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Variability of low-energy ion flux profiles on interplanetary shock fronts

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[1] Time-intensity profiles of 20–126 keV ions across interplanetary shocks are studied using data from ACE and Wind to determine the dependence of the profiles on spacecraft separation. Each pair of time-intensity profiles is examined to determine whether or not the same features (flat, classic energetic storm particle (ESP) rise, spikes, step functions, or complex patterns) are seen at both spacecraft. The persistence of particle profile patterns has a scale length in the plane of the shock of ~2.9 Mkm, but the scale length along the shock normal direction is not well determined.

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1. Introduction

[2] Collisionless shocks are believed to be the major source of energetic particles in space. It has been found, however, that particle profiles are highly variable from shock to shock, even for a given particle type within a limited energy range. Direct comparison between spacecraft observations and theoretical or numerical models of shock acceleration is complicated by the fact that energetic particles, being quite mobile, are accelerated at, and arrive from, different locations on the shock. Data from two or more spacecraft can be used to obtain a better understanding of the variability of energetic particles associated with interplanetary shocks. Here we perform just such a study by examining the intensity profiles of low-energy ions across interplanetary shocks seen by both ACE and Wind.

[3] In studying time profiles of ion fluxes or of the slopes of ion spectra at energies greater than a few tens of keV, several groups [*van Nes et al.*, 1984; *Tsurutani and Lin*, 1985; *Kallenrode*, 1995; *Lario et al.*, 2005a] have identified common patterns. Briefly, the shock observations can be categorized as (1) flat profiles with no intensity enhancement at the shock passage, (2) a slow, relatively smooth rise in intensity over several hours before the shock crossing (called Energetic Storm Particle, or classic ESP events), (3) spike events with increased fluxes or changes in spectral slope for a few minutes at or near the shock crossing, (4) step-like postshock intensity increases, and (5) irregular or complex profiles. Some regularities of the dependence of the particle categories on the properties of the shock were found by *van Nes et al.* [1984] and *Tsurutani and Lin* [1985], and, at higher energies, by *Kallenrode* [1995]. The studies generally agreed that (1) flat profiles are associated with slow, weak shocks, although not all weak shocks have flat profiles, (2) ESP events are associated with fast, strong, oblique shocks, and (3) spike events are associated with quasi-perpendicular shocks. By increasing the number of low-energy events analyzed, *Lario et al.* [2005a] showed that this observational trend is maintained but that the shock parameters do not uniquely determine the category of a shock's energetic particle profile.

[4] The theory of diffusive shock acceleration for a steady state, planar shock predicts a simple power law dependence of the energy spectrum of particles downstream of the shock. It also predicts that the intensity should increase exponentially upstream and become flat, or uniform, downstream of the shock. That this is very rarely seen in solar energetic particle events indicates that these shocks probably vary in time and space [*Lario et al.*, 2005b]. Additionally, it takes time to accelerate particles at a shock, and this acceleration time depends strongly on the angle between the magnetic field and shock normal direction, which varies considerably in the turbulent solar wind. The shock normal angle may also be important with regards to the injection problem, but recent studies have indicated that there is probably enough turbulence in the solar wind so that this is actually not a problem [*Giacalone*, 2005]. These considerations complicate the interpretation of direct comparisons between shock-acceleration theories and models and spacecraft data.

[5] Observations of the same shock by several spacecraft can be a useful tool to complement statistical studies of particle acceleration at a large number of shocks. Widely separated spacecraft have revealed global variations of both shock parameters and particle acceleration. For example, *Burlaga et al.* [1980] used Helios, Voyager, and IMP detectors to study the radial evolution of shock-associated energetic particles between 0.6 and 1.6 AU. For another example, *Kallenrode et al.* [1993] used Helios, Venera, and IMP data with radial separations up to 0.67 AU and angular separations up to 121° to study the variable efficiency of shock acceleration with distance from the Sun and from the nose of the shock. At the other extreme, the four Cluster

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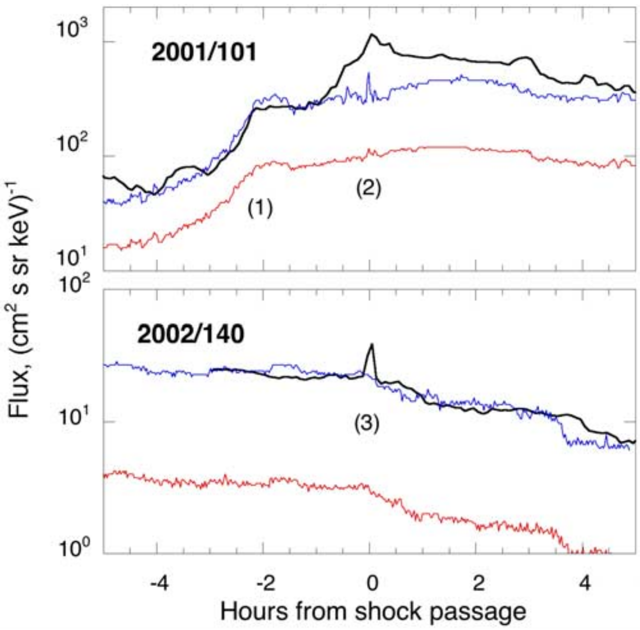

Figure 1. Flux of ions observed by ACE at 47–66 keV (black) and by Wind at 20–58 keV (blue) and 58–126 keV (red). (top) Two shocks observed on day 101 of 2002. The data have been time shifted to line up the passage of the second interplanetary shock. (bottom) A shock observed on day 140, 2002.

spacecraft can be used to study structures and processes on scales of hundreds to thousands of kilometers. At 1 AU, for example, shock reformation processes occur on scales of hundreds of kilometers [*Burgess*, 1989; *Scholer et al.*, 2003]. The several spacecraft orbiting Earth or near the L1 Lagrange point (0.01 AU sunward of Earth) can provide insights on intermediate scales up to 2 or 3 Mkm where interplanetary turbulence plays a role.

[6] In a study of shocks observed by five or more near-Earth spacecraft, *Neugebauer and Giacalone* [2005] showed that the shock normal directions were variable, with the most probable radii of curvature of the ripples in the shock surface being a few Mkm. The question then arises whether the time profile of a shock-associated energetic particle event changes on the same scale. If, as suggested by *Lario et al.* [2005a], the event type or category is not uniquely determined by shock parameters such as θ_{Bn}, the type might be intrinsic to a large section of a given shock front. In this paper we examine the stability or the variability of the intensity profiles of ions across shock surfaces over distances up to 2.5 Mkm which can be studied by the separation of the ACE and Wind spacecraft. The study is limited to low energies at which particles are most likely to be affected by local shock parameters.

2. Method of Analysis and Results

[7] For the present study we analyzed 86 shock events seen by both ACE and Wind. All particle data used in the analysis were level-2 (verified) data acquired through the CDAWeb service of the National Space Science Data Center. The energetic particle data for ACE are from the EPAM instrument [*Gold et al.*, 1998]. Specifically, we used spin-averaged data from the 47–66 keV channel of the LEMS120 telescope with a time resolution of 5 min. The corresponding data for Wind came from the 3DP experiment [*Lin et al.*, 1995], averaged over all directions, for the energy channels bracketing that of ACE-EPAM at 20–58 keV and 58–126 keV. The time resolution of the Wind particle data was 92 s.

[8] Magnetometer data were also used to find the time shift between shock passage at ACE and Wind. Data for this purpose again came from CDAWeb. We used 16-s data from the ACE magnetometer [*Smith et al.*, 1998] and 1-min data from Wind [*Lepping et al.*, 1995].

[9] Shock normal directions and other shock parameters were acquired from the eight-parameter fits to the Rankine-Hugoniot (RH) jump relations compiled by MIT (http://space.mit.edu/home/jck/shockdb/shockdb.html). There were a few Wind shocks for which other algorithms were deemed to be more accurate than the eight-parameter R-H fit, in which case we used the preferred results. For the few shock crossings for which ACE data were not included in the MIT database, we obtained shock parameters from the University of New Hampshire site (http://www-ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html).

[10] Spacecraft locations were obtained from the Satellite Situation Center of the National Space Science Data Center and were corrected for the time shift of the GSE coordinate system between the times of shock observations at the two spacecraft.

[11] Three sample shocks (labeled 1, 2, and 3) are shown in Figure 1 to illustrate the method used. The black curves

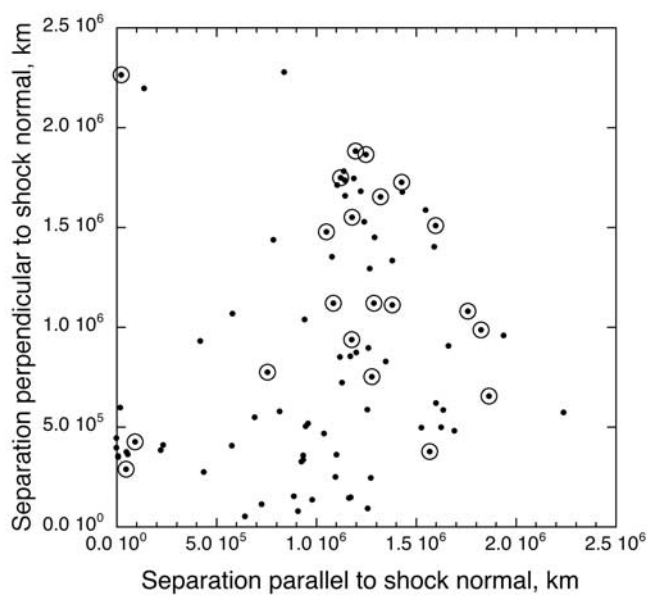

Figure 2. Scatterplot of the separation of the ACE and Wind spacecraft at the times of observation of the 86 interplanetary shocks included in the study. The vector separations are broken into their components along the shock normal and in the shock plane as determined at Wind. Circles denote a change in shock classification between ACE and Wind.

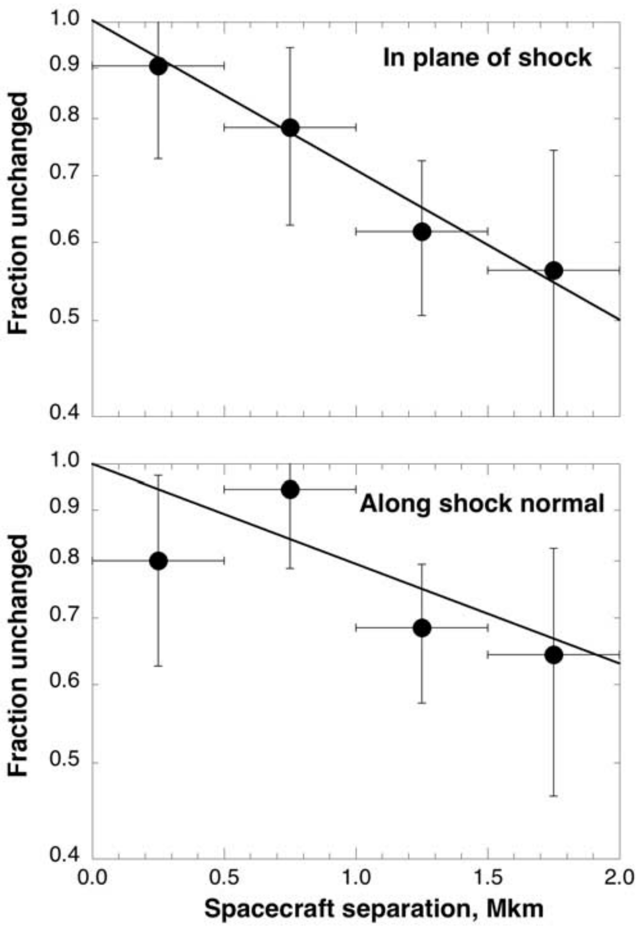

Figure 3. Fraction of energetic particle profiles that maintained their patterns between ACE and Wind as a function of the separation of the spacecraft in the plane of the shock and along the shock normal, based on shock normal directions calculated from Wind data. The lines indicate a fit to an exponential drop off with distance.

show the 47–66 keV data from ACE, while the blue and red curves show the 20–58 and the 58–126 keV data from Wind, respectively. For the top panel of Figure 1 the data were aligned according to the time of passage of the second shock as indicated by the magnetometer data. In all the other cases studied there was only a single shock at which the data were aligned. Plots similar to those shown in Figure 1 were drawn for each of the 86 shocks in the sample. Each plot contained data for 5 hours before and after the shock passage with a flux range sufficient to cover the data, typically two orders of magnitude. From those intensity profiles we judged whether the profiles seen at the two spacecraft had the same or different features such as spikes, slow or irregular rises to peaks at the shock, or null responses. When the Wind profile at 92-s resolution showed a spike and the ACE profile at 5-min resolution did not, we examined 1-min resolution ACE data to eliminate any bias associated with time resolution.

[12] The first shock in Figure 1, observed about 2.2 hours before the second, had a classic ESP profile at both spacecraft. The profiles differed, however, for the second shock, with ACE again exhibiting an ESP profile while the Wind profile was nearly flat. Both profiles showed a hint of a small spike at the second shock crossing. For the third shock, shown in the bottom panel of Figure 1, there was a spike at ACE but none at Wind. Thus shock 1 was judged to have similar profiles at both spacecraft while shocks 2 and 3 were judged to have different profiles.

[13] The results of this type of analysis for all 86 shock crossings are summarized in Figure 2. From the shock normal directions calculated from Wind data, the times of shock crossings at each spacecraft, and the locations of the two spacecraft, the spacecraft separations were calculated along the normal to the shock surface and in the shock plane (perpendicular to the shock normal). The two components of the vector separation serve as the abscissa and ordinate, respectively, for the data plotted in Figure 2 where each shock is indicated by a dot. Shocks for which the features of the particle profiles differed between the two spacecraft are circled (a total of 21 shocks or 24% of the events analyzed).

[14] Scale sizes for the preservation of profile type can be estimated by calculating the fraction of events for which the type did not change for bins of 0.5 Mkm along the two axes in Figure 2. The results are shown in Figure 3, excluding the bins from 2.0 to 2.5 Mkm for which there were very few events. The vertical error bars denote the probable error based on the number of shocks in each interval. The horizontal error bars denote the range of separations included in each estimate. The dropoff of the unchanged fraction as a function of separation in the plane of the shock (top of Figure 3) can be fit to a straight line in a log-linear plot to estimate a 1/e folding distance of 2.9 ± 0.2 Mkm. The exponential fit along the normal direction yields a 1/e folding distance of 4.2 Mkm, but the scatter is large. Part of the reason for the greater scatter along the shock normal is that the normal direction of the shock often changes between ACE and Wind (see *Neugebauer and Giacalone* [2005] and below), and the lower panel in Figure 3 is more sensitive to that effect than is the upper panel.

[15] Some parameters for the shocks shown in Figure 1 are listed in Table 1. The parameter θ_{Bn} is the angle between

Table 1. Shock Parameters for the Three Shocks Shown in Figure 1[a]

	Year/Day/UT	S/C	θ_{Bn}, deg	V_s, km/s	R_B	M_f
1	2001/101/1312	ACE	27.2 ± 8.7	622 ± 25	2.68 ± 0.56	1.80 ± 0.19
	2001/101/1409	Wind	16.2 ± 10.1	686 ± 23	3.60 ± 1.59	1.68 ± 0.40
2	2001/101/1524	ACE	44.4 ± 3.0	590 ± 80	1.93 ± 0.25	2.49 ± 0.07
	2001/101/1617	Wind	18.7 ± 9.9	801 ± 24	2.34 ± 0.24	1.25 ± 0.07
3	2002/140/0300	ACE	59.8 ± 2.3	641 ± 270	1.41 ± 0.11	2.37 ± 0.08
	2002/140/0336	Wind	28.0 ± 3.6	542 ± 20	1.77 ± 0.16	1.60 ± 0.05

[a]See the text for definitions.

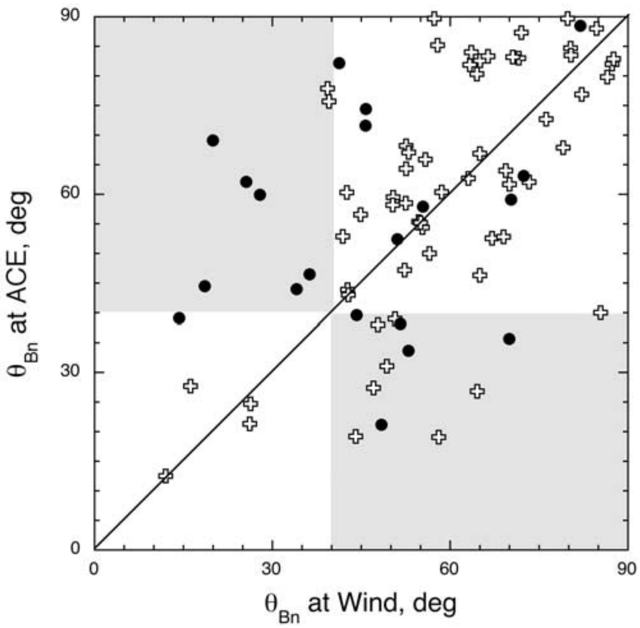

Figure 4. Angles between the shock normal and upstream field observed at ACE and Wind. Circles denote shocks that exhibited a change in the features of energetic particle profiles and crosses denote shocks whose profiles maintained their basic features. Shock events in the shaded regions of the plot changed between quasi-parallel and quasi-perpendicular, or vice versa.

the upstream field and the shock normal; V_s is the speed of the shock in the spacecraft frame; R_B is the compression ratio of the magnitude of the magnetic fields ahead of and behind the shock; and M_f is the fast Mach number. The systematics proposed by *van Nes et al.* [1984] and *Tsurutani and Lin* [1985] are consistent with the differences exhibited by shocks 2 and 3. For shock 2, the shock at ACE better met the criterion of a strong oblique shock associated with ESP profiles than did the shock seen at Wind; i.e., it was both stronger and more oblique. For shock 3, the greater value of $\theta_{\rm Bn}$ at ACE is consistent with the appearance of a spike which was absent for the weaker quasi-parallel shock seen by Wind.

[16] Of the 21 shocks whose profiles differed between ACE and Wind, 10 had differences greater than 20° in $\theta_{\rm Bn}$, six had statistically significant differing shock speeds, 10 had statistically significant differing compression ratios, and 11 had statistically significant differing Mach numbers. Some differed in two, three, or all four of those parameters. For one of the shocks with differing profiles, the difference in $\theta_{\rm Bn}$ was < 20° and the other three parameters agreed within their statistical limits, but the uncertainties in the shock speeds and Mach numbers were large.

[17] Figure 4 displays the values of $\theta_{\rm Bn}$ at ACE (on the ordinate) and Wind (on the abcissa) for 20 of the 21 shocks with differing profiles (indicated by circles) and 60 of the 65 shocks with similar profiles (crosses); shock angles were not available for six shocks. If the boundary between quasi-parallel and quasi-perpendicular shocks is defined by $\theta_{\rm Bn}$ = 40°, we see that slightly over half of the differing shocks are plotted in the shaded areas of the figure indicating a change from quasi-parallel to quasi-perpendicular, or vice versa. The other differing shocks were quasi-perpendicular at both spacecraft. Nine other shocks changed between quasi-parallel and quasi-perpendicular while maintaining the nature of their profiles. The correlation coefficient between $\theta_{\rm Bn}$(ACE) and $\theta_{\rm Bn}$(Wind) was 0.64 for shocks with similar profiles but only 0.16 for those shocks whose profiles changed.

[18] Ten of the 21 differing shocks showed a spike at only one of the spacecraft. For seven of those ten, the spike was present only at the spacecraft with the larger value of θ_{Bn}, in agreement with the earlier results of *van Nes et al.* [1984] and *Tsurutani and Lin* [1985].

3. Conclusions

[19] When examined over a time span of only a few minutes, the details of energetic particle fluxes in the vicinity of interplanetary shocks have been found to differ between ACE and Wind [*Neugebauer and Giacalone*, 2005]. The type or classification of an energetic particle event as defined by *Tsurutani and Lin* [1985], *Lario et al.* [2005a], and others becomes apparent only on a time scale of hours. The general features or classification of a profile can remain stable even while the details change.

[20] In the present study, 65 of 86 shocks had the same features at ACE and Wind, while 21 changed. For all but two of those 21, there was significant change in one or more of the shock parameters $\theta_{\rm Bn}$, V_s, R_B, or M_f as well as in the profiles. About half of the shocks with differing profiles changed from quasi-parallel to quasi-perpendicular, or vice versa; the other half were quasi-perpendicular at both spacecraft. For about two-thirds of the shocks with changing profiles, the profile differences were consistent with the earlier results of *van Nes et al.* [1984] and *Tsurutani and Lin* [1985], but the other third were not readily explained on the basis of the local shock parameters, in agreement with *Lario et al.* [2005a].

[21] The scale size of persistent particle features in the plane of the shock was 2.9 Mkm. Not surprisingly, this is approximately the same as the correlation length of the interplanetary magnetic field [*Jokipii and Coleman*, 1968; *Matthaeus et al.*, 1986] and of the radius of curvature of ripples on the shock surface [*Neugebauer and Giacalone*, 2005]. The scale size along the direction of the shock normal direction was less well determined, but appears to be greater, perhaps ~4.2 Mkm, than in the plane of the shock.

[22] The question of whether the observed profile changes are spatial, temporal, or both cannot be definitively answered by observations with only two spacecraft. We intend to address that question by simulation studies.

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