Energetic Neutral Atoms from Solar Flares

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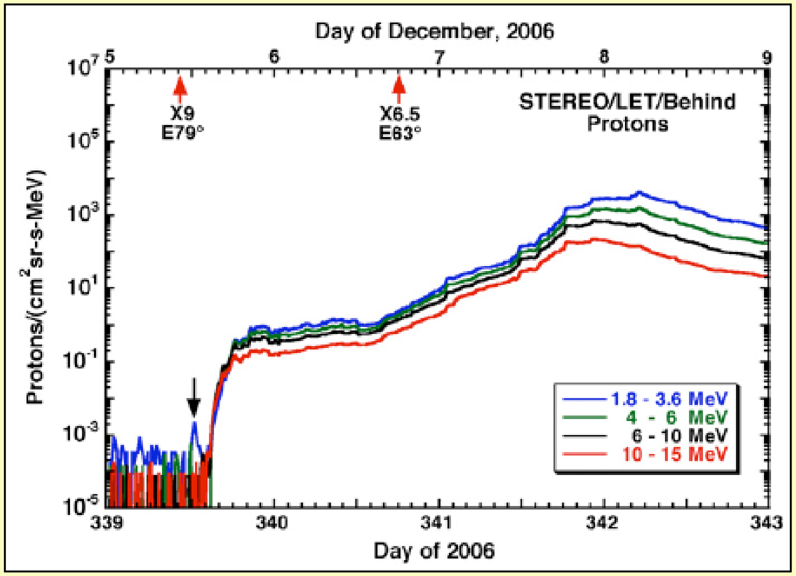
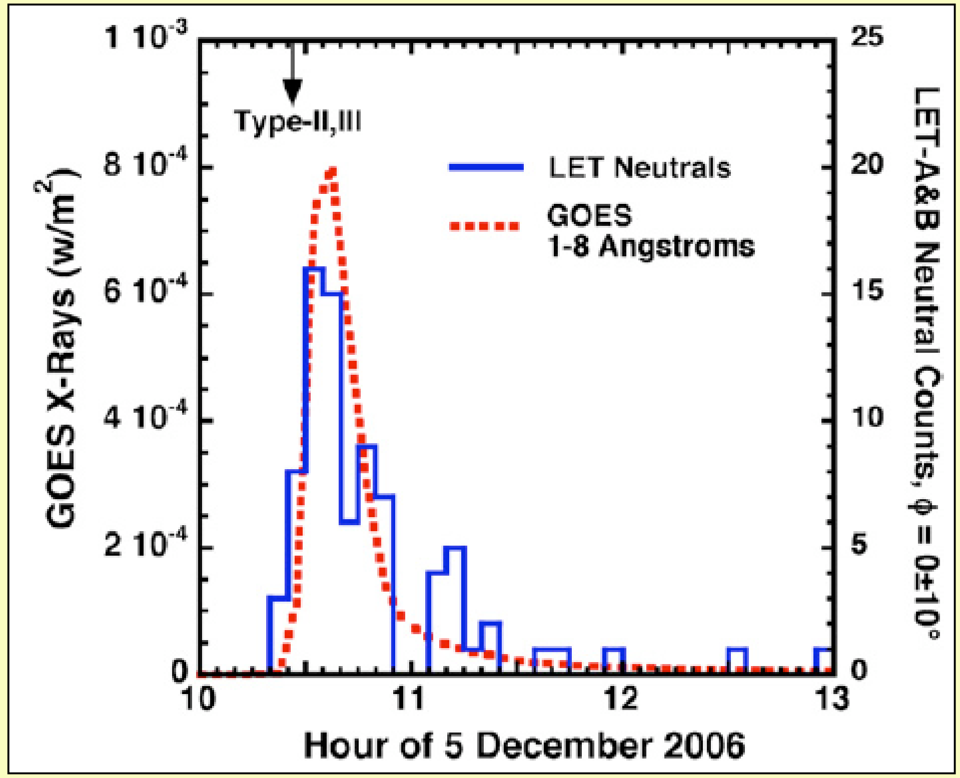
Overview

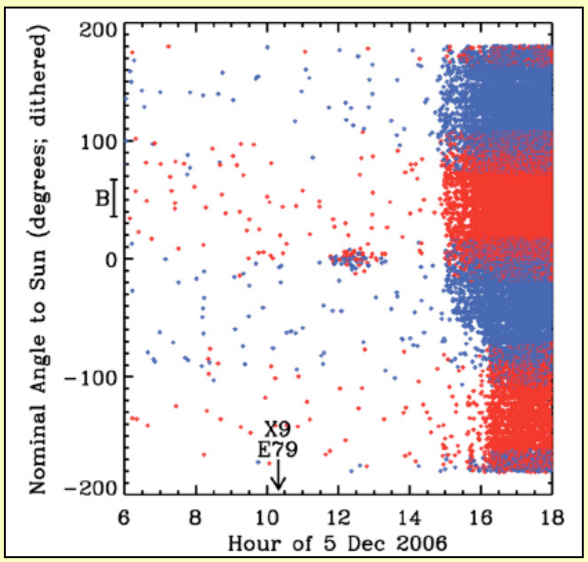
- Mewaldt et al. (2009)* have observed ENAs from a flare for the first time.
- This was unexpected but highly significant - it reveals a virtually unknown parameter space (flare-associated protons below a few MeV).
- The flare ENAs could come from the CME shock acceleration, or from the flare γ-ray sources.
- We are studying the ENA sources by Monte Carlo techniques.

*ApJ 693, L11 (2009)

Mewaldt et al. Figures







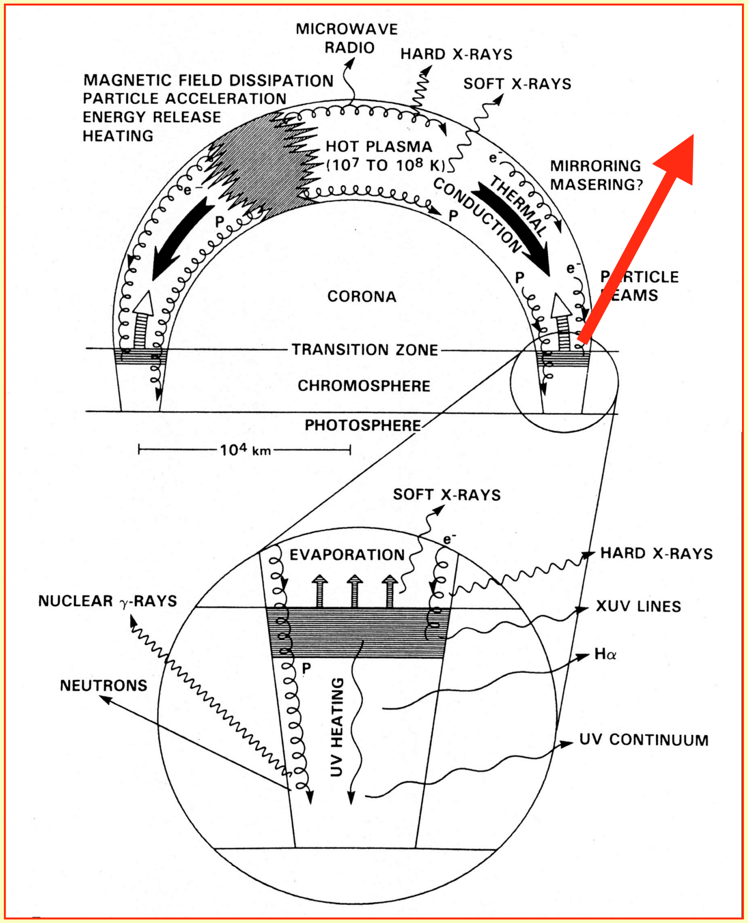
- The STEREO observations provide both spatial and temporal signatures that clearly identify the particles as hydrogen
- The injection times closely match the GOES light curve of the flare

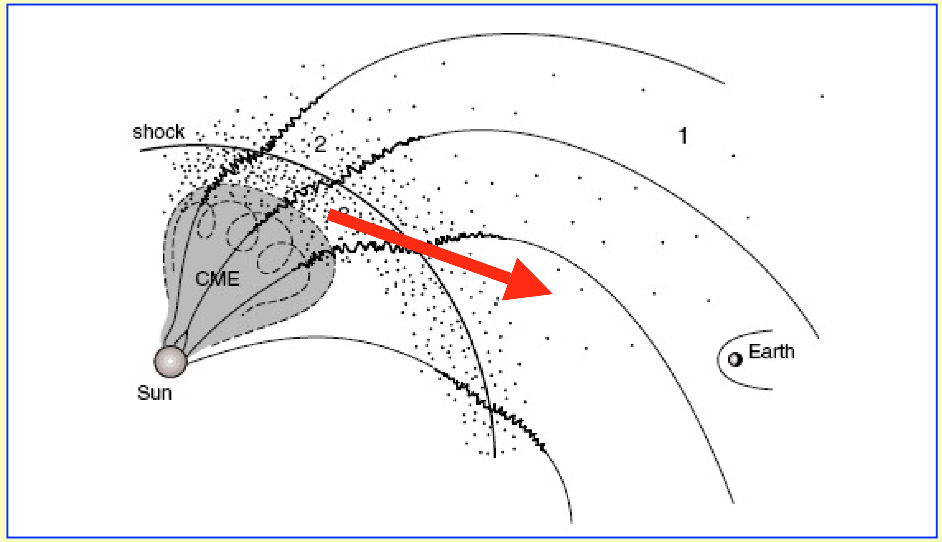
How many particles?

- Mewaldt et al. estimate a total of 1.8×10^{28} ENA particles (hydrogen atoms) assuming isotropic emission in a hemisphere
- RHESSI γ-ray observations imply a total of 1.3×10^{31} protons above 30 MeV
- Assuming a spectral index of 3.5, this implies a total of 2×10^{34} protons above 1.6 MeV

The escape efficiency of 2 MeV ENAs may be of order 10^{-6}

Whence flare ENAs?





Neutralization and re-ionization on open field lines: Mikic & Lee, 2006

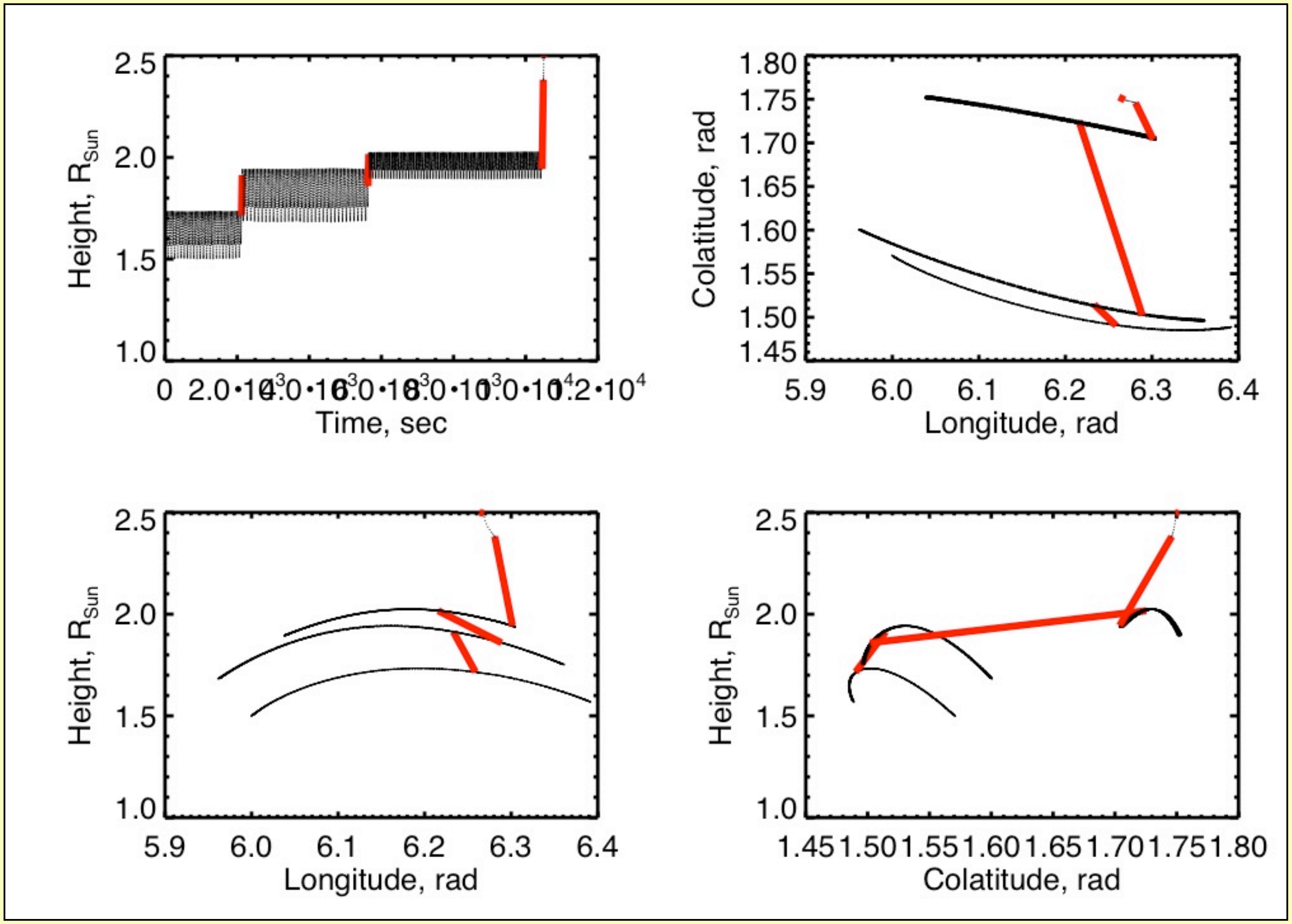
Neutralization and re-ionization on closed field lines: Dennis & Schwartz, 1989

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

Monte Carlo simulations

- Neutral hydrogen and protons are alternative states of the same particle. Can successive ionizations and neutralizations allow flare ENAs to originate from the flare γ-ray sources in the deep corona?
- If so, do the emergent ENAs retain any information about the spectrum, source structure, or time profile?
- Everything is very complicated, so we are trying to extract answers via Monte Carlo simulations embodying enough of the physics

Proton injected at 1.2 R_{sun} @ 2 MeV (example)



What do we want to learn from the Monte Carlo model?

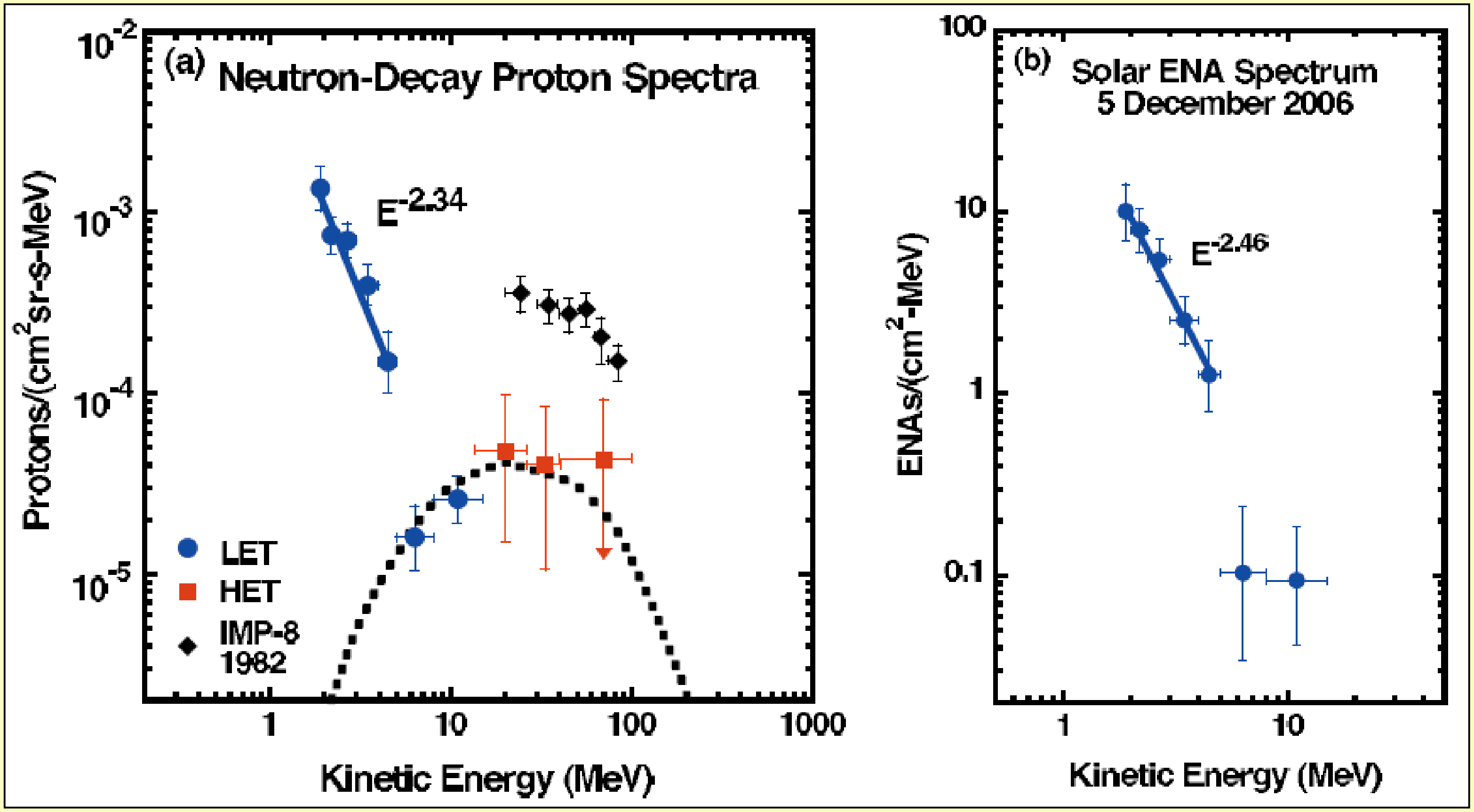
- The escape efficiency as a function of injection height and other parameters
- The spectrum of the escaping ENAs, ditto
- The angular distribution of the emerging ENAs
- The spatial structure of the apparent ENA source

Conclusions

- The Mewaldt et al. (2009) result is one of the most important for flare high-energy physics in this century, since it opens a vast new parameter space
- Interpretation is wide open at present. Our Monte Carlo model suggests that ENA escape from the flare γ-ray sources may be feasible, but it is preliminary work
- If the ENAs come from CME shock acceleration, we will need to revise our views of where this is happening

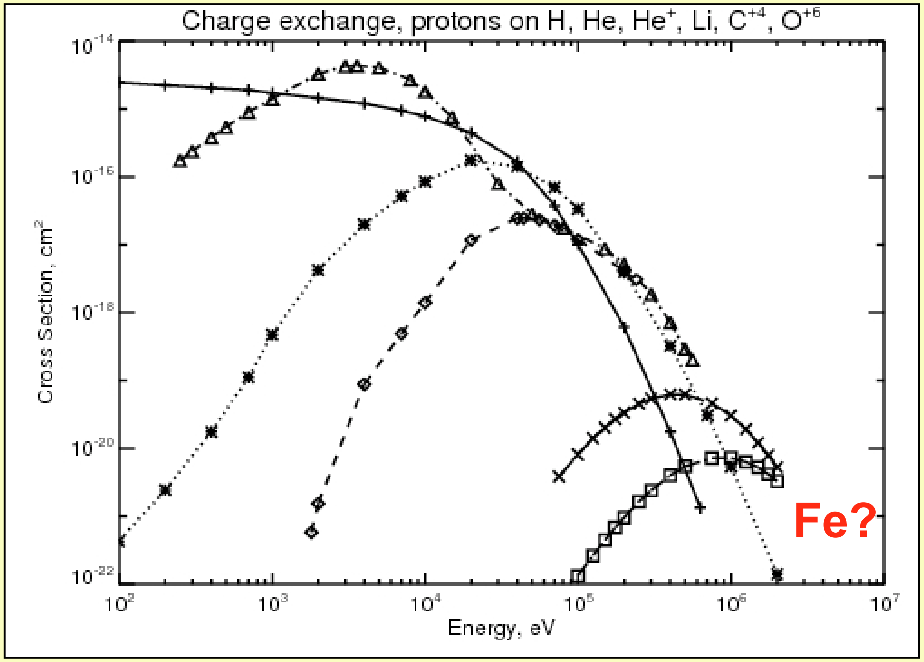
Backup slides

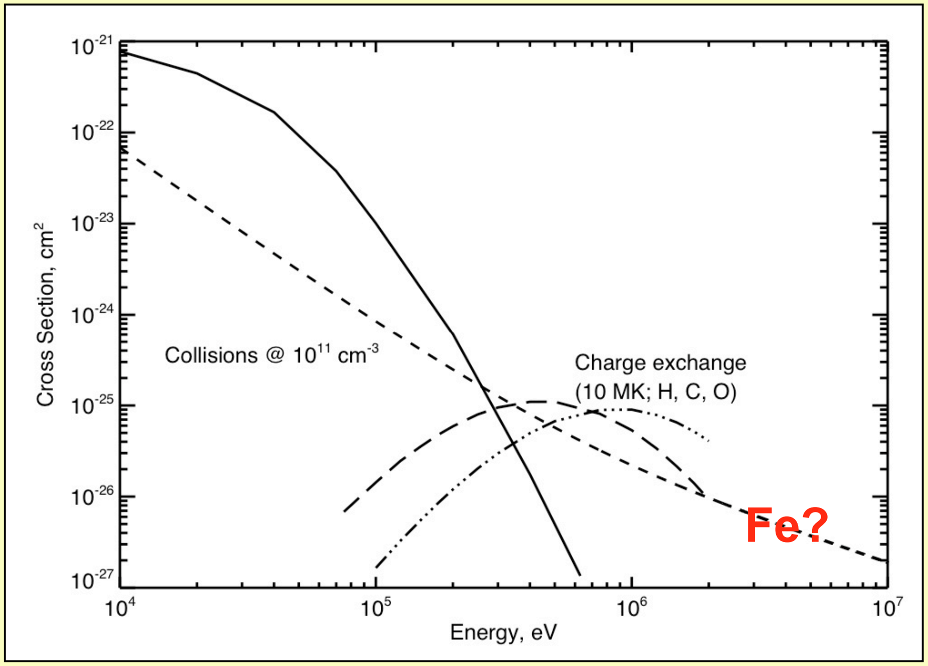
Mewaldt et al. Figures (II)



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

Some necessary physics



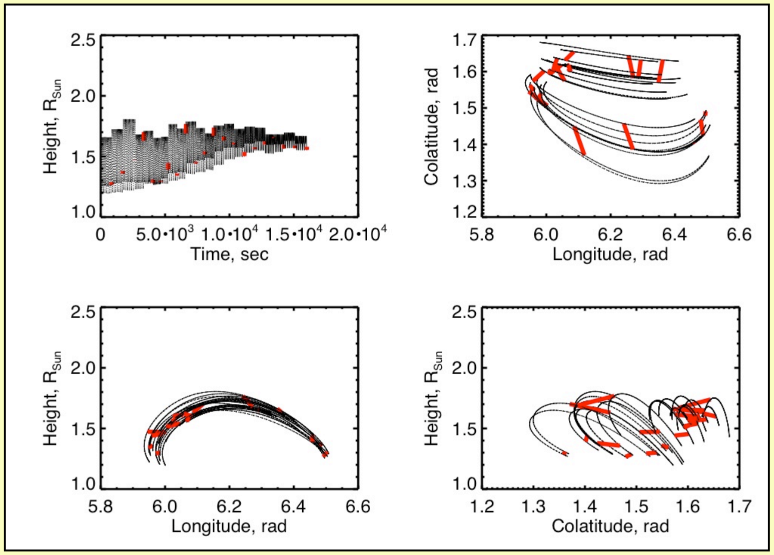


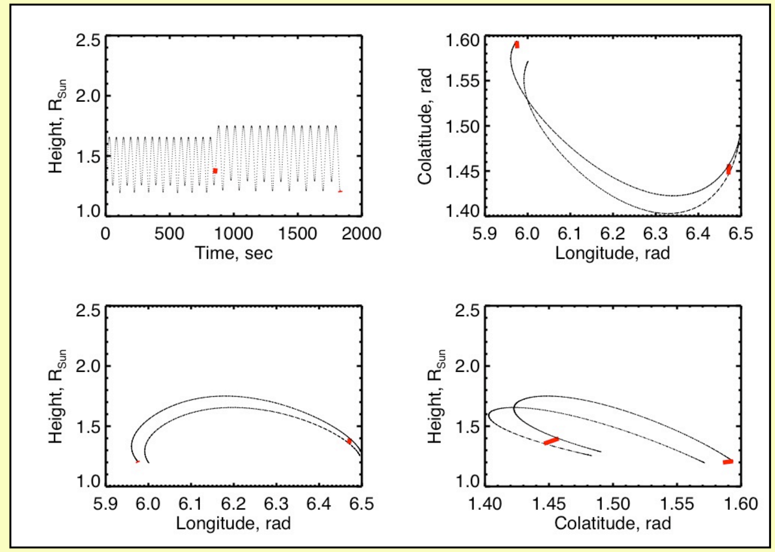
- Charge exchange cross-sections (H-like and He-like only)
- Charge exchange vs collisions
- Impact ionization $\sigma_i = 2.3 \times 10^{-17} E_p^{-0.897}$ cm^2 (Barghouty, 2000)

Notes on Monte Carlo model

- The calculation includes ion flight with RK4 tracing of the guiding center in a Schrijver-DeRosa PFSS model of the coronal field (Hudson et al., 2009)
- Ion dE/dx from Weaver & Westphal (2003); ion stripping from Barghouty (2000); charge-exchange on K-shell minor ions from Kuang (1992); ionization equilibrium from Mazzotta
- The plots show successive ion and neutral flights (red) for a few particles with different fates

Protons injected at 1.2 Rsun @ 2MeV (examples)





1. Energy decay
2. Footpoint ENA flight
3. Time out
4. Solar wind ENA flight