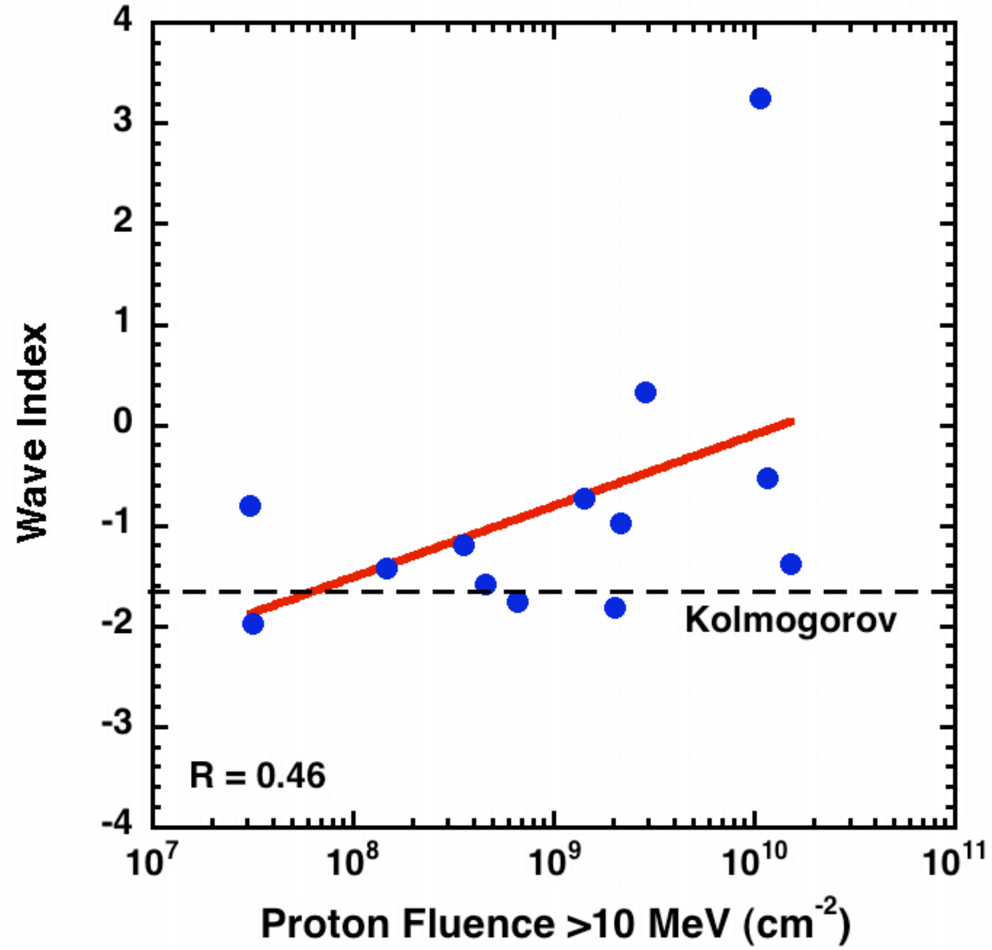
This implies $\alpha = b/(2-b)$ where b is our Q/M index

Values of α are typically $\alpha \approx 1$, but vary considerably, suggesting considerable variation in the rigidity dependence of the diffusion coefficient

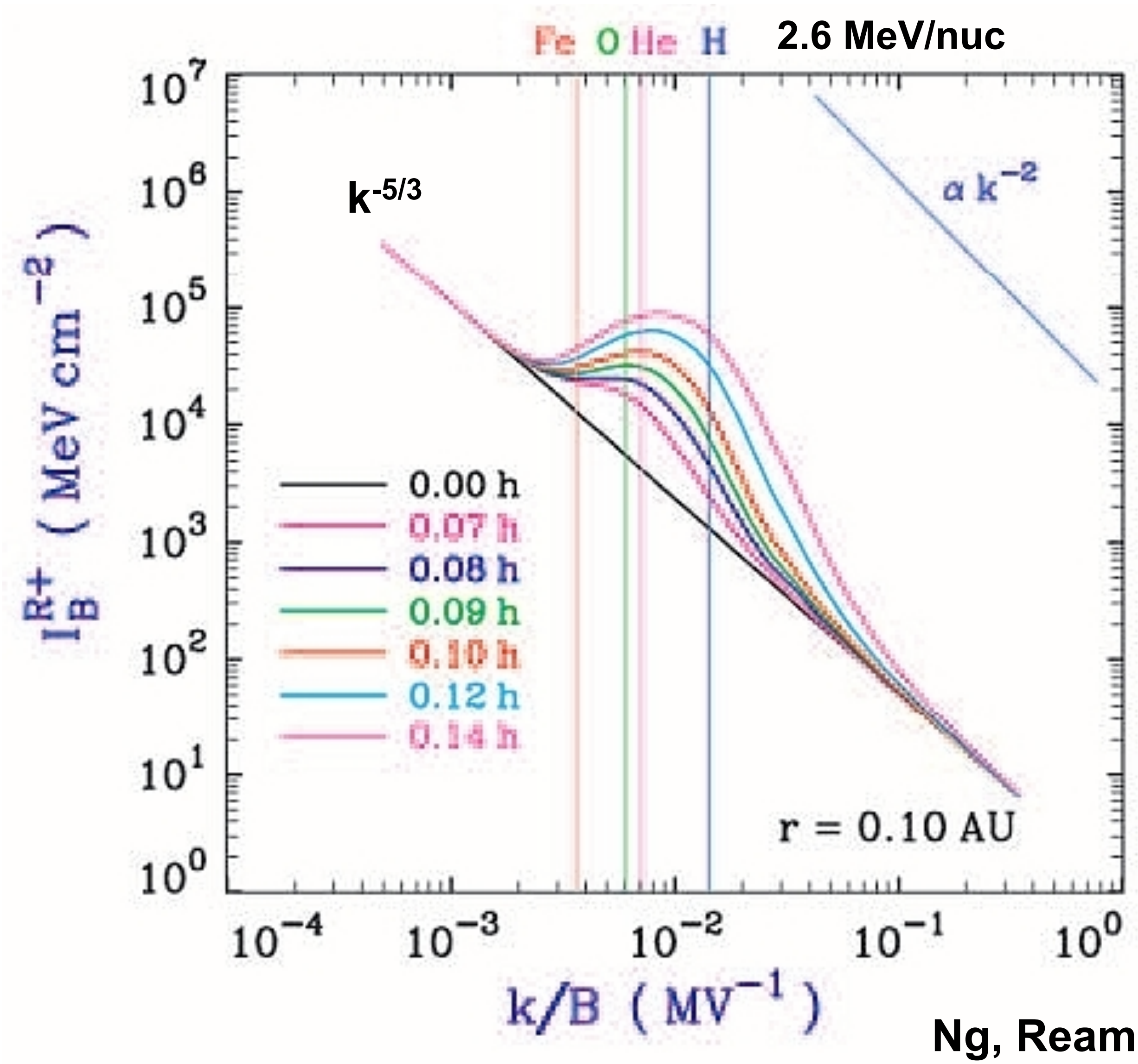
The values of α can be related to the turbulence spectrum, assumed to be a power-law in wave number, or k^q, by

$\alpha = 2+q$ (Droege, 1994)

Wave indices of $q \geq 0$ suggest that an additional source of turbulence is present. This is apparently more likely in those events with higher proton intensities, as expected



Cohen et al. suggested that proton-amplified Alfven waves (Lee 1983; Ng, Reames & Tylka, 2003) are responsible for the additional turbulance and for organizing the Q/M-dependent spectral breaks



Ng, Reames, and Tylka 2003

breaking energy E_0 for case 1&2

Case A: Bohm approx.

$\gamma = 2, \delta = 1$

$E_0 \sim (Q/A)$

Seen in observation e.g. *Tylka (2001)*

*Bohm approximation may **NOT** be a bad approximation*

Case B: parallel shock with $I(k) \sim k^{\beta}$

$E_0 \sim (Q/A)^{2(\beta+2)/(\beta+3)}$

$\beta = -2 \quad \Rightarrow \quad E_0 \sim (Q/A)^{0}$

$\beta = -1.5 \quad \Rightarrow \quad E_0 \sim (Q/A)^{2/3}$

$\beta = 0 \quad \Rightarrow \quad E_0 \sim (Q/A)^{4/3}$

Case C: perpendicular shock: $\gamma = 1, \delta = 1/9$

$E_0 \sim (Q/A)^{2/9}$ → Not seen yet

Can perp. Shock be responsible for large SEP events?

Summary

• Spectral break energies generally correlate with with Q/M, including those for protons, with Q/M indices ≈1, on average.

• There are now theoretical predictions of how spectral breaks depend on Q/M and energy. They suggest that we should investigate more complex functions than $E^{-\gamma}exp(-E/Eo)$

• By studying the location and systematics of spectral breaks we can hope to understand:

- Acceleration processes
- Transport in the interplanetary medium
- The charge states of SEPs
- How to predict the conditions under which SEP events of space weather concern occur (e.g., hard spectra at high energies).