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Investigating the Causes of Solar-Cycle Variations in Solar Energetic Particle Fluences and Composition

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Measurements with the ACE, STEREO, and GOES spacecraft during the first 5.8 years of solar cycle 24 show that the number of large Solar Energetic Particle (SEP) events is reduced by ~32% compared to this point of cycle 23, while the fluences of >10 MeV/nucleon ions from H to Ni are reduced by factors ranging from 4 to ~10. A comparison of H, O, and Fe energy spectra from the ten largest events of the two cycles shows that the spectral breaks that are typically observed in SEP energy spectra are occurring ~3 times lower in energy/nucleon than in cycle 23. We investigate the origin of these cycle-to-cycle fluence, spectral and composition differences by evaluating possible factors that include: 1) the properties of the associated CMEs; 2) the interplanetary magnetic field strength; and 3) the density of suprathermal seed particles. These properties are evaluated in the context of existing SEP acceleration models. We conclude that both the reduced magnetic field strength and the reduced seed particle densities are contributing to the reduction in SEP output during cycle 24. In particular, we point out that in the standard model for SEP shock acceleration the maximum energy achieved is a strong function of the rate at which protons are injected into the shock acceleration process.

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1. Introduction

The largest Solar Energetic Particle (SEP) events are generally believed to be accelerated by shocks driven by fast, wide, coronal mass ejections (CMEs) traveling at speeds of ~1000 up to 3000 km/s (see, e.g., [1]). This process can be remarkably efficient, accelerating protons to GeV energies in a matter of ~10 minutes [2], resulting in greatly elevated radiation levels that can last for up to a week, with peak >10 MeV intensities of >10^5 times the Galactic cosmic-ray background. The United States National Oceanic and Atmospheric Administration (NOAA) catalogs the properties of solar proton events with peak intensities >10 protons/(cm^2sr-s) known as 10 proton flux units (PFU) as measured by their Geosynchronous Orbiting Environment Satellites (GOES). We refer to these as "GOES SEP Events". In Figure 1 we show the daily fluence of >10 MeV protons over the last 2.5 solar cycles. When solar cycle 23 (with solar maximum from 1997-2005) experienced the largest fluence of >10 MeV protons of the space era, there were some expectations that solar cycle 24 (SC24) might continue this trend. However, Figure 1 shows that during the first half of SC24 SEP intensities were significantly lower than in Cycles 22 and 23.

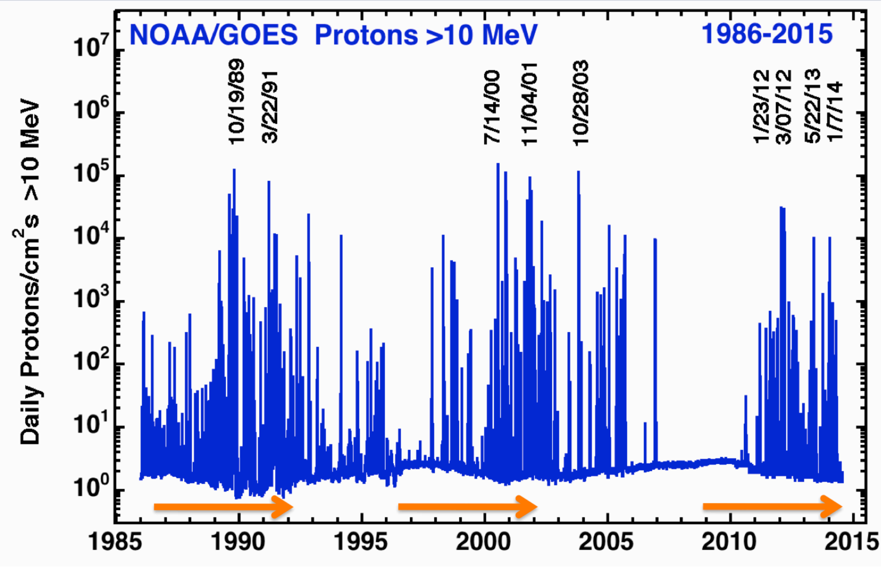

Figure 1: Daily average >10 MeV proton fluences from 1986 –2014 including solar cycles 22, 23, and 1/2 of SC24 with data from NOAA's series of GOES satellites in geosynchronous Earth orbit [3]. This paper considers the first 5.8 years of each cycle.

In an earlier study Gopalswamy et al. [4] found that the number of GOES SEP events with >PFU in the first 5.3 years of SC24 was consistent with that in SC23, but they noted a significant reduction in the number of SEP events with >500 MeV protons. They also noted anomalous expansion in SC24 CMEs as a result of the ~40% reduction in solar wind magnetic + plasma pressure in this cycle, which apparently reduced their effectiveness in producing magnetic storms. Gopalswamy et al. [4,5] also suggested that the reduced magnetic field strength in SC24 may have reduced the efficiency of shocks in accelerating particles to 500 MeV. The present paper provides additional comprehensive evidence of the reduced SEP output in SC24 by comparing the fluences of ten heavier elements in SC23 and SC24, and by measuring and fitting H, O, and Fe energy spectra for the 10 largest events in the first 5.8 years of both cycles. We then discuss possible explanations for the reduced SEP activity in SC24.

The SEP, solar wind, and CME measurements in this paper come from a variety of spacecraft in addition to GOES, including the Advanced Composition Explorer (ACE [6]) and Solar and Heliospheric Observatory (SOHO [7]), both in orbit about L1, and NASA's twin Solar Terrestrial Relations Observatories (STEREO-A and STEREO-B; [8]) that carry in situ and imaging instruments in ~1-AU orbits ahead and behind of Earth, respectively.

In order to make a more quantitative comparison of the SEP output during the present and last two solar cycles Figure 2 shows the integrated output of >10 and >100 MeV protons versus the day of the cycle (each new cycle starts at sunspot minimum; the relevant start dates are February 1987; May 1996, and December 2008). Note in Figure 2 that while Solar Cycle 24 started out strong with several large SEP events in early 2012, since that time it has fallen well behind, with little chance of catching up to SC22 and SC23. As of 30 September 2014 the integrated >10 MeV fluence was a factor of 3.6 to 4.4 behind SC22 and SC23, and the SC24 >100 MeV fluence was lower by factors of 6.4 to 9.0.

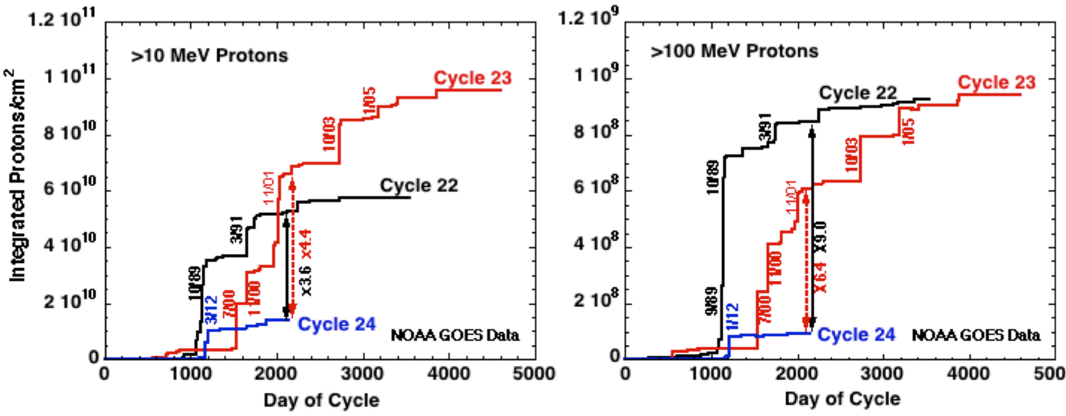

Figure 2: (Left) Integrated >10 MeV proton intensities measured by the GOES satellites in solar cycles 22, 23, and 24 are plotted versus day of the cycle. The times of selected large SEP events or series of events are indicated. As of September 30, 2014 the cycle-24 fluence trailed those of SC22 and 23 by factors of 3.6 and 4.4, respectively. (Right). The same comparison is shown for >100 MeV protons.

The dates of some of the largest SEP events in each cycle are labeled in Figure 2, including events in September-October 1989 during SC22, the Bastille Day (14 July 2000) event in 2000, and large events in November of 2000 and 2001. It is clear that there are two (related) reasons why solar cycle 24 is so far behind: (1) there has been a lack of very large SEP events affecting Earth in SC24, thereby reducing the SEP fluence, and (2) there is an energy dependence to this reduction – the deficit at >100 MeV is a factor of ~2 greater than at >10 MeV.

What about the fluence of heavier ions? In Figure 3 we plot the SC24/SC23 ratio of the 10-30 MeV/nuc fluences for 11 species as a function of their ionic charge to mass (Q/M) ratio. These data include the fluence of all SEP events (large and small) observed at L1 during the first 5.8 years of each cycle, but the fluences are dominated by the largest events. Note the strong dependence on Q/M, with protons reduced by a factor of ~4 [as in Figure 2 (left)] and Fe and Ni lower by factors of ~10.

One might ask whether the Earth has just been lucky – maybe most of the large SEP events have originated on the far side of the Sun in this cycle. Fortunately, STEREO A & B have been observing the far side of the Sun since 2011, and, as of late September 2014, the >10 MeV fluences at the two STEREOs and Earth were remarkably consistent: the >10 MeV fluence at STEREO-A was essentially the same as that at Earth, and the >10 MeV fluence at STEREO-B lagged by ~10% [9]. However, it is true that the most intense SC24 event to date did originate on the far side of the Sun. If the July 23, 2012 SEP event observed by STEREO-A [10] had been magnetically well-connected to Earth instead of STEREO-A, it would have been the 3rd most intense >10 MeV proton event since 1976 [9].

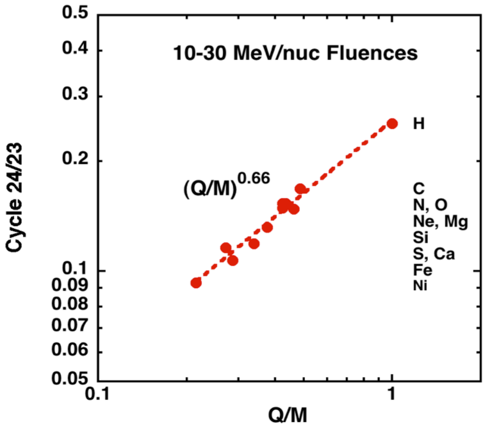

Figure 3: The ratios of the SC24 to SC23 fluences of 10-30 MeV/nuc SEP elements from H to Ni are plotted versus mean charge-to-mass (Q/M) ratios measured by Leske et al. [11]. The proton data are from GOES and the heavy ion data are from the Solar Isotope Spectrometer (SIS) on ACE.

Table 1 summarizes comparisons of SEP-related phenomena tabulated for the first 5.8 years of SC23 and SC24. Up through September 2014 the sunspot number was significantly lower than in SC23 and this reduced activity was reflected in a very significant (~66%) drop in the number of X-class flares. Of course, it is generally believed that most >10 MeV SEP events at Earth are due to shock acceleration driven by fast CMEs rather than flare-acceleration (for which most particles do not escape the solar atmosphere). The number of fast (≥1000 km/s) and (≥60° wide) CMEs observed by SOHO/LASCO in SC24 is reduced by ~25%, considerably less than the reduction in X-Class flares. As for CME properties, Gopalswamy et al. [5] compared CME speeds for GOES-class SEP events in the first 5.25 years of both cycles and found an average SC24 speed 8% greater than in SC23. We find mean CME kinetic energies for the 9 largest SC24 SEP events ~19% greater than for the 9 largest SC23 SEP events. So CME properties do not appear to be the issue.

There was a 32%±16% reduction in the number of GOES SEP events in SC24. (The reduction is 48% compared to Cycle 22; see [13] for a list of GOES events since 1976. The reduced number of GOES SEP events (32%) is roughly comparable to the reduced number of fast CMEs (25%), and the reduction in sunspot number (35% - 41%). However, the reduction in SEP events that trigger Ground-Level Enhancements (GLEs) observed by neutron monitors is much greater (~80%), confirming that the energy spectra of the largest SEP events in this cycle differ significantly from events in SC23 (see also Figure 2 and. [4,5]).

Table 1: Comparison of Solar Cycles 23 and 24 (Through September, 2014)

Property	Cycle 23	Cycle 24	24/23 Ratio	Comments/References
Sunspot Number Peak (Mean)	180 (108)	116 (64)	0.65 (0.59)	http://sidc.oma.be/silso/
X-Class Flares	88	30	0.34	[12]
CMEs >1000 km/s and >60° wide	159	119	0.75	http://cdaw.gsfc.nasa.gov/CME_list/
V_{CME} in GOES SEP Events (km/s)	1425	1533	1.08	[4]
CME Kinetic Energy (x 10^{30} ergs)	114	136	1.19	In the solar wind rest frame
GOES SEP Events (>10 PFU)	53	36	0.68	[13]
Severe SEP Events (>10,00 PFU)	6	1	0.17	[13,14]
Ground Level SEP Events	9	2	0.2	[15]
Interplanetary B-Field (nT)	6.95	5.33	0.77	http://www.srl.caltech.edu/ACE/ASC/
Severe Geostorms	22	2	0.1	[16]

Solar energetic particle events are also affected by solar wind properties. During the deep, extended solar minimum of 2006-2009, the solar wind density, speed, dynamic pressure, and magnetic field strength reached the lowest levels of the space era (e.g. [17,18]). This pattern continued in the first half of Cycle 24 during which the mean magnetic field strength was reduced by a factor of ~23% compared to SC23, which affects both SEP acceleration and transport processes. The picture that emerges is one in which general solar activity in SC24 is reduced by ~20%-40%, as reflected in the Sunspot number, solar wind properties, and the number of CMEs and SEP events. However, there has been an even greater reduction in the frequency of more extreme events such as X-class flares, GLE events, and what NOAA identifies as Severe solar proton events and Severe geostorms [14].

In Sections 2 and 3 we investigate how SEP energy spectra from SC23 and SC24 differ. We then investigate why particles are not being accelerated as high in energy in the largest SEP events of SC24 as they were in SC23, focusing on the reduced IMF intensity in this cycle, and on the properties of the seed particle populations that are accelerated by CME shocks. These properties are discussed in the context of current SEP acceleration models.

2. Solar Energetic Particle Energy Spectra

The energy spectra of SEP protons integrated over a several-day long event at 1 AU typically include a low-energy section (e.g., from ~0.1 to ~10 MeV) that is well represented by a power-law in kinetic energy (E) measured in MeV, followed by a spectral “break” that transitions to a somewhat steeper spectrum. Figure 4 shows an example of one of the largest solar proton events from both SC23 and SC24 fit with the double power-law function of Band et al. [19]. Fits to the energy spectra of the 16 GLE events of solar cycle 23 [20] showed that in all cases that the Band function fit better than the Ellison and Ramaty [21] form (power-law with an exponential cutoff), or a modified Bessel function in rigidity (momentum per unit

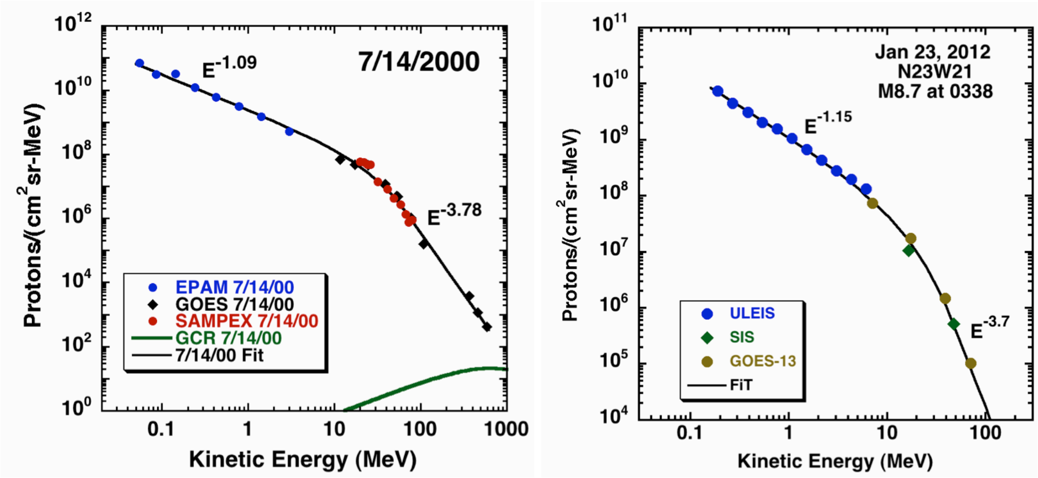

Figure 4: Examples of large proton spectra from Cycle 23 (left [20]) and from Cycle 24 (right). Both spectra are fit with the broken power-law form of Band et al. [19]. The slopes of the two power laws are indicated. The break-energy (intersection of the two power-laws) is 30.0 MeV on the left and 16.7 MeV on the right. The 7/14/2000 event had a >10 MeV fluence of 24,000 per cm^{2}sr-, ~4 times greater than that of the January 23, 2012 event.

charge). The low-energy power-law typically has a slope between $E^{-0.8}$ to E^{-2}, while the slopes above the break range from about -2.5 to -6 [20].

We define the spectral "break energy" for Band Function spectra to be the intersection of the two power laws (e.g., [20]). In order to compare the location of spectral breaks in the two solar cycles we selected the ten largest SEP events in the first 5.8 years of SC23 and SC24 and constructed fluence spectra for H, O, and Fe. These events included >95% of the >10 MeV fluence in each cycle. Figure 5 shows fits to the O and Fe spectra for the ten largest events of SC23 and the five largest of SC24. It is clear that the spectral breaks occur at higher energy/nuc for the SC23 (blue) spectra than for the SC24 (red) spectra. [Note that at low energies (<1 MeV/nuc) intensities in the two cycles are very similar, while at higher energies (>5 MeV/nuc) typical SC24 intensities are much lower than in SC23. This is also apparent in comparing the summed spectra (dotted lines) for the first 5.8 years of the two cycles. Table 2 quantifies this comparison. For all three species the spectral breaks are significantly reduced in energy during SC24 by an average factor of 3.1.

Table 2: Mean Break Energies for Solar Cycles 23 and 24

Element	Cycle-23: Mean Break Energy (MeV or MeV/nuc)	Cycle-24: Mean Break Energy (MeV or MeV/nuc)	Cycle 24/23 Ratio
H	29.1	10.0	0.34
O	18.9	5.8	0.31
Fe	8.6	2.4	0.28
Notes:	Only Nine Fe and O values in Cycle 23: The 6 Nov 1997 event was fit best by a single power-law for O & Fe.		

These data make it clear that the reduced energy/nuc at which the spectral breaks occur plays a significant role in explaining why there are not as many high-energy ions in solar cycle 24. A key question is: *What caused the large reduction in SEP spectral break energies from solar cycle 23 to solar cycle 24?*

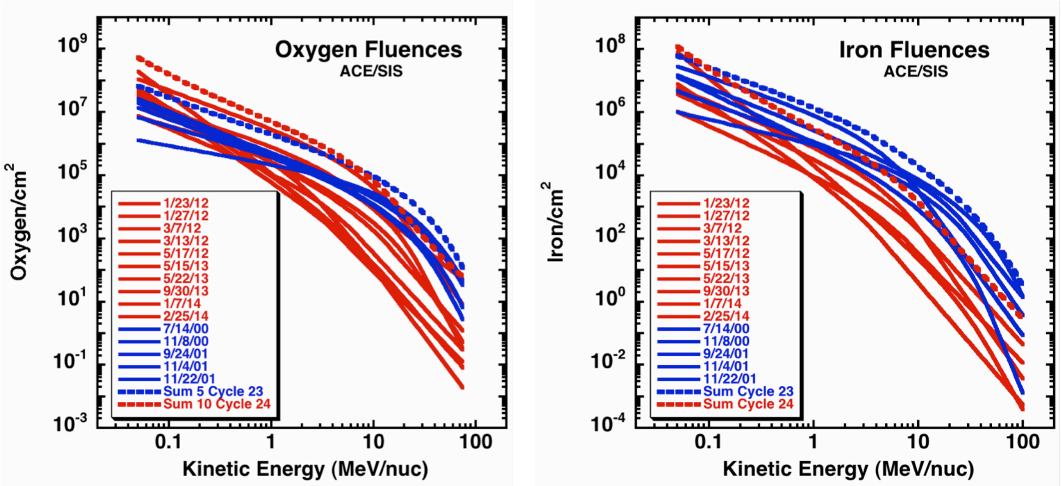

Figure 5: (left) Fits to oxygen spectra from the 10 largest proton events of the first 5.75 years of SC23 (red) and the 5 largest proton events of SC23 (blue). Also shown are the sums of these spectra (dotted). The right panel shows fits to the Fe spectra from the same events. Note that the spectral breaks from the Cycle 23 events generally occur at higher energies than those from Cycle 24. The data are from the SIS, ULEIS, and EPAM instruments on ACE.

3. Origin of Solar Energetic Particle Spectral Breaks

In the theory of the SEP shock acceleration process developed by Lee [22] that is illustrated in Figure 6 accelerated protons streaming upstream of the shock excite turbulence that, in combination with the shock-heated turbulent region downstream of the shock, manages to trap SEPs near the shock where they are further accelerated by a first-order Fermi process (see also Ng and Reames [24]). The process pictured in Figure 6 describes acceleration at a quasi-parallel shock. Particles can also be accelerated at a quasi-perpendicular shock, in which case they can quickly gain energy by drifting along the shock surface and crossing the shock multiple times. As particles continue to gain energy, at some point they are no longer confined by the shock and they escape upstream and eventually cross 1 AU, where instruments such as those in this study can measure them. The vast majority of ions that escape downstream of the shock are mirrored in the stronger IMF near the Sun and return to the shock.

SEP studies during SC23 first produced energy spectra over a broad energy range for elements from H to Fe and demonstrated how spectral breaks in large SEP events are organized by the ionic Q/M ratio [25,26,27,28,29]. Li, Zank and Rice [30] considered how energy spectra of accelerated H, CNO, and Fe that escape upstream from the Region-2 turbulence in Figure 6 are affected by appropriate diffusion coefficients, which depend on ionic Q/M ratios. Using Q/M=1 for H, 6/14 for CNO and 14/56 for Fe they found that ions escape from the acceleration process at essentially the same rigidity (momentum per unit charge), which resulted in spectral breaks for CNO and Fe that were progressively lower in energy/nuc than those for H. Li et al. [29] have shown how the Q/M dependence of spectral breaks depends on shock geometry.

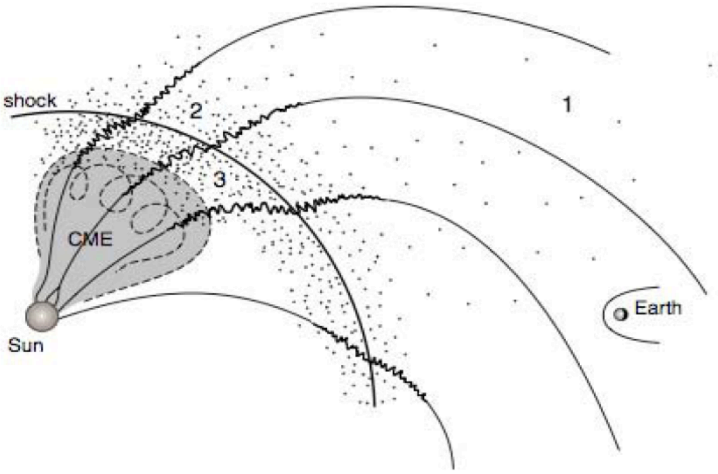

Figure 6: Cartoon of diffusive shock acceleration (from Lee [23]) at an evolving coronal/interplanetary shock moving into the solar wind (Region 1). Solar wind and suprathermal particles (dots) are injected into the acceleration process in a sheath of enhanced turbulence upstream of the shock (Region 2) and between the shock and the CME (Region 3). Particles that stream into the solar wind with speeds that exceed the Alfven speed (V_A) excite hydro-magnetic turbulence in a sheath upstream of the shock (Region 2). Particles that move between Region 2 and the turbulent shock-heated sheath downstream of the shock gain energy by a first-order Fermi process.

Li and Lee [31] have proposed an alternate interpretation of SEP spectral breaks. In a study of SC23 GLE events they find that the double power-law spectrum can be produced naturally from scatter-dominated transport of a power-law source. They do not address the question of the differences between the location of the breaks in SC24 and SC23.

4. Suprathermal Seed Particles

The theory of particle acceleration by CME-driven shocks originally focused on the injection and acceleration of a small fraction of solar wind ions. However, there is considerable evidence that CME-driven shocks accelerate mainly suprathermal ions. For example, the composition the solar wind and SEP compositions differ in several key respects, including their C/O ratio, their fractionation according to first ionization potential (FIP), and the fact that SEP events often have large excesses of ^{3}He and He$^+$ that are believed to be accelerated from coronal or interplanetary suprathermal particle sources [32,33,34,35]. To investigate cycle-to-cycle differences in SEP acceleration we have compared the average density of suprathermal ions in SC23 and SC24. To determine this we used ACE/ULEIS data from each cycle to measure the density of suprathermal H from 0.16 to 2.56 MeV, O from 0.04 to 2.56 MeV/nuc, and Fe from 0.04 to 3.1 MeV/nuc. Densities were computed for ~1500 days from each cycle when the daily-average intensity of >10 MeV protons was <10 PFU, such that NOAA would say there was not a significant solar proton event in progress.

Histograms of the logarithmic means of the daily number densities are shown in Figure 7. Although the spread in number densities is large, the mean densities in SC24 are lower by factors of 3.6 for H, 3.2 for O, and 7.0 for Fe (see Table 3).

Table 3: Logarithmic Mean Number Densities of Suprathermal Ions at L1 (ions/m^3)			
Element	Energy (MeV/nuc)	Feb 1998–Feb 2002	Sept 2010–Sept 2014
H	0.16 – 2.56	0.300	0.080
O	0.04 – 2.56	0.00086	0.00027
Fe	0.04 – 3.1	0.00083	0.00012

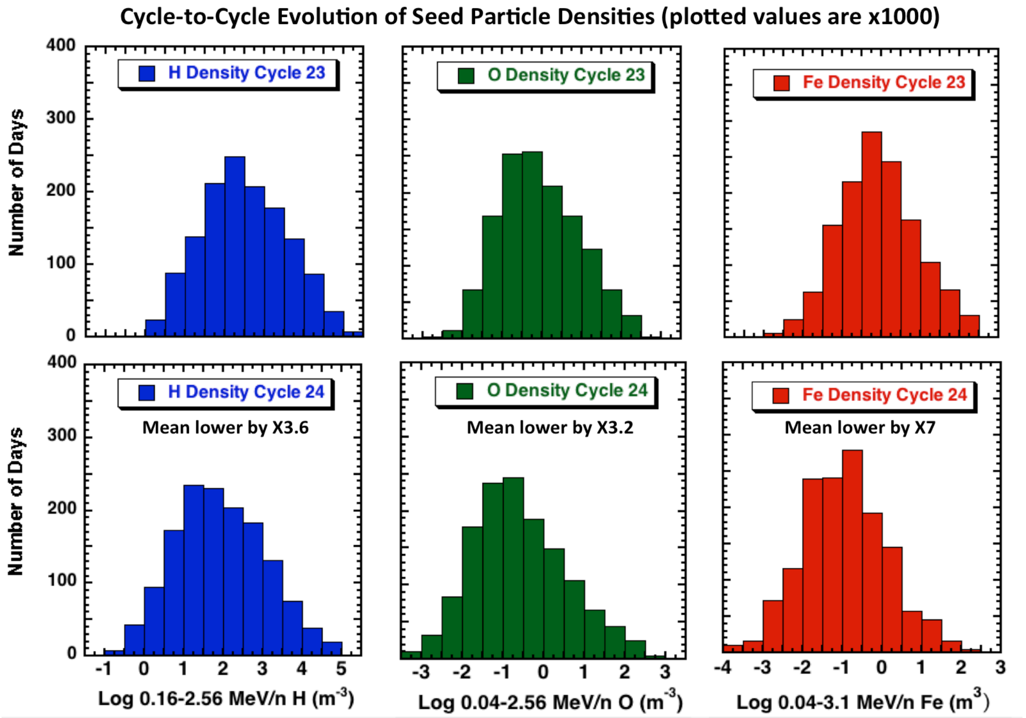

Figure 7: Distribution of suprathermal seed-particle number densities for H , O and Fe. The units are particles per m^3 x 1000. The measurements were made by the ACE/ULEIS instrument during SC23 days between February 19, 1998 and Feb 28, 2002, and during SC24 days between August 21, 2010 and September 29, 2014, whenever the daily GOES >10 MeV proton intensity was <10 PFU. Reduction factors from SC23 to SC24 for the logarithmic means of the densities are indicated.

5.0 SEP Acceleration Models

5.1. The Effects of a Reduced Interplanetary Magnetic Field Strength

We have identified two possible factors that can reduce the yield of very high particles: the reduced interplanetary magnetic field strength, and reduced mean density of suprathermal seed particles. We now try to estimate their effect on the maximum energy that is reached in models of CME-driven shock acceleration.

Giacalone [36] has recently simulated diffusive shock acceleration of protons at fast interplanetary shocks and commented on the reduced SEP output in SC24. He finds that a 35% increase in the diffusion coefficient, which might be expected if the interplanetary magnetic field is 35% weaker upstream of any given shock, leads to a decrease in the total integrated intensity by a factor of ~5. He explains that the larger diffusion coefficient in SC24 (assumed to be proportional to $p^{1.5}$, where p is momentum) "leads to a slower acceleration rate, thereby resulting in fewer high-energy SEPs". Although the actual decrease in the mean magnetic field strength in the first 5.8 years of SC24 is closer to 23% than 35% (see Table 1), the factor of 5 reduction that Giacalone derives is also somewhat greater than the factor of 4 we observe for >10 MeV protons (Figure 2). As noted above, Gopalswamy et al. [4] also suggested that the weaker IMF may have decreased the efficiency of the shock acceleration process in SC24, but they did not make quantitative estimates of this effect.

A theoretical study of shock acceleration at quasi-parallel and quasi-perpendicular shocks by Zank et al. [37] estimated the maximum energy that could be achieved versus distance from the Sun as a function of several key parameters that depend on radius (see Figure 8). Note that

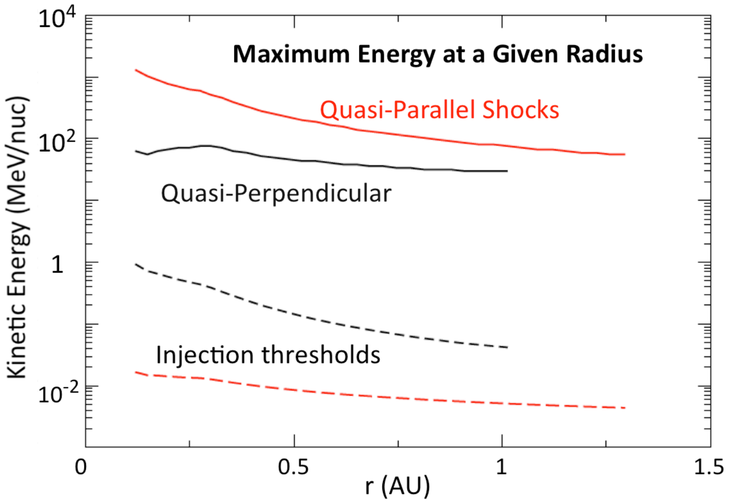

Figure 8: The solid curves show the radial dependence of the maximum energy that ions can be accelerated to at quasi-parallel and quasi-perpendicular shocks in the model of Zank et al. [37]. The dashed curves show the threshold energies that the ions must have to get injected into the acceleration process. Note that quasi-parallel shocks have lower injection thresholds and can accelerate to higher energies under the same conditions.

Zank et al. found that the injection energies are considerably greater for quasi-perpendicular shocks than for quasi-parallel shocks and the maximum energies reached are also greater for quasi-parallel shocks for the same CME and IMF properties. We consider here only quasi-parallel shocks, assuming they are responsible for the largest SEP events of the last two cycles (see Figure 8). Omitting constant factors in Equation 22 of Zank et al. [37] the maximum energy/nuc is proportional to:

$$E_{max} \approx [s/(s-1)]^{1/2}\,(Q/M)^{1/2}\,V_s^{0.5}\,B^3\,\delta B^{-5/2}, \tag{1}$$

where E_{max} is in energy/nuc, s is the shock compression ratio, V_s is the CME shock velocity, δB is the strength of slab turbulence at a given radial distance, and B is the mean magnetic field strength as a function of R. We assume that E_{max} in Equation 1 is proportional to the break energies that we observe in Figures 4 and 5. We would like to substitute appropriate values for conditions near the Sun into Equation 2 to investigate how E_{max} changes from one cycle to the next. Although there are recent measurements of magnetic field properties at ~0.3 AU from MESSENGER, there is no such record from 1997-2002. To estimate B near the Sun we can use

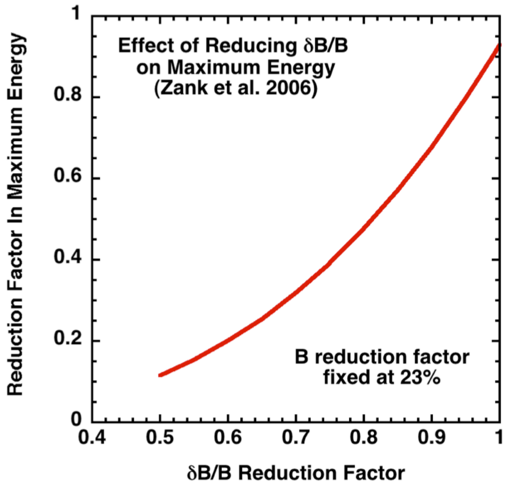

Figure 8: In the Zank et al. [37] theory of acceleration at quasi-parallel shocks the maximum energy scales $B^3(\delta B)^{-5/2}$ times $V_S^{1/2}$ (see Equation 1). The mean field (B) in SC24 is 23% lower than in SC23, but δB close to the Sun is unknown. We use CME velocities for the 10 largest events of the two cycles, which are very similar. Shown above is the effect of reducing the δB/B ratio close to the Sun, which could be the reason that particles are generally not being accelerated to high energies in solar cycle 24.

data from 1 AU and the fact that the mean field strength scales as $1/R^2$. There are also CME velocity data for the largest SEP events of both cycles. However, we do not have information on δB or on shock compression ratios near the Sun for these periods.

Although we lack measurements of δB for these periods it is possible calculate how the maximum energy changes as a function of δB/B, as shown in Figure 9. This figure uses CME speeds from SOHO/LASCO for the 10 largest SEP events in the first 5.8 years of Cycle 23 and 24. It also assumes that the IMF strength (B) was uniformly 23% lower in cycle 24 than in cycle 23, but it ignores possible differences in the shock compression ratios from event to event or from one cycle to the next. Note that to achieve a factor of ~3 reduction in E_{max} requires that δB/B be reduced by ~30%, which does not seem unreasonable during a solar cycle with significantly reduced solar activity. In an attempt to relate δB/B in this cycle to that in last cycle we are also involved in a study to measure δB/B changes during solar cycles 23 and 24 using 1-AU data. This work will be reported in a future publication.

5.2 Effects of Reduced Seed Particle Densities

In a 2011 paper Li [38] looked at the conditions that result in the largest events of the solar cycle, focusing on injection efficiency, the maximum attainable kinetic energy, and the dependence on shock geometry (θ_{BN}, the angle between the magnetic field direction and the normal to the shock). Assuming suprathermal ion spectra characterized by Kappa distributions with Kappa = 2, 3, and 6; using injection thresholds based on kinematic considerations; and using V_{CME} = 2500 km/s Li [2011] found that the efficiency for injection into the acceleration process depends strongly on θ_{BN} with quasi-perpendicular shocks having injection efficiencies orders of magnitude lower than quasi-parallel shocks (see also Capriano and Spitkovsky [39]). Li [39] also found that harder suprathermal spectra (smaller values of K) lead to higher injection efficiencies, resulting in much greater maximum energies (see Figure 10).

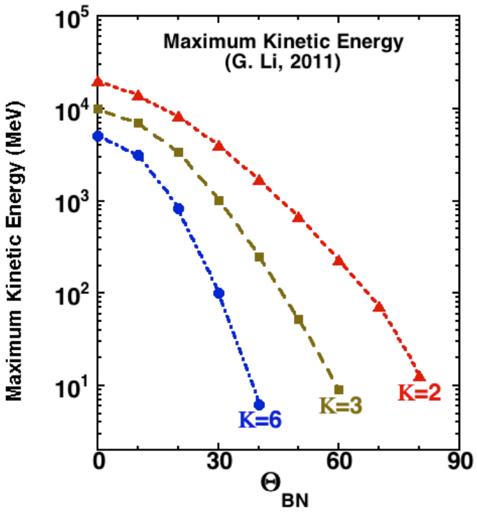

Figure 10: These simulations by Li [38] assume a CME speed of 2500 km/s and progressively harder spectra represented by Kappa functions with K = 6, 3, and 2. The injection efficiency is found to be a strong function of both K and $\Theta_{BN.}$ These results support the conclusion that the maximum kinetic energy is achieved when the proton injection efficiency is a maximum.

At first glance one might expect the fluence of an SEP event to increase in direct proportion to the pre-existing density of seed particles that have energies above the injection energy, without necessarily affecting E_{max} or the shape of the resulting fluence spectrum. However, we assert here that the standard theory of shock acceleration illustrated in Figure 7 can actually be a very non-linear process. For example, in the Li, Zank & Rice [30] model the wave intensity I is proportional to the injection rate N (see their Equations 19 and 20), where N [in units of ions/(cm^{2}s)], is given by N = $\alpha n u_{up}$. Here n is the seed-particle density (per cm^3), u_{up} is the background fluid speed measured in the shock frame, and α is a constant representing the fraction of seed particles that get injected. In this model the diffusion coefficient K is proportional to 1/I (see Equation 10 in [30]), and it is K that determines Emax. Thus, according to this model, the reduction in the seed particle density (n) in SC24 will in turn reduce the wave intensity (I) and allow ions to escape the shock more easily, resulting in a reduction in the maximum momentum P_{max} (and E_{max}), consistent with the average behavior in Figure 5 and Table 2. This conclusion is supported by the results in Figure 10, which shows that the maximum kinetic energy is a strong function of the proton injection rate.

Reducing the proton injection rate also causes spectral breaks for heavier ions to occur at lower energy, reducing the intensity above the break, in addition to the effect of the general reduction in heavy-ion suprathermal densities (Figure 9 and Table 3). Although heavy ions make a negligible contribution to the wave intensity (I), they respond to the waves produced by the protons and serve as test particles. The fact that heavy-ion spectra now break well below 10 MeV/nuc in SC24 leads to their greater reduction in Figure 3. The effects of variations in seed-particle densities were not considered in Zank et al. [37] or Li, Zank and Rice [30]. However, it is clear from their equations that the rate at which protons are injected into the acceleration process plays a key role in determining how high in energy ions are accelerated.

6. Discussion and Summary

We have identified two possible causes for the reduced SEP intensities in Solar Cycle 24: a significantly weaker coronal and interplanetary magnetic field and a reduction in the mean density of suprathermal seed particles with energies less than ~1 MeV/nucleon. Although we know that the weaker field affects the acceleration rate and thus the efficiency and maximum energy of SEP acceleration processes, we cannot quantify these effects without knowledge of $\delta B/B$ near the Sun. In this paper we propose that the reduction in seed particle densities during SC24 may also limit the maximum SEP energy at quasi-parallel shocks because the proton injection rate controls the growth of wave activity that keeps particles confined near the shock.

Two studies have shown an increase in SEP fluences as a function of the seed particle density (at 1 AU) prior to the SEP onset. Mewaldt et al. [40] found the maximum intensity of >10 MeV/nuc Fe was approximately proportional to the 1-AU number density of 0.04-2.3 MeV/nuc Fe one day previous to the event. They attributed this to the proposition that CME shocks accelerate mainly suprathermal seed particles, and suggested that the peak intensity was limited in part by seed particle availability. Kahler and Vourlidas [41] found a significant correlation between the pre-existing intensity of 2 MeV protons and the peak intensity of >20 MeV proton events. They suggested that the correlation “is explained by a general increase in both background seed particles and more frequent CMEs during times of higher solar activity”. These two statements are not inconsistent, and they may also offer a possible explanation for the somewhat controversial finding [42] that SEP events are generally more intense if they are preceded by a CME from the same active region during the previous 24 hours. The role of seed-particle densities in determining the intensity and maximum energy in SEP events needs to be tested with a series of controlled simulations exploring the key parameters.

It is likely that both of these factors are at work, but the reduced solar and interplanetary magnetic field strength is probably the more important of the two. The reduced coronal and interplanetary magnetic field strength is common to the entire SC24 time period under study (~71% of the time B was weaker during this cycle than on the corresponding day of the previous cycle). The effects of the reduced IMF are evident in greatly reduced geomagnetic activity during this period, and while we currently lack knowledge of dB/B near the Sun, it is generally true that particle acceleration proceeds more slowly in a weaker magnetic field (e.g. [40]). The SC24 suprathermal ion densities are significantly lower in SC24, but there is considerable overlap between the SC23 and SC24 density distributions in Figure 9.

Further theoretical work, modeling, and solar wind and SEP data will help decide the relative importance of these two factors. These issues will also undoubtedly be an early focus of studies by the upcoming Solar Probe Plus and Solar Orbiter missions.

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7. References

[1] M. A. Lee, J. Giacalone, and R. A. Mewaldt, *"Shock Acceleration of Ions in the Heliosphere",* Space Science Reviews 143, 247, doi:10.1007/s11214-012-9932-y (2012).

[2] C. K. Ng, and D. V. Reames, *"Shock Acceleration of Solar Energetic Protons, the first 10 Minutes",* Astrophysical Journal, 686: L123, 20, 2008.

[3] T. G. Onsager, R. Grubb, et al., *"Operational Uses of the GOES Energetic Particle Detectors"*, in GOES-8 and Beyond, SPIE Conf. Proc. 2812, 281, E. R. Washwell, ed. (1996)

[4] N. Gopalswamy, Sachiko Akiyama et al., *Anomalous Expansion of Coronal Mass Ejections during Solar Cycle 24 and its Space Weather Implications*", Geophysical Research Letters, 41, 2673, doi:10.1002/2014GL059858 (2014).

[5] N. Gopalswamy, Hong Xie, et al., "*Major Solar Eruptions and High-Energy Particle Events during Solar Cycle 24*", Earth, Planets and Space, 66:104, doi:10.1186/1880-5981-66-104 (2014).

[6] E. C. Stone, A. M. Frandsen, et al., *"The Advanced Composition Explorer"*, Space Science Reviews, 86, 1 (1998).

[7] SOHO.esac.esa.int and SOHOwww.nascom.nasa.gov/home.html

[8] M. L. Kaiser, T. A. Kucera, et al., *"The STEREO Mission: An Introduction"*, Space Science Reviews, 136, 5, DOI://10.1007/978-0-387-09649-0_2 (2008).

[9] R. A. Mewaldt, C. M. S Cohen et al. *"A 360° Survey of Solar Energetic Particle Events, and one Extreme Event",* in Proceedings of Science, The 34th International Cosmic Ray Conference (2015).

[10] C. T. Russell, R. A. Mewaldt, et al., "*The very Unusual Interplanetary Coronal Mass Ejection of 2012 July 23: A Blast Wave Mediated by Solar Energetic Particles"*, Astrophysical. Journal, 770, doi:10.1088/0004-637X/770//1/38 (2013).

[11] R. A. Leske, J. R. Cummings et al., *"Measurements of the Ionic Charge States of Solar Energetic Particles using the Geomagnetic Field*, Astrophysical Journal, L149, 1995.

[12] www.ngdc.noaa.gov/stp/solar/solarflares.html#xray

[13] www.umbra.nascom.nasa.gov/SEP/

[14] www.swpc.noaa.gov/noaa-scales-explanation

[15] N. Thakur, N. Gopalswamy et al., *"Ground Level Enhancement in the 2014 January 6 Solar Energetic Particle Event",* Astrophysical Journal Letters, 790:L13, doi:10.1088/2041-8205/790/1/L13 (2015).

[16] www.ngdc.n0aa.gov/stp/geomag/kp_ap.html

[17] R. A. Mewaldt, A. Davis, et al., *"Record Breaking Cosmic Ray Intensities During 2009-2010"*, *Astrophysical Journal Letters* 723, L1, doi:10.1088/2041-8205/723/1.

[18] D. J. McComas, N. Angold, et al., *"Weakest Solar Wind of the Space Era and the Weak Mini-Maximum",* Astrophysical Journal, 779:2, doi:10.1088/0004-637X/779/1/2 (2013).

[19] D. Band, J. Matteson et al., "*BATSE Observations of Gamma-Ray Burst Spectra*", Astrophysical Journal, 413, 281 (1993).

[20] R. A. Mewaldt, M. D. Looper, et al., "Energy Spectra, Composition, and Other Properties of Ground-Level Events During Solar Cycle 23", *Space Science Reviews,* 171, 97, doi:10.1007/s11214-012-9884-2 (2012).

[21] D. C. Ellison and R. Ramaty, *"Shock Acceleration of Electrons and Ions in Solar Flares"*, Astrophysical Journal 298, 400 (1985).

[22] M. A. Lee, "*Coupled Hydromagnetic Wave Excitation and Ion Acceleration at Travelling Interplanetary Shocks*", Journal of Geophysical Research, 88, 6109 (1983).

[23] M. Lee, "*Diffusive Ion Acceleration by CME-Driven Shocks"*, in Solar Eruptions and Energetic Particles, AGU Monograph 165, M. Gopalswamy, R. Mewaldt, and J. Torsti, eds, p. 245 (2006).

[24] C. K. Ng and D. V. Reames, *"Focused Interplanetary Transport of Approximately 1 MeV Solar Energetic Protons through self-generated Alfven Waves*", Astrophysical Journal 424, 1032 (1994).

[25] C. M. S. Cohen, E. C. Stone et al., *"Heavy Ion Abundances and Spectra from the Large Solar Energetic Particle Events of October-November 2003",* Journal of Geophysical Research, 110, A09S16, doi:10.1029/2005JA011004 (2005).

[26] R. A. Mewaldt, C. M. S. Cohen, et al., *"Proton, Helium, and Electron Spectra during the Large Solar Particle Events of October-November 2003",* Journal of Geophysical Research, 110, A09S18, doi:10.1029/2005JA011038 (2005).

[27] R. A. Mewaldt, C. M. S. Cohen, et al., *"Solar Energetic Particle Spectral Breaks",* in The Physics of Collisionless Shocks*,* 4th IGPP International Astrophysics Conference, AIP Conf. Proceedings #781, G. Li, editor, pp. 227-232 (2005).

[28] A. J. Tylka, C. M. S. Cohen,, et al., *"Shock Geometry, Seed Populations, and the Origin of Variable Elemental Composition at High Energies in Large Gradual Solar Energetic Particle Events"*, Astrophysical Journal, 625, 474 (2005).

[29] G. Li, G. P. Zank et al., *"Shock Geometry and Spectral Breaks in Large SEP Events",* Astrophysical Journal, 702, 998, doi:10.1088/0004-637X/702/2/998 (2009).

[30] G. Li, G. P. Zank, et al., *"Acceleration and Transport of Heavy Ions at Coronal Mass*

Ejection-Driven Shocks" G. Li, Journal of Geophysical Research, 110, doi:10.1029/2004JA010600 (2005).

[31] G. Li and M. A. Lee, *"Scatter-Dominated Interplanetary Transport of Solar Energetic Particles in Large Gradual Events and the Formation of Double Power-Law Differential Fluence Spectra of Ground-Level Events during Solar Cycle 23",* Astrophysical Journal, 810:82 doi:10.1088/0004-637X/810/1/82 (2015).

[32] G. M. Mason, J. E. Mazur, et al., "*^{3}He Enhancements in Large Solar Energetic Particle Events*", Astrophysical Journal, 525, L133 (1999).

[33] H. Kucharek, E. Moebius, et al., *"On the Source and Acceleration of Energetic He$^+$: A Long-Term Observation with ACE/SEPICA"*, Journal of Geophysical Research, 108, A10, 8040, doi:10.1029/2003JA009938, (2003).

[34] M. I. Desai, G. M. Mason, et al., "*Heavy-Ion Elemental Abundances in Large Solar Energetic Particle Events and Their Implications for the Seed Population*", Astrophysical Journal 649, 470 (2006).

[35] R. A. Mewaldt, C. M. S. Cohen, et al., "*On the Differences in Composition between Solar Energetic Particles and Solar Wind"*, Space Science Reviews, doi:10.1007/s11214-007-9187-1 (2007).

[36] J. Giacalone,*"Diffusive Shock Acceleration of High-Energy Spectra of Ground-Level Events during Shock Acceleration of High Energy Charged Particles at Fast Interplanetary Shocks: A Parameter Study:* Astrophysical Journal, 799:80, doi:10.1088/0004-637X/799/1/80 (2015).

[37] G. P. Zank, G. Li, et al., *Particle Acceleration at Perpendicular Shock Waves: Model and Observations"*, Journal of Geophysical Research, 111, A06108, doi:10.1029/2005JA011524 (2006).

[38] G. Li, *"Particle Acceleration and Transport in the Inner Heliosphere",* in 32nd International Cosmic Ray Conference, Bejing, (2011).

[39] D. Caprioli and A. Spitkovsky, *Simulations of Ion Acceleration at Non-Relativistic Shocks. I. Acceleration Efficiency,* Astrophysical Journal, 783:91, doi:10.1088/0004-637X/783/2/91 (2014).

[41] R. A Mewaldt, C. M. S. Cohen, et al., *"The Dependence of Solar Energetic Particle Fluences on Suprathermal Seed-Particle Densities",* in Space Weather: The Space Radiation Environment, Q. Hu et al. editors, AIP Conference Proceedings 1500 (2012).

[42] S. W. Kahler and A. Vourlidas, *Do Interacting Coronal Mass Ejections Play a Role in Solar Energetic Particle Events?* Astrophysical Journal, 784:47, doi:10.1088/0004-637X/784/1/47 (2014).

[43] N. Gopalswamy, S. Yashiro, et al., "*Intensity Variation of Large Solar Energetic Particle Events associated with Coronal Mass Ejections*", Journal of Geophysical Research, 109, A12105, doi:10.1029/2004JA010602 (2004).

[44] T. K. Gaisser, *Cosmic Rays and Particle Physics,* Cambridge University Press, Cambridge (1993).