Properties of solar energetic particle events inferred from their associated radio emission

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Motivation

We constrained the particle acceleration and release processes in Solar Energetic Particle (SEP) Events, using the:

- Association of SEP events with Transient Radio Emissions.

- Timings between the energetic proton release time and
  - Type-III related electrons
  - Energetic electrons

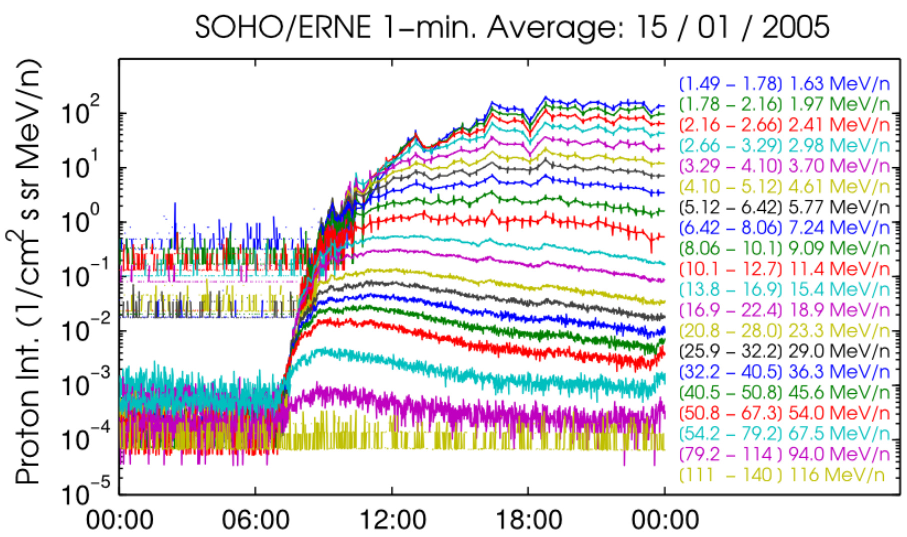
- Energetic Proton release height

Introduction – Data Selection

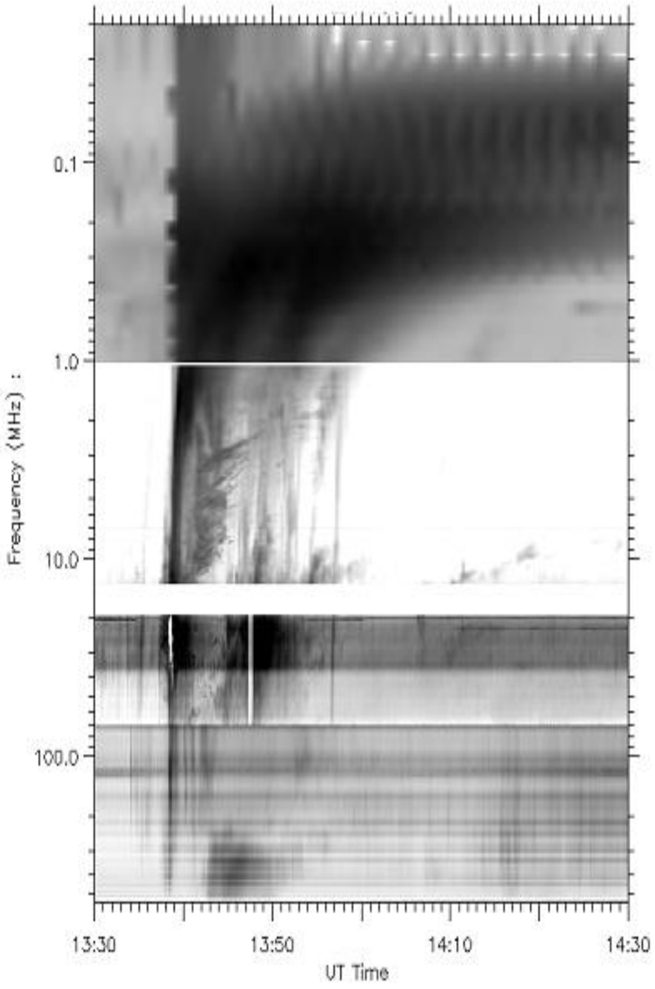
Solar Energetic Particle Events (SEP)

- Proton or Electron intensity enhancements.
- Energies: ~keV -- ~GeV
- Duration: ~hours -- ~days

Proton event selection: 115 high-energy solar proton events recorded by SOHO/ERNE from 1996 to 2010. (Vainio et al. 2013)

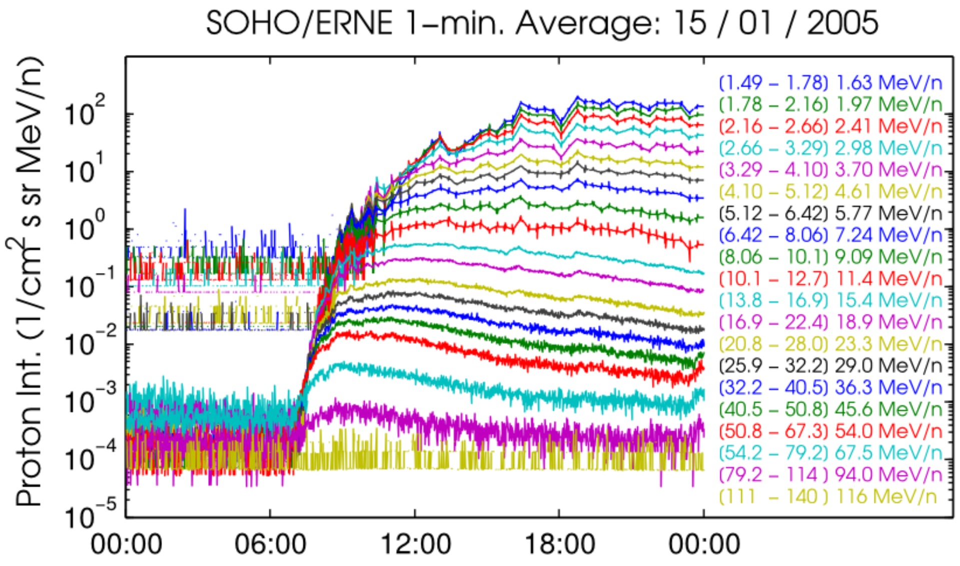


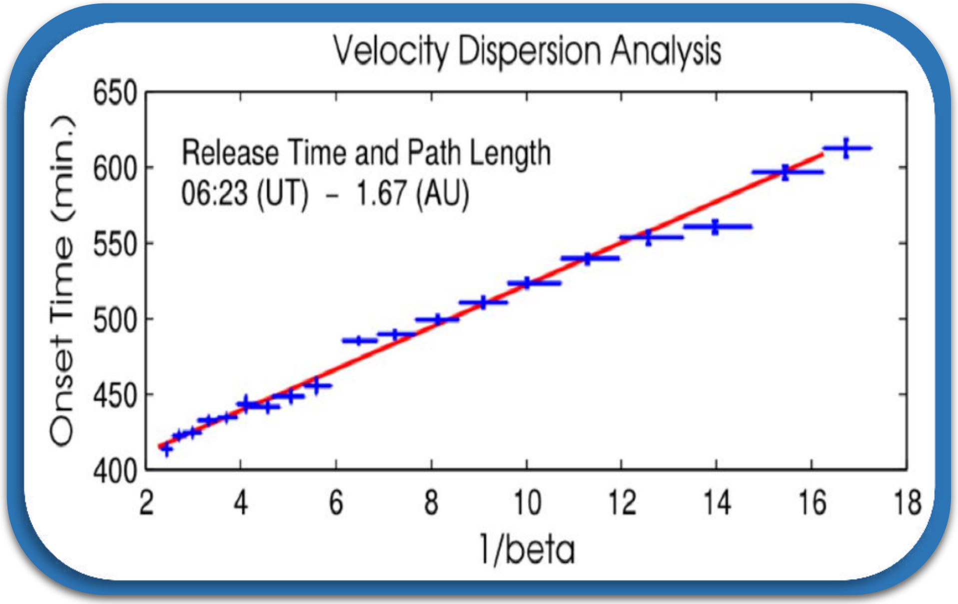
Composite Radio Spectra and Transient Radio Emissions

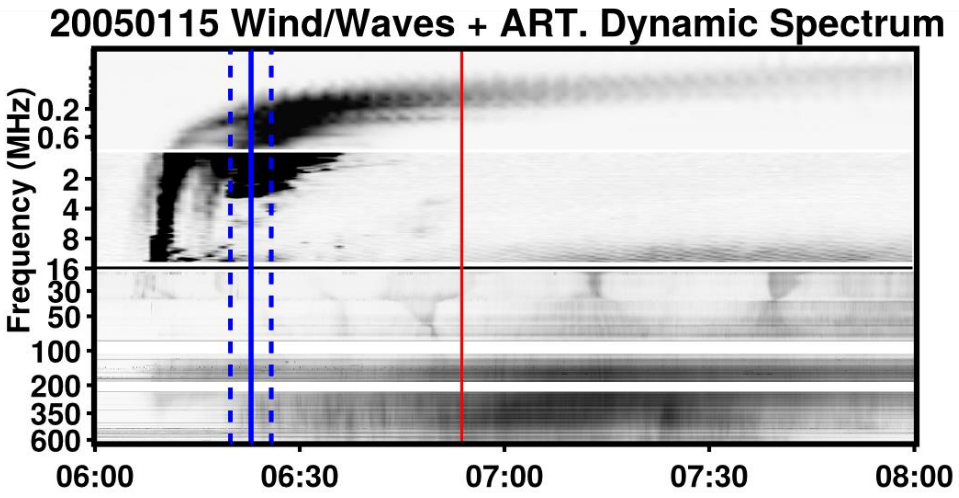


- Different types of radio bursts
  - e- beams (Type III)
  - e- accel. Shock waves (Type II)
  - e- confined at close loop structures (Type IV)
- Radio spectra with data from ground-based (ARTEMIS-IV, RSTN, DAM, Culgoora) and space-born radio-spectrographs (Wind/Waves)

Estimate of Proton Release Time



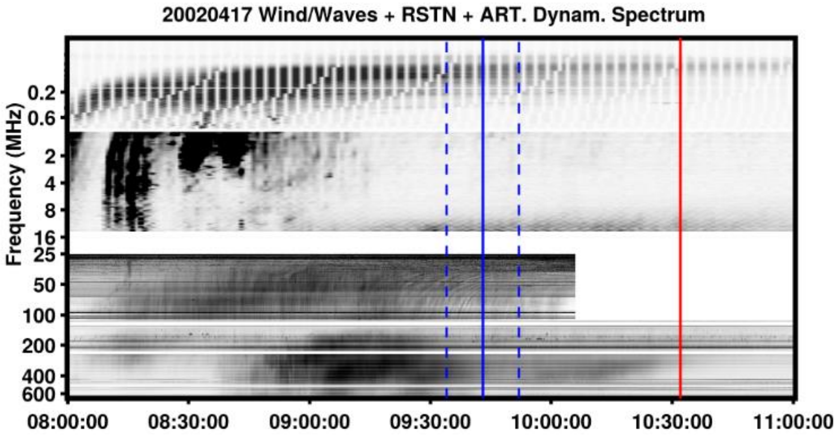




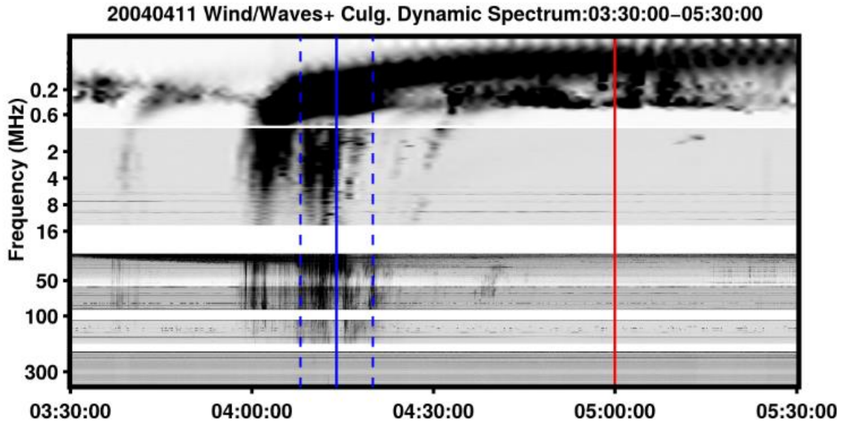
Velocity Dispersion Analysis (VDA)

- Onset Time Determination (Poisson-CUSUM)
- Estimate of Onset Time Uncertainty (Monte Carlo)
- Onset Time vs Energy $t_{rel} = t_{onset}(E) - s \cdot \beta^{-1}(E) + 8.33\,min.$
- 32 cases were initially rejected (unrealistic VDA)

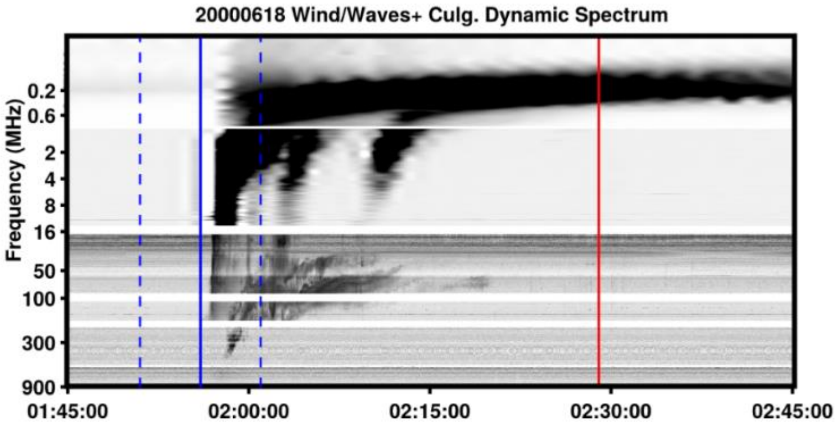
SEP Radio Associations (I)



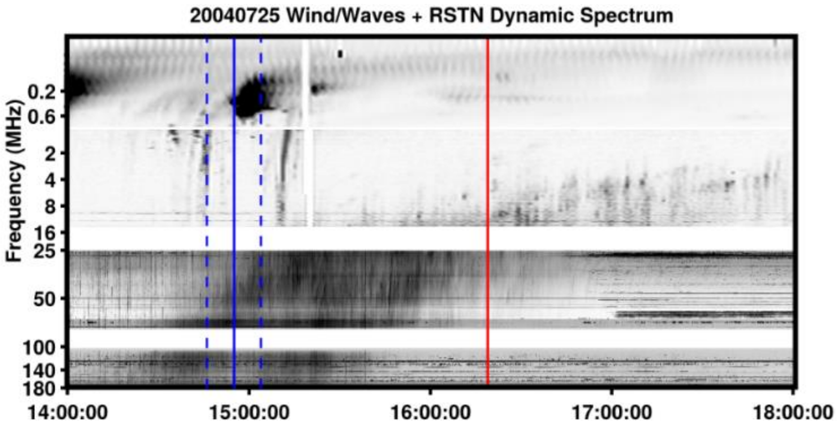
Type IV-only



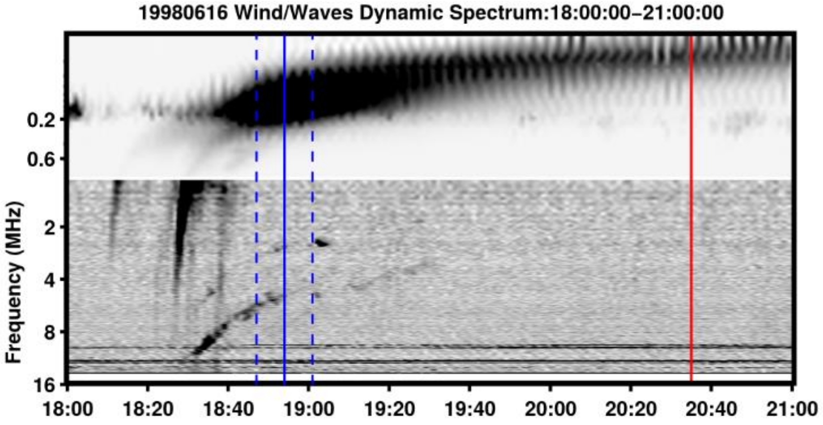
Type III-only



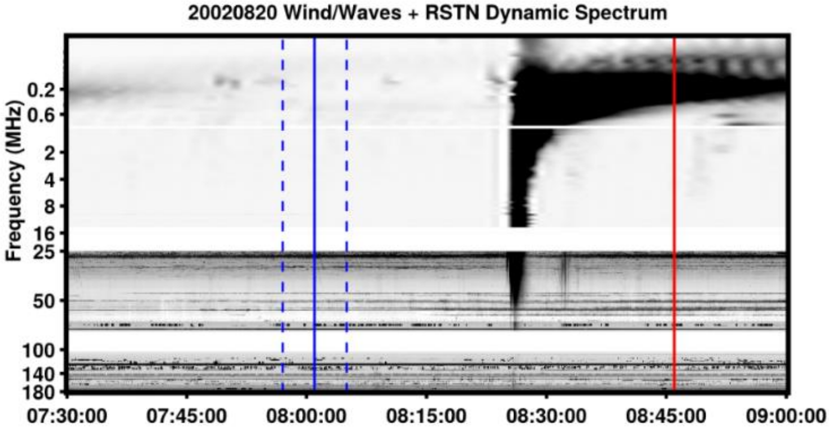
Type III/II



Type III/IV



Type II-only



No association

SEP Radio Associations (I)

	Radio Association Cases: III/II	III	II	mix/IV-c	Total	No Assoc.
†	25	18	7	15	65	18
	38%	28%	11%	23%	100%	
‡	34	10	0	21	65	0
	52%	16%	0%	32%	100%	

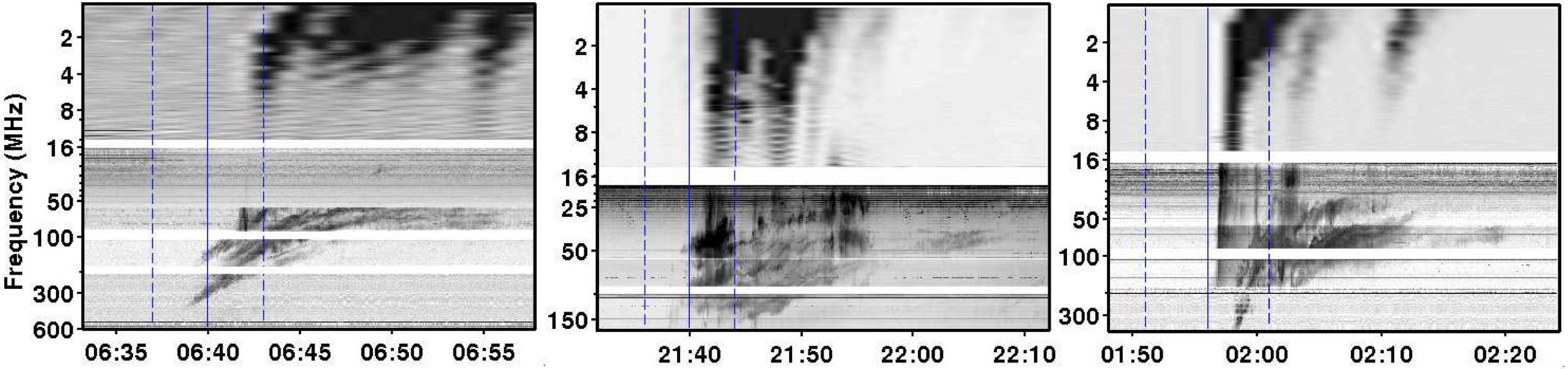
†: Radio association rates *within* proton release window.
‡: Radio association rates within ±1 h. from proton release time.

- Both flare- and shock-related particle release processes are observed in at least 25 cases (38%).
- 18 cases (28%) associated with flare-related particle release processes
- 7 cases (11%) associated with shock-related particle release processes.

Mixed III/II Radio Associations: Flare- or Shock- Release Process?

Radio Spectral Characteristics

In 18 cases the type III emanates from the type II, while, in 7 cases it does not.

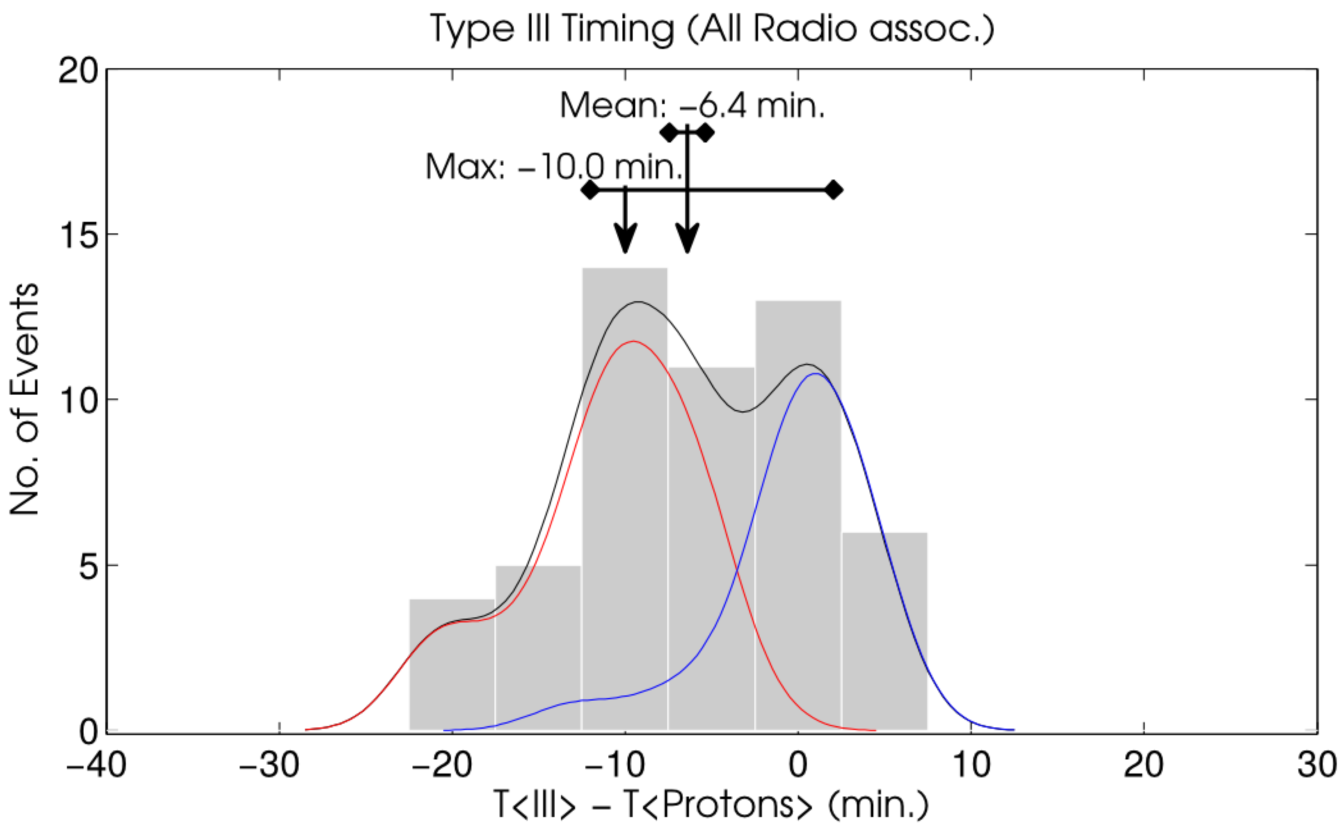


Proton Energy Spectra

We have also examined if the type III/II and II only associated SEP events have a flatter/harder energy spectrum than the type III only events. The spectral hardening of the type II cases compared to the type III shows that the shock related type II is contributing to the SEP acceleration.

Proton and Electron Release Timing (I)

Proton and Type III Timing



We used type III bursts as proxies of the initial electron acceleration and escape.

Following Krucker et al. 1999:

- Simultaneously released events

$$(t_{III} - t_{rel}) \,/\, \delta t > -1$$

- Delayed events

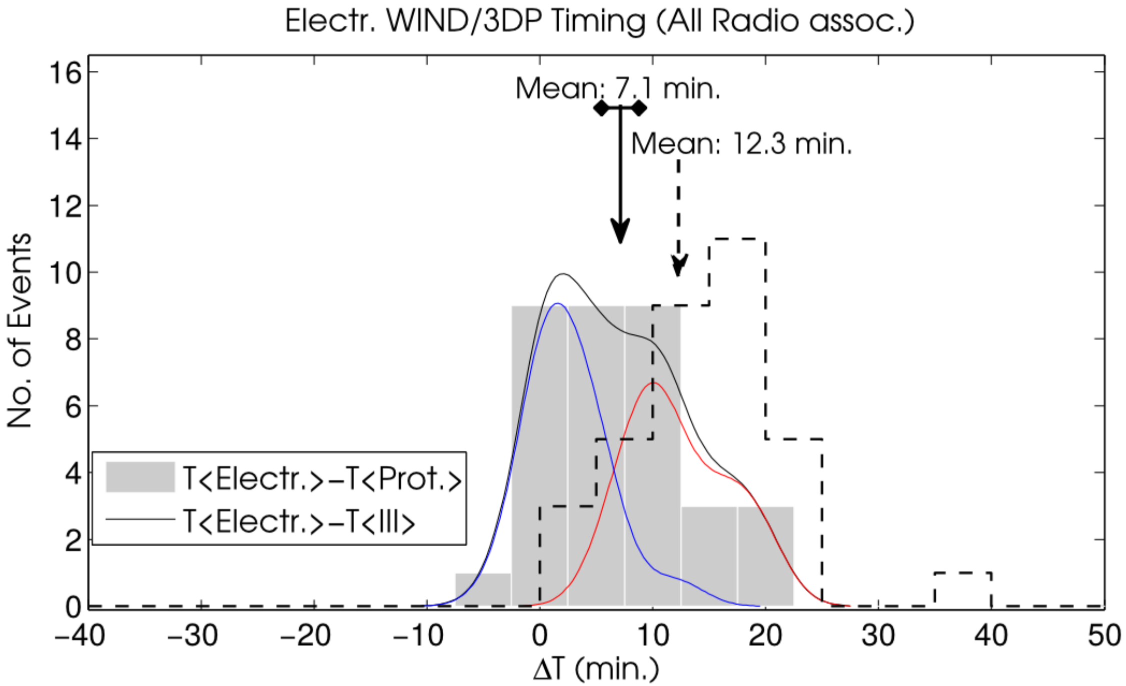
$$(t_{III} - t_{rel}) \,/\, \delta t \leq -1$$

In general, we found a late release for protons. In 59% of our cases the type III-related electron release occurred well before the time of proton release; these cases have been characterized as delayed.

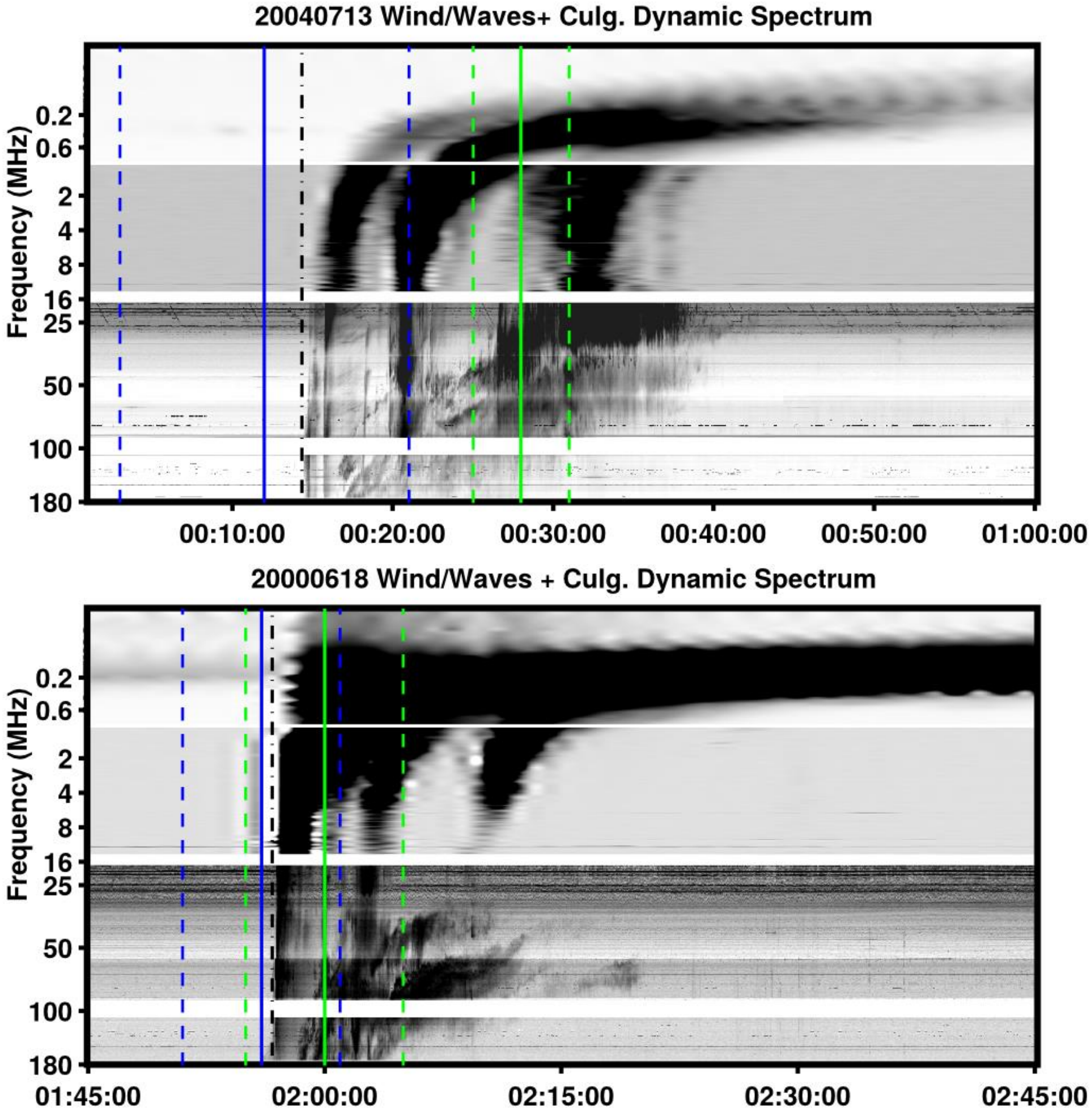
The apparent delay between the proton release and the type III radio emission can be ascribed to several reasons, *such as selective acceleration, transport effects, particle diffusion, and particle trapping*.

Proton and Electron Release Timing (II)

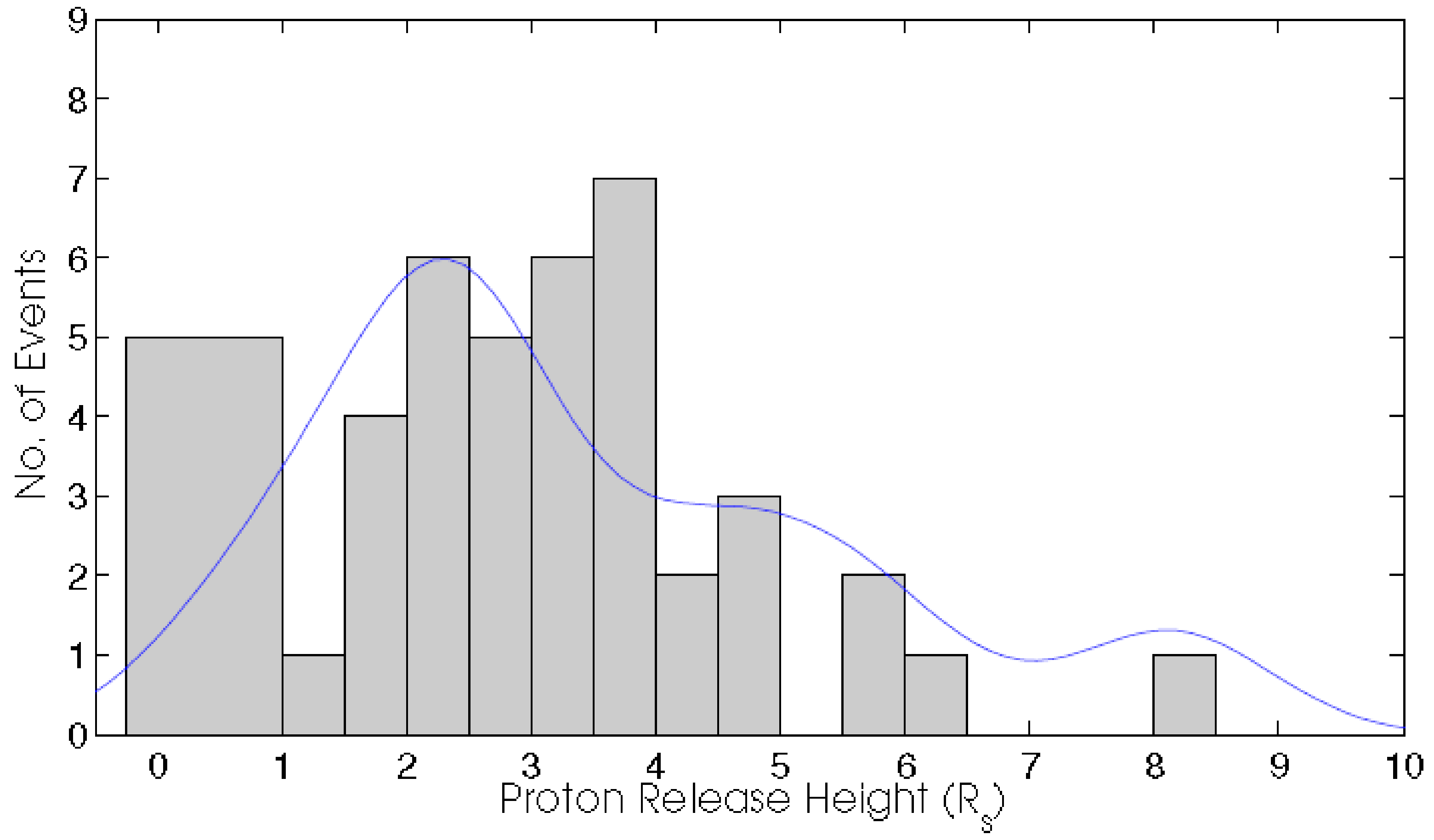
Proton and Wind/3DP electron Timing



We separate the events into simultaneously released and delayed events we found that in 53% of our cases the electron release (observed by Wind/3DP) compared to the proton release (observed by SOHO/ERNE) was simultaneous within the statistical uncertainty.



SEPs with type IIs: Proton Release Heights



- For each SEP event we determined the corresponding CME observed by the SOHO/LASCO.
- We used the information for the height of the CME leading edge.
- We extrapolated (or interpolated) their projected height-time measurements to the time of the proton release as estimated from the VDA.

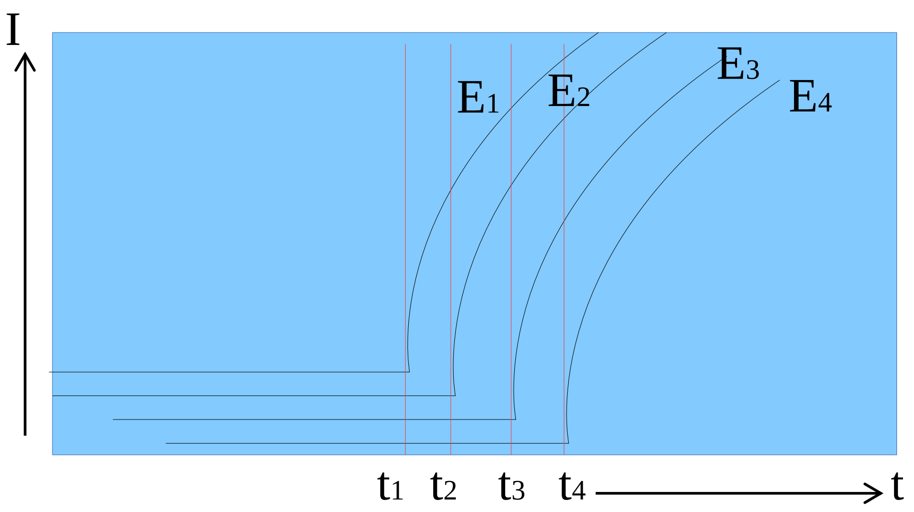
Conclusions

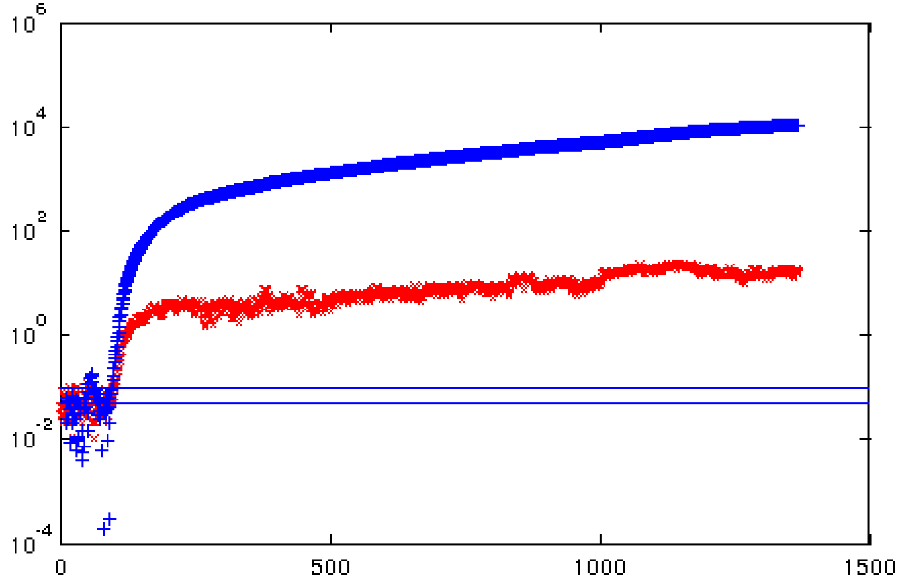
Our key findings are:

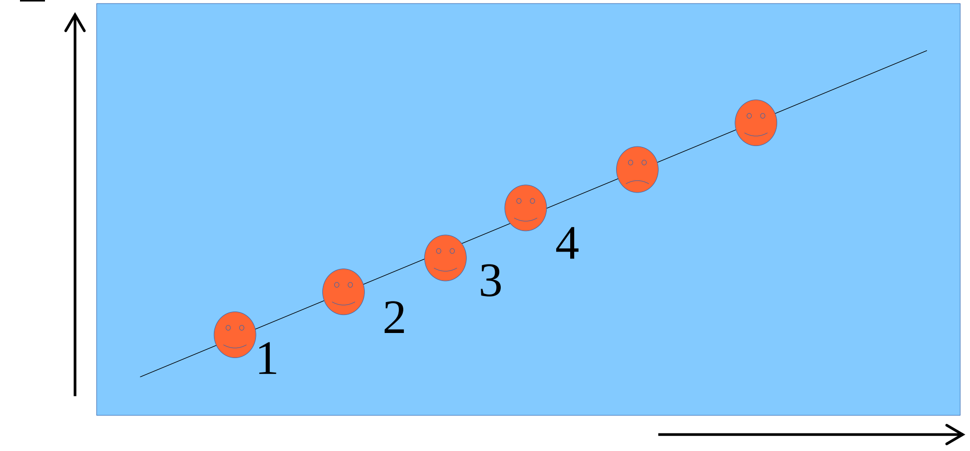
- Both flare- and shock-related particle release processes are observed in high-energy proton events at >50 MeV. A clear cut distinction between flare-related and CME-related SEP events is difficult to establish.
- Proton release is most frequently accompanied by both type III and II radio bursts (38%), but there is a significant percentage of cases with only type III occurrence (28%).
- Typically, the protons are released after the start of the associated type III bursts and simultaneously or before the release of energetic electrons.
- The proton release for the type II associated cases typically occur at heights from 2.0 to 3.5 R.

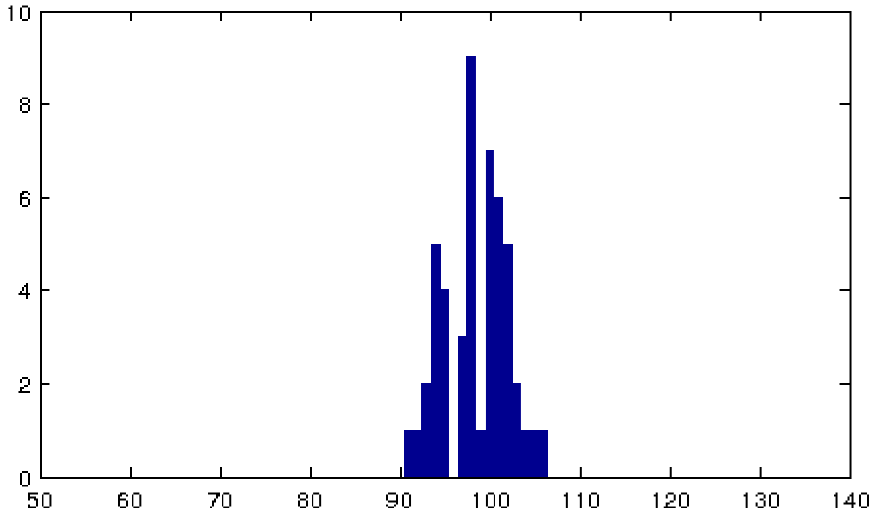
(Supp.) VDA and Monte Carlo CUSUM

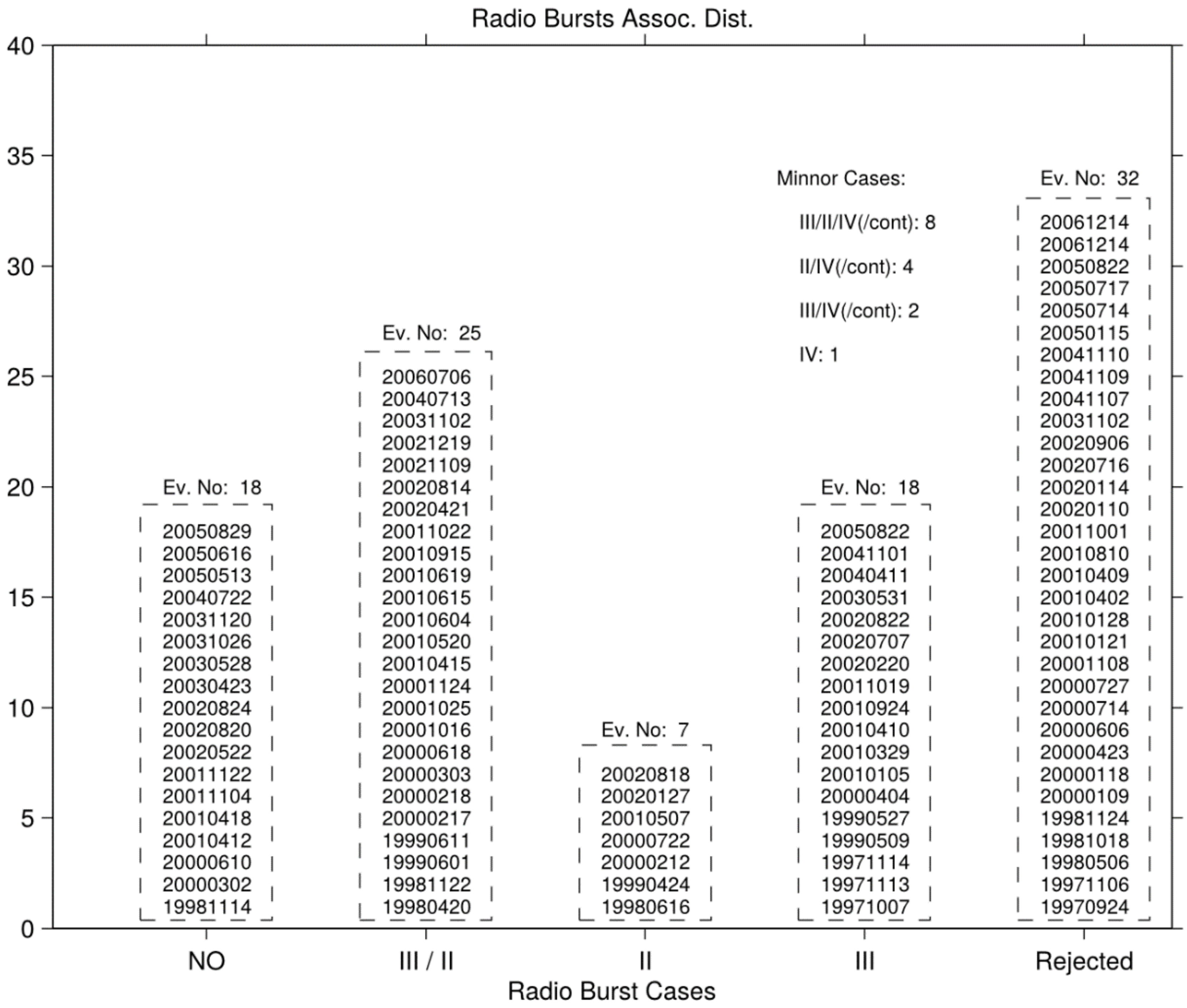
$$t_{rel} = t_{onset}(E) - s \cdot \beta^{-1}(E) + 8.33\,min.$$



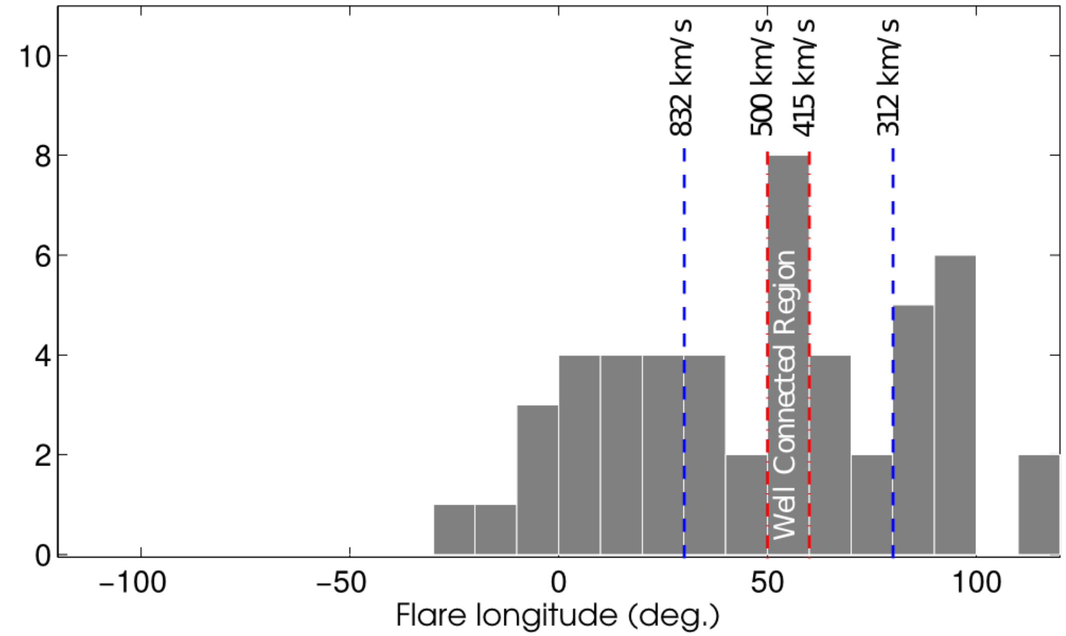




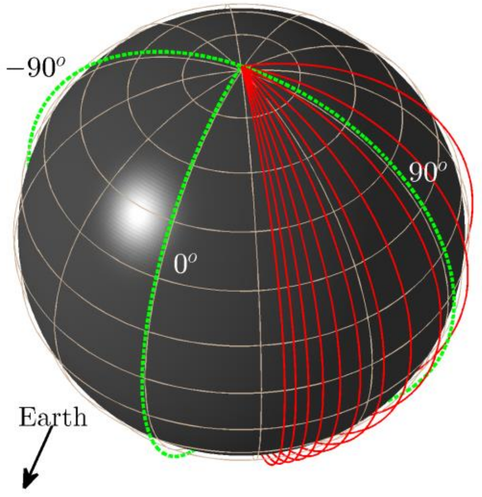


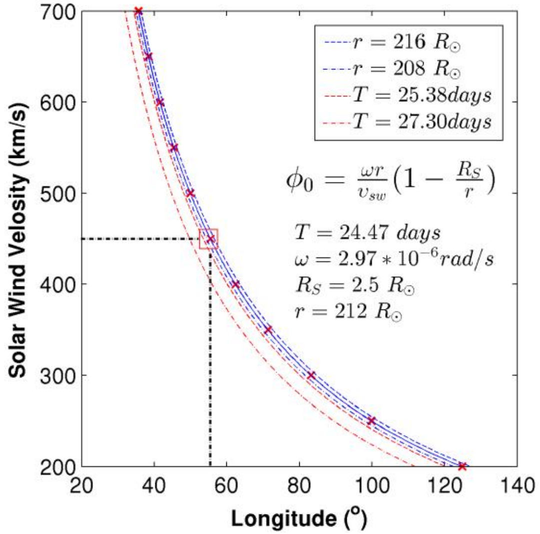

Radio Bursts Assoc. Dist.
40
35
30
25
20
15
10
5
0
Ev. No: 18
20050829
20050616
20050513
20040722
20031120
20031026
20030528
20030423
20020824
20020820
20020522
20011122
20011104
20010418
20010412
20000610
20000302
19981114
Ev. No: 25
20060706
20040713
20031102
20021219
20021109
20020814
20020421
20011022
20010915
20010619
20010615
20010604
20010520
20010415
20001124
20001025
20001016
20000618
20000303
20000218
20000217
19990611
19990601
19981122
19980420
Ev. No: 7
20020818
20020127
20010507
20000722
20000212
19990424
19980616
Minnor Cases:
III/II/IV(/cont): 8
II/IV(/cont): 4
III/IV(/cont): 2
IV: 1
Ev. No: 18
20050822
20041101
20040411
20030531
20020822
20020707
20020220
20011019
20010924
20010410
20010329
20010105
20000404
19990527
19990509
19971114
19971113
19971007
Ev. No: 32
20061214
20061214
20050822
20050717
20050714
20050115
20041110
20041109
20041107
20031102
20020906
20020716
20020114
20020110
20011001
20010810
20010409
20010402
20010128
20010121
20001108
20000727
20000714
20000606
20000423
20000118
20000109
19981124
19981018
19980506
19971106
19970924
NO
III / II
II
III
Rejected
Radio Burst Cases

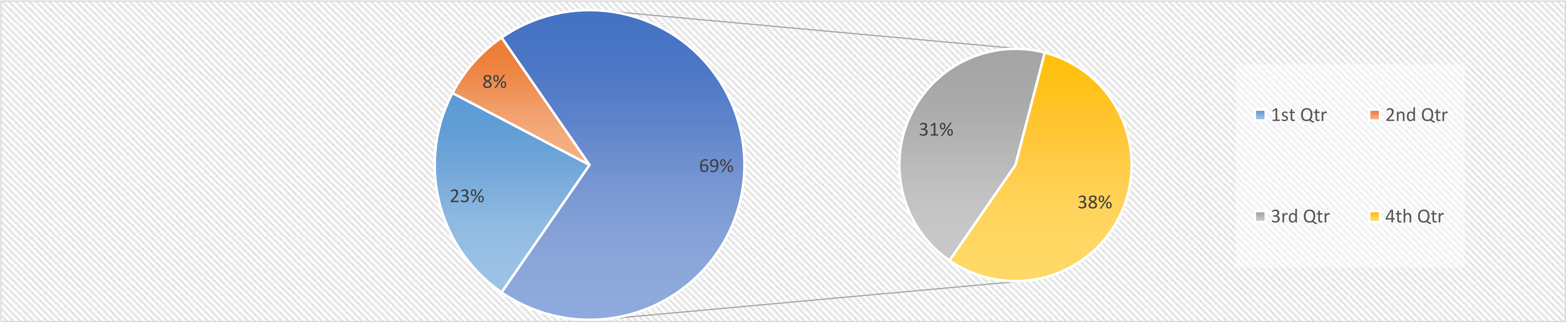
Locations of the SEP Related Flares



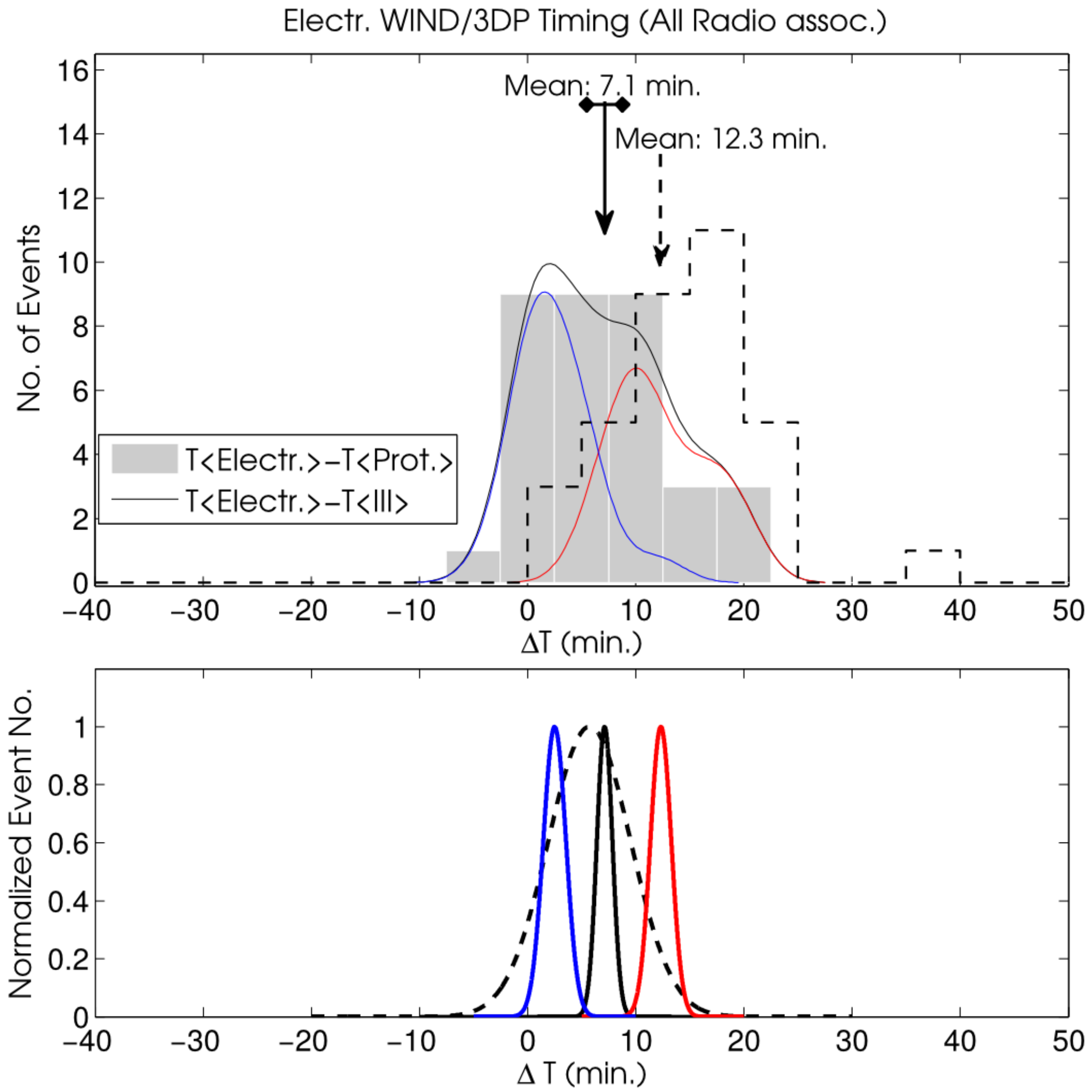
Parker Spiral – Well connected Regions



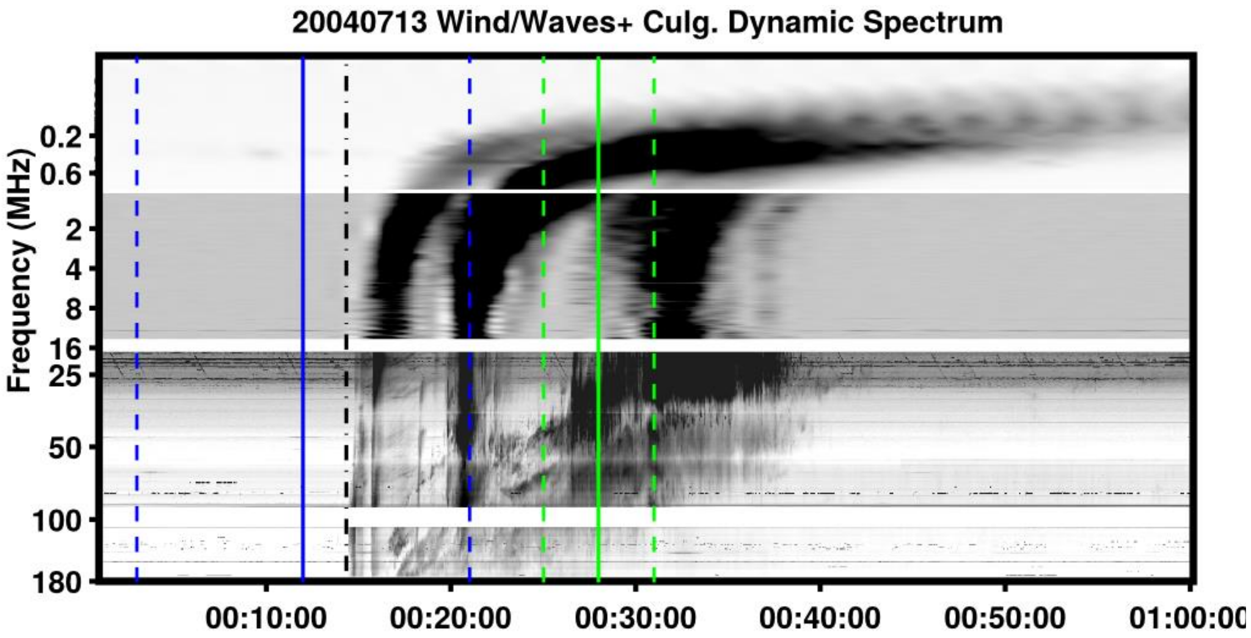


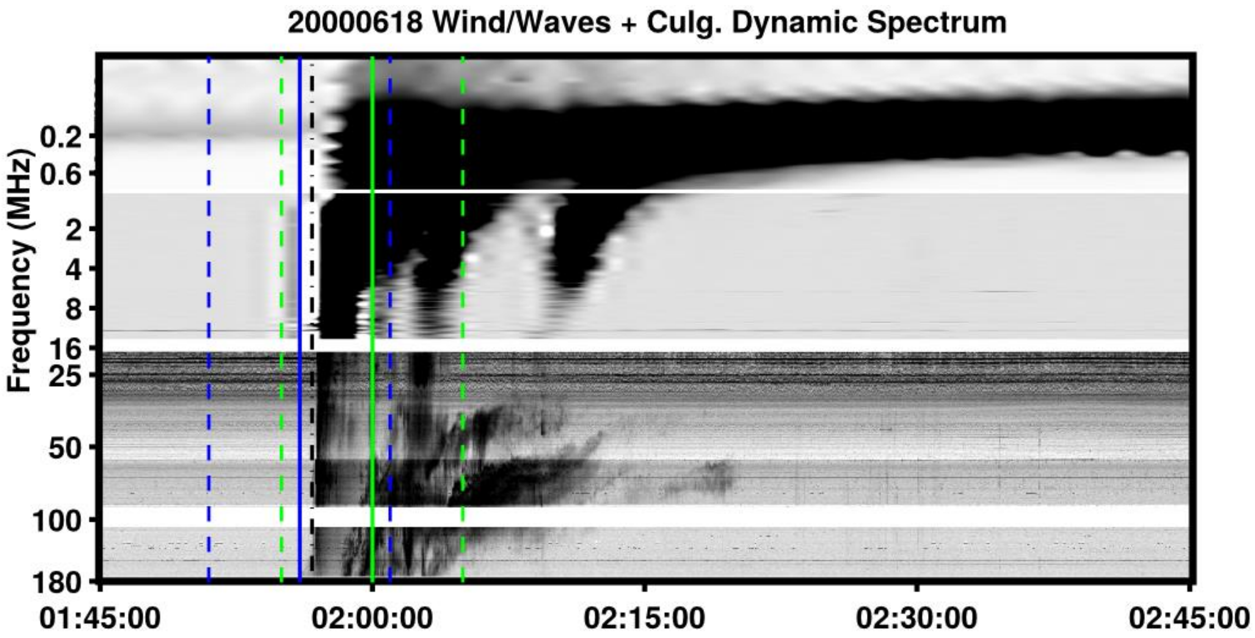


(Supp.) Monte Carlo Timing

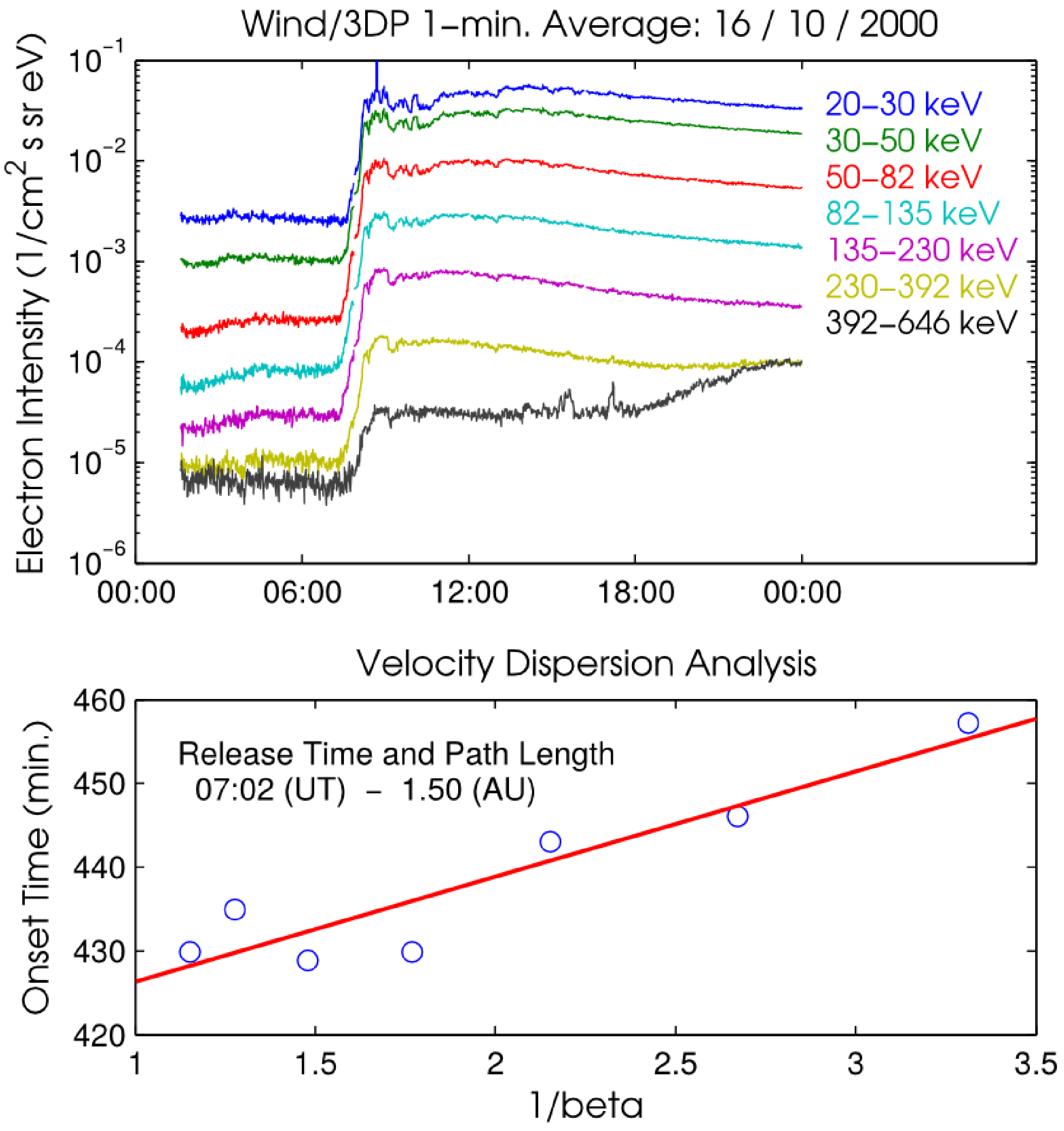


(Supp.) Electron Release Associated Radio Emission





In 33 cases with inferred radio association we registered 23 cases with type III and II association (III/II); 7 cases with only a type III radio burst and 3 cases with mixed type IV-c association.



Wind/3DP 1-min. Average: 16 / 10 / 2000
Electron Intensity (1/cm2 s sr eV)
10−1
10−2
10−3
10−4
10−5
10−6
00:00
06:00
12:00
18:00
00:00
20–30 keV
30–50 keV
50–82 keV
82–135 keV
135–230 keV
230–392 keV
392–646 keV
Velocity Dispersion Analysis
Onset Time (min.)
460
450
440
430
420
Release Time and Path Length
07:02 (UT) – 1.50 (AU)
1
1.5
2
2.5
3
3.5
1/beta

Radio Association Cases:

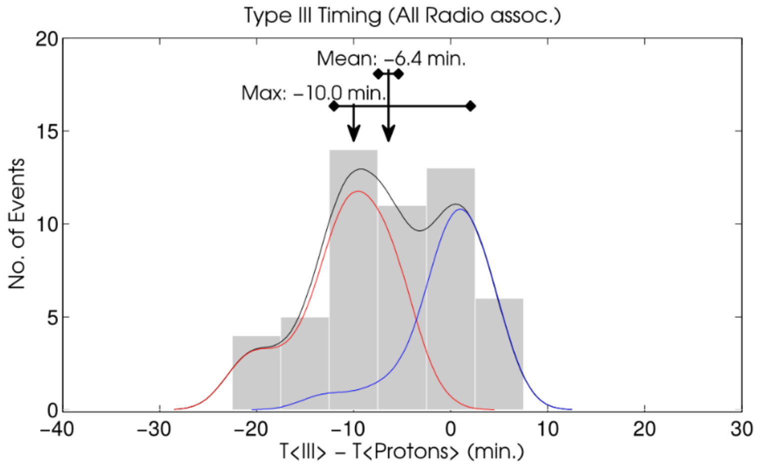
	III/II	III	II	III/II/IV-c	III/IV-c[†]	II/IV-c[†]
γ_{LEC}	-2.41	-3.22	-2.79	-2.35	-4.25	-2.28
γ_{HEC}	-2.98	-3.54	-3.60	-2.84	-3.75	-2.77
I_{max}[‡]	0.043	0.023	0.005	0.111	0.002	0.106

[†]: Associations with small statistical sample.

[‡]: Maximum SEP intensity in the energy range 54.8–80.3 MeV.

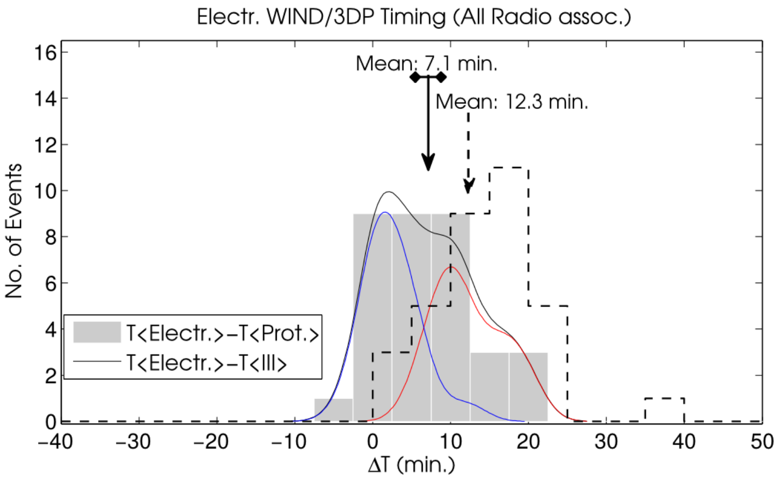
(Supp.) Proton-Electron and Type III Timing (I)

The apparent delay between the proton release and the type III radio emission can be ascribed to several reasons, such as selective acceleration, transport effects, particle diffusion, and particle trapping.



Similar results have been presented by Cliver et al. (1982).

This delay could be attributed to turbulence or waves associated with the CME-driven shock that traps the low-rigidity electrons much more effectively than the protons, selective acceleration or transport effects.



Krucker et al. (1999) attributed this delay to two distinct populations of electrons, the low-energy population associated with the type III radio burst and the high-energy population representing the delayed electrons.

Haggerty & Roelof (2002) showed that the electron delay with respect to the type IIIs could be due to the acceleration and release of the near-relativistic electrons by an outgoing coronal shock.

Cane (2003) showed that the low- and high-energy electrons belong to the same population thus interaction effects in the interplanetary medium might cause the delays.

(Supp.) Proton-Electron and Type III Timing (II)