What causes the variability in the properties of energetic storm particle (ESP) events?

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Abstract. Energetic storm particle (ESP) events are enhancements above ~0.05 MeV/nucleon ions near 1 AU in association with the passage of an interplanetary (IP) coronal mass ejection (ICME). The primary candidate of producing these enhancements is diffusive shock acceleration (DSA). ESPs can produce significant increases in the near-Earth particulate radiation and pose severe hazards to astronauts and hardware in space. Physical parameters thought to affect ESP production include IP shock properties (e.g., speed, strength, obliquity) and conditions upstream of the propagating shock (e.g., seed population, ambient plasma conditions). Several theoretical and observational studies tried to relate ESP production to these drivers; however, reliable prediction of ESP properties (e.g. intensities, spectra, abundances), including their event-to-event variability, has so far proven elusive. This indicates an incomplete understanding of how ICME-driven IP shocks accelerate ESPs.

Using instruments onboard ACE, we investigate the relations between a large set of parameters (28) that characterize (i) ESP properties, (ii) IP shock and ICME properties, and (iii) the upstream and downstream conditions measured across the IP shock. Ee present a comprehensive correlation matrix between all parameters and those of the ESP properties, in an attempt to identify the dominant parameters that influence ESP production and variability. We find that within the selected dataset, (1) spectral and compositional relations strongly indicate a rigidity-dependent acceleration mechanism, (2) correlations between observations and DSA predictions are poor, (iii) ICME sheath temperature appears to play a role in determining the ESP peak intensities.
1. Introduction

Fast interplanetary (IP) coronal mass ejections (CMEs) often drive shock waves through the corona and the IP medium. These shocks are sometimes accompanied by enhancements in the intensities of energetic ions above ~0.05 MeV/nucleon (e.g., Armstrong et al. 1985; Richter et al. 1985; Scholer 1985; Kennel et al. 1986; Reames 1999) known as energetic storm particle (ESP) events. ESPs can last for several hours and their associated particle enhancements might arrive ahead or behind the shock (e.g., Cohen 2006, Giacalone 2012). A classic ESP event (see Lario et al. 2005 for ESP categorization) is illustrated in Figure 1.

![Figure 1](image.png)

Figure 1: A classic ESP event observed at ACE. (a) Intensity-time profiles of 0.5–2.0 MeV/nucleon \(^{3}\)He, \(^{4}\)He, O, and Fe nuclei. (b) 5 minute average of the magnetic field magnitude B (in blue) and the 5 minute average of the solar wind speed from 2000 June 20 through 26. Purple vertical line marks the arrival of the interplanetary shock at ACE at 1227 UT on 2000 June 23.

The primary candidate for accelerating energetic particles at CME-driven shocks is thought to be the diffusive shock acceleration (DSA), comprising the shock-drift mechanism at quasi-perpendicular shocks (Decker, 1981), and the first-order Fermi mechanism at quasi-parallel shocks (Lee, 1983). DSA theory lays some expectations for ESP properties and how they relate to their IP shock properties and ambient conditions. For instance, (i) the acceleration of a mono energetic seed population results in a power-law with a spectral index, \(\gamma\), that is independent of ion species and determined solely by the IP shock density compression ratio, (e.g. Van Nes et al. 1984). The stronger the compression, the flatter (i.e., lower spectral index) the spectrum. Tylka et al. (2005) suggested that particle abundances at the shock have a dependence on shock obliquity, with quasi-perpendicular shocks being more likely to produce heavy ion enhancements compared to quasi-parallel shocks. This ties into the effects that limit the acceleration processes, such as shock geometry (width, curvature), escape of ions from shock, and/or finite acceleration time, to produce a characteristic exponential rollover with e-folding energy \(E_0\) that is species-dependent (e.g., Jones & Ellison 1991; Li et al. 2003). \(E_0\) in this case depends on the diffusion coefficient, which increases with ion rigidity, such that higher rigidity ions (e.g., Fe) are accelerated less efficiently than lower rigidity ions (e.g., O). Furthermore, Zank et al. (2006) suggested that quasi-parallel shocks accelerate protons to higher energies more efficiently than quasi-perpendicular shocks, and that the latter are more likely to accelerate particles out of a pool of pre-
energized source material than from to the solar wind, thereby producing ESP events with different composition than those generated by parallel shocks. These authors suggested that the maximum energy that particles can attain is a function of the upstream turbulence for perpendicular shocks and the generation of self-excited waves by the accelerated particles for parallel shocks. For the latter case, Giacalone et al. (2003, 2005) argued that sometimes the self-excited waves are not necessary for the particle acceleration. Other approaches have included detailed treatment of field geometry and shock evolution (e.g., Lee 2005), coupling particle acceleration, transport, and wave generation (Vainio & Laitinen 2007, 2008; Ng & Reames 2008), parameterizing the particle source at the shock and comparing with observations (e.g., Lario et al. 1998; Aran et al. 2005), and finally, a hybrid approach that combines analytical, MHD, and numerical simulations (Zank 2000; Li et al. 2003; Rice et al. 2003).

Observational evidence is undoubtedly a decisive way to test the ESP theoretical predictions. Measurements at 1 AU have shown that ESP properties exhibit significant event-to-event variations. Reames et al. (2012; see also Mäkelä et al. 2011) found that ESP proton intensities strongly correlate with the IP shock speeds, but these intensities varied broadly for similar shock speeds, as shown in figure 2a. This indicates that the physical processes responsible for producing this variability are likely dependent on the interplay of several parameters associated with ESP events.

**Figure 2:** (a) Large intensity variations for similar shock speeds, suggesting complex inter-connected physical processes at play. (b) Upstream Fe/O is related to the ratio present at the shock. (c), (d) Predictions of the DSA theory do not often agree with observations when numerous events are involved. Predicting ESP properties from DSA theory has proven to be difficult.
ESP abundance ratios and spectral properties have also proven difficult to predict due to their high variability when correlated with various parameters. Desai et al. (2003; 2004) surveyed ~72 IP shocks and associated ESP events that occurred during the ascending phase of solar cycle 23 and found that the Fe/O ratio exhibited strong energy-dependent behavior only in ~25% of these events. The authors also found that the 0.5–2 MeV/n. Fe/O ratio during the ESP event is well correlated with that measured upstream prior to the event (see figure 2b), the 0.1–0.5 MeV/n. oxygen spectral indices in ESP events at 1 AU are poorly correlated with the steady state prediction of the indices using the magnetic compression ratio at the shock (figure 2c), and that there is poor agreement between the spectral break energy and the local shock speed and obliquity. The latter results were confirmed by a multi-spacecraft study performed by Ebert et al. (2016) using ESP events measured at longitudinally-separated spacecraft, as illustrated in figure 2d. Finally, Lario et al. 2005 performed a detailed ESP case-study in context of the DSA theory predictions and found that although many of the event signatures were consistent with the predictions of DSA, heavy-ion elemental abundances were indeed poorly correlated with the solar wind composition.

To summarize, numerous theoretical and observational studies showed that IP shock and ESP properties exhibit large event-to-event variability and non-conclusive linkage, but the associated parameters provide strong insights into the physical mechanisms that produce ESPs. A detailed systematic examination of these parameters, along with modeling, is thus critical to characterize the ESP event-to-event variability, sources, acceleration, and transport processes and to understand and ultimately be able to predict ESP properties at 1 AU.

In this article, we perform a comprehensive analysis using several instruments onboard the Advanced Composition Explorer (ACE; Stone et al. 1998a) spacecraft, and examine the linear correlations between a large set of parameters that characterize (i) ESP properties, (ii) IP shock and ICME properties, and (iii) the upstream and downstream IP conditions measured near the IP shock.

2. Data Selection and Observations

We use energetic ion, solar wind plasma, and magnetic field data from the Ultra–Low-Energy Isotope Spectrometer (ULEIS; Mason et al. 1998), Solar Isotope Spectrometer (SIS; Stone et al. 1998b), the Solar Wind Electron Proton Alpha Monitor (SWEPAM; McComas et al. 1998), and the magnetometer (Smith et al. 1998) on board ACE. To select the events in this study, we started with a list of 72 CME-driven IP shocks that were associated with ESP enhancements identified in Desai et al. 2003 between 1997 October 1 and 2002 September 30. The selection criteria for the events were constrained by the following conditions, (1) The 0.5–2.0 MeV/n. $^4$He, O, and Fe intensities should increase by at least a factor of 5 within a 24 hour period centered on the arrival of the shock. (2) The intensity-time profiles of different species should track each other, indicating a common acceleration and transport history for all species. (3) The associated Fe-group ions in the 0.3–3.0 MeV nucleon energy range should not exhibit velocity dispersion during onsets, indicating that the ions are accelerated in Interplanetary space near 1 AU.

We then visually examined all events and eliminated those where the IP shock appeared to be a driveless event, meaning that the event was not driven by a ICME or a corotating interaction region (CIR) [e.g., Gopalswamy et al., 2009]. The presence of a magnetic ejecta and a sheath region were used as signatures to determine the ICME boundaries (see Richardson and Cane 2010). These criteria left us with 62 ICME-associated ESP events. For each identified event, we then derived a comprehensive list of parameters that are descriptive of the properties and conditions of the IP shock, the ICME, the ESP event, and the ambient environment near the shock. Because the energetic particle event (i.e., the ESP component) evolves continuously with the traveling shock, whereas the shock itself is a discontinuity and many of its properties are very localized, the inferred parameters were calculated using different sampling time periods. Parameters of interest and a brief description of how they were determined are detailed in the following subsections.
2.1 ESP properties

ESP properties include the spectral and composition properties of heavy ions ($^3$He, $^4$He, C, O, Fe), following the procedure illustrated in Desai et al. 2003, 2004. Spectral indices are determined by fitting a power-law of the form $j(E) = j_0 E^{-\gamma}$ ($0.1$-$0.5$ MeV/n.) and the e-folding energies ($E_0$) are determined from fitting the spectral function $j(E) = j_0 E^{\gamma} \exp(-E/E_0)$, at ~$0.1$-$5$ MeV/n. Peak O intensity ($I_{\text{max}}^0$) is the maximum hourly averaged $0.5$–$2.0$ MeV/n. helium mass histograms (for examples, see Desai et al. 2001, Dayeh et al. 2017) and the average $0.5$–$2.0$ MeV/n. helium mass histograms. The $^3$He/$^4$He and Fe/O ratios are respectively calculated from the $0.5$–$2.0$ MeV/n. helium mass histograms and the average $0.5$–$2.0$ MeV/n. helium mass histograms.

2.2 IP shock and interplanetary environment properties

Measurable quantities upstream and downstream of the shock are determined over a fixed analysis interval of eight minutes, following the procedure described in Kilpua et al. 2015. The number of data points within the analysis intervals varied with the data resolution and availability. A minimum of three points was required to determine an average. If a particular data product is not available for the shock time period (e.g., data gap, saturation), the value of the respective parameter gets flagged and excluded from the analysis via pairwise deletion. Values were cross-checked with the ip shocks database hosted at (http://ipshocks.fi; see also Kilpua et al. 2015). Inferred parameters include, upstream and downstream magnetic field magnitude, proton number density, speed, and temperature ($B_U$, $B_{U_i}$, $n_{U_i}$, $V_{U_i}$, $V_{U_i}$, $T_{U_i}$, $T_{U_i}$ respectively), in addition to the shock speed and obliquity ($V_{\text{shock}}, \theta_{\text{B_i}}$). Finally, Fe/O upstream and downstream were also calculated from the average $0.5$–$2.0$ MeV nucleon$^+$ Fe and O intensities 3 hours before (Fe/O$^U$) and after (Fe/O$^D$) the shock arrival time.

2.3 ICME shock properties

Focus here is on the plasma parameters in the sheath region, namely, the sheath pressure ($P_{\text{sheath}}$), temperature ($T_{\text{sheath}}$), and number density ($n_{\text{sheath}}$). Values are calculated using the corresponding data within three hours after shock arrival (i.e., downstream).

A total of 28 parameters were inferred for each of the selected 62 events. We then performed a Pearson correlation analysis between all parameters and those of the ESP properties, as indicated in table 1. This table shows a heatmap that is color-coded between -1 and +1, and provides the correlation coefficient ($r$) between ESP properties and each of the parameters characterizing (i) ESP properties, (ii) IP shock properties, and (iii) ICME properties. Values of $r$ between $+0.7$ to $+1$ indicate a strong positive correlation, between $+0.4$ to $+0.7$ indicate a moderate positive correlation, and below $+0.4$ poor or no correlation. Similar classification is adopted if $r$ is negative. Overlaid numbers are those corresponding to the values of $r$ in each cell. Bold numbers indicate that the correlation is statistically significant within 0.05 significance level. We emphasize here that these correlation coefficients are descriptive of the linearity correlation only, which is not necessarily the only relation, since different quantities could be related by non-linear relationships and still show some linearity. Inspection of the scatter plot is thus necessary in all cases. However, the work reported here is meant to only examine the linearity between different parameters and full analysis is beyond the scope of this article.
Table 1: Correlation heatmap of all inferred parameters with those of ESP properties.
3. Discussion
Linear correlations between parameters associated with ESP events are presented. In the following subsections, we comment on some of these correlations in context of their driving physical mechanisms.

3.1 ESP vs. ESP correlations
Top 9 x 9 cells in table 1 show the correlation results for the spectral and compositional properties of the 62 ESP events. The correlation between parameters varies from poor to high. Figure 3a plots the Oxygen peak intensity at ~1 MeV/n. versus the Oxygen spectral index. A moderate negative correlation ($r = -0.54$) is shown. This trend indicates that the most intense ESP events tend to have harder (i.e., flatter) spectra. Similarly, smaller ESP events would be characterized with softer (steeper) spectra.

Figure 3: (a) power-law spectral indices of O vs. the maximum O peak flux at ~1 MeV/nucleon. (b) e-folding energies of O vs. that of Fe. The solid line has slope = 1 and represents a 1:1 correlation. (c) Scatter plot of Fe/O ratio and the e-folding energy of O. In all panels, N, r, and p denote the number of points, the linear correlation coefficient, and its statistical significance.

Figure 3b shows the relation between the e-folding energies of Fe and O. A moderate positive correlation ($r=0.47$) exits between the two quantities. Except for the two events at both extremes of $E^{Fe}_0$ (at ~0.12 and ~4.5 MeV/n.), the clustering of points shows that the relation between the two parameters is monotonic but not a 1:1 relation. Instead, it is obvious that $E^{O}_0$ extends to higher energy values (between ~0.3 and ~11 MeV/n.) compare to Fe (between ~0.2 to 2 MeV/n.). This could be explained by the rigidity-dependent acceleration mechanisms, where ions with higher charge-to-mass ratio (M/Q), such as Fe, are accelerated less efficiently than those with lower M/Q, such as O, leading to a faster roll over in the Fe spectrum before that of Oxygen, and producing the observed behavior. Figure 3c shows the relation between Fe/O ratio and $E^{O}_0$. A moderate correlation exists ($r=0.41$) and is also expected from a rigidity-dependent acceleration mechanism.

This part of table 1 also shows other moderate or strong correlations including,
- C and O spectral indices are strongly correlated, with the Fe correlation slightly weaker. This is probably not at odds assuming that C and O have very similar Q/M values, compared to Fe.
- $^3$He/$^4$He ratio is moderately correlated with Fe/O ratio ($r=0.55$). One mechanism that could produce behavior is the reacceleration of impulsive flare material by the IP shock. However, a closer examination of this correlation shows that that it is driven by 4 events, which have consistently high Fe/O and $^3$He/$^4$He ratios. The remaining events show no correlation.

3.2 ESP vs ICME properties
Figure 4 shows the relation between the downstream sheath temperature and the O peak flux at ~1 MeV/n. Sheath temperature is calculated as the 3-hour average downstream of the shock. While the
The total linear correlation coefficient is moderate ($r=0.44$), the trend behavior is quite interesting. For low sheath temperatures (below $\sim 2 \times 10^5$ K), O peak fluxes do not exceed $\sim 100$ particle/(cm$^2$ sr s MeV/n.); for higher temperatures (above $\sim 2 \times 10^5$ K), there seem to be a consistent trend of increasing peak fluxes with increasing temperature. This behavior suggests that there might be a threshold above which the ESP peak fluxes increase monotonically with the ICME sheath temperature. Such a trend could be a manifestation of many effects. For instance, it may be related to the shock geometry: temperature jumps at a quasi-parallel ($\theta_{Bn} \leq 45^\circ$) can differ significantly from a quasi-perpendicular shocks ($\theta_{Bn} > 45^\circ$) depending on plasma beta (e.g., Leroy et al., 1982; Burgess et al., 2005). Across a quasi-parallel shock, the jump of magnetic field is small; therefore the kinetic energy of the flow converts mostly to downstream thermal energy. At a quasi-perpendicular shock, however, the magnetic field jump is significant, so that part of the flow kinetic energy is converted to downstream magnetic field energy. This suggests that for shocks of similar compression ratio with similar upstream medium, the downstream temperature is higher for a quasi-parallel shock. Preliminary analysis of examining the effect of geometry on the observed trend of figure 4 does not confirm this (not shown). This, however, is mainly because in our sample, the number of quasi-parallel events is too little ($\sim 10$) compared to the quasi-perpendicular events ($\sim 50$), a larger sample is thus required to test the possible geometry dependence hypothesis. Furthermore, one should also compare the upstream plasma properties between quasi-perpendicular and quasi-parallel shocks.

Indeed, the observed trend could also be a result of an elevated upstream temperature for those large ESP events, a factor that could well be related to the accelerated particle intensities at IP shocks (e.g., Lario et al. 2017). Finally, the turbulence levels associated with all shocks involved might also contribute the observed trend, since turbulence is more intense behind quasi-parallel shocks than behind the quasi-perpendicular shock [Lucek et al., 2005]. Streaming protons can excite Alfvén waves in the upstream region, which are then transmitted into the downstream region. This process is much more efficient at a quasi-parallel shock than at a quasi-perpendicular shock. In the latter case, the inability of particles to stream away from the shock results in the very inefficient excitation of the upstream waves (Lee 1980, 2005; Zank et al 2000, 2006; Li et al. 2003, 2005).

![Figure 4: Sheath temperature ($T_{sheath}$) versus O peak flux at $\sim 1$ MeV/nucleon. Small and large ESP events appear to behave differently as a function of $T_{sheath}$.](image)

### 3.3 ESP vs IP shock properties

Figure 5a plots the shock obliquity and the O spectral indices averaged over two-hour intervals centered on the IP shock. Figure 5b shows the relation between the magnetic compression ratio and the O spectral indices. In both plots, the correlation is poor and quantities appear to be uncorrelated. The one-dimensional steady state theory predicts that density compression ratio and the spectral index
are correlated (e.g., Van Nes et al. 1984, Parker and Zank 2012, Zank et al. 2006, Giacalone 2012). Results shown indicate that the acceleration is likely less efficient than the theoretical predictions, or the simplified form of the DSA is just not applicable for comparison will all types of ESP events. Several studies (e.g., Lario et al. 2004; Ho et al. 2005) attempted to relate observed shocks of varying obliquity to the particle spectra expected from DSA theory. While DSA appears to be the most feasible explanation for particle acceleration at shocks, unfortunately, there are very few examples of one-to-one correspondence between DSA predictions and observations (e.g., Giacalone 2012 and references therein).

\[ \text{Figure 5: (a) shock obliquity versus the O spectral indices. (b) O spectral indices versus the magnetic compression ratio.} \]

Furthermore, we note that table 1 indicates a high correlation between the magnetic compression ratio \((B_d/B_u)\) and the roll-over energies of O and C in table 1. Upon closer investigation, the correlation appears to be driven by few events only. Finally, Shock speed \((V_{\text{shock}})\) shows moderate/poor correlation with all ESP properties.

In summary, using instruments onboard ACE, we investigate the relations between a large set of parameters (28) parameters that characterize (i) ESP properties, (ii) IP shock and ICME properties, and (iii) the upstream and downstream IP conditions measured near the IP shock. We present a comprehensive correlation matrix between all parameters and those of the ESP properties. We find that within the selected dataset, the (1) spectral and compositional relations strongly indicate a rigidity-dependent acceleration mechanism, (2) correlations between observations and the DSA predictions are poor, (iii) ICME Sheath temperature appears to play a role in determining the ESP peak intensities.

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5. References

[1] Aran A, Sanahuja B, Lario D 2005 Ann. Geophys. 23, 3047
[2] Armstrong T P, Pesses M E, Decker R B 1985 geo. mono. series, pp 271–285. doi:10.1029/GM035p0271
[3] Burgess D, Lucek E A, Scholer M, Bale S D, Balikhin M A, Balogh A, et al. 2005 Space Sci. Rev., 118, 205–222
[4] Cohen C M S 2006 Geophys. Monogr. Ser., 165, 275–282
[5] Dayeh M A et al. 2017 Astrophys J., 835, 155
[6] Decker R B 1981 J. Geophys. Res., 86, 4537
[7] Desai M I et al. 2003, Astrophys J., 588, 2 1149, 2003
[8] Desai M I et al. 2004, Astrophys J., 611, 2, 1156, 2004
[9] Desai M I, et al. 2001, Astrophys J. Lett., 553, L89, 2001
[10] Ebert R W et al. 2016, Astrophys J., 831 (2), 153
[11] Giacalone J 2012 Astrophys. J. 761, 28
[12] Giacalone J 2005 Astrophys J., 628, L37
[13] Giacalone J 2003 Plan. Sp. Sci., 51, 659
[14] Giacalone J and J R Jokipii 2012 Astrophys. J., 751, L33
[15] Gopalswamy N, Makela P, Xie N H, Akiyama S and Yashiro S 2009 J. Geophys. Res., 114, A00A22, doi:10.1029/2008JA013686.
[16] Ho G C, Roelof E C and Mason G M 2005, Astrophys. J., 621, L141
[17] Jones F C and Ellison D C 1991 Space Sci. Rev., 58, 259
[18] Kennel C F, Coroniti F V, Scarf F L, Liv esey W A, Russell C T and Smith E J 1986 J. Geophys. Res. 91:11917–11928. doi:10.1029/JA091iA11p11917
[19] Kilpua E K J, Lumme E, Andreeova K, Isavnin A and Koskinen H E J 2015 J. Geophys. Res., 120, 4112–4125, doi:10.1002/2015JA021138
[20] Leroy M M, Winske D, Goodrich C C, Wu C S and Papadopoulos K 1982 J. Geophys. Res., 87, 5081
[21] Lario D, Decker R B, Roelof E C, Viñas A F, Wimmer-Schweingruber R F and Berger L 2017 J. Phys.: Conf. Ser. 900 012012
[22] Lucek E A, Constantinescu D and Goldstein M L, et al. 2005, SSRv, 118, 95
[23] Lario D, Livi S, Roelof E C, et al. 2004, J. Geophys. Res., 109, A09S02
[24] Lario D, Sanahuja B and Heras A M 1998, Astrophys. J., 509, 415
[25] Lario D, et al. 2005 J. Geophys. Res., 10, A09S11, doi:10.1029/2004JA010940
[26] Lee M A 2005, Astrophys. J. Supp., 158, 38
[27] Lee M A 1983 J. Geophys. Res., 88, 6109
[28] Li G, Zank G P and Rice, W K M 2003, J. Geophys. Res., 108, 1082
[29] Li G, Zank G P and Rice, W K M 2005, J. Geophys. Res. A, 110, 06104
[30] Mäkelä P et al. 2011 J. Geophys. Res., 116, A8, A08101
[31] Mason G M, Gold R E, Krimigis S M, Mazur J E, Andrews G B, Daley K A, Dwyer J R, Heuerman K F, James T L, Kennedy M J, LeFev eres T, Malcolm H, Tossman B, Walpole P H 1998 Rev. Space Phys., 86, 1–4, pp 409–448
[32] McComas D J, Bame S J, Barker P, Feldman W C, Phillips J L, Riley P and Griffie J W 1998 Rev. Space Phys. 86, 1–4, pp 563–612
[33] Ng C K, Reames D V 2008 Astrophys. J. Lett. 686, L123
[34] Parker L N and Zank G P 2012 Astrophys. J., 757:97, 11pp
[35] Reames D V 1999 Space Sci Rev 90:413–491 doi:10.1023/A:1005105831781
[36] Reames D V 2012, Astrophys. J., 757, 93
[37] Rice W K M, Zank G P and Li G 2003, J. Geophys. Res., 108, A10
[38] Richardson I G and Cane H V 2010, Sol. Phys., 264
[39] Stone E C, Frandsen A M, Mewaldt R A, Christian E R, Margolies D, Ormes J F and Snow F 1998 Rev. Space Phys. 86, 1–4
[40] Stone E C, Cohen C M S, Cook W R, Cummings A C, Gauld B, Kecman B, Leske R A, Mewaldt R A and Thayer M R 1998 Rev. Space Phys. 86, 1–4, pp 357–408

[41] Smith C W, L’Heureux J, Ness N F, Acuña M H, Burlaga L F, Scheifele J 1998 Rev. Space Phys., 86, 1–4, pp 613–632

[42] Tylka A J et al. 2005 Astrophys. J., 625, 1, 474

[43] van Nes P et al. 1984 J. Geophys. Res., 89, 2122

[44] Vainio R and T Laitinen 2007 Astrophys. J., 658, 622–630

[45] Vainio R, and T Laitinen 2008 J. Atmos. Sol. Terr. Phys., 70, 467–474

[46] Zank G P, Rice W K M and Wu C C 2000, J. Geophys. Res., 101, 17093

[47] Zank G P, Li G, Florinski V, et al. 2006 J. Geophys. Res., 111, A06108

[48] Zank G P, Li G, Florinski V, Hu Q, Lario D, Smith C W 2006 J. Geophys. Res., 111, A06108, doi:10.1029/2005JA0111524

[49] Zank G P et al. 2000 J. Geophys. Res., 105, A11

[50] Zank G P et al. 2006 J. Geophys. Res., 111, A06108, 25079