How particles are accelerated to high energies in large SEP events?

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Disclaimer

OKeia ke panepo'o o keia halawai.

Everything
presented in the
next 30 minutes
could be

right.

Characteristics of Large SEP Events

- **Infrequent:** *~5 - 10 large events/year in solar-active years. Associate with fast CME-driven Shocks (top 1-2%) and/or large flares.*
- **Energetic**: *10 keV < K < 10 GeV*
- **Power law spectrum:** *reasonably "universal ".*
- **High intensity:** *intensity > 10 pfu (proton cm-2 s-1sr-1) at >10 MeV channel (corresponding to $10^2 – 10^6$ increase depending on energy)*.
- **Composition:** *electrons, protons, heavy ions*.

First order Fermi acceleration?

problems:

Strong shocks not always lead to SEP

Spectral and abundances variability

Answers?

- Shock geometry?
- *Pre-existing turbulence?*

Pre-turbulence-- Hint from observation

Correlation between large SEP events and intersections of multiple CMEs.

Individual large SEP events at 1 AU may correspond to multiple CMEs near the Sun. (seen also Feynmann et al.)

Primary CME travels faster than one or several preceding CMEs, leading to CME intersections.

Gopalswamy et al (2004) concluded that: Higher SEP intensity results whenever a CME is preceded by another wide CME from the same source region. And the correlation between the peak intensity and the CME speed is improved substantially over earlier work (Kahler, 2001).

Gopalswamy et al. JGR, 2004
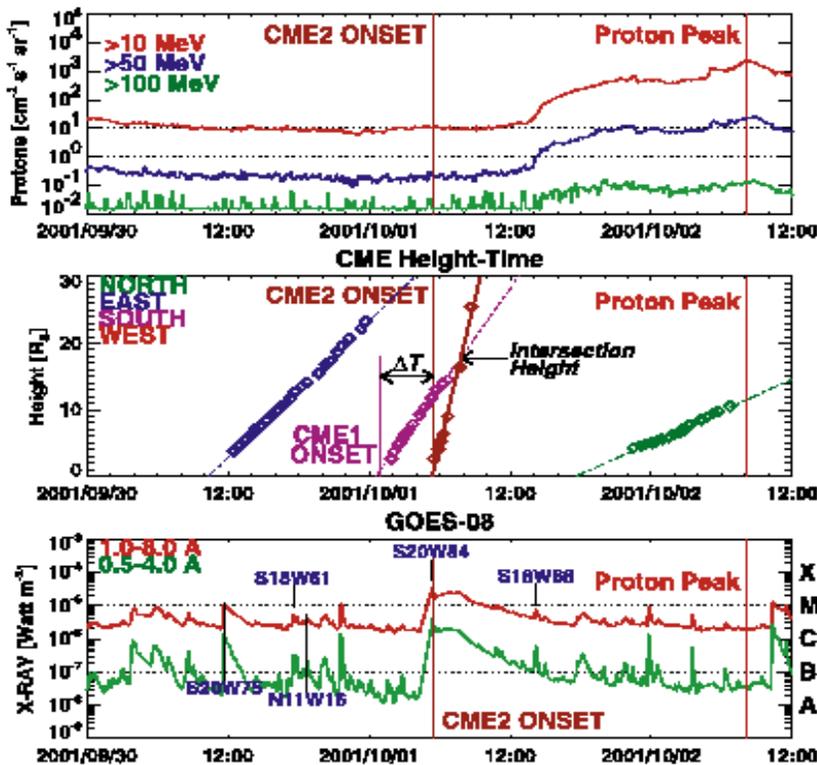
The survey

Table 1. Major Solar Energetic Particle Events of Cycle 23, 1996–2003

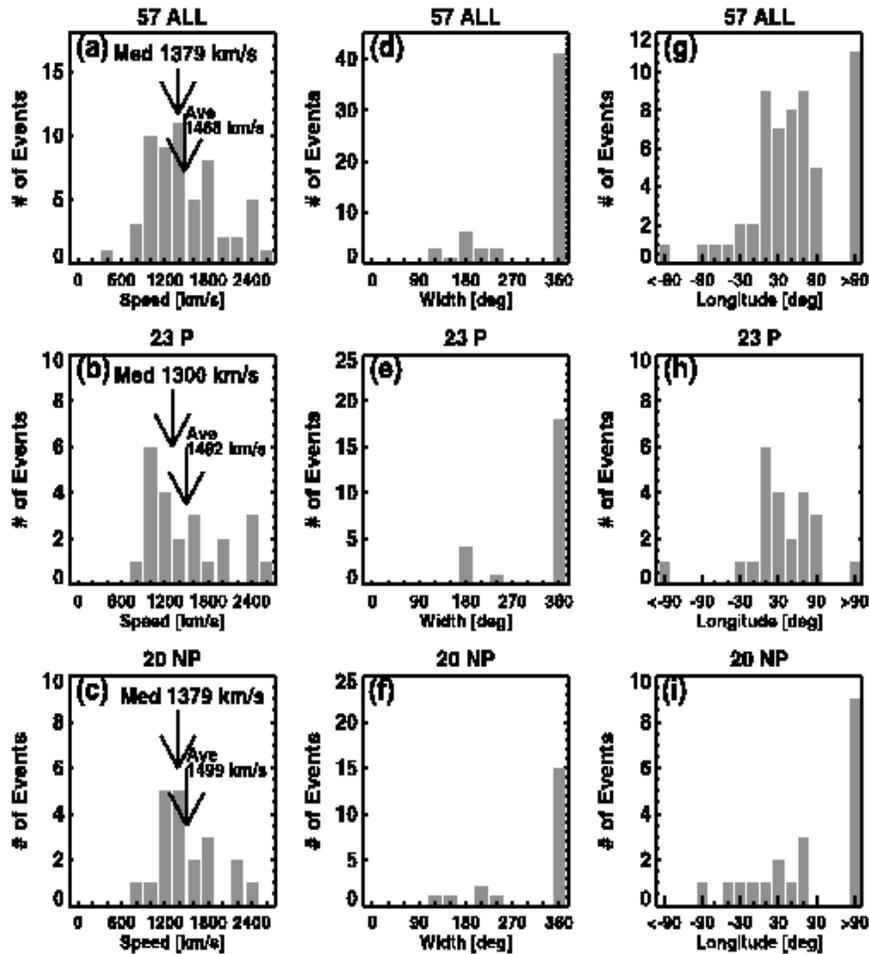| No.	SEP Date	SEP Time	CME Time	V2, km/s	W2, deg	M*	Source Loc.[h]	AR No.	Flare Imp.[c]	Flare Onset	Metric II Onset[d]	DH II Onset[e]	I_p pfu[f]	I_e efu[g]
01	1997/11/04	0700	0610 P	785	H	10	S14W33	8100	X2.1/2B	0552	0558	0600	72	2.1e-02
02	1997/11/06	1300	1210 P	1556	H	..	S18W63	8100	X9.4/2B	1149	1153	1210	490	1.0e-01
03	1998/04/20	1100	1007 O	1863	165	24	S43W90	...	M1.4/?	0938	0956	1025	1700	3.4e-02
04	1998/05/02	1400	1406 P	938	H	8	S15W15	8210	X1.1/3B	1331	1341	1425	150	4.8e-02
05	1998/05/06	0800	0829 P	1099	190	70	S11W65	8210	X2.7/1N	0758	0805	0815	210	8.1e-02
06	1998/05/09	0500	0335 P	2331	178	8	>SW90	8210	M7.7/?	0304	0326	0335	12	3.8e-03
07	1999/04/24	1500	1331 NP	1495	H	19	>NW90	...	...	...	N?	1350	32	3.7e-03
08	1999/05/03	1300	0606 NP	1584	H	..	N15E32	8530	M4.4/2N	0536	0550	0550	14	...
09	1999/06/01	2000	1937 NP	1772	H	11	>NW90	...	C1.2?	1853	N?	1850	48	6.2e-03
10	1999/06/04	0800	0726 NP	2230	150	5	N17W69	8552	M3.9/2B	0652	0702	0705	64	2.6e-02
11	2000/02/18	1000	0954 NP	890	118	5	>NW90	...	...	...	0919	0938	13	2.0e-02
12	2000/04/04	1700	1632 NP	1188	H	6	N16W66	8933	C9.7/2F	1512	1525	1545	55	1.4e-02
13	2000/06/06	1900	1554 P	1119	H	18	N20E18	9026	X2.3/?	1458	1516	1520	84	...
14	2000/06/10	1800	1708 NP	1108	H	11	N22W38	9026	M5.2/3B	1640	1655	1715	46	...
15	2000/07/14	1100	1054 P	1674	H	..	N22W07	9077	X5.7/3B	1003	1019	1030	24000	1.9e-01
16	2000/07/22	1200	1154 NP	1230	105	15	N14W56	9085	M3.7/2N	1117	1125	1145	17	7.3e-03
17	2000/09/12	1300	1154 NP	1550	H	..	S17W09	9163	M1.0/2N	1131	1133	1200	320	2.3e-02
18	2000/10/16	0800	0727 NP	1336	H	..	>W90	9193	M2.5/?	0640	0708	0710	15	3.3e-03
19[b]	2000/10/25	1200	0826 O	770	H	18	N10W66	9199	C4.0?	0845	N	0930	15	1.6e-03
20	2000/11/08	2300	2306 O	1345	H	..	N10W77	9213	M7.4/3F	2242	2315	2320	14800	3.2e-01
21	2000/11/24	1400	1530 P	1245	H	10	N22W07	9230	X2.3/2B	1451	1507	1525	94	...
22	2001/01/28	1700	1554 O	916	250	12	S04W59	9313	M1.5/1N	1540	N	1545	49	9.8e-03
23	2001/03/29	1100	1026 P	942	H	3	N20W19	9393	X1.7/1F	0957	1003	1012	35	2.3e-02
24	2001/04/02	2300	2206 P	2505	244	10	N19W72	9390	X20/?	2132	2152	2205	1100	1.1e-01
25	2001/04/10	0800	0530 P	2411	H	17	S23W09	9415	X2.3/3B	0506	0513	0524	355	1.6e-02
26	2001/04/12	1200	1031 P	1184	H	5	S19W43	9415	X2.0/?	0939	1018	1036	51	...
27	2001/04/15	1400	1406 P	1199	167	..	S20W85	9415	X14/2B	1319	1348	1405	951	1.2e-01
28	2001/04/18	0300	0230 NP	2465	H	8	S23W92	9424	C2.2/?	0211	0217	0255	321	2.2e-02
29	2001/04/26	1400	1230 P	1006	H	9	N17W31	9433	M7.8/2B	1126	1335	1240	57	...
30	2001/05/07	1300	1206 NP	1223	205	30	>NW90	...	...	...	N?	1312	30	2.8e-03
31	2001/06/15	1600	1556 NP	1701	H	8	>SW90	...	...	1524	1533	1542	26	9.9e-03
32	2001/08/09	1900	?	...	...	11	S17E19?	9570	C7.8/?	1822	N	N	17	...
33	2001/08/16	0100	2354[j] B	1575	H	40	Backside	...	...	...	N?	0010	493	...
34	2001/09/15	1200	1154 O	478	130	4	S21W49	9608	M1.5/1N	1104	1129	1150	11	3.0e-03
35	2001/09/24	1100	1030 P	2402	H	22	S16E23	9632	X2.6/?	0932	N	1045	12900	5.5e-02
36	2001/10/01	1300	0530 P	1405	H	22	S20W84	9628	M9.1/?	0441	N	0536	2360	...
37	2001/10/19	1730	1650 P	901	H	5	N15W29	9661	X1.6/2B	1613	1624	1645	11	3.4e-03
38	2001/10/22	1700	1506 NP	1336	H	11	S21E18	9672	M6.7/2N	1427	1453	1515	24	8.2e-03
39	2001/11/04	1700	1635 O	1810	H	11	N06W18	9684	X1.0/3B	1603	1610	1630	31700	1.2e-01
40	2001/11/17	0600	0530 NP	1380	H	15	S13E42	9704	M2.8/1N	0449	0500	0520	34	3.1e-03
41	2001/11/22	2100	2030 NP	1443	H	...	S25W67	9704	M3.8/2B	2018	2022	2050	...	...
42	2001/11/22	2400	2330 O	1437	H	13	S15W34	9704	M9.9/?	2232	2231	2240	...	7.3e-03
43	2001/12/26	0530	0530 O	1406	212	7	N08W54	9742	M7.1/1B	0432	0502	0520	779	1.0e-01
44	2001/12/28	2400	2006 NP	2044	H	25	S26E90	9756	X3.4/?	2002	1959	2030	76	...
45	2002/01/08	0300[k]	1754 O	1794	H	25	>NE90	...	...	...	N?	1830	91	...
46	2002/01/14	2400	0535 O	1492	H	35	S28W83	...	M4.4/?	0529	608	0625	15	...
47	2002/02/20	0600	0630 NP	952	H	48	N12W72	9825	M5.1/1N	0552	615	0620	13	4.3e-02
48	2002/03/15	0300[k]	2306 O	907	H	10	S08W03	9866	M2.2/1F	2209	N	2245	13	2.2e-01
49	2002/03/18	0600	0254 O	989	H	18	S09W46	9866	M1.0/?	0216	N	0255	53	...
50	2002/03/22	1330	1106 NP	1750	H	15	>SW90	9866	M1.6/?	1012	1047	1130	16	1.2e-03
51	2002/04/17	1030	0826 NP	1218	H	10	S14W34	9906	M2.6/2N	0746	0808	0830	24	...
52	2002/04/21	0230	0127 O	2409	241	9	S14W84	9906	X1.5/1F	0043	0119	0130	2520	6.5e-02
53	2002/05/22	0600	0350 P	1494	H	15	S30W34		C5.0/?	0318	N	0410	820	2.1e-02
54	2002/07/07	1300	1106 NP	1329	>205	12	>W90	10017	M1.0/?	1115	N	1135	22	8.7e-03
55	2002/07/15	1030[k]	2130 P	1300	>188	10	N19W01	10030	M1.8/?	2103	N	2115	234	9.0e-04
56	2002/07/20	0600	2130 P	2017	H	10	>SE90	10039	X3.3/?	2104	2107	2130	28	...
57	2002/08/14	0300	0230 O	1309	133	7	N09W54	10061	M2.3/1N	0147	0157	0220	26	5.0e-02
58	2002/08/22	0230	0206 P	1005	H	12	S07W62	10069	M5.4/2B	0147	0155	0245	36	1.0e-02
59	2002/08/24	0130	0127 O	1878	H	8	S02W81	10069	X3.1/1F	0049	0109	0145	317	5.9e-02
60	2002/11/09	1500	1331 P	1838	H	7	S12W29	10180	M4.6/2B	1308	1317	1320	404	7.1e-02

total of 57 events between 1996-2002 are selected, with intensity > 10 pfu (proton cm-2 s-1sr-1) at >10 MeV channel.

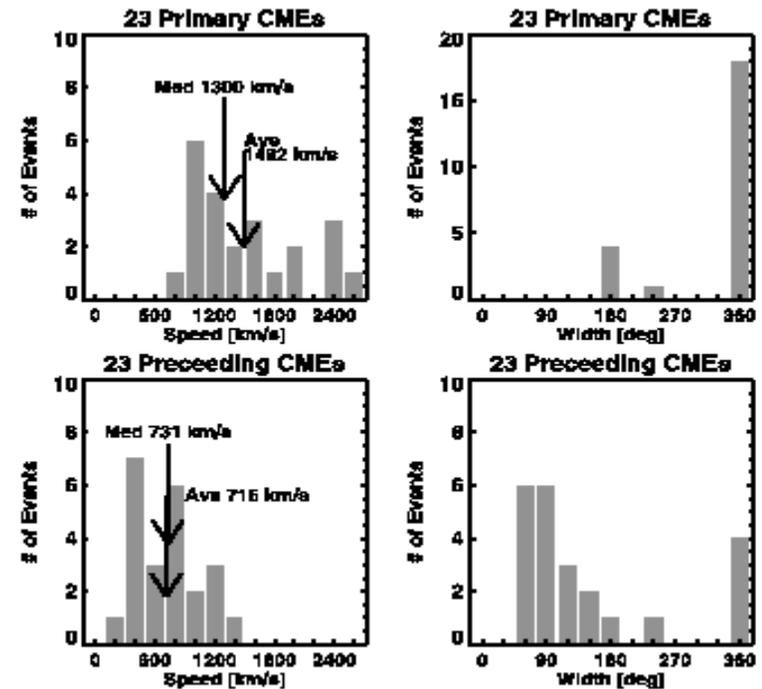23 with preceding CMEs (within 1 day)

20 without preceding CMEs

Primary and Preceding CME shock properties
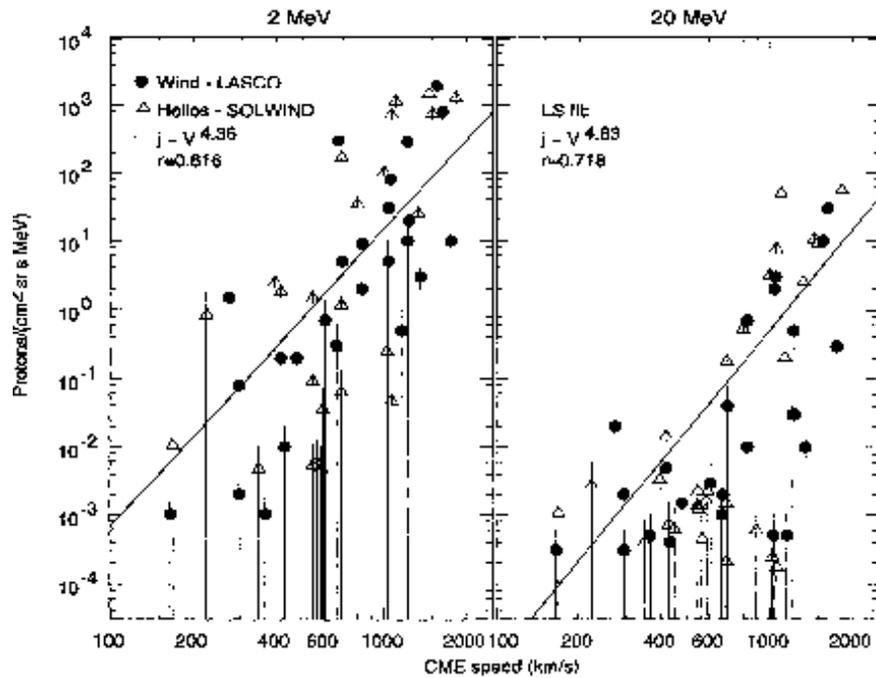
primary

preceding

The shock speeds and source longitudes are similar for shocks with and w/o preceding shocks.

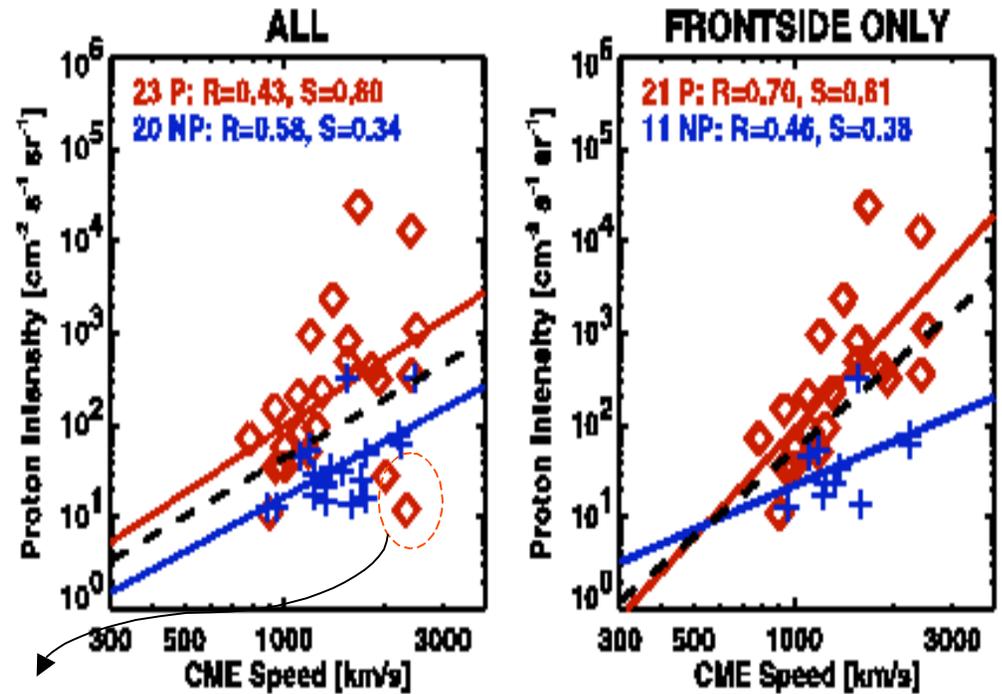The preceding CMEs are generally weaker

Gopalswamy et al. JGR, 2004

Correlation of intensity with CME shock speed

Reames, AIP conf. 516, 2001

Gopalswamy et al. JGR, 2004

Nat's mistake

Old data from WIND, IMP-8, Helios.
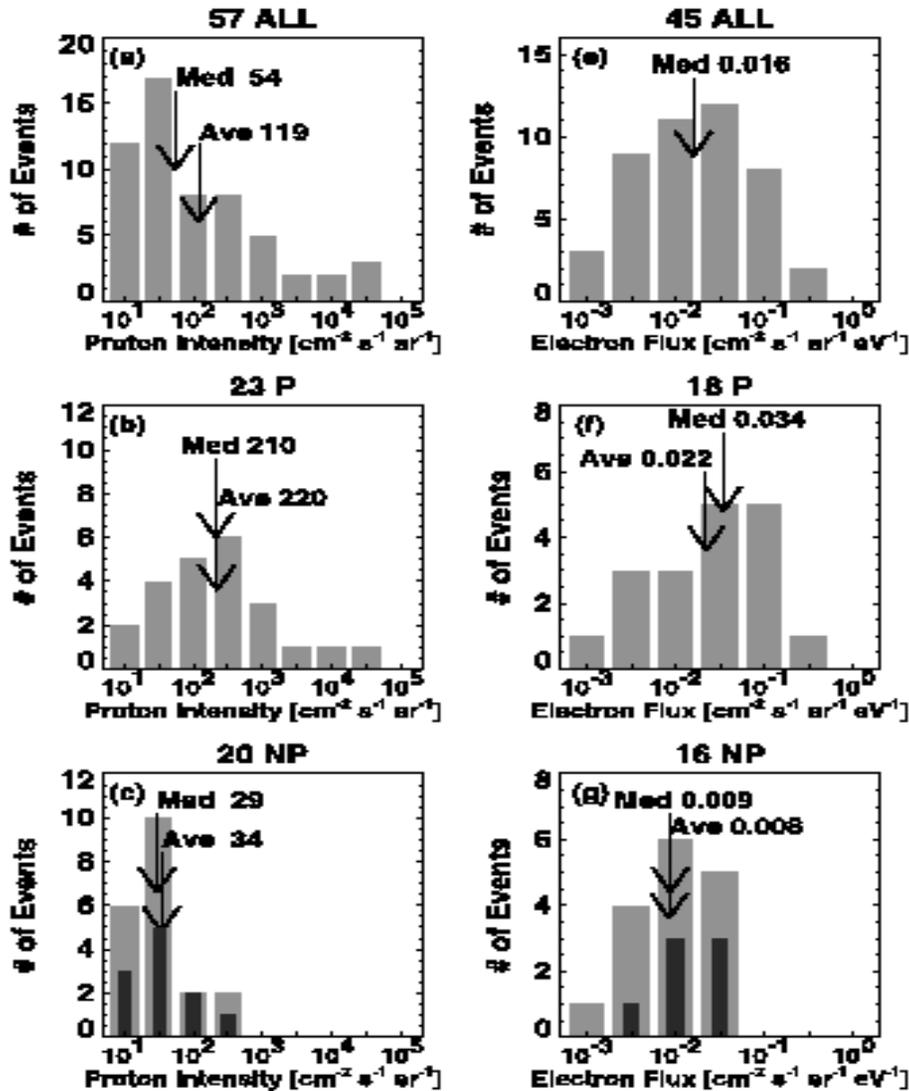
Peak intensity at 2 MeV and 20 MeV.

CMEs with and w/o preceding CMEs are clearly separated. Particle intensities w/o preceding shocks are generally smaller.

Distribution of particle intensity

proton   electron

Gopalswamy et al. JGR, 2004

Primary CMEs with preceding CMEs tend to have higher particle intensity than CMEs without preceding CMEs.

A strong correlation between high particle intensity events and the existence of preceding CMEs.

Assume the enhanced intensity is due to the presence of multiple shocks.

Question: How and why multiple shocks can accelerate particles to higher energy and increase the intensity?

Fermi acceleration and time scales

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}(\kappa\frac{\partial f}{\partial x}) - \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + \frac{f}{\tau} = \frac{f_s}{\tau_s}$$

$$f = \begin{cases} A(p) & \text{downstream} \\ B(p)exp[(u/\kappa)(1+\delta)x] & \text{upstream} \end{cases}$$
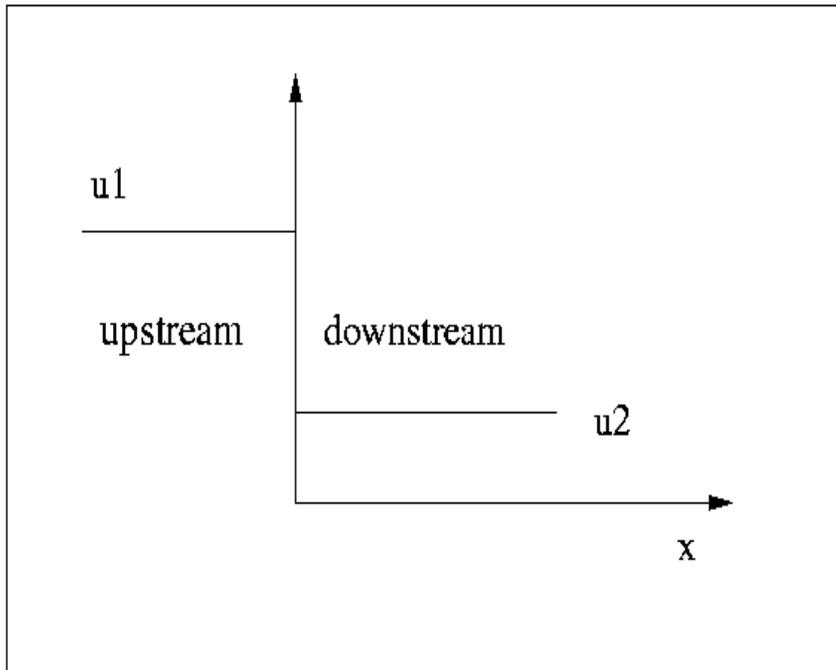
$$\delta = \frac{-1 + \sqrt{1 + 4\alpha\kappa/u_1^2}}{2}$$

$$f(p) \sim p^{-(1+\delta)[3s/s-1]}$$

steady state, with boundary
   conditions:
a) f ->0 at the upstream boundary.
b) f = some non-zero value at down
   stream boundary.

Li et al 2005

$\tau \sim$ loss time scale

$\tau_{acc} \sim \kappa/u_1^2$ acceleration time scale

another time scale $t_{sh} \sim$ shock life time

Acceleration time scale and maximum energy

The highest energy is decided by the acceleration time scale.

$$\Delta t = \frac{3s}{s-1} \frac{\kappa(p)}{u_{sh}^2} \frac{\Delta p}{p}$$ Drury (1983)

$$\kappa(p) = p^\alpha = \kappa(p_0)(\frac{p}{p_0})^\alpha = \kappa_0(\frac{p}{p_0})^\alpha$$

$$t = \frac{3s}{s-1} \frac{\kappa_0}{u_{sh}^2} \frac{1}{\alpha} (\frac{p_i}{p_0})^\alpha [(p_f/p_i)^\alpha - 1]$$

Define p0 $$\frac{3s}{s-1} \frac{\kappa_0}{u_{sh}^2} \frac{1}{\alpha} = t$$

$$(p_0/p_i)^\alpha = [(p_f/p_i)^\alpha - 1]$$

$$p_f/p_i = (1 + (p_0/p_i)^\alpha)^{1/\alpha}$$

If $\lambda \sim p^{1/3}$, $\alpha = 4/3$.

$$p_i \ll p_0, \qquad p_f = p_0,$$

$$p_i \sim p_0, \qquad p_f = 2^{1/\alpha} p_0,$$

$$p_i \gg p_0, \qquad p_f = p_i$$

p0 defines the highest accelerated momentum when the injection momentum is small. p0 is decided by the acceleration time scale.

Role of the preceding shock

Assume a first shock accelerate particles from, say 10 keV to 10 MeV.

Expect the second shock, to only accelerate particles of 10 MeV to 20 MeV or so, *if the acceleration time scales are the same*.

Expect the (integrated) intensity of energetic particle remains the same order of magnitude if the injection energies are similar.

The higher intensities at high energies when there are preceding shocks ---> smaller acceleration time scale and lower injection energy at the 2nd shock.

__Lower Injection energy__: stronger turbulence helps particles to go cross the shock more easily.)

__Smaller acceleration time scale__

$$\Delta t = \frac{3s}{s-1} \frac{\kappa(p)}{u_{sh}^2} \frac{\Delta p}{p}$$

➔ A smaller κ at the second shock.

A decrease of k by 10 --> an increase of 32 for the maximum kinetic energy.

Decrease of κ from observation

$\kappa \approx 1/I$ I: intensity of magnetic turbulence.   10/28/2003 event

upstream   downstream
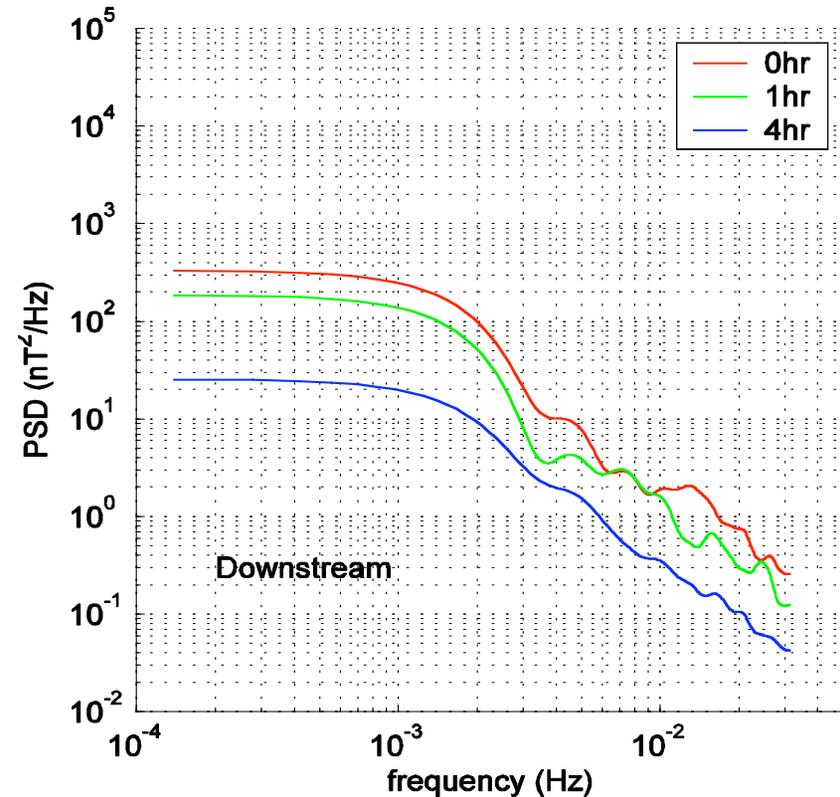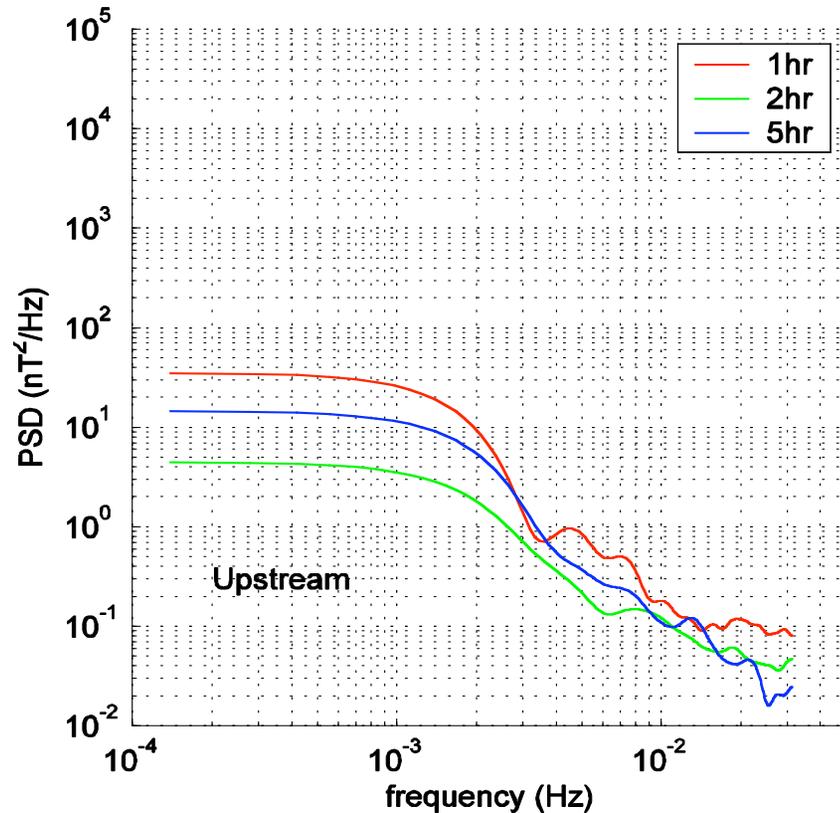
- Streaming particles at a (parallel) shock can enhance the interplanetary turbulence (upstream).

- The turbulence will further increase when cross the shock front.

- The downstream region of the preceding shock is the upstream region of the primary shock.

- Wave (inverse) cascading exist.

A simple calculation

Assuming a spectrum of $f(p) = p^{-\gamma}$ $\quad p_1 < p < p_2$ after the first shock,

What is the spectrum g(p) after the second shock?

Consider particles in (q, q+ dq), after the passage of the second shock:

$$g(p, q) = c(q)p^{-\beta} \quad q < p < p_{max}(q) \quad p_{max}(q) = q(1 + (q_0/q)^\alpha)^{1/\alpha} \quad \beta = 3s/(s-1)$$

Number conservation: $\quad c(q) = [\beta - 3/(q^{3-\beta} - p_{max}(q)^{3-\beta})](q)q^{2-\gamma}dq$

Integrate over q: $$g(p) = \int_{p1}^{p2} \frac{(\beta - 3)q^{2-\gamma}}{q^{3-\beta} - p_{max}(q)^{3-\beta}}dq \ p^{-\beta}$$

Special case: $\quad t - > \infty \qquad p_{max}(q)^{3-\beta} - > 0$

$$g(p) = \frac{\beta - 3}{\beta - \gamma}(p_2^{\beta-\gamma} - p_1^{\beta-\gamma})p^{-\beta}$$

Two cases

1) $\beta > \gamma$

spectrum does not change

$$f(p) = p^{-\gamma} \quad p_1 < p < p_2$$

$$g(p)/f(p) = \frac{\beta - 3}{\beta - \gamma}$$
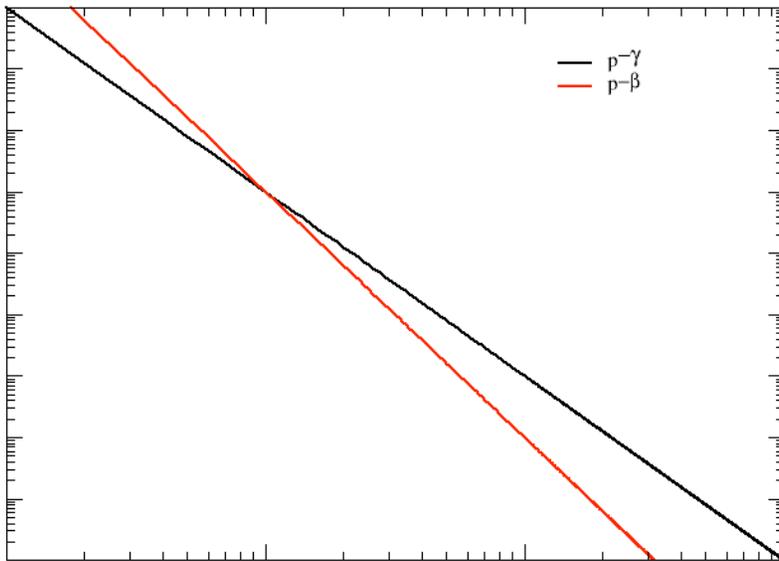
2) $\beta < \gamma$

Harder spectrum, dramatic increase of intensity at high energies

$$g(p)/f(p) = \frac{\beta - 3}{\gamma - \beta}(p/p1)^{\gamma - \beta}$$
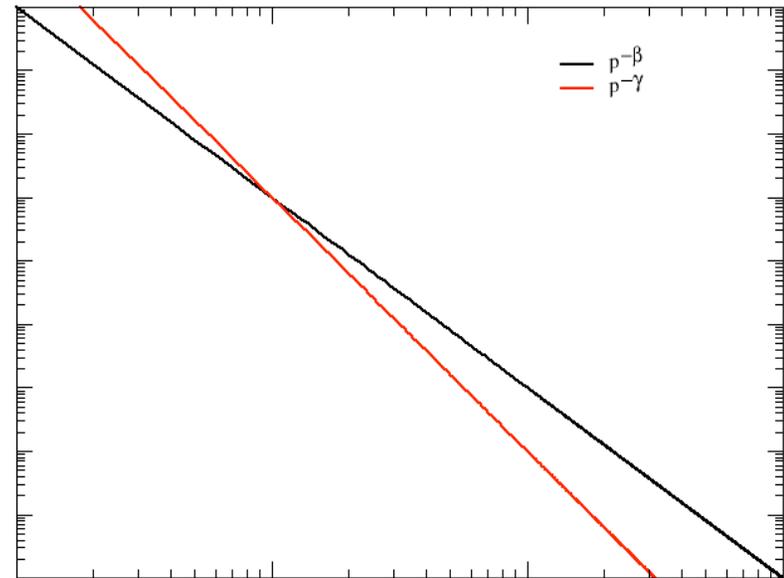
The downstream magnetic turbulence, which decide both the acceleration time scale and injection energy at the 2nd shock is the single most important quantity!
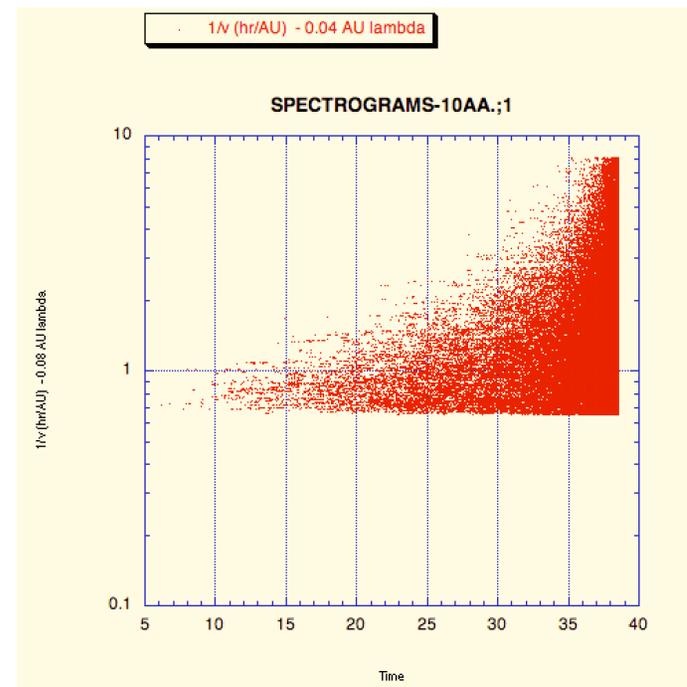
Possible signatures from observation

- Spectrogram– the story-teller: *(Li, Mason, Desai et al. 2005)*

Particles escaped from the second shock will propagate in the turbulence-enhanced "downstream" region of the first shock.
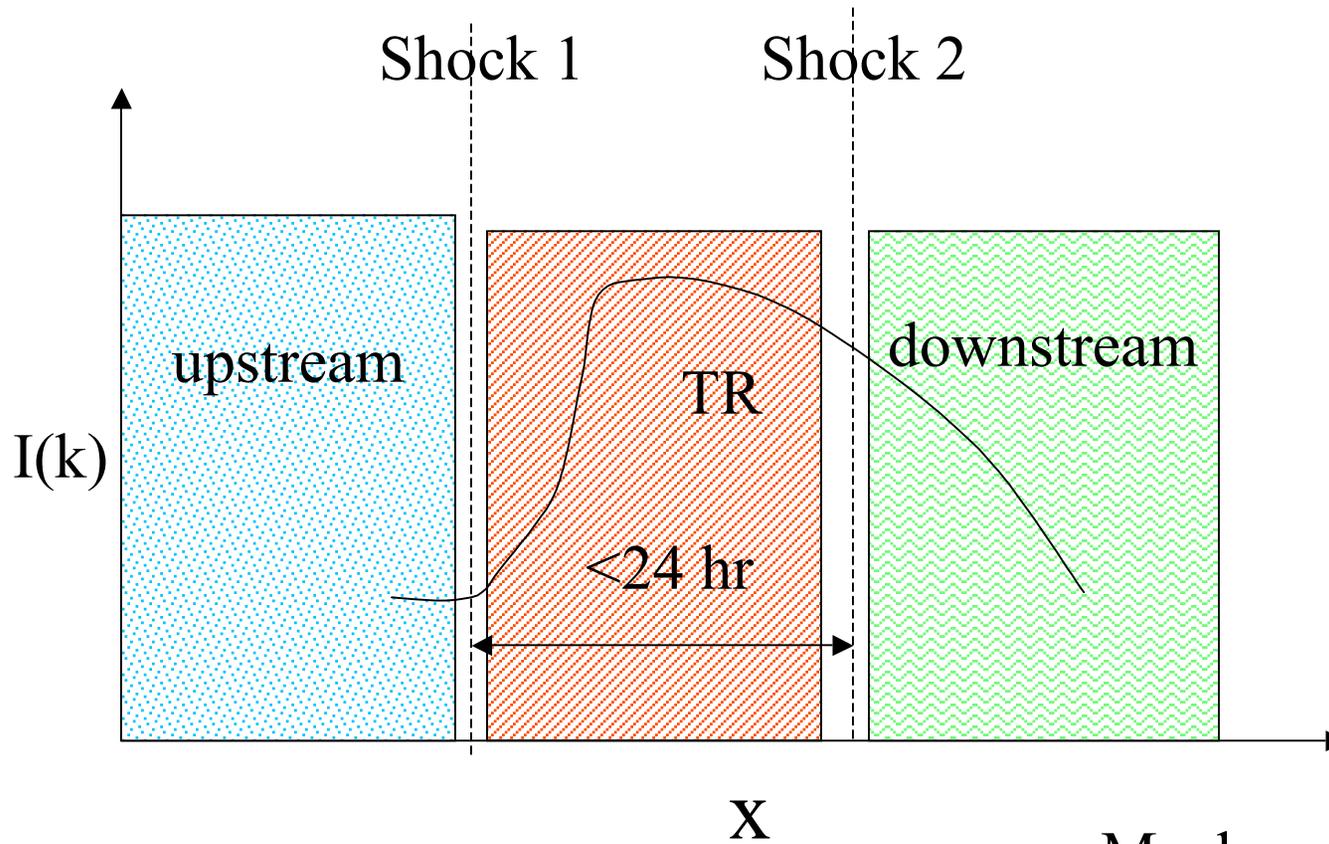
Expect smaller mean free path.
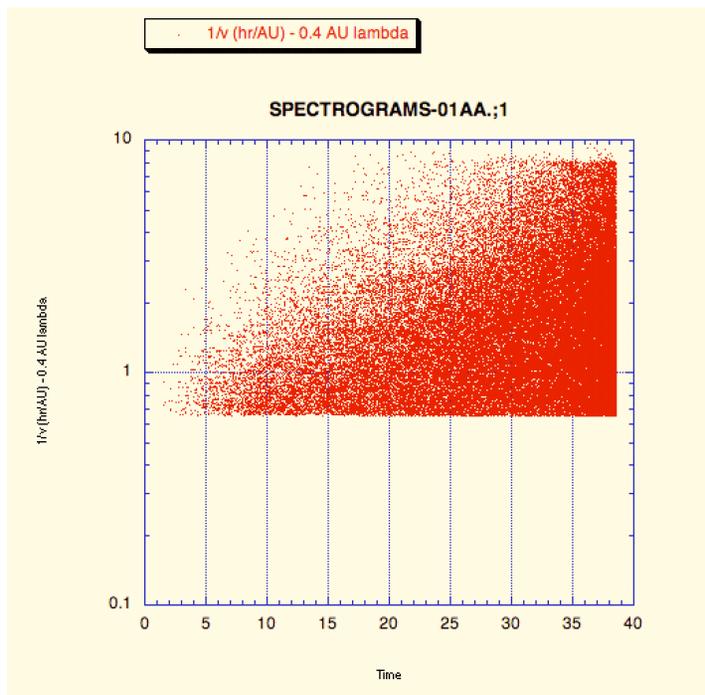
The "left" shape   The "right" shape

Complication of reality

• If the separation between two shocks is too large, the turbulence may drop to background level.

• Mean free path between two shocks should be x-dependent.

• Maybe additional acceleration between the two shocks?

TR: Turbulent Region

The secret recipe

1) Take some truth from observation.

2) Add some beauty from a simple theory.

3) Perform a model calculation till exhausted.

Perp. shock acceleration
-- Hint from observation

Comparison of Fe/C ratio for 2002/4/21 & 2002/8/24 events
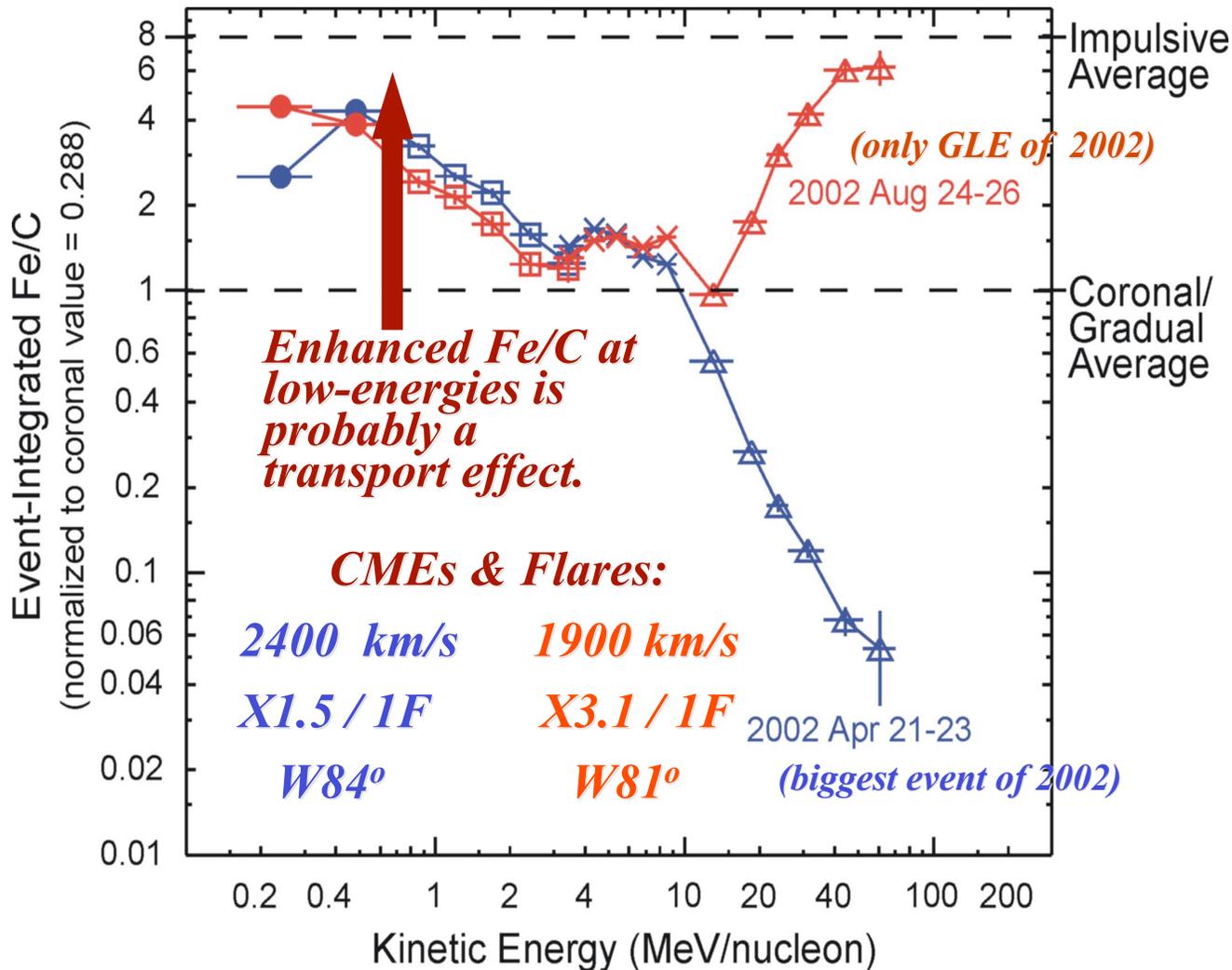
below 10 MeV/Nuc, Fe/C are similar but diverges at high energies.

The seed population must be different --- These two shocks have different selection windows.

Perpendicular shocks?

Courtesy of Allen Tylka

Time scale and Maximum energy

- *Assume at a given time in the simulation, the shock has had sufficient time to accelerate all the particles.*

- **When particle complete one cycle of traverse, The momentum gain is:**

$$\Delta p = \frac{4}{3} \frac{u_1 - u_2}{v} p$$

- **The time it takes (assuming a momentum p (velocity v) with diffusion coefficient $\kappa(p)$) is :**
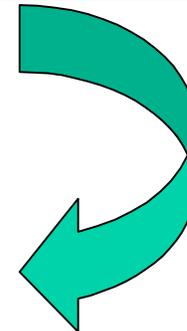
$$\Delta t = \frac{4}{v} \frac{\kappa(p)}{u_1}$$

The acceleration time scale is therefore:

Dynamic shock time scale

(modified shock life time):

$$\frac{q(t)}{u_1^2} \int_{p_{min}}^{p_{max}} \kappa(p') d(\ln(p'))$$

$$\frac{R(t)}{\dot{R}(t)}$$

Role of the preceding shock

_ If the first shock can acceleration particles from, say 10 keV to 10 MeV.

_ The second shock, however, can only accelerate particles of 10 MeV to 20 MeV or so, *if the acceleration time scales are the same*.

_ *The higher intensities at high energies when there are preceding shocks ---> smaller acceleration time scale at the 2nd shock.*
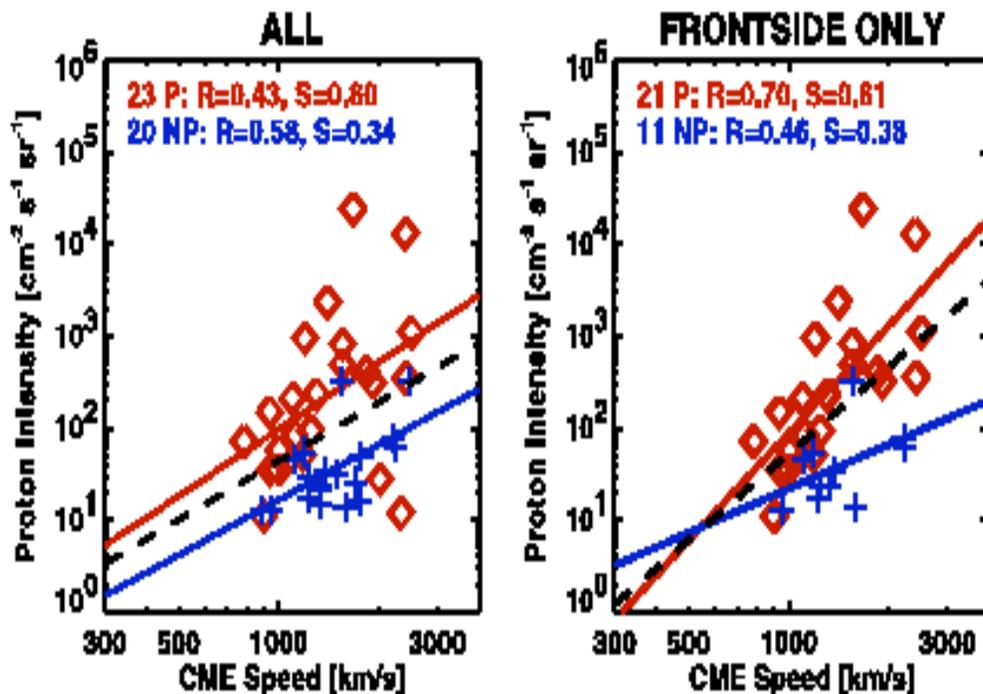
$$\Delta t = \frac{3s}{s-1} \frac{\kappa(p)}{u_{sh}^2} \frac{\Delta p}{p}$$

κ at the second shock must be smaller.

A decrease of k by 10 --> an increase of 32 for the kinetic energy.

Possible signatures from observation

- Spectrogram– the story-teller: *(Li, Mason, Desai et al. 2005)*

1) for the 2nd shock to catch the first shock, it must have a higher speed

2) for the acceleration to be noticeable at higher energies, the compression ratios for P shocks may be larger than NP cases?

Spectral time evolution at mid-energies:

- Intensities at lower energies:

Expect NO differences between the injection energies for the first and the second shock.

The intensities at (near) injection energy should NOT show dependence on event being P or NP.

Study the energy dependence of the correlation