Things we don't yet understand about solar driving of the radiation belts

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On detail at NASA GSFC

Making the Case for Prediction

What feature(s) on the sun and/or in the solar wind directly cause a radiation belt response? *What response?*

What feature(s) in the solar wind/magnetosphere/ionosphere set up a chain of actions/reactions that ultimately effect a radiation belt response? *What response?*

FEATURE → **RESPONSE**

Are we there yet?

What do we know or think we know?

State of radiation belts depends on competing sources, enhancement, transport, and loss

Loss	Enhancement
Outward through the magnetopause	Inward radial diffusion
Into the atmosphere	Local acceleration

Loss through the magnetopause

Sudden inward motion of the magnetopause due to solar wind pressure pulse (CME or HSS). Charged particles find themselves outside the last closed drift shell and are lost – termed magnetopause shadowing.

Outward radial transport due to ULF waves.

Can be associated with main phase of geomagnetic storm, or independent.

$L^* > \sim 4$

Energization by inward radial diffusion

~1MeV electrons at geosync orbit mainly due to global convection, injections from the plasma sheet.

Inward radial diffusion seen for HSS with no evidence of a shock and weak Bz / Dst.

Radial diffusion model vs data; discrepancy due to local heating not included in RD model.

RD better explains dynamics for low μ electrons, while a local accelearation mechanisms becomes important for high M μ electrons.

Loss into the atmosphere

EMIC and Chorus waves cause pitch angle diffusion - scattering - into the loss cone. Occur under conditions of geomagnetic storms, high AE, SymH, growth favorable with temperature anisotropy.

ULF waves correlated with losses into atmosphere.

EMIC waves causing loss are most effective for high energy (μ), high mirroring latitude (K)

Chorus waves causing loss are most effective for low energy (μ).

$L^* < \sim 4$

Energization by local acceleration

Multiple examples of local acceleration in the heart of the radiation belts.

Chorus scattering solely responsible for the evolution of energy and angular distribution of relativistic e flux increase for some storms.

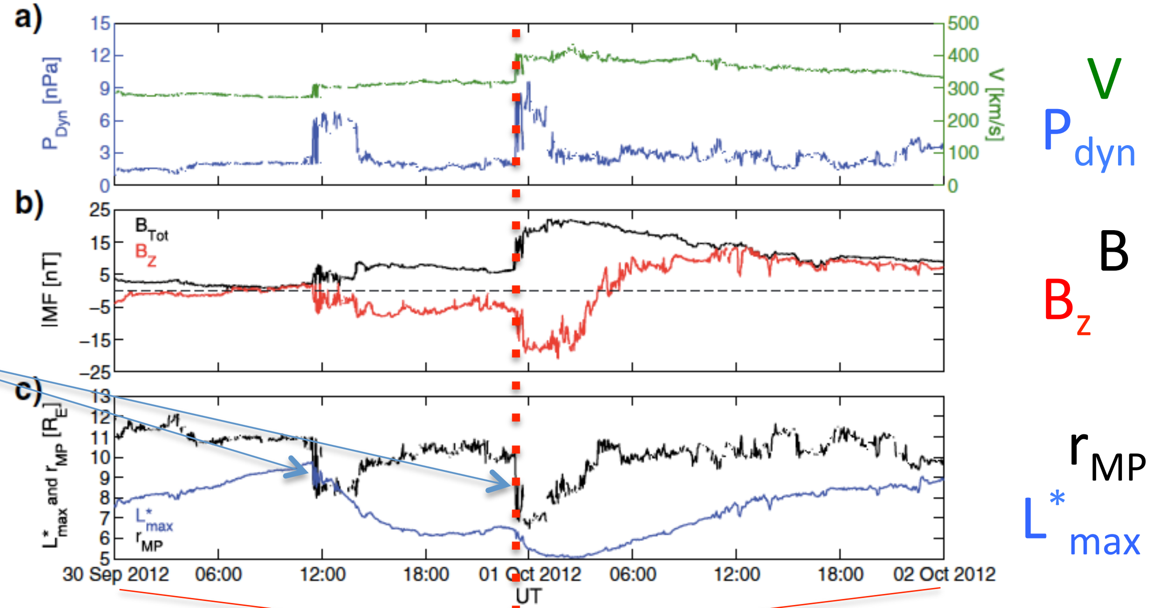
To explain different behavior in different storms, diffusion in all three dimensions coupled with data-driven, event-specific inputs, and boundary conditions is required.

Sometimes radial diffusion explains data better.

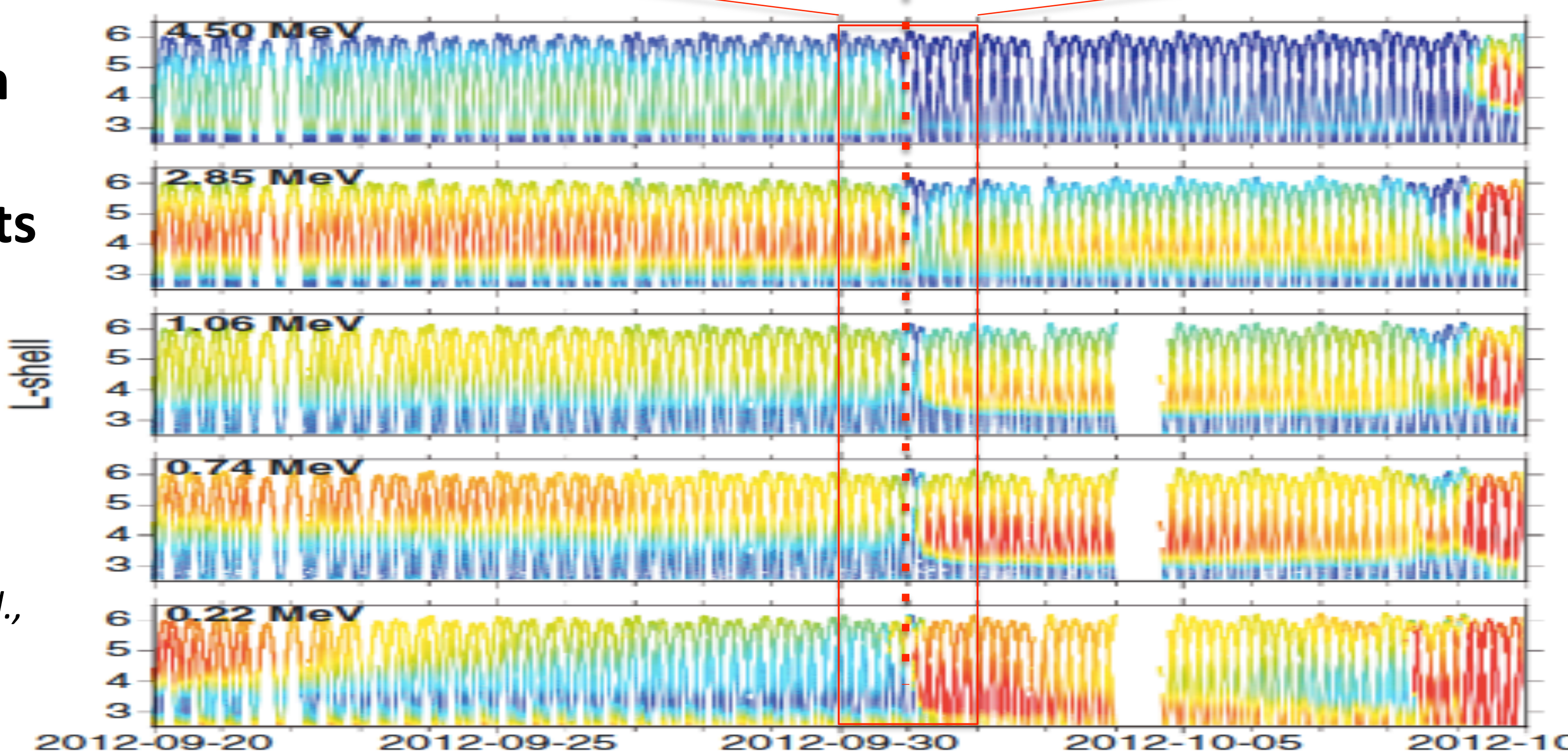
Sudden solar wind pressure increase

causes inward motion of magnetopause

and subsequent loss of high energy electrons.



Electron Flux Dropouts in 2nd case

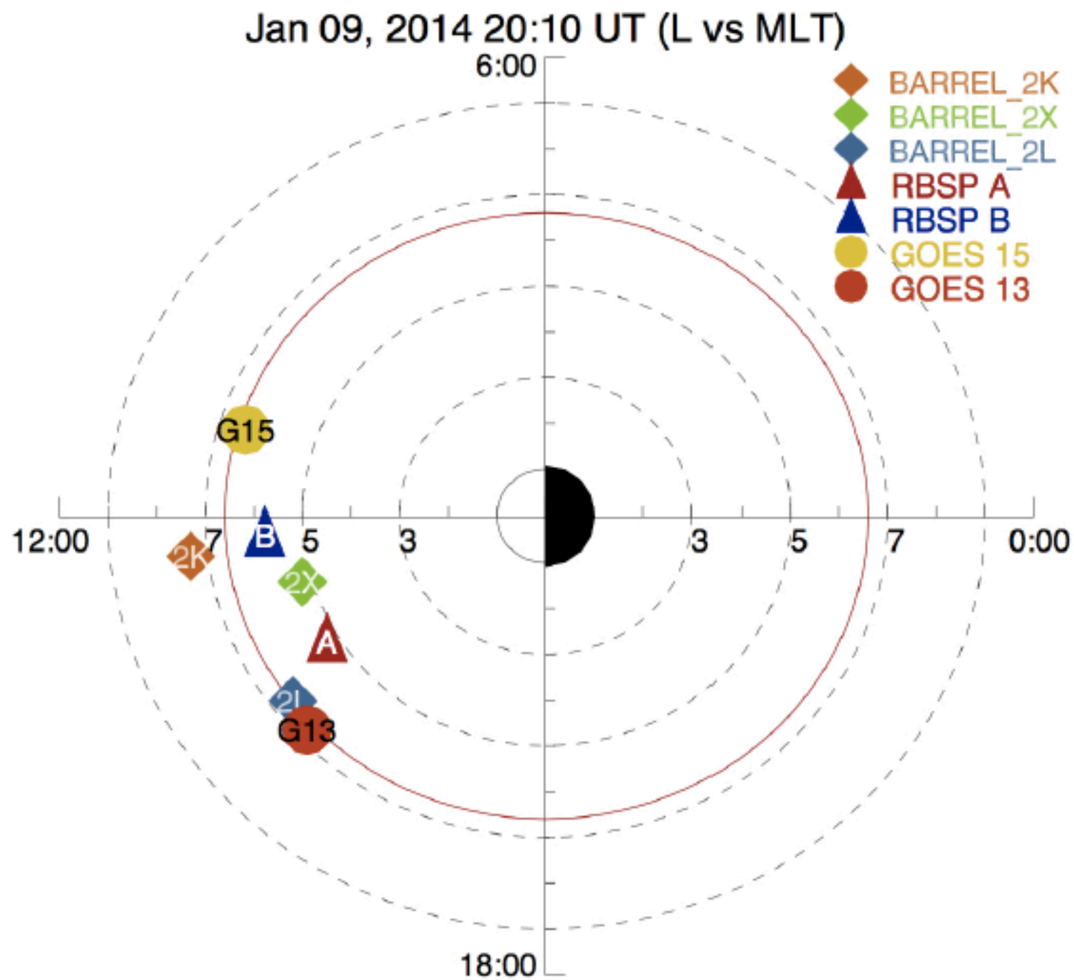


Turner et al., 2014b

BARREL observations of precipitation in close conjunction with Van Allen Probes and GOES satellites

ICME-shock with P_{dyn} increase but B_z northward or modestly southward.

Compression from the shock impact led to the loss of radiation belt electrons.

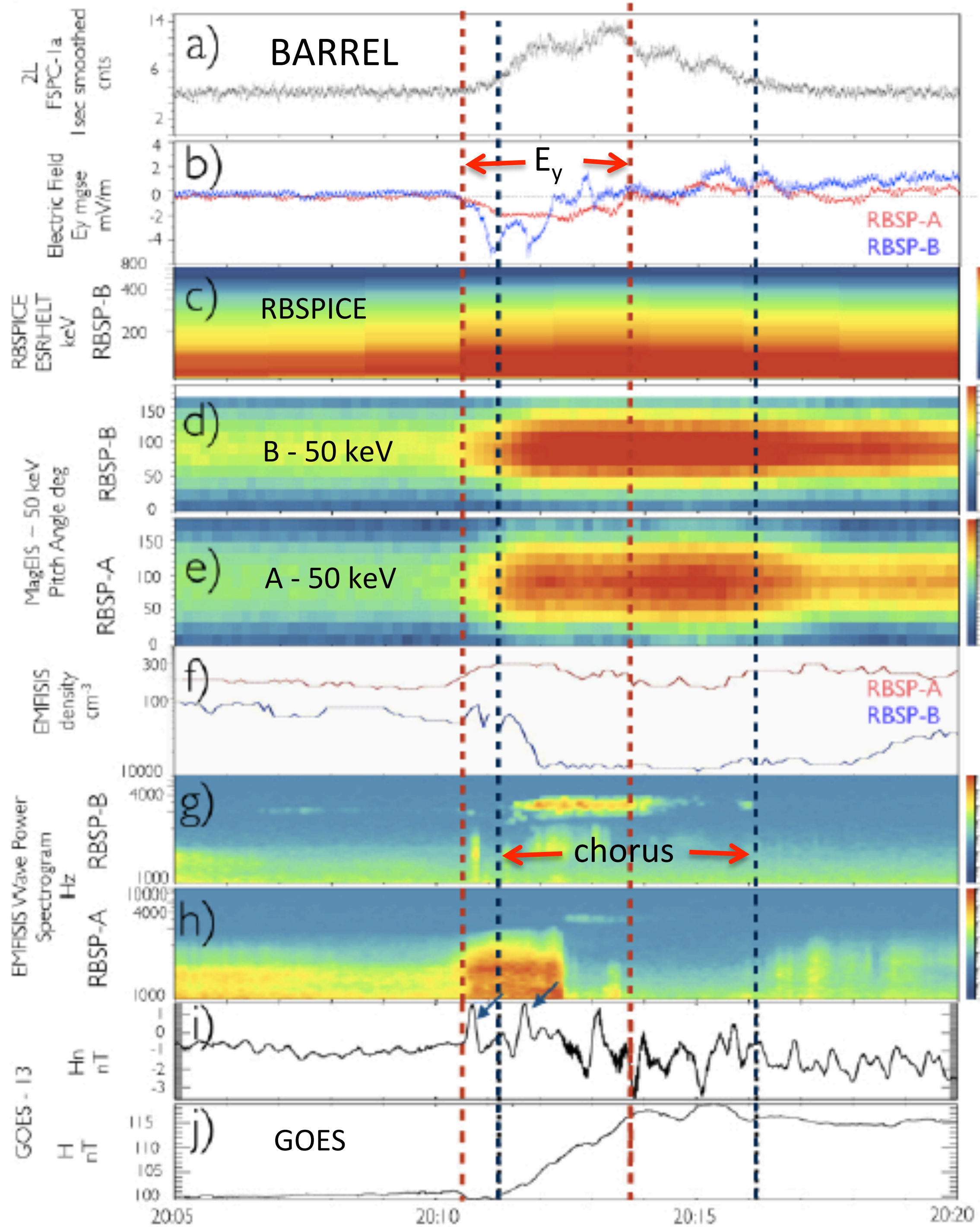


Halford et al., 2015

An azimuthal electric field impulse generated by magnetopause compression caused inward electron transport and minimal loss.

Chorus waves were responsible for most of the precipitation observed outside the plasmapause.

ULF waves were correlated with the structure of the precipitation.



Chorus is excited following injection of 1-30 keV plasma sheet electrons into the inner magnetosphere during geomagnetically disturbed times.
[Li et al., 2010]

Could chorus be excited by temperature anisotropy like EMIC?

Halford et al., 2015

Loss/Enhancement can be initiated by solar wind event

HSS (High Speed Stream)
CME (Coronal Mass Ejection)

P_{dyn} increase
IMF B_z southward

Take simplest (?) case

FLUX DROPOUT EVENTS

The drastic decrease in relativistic electron flux over a broad range in energy, equatorial pitch angle, and radial distance in only a few hours. The dominant mechanisms responsible remain a topic of debate.

Can we predict when this will occur?

Numerous Case Studies of Electron Flux Dropouts

(see review by Turner et al., 2012)

Some Statistical Studies of Electron Flux Dropouts

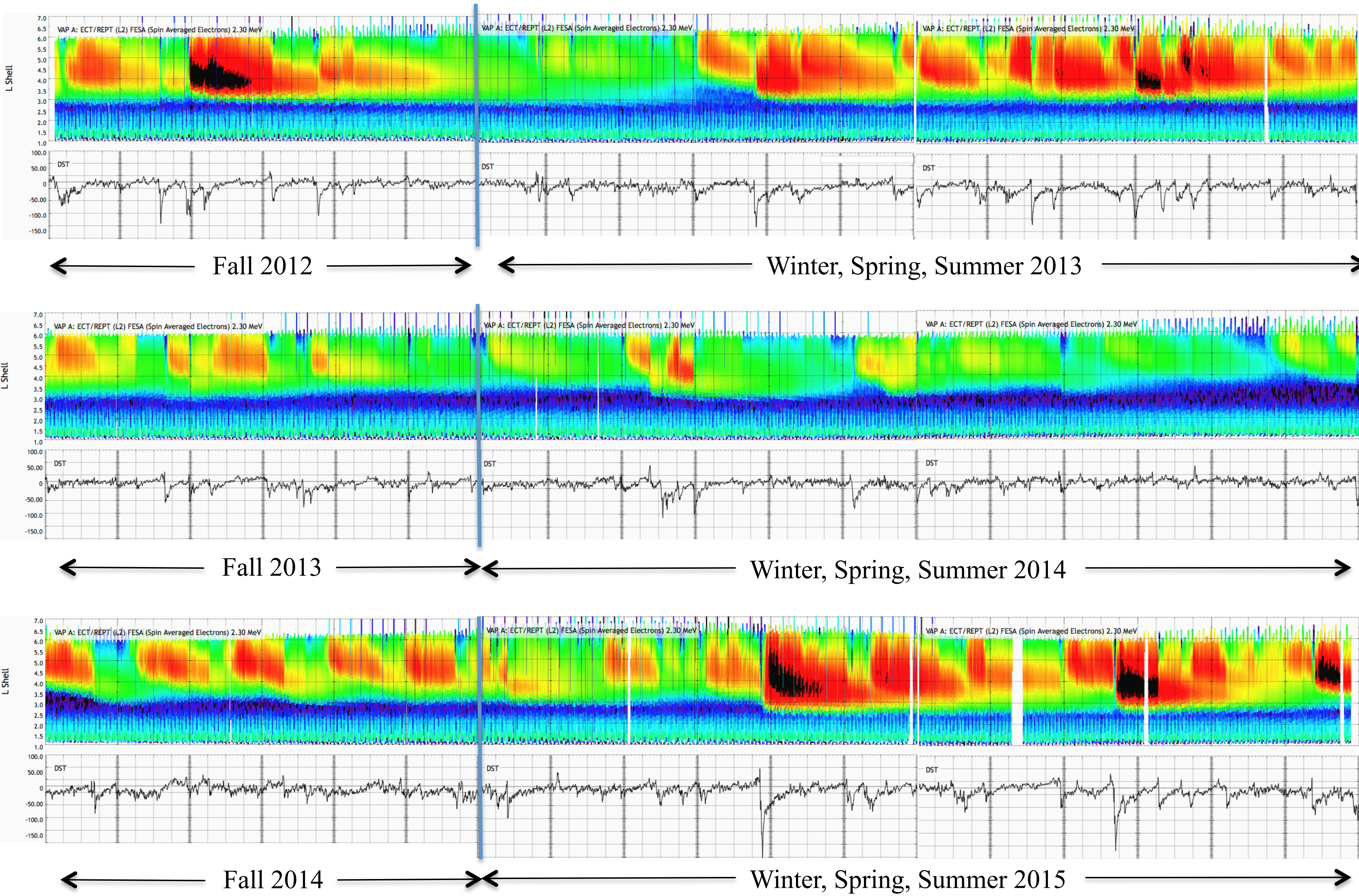
superposed epoch analysis in context with geomagnetic storms
using geosynchronous and other data
(most recent, Gao et al., 2015)

Gao et al. found that

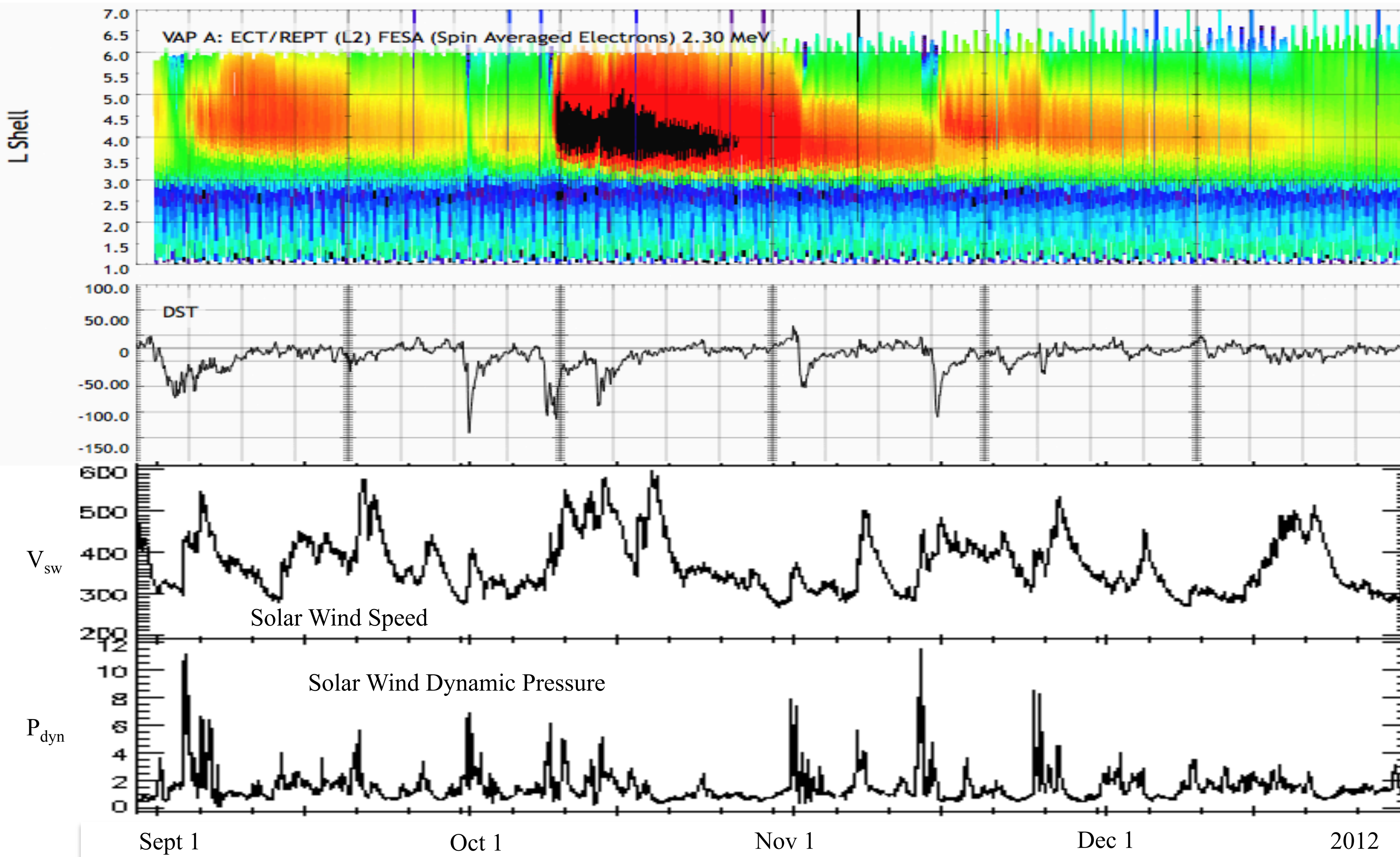
- BOTH solar wind dynamic pressure, $\mathbf{P_{dyn}}$, and IMF $\mathbf{B_z}$ play key roles in causing dropouts.
- Either **by themselves** are capable of producing significant depletion.
- Dropouts occurred when magnetopause is compressed, but also when magetopause at ~10 R_E.

Need to examine statistics of Van Allen Probes dropout events.

Van Allen Probes ECT/REPT 2.3 MeV electron flux Representative Space Weather



Do Solar Wind Speed and Dynamic Pressure add clarity?



Van Allen dropout events (~90 so far)

Results ~ as expected?

- Loss (L = 6 to 5.5) occurs with no storm or nominal storm (moderate P_{dyn} increase, B_z usually negative)
- Loss (L = 5 to 4.5) occurs with storm (moderate P_{dyn} increase, B_z negative)
- Loss (L = 4) occurs with large storm (variable P_{dyn} increase, B_z negative & large)
- Loss (L = 3.5) occurs with very large storm (P_{dyn} change positive and negative, B_z negative & large)

Loss
L = 6 → 3.5

Dst
pos → -150

		apogee			loss inward to L of							Solar Wind parameters						Dst							
#	date	MLT	Driver	L begin	6	5.5	5	4.5	4	3.5	3	P (nPa)	delta P	V (km/s)	delta V	Bz (nT)	delta Bz	pos	< 25	25-50	50-75	75-100	100-125	125-150	>150
29	2013-6-9 1200	21			x							6	2	430	0	-2	0	x							
5	2012-10-23 0600	7	1	6.5	x							3	2	375	25	-4	-4		x						
18	2013-5-6 0600	22			x							8	6	530	130	-5	-5	x							
1	2012-9-13 0000	8	2	6		x						6	3	400	100	-8	-20		x						
6	2012-10-31 2000	7	1	6		x						6	2	360	20	-6	-12	x							
14	2013-4-13 2300	23				x						5	4	500	100	-3	-3	x							
17	2013-5-5 0600	22				x						1	0	350	0	-5	-2			30					
19	2013-5-7 0300	22				x						4	1	520	30	-2	-7		x						
26	2013-5-31 1900	21	2			x						6	7	400	70	-6	-6	x							
30	2013-6-10 0200	21				x						4	2	370	30	-7	-3		x						
34	2013-6-28 0000	20	1	6		x						8	7	430	60	10	10	x							
38	2013-7-5 0600	20				x						3	-1	360	10	-5	-7		x						
42	2013-7-11 0400	20				x						3	2	430	-20	-6	-3			x					
43	2013-7-14 0200	20				x						1	0	410	-10	-8	-6		x						
45	2013-7-18 1400	20				x						9	5	480	50	-10	-10	x							
46	2013-7-18 2000	20				x						3	-2	500	0	-7	-4		x						
47	2013-7-25 1800	19				x						7	6	400	70	-10	-10		x						
50	2013-8-12 2200	19				x						4	2	380	40	-8	-4		x						
51	2013-8-13 1900	19				x						4	2	430	40	-4	-4	x							
61	2013-10-22 1200	18				x						5	4	380	70	-5	-7		x						
82	2014-9-7 0200	5	3	6		x						3	1	420	20	-7	-12		x						
85	2014-10-8 1400	4	1	6		x						6	5	350	0	-5	2		x						
88	2014-11-1 0000	3				x													x						
72	2014-3-13 0000	11				x-						5	4	320	20	-9	-7			x					
53	2013-8-21 0400	19					x					2	-6	430	30	-8	-8			x					
70	2014-2-23 1600	12					x					6	4	450	0	-10	-10				x				
2	2012-9-19 2300	8	3	5.5			x					6	3	420	40	-8	-16			x					
7	2012-11-1 1400	6	3	5.5			x					5	4	350	-10	-12	-20				x				
11	2012-11-23 2200	6					x					6	5	400	80	-6	-3			x					
13	2013-3-27 1000	0					x					6	4	450	80	-5	-8			x					
20	2013-5-14 1200	22					x					2	0	400	30	-5	-8		x						
24	2013-5-24 1800	21					x					8	7	550	100	-11	-6		x						
31	2013-6-20 0200	21					x					4	2	310	30	-8	-5		x						
36	2013-6-29 1800	20					x					6	3	460	30	-4	-5				x				
37	2013-6-30 2200	20					x					1	0	540	30	-3	-1			x					
39	2013-7-6 0600	20					x					1	0	350	0	-12	-8				x				
41	2013-7-9 2100	20					x					6	5	420	80	14	8	x							
44	2013-7-14 2000	20					x					1	0	380	20	-10	0				x				
48	2013-7-26 0100	19					x					6	0	500	0	-5	-5		x						
52	2013-8-15 2300	19					x					5	3	620	70	5	5		x						
54	2013-8-27 1800	19					x					6	5	400	60	-13	-8				x				
56	2013-9-10 1800	18					x					4	3	380	40	-5	-9		x						
65	2013-12-25 1000	15					x					5	4	320	40	-8	-12			x					
67	2014-1-8 0400	14					x					25	20	450	0	-10	-15		x						
73	2014-4-05 2200	10					x					18	8	440	10	-8	-15		x						
80	2014-8-12 0100	6					x					2	1	550	120	-5	-7		x						
83	2014-9-12 0400	5					x					10?	7	450	70	?	?		x						
8	2012-11-6 2200	6	2	5				x				8	6	370	70	-12	-15		x						
15	2013-4-24 0200	23						x				8	2	340	20	-10	-5			x					
16	2013-5-1 0800	22						x				6	3	450	50	-10	-5			x					
32	2013-6-20 2000	21						x				8	5	460	80	-10	-15		x						
33	2013-6-21 0200	21						x				5	-1	500	0	-6	0		x						
49	2013-8-4 1800	19						x				8	6	500	150	-12	-17			x					
55	2013-8-31 0000	19						x				2.5	0	400	0	-8	-8			x					
57	2013-9-24 1000	18						x				7	5	420	80	-10	-12			x					
60	2013-10-14 1800	18						x				6	5	450	120	-8	-7				x				
63	2013-11-9 0600	17						x				8	6	550	150	-14	-14				x				
66	2014-1-1 1200	15						x				6	4	550	150	-8	-13			x					
68	2014-2-16 0000	13						x				20	18	420	80	-10	-8		x						
76	2014-5-4 0000	9						x				4	2	340	40	-5	-5			x					
78	2014-6-8 0600	8						x				15	10	550	100	18	25				x				
86	2014-10-9 0600	4						x				2	0	380	20	-6	-5			x					
9	2012-11-12 2300	6	3	4.5				x-				12	9	370	60	-15	-10		x						
22	2013-5-17 0000	22						x-				2	0	370	-10	-6	-8			x					
64	2013-11-16 0000	16						x-				6	5	500	150	-7	-3			x					
21	2013-5-16 0300	22						x+				5	3	420	20	-7	-12		x						
12	2013-3-17 0800	1							x			15	14	700	250	-18	-20						x		
23	2013-5-18 0400	22	3						x			8	7	440	70	-12	-7				x				
25	2013-5-25 0600	21							x			3	0	500	0	-3	2				x				
58	2013-10-2 0600	18							x			33	30	620	280	-28	-30					x			
59	2013-10-8 2200	18							x			18	16	600	300	-28	-28				x				
62	2013-10-30 1200	17							x			2	1	320	40	-8	-12				x				
75	2014-4-29 2200	9							x			5	3	320	10	-8	-8				x				
77	2014-5-22 1900	9							x			4	2	360	40	-9	-12			x					
79	2014-6-18 0000	8							x			2	0	460	100	-6	-11			x					
81	2014-8-27 0800	6							x			6	2	300	0	-13	-13				x				
84	2014-9-12 2300	5	3						x			10	5	700	100	-12	-20					x			
87	2014-10-14 1600	4							x			10	8	450	50	-8	-13				x				
89	2014-11-4 1000	3							x											x					
40	2013-7-6 2200	20							x+			1	0	320	-20	-8	4				x				
3	2012-9-30 2300	8	1	4.5						x		8	6	420	100	-18	-12							x	
4	2012-10-8 0600	7	1	4						x		6	5	400	80	-15	-10						x		
10	2012-11-14 0300	6								x		4	3	400	40	-17	-7						x		
27	2013-6-1 0800	21								x		4	-4	500	100	-20	-35							x	
28	2013-6-7 0000	21								x		2	1	420	-40	-12	-9					x			
35	2013-6-29 0000	20								x		4	3	350	-30	-10	-20						x		
69	2014-2-19 0800	13								x		6	5	440	40	-12	-7						x+		
71	2014-2-28 1800	12								x		15	12	470	120	-18	-18						x-		
74	2014-4-12 0600	10								x+		4	2	340	-20	-9	-9					x			

Conclusions

- A lot left to do to be able to make accurate predictions even for simplest response (dropouts) at one energy (2.3 MeV)
  - How large must P_{dyn}, B_z be for loss to occur at each L level?
  - Does duration of increase matter?
  - Does V_{sw} matter?
  - Does it matter which increases first?
  - Are other solar wind features important?
- Need more simulations of the smaller events
- Need to better understand the processes, chain-of-events
- Need to add in all energies, multipoint observataions in all relevant regions.