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14. ABSTRACT

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A REVISED CLASSIFICATION SCHEME FOR SOLAR ENERGETIC PARTICLE EVENTS

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Abstract. We propose a revision of the standard "impulsive/gradual" classification scheme for solar energetic particle (SEP) events. In the new scheme, SEP events are divided into two basic classes: "Flare" and "Shock". The flare class corresponds to the old impulsive class, or more specifically, the ^{3}He-rich subset of that class. The shock class, which replaces the gradual class, consists of two subclasses based on shock geometry and seed particle population, either quasi-perpendicular (operating on flare particle seeds) or quasi-parallel (coronal or solar wind suprathermals). Our revision was motivated by recent observations of large and presumably gradual events that had impulsive event composition and charge states at high energies. The new classification scheme is based on the Tylka *et al.* (2005) study linking shock geometry and seed populations to Fe/O variation in large SEP events. We show that flare time scale, the organizing parameter in the current two-class picture, can be incorporated naturally into the revised SEP classification scheme, and we review recent evidence that supports the proposed framework.

Key words: Sun - energetic particles - shock wave

1. Introduction

The two-class picture of SEP acceleration at the Sun [Table I; Reames, 1993; see also Klecker *et al.* (1990) and Reames (1990, 1995, 1999)], developed during the past ~20 years by Don Reames (Figure 1) and others, was challenged by observations of four large and, therefore, presumably gradual events (6 November 1997, 2 May 1998, 6 May 1998, 14 November 1998) that had both impulsive composition (Fe/O ~1; Cohen *et al.*, 1999) and (in at least two cases) charge states (~19 for Fe; e.g., Mazur *et al.*, 1999) at energies > 25 MeV amu^{-1}. Proposed revisions to SEP classification to account for these discordant events have taken two paths: (1) Cane and colleagues (Cane, Erickson and Prestage, 2002; Cane *et al.*, 2003, 2006) have argued that flares dominate SEP acceleration above 25 MeV amu^{-1}; (2) Tylka and

Figure 1: Don Reames, key figure in establishing the two-class picture of SEP events.

co-workers (Tylka *et al.*, 2005, 2006; Tylka and Lee, 2006) interpret the large SEP events with impulsive characteristics in terms of quasi-perpendicular shocks operating on a seed population enhanced in flare suprathermals.

In Section 2, we propose a modified SEP classification scheme based on the shock-centred analytical and theoretical work of Tylka and colleagues. In Section 3 we examine the role of flare time scale in the proposed new framework for SEP events and in Section 4 we summarize recent supporting evidence for the new picture.

2. A New Taxonomy for SEP Events

Table II (Cliver, 2008a,b) contains our proposed revision of the classification scheme in Table I. The essential new aspect is the subdivision of the old gradual class, referred to here as the "Shock" class, into two subclasses representing the extreme possibilities of shock geometry (seed populations): quasi-perpendicular (flare suprathermals (STs)) and quasi-parallel (coronal/solar wind STs). This revision reflects the differences between the ^{3}He-rich events [now Flare] of Reames, von Rosenvinge and Lin (1985) and the energetic impulsive events of Cane, McGuire and von Rosenvinge (1986) [now Quasi-Perp] which were erroneously combined in the original two-class picture (Reames, 1993) [see Cliver (2008b) for a discussion of the evolution of the two-class paradigm]. Given that SEP events spanning nearly the full range of intensities can be associated with short-duration flares and that the larger SEP events following short-duration flares can be relatively long-

Table I: Two-class Paradigm for SEP Events

	IMPULSIVE	GRADUAL
Particles:	Electron-Rich	Proton-Rich
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
H/He	~10	~100
Q_{Fe}	~20	~14
Duration	Hours	Days
Longitude Cone	$< 30°$	$\sim 180°$
Radio Type	III,V(II)	II,IV
X-Rays	Impulsive	Gradual
Coronograph	—	CME
Solar Wind	—	IP Shock
Events/Year	~1000	~10

lived, e.g., the event on 6 November 1997, we use "Flare" (as shorthand for the particle acceleration process(es) operating in flares; e.g., Miller *et al.*, 1997) instead of "Impulsive" for the other main category heading.

3. The Role of Flare Time Scale in Table II

Flare time scale, the key organizing parameter in Table I, can be naturally incorporated into the revised classification scheme of Table II. In Table I, flare time scale is used to separate flare- and shock-dominated SEP events. In Table II it retains this function but here we show that it also bears on Fe/O ratios and electron-to-proton (e/p) ratios within the shock class. Following Cane, McGuire and von Rosenvinge (1986), we use flare soft X-ray durations (at one-tenth of peak intensity) as the time scale parameter. Those authors designated flares for which this parameter was ≤ 1 hour ($>$ 1 hour) as "impulsive" ("gradual").

As argued by Cliver (2008b), a short flare time scale suggests that the associated eruption originates on a small spatial scale. Upon eruption, the coronal mass ejection (CME) undergoes rapid (but limited) lateral expansion, driving a shock tangential to the solar surface with shock nor-

Table II: Revised SEP Event Classification[a]

	Flare	Shock	
		Quasi-Perp	Quasi-Par
H Upper Limit[b]	$\sim$3 pr	$\sim 10^3$ pr	$\sim 10^4$ pr
e/p[b]	$\sim 10^2$-10^4	$\sim$100	$\sim$50
$^3He/^4He$[c]	$\sim 10^3$-10^4	$\sim 10^1$-10^2	$\sim$1
Fe/O[d,e]	$\sim$8	$\sim$3	<1
Z(>50)/O[d,f]	$\sim 10^2$-10^3	$\sim 10^{-1}$-10^1	$\sim 10^{-1}$-10^1
Ion Spectra[g]	—	Power-law	Exp. Rollover
QFe[h]	$\sim$20	$\sim$20	$\sim$11
SEP Duration	<1-20 hr	$\sim$1-3 days	$\sim$1-3 days
Longitude Cone[i]	<30-70°	$\sim$100°	$\sim$180°
Seed Particles	N/A	Flare STs	Coronal STs
Radio Type[j]	III	II	II
X-ray Duration	10-60 min	$\sim$1 hr	>1 hr
Coronagraph[k]	*	CME	CME
Solar Wind	—	IP Shock	IP Shock

Notes to Table II:

[a]See Cliver (1996, 2000) for an early attempt to accommodate large SEP events with impulsive characteristics.

[b]Cliver and Ling (2007), this paper; 10 MeV protons and 0.5 MeV electrons.

[c]Relative to solar wind at $\sim$1 MeV amu^{-1}. Problem events on 6 November 1997, 2 May 1998, and 6 May 1998 had enhanced $^3He/^4He$ ratios.

[d]Relative to coronal abundances at 5-12 MeV amu^{-1}.

[e]For the Flare class, the energy range is 5-12 MeV amu^{-1} (Reames, 1999); Shock class, the energy range is 30-40 MeV amu^{-1} (Tylka *et al.*, 2005).

[f]Reames and Ng (2004).

[g]For a study of ion spectra in Flare events, see Mason *et al.*, 2002. Spectral shapes for Shock events are for 3-100 MeV amu^{-1} (Tylka *et al.*, 2005).

[h]Flare (< 1 MeV amu^{-1}; Klecker *et al.*, 1984); Shock ($\sim$40 MeV amu^{-1}; Mazur *et al.*, 1999).

[i]Lin, 1970; Reames *et al.*, 1991; Kallenrode *et al.*, 1992.

[j]Defining radio type in low frequency range from 14-1 MHz.

[k]The larger flare events can have associated CMEs (Kahler *et al.*, 2001).

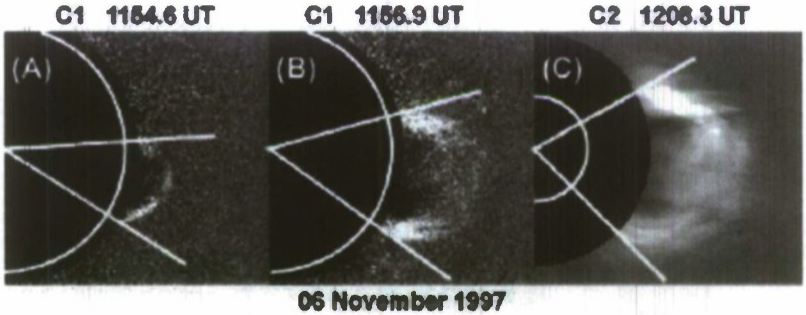

Figure 2: Fast lateral expansion of the 6 November 1997 CME. [From Cliver *et al.*, 2004.]

mal perpendicular to the radial magnetic field near the Sun, i.e., a quasi-perpendicular shock, resulting in enhanced Fe/O and e/p ratios. More gradual eruptions originate on larger spatial scales with a slower rate of energy release and the lateral expansion in these cases is less violent, implying a reduced role for quasi-perpendicular shocks. Once the lateral expansion stops, quasi-parallel acceleration due to the outward motion of the CME will dominate near the Sun.

In Tylka's model, large SEP events with impulsive characteristics (e.g., those in Cohen *et al.*, 1999) are explained in terms of quasi-perpendicular acceleration and, indeed, in the 6 November 1997 event, there is evidence (Figure 2) for the requisite fast lateral expansion of a CME that could drive such a shock. We suggest that the the tendency for SEP events with enhanced Fe/O ratios to originate in western hemisphere sources (Cane *et al.*, 2006) is due to the limited extents/lifetimes of these quasi-perpendicular shocks. The incorporation of flare time scale as a parameter in the shock events finds anecdotal support from the study of Nitta, Cliver and Tylka (2003) that linked certain large events with high Fe/O ratios, including the 6 November 1997 event, to "explosive" eruptions on the Sun, and others with low Fe/O ratios to less abrupt mass ejections. We note that the three "problem" SEP events with visible disc flare associations reported by Cohen *et al.* (1999) had soft X-ray durations $<$ 1 hour.

3.1. Fe/O ratio vs. flare duration

To substantiate the anecdotal evidence from Nitta, Cliver and Tylka (2003) that flare time scale is a crude organizer of the Fe/O ratio in large SEP

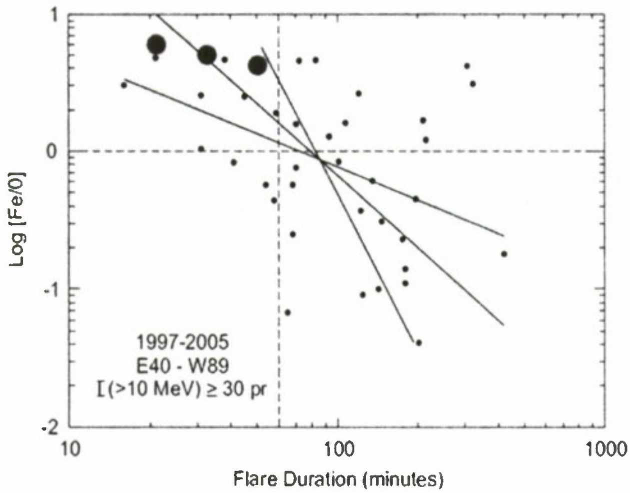

Figure 3: Scatter-plot of Fe/O ratio (at 30-40 MeV) vs. flare duration. Positions of the "problem" storms of Cohen *et al.* (1999) that originated in visible disc eruptions are indicated by three gray circles.

events, we considered a data base (Table III) of 49 prompt intense [I($>$ 10 MeV) $\geq$ 30 proton flux units (pfu)] SEP events from 1997-2005, associated with flares located from E40-W150. Events of this size are ten times larger than the largest impulsive $>$ 10 MeV proton events and should be shock-dominated (Cliver and Ling, 2007). Sources for flare associations, electron and proton data, and Fe/O ratios are given in the notes to the table.

Figure 3 is a scatter plot of Fe/O ratio vs. flare duration for the SEP events in Table III that were associated with visible disc flares [from E40-W89 for which the soft X-ray duration (at one-tenth peak intensity) could be determined]. A tendency can be seen for shorter flares to be associated with SEP events with higher Fe/O ratios. The correlation between the logs of Fe/O and flare duration improves slightly from $r = -0.46$ (39 events) for E40-W89 SEP sources to $r = -0.52$ (27 points) when only W20-89 sources are considered. The dashed vertical line drawn at a duration of 1 hour shows that when a large SEP event has an associated impulsive flare, it is likely to have an enhanced ($\geq$ 1) Fe/O ratio. At the same time, it is clear that many large SEP events with Fe-enhancements arise in gradual flares.

Table III: List of Large [I(> 10 MeV) ≥ 30 pfu] SEP Events, 1997-2005

	1-8 Å Flare		SEP Event			
Date/Peak Time[a]	Int/Dur[b]	Location[c]	0.5 MeV[d]	>10 MeV[e]	e/p	Fe/O[f]
97-11-04/05:58	X 2.1/00:16	S014W033	6.52e+03	5.46e+01	1.19e+02	3.030±0.230
97-11-06/11:55	X 9.4/00:21	S018W063	5.31e+04	4.39e+02	1.21e+02	5.780±0.100
98-04-20/10:21	M 1.5/—	W090	1.40e+04	3.40e+02	4.11e+01	0.019±0.003
98-05-02/13:42	X 1.2/00:33	S015W015	1.31e+04	1.28e+02	1.03e+02	4.930±0.320
98-05-06/08:09	X 2.8/00:48	S011W065	4.64e+04	1.42e+02	3.27e+02	3.990±0.440
98-08-24/22:12	X 1.1/01:41	N030E007	8.80e+03*	1.73e+02	5.08e+01	0.840±0.090
98-09-30/13:48	M 3.0/03:29	N023W081	2.76e+04*	9.79e+02	2.82e+01	1.680±0.070
98-11-14/05:18	C 1.8/—	W120	3.80e+04	2.87e+02	1.32e+02	4.460±0.130
99-08-01/19:03	C 1.3/—	W120	1.57e+03	3.48e+01	4.51e+01	4.730±0.300
99-08-04/07:03	M 4.2/00:45	N017W069	4.82e+03	5.08e+01	9.48e+01	2.500±0.350
00-04-04/15:39	M 1.0/ ?	N016W066	5.22e+02	3.17e+01	1.65e+01	0.600±0.190
00-06-10/17:00	M 5.6/01:12	N022W036	2.43e+03	4.07e+01	5.97e+01	4.580±0.880
00-07-14/10:23	X 8.1/01:08	N022W007	4.86e+05*	7.94e+03	5.87e+01	0.570±0.020
00-09-12/12:12	M 1.0/05:21	S017W009	6.57e+03	1.76e+02	3.69e+01	3.100±0.530
00-11-08/23:27	M 7.9/03:21	N010W075	2.45e+05	1.15e+04	2.13e+01	0.041±0.006
00-11-24/15:13	X 2.5/00:31	N022W007	9.94e+03	7.66e+01	1.30e+02	2.550±0.420
01-04-02/21:50	X16.4/00:59	N016W062	3.41e+04	6.59e+02	5.17e+01	1.900±0.050
01-04-10/05:28	X 2.3/01:10	S023W009	2.02e+03	7.89e+01	2.56e+01	0.780±0.040
01-04-12/10:28	X 2.2/01:10	S019W042	2.19e+03	3.90e+01	5.81e+01	1.580±0.550
01-04-15/13:50	X15.8/00:21	S020W085	8.21e+04	9.00e+02	8.90e+01	4.760±0.190
01-04-16/02:14	C 2.4/—	W120	6.11e+03	2.03e+02	3.01e+01	2.950±0.190
01-08-15/23:55	/—	W140	4.36e+04	3.64e+02	1.20e+02	0.800±0.030
01-09-24/10:35	X 2.7/02:04	S016E023	7.65e+04	1.53e+03	5.00e+01	0.091±0.008
01-10-01/05:15	M 9.1/—	S022W091	7.32e+03	1.46e+02	5.01e+01	0.500±0.120
01-11-04/16:19	X 1.1/02:28	N008W016	1.27e+05	2.99e+03	4.27e+01	0.310±0.030
01-11-22/23:27	X 1.0/03:18	S015W034	3.20e+04	2.99e+03	1.07e+01	0.450±0.030
01-12-26/05:38	M 7.8/05:06	N008W054	2.79e+04	7.24e+02	3.85e+01	4.160±0.120
02-04-21/01:47	X 1.7/02:59	S014W084	6.70e+04	2.09e+03	3.20e+01	0.140±0.010
02-08-22/01:57	M 5.9/00:38	S007W082	1.90e+03	3.13e+01	8.07e+01	4.640±0.750
02-08-24/01:11	X 3.5/01:23	S008W081	2.22e+04	3.03e+02	7.33e+01	4.810±0.280
02-11-09/13:23	M 4.9/01:08	S012W029	8.00e+03	2.14e+02	2.80e+01	0.250±0.120
03-10-28/18:11	X 1.4/03:34	N002W038	4.35e+04	3.74e+02	1.16e+02	1.210±0.080
03-10-28/11:10	X18.4/01:05	S018E006	5.72e+04	6.28e+03	8.90e+00	0.066±0.012
03-10-29/20:49	X10.8/00:41	S015W002	1.13e+05	1.71e+03	8.63e+01	0.630±0.040
03-11-02/17:25	X 9.3/00:54	S020W058	6.26e+04	1.31e+03	4.77e+01	0.570±0.040
03-11-04/19:44	X18.4/00:58	S019W083	6.51e+03	3.03e+02	2.15e+01	0.440±0.050
03-12-02/09:46	C 7.6/ ?	S013W065	1.15e+03	6.69e+01	1.29e+01	0.870±0.490
04-07-25/15:15	M 1.2/07:00	N008W033	3.61e+03	3.83e+01	9.42e+01	0.180±0.090
04-09-19/17:11	M 2.0/01:47	N003W058	8.98e+03*	4.58e+01	1.98e+02	1.610±1.100
04-11-01/06:00	/—	W120	3.58e+03	5.45e+01	8.57e+01	2.480±0.800
04-11-07/18:06	X 2.2/ ?	N009W017	8.29e+03	3.89e+02	2.13e+01	0.430±0.140
04-11-10/02:13	X 2.6/00:31	N009W049	9.93e+03	2.84e+02	3.76e+01	1.040±0.060
05-01-15/23:00	X 2.9/02:55	N015W005	1.22e+04	1.05e+02	1.17e+02	0.230±0.030
05-01-17/09:52	X 4.2/02:22	N015W025	1.66e+05	3.62e+03	4.67e+01	0.100±0.010
05-01-20/07:00	X 7.9/01:33	N014W061	1.20e+05	1.44e+03	6.36e+01	1.260±0.060
05-08-16/20:22	M 4.3/02:00	N009W087	8.25e+03	4.13e+01	1.51e+02	2.630±0.470
05-07-14/10:54	X 1.4/02:15	N010W089	2.44e+03	5.69e+01	4.29e+01	0.610±0.060
05-06-22/17:28	M 8.2/02:02	S012W060	2.49e+04	2.79e+02	6.91e+01	0.370±0.050
05-09-13/20:04	X 1.6/02:59	S009E010	3.68e+03*	1.05e+02	3.49e+01	0.110±0.020

Notes to Table III:

[a]Peak of 1-8 Å flare except for 2001 August 15 and 2004 November 01 for which cases the listed times refer to the onset of 14-1 MHz radio emission. [b]Full-width at one-tenth peak intensity of 1-8 Å flare. [For the 2000 April 4 event, the peak intensity did not rise 10 times above background. For two events with complex 1-8 Å profiles (2003 December 02 and 2004 November 07), we were unable to determine the duration. For these three events, a "?" is given for the Duration.] [c]Flare locations from Cane *et al.* (2006). [d]From *SOHO* COSTEP. "*" indicates that the intensity is based on *ACE* EPAM 175-315 keV data using a correlation with *SOHO* 0.5 MeV data given in Cliver and Ling (2007). [e]From *GOES*. [f]From Tylka *et al.* (2005), A.J. Tylka (2006, personal communication), and Cane *et al.* (2006).

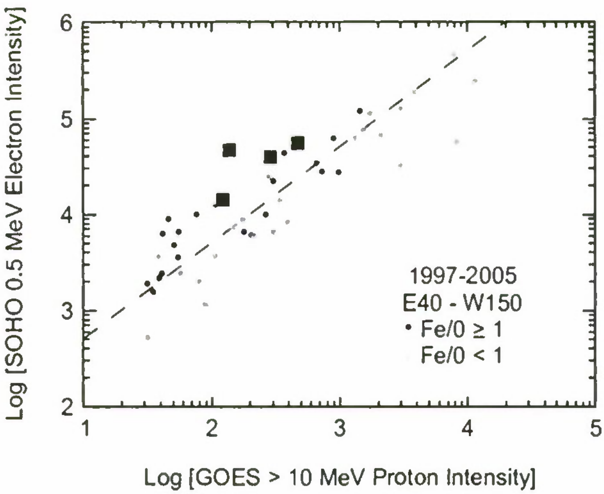

Figure 4: Scatter plot of 0.5 MeV electron intensity vs. peak > 10 MeV proton intensity of intense > 10 MeV SEP events. Two categories of Fe/O ratios [either enhanced (≥ 1) or depleted (< 1), relative to the nominal coronal value] are indicated. The dashed line is drawn at the sample median e/p ratio. The squares denote the four "problem events" reported by Cohen *et al.* (1999).

3.2. ELECTRON-TO-PROTON RATIOS

Figure 4 is a scatter plot of 0.5 MeV electron intensity vs. > 10 MeV proton intensity for the events in Table III. Red data points (filled circles) are used to indicate events with enhanced Fe/O ratios (≥ 1, relative to normal coronal abundances) and blue points are used for those with low Fe/O ratios (< 1). Red squares denote the four "problem events" reported by Cohen *et al.* (1999). The dashed line is drawn at an e/p ratio of 51, the median value of all the events in the plot. Figure 4 reveals a tendency for large SEP events with enhanced Fe/O ratios to have higher e/p ratios than those with low Fe/O ratios. Of the 25 events that lie above the median e/p line, 18 have Fe/O ≥ 1. Below the line Fe-poor events outnumber Fe-rich events by 18 to 6. Yates' χ^2-test (Langley, 1970) shows that the probability of such a distribution arising by chance is $< 1\%$.

The logs of the Fe/O and e/p ratios in Figure 4 are weakly correlated with $r = 0.45$ (49 events) vs. $r = 0.44$ for a longitude range of W20-90

(30 events). There are theoretical and observational reasons to believe that quasi-perpendicular shocks will produce both of these (Fe/O and e/p) abundance effects (theoretical: Lee, 2005; Tylka and Lee, 2006; observational: Tsurutani and Lin, 1985; Nitta, Cliver and Tylka, 2003; Tylka *et al.*, 2006).

4. Evidence for Shock-Domination of Large SEP Events

Several lines of evidence support a shock-based picture to accommodate the large SEP events with impulsive characteristics (Cohen *et al.*, 1999; Mazur *et al.*, 1999) versus an alternative view based on acceleration of high-energy SEPs in a flare resident process.

4.1. Role of shock geometry and seed particles

Some of the most compelling evidence for the revised SEP classification scheme in Table II is provided by signatures of the effects of shock geometry and seed particle variability in large SEP events.

4.1.1. Fe/O vs. energy in interplanetary shocks

A key insight into the high-energy acceleration process in large SEP events occurred when Tylka *et al.* (2005) noted that the bounding types of variation of Fe/O with energy in large SEP events are similar to those observed in situ (at lower energies) for interplanetary shocks. For IP shocks, the shock geometry and seed populations can be directly determined and Tylka *et al.* (2005) noted that the IP particle events with elevated Fe/O ratios at high energies tended to be associated with both quasi-perpendicular shocks (large θ_{BN}) and flare seed particles (enhanced ^{3}He/He^4) (Figure 5). These associations for IP shocks suggest that the similar Fe/O variability for large SEP events result from shock acceleration.

4.1.2. Breneman and Stone charge-to-mass fractionation effect

Breneman and Stone (1985) reported that "the ionic charge-to-mass ratio ratio (Q/M) is the principal organizing factor for the fractionation of ...

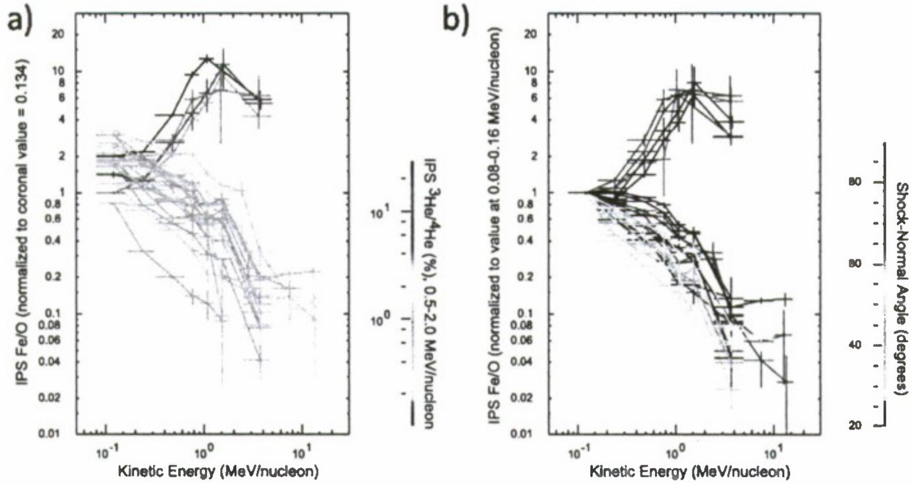

Figure 5: Fe/O vs. energy for 23 travelling IPS events (analysed by Desai *et al.* 2003, 2004). (a) Fe/O is normalized to the nominal coronal value and the colour indicates measured $^{3}He/^{4}He$). (b) Fe/O is normalized to each event's observed value at 0.08-0.16 MeV amu^{-1}, and the colour indicates the value of θ_{BN}. [From Tylka and Lee, 2006.]

SEPs by acceleration and propagation processes and for flare-to-flare variability." Those authors found that the ratios of elemental abundances in a given event relative to mean SEP abundances formed power laws when plotted vs. Q/M. Depending on the event, these power laws could increase or decrease with increasing Q/M. Tylka and Lee (2006) used an analytic model of shock acceleration which included shock geometry and seed particle composition to encompass the extremes of SEP abundance organization revealed by the Breneman and Stone (1985) charge-to-mass (Q/M) fractionation effect and, in so doing, provided the first quantitative insight into a ~20-yr puzzle of SEP physics. They found that quasi-perpendicular shocks operating on flare STs produced falling power laws in Q/M while quasi-parallel shocks operating on coronal STs produced rising power laws.

4.1.3. Shocks vs. flares in large SEP events

Recent evidence that strong shocks rather than flares are the essential phenomenon required for a large > 25 MeV SEP event include the following:

(a) Gopalswamy *et al.* (2002) and Cliver, Kahler and Reames (2004)

Table IV: Contingency matrix for association of a western hemisphere (W00-90) metric Type II burst with a DH Type II burst and a detectable > 20 MeV proton event. [From Cliver, Kahler and Reames, 2004.]

		> 30 MeV SEP Event	
		Yes	No
Western Hemisphere Metric Type II	DH Type II	26	3
	No DH Type II	17	52

have reported a strong (~100%) association between large SEP events and type II bursts observed in the decametric-hectometric (DH; 14 -1 MHz) wavelength range. Cliver, Kahler and Reames showed (Table IV) that metric type II bursts with a DH type II counterpart had a ~90% association rate with > 20 MeV proton events vs. only ~25% for metric IIs that lacked such DH emission. Table IV implies a correlation between shock strength and high energy SEP production that would be expected if shocks were responsible for the acceleration of high energy SEPs.

(b) While it might be argued that such a correlation is yet another manifestation of the Big Flare Syndeome (Kahler, 1982), there are examples of highly energetic SEP events that were associated with only weak flares. Cliver (2006) presented observations of two ground Level events (GLEs; caused by > 500 MeV protons) that were associated with flares with peak ~9 GHz peak intensities < 30 sfu. All other GLE-associated flares had ~9 GHz peak intensities that were at least 10 times larger. Both of these GLEs (21 August 1979 and 10 May 1981) originated in active regions with relatively low values (~100 millionths of a solar hemisphere) for sunspot area. In both cases a strong metric shock was observed (14-1 MHz observations were not available) and the pre-GLE > 10 MeV proton flux at Earth was 3-4 orders of magnitude above normal background. In the context of Tylka *et al.* (2005), the elevated proton populations at Earth suggest an enhanced seed particle population in the low corona (Figure 6, from Cliver, 2006) that enabled two otherwise relatively unimpressive solar eruptions to "over-achieve".

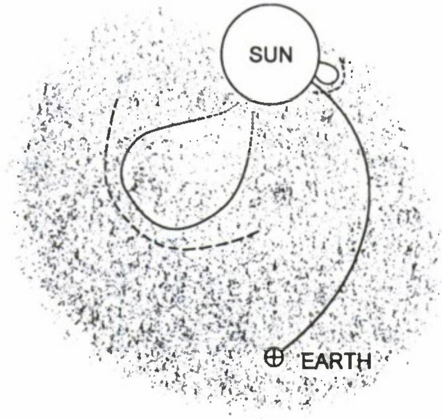

Figure 6: Relative positions of the CMEs responsible for the preceding SEP events in 1979 August and 1981 May (responsible for the high backgrounds) and the GLE-associated eruptions. Shocks driven by the large eastern hemisphere eruptions, which occurred in each case about two days prior to GLEs, presumably provided seed particles (indicated by the gray shading) for the favourably located CME-driven shocks linked to the GLEs.

(c) Cliver and Ling (2007) showed that e/p ratios [I(~0.5 MeV electrons) / I(> 30 MeV protons)] in large SEP events [I(> 10 MeV) ≥ 10 pfu] were essentially independent of longitude over a range from E40-W150 and that the ~0.5 MeV electron and > 30 MeV proton intensities were correlated over several orders of magnitude (Figure 7). Given the strong association of these SEP events (black points in the scatter plots) with DH type II bursts, Figure 7 suggests that widespread acceleration by shocks is the dominant process for both > 30 MeV protons and ~0.5 MeV electrons. Note that the flare SEP events (blue points) have a relatively narrow cone of emission and can exhibit much higher e/p ratios. Cliver and Ling (2007) reported an observational upper limit of ~3 pfu at > 10 MeV for the flare SEP events vs. 10^3 -10^4 pfu for large shock-associated SEP events.

(d) Recently, Cliver and Ling (2009) showed that there is a lack of correlation between > 30 MeV proton intensity and the integrated intensity of ~ 1 MHz type III emission (Figure 8), another unexpected result if such bursts are signatures of > 25 MeV amu^{-1} SEP acceleration in flares. In the large SEP events they considered (black points) there is a tendency for association with complex rather than simple type III emission (in agreement

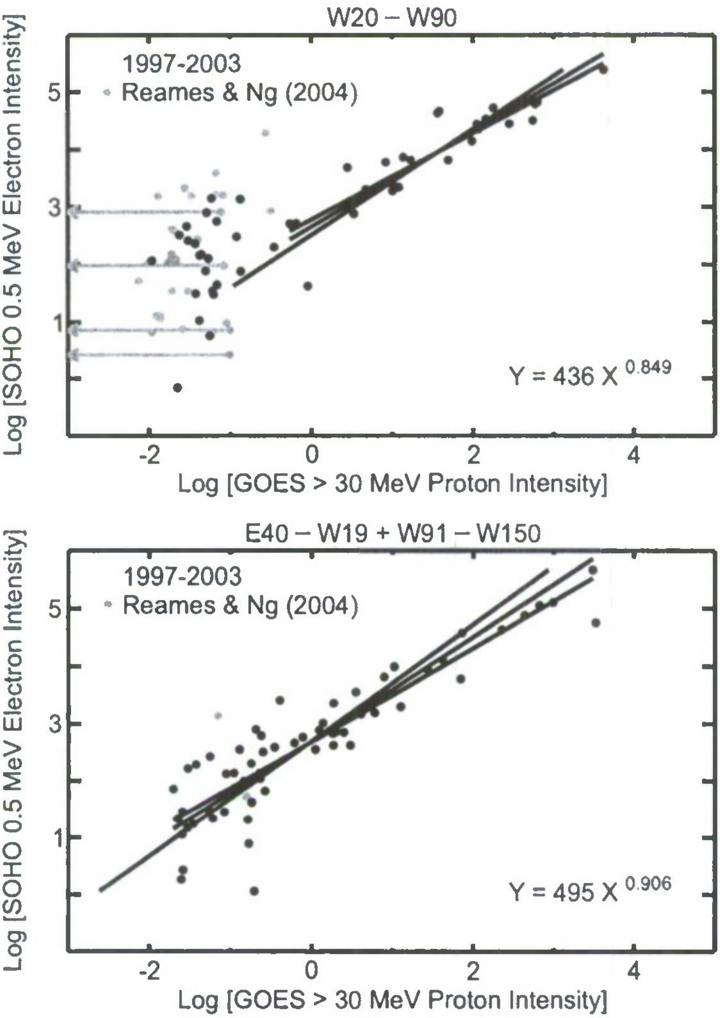

Figure 7: *Top*: Plot of peak 0.5 MeV electron intensity vs. peak > 30 MeV proton intensity for well-connected (W20°-W90°) SEP events from 1997 January to 2004 April. The filled gray circles indicate the intense impulsive SEP events of Reames and Ng (2004). The least-squares fit is for events with peak > 10 MeV intensities > 3 pfu. *Bottom*: Same as top, except for poorly connected (E40°- W19° and W91°-W150°) SEP events. In this case the least-squares fit is over the full range of data. [From Cliver and Ling, 2007.]

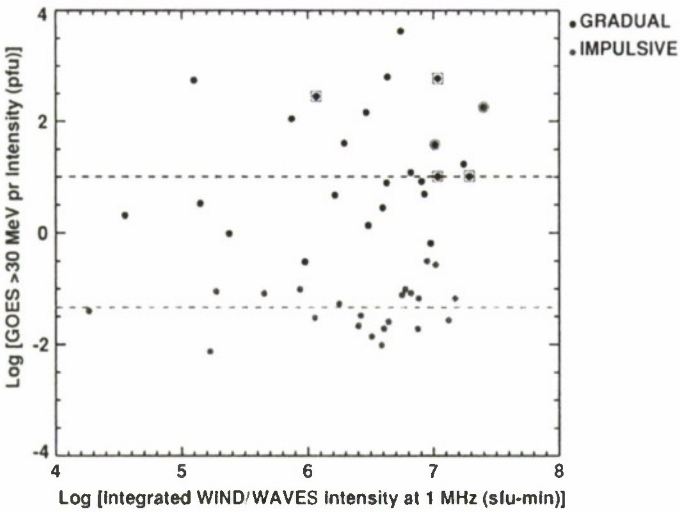

Figure 8: Scatter plot of > 30 MeV proton intensity vs. time-integrated ~1 MHz radio intensity for a sample of large gradual SEP events (black points) and large impulsive SEP events (gray points). All of these SEP events were associated with flares between W20-89. The two gradual points enclosed by circles correspond to two of the large ACE events with impulsive event characteristics reported by Cohen *et al.* (1999). Four additional events with Fe/O ratios ≥ 4 are enclosed by squares. [From Cliver and Ling, 2009.]

with Cane, Erickson and Prestage, 2002), but this is expected in the shock scenario as well because of the reconnection process set up by a fast CME. In a reverse study that began with a list of large [peak ~1 MHz intensity ≥ 3.16 x 10^5 solar flux units (sfu); duration at (≥ 2000 sfu) ≥ 15 minutes; time-integrated intensity ≥ 2 x 10^6 sfu-minutes] favourably-located (W20-W89) type III bursts, Cliver and Ling (2009) found that a large type III burst, in itself, was unlikely to give rise to a large (≥ 1 pfu) > 30 MeV proton event. If such a type III was associated with a DH type II, it was 10 times more likely to be followed by a large SEP event. They concluded that large > 30 MeV proton events were dominated by shock acceleration.

5. Conclusion

5.1. Summary

We have proposed a modification (Table II) to the current two-class scheme (Table I) for organizing SEP events. We have added a new column between the impulsive and gradual classes in Table I. The new column in Table II represents large events that were erroneously incorporated into the old impulsive class (see Cliver, 2008b) and which now more properly become a subset of the gradual class. As a semantic change in Table II, we relabel the modified impulsive class as "Flare" events and the expanded gradual class as "Shock" events. Following Tylka *et al.* (2005), the shock class consists of two groups of SEP events dominated by quasi-perpendicular (the new middle column) and quasi-parallel shock acceleration, respectively. The quasi-perpendicular events were revealed by observations of SEP composition and charge state during cycle 23 at higher (> 25 MeV) energies than previously possible. Tylka *et al.* (2005) also emphasized the importance of seed particle populations, noting that since quasi-perpendicular shocks require a higher initial particle injection speed, they preferentially accelerate seed particles from flares.

We emphasize that the basic two-class picture remains intact in the sense that SEPs are accelerated either in a flare-resident process (or processes) or at a CME-driven shock wave. Moreover, we have shown that the flare time scale - in addition to discriminating between flare- and shock-dominated SEP events - parameterizes the shock class, with shorter duration (≤ 1 hour) flares more likely to be associated with SEP events with enhanced Fe/O and e/p ratios. Such SEP events are attributed to perpendicular shocks operating on flare seed particles. Finally, we have summarized various lines of evidence from recent studies indicating that shocks rather than flares dominate acceleration of high-energy SEPs. These lines of evidence include: (1) common characteristics in SEP events and particle events associated with IP shocks that can be attributed to shock geometry and seed particle variability; (2) modelling of the Breneman and Stone Q/M fractionation effect by an analytic shock model that takes shock geometry and seed particle composition into account; (3) statistical associations of SEPs and low-frequency radio bursts; (4) GLEs associated with weak flares; and (5) differences in e/p ratios between flare and shock SEP events.

5.2. Closing caveat 1: Variety in the flare class

The flare class in Table II represents events ranging from the low energy electron events without chromospheric flare signatures reported by Potter, Lin and Anderson (1980) to large events like 1 May 2000 (Reames, 2000) and 14 April 2001 with strong enhancements of trans-Fe events, that can involve CMEs (Yashiro *et al.*, 2004). Cliver and Kahler (1991) have proposed that the "high coronal flares" of Potter, Lin and Anderson (1980) arise in magnetic reconnection events at the neutral current sheet in coronal streamers. Such events would not involve detectable CMEs. The suggested magnetic field topology for the large trans-Fe-enriched SEP events (Kahler, Reames and Sheeley, 2001; Shimojo and Shibata, 2000) may be fundamentally different. For these events, recent evidence (Wang, Pick and Mason, 2006; Nitta *et al.*, 2006) supports the idea that the reconnection process occurs between closed field lines of active region loops and open field lines of adjacent coronal holes.

5.3. Closing caveat 2: Ideal cases and the continuum of shock events

We emphasize that, just as in Table I, the SEP classes in Table II represent idealized "pure" cases. In reality, since flares invariably accompany fast CMEs, there will be intermediate events encompassing both direct flare and shock populations. The shock class in Table II represents large SEP events in which the shock component is dominant. Following Cliver and Ling (2007, 2009), we believe that this will be the case for large SEP events meeting the current Space Weather Prediction Center threshold of $I(> 10$ MeV) ≥ 10 pfu. The flare associated with the CME that drives the shock may also supply seed particles for reacceleration by the shock, provided that these particles can escape the confines of the CME (Cliver, Kahler and Reames, 2004). Within the shock class, the subclasses represent the ends of a continuum. In nature, the shock normal will evolve during an event (Tylka *et al.*, 2006; Tylka and Lee, 2006) and the seed particle composition will vary from event to event, resulting in a range of possibilities between the extreme cases of a dominant quasi-perpendicular shock acting on flare suprathermals and a dominant quasi-parallel shock accelerating coronal / solar wind suprathermals.

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