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Energetic Particle Responses to Interplanetary Shocks Observed by ACE

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At very strong shock passages, protons (and other ions) may be accelerated at or near a spacecraft resulting in substantial particle intensities increases. Such events may be a significant space weather hazard, yet we are still unable to accurately forecast their arrival time or the magnitude of the particle increase. Here, we classify the >10 MeV proton response (observed by ACE/SIS) to passing shocks (identified by ACE/MAG, ACE/SWEPAM, SOHO/PM), examine heavy ion properties, and relate them to the measured shock parameters in an effort to further our understanding of these events and our ability to predict them.

1. Introduction

Increases in energetic particle intensities coinciding with the passage of an interplanetary shock have been studied for over 30 years. They were first reported by in 1962 [1] and named 'energetic storm particle events' (ESP events). Studying ESP events is a important aspect of space weather investigations. While energetic particle intensities are typically limited in solar energetic particle (SEP) events by the streaming limit [2], ESP increases can be orders of magnitude [3], potentially resulting in hazardous radiation levels. Only by studying these events and the related shocks can we hope to eventually be able to predict such situations and shock arrival times which are a key aspect of forecasting geomagnetic storms.

Additionally, ESP events currently afford us the only opportunity to study interplanetary shock acceleration *in situ*. Much is still not understood about shock acceleration and the resulting composition and spectra of energetic particles. Whether the orientation of the shock partially governs the heavy ion composition at >10 MeV/nucleon is currently under debate [4]. With spacecraft such as ACE and Wind we can measure the shock properties while concurrently studying the composition of the locally accelerated particle population.

In this work we started with a list of shocks identified by the ACE/MAG and ACE/SWEPAM teams (http://www-ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html) and added those shocks in 2005 as identified by the SOHO/PM team (http://umtof.umd.edu/pm/FIGS.HTML). We then examined ACE/SIS >10 and >30 MeV proton rates for 2 days surrounding the shock and classified the energetic particle response into 6 types. The first 5 types are identical to those detailed by [5]: (0) no enhancement, (1) classical ESP signature, (2) intensity spike at the shock, (3) classical ESP + intensity spike, (4) step-like increase at the shock, and (5) irregular profile. We have added a category (6) for those events where the particle intensity drops significantly or has a sharp change in decay rate at the shock. Although this last category cannot accurately be referred to as an ESP event (as there is no increase), there is a clear affect of the shock on the particle intensities which we wish to note.

Of the 354 shocks examined, only 57 of them had noticeable affects at >10 MeV. Of these 19 were in category 6 and so did not have increases in the particle intensity (see distribution in Figure 1, left panel). Clearly most shocks observed at 1 AU do not have an observable impact on the >10 MeV proton intensities.

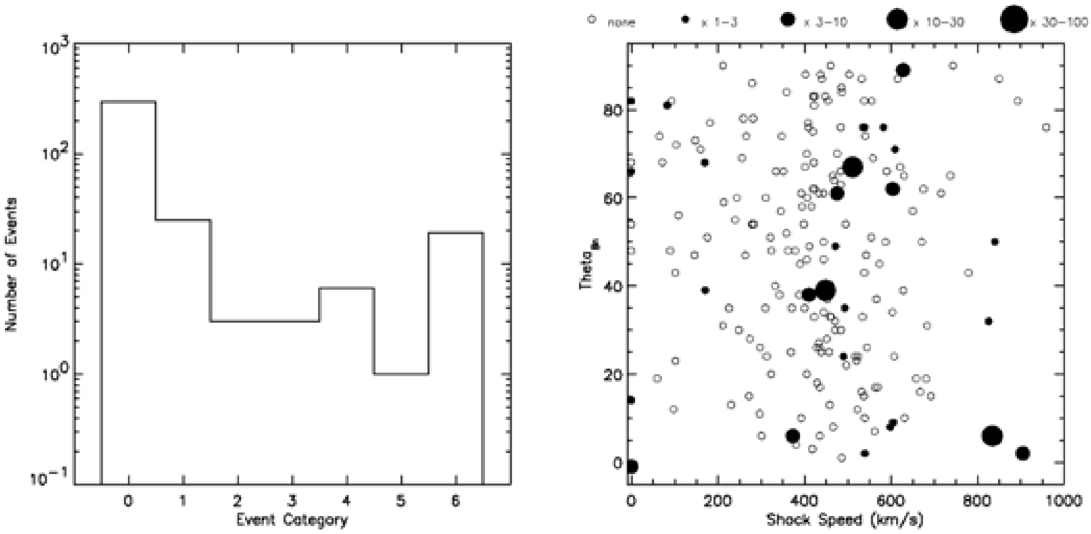

Figure 1. Distribution of events by category (left panel) and angle between the shock normal and the magnetic field versus shock speed for all examined shocks (right panel). Symbol size indicates factor by which the particle intensity increased in the event.

This is also consistent with studies at lower energies [5]. That there are fewer spike events (categories 2 and 3) is expected in that such events are typically observed only to ~5 MeV/nucleon [6]. The angle between the shock normal and the magnetic field (θ_{Bn}) is shown as a function of shock speed in the right panel of Figure 1 for all the events (events without calculated θ_{Bn} or shock speeds are plotted at -1). The symbol size and type indicates the magnitude of the particle increase as calculated by comparing the peak proton intensity within 1 hour of the shock passage to the intensity 4 hours prior to the shock passage. The size of the ESP event (i.e., increase factor) does not appear to be dependent on either the shock speed or the θ_{Bn} values. This, too, has been noted in previous studies at lower energies [e.g., 7].

2. Selected Largest Events

We have selected 6 events with large increases and sufficient oxygen intensities to create spectra (Table 1). A comparison of the >10 MeV H^+ and 8 MeV/nucleon O time profiles of these events is shown in Figure 2 (each trace is arbitrarily scaled vertically for clarity). It is rather surprising, given the similarity in the speeds and θ_{Bn} values of these events (except for 7/28/00 and 7/26/04, for the latter no parameters are available yet), that they are so different in magnitude and duration. Additionally, the H^+ and O time profiles for a given

Table 1. Selected Large ESP Events

Shock Time	Shock Speed (km./s)*	θ_{Bn} (degrees)*	>10 MeV H^+ increase	Fe/O (12-35 MeV/n)	γ-oxygen (8-30 MeV/n)
9/24/98 2315 UT	729 ± 38	71 ± 7	x 8.9	0.08 ± 0.06	-5.8 ± 01
7/28/00 0543 UT	472 ± 15	56 ± 5	x 28.0		-4.2 ± 1.2
4/19/02 0802 UT	748 ± 52	81 ± 4	x 10.7		-5.0 ± 0.1
5/23/02 1015 UT	764 ± 150	81 ± 2	x 20.2	0.018 ± 0.004	-4.88 ± 0.015
9/07/02 1610 UT	611 ± 27	87 ± 2	x 9.8	0.02 ± 0.01	-4.4 ± 0.1
7/26/04 2230 UT			x 3.8	0.03 ± 0.01	-4.4 ± 0.2

* from [8] http://space.mit.edu/home/jck/shockdb/shockdb.html

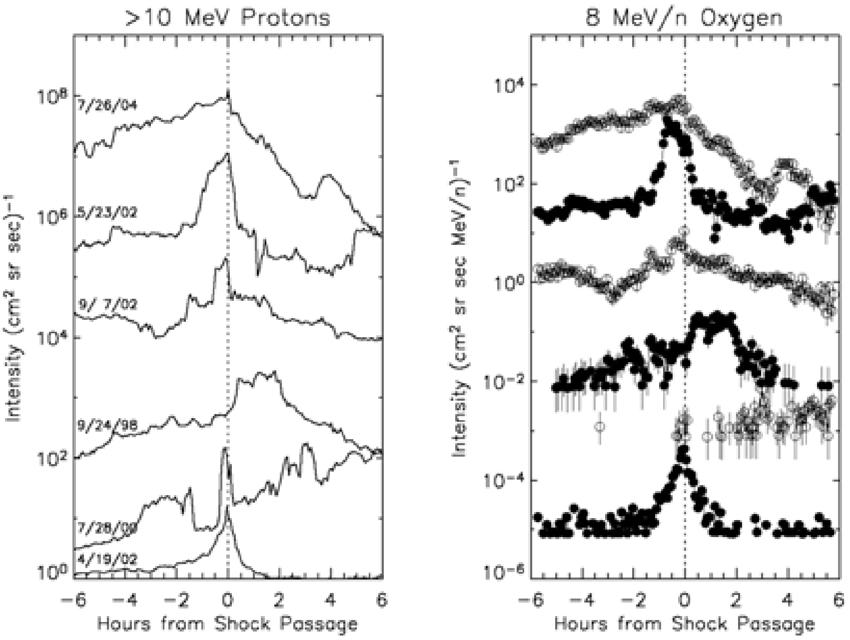

Figure 2. Observed intensity increases in >10 MeV protons (left panel) and 8 MeV/nucleon oxygen (right panel) as a function of hours from the passage of the shock for 6 selected events. Intensities have been scaled for clarity.

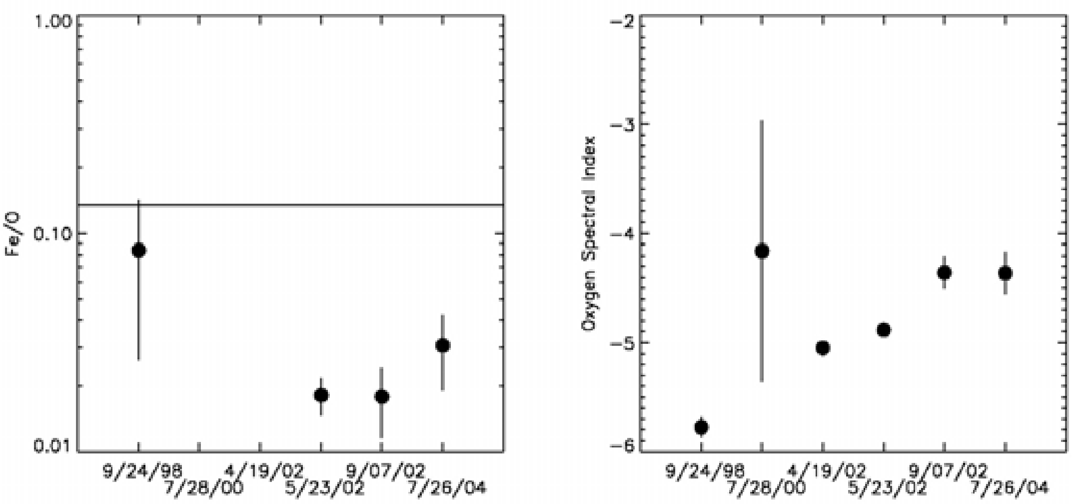

Figure 3. Event-integrated Fe/O abundances from 12 to 35 MeV/nucleon (left panel) for selected events. The horizontal line marks the average large SEP Fe/O value from [9]. Spectral indices of power-law fits to 8-30 MeV/nucleon oxygen intensities (right panel) for selected events.

event can be dissimilar (e.g., the 5/23/02 event). Perpendicular shocks (i.e., $\theta_{Bn} > 70$ or so) typically produce ESP events that are of short duration, centered at the shock passage, and limited to energies below ~5 MeV/nucleon [6], so it is surprising that most of these large events occur at perpendicular shocks and that the 9/24/98 event peaks well after the shock passage.

We have integrated the oxygen and iron intensities over the duration of the events (determined by eye). The Fe/O abundance ratios were determined by further integrating from 12 to 35 MeV/nucleon, although for two events there was insufficient Fe to calculate a ratio. The resulting values are plotted in the left panel of Figure 3 and listed in Table 1. Three of the 4 Fe/O ratios are significantly lower than that of average large SEP events (indicated by the horizontal line, [9]). This is perhaps surprising if one expects perpendicular shocks to produce enhanced Fe/O ratios [10], but could indicate an insufficient level of flare suprathermals. Further, it is difficult to fully account for the influence of the underlying SEP event on the composition.

The oxygen spectra were fit to a power law from 8 to 30 MeV/nucleon and the indices are shown for each event in Figure 3 and listed in Table 1. All of the events are quite soft with indices less than -4, consistent with previous observations [6]. The spectral indices do not appear to be organized by shock speed but do increase with increasing θ_{Bn}. This is opposite to what is expected, as ESP events associated with parallel shocks typically extend to higher energies than those of perpendicular shocks [6]. However this is largely a consequence of the relative ease of maintaining a parallel orientation for extended periods of time over sustaining a perpendicular one. Given the same amount of time, the shock processes involved at perpendicular shocks are generally faster and more efficient at generating high energy particles [6,10]. Unfortunately, the relatively small spread in θ_{Bn} values in this sample limits our ability to draw general conclusions regarding correlations.

3. Summary

In examining the >10 MeV proton response to shocks identified by the ACE/MAG, ACE/SWEPAM, and SOHO/PM instruments, we find most of shocks do not produce a measurable effect. For several large ESP events we have analyzed the oxygen and iron intensities and generally found low Fe/O ratios and very soft oxygen spectra. That the spectra are soft bodes well for those concerned about space radiation hazards, however increases by factors of ~10 in the proton intensities (as seen in several events) can be a large concern if intensities are already high. Work is currently ongoing to identify such events in real time using the ACE Real-Time-Solar-Wind data to provide some advanced warning for near-Earth space endeavors and those interested in geomagnetic storms.

4. Acknowledgements

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