Solar energetic particles in space and EM signatures in the corona: spatial connection between the Sun and Earth

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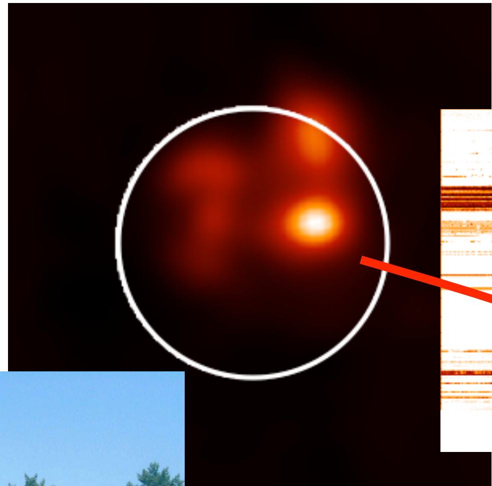
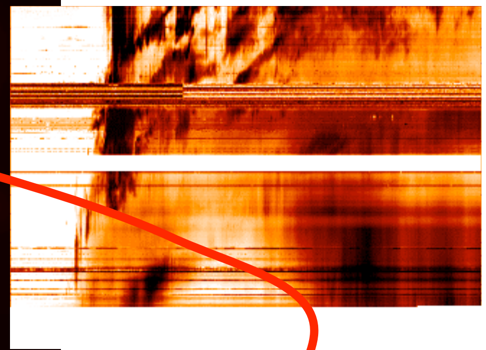
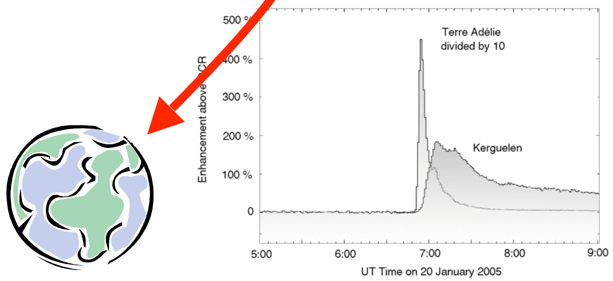


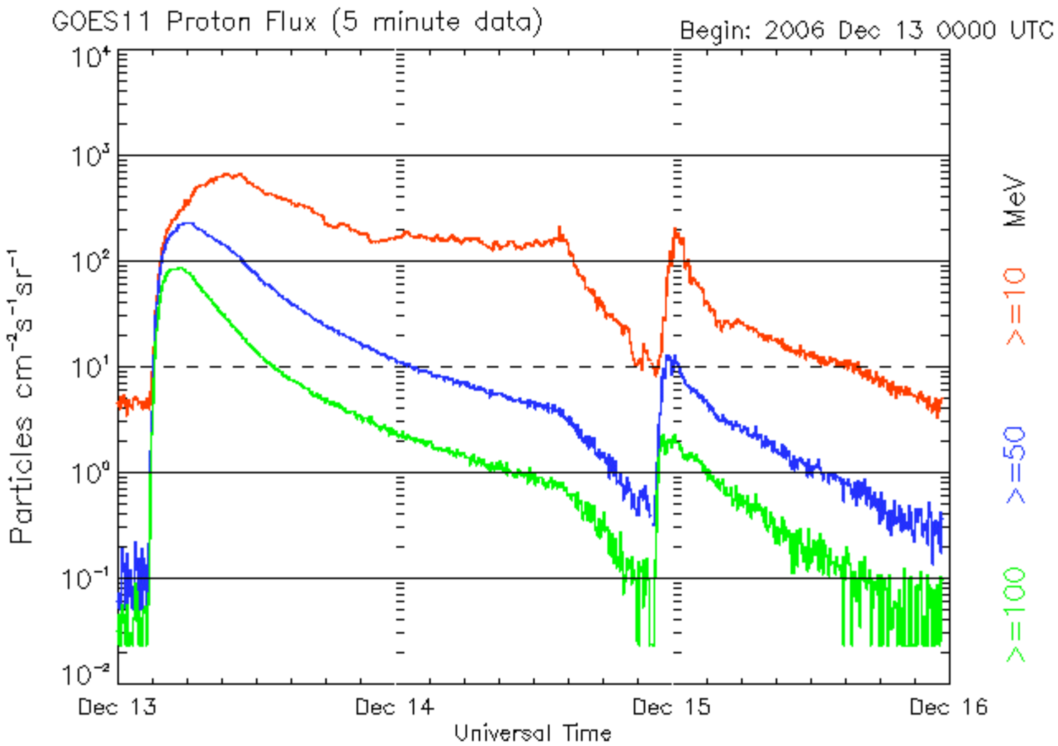




collaborators

G. Trottet, A. Klassen (Kiel), S. Krucker (Berkeley), G. Lointier (Orléans), S. Samwel (Helwan/Cairo)

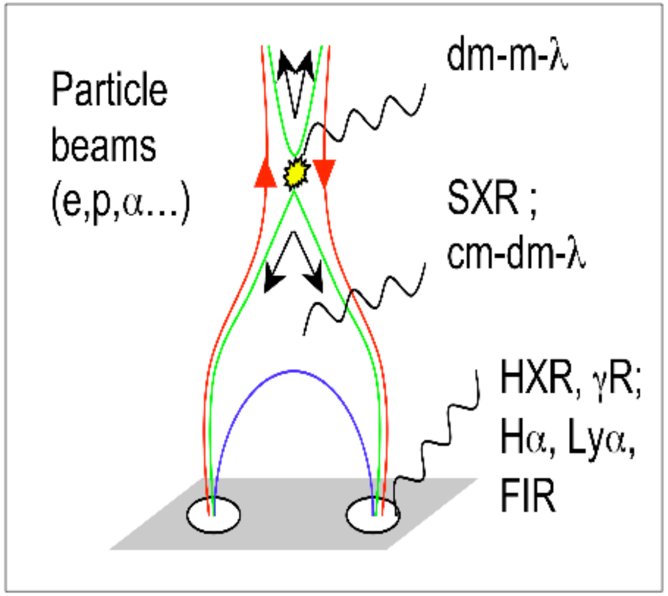
Flares, CMEs, and the acceleration of solar energetic particle (SEP) events



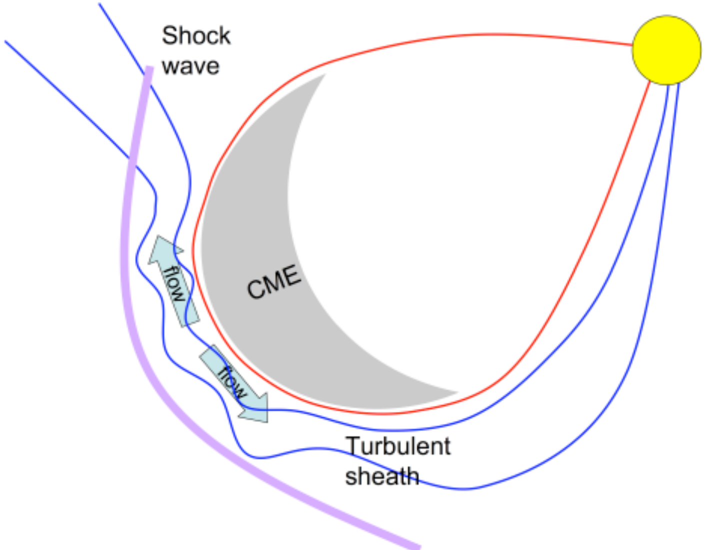
- Before the discovery of CMEs (1971-73), flares and filament eruptions were the only form of prominent transient activity. All other time-coincident activity (e.g. SEP events) was related to them.
- Since 1980s CMEs appeared as a new candidate particle accelerator, through the shock the fastest of them are expected to drive.

Solar energetic particle events: scenarios of acceleration

- “Flare acceleration”: SEP accelerated together with the particles radiating γR, HXR, radio; escape to open flux tubes towards IP space



after K.-L. Klein., Sol Ortb Workshop, Athens, ESA-SP

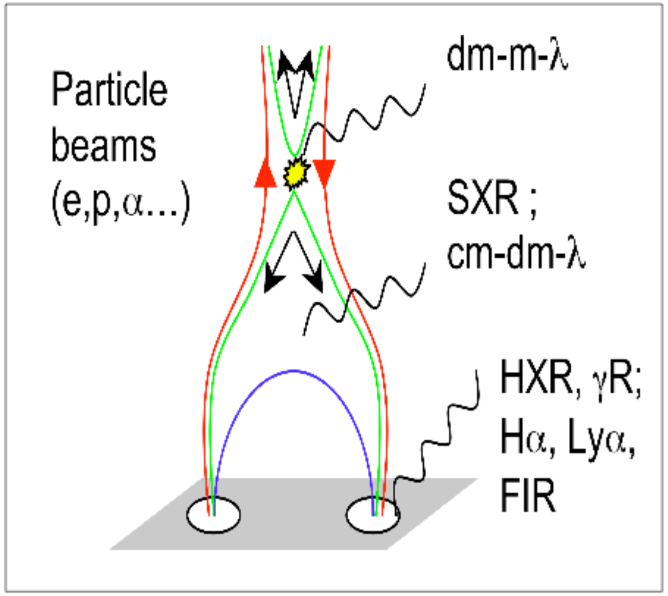


after Y. Liu et al., J. Geophys. Res., 111, A09108

- CME shock acceleration: SEP accelerated at the bow shocks of fast CMEs

Solar energetic particle events: scenarios of acceleration

- Major SEP events associated with both flares and CMEs.
- Complex interplay of acceleration (flare, CME) and propagation (evolving coronal structures) ⇒ no simple distinction between « flare accelerated » and « CME shock accelerated »



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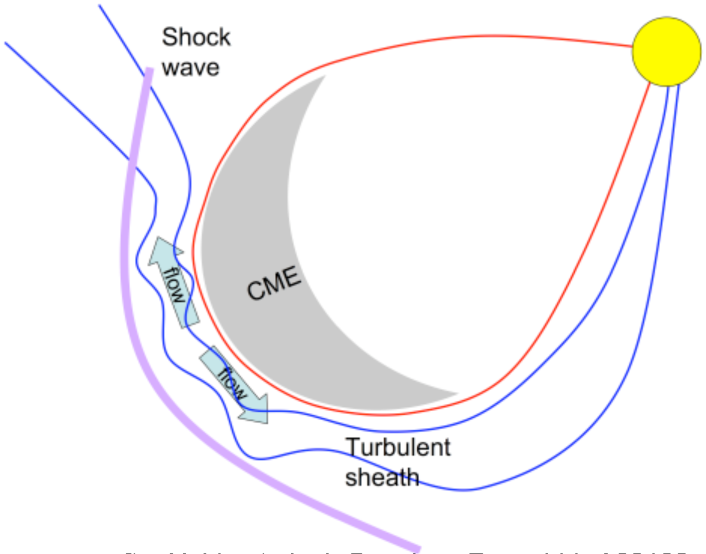

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- This contribution: Sun-Earth connection & coronal structures, simple SEP events

Strong SEP-less flares

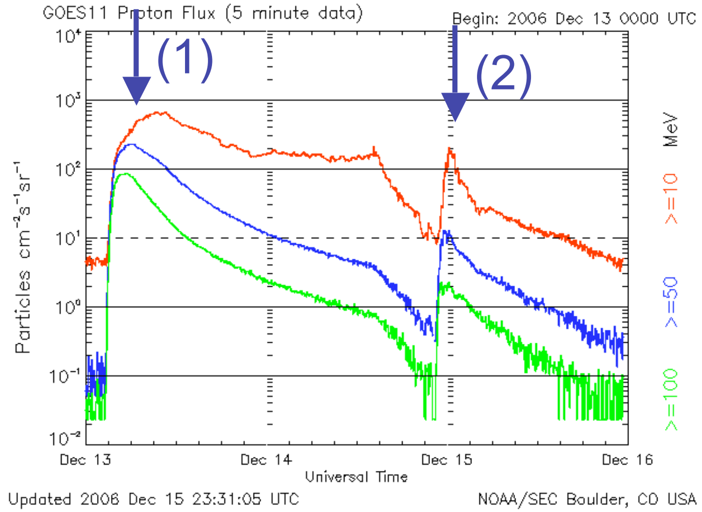
Magnetic confinement of flare-accelerated particles

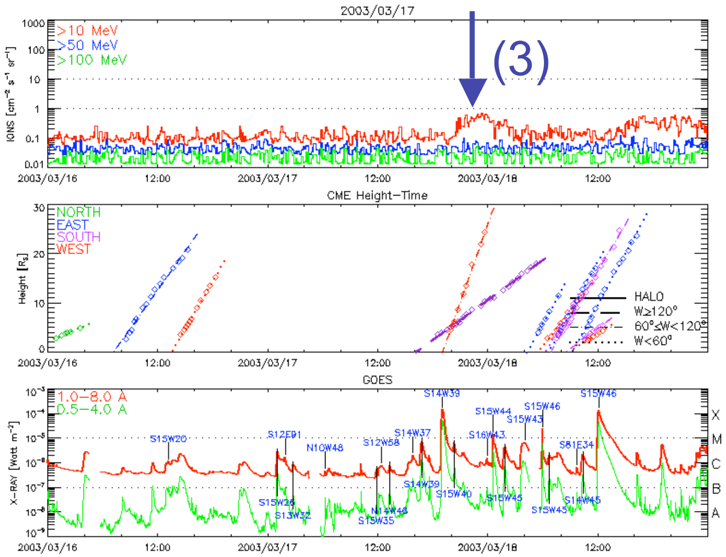
GOES X class flares in the western hemisphere and SEP events

Total of GOES X class flares
W 0°-90°, 1996-2006: 69

1) with NOAA SEP events: 21
2) where SEP missed by NOAA (threshold): 13
3) where SEP < 10 pfu: 10
4) without GOES SEP: 22
5) Uncertain SEP assoc.: 3

GOES (NOAA + Yashiro, CME catalog)





Why are there X class flares without SEP ?

- Intensity too weak ? No: proton intensity > 10 MeV expected from SXR properties (Garcia 2004): 4-34 pfu

- Poor magnetic connection ? No: W14°-90°, median W 48°

Why are there X class flares without SEP ?

- Intensity too weak ? No: proton intensity > 10 MeV expected from SXR properties (Garcia 2004): 4-34 pfu
- Poor magnetic connection ? No: W14°-90°, median W 48°
- Confinement of flare-accelerated particles ?
- Absence of a coronal shock wave ?

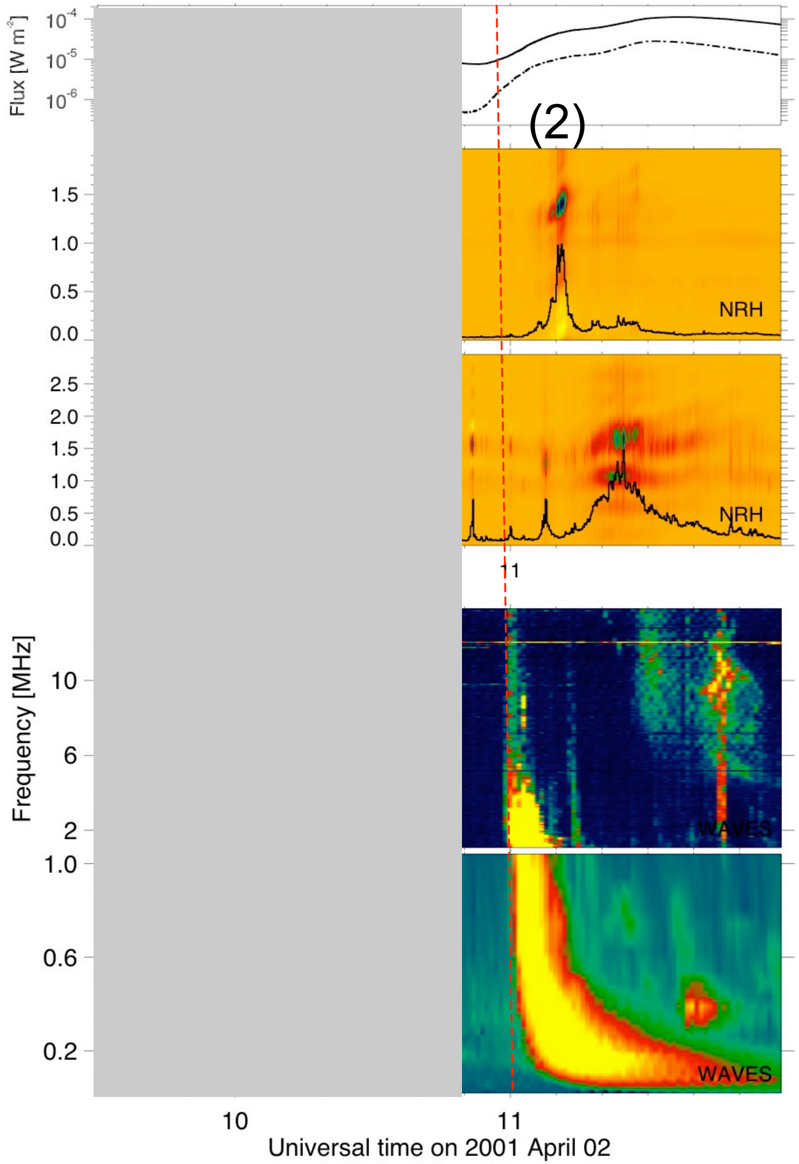
The case of magnetic confinement

Two X class flares 2001 Apr 02:

- The second with DH type III signalling escaping electrons (10 keV)
- with m-wave emission (moving IV; CME)
- with a moderate SEP event (4 pfu)

- The first without DH type III or m-wave radio bursts (besides noise storm, unrelated to the flare)
- without SEP event (<0.8 pfu)

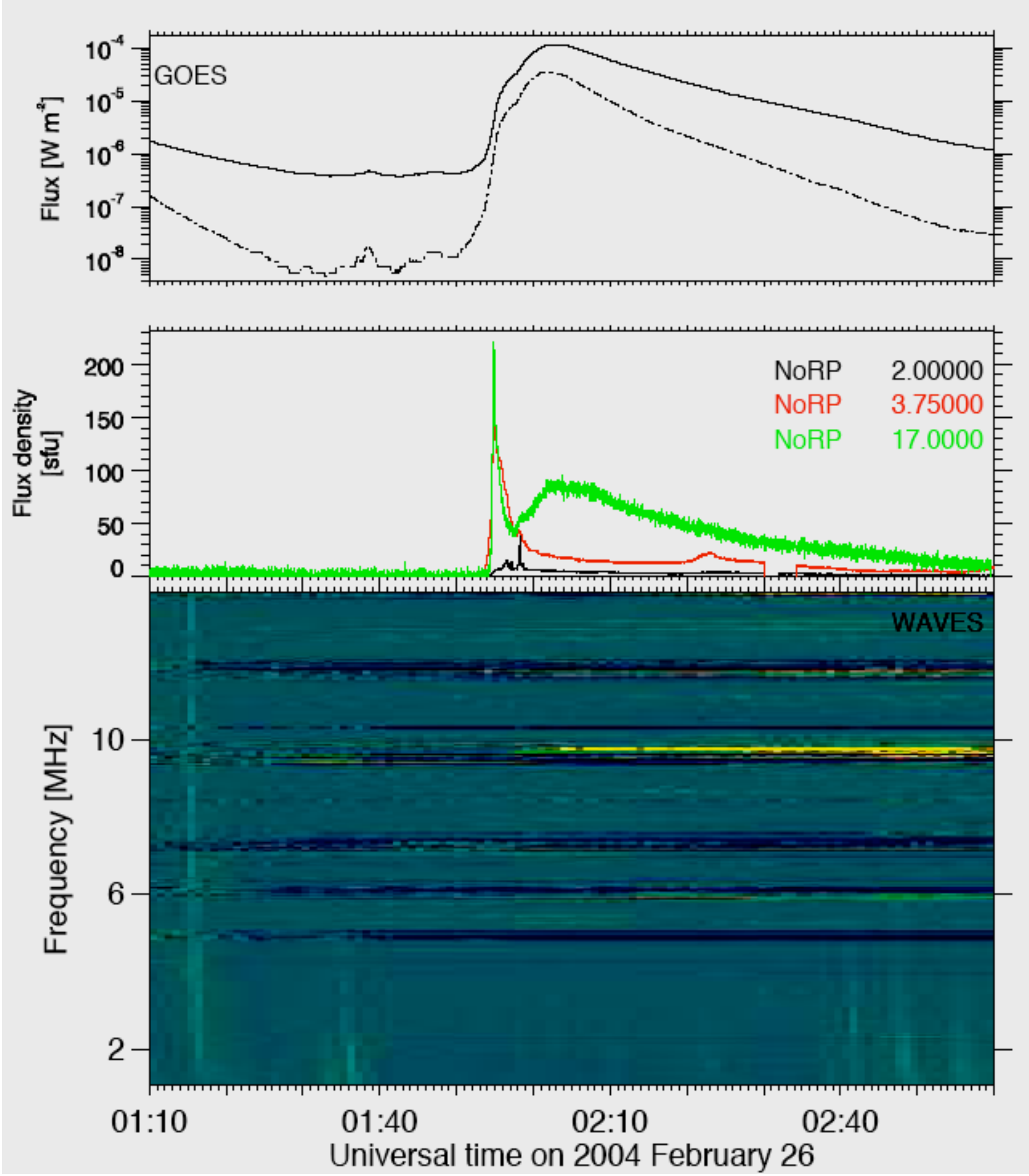
Use radio emission as a tracer of electron (particle) escape to the high corona and IP space



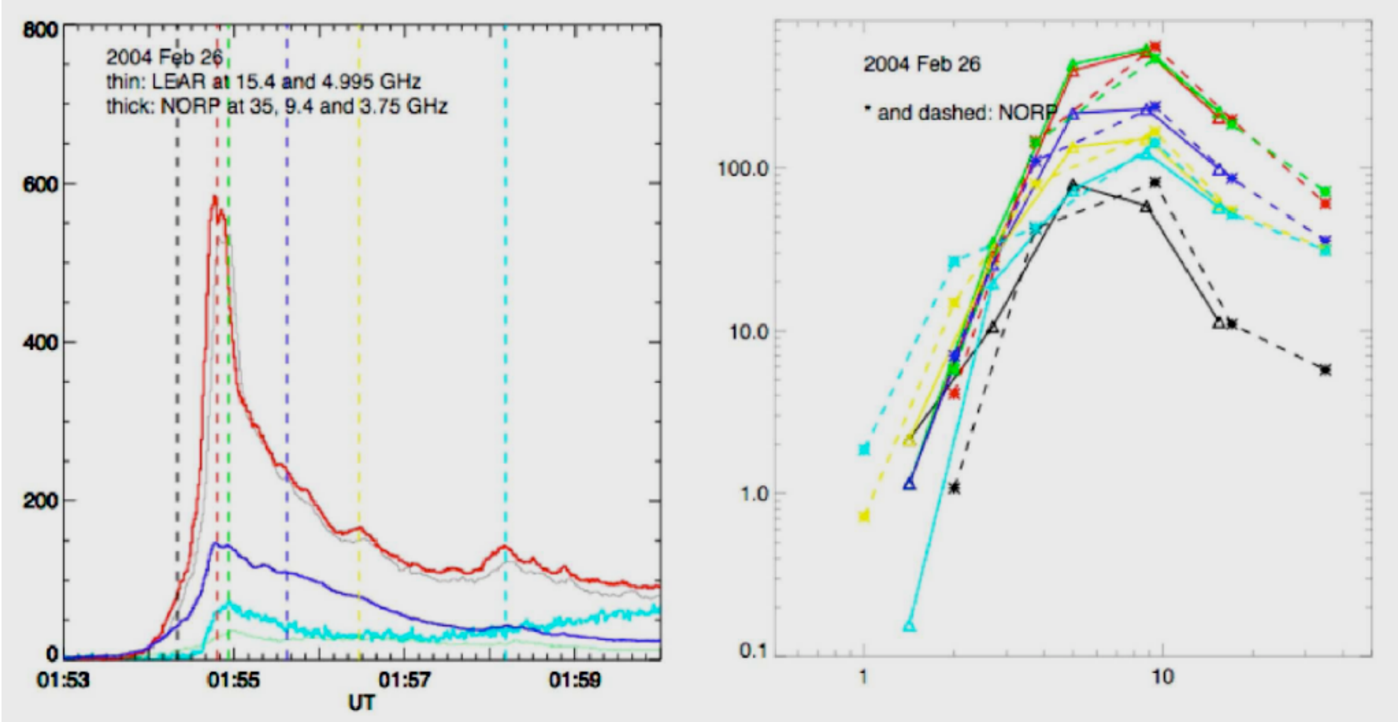
The case of magnetic confinement

SEP-less flare 2004 Feb 26:

- Particle acceleration in the corona (microwave burst, e^- 100s of keV)
- Particles remain confined in the (low) corona:
  - cutoff at dm-m-λ
  - no type III
  - => no particle escape / no SEP



The case of magnetic confinement

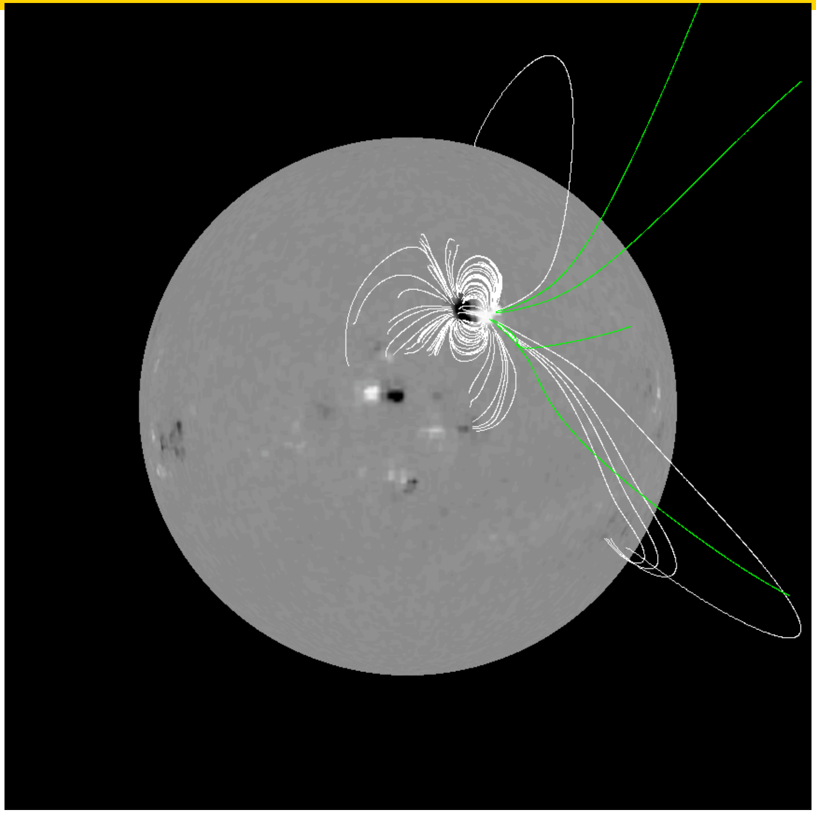


Microwave emission on 2004 Feb 26 (RSTN & Nobeyama):

- Steep low-frequency spectrum (steeper than $\sim\nu^{5/2}$ self-absorbed gyrosynchrotron emission from a uniform source): Razin-suppressed emisson from a dense plasma,

$$n_e > 3\times10^{10}\left(\frac{\nu}{2\ \mathrm{GHz}}\right)\left(\frac{B}{300\ \mathrm{G}}\right)\ \mathrm{cm}^{-3}$$

The case of magnetic confinement



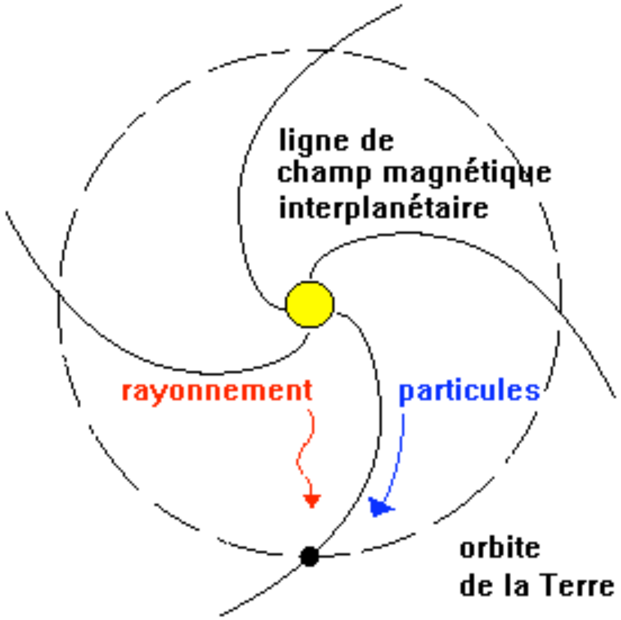
MDI/SoHO + PFSS extrapolation (Schrijver & Derosa) :

- Flaring AR contains open field lines (that exst prior to the flare)
- Flare-accelerated particles have no acces to these open field lines

The case of magnetic confinement

- Observation:
  - 12/22 SEP less flares show radio evidence for the confinement of flare-accelerated electrons, especially no DH type III at the time of the microwave burst.
  - 6 have no CME, 6 have a CME.
  - PFSS: open field lines exist in the parent AR.
- Interpretation:
  - Common criterion of occurrence: CMEs (Wang & Zhang 2007) and type III bursts (Axisa 1974, Zlobec et al. 1990, Hofmann & Ruzdjak 2007) occur only when energy is released at the periphery of an active region.
  - CME is not the process that opens field lines to IP space. Only when particles get access to *previously open* magnetic field lines will they escape from the flare region.

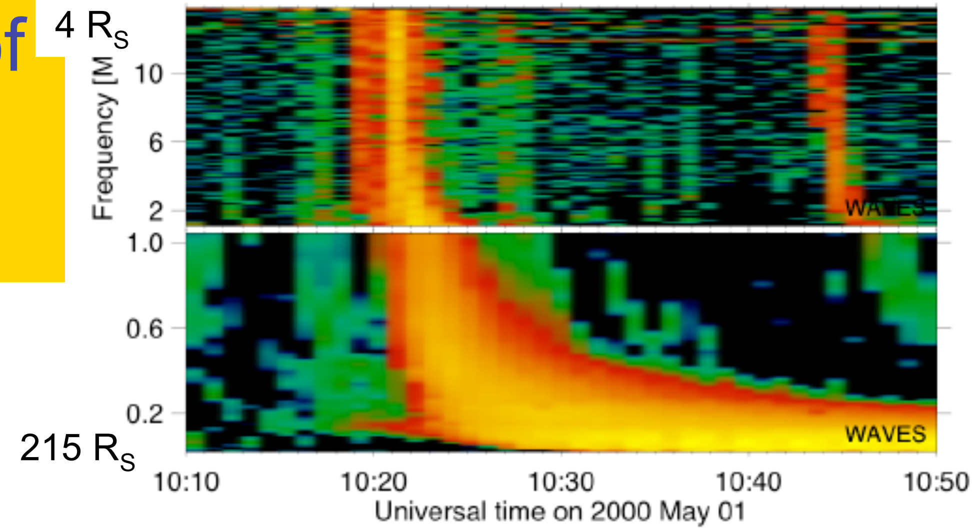
The coronal magnetic field and SEP transport

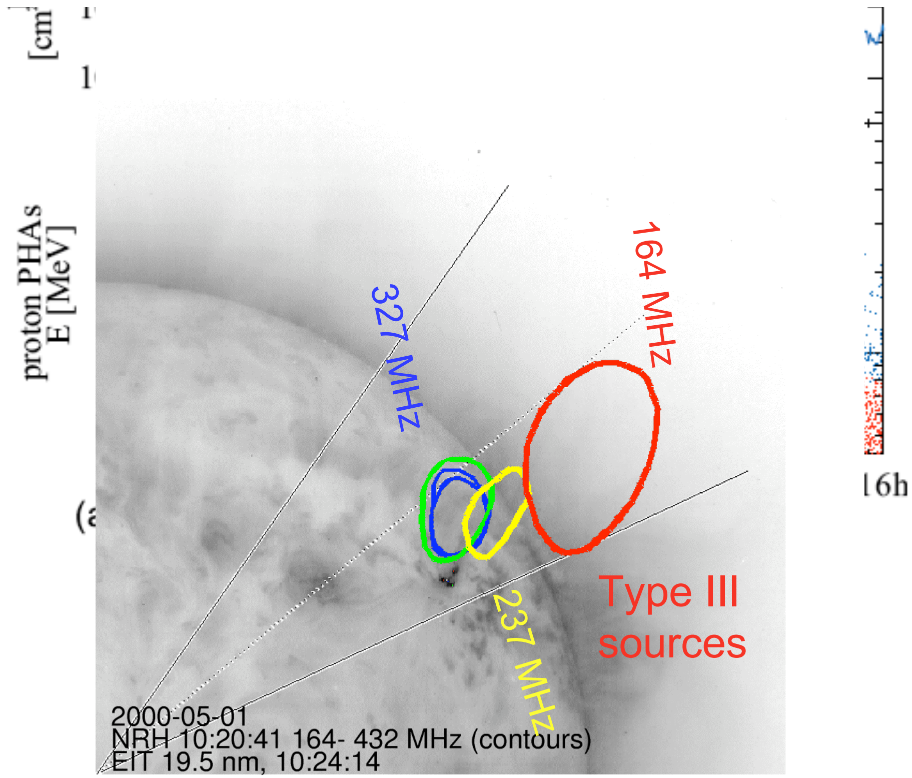


Case studies using radio observations and magnetic field extrapolations.

Type III bursts and PFSS extrapolations as tracers of open flux tubes in the corona

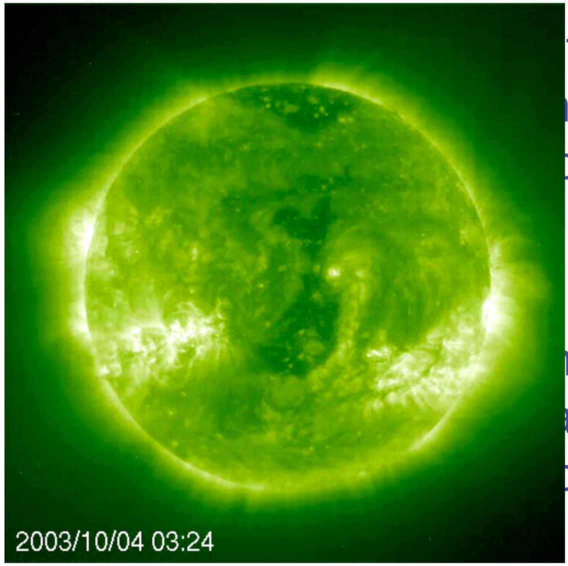
- Solar release time of energetic particles (p 5-55 MeV, SoHO/COSTEP; e 30-500 keV, Wind/3DP) from energy dispersion of onset times.
- Events accompanied by type III bursts (e^- beams ~10 keV)
  - Track radio emission to 1 AU (ground + Wind/WAVES)
  - m-λ maps at several ν - sections of open flux tube at several altitudes in the corona (Nançay Radioheliograph).
- Compare with potential magnetic field extrapolations (*SolarSoft*; Schrijver & DeRosa).





Type III bursts as tracers of particle propagation in the coronal and IP magnetic field: longitude

- Impulsive SEP accompanied by m-λ type III bursts (e^- beams ~10 keV)
- Type III maps (solar corona; Nançay RH) & potential field extrapolations (Schrijver & DeRosa): e^- beams reveal rapidly diverging open flux tubes (factor 10-20 low corona / 2.5 R_S)



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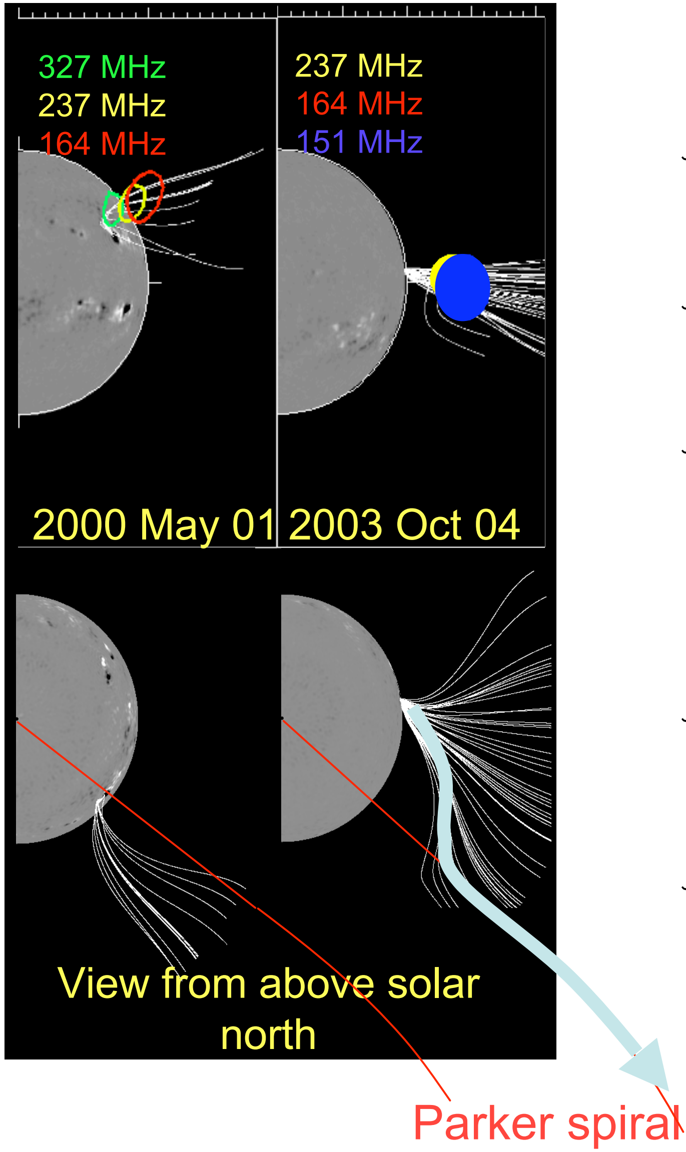
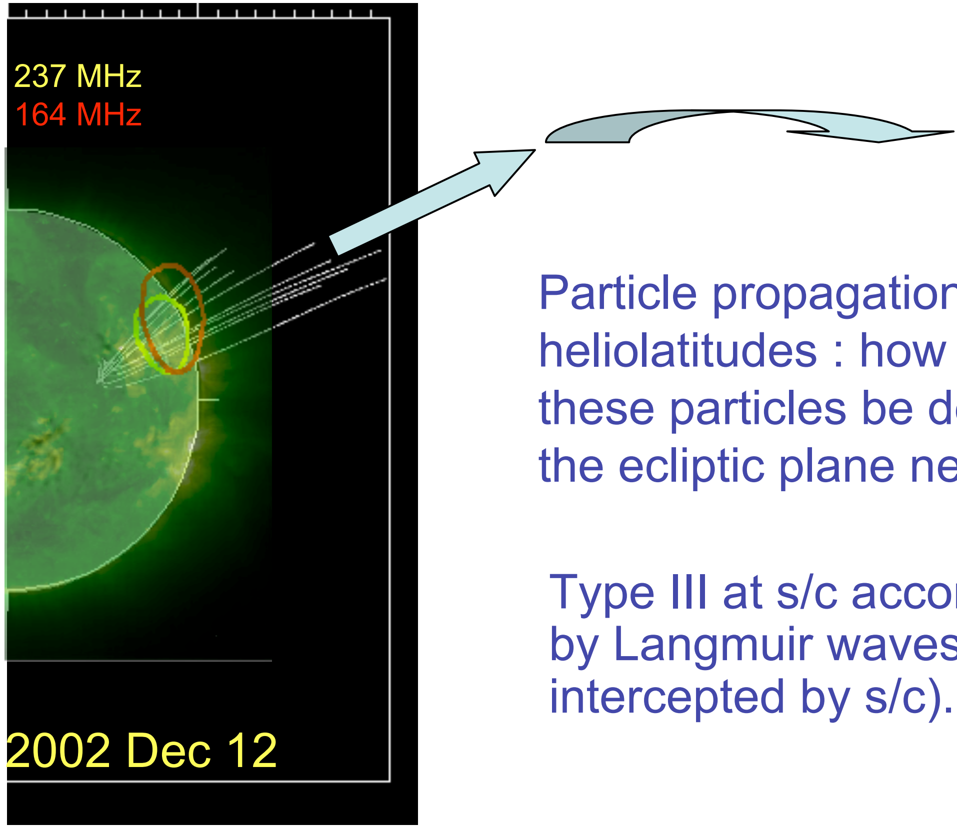


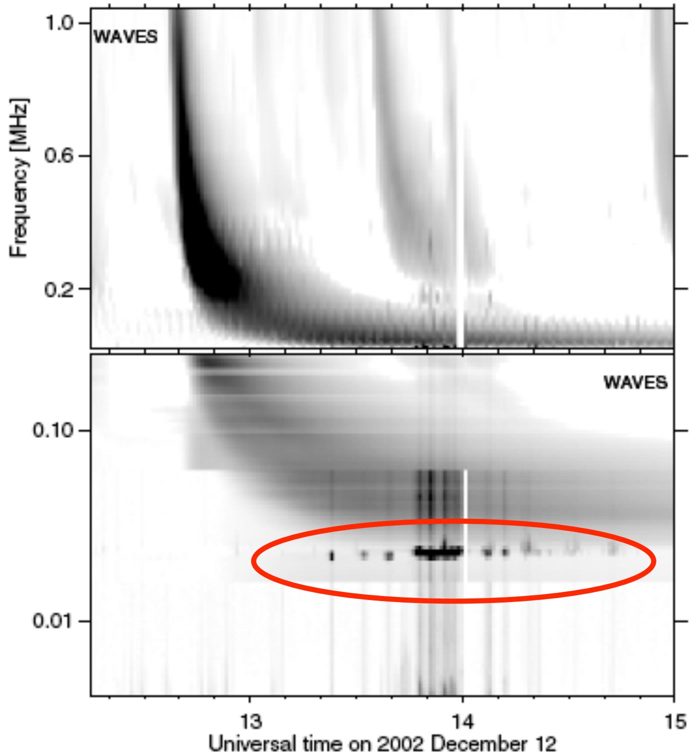
Klein, Krucker, Lointier, Kerdraon 2008, A&A 486, 589

Type III bursts as tracers of particle propagation in the coronal and IP magnetic field: longitude



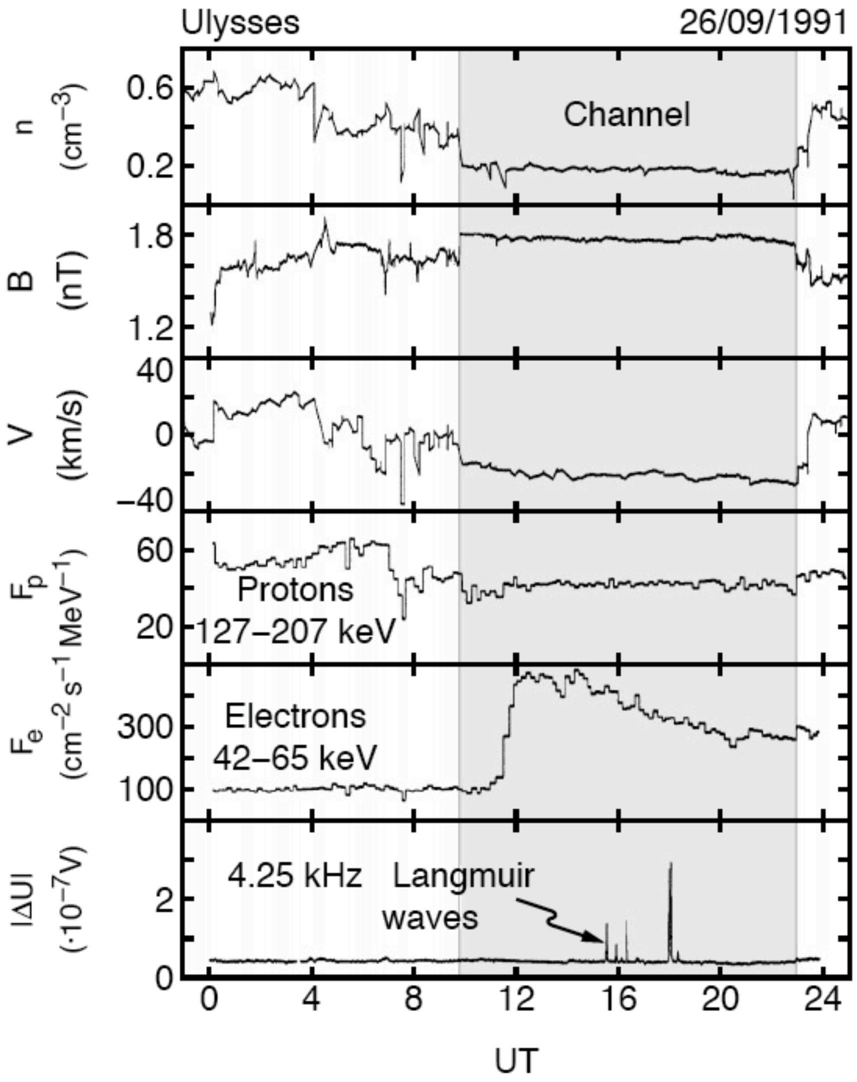
Particle propagation to high heliolatitudes : how can these particles be detected in the ecliptic plane near 1 AU ?

Type III at s/c accompanied by Langmuir waves (e^- beam intercepted by s/c).

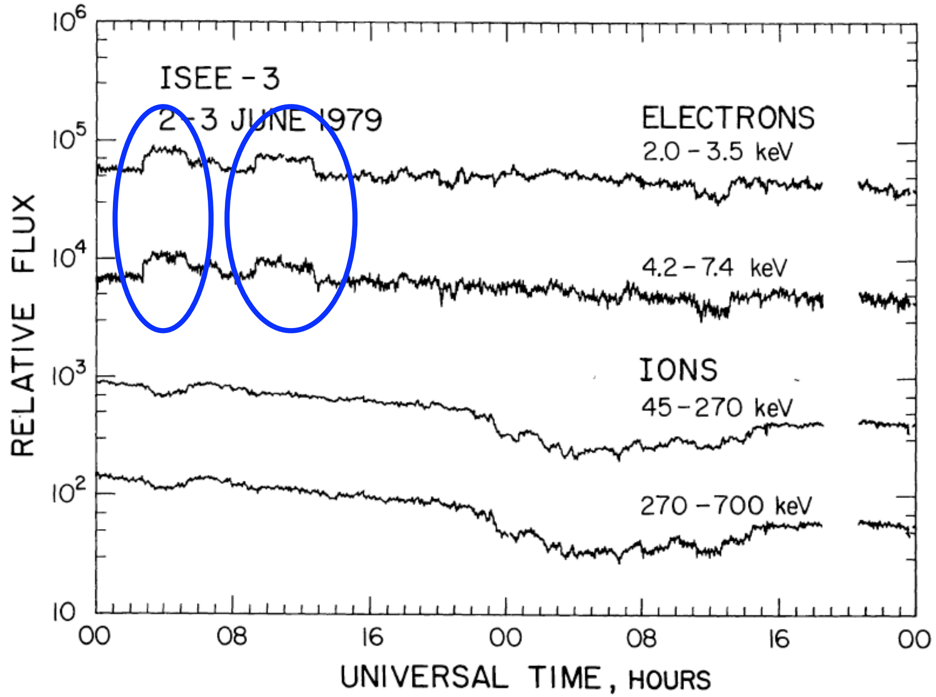


⇒ The parent AR is connected to the source surface at high latitude, but the IP field line curves down to the ecliptic before reaching 1 AU (≠ Parker).

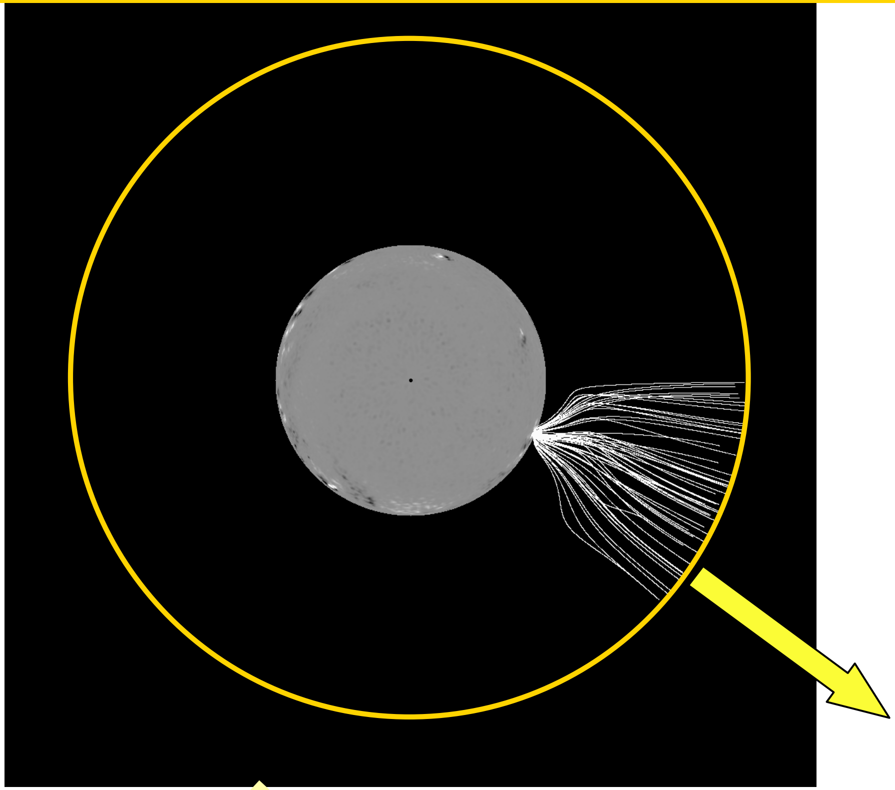
Type III bursts as tracers of SEP propagation: IP flux tubes and coronal acceleration regions



- When observed in situ, impulsive SEP propagate in narrow flux tubes; at 1 AU : Ø=6×10^6 km (keV e$^-$ Buttighoffer 1998 A&A 335, 295; MeV/n ions Mazur et al 2000 ApJ 532, L79)



Type III bursts as tracers of SEP propagation: IP flux tubes and coronal acceleration regions



- When observed in situ, impulsive SEP propagate in narrow flux tubes; at 1 AU : Ø=6×10^6 km (keV e^- Buttighoffer 1998 A&A 335, 295; MeV/n ions Mazur et al 2000 ApJ 532, L79)
- Cross section << open flux tubes at source surface inferred from PFSS; subset of open field lines.

- Cross section in the low solar atmosphere: a few 10^3 km
- consistent with small-scale acceleration regions in flares
- SEP injection into boad range of longitudes may occur in AR, not only at extended shocks !

Radio astronomical constraints on energetic particle propagation in the corona

- The radio emission of electron beams (« type III bursts ») can be used as tracer of open coronal magnetic flux tubes.

- Type III bursts and magnetic field extrapolations show that
  - open magnetic field lines rooted in small surfaces in active regions diverge rapidly with height and can easily cover 90° in solar longitude;
  - strongly curved open field lines connect solar active regions to the nominal Earth-connected Parker spiral even when the parent active region is several tens of degrees away in longitude.

- Type III bursts and Langmuir waves in situ imply that the interplanetary field lines may curve downward (≠Parker)

- The divergence of open magnetic flux tubes rooted in AR allows for SEP events to be detected over a broad range of longitudes (many tens of degrees) without requiring a similarly extended accelerator (CME shock)