The He II 304 A Line Wings and Charge Exchange

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Low-energy cosmic rays

- Accelerated ions couple poorly to radiation
  - proton bremsstrahlung is reduced by m_e/m_p
  - ditto synchrotron radiation etc.
  - γ-ray cross-sections have energy thresholds of order 10 MeV
- Such particles nevertheless can have significant energy and momentum content
- Charge-exchange reactions might reveal them (Orrall & Zirker 1976) via Ly-α wings

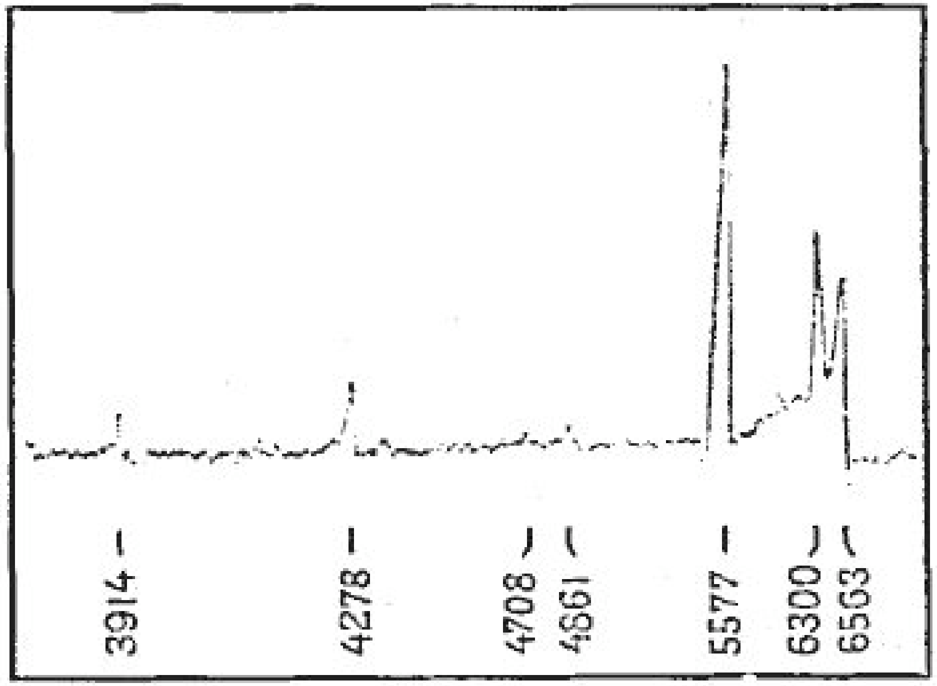
Charge-exchange reactions

- Charge-exchange reactions in astrophysics have two main channels

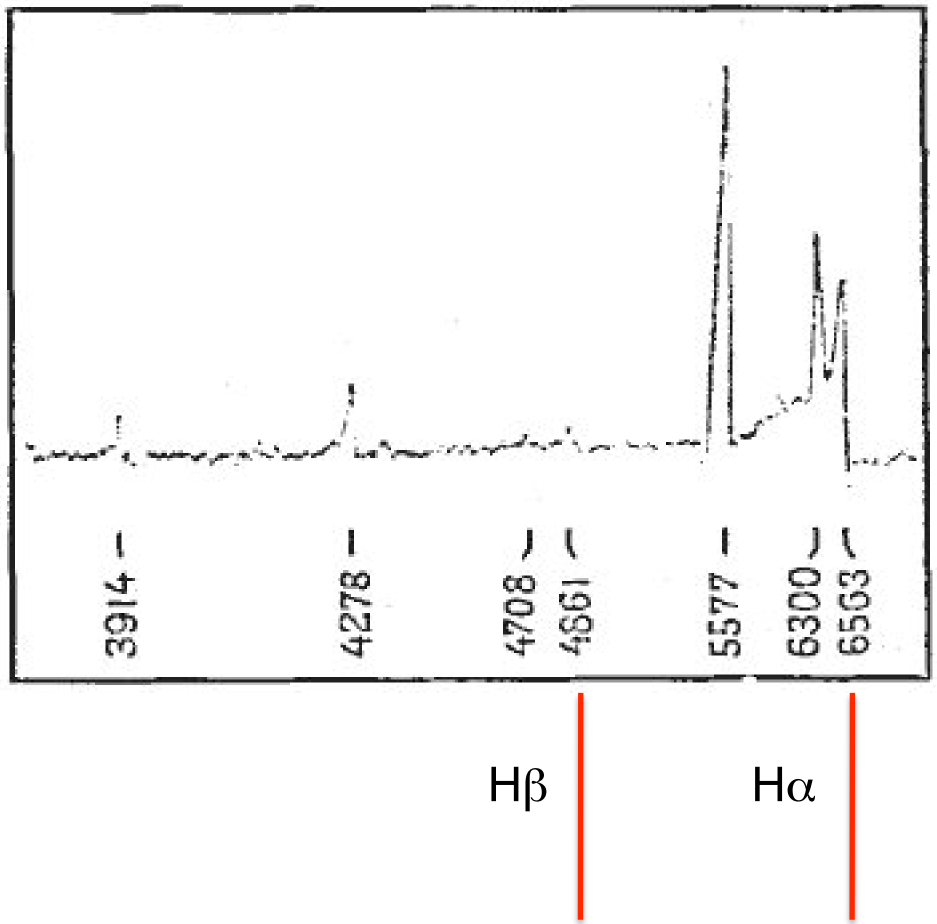
  - Radiative decay (Aurora, comets…)

  - Energetic neutral atoms (Ring current, heliopause, solar flares…)
- The ENA observations of solar flares (Mewaldt et al. 2009) reflect 2-5 MeV primary protons
- Here I discuss radiative-decay emission from comparable α-particles

Discovery?

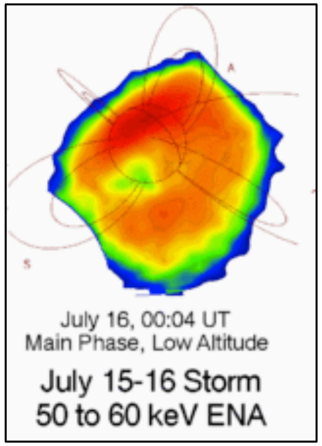


Discovery?

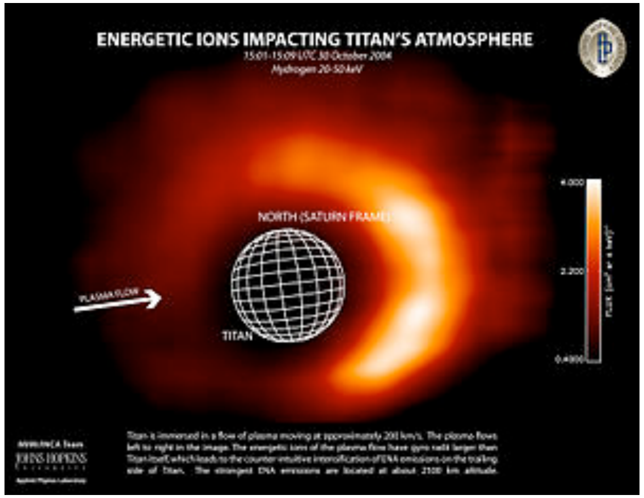


Vegard, 1939

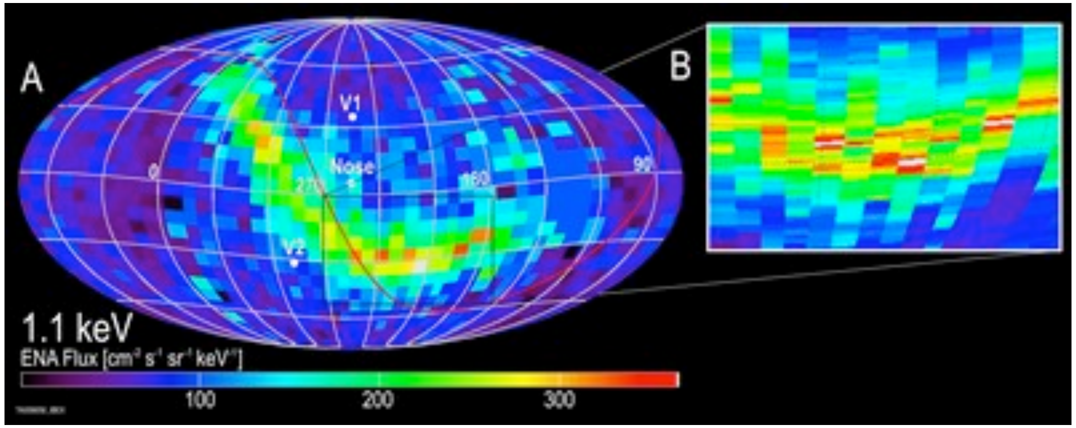
Energetic Neutral Atoms in the Heliosphere



Auroral substorm



Titan

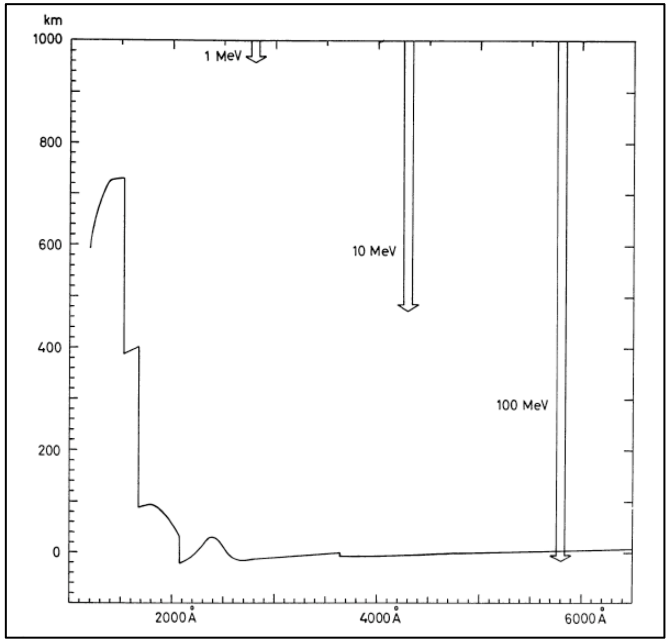


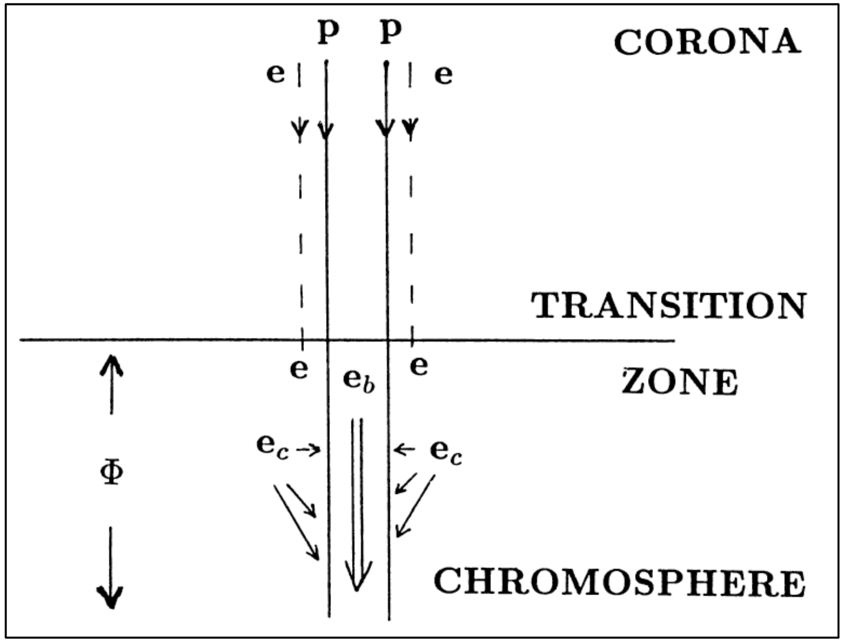
Heliopause

Charge-exchange physics

- The relatively abundant He-like and H-like states of the CNO elements give a resonant boost for charge exchange in the vicinity of 1 MeV
- At some level, we should therefore see the He II 304 Å and H I 1216 Å line wings, and directly remote-sense the accelerated particles at energies *below the γ-ray production thresholds*
- Kahler & Ragot (2008, 2009) have discussed related remote-sensing ideas
- The Mewaldt et al. (2009) observation of ENAs confirms the basic physical idea for charge-exchange physics

Particle precipitation in flares



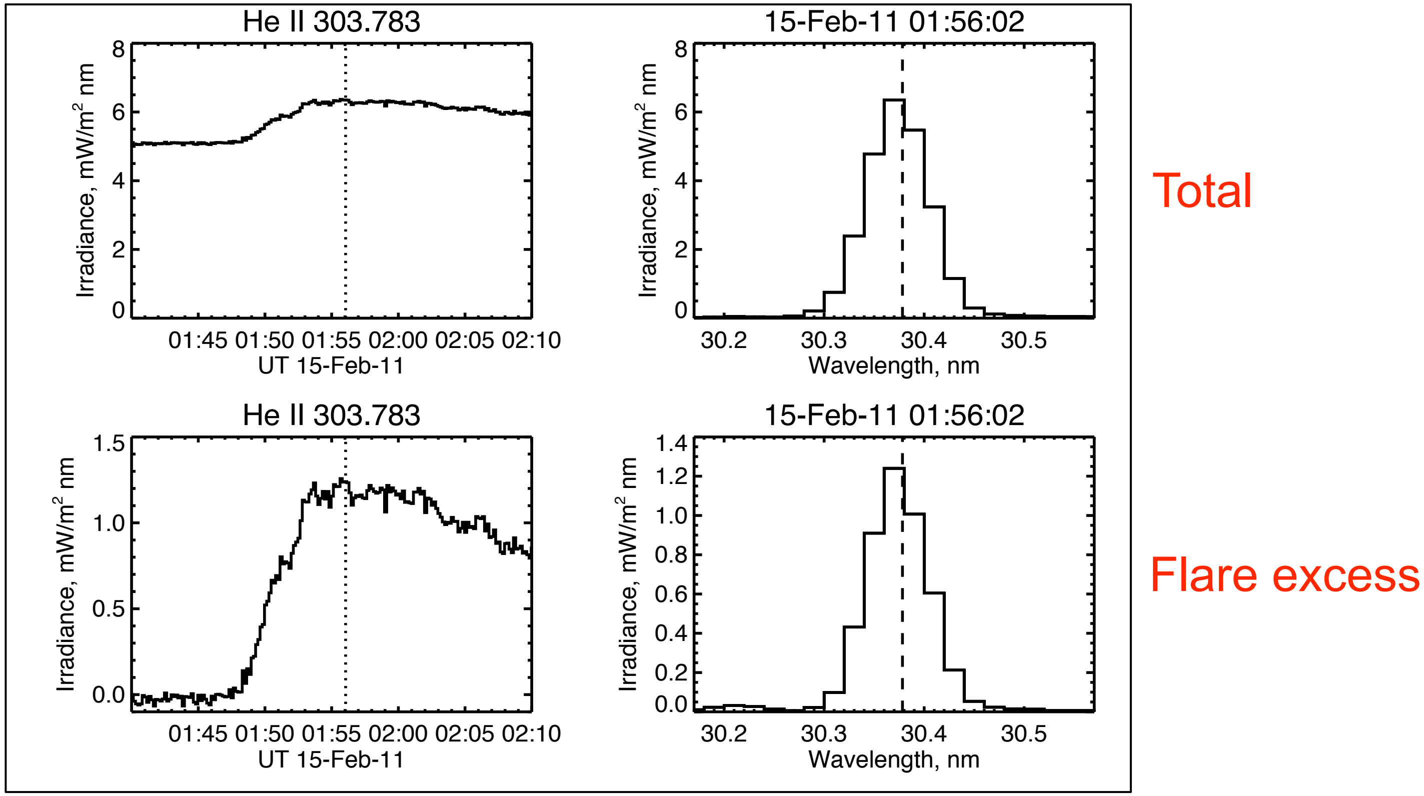


Plot from Svestka (1970) showing the height of optical depth unity in the solar atmosphere, in comparison with proton range

Plot from Simnett & Haines (1990), suggesting electrodynamic effects in flare footpoint sources excited by ion flows

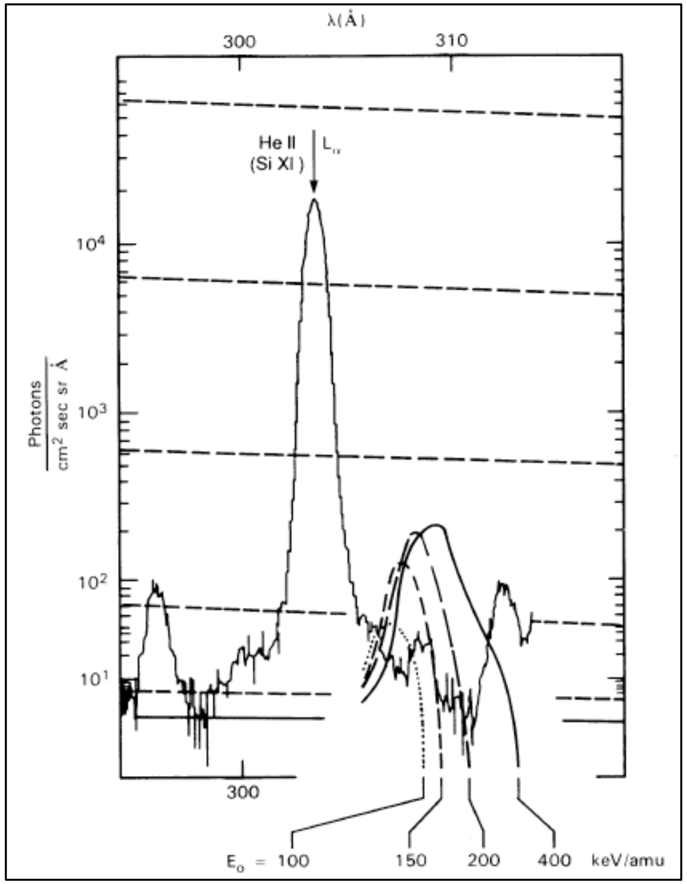
The acceleration of heavy particles in the corona, either as ions or as a neutral (e.g., MHD) flow, should lead to interactions in the partially ionized chromospheric layers

EVE line profiles

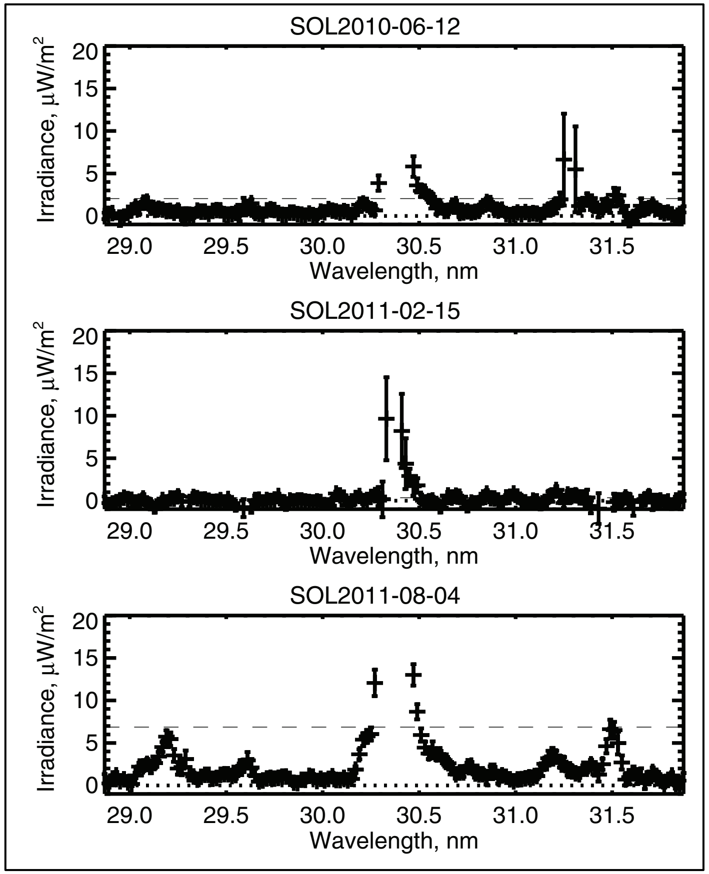


The EVE 304 Å line time series (left) and line profile (right) for SOL2011-02-15. The lower figures show the flare excess light curve and profile. This line has both an impulsive-phase and a gradual-phase component.

Alpha particles in the chromosphere



Prediction from Peter et al. (1990) for a weak particle beam (10^6 erg/cm^2 sec)



EVE observations from Hudson et al. (2012) for X-class flares with strong beams (>10^{10} erg/cm^2 sec?). Dashed lines at 1% peak of line in flare excess, impulsive phase

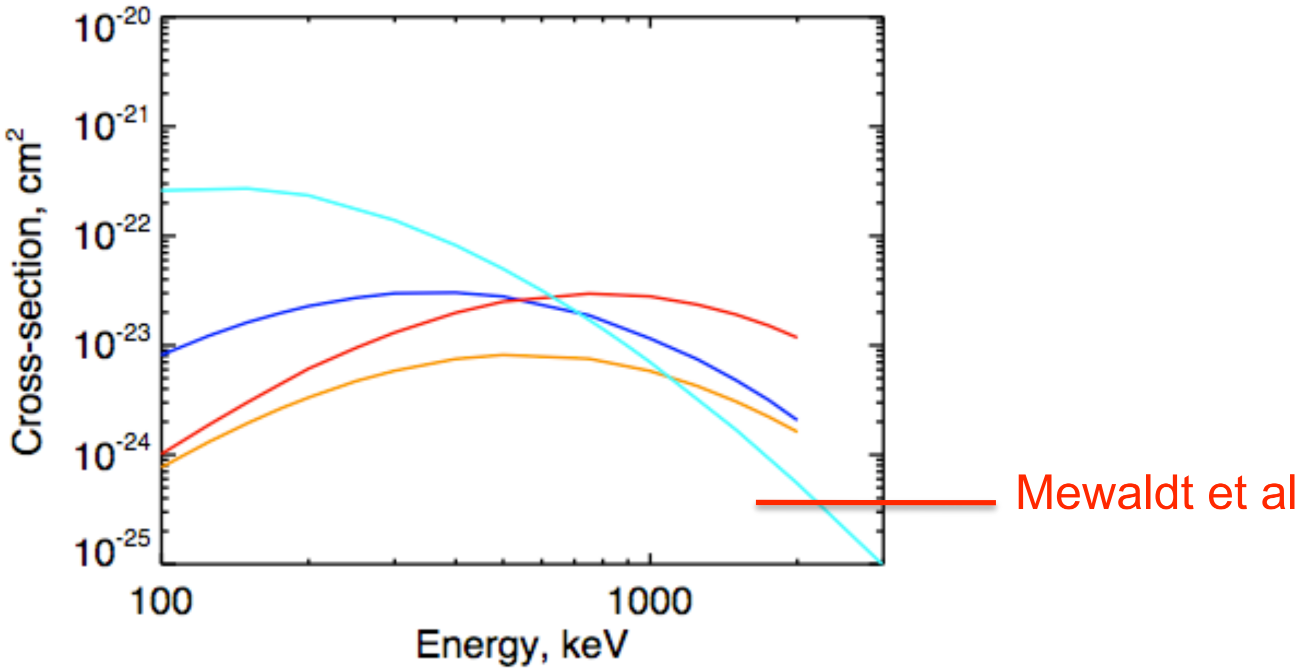
Conclusions for chromosphere

- The signature of the charge-exchange reaction leading to He II Ly-α line (304 Å) – a red-wing excess – is systematically not present in major flares
- This is a surprise, given the presence of strong γ-ray emission from such flares; we know that the particles are there and that they interact in a thick target.
- The theory involves several strong assumptions, and needs to be re-done more realistically
- Future imaging spectroscopy will be much more sensitive than EVE, and the Orrall-Zirker effect must be found. We should not be pessimistic about this!

Alpha particles in the solar wind

- The same charge-exchange mechanism will produce a signature from the point of acceleration, e.g., in a CME-driven shock
- Mewaldt et al. (2009) have clearly detected few-MeV neutral atoms (ENAs) from a flare – related physics
- The detection of broadened He II emission should pinpoint the acceleration site and determine the low-energy particle distribution function (~1 MeV/nucleon)

Cross-sections



Cross-sections for charge exchange on He I (pale blue), O VI (red), N V (gold), and C IV (dark blue), weighted according to Mazzotta et al. ionization equilibria at a “freezing-in” temperature of 1.5 MK, for coronal abundances. CNO theory from Kuang, 1992 (ground state only), and He from Mancev, 2003. The peak resonant energy increases monotonically with Z. The cross-sections are small, but the α particles may be numerous

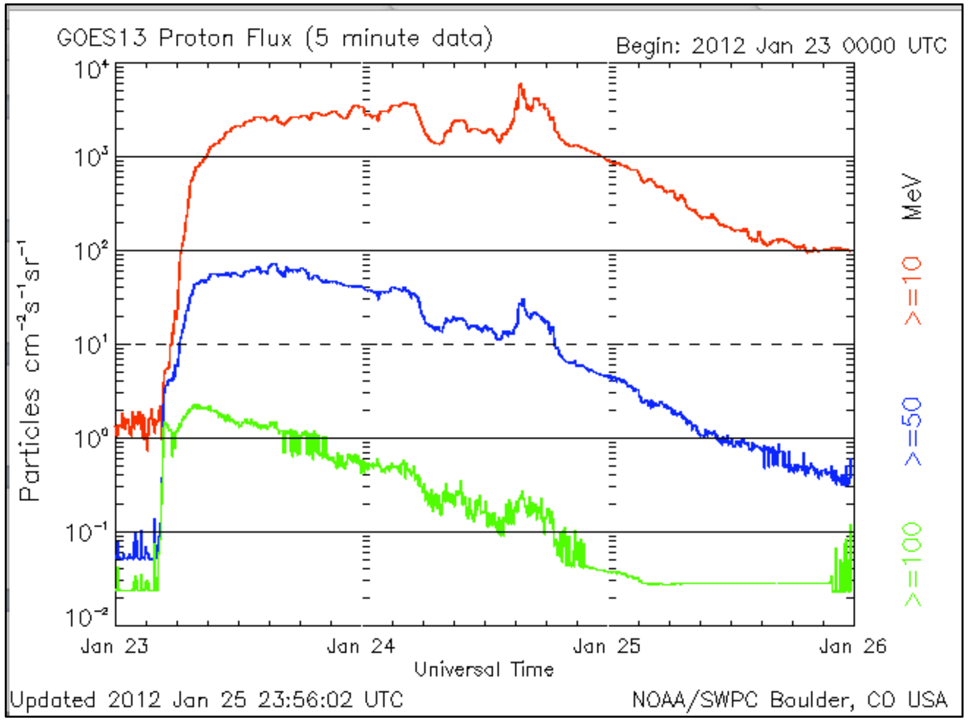
“Theory”

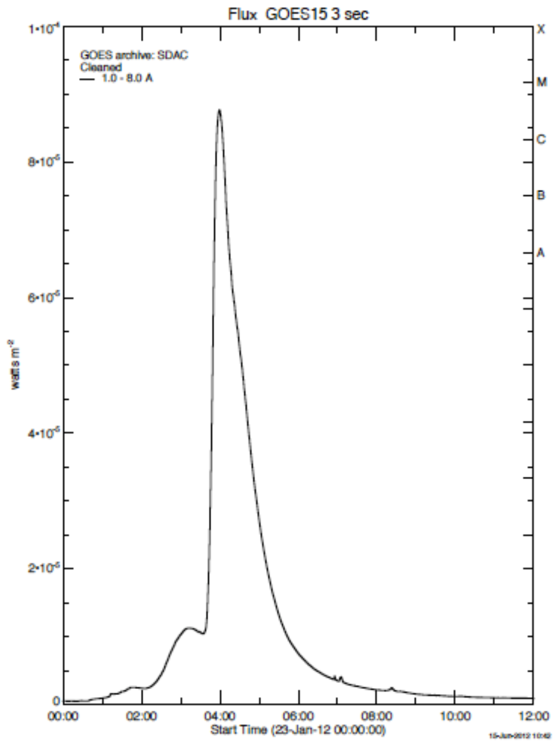
- Cross-section $\sigma \sim 10^{-22}$ cm^2
- Column density $\xi \sim 10^{17}$ cm^{-2}
- α particle number N $\sim 10^{35}$

Photon fluence @ 1 AU $\sim N \, \xi \, \sigma \, / \, 4 \, \pi \, AU^2$

$\sim 10^3$ photons

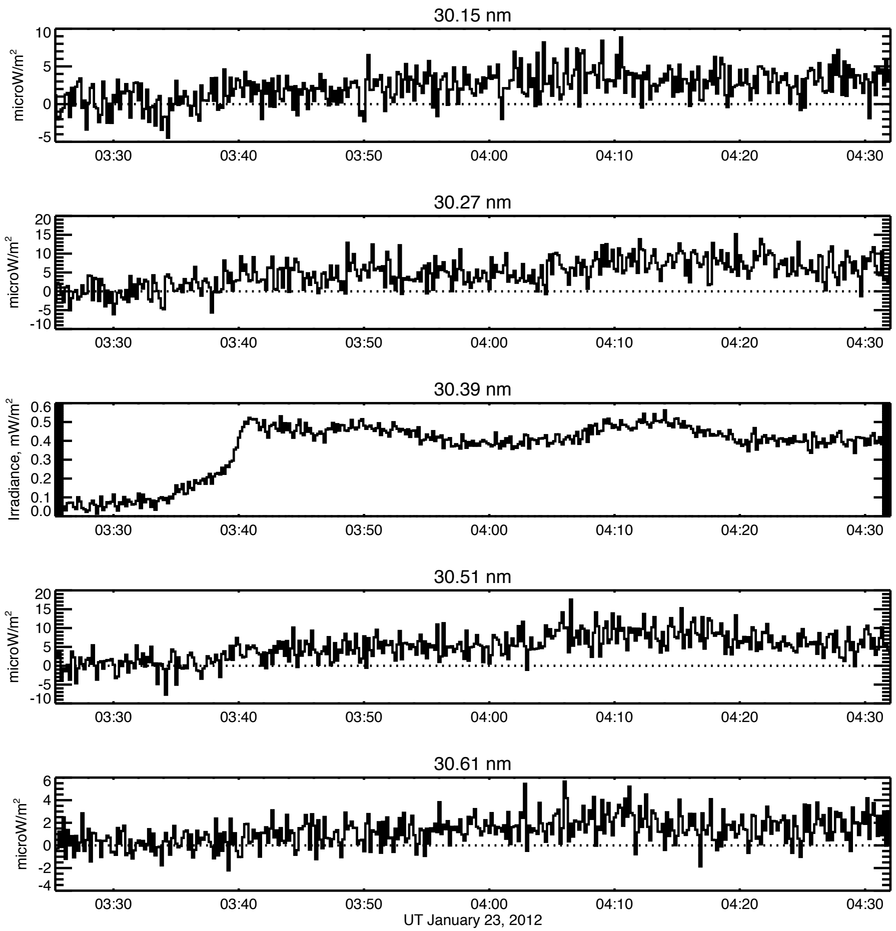
An EVE search - I





This is the most energetic particle event of the current solar cycle and of the EVE database. The parent flare is SOL2012-01-23 (M8.7, N28W21). In this position, a shock wave vertically above the flare site should be in the EVE field of view.

An EVE search - II



Time series of EVE spectral irradiances at line center (center panel) and at +- 1.2, 2.4 Å in the blue and red wings (the flare excess). These correspond to maximum Doppler shifts for 1-2 MeV/nucleon in the line of sight.

There is a weak signature of line broadening, but it is roughly symmetrical and does not coincide in time with the expected arrival the shock at a few $R_{\odot}$ (e.g.,Kahler, 1994). Instrumental line broadening in EVE needs to be considered too. This is a possible detection of the effect, but is not certain.

Conclusions for corona

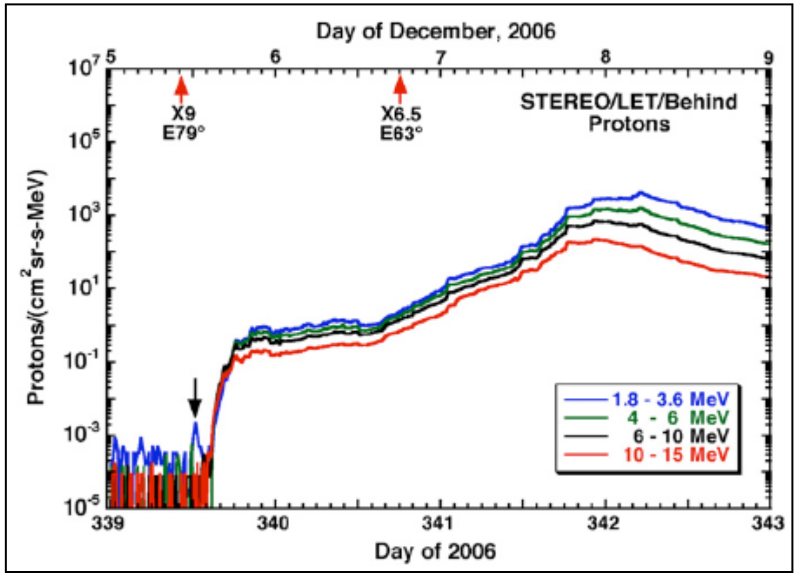
- We do not see a (strong) signature of charge exchange in the most energetic SEP event to date.
- For the cross-sections shown above, and for coronal column densities of 10^{17} cm^{-2}, assuming no trapping in the shock region, it is unlikely theoretically that the detected signal is from charge exchange.
- An imaging instrument with spectral resolution $\lambda/\Delta\lambda \sim 3000$ at 304 Å, observing as a coronagraph, should have sufficient sensitivity to see the charge-exchange effects and we strongly recommend its development.

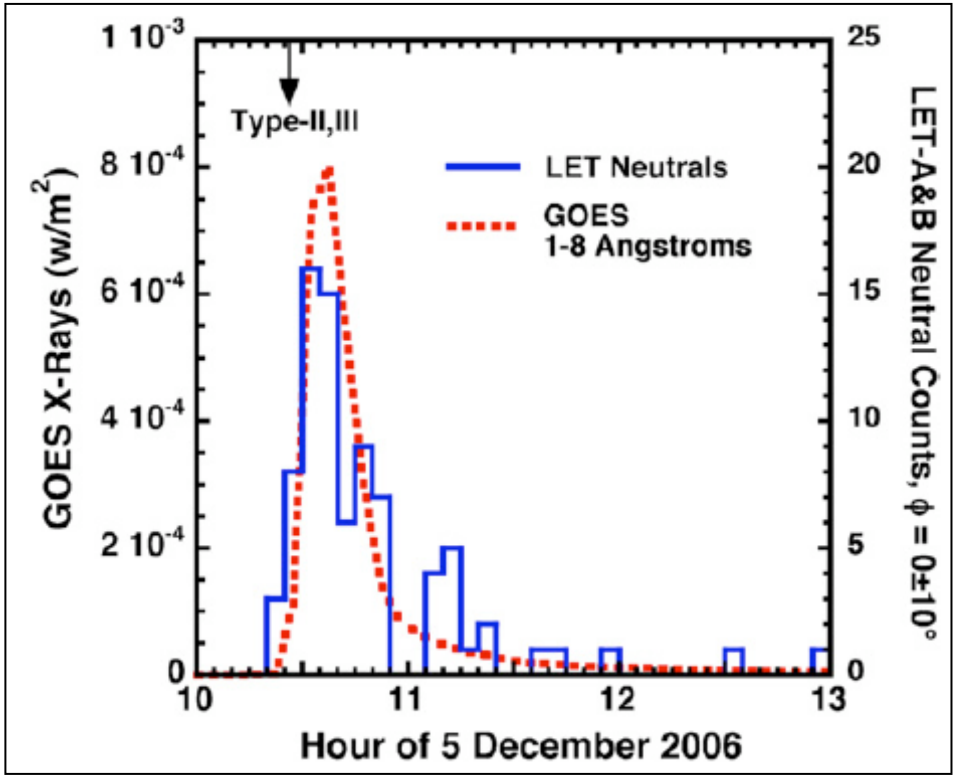
Literature

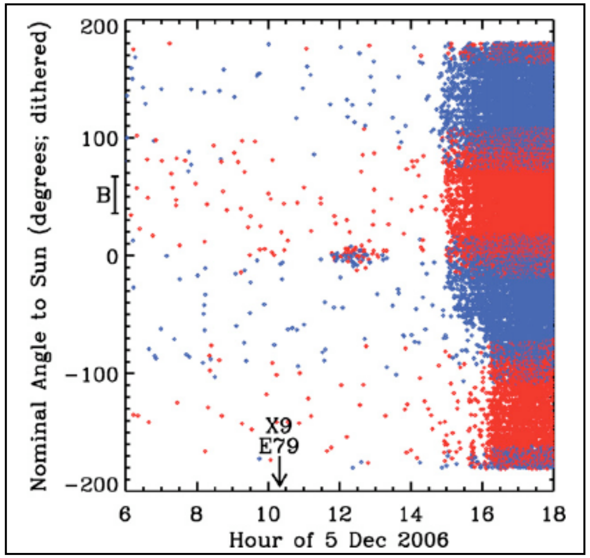
- Orrall & Zirker (Ap J 208, 816, 1976) introduced the idea of charge-exchange reaction leading to hydrogen Ly-α red wing enhancement
- Canfield & Chang (ApJ 295, 275, 1985) extended of Orrall-Zirker idea to intense beams
- Peter et al. (ApJ 351, 317, 1990) followed up the idea for the He II Ly-α line (304 Å)
- Woodgate et al. (Ap J 397, 95, 1992) possibly detected the H Ly-α red wing in a stellar flare
- Brosius (ApJ 555, 435, 2001) found no evidence for an H Ly-α red wing via CDS observations of a C-class flare
- Hudson et al. (ApJ 752, 84, 2012) used EVE observations of many X-class flares and did not detect the Orrall-Zirker effect via the He II Ly-α line (304 Å) red wing

More slides

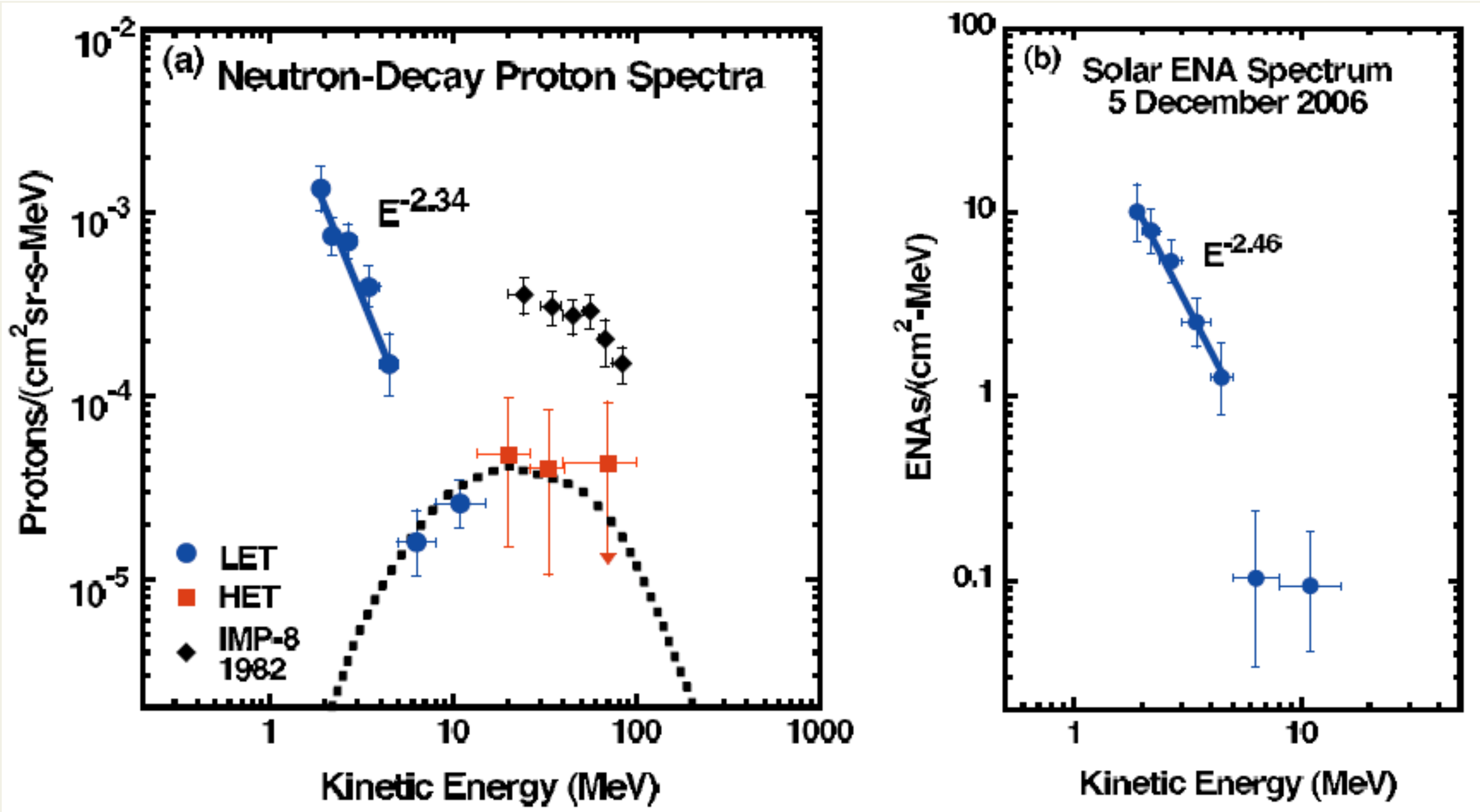
Mewaldt et al 2009





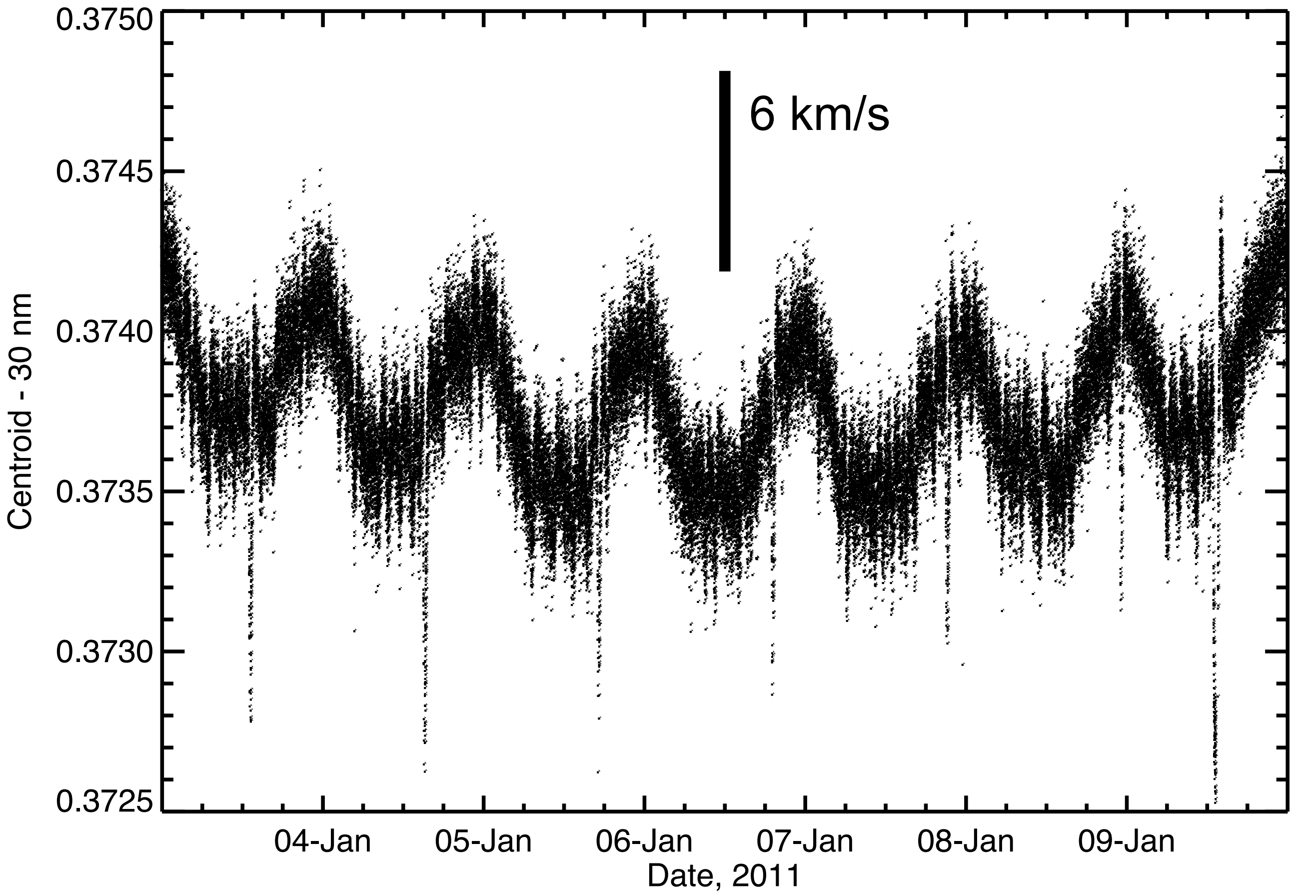


Mewaldt et al. Figures (II)

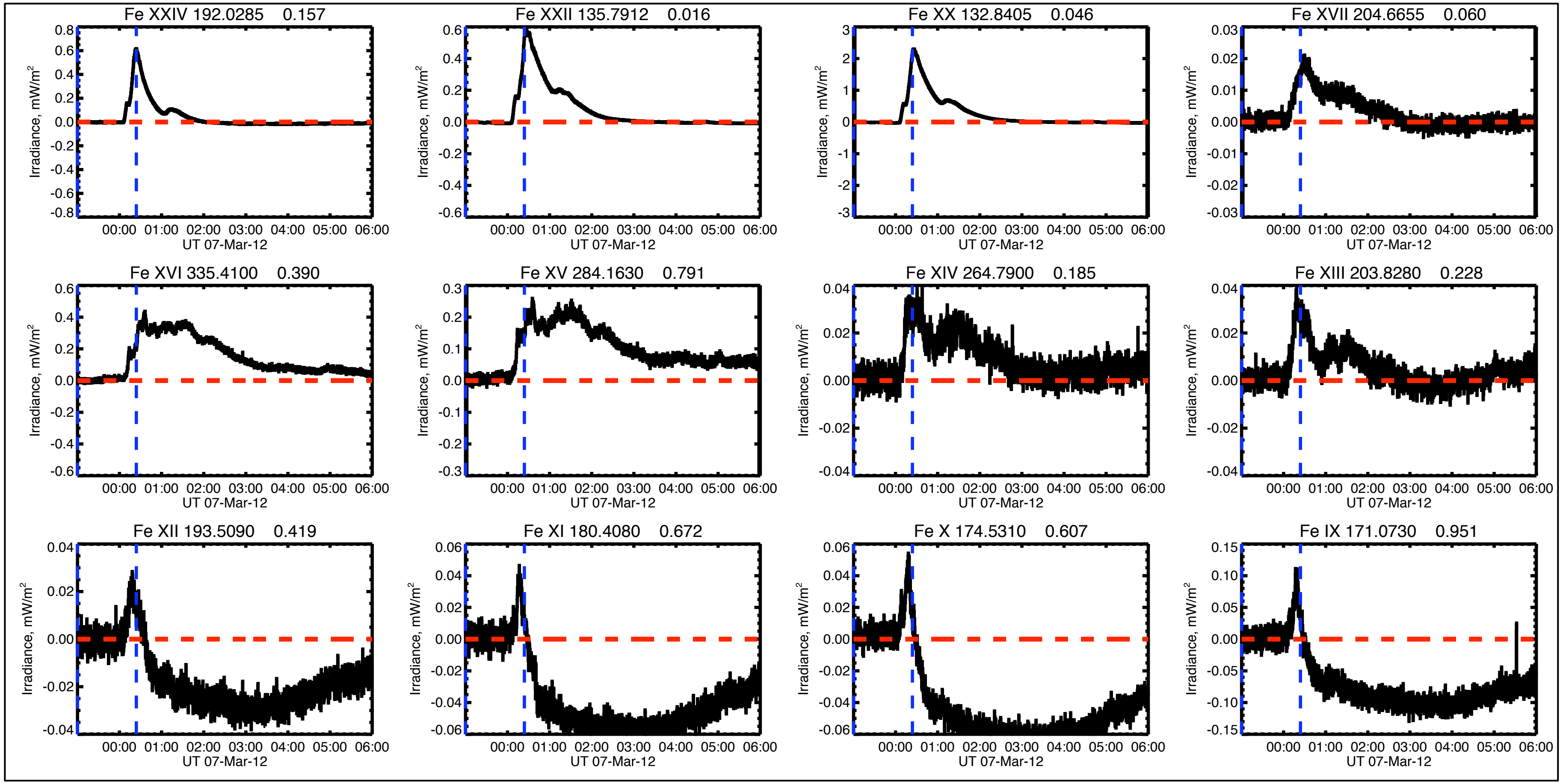


- The HET counts resemble those expected from neutron decay
- The LET spectrum appears to steepen > 5 MeV

EVE Doppler sensitivity



“Fe Cascade”



SOL2012-03-07 (X5.3)